Chapter 3

Mechanisms of Charge Transport and Photoelectric Conversion in CdTe-Based X- and Gamma-Ray Detectors

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Additional information is available at the end of the chapter

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Abstract

This chapter deals with (i) the charge transport mechanisms in X- and gamma-ray detectors both Ohmic and Schottky types based on CdTe and its alloys with an almost intrinsic conductivity (the peculiarities of the formation of self-compensated complexes due to the doping of Cd(Zn)Te crystals with elements of III or V groups (In, Cl) are taken into account); (ii) the reasons of insufficient energy resolution in the X- and gamma-ray spectra taken with the detectors under study; (iii) the quantitative model which describes the spectral distribution of the detection efficiency of Cd(Zn)Te crystals with Schottky diodes; (iv) a correlation between the concentration of uncompensated impurities in the Cd(Zn)Te crystals and collection efficiency of photogenerated charge carriers in the detectors with a Schottky contact; (v) the possibility of applications of CdTe thin films with a Schottky contact as an alternative to the existing X-rays image detectors based on a-Se.

Keywords: X- and gamma-ray detector, CdTe, CdZnTe, CdMnTe, self-compensation, Schottky diode, concentration of uncompensated impurities, detection and collection efficiency

1. Introduction

The current state and development of technology, science, medicine and other fields of human activity are impossible without elemental analysis—a combination of methods of detection and quantitative determination of the elemental composition of objects of the material

world. The rapid development of the methods of elemental analysis began in the 1950s, when ionization chambers and scintillation devices were replaced with solid-state semiconductor devices—detectors of X- and γ-rays (X/γ-rays). Germanium (Ge) and silicon (Si) were the first materials for semiconductor detectors. Such detectors have high-energy resolution; however, cryogenic cooling is required to reduce "dark" electrical noise, which in many cases is impractical or even impossible. Because of the small atomic number Z, the absorptive capacity of Si (Z = 14) is low. Therefore, the registration of quanta with energies above 30–50 keV is practically impossible. The atomic number is Ge higher (Z = 32), but due to the narrower band gap, the problem of too large dark current becomes even more serious. For a long time, intensive search of alternative semiconductors for X/γ-rays detectors is being carried out. The main purpose is to reduce or even eliminate the disadvantages of Si- and Ge-detectors, namely, reducing of the "dark" current due to the expansion of the bandgap, detecting of higher energy quanta (>30–50 keV) due to the increase in Z and material density, and improving of the energy and time resolution due to increase in the life time and the mobility of charge carriers ($\tau\mu$ product). The possibilities of application as elementary semiconductors and insulators (e.g., diamond) as binary compounds (GaAs, GaP, HgI_2, PbI_2, CdSe, SiC, etc.) are studied. Currently, the most common semiconductors among binary and ternary II–VI compounds are CdTe and $Cd_{1\,x}Zn_xTe$.

Over 30 years, the heightened interest in CdTe and $Cd_{1-x}Zn_xTe$ detectors resulting from their high power and coordinate energy resolution, which allowed to expand their applications, in particular, in the devices for customs control and movement of dangerous goods, security systems in the airports, railway stations, transport highways, in crowded places [1–3]. Such detectors are also used in metallurgical, chemical, mining and nuclear industries, for radiation control by environmental services, for astrophysical applications. In addition, it is extremely promising to use CdTe as the base material in multielement (pixelated) detectors, which opens up the possibility of creating image detectors with direct X-rays conversion into electrical signals, in contrast to the "classical" X-ray devices where the detector is a screen, covered with a luminophore and hidden X-image can either observe or fix with a photoemulsion. A multielement detector allows you to convert information generated by passing X/γ-rays through an object directly into an array of digital electrical signals without using an intermediate visible image on a fluorescence screen. Such detectors allow real-time visualization of the X-ray image and sufficiently enhance the image resolution. The X- and γ-image CdTe detectors are already widely used in the flaw detection of materials with high spatial resolution, in medical tomographs with a small dose of a patient's irradiation, in mammographs, dental appliances, in the diagnosis of cancerous tumors.

Modern technology provides the growth of perfect CdTe crystals with almost intrinsic electrical conductivity. However, Ohmic detector's dark currents restrict the high-bias voltage for creation of a strong electric field which is necessary to full charge collection. In the 1990s, research of CdTe-based ternary compounds for X/γ-rays detectors has started. In particular, $Cd_{1-x}Zn_xTe$ (x = 0.1–0.2) crystals with a wider band gap, higher resistivity and lower dark currents in comparison with the CdTe detector has been studied. However, the expected prospects of $Cd_{1-x}Zn_xTe$ crystals remain unfulfilled because of high temperature of crystal growth, their crystalline imperfection, and the effect of segregation. This lack is absent in

$Cd_{1-x}Mn_xTe$ crystals, since the growth temperature of $Cd_{1-x}Mn_xTe$ crystals is lower than that of $Cd_{1-x}Zn_xTe$. Moreover, about two times less manganese in $Cd_{1-x}Mn_xTe$ than that zinc in $Cd_{1-x}Zn_xTe$ should be introduced for the expansion of the CdTe band gap. In the late 1990s, the first studies of the $Cd_{1-x}Mn_xTe$-based X/γ-ray detectors were carried out in the USA, Japan, and Europe. However, the spectrometric characteristics of the detectors are still significantly worse than those of CdTe and $Cd_{1-x}Zn_xTe$. At the end of the 1990s, CdTe detectors with Schottky diodes were developed. The detectors showed significantly better energy resolution in the wide range of photon energy up to 1 MeV and above [4]. However, spectrometric parameters not reproduced in all detectors made on the crystals with the same resistivity, carrier mobility and lifetimes. All this range of issues have led us to research, important both from the scientific and applied point of view, aimed at solving a number of physical problems, in particular: (1) investigation of the features of CdTe and $Cd_{1-x}Zn_xTe$ crystals electrical conductivity mechanism, doped with elements of the III or VII groups of the periodic system, taking into account the self-compensation effect; (2) determination of the reasons of low energy resolution of Cd(Zn,Mn)Te-based Ohmic detectors and finding the possibilities to improve the performance of detectors; (3) identify the charge transport mechanisms and the possibilities of reducing the current at high voltages in the X/γ-rays detectors with the Schottky diode in order to improve the device spectrometric characteristics; (4) search for a physical model of quantum efficiency spectral distribution which would explain a significant difference in energy resolution of the ^{55}Fe, ^{241}Am, ^{57}Co, ^{133}Ba, ^{137}Cs isotopes emission spectra taken with CdTe- and $Cd_{1-x}Zn_xTe$-based X/γ-rays detectors; (5) determining the influence of the Schottky diode's space charge region width and the concentration of uncompensated impurities both on the X/γ-rays detectors' quantum efficiency and the charge collection; (6) finding out the possibility of use of CdTe thin polycrystalline films with a barrier structure in detectors with direct X-ray conversion that provides low values of dark current, eliminates the problem of charge collection. Here, we summarize the results of our studies in the above-mentioned areas.

2. Features of conductivity of semi-insulating CdTe and CdZnTe single crystals

This section deals with the results of studies of CdTe crystals, doped with Cl and $Cd_{0,9}Zn_{0,1}Te$ crystals, doped with In, which are widely used for the creation of detectors. The results of the research reveal important features of the electrical characteristics of the crystals. **Figure 1a** presents the typical temperature dependences of the resistivity $\rho(T)$ of the CdTe [5–8] and CdZnTe [9, 10] crystals under study.

The temperature dependence of the intrinsic resistivity of CdTe and CdZnTe crystals $\rho_i(T) = 1/qn_i(\mu_n + \mu_p)$ is also shown for comparison (where де $n_i = (N_cN_v)^{1/2}\exp(-E_g/2kT)$ is the concentration of intrinsic charge carriers, $N_c = 2(m_nkT/2\pi\hbar)^{3/2}$ and $N_v = 2(m_pkT/2\pi\hbar)^{3/2}$ are the effective density of states in the conduction band and the valence band of the semiconductor, respectively). As seen, the values of ρ and ρ_i of both CdTe and CdZnTe are quite close in the whole temperature range, which is important taking into account the necessity to minimize

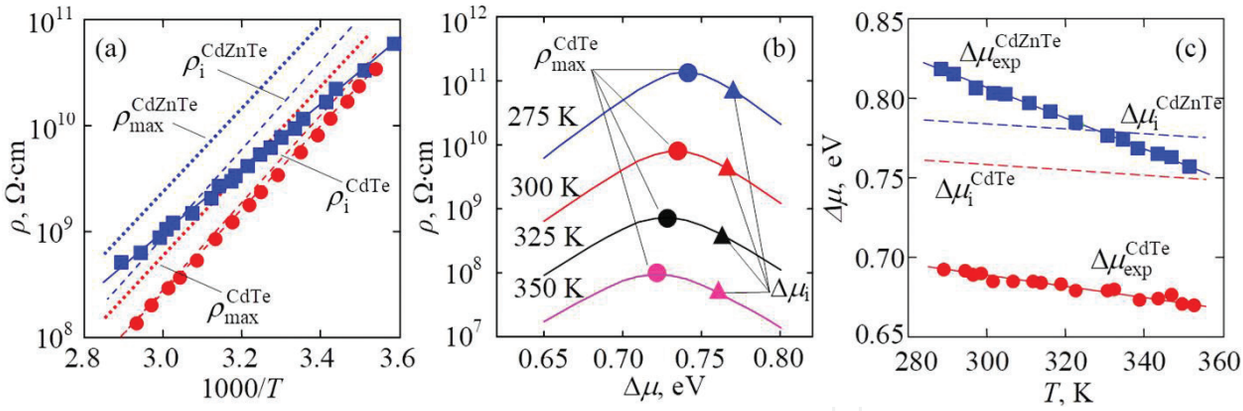

Figure 1. (a) Temperature dependences of resistivity of the CdTe and $Cd_{0,9}Zn_{0,1}Te$ crystals. Dashed lines show the temperature dependences of resistivity of CdTe and $Cd_{0,9}Zn_{0,1}Te$ crystals with intrinsic conductivity ρ_i, dotted lines show its maximum possible values ρ_{max}. (b) Dependence of resistivity of CdTe on position of the Fermi level at different temperatures. The Fermi level energy $\Delta\mu_i$ in intrinsic CdTe is also shown. (c) Temperature dependences of the Fermi level energies in CdTe and CdZnTe crystals. Circles and squares show the values of $\Delta\mu$ (T) calculated with Eq. (1). Solid lines show $\Delta\mu_{calc}(T)$ calculated with Eq. (2). Dashed lines show the Fermi levels in the intrinsic materials.

the dark current in X/γ-rays detectors. At temperatures above the room temperature (>320–330 K), the resistivity ρ of CdTe crystal exceeds its value for a material with intrinsic conductivity ρ_i. At temperatures below ~ 280 K, the resistivity of CdTe crystal exceeds the resistivity of $Cd_{0,9}Zn_{0,1}Te$ with a wider (!) bandgap. The observed excess ρ over ρ_i is explained, the much lower mobility of holes in comparison with the mobility of electrons. If the Fermi level shifts from its position in the intrinsic semiconductor toward the valence band, the contribution of holes into electrical conductivity increases and thus resistivity also increases. However, with further displacement of the Fermi level the resistivity decreases, as the concentration of holes becomes too large. As a result, the thermal activation energy of the electrical conductivity decreases. Giving ρ as $1/q(n\mu_n + n_i^2\mu_p/n)$ and equating to zero the derivative $d\rho/dn$, is easy to show that the maximum value of the resistivity is determined by $\rho_{max} = (2qn_i(\mu_n\mu_p)^{1/2})^{-1}$. As shown in **Figure 1b**, the value of the maximum possible resistivity ρ_{max} significantly exceeds the intrinsic resistivity of CdTe crystal in the whole temperature range. In the case of a semiconductor with almost intrinsic conductivity, the solution of equation $\rho = 1/q(n\mu_n + p\mu_p)$ for Fermi energy $\Delta\mu$ has the form as follows:

$$\Delta\mu = \mathrm{kT}\ln\left(\frac{1 \pm \sqrt{1 - 4\,q^2\,\rho^2\,\mu_n\,\mu_p\,n_i^2}}{2\mathrm{q}\rho\,\mu_n\,n_i^2/N_v}\right), \tag{1}$$

where "+" and "−" correspond to n- and p-type semiconductor, respectively. That is, one can find the $\Delta\mu(T)$ dependences of the crystals under study (**Figure 1c**) from the temperature dependence of the resistivity $\rho(T)$ (**Figure 1a**), taking into account the temperature dependences of n_i and mobilities of electrons μ_n and holes μ_p [5]. The Fermi-level energy of the samples calculated with Eq. (1) (**Figure 1c**) shows that the Fermi level is noticeably removed from the conduction band when temperature increase, which slows the growth of the electrons concentration, consequently, leads to a decrease in the of thermal activation energy. As a consequence, despite the fact that the Fermi level located near the middle of the band

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gap in the whole temperature range, the thermal activation energy is much smaller than that of intrinsic semiconductor. Another important conclusion is that the Fermi level crosses the Fermi level in intrinsic $Cd_{0,9}Zn_{0,1}Te$ at a temperature of ~330 K, that is the material changes the type of conductivity.

An analysis of the statistics of electrons and holes in a semiconductor, in which donor defects form self-compensated complexes, provides additional information on the compensation mechanism in the CdTe and $Cd_{0,9}Zn_{0,1}Te$ crystals. Consideration of the features of self-compensated semiconductors minimizes the number of independent parameters in the calculations [11]. It is important that the concentration of the donor impurity (Cl or In) is significantly higher than the concentration of background impurities and defects. Under this condition, calculations can be made using the simplified scheme of levels in the bandgap, namely, the deep donor and deep acceptor level, as well as the shallow level of donors that did not form complexes, that is, on the "three-level" compensation model [12]. In the electroneutrality equation for semi-insulating wide-band semiconductor with a high concentration of impurities (~10^{18} см$^{-3}$), the concentration of free carriers n and p (which do not exceed 10^7 to 10^8 cm^{-3} even at elevated temperatures) can be neglected. It is natural to assume that the level of compensating acceptors is located in the lower part of the bandgap (or at least ~5kT below the Fermi level), that is, they are almost completely ionized, and it can be taken $N_a^+ \approx N_a$, where N_a is the concentration of acceptors. Such acceptors may be Cd or Zn vacancies with ionization energy of 0.43–0.47 eV. With such simplifications, the electroneutrality equation is reduced to the expression $N = N_d^+$, and its analytical solution is

$$\Delta\mu = E_d + \mathrm{kTln}\left[\frac{1-\xi}{\xi}\right]. \quad (2)$$

Thus, the Fermi-level energy at a temperature T is determined by the energy of the donor level E_d and its compensation degree $\xi = N_a/N_d$, which can be found by comparing the results of the calculation according to Eq. 2 with the experimental dependences $\Delta\mu(T)$ obtained from the results of measurements of resistivity $\rho(T)$, as shown in **Figure 1c**. The best match of the calculated and experimental dependencies $\Delta\mu(T)$ corresponds to E_d = 1.081 eV, ξ = 0.99998 for $Cd_{0,9}Zn_{0,1}Te$ and E_d = 0.783 eV, ξ = 0.976 for CdTe. The obtained values of ionization energy are in the range, in which the photoluminescence bands were detected, which is also consistent with the results of the study of energy levels in the band gap CdTe and $Cd_{1-x}Zn_xTe$ by other methods. Obtained high degree of donor compensation ξ = 0.979 for CdTe and ξ = 0.99998 for $Cd_{0,9}Zn_{0,1}Te$ confirms the known theoretical fact that an element of Group III or VII of the Periodic system (in this case, Cl and In) as a donor impurity introduced in the crystal lattice, causes the appearance of approximately the same amount of compensating intrinsic defects, which leads to the formation of complexes. It should be emphasized that the obtained values ξ are close to the degree of compensation provided by the Mandel theory for CdTe and ZnTe [13].

These results are important from a practical point of view: (1) At E_d = 0.60 eV (as in the crystal $Cd_{0,9}Zn_{0,1}Te$ under study), the values of ρ become close to the maximum value in a very narrow range of ξ (**Figure 2a**). When shifting of the donor to the middle of band gap dome-shaped curve $\rho(\xi)$ expands and its maximum shifts toward values of ξ, close to 0.5. The achievement of the semi-insulating state $Cd_{0,9}Zn_{0,1}Te$ E_d = 0.60 eV and ξ = 0.99998 became

possible due to doping by self-compensated donors and the formation of A- or DX-centers, the concentration of which is practically equal to the concentration of acceptors due to the very nature of these centers. (2) In a certain combination of ionization energy and the compensation degree, changes in the temperature dependence of resistivity and/or inversion of the conductivity type of the crystal in the climate-change temperature range may occur that may affect on the operation of the X/γ-ray detector with the Schottky diode. If the donor level located near the middle of the band gap of the $Cd_{0,9}Zn_{0,1}Te$ crystal (E_d = 0.7 eV), to obtain the resistivity $\rho = 10^{10}$ Ω·cm at 300 K (**Figure 2b**), the compensation degree equals to ξ = 0.679, and the thermal activation energy of conductivity is close to the half of the $Cd_{0,9}Zn_{0,1}Te$ band gap at 0 K (ΔE = 0.84 eV). If E_d = 0.5 eV to ensure $\rho = 10^{10}$ Ω·cm at 300 K, the compensation level should be increased to 0.99979, which leads to a decrease of ΔE to 0.65 eV. When E_d = 0.3 eV, the compensation degree should further increase to 0.9999999, making activation energy decreases to 0.47 eV. If E_d equals to 0.9 eV to ensure $\rho = 10^{10}$ Ω·cm, the compensation degree should be considerably less than 1/2, namely ξ = 0.00047. In this case, the thermal activation energy ΔE will be 1.04 eV, that is, it becomes "abnormally" high [5, 7, 9].

Figure 2c shows the calculated temperature dependences of the Fermi level energy in $Cd_{0,9}Zn_{0,1}Te$ at different compensation degrees of donor (In) with ionization energy E_d = 0.45 eV, which corresponds to the often observed in these crystals photoluminescence band (~1.08 eV). The position of the Fermi level in the intrinsic $Cd_{0,9}Zn_{0,1}Te$ is shown by dashed line. As seen, the Fermi level is located above the Fermi level in the intrinsic semiconductor at the compensation degree ξ = 0.9999 in the whole temperature range, that is, the semiconductor has an n-type of conductivity. At sufficiently higher compensation degree (ξ = 0.999999), the Fermi level is located below the Fermi level in the intrinsic $Cd_{0,9}Zn_{0,1}Te$, that is, the crystal has p-type conductivity [9]. It is also possible the condition when type of conductivity changes in the

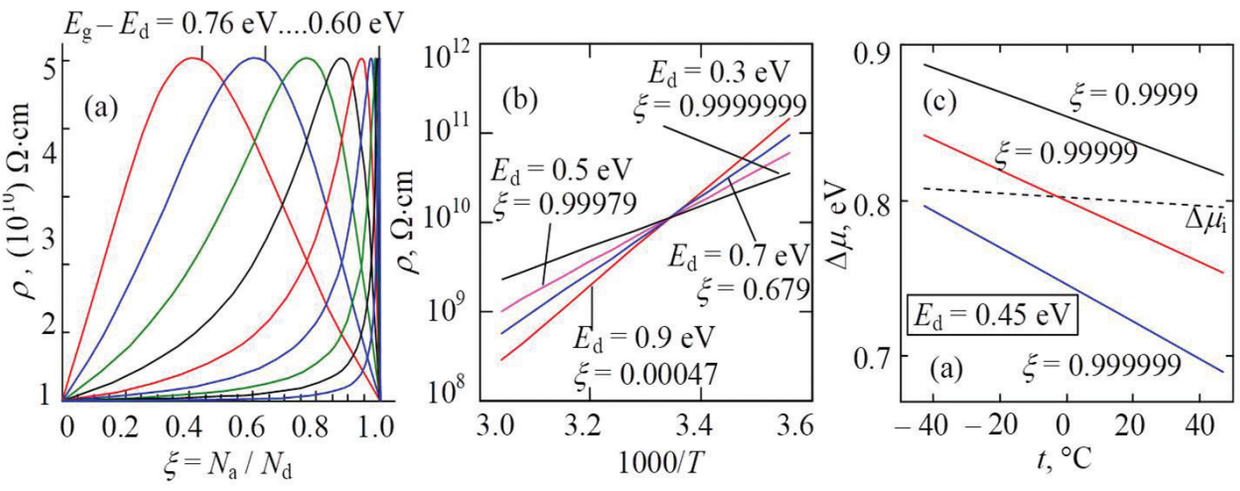

Figure 2. (a) The dependence of resistivity of $Cd_{0,9}Zn_{0,1}Te$ crystal on the compensation degree ξ. (b) Temperature dependences of resistivity ρ at the different ionization energies E_d and compensation degree $\xi = N_a/N_d$, which provides the same ρ, but different thermal activation energies ΔE. (c) The temperature dependences of the Fermi level energy $\Delta\mu$ (T) in $Cd_{0,9}Zn_{0,1}Te$ crystal at the different compensation degrees ($\Delta\mu_i$ - is the Fermi level energy in a crystal with intrinsic conductivity).

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climate-change temperature range, which is observed at an intermediate value of $\xi = 0.99999$. Unlike $Cd_{0,9}Zn_{0,1}Te$ with a high compensation degree, in CdTe crystals the compensation degree is much lower and the dependence of the Fermi level on ξ is much weaker. Therefore, in CdTe, the transition from p- to n-type of conductivity occurs at an increase from 0.90 to 0.99, that is, by 9%, while in $Cd_{0,9}Zn_{0,1}Te$—only by 0.01%. This explains how much harder is to grow a homogeneous $Cd_{0,9}Zn_{0,1}Te$ crystal in comparison with CdTe.

3. Charge collection efficiency in CdTe-based Ohmic detectors

The operation of CdTe detector in spectrometric mode assumes complete collection of the charge generated by the absorption of high-energy quanta. Since the lifetime of charge carriers in the most perfect CdTe crystals does not exceed several microseconds, it is necessary to apply a rather high voltage to prevent the "capture" of the carriers by deep impurities (defects). At low voltage applied to the CdTe crystal with ohmic contacts, *I-V* characteristic is linear, but at higher bias a superlinear increase in current is always observed [14]. Attention is drawn to the fact that the deviation from linear *I-V* relationships at higher voltage is observed stronger when the temperature decreases (**Figure 3b**, inset). Therefore, we can assume that an additional charge transport mechanism with much weaker temperature dependence comes into play with increasing voltage. This is confirmed by the data in **Figure 3b**, which show the voltage dependences of the difference ΔI between the measured current I and a linearly extrapolated current I_o ($\Delta I = I - I_o$). As seen, the current excessive over linearly extrapolated current is virtually independent of temperature. A deviation of *I-V* characteristics from linearity due to lowering the barrier at imperfect Ohmic contact should be rejected because such a mechanism leads to an exponentially increase in the current with temperature [15]. The current caused by tunneling transitions of electrons from the Fermi level in the metal (or slightly below it) into the semiconductor can be almost temperature independent [16]. However, at bias voltage in the range 10–100 V, the probability of tunneling is practically zero. A much greater probability of tunneling is through a thin interfacial oxide layer, whose presence on the crystal surface before metal deposition cannot be excluded (**Figure 3c**). At higher voltages, the linear behavior of the *I-V* characteristic of the CdTe crystal is replaced by a quadratic dependence on V, as in the case of space charge limited current (SCLC)] according to the Mott-Gurney law [17]. It is confirmed by comparing the experimental data with the extrapolation of the quadratic *I-V* dependence (**Figure 3b**). According to theory, SCLC can be formed by injection of charge carriers into the valence or conduction band. In the case of semi-insulating CdTe, the injection of electrons into the conduction band should be preferred. Firstly, the excess concentration of electrons above the electron equilibrium concentration is achieved much easier, since in the CdTe:Cl crystals the electron concentration approximately two orders of magnitude lower than that of holes. Second, the electron mobility in CdTe is more than an order of magnitude higher than that of holes, and the SCLC is proportional to the charge carrier mobility. Finally, the electron current injected by tunneling is almost temperature independent, that is, observed from the experience and just this one needs to explain. Taking into account the current of thermally generated holes and SCLC we can write:

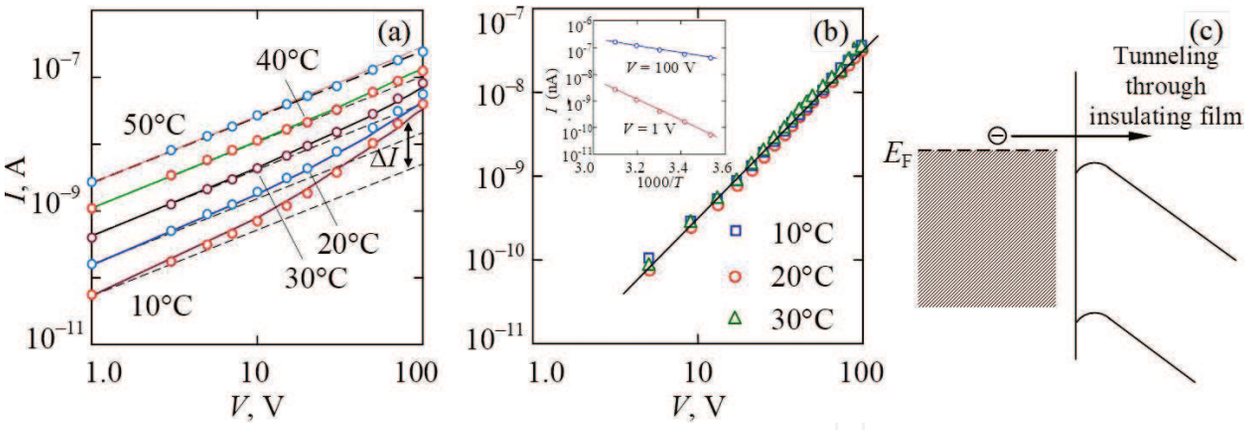

Figure 3. (a) *I-V* characteristics of CdTe crystal measured (circles) and calculated using Eq. (3) at different temperatures (solid lines). The dashed lines show linear extrapolation of *I-V* dependencies at low *V*. (b) Voltage dependence of difference ΔI between the measured current *I* and a linearly extrapolated current I_o for three temperatures. The straight solid line extrapolates quadratic dependence of the current on voltage. The inset shows temperature dependences of the currents at 1 and 100 V. (c) Energy diagram of the metal/CdTe contact showing tunneling of electrons through an intermediate oxide film on the CdTe crystal surface.

$$I = \mathrm{sqp}_o(T)\,\mu_p \frac{V}{d} + \mathrm{sK}\frac{9}{8}\frac{\varepsilon\varepsilon_o \mu_n}{d^3} V^2, \tag{3}$$

where ε is the dielectric permittivity of the semiconductor, ε_o is the dielectric constant of vacuum, μ_n and μ_p is the mobility of charge carriers, *s* is the area of the contact, p_0 is the equilibrium concentration of holes in the crystal, *K* is the coefficient, which takes into account the probability of electron tunneling through the oxide film and reducing the contribution of the SCLC.

Temperature variation leads to a change in current through the crystal, depending on the SCLC contribution. For the best agreement, the calculation results by Eq. (3) with the experimental data we should substitute $K = 2.3 \cdot 10^{-4}$. As seen, Eq. (3) well reproduces the voltage dependences of the current and its temperature changes in detail (**Figure 3a**). SCLC negatively impacts on the detector performance since it leads to an increase in leakage current, and hence degrades the energy resolution of the detector. Moreover, the contribution of the SCLC increases with decreasing temperature due to increasing the holes mobility (by 5–6% per 10°C) (**Figure 4a**). Such a character of the SCLC does not allow reduce significantly the leakage current by thermoelectrically cooling of the detector as in the case of CdTe detectors with Schottky diode [18].

SCLC is proportional to the squared voltage and is inversely proportional to the crystal thickness *d*; therefore, the relationship between the CdTe crystal thickness *d* and the drift length of carriers λ_p increases with decreasing *d* (**Figure 4a**, inset), which, in turn, improves the energy resolution of detector. Thus, too low energy resolution of X/γ-rays CdTe-detector with two Ohmic contacts (6–8%) caused by ineffective charge collection. One of the reasons might be the recombination of charge carriers in the bulk and on the front and back surfaces of the crystal. Analysis of the influence of surface recombination can be made on the base of continuity equation (with the corresponding boundary conditions) and taking into account the drift and diffusion components of the current. The calculations show that for the actual thicknesses

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of the crystal and the applied voltages, the recombination on the surfaces of the crystal can be neglected. Neglecting recombination losses at the crystal surfaces, we have to assume that the low efficiency of charge collection in Ohmic-type CdTe detectors is caused by trapping of photogenerated charge carriers by deep levels of impurities (defects) in the crystal bulk. These losses is strongly dependent on the lifetime of charge carriers (τ_n and τ_p), which at a given electric field F (together with their mobility (μ_n and μ_p) determine the drift length of carriers $\lambda_n = \mu_n F\tau_n$, $\lambda_p = \mu_p F\tau_p$. In this view, the relationship between the CdTe crystal thickness and the drift length of carriers (**Figure 4a**, inset) is very important. A quantitative description of the collection losses of photogenerated charge carriers gives the well-known Hecht equation, which for a uniform electric field has the form [19].

$$\eta_H(x) = \frac{\lambda_n}{d}\left[1 - \exp\left(-\frac{d-x}{\lambda_n}\right)\right] + \frac{\lambda_p}{d}\left[1 - \exp\left(-\frac{x}{\lambda_p}\right)\right]. \quad (4)$$

Taking into account the most important processes which determine the spectral distribution of the quantum detection efficiency, in particular, absorption in the bulk of crystal and an electrode material (Pt), the losses caused by trapping of charge carriers in the bulk of crystal, the detection efficiency depending on the absorption coefficient α_γ in the crystal with Ohmic contacts can be written as

$$\eta(\alpha_\gamma) = \int_0^d T_{Pt}(\alpha_\gamma)\,\alpha_\gamma \exp(-\alpha_\gamma x)\,\eta_H(x)\mathrm{d}x, \quad (5)$$

where $T_{Pt}(\alpha_\gamma)$ takes into account the radiation attenuation after passing through an electrode material; $\eta_H(x)$ is Hecht function (4); $\alpha_\gamma \exp(-\alpha_\gamma x)$ is the generation rate of electron–hole pairs per incident photon [16].

Insufficient absorptive capacity in high spectral range significantly reduces the registration of X/γ-rays but does not affect the processes that take place after photon absorption. Therefore,

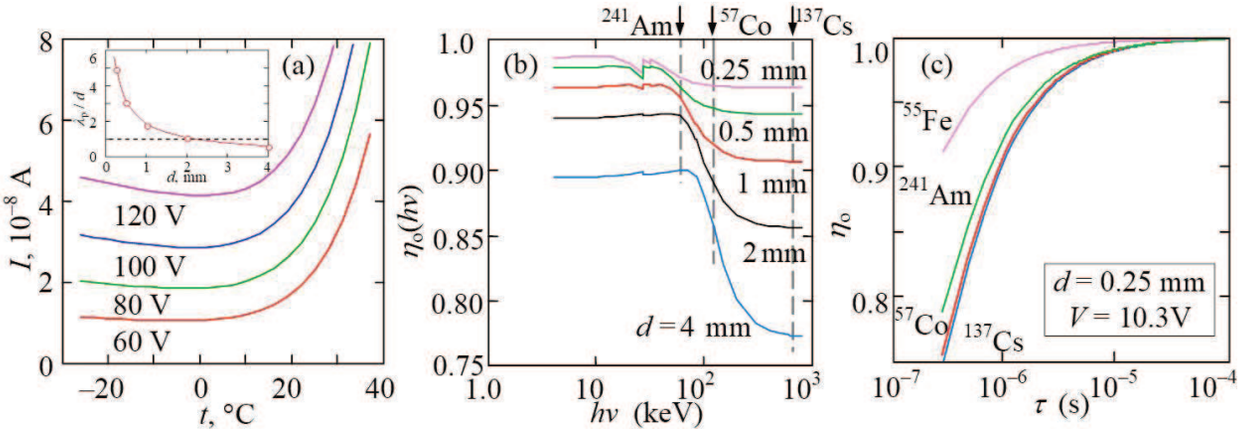

Figure 4. (a) Temperature dependences of the current at different voltages applied to the CdTe crystal. The inset shows the dependences of the drift length of holes on the thickness of the CdTe crystal at voltage when the same leakage current of 3×10^{-8} A is achieved. (b) Charge collection efficiency spectra for CdTe crystals of different thicknesses at voltages that corresponds to the same current 3×10^{-8} A. (c) Energy resolution in the spectra of different isotopes for the detector thickness of 0.25 mm at voltage of 10.3 V.

the spectral distribution of the charge collection efficiency (the value determining the energy resolution of the detector) is obtained by dividing the detection efficiency $\eta(h\nu)$ by the absorption capacity of the crystal $A(h\nu) = 1 - \exp(-\alpha_\gamma d)$. **Figure 4b** shows the collection efficiency curves $\eta_o(h\nu)$ calculated for the different thicknesses of CdTe and voltages at which the current is the same as at voltage of 60 V for crystal thickness of 1 mm ($3 \cdot 10^{-8}$ A). As seen, when the crystal thickness is 4 mm, the charge collection efficiency $\eta_o(h\nu)$ in the photon energy $h\nu < 100$ keV is 90%, while for $h\nu \approx 1$ MeV $\eta_o(h\nu)$ is reduced to 77% (**Figure 4b**). When the crystal thins, the charge collection efficiency is significantly improved reaching a level of 97–98%. With the thickness of 0.25 mm the charge collection efficiency is above 97% throughout the whole spectral range. However, increasing the charge collection efficiency $\eta_o(h\nu)$ with thinning of the crystal is achieved with a significant decrease in the efficiency of detection (registration) in the range of high-energy photons. A significant increase in the energy resolution can be achieved by improving the quality of CdTe crystals and, thus, increasing the lifetime of charge carriers. Our calculations show that with increasing the electron lifetime by the order of magnitude from 3×10^{-6} s to 3×10^{-5} s, for the crystal thickness of 0.25 mm at voltage that corresponds to the current 3×10^{-8} A (10.3 V) the energy resolution in the spectra of all isotopes is higher than 99% [20] (**Figure 4c**).

CdZnTe and CdMnTe-based X/γ-rays Ohmic detectors can have electrical characteristics both similar to presented above and different. This is largely due to the choice of contacts material, the treatment of the crystal surface before contacts fabrication, conditions of post-deposition treatment. At low voltage applied to the p-$Cd_{1-x}Mn_xTe$ (x = 0.3) crystal *I-V* characteristics are linear, but at higher bias a superlinear increase in current is observed approximately the same extent at different temperatures. The fact that the voltage dependence of difference between the measured current and a linearly extrapolated current is quadratic, which indicates that the observed supernular growth of current is due to by space charge limited current (SCLC) according to the Mott-Gurney law [17]. The activation energy of the conductivity caused by the equilibrium holes (at V = 10 V) equals to 0.39 eV. Attention is drawn to the fact that the energy of acceptor trap at the formation of the SCLC in the Ni/CdMnTe contact (at V > 200 V), equal also 0.39 eV, that is, impurity (or defect), responsible for electrical conductivity of material and trap of injected charge carriers clearly have the same nature. Therefore, the same activation energy for the current of equilibrium holes and the current surplus of equilibrium current confirms the fact that SCLC in the Ni/CdMnTe/Ni detector is formed by the injection of majority carriers (holes) from the metal, not by the tunnel injection of minority carriers (electrons) as in the case of Pt/CdTe/Pt detectors discussed above.

$Cd_{1-x}Zn_xTe$ (x = 0.1) n-type crystals with gold Ohmic contacts show other features of superlinear current growth at high voltages. At voltages, lower ~ 10 V *I-V* characteristic are linear, but at higher bias, the superlinear increase is observed. However, the voltage of deviation from the linear law is 10–20 V regardless of temperature. It turns out that the current of equilibrium electrons and the excess current in the Au/CdZnTe/Au detector are growing approximately equally with the temperature. This is confirmed by the fact that the thermal activation energy of the crystal $Cd_{0,9}Zn_{0,1}Te$ is 0.74 eV, and the thermal activation energy of the excess current at

100 V is also quite high ΔE = 0.65 eV, which causes its significant growth from temperature. The voltage dependence of the current, surplus of equilibrium current, found by extrapolation of the linear part of the *I-V* characteristic at low voltages has a complex form. In the voltage range V = 20–40 V the current is rapidly increasing, at high voltages (up to the highest voltages), the power $\Delta I \sim V^{2,4–2,5}$ is observed. This behavior of the Au/CdZnTe/Au detector characteristics contradicts the SCLC theory. Therefore, the reason for the deviation of the current from the linear dependence is the injection of minority charge carriers (holes) due to the imperfection of Ohmic contacts.

4. Electrical characteristics of Schottky diodes based on semi-insulating CdTe single crystals

The section deals with electrical characteristics of Ni/CdTe/Ni X/γ-rays detectors with Schottky diodes based on high-resistivity CdTe single crystals ($\rho \sim 10^9$ Ω·cm (300 K)).

The theoretical analysis of experimental results allows identifying and explaining the essential features of the charge transport mechanisms depending on the resistivity of the material and the parameters of the diode structure, in particular the concentration of uncompensated impurities (defects) and the height of the potential barrier on Schottky contact [21]. According to the Sah-Noyce-Shockley theory, the current through the diode is determined by the integration of the generation-recombination rate over the whole space charge region (SCR) width [22].

$$I_{g-r} = Aq \int_0^W \frac{n(x,V)p(x,V) - n_i^2}{\tau_{po}\left[n(x,V) + n_1\right] + \tau_{no}\left[p(x,V) + p_1\right]} \mathrm{dx}, \tag{6}$$

where A is the diode area, q electron charge, W is the width of the SCR, $n(x,V)$ and $p(x,V)$ - are the concentrations of charge carriers in the conduction and valence bands, respectively, τ_{no} and τ_{po} - are the effective lifetimes of electrons and holes in the SCR, and the quantities $n_1 = N_c \exp(-E_t/kT)$ and $p_1 = N_v \exp[-(E_g - E_t)/kT]$ are determined by the depth of the generation-recombination level E_t. The results of calculations of the *I–V* characteristic, by using formula (6) show that the model of generation-recombination processes in the SCR adequately describes not only the current dependence on the voltage, but also the temperature induced variations in the Ni/p-CdTe Schottky diode *I–V* characteristic: (1) The reverse current, which has a generation origin, cannot vary in a wide range of the material resistivity ρ since this current is governed by the carrier lifetime and by the thickness of the SCR, which have no direct relation with a value of ρ. (2) In the region of low forward biases, where the dependence $I \propto \exp(qV/2kT) - 1$ holds, the current is governed by the same parameters and, therefore, is also only slightly ρ-dependent. (3) As ρ increases, the Fermi level recedes from the valence band; that is, $\Delta\mu$ increases at the same time as φ_0 decreases. In this case, the part of the forward branch, where the forward current is proportional to $\exp(qV/2kT)$, is increasingly restricted from above, as is observed in the experimental curves.

The Ni/CdTe/Ni diode structure with Schottky and near-Ohmic contacts at the CdTe(111)A and CdTe(111)B surfaces of semi-insulating CdTe single crystals (ρ = (2–4)·10^9 Ω·cm) demonstrates absence of rectification properties at bias voltages lower than 6–7 V, which can be attributed to a very high resistance of the CdTe substrate, that is, the voltage drop across the bulk part of the crystal should be taken into account. It should be noted that consideration of the voltage drop has strongly modified the shape of the forward *I-V* characteristic of the studied diode structure (**Figure 5b**) [21, 23]. A sharp increase in the current at higher forward bias voltages is attributed to the injection of minority carriers from the Schottky contact into the neutral part of the crystal and the modulation of its electrical conductivity, which is confirmed by the results of calculations. It should be emphasized that the Ni/CdTe/Ni detectors with Schottky and near-Ohmic contacts demonstrates low reverse current (~10^{-9} A/cm^2 at 300 K) at high reverse bias due to significant bending on the Ni/CdTe Schottky contact and low enough level of minority carrier injection from the near-Ohmic CdTe/Ni contact into the neutral part of the diode structure. It should be noted, the generation-recombination Sah-Noyce-Shockley theory analytically describes the *J-V* characteristic of the diode structure at different temperatures (**Figure 5b**) [24, 27]. Analysis of the voltage dependence of the differential resistance R_{diff} shows, at forward connection decreases with increasing in the low-bias region (**Figure 5c**). In the voltage range V = 1–3 V, the R_{diff} saturates, which means that the energy barrier is practically compensated by applied voltage and further voltage drop takes place across the bulk part of the diode structure. With further increasing the forward bias voltage, a sharp decrease in R_{diff} is observed. The value of R_{diff} becomes 2–3 orders of magnitude less than resistance of the bulk part of the diode R_s. Such lowering of R_{diff} is explained by injection of electrons (minority carriers) from the forward-biased Schottky contact into the bulk part of the crystal and modulation of its resistance (**Figure 5a** and **c**). Indeed, at higher forward voltage the barrier φ_o lowers and electron injection in the bulk part of the crystal is increasingly enhanced.

Analysis of the reverse *J-V* characteristic at high-bias voltages that is most important and interesting in the application of CdTe diodes as X/γ-ray detectors (V < 600–700 V) shows that the reverse current through the diode structure is controlled by the reverse-biased Schottky contact. A sublinear rise in the current (it is typical for the generation charge transport mechanism) corresponds to a gradual increase in the differential resistance (**Figure 5c**). However, on exceeding 600–700 V, the differential resistance decreases increasingly and then steeply decays at similarly to that at forward connection of the diode at voltages higher than a few volts. It can be explained by injection of electrons from the near-Ohmic contact into the bulk of the crystal [21, 23, 24] (**Figure 5a**). With an increase in the current, a fraction of the applied voltage, much like for a forward connection of the device, drops across the neutral part of the crystal and only a small its fraction drops across the near-Ohmic contact on the opposite side of the crystal. Thus, we have come to not at all trivial conclusion that at relatively high reverse bias, the processes in the "Ohmic" contact affect the reverse-biased Schottky contact on the opposite side of the crystal [15, 21, 23, 24]. A decrease in injection of carriers from the near-Ohmic contact in a Schottky diode with Ni/CdTe/Ni electrode configuration is an important way to reduce the leakage current and improve the performance of CdTe based X/γ-ray detectors. On increasing the operating voltage at low-leakage current allows to enhance the detection efficiency of the device especially in the region of high energy of photons.

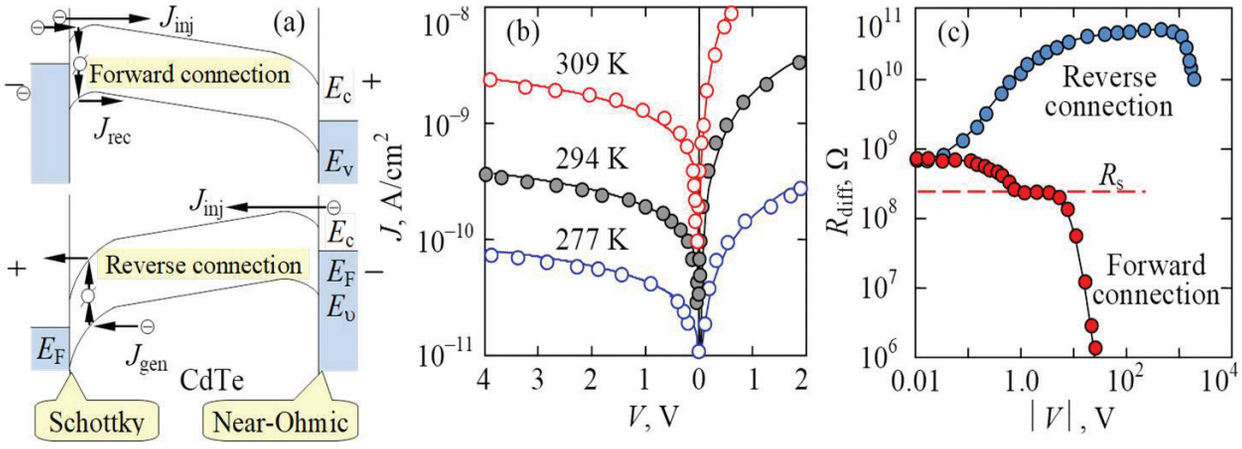

Figure 5. (a) The energy diagram of the forward and reverse biased Ni/CdTe/Ni diode structure shown at the top and bottom, respectively. The recombination (J_{rec}), generation (J_{gen}) an injection (J_{inj}) currents are shown by arrows. (b) *J-V* characteristics of the Ni/CdTe/Ni structure at different temperatures. The circles show the measurement results; the lines are the results of calculations by Eq. (6). (c) Differential resistance of the detector in a wide range of forward and reverse biased. The dashed straight line shows the resistance of the bulk part of the diode structure R_s.

5. Detection efficiency of CdTe based X/γ-ray detector

The parameters of crystal and diode structure significantly affect the quantum detection efficiency and energy resolution of detectors based on semi-insulating CdTe and $Cd_{0,9}Zn_{0,1}Te$ crystals with Schottky diode. In such crystals with deep levels of impurities (defects) in the band gap, the density of the space charge and the intensity of the electric field grow rapidly near the crystal surface, enhanced with the increase in the degree of compensation of the semiconductor (in contrast to the Schottky diodes on the semiconductor with shallow impurities levels). Minority charge carriers play an insignificant role in the formation of space charge, despite the presence of an inverse layer near the surface of the semiconductor. In spite of the features of the formation of SCR in the Schottky diodes based on self-compensating semiconductors (which are CdTe and $Cd_{0,9}Zn_{0,1}Te$ crystals, doped with Cl or In), the difference between the value of the SCR width, as determined by the solution of the Poisson equation, and by means of the known the formula for the Schottky diode does not exceed 15–16% even with a high compensation degree, that is, the width of the SCR is quite accurately determined by the concentration of uncompensated impurities. The charge collection efficiency in X/γ-ray detectors with a Schottky diode essentially depends on the carrier lifetime τ. It is important for practice that the charge collection efficiency is noticeably lower than 1 when the lifetime is less than 10^{-8} s, whereas to provide practically the total charge collection (99%) in the Ohmic detector the carrier lifetime should be equal to or exceed ~10^{-6} s.

The resistivity of CdTe and CdZnTe crystals under study at room temperature are (2–3)·10^9 and (3–5)·10^{10} Ω·cm, respectively. The band gap of the crystals E_g for CdTe equals to 1.47–1.48 eV, for $Cd_{0,9}Zn_{0,1}Te$ E_g = 1.53 eV at room temperatures. Our studies of the relaxation curves of the rise and decay of the photocurrent excited by rectangular pulses of semiconductor laser (λ = 782 nm) showed that the lifetimes of the charge carriers in the SCR and in the neutral part of the CdTe crystal differ significantly. In the case of CdTe crystal with two Ohmic contacts, the lifetimes of electrons amount to a few microseconds, which is consistent with the data presented on the site of Acrorad Co. Ltd. [14]. If the crystal is irradiated through a

semitransparent Schottky contact, the laser radiation is absorbed in a thin near-surface layer of the SCR and lifetimes of carriers are relatively short (10–20 ns).

Although all crystals had high resistivity and minority carrier lifetime, the diodes showed significant differences in the registration of spectra from ^{137}Cs (662 кеВ), ^{133}Ba (356 кеВ), ^{57}Co (122 кеВ), ^{241}Am (59 кеВ), ^{55}Fe (5,9 кеВ) isotopes. The CdTe detector was a high resolution detector, however the CdZnTe registered the spectra but with lower resolution (**Figure 6a**). At first glance it seems unclear as CdTe inferior in characteristics $Cd_{0,9}Zn_{0,1}Te$. Obviously, the detecting properties of the diode structure are influenced by other characteristics of the material. There is an assumption that such a parameter is the SCR width of a Schottky diode, which in a compensated semiconductor can be significant. Indeed, in the detector with Schottky diode, the SCR itself is an active area of the detector, and its width, of course, is one of the most important parameters. Therefore, in compensated semiconductor in addition to the high resistivity and long carrier lifetimes that is necessary for high detection efficiency, another mandatory requirement to the concentration of uncompensated impurities in the material (which determines the SCR width of a Schottky diode) is substantiated.

The detection efficiency spectra of CdTe-based crystals with Schottky diode taking into account the drift and diffusion components can be expressed as [25].

$$\eta = \frac{\lambda_n}{W}\left[1-\exp\left(-\frac{W}{\lambda_n}\right)\right]\left(\int_0^W \alpha_{CdTe}\exp(-\alpha_{CdTe}x)dx + \frac{\alpha L_n}{1+\alpha L_n}\exp(-\alpha W)\right). \quad (7)$$

Figure 6b shows the detection efficiency spectra of CdTe ($Cd_{0,9}Zn_{0,1}Te$) crystals with Schottky diode at the voltage V = 400 V applied to the detector and different concentrations of uncompensated donors $N_d - N_a$ in the material. The results clearly illustrate the fact that the spectra of $\eta(h\nu)$ can significantly be modified when $N_d - N_a$ is changed. If $N_d - N_a$ decreases from 10^{14} to 10^{10} cm^{-3}, the detection efficiency of ^{55}Fe ($h\nu$ = 5.9 keV) and ^{241}Am ($h\nu$ = 59.5 keV) isotopes vary almost by 3 and 2 orders of magnitude, respectively. At the same decreasing N_d - N_a, the detection efficiency of ^{57}Co ($h\nu$ = 122 keV) isotope varies within one order of magnitude and the detection efficiency of ^{133}Ba (356 keV) and ^{137}Cs (662 keV) isotopes vary relatively weak. An important feature of the results is that the dependences $\eta(N_d–N_a)$ for all the isotopes are described by a curve with maximum (**Figure 6c**) [6, 10, 11, 25]. As seen, in all cases, the detection efficiency rather rapidly increases as the SCR widens starting at high uncompensated impurity concentrations (10^{15} cm^{-3}). In addition, recombination losses in the SCR also increase and ultimately become so significant that the detection efficiency decreases with a further increase in $N_d - N_a$. The obtained results for the measurements and calculations show that, together with high resistivity, lifetime and mobility of charge carriers, the concentration of uncompensated impurities in the range 10^{11}–10^{13} cm^{-3} can be considered also necessary condition for the efficient operation of X/γ-rays detectors based on CdTe and $Cd_{0,9}Zn_{0,1}Te$ [10, 11]. It is the concentration of uncompensated impurities of 10^{12} cm^{-3} in CdTe crystals made it possible to obtain ^{137}Cs radioisotope energy spectrum by an Ni/CdTe/Ni diode detector at applied reverse bias voltage of 1200 V with the record values of energy resolution at room temperature (2.8 keV of FWHM at 662 keV) (**Figure 6c**, inset).

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To determine the concentration of uncompensated impurities in crystals of CdTe and $Cd_{0,9}Zn_{0,1}Te$, we compared the detection efficiency with irradiation of the crystal by the Ohmic contact side and the Schottky contact side. In the high-energy region of the spectrum, in which the absorption coefficient for X/γ-rays (α_γ) is small, excitation occurs virtually uniformly over the entire crystal volume and the detection efficiency for a crystal with the Schottky contact is independent of which side of the detector is irradiated, the side of the Schottky contact or the side of the Ohmic contact. This is confirmed experimentally. If a CdTe detector with a Schottky contact is subjected to the radiation of the ^{137}Cs isotope, the peak height at the photon energy 662 keV ($\alpha_\gamma \approx 0.1$ cm^{-1}) is practically the same when different sides of the sample are irradiated, the side of the Schottky contact or the side of the Ohmic contact. If the isotope ^{55}Fe is used ($\alpha_\gamma \approx 4000$ cm^{-1}), the peak height in the case of irradiation of the Schottky contact side is by two orders of magnitude, than that in the case of irradiation of the Ohmic contact side, as is shown in **Figure 6a** (inset) [11]. This is accounted for by the fact that, at $\alpha_\gamma \approx 4000$ cm^{-1}, the effective depth of radiation penetration into the material is smaller than 1 μm, therefore, in the case of irradiation of the Ohmic contact side, a significant portion of electrons, which appeared as a result of γ-photon absorption, do not reach the SCR by diffusion [17]. Evidently, in this case, the peak height greatly depends on the SCR width and, consequently, on the concentration of uncompensated impurities in the semiconductor, which can be used to determine the value of $N_d - N_a$. Thus, there is a significant difference between the concentrations of uncompensated impurities in CdTe and $Cd_{0,9}Zn_{0,1}Te$ crystals, which are used in the fabrication of X/γ-rays detectors. The concentration of uncompensated impurities is ~(1–3) × 10^{12} cm^{-3} for CdTe crystals and (1–5) × 10^8 cm^{-3} (i.e., four orders of magnitude lower) for $Cd_{0,9}Zn_{0,1}Te$ crystals [11]. The low concentration of uncompensated impurities (10^8–10^9 cm^{-3}) is the reason for the unsatisfactory detectivity of $Cd_{0,9}Zn_{0,1}Te$ detectors regardless of a fully acceptable resistivity of crystals (> 10^9 Ω·cm) and the lifetime of charge carriers (> 10^{-6} s) [10].

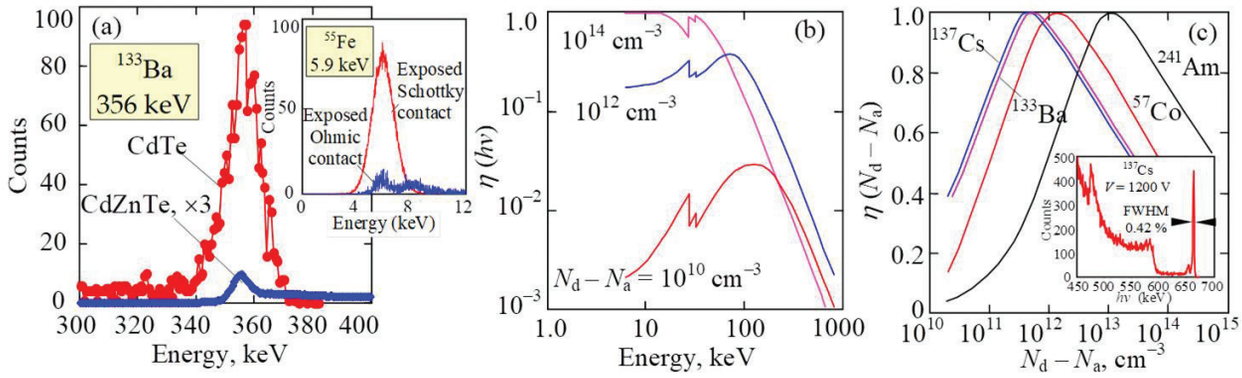

Figure 6. (a) Spectra of ^{133}Ba isotope taken with Schottky diode detectors based on CdTe and at V = 500 V. The inset shows the emission spectra of the ^{55}Fe isotope measured by a CdTe detector with a Schottky contact under irradiation of different sides of the sample. (b) Detection efficiency spectra of CdTe-based detector with Schottky diode calculated for different concentrations of uncompensated donors $N_d - N_a$. (c) Normalized detection efficiency of different isotopes as a function of $N_d - N_a$. The inset shows the typical ^{137}Cs radioisotope energy spectrum detected by an Ni/CdTe/Ni diode detector.

6. CdTe-based Schottky diode X-ray detectors for medical imaging

In the section the possibilities of using diode structures based on relatively low resistivity p-CdTe and n-CdTe ($\rho = 10^3$–10^4 Ω·cm), and polycrystalline CdTe in direct-conversion digital flat-panel X-ray image detectors are discussed.

Investigation of electrical properties, charge collection processes and the spectral distribution of the detection efficiency of X/γ-ray detectors based on CdTe with relatively low resistivity and Schottky contact confirm that their characteristics are generally inferior to technologically more complicated detectors with diodes Schottky based on semi-insulating CdTe. In particular, the currents of Schottky diodes under study are rather small for this type of diode structures—about 1 nA with a contact area of 3.5 mm^2. The current are determined by the generation-recombination in the SCR according to the Sah-Noyce-Shockley theory [22, 26].

The total detection efficiency for a detector utilizing a Schottky diode is the sum of the drift and diffusion components [27, 28]. As shown in **Figure 7a**, the contribution of the diffusion component to the total efficiency of the detector is quite important at $\tau_p = 10^{-6}$ s and in the case of high-energy photons (i.e., at lower absorption coefficients) it is dominant. The efficiency of charge collection of the X/γ-rays detector with the Schottky diode substantially depends on the lifetime of charge carriers τ and concentration of uncompensated donors N_d - N_a (**Figure 7b**, inset). If N_d - N_a value is ~10^{14} cm^{-3}, in order to ensure a practically complete charge collection (>99%), the lifetime of the carriers should equal or exceed ~10^{-7} s. If N_d - $N_a \approx 10^{16}$ см$^{-3}$, the lifetime of charge carriers should not exceed 10^{-9} s, which is quite real when using even poor quality CdTe crystals. For X-ray examination of a breast, in the photon energy region $h\nu < 30$ keV n-type CdTe detector is more acceptable (**Figure 7b**). However, for X-ray examination of a chest ($h\nu > 50$ keV) p-CdTe should be chosen (**Figure 7c**). The detection efficiency of X-ray in the Al/p-CdTe diode structure at the maximum possible electron lifetime (a few microseconds) is 50–70 and 20–40% in the photon energy ranges of 20–30 and 50–80 keV, respectively (**Figure 7c**). Such characteristics seem to be acceptable for mammography and chest radiography.

The use of a stacked CdTe detector with a Schottky diode, which is already practiced, can significantly improve the detecting efficiency of the device especially in the high-energy range of the spectrum. In the energy range ~100 keV the efficiency of a stacked detector is greater than that of a single layer detector [28]. The highly developed technology of the deposition of polycrystalline CdTe layers of large area with a surface-barrier structure in solar cells can be adapted to the fabrication of flat-panel X-ray image detectors. The presence of a barrier structure in the relatively low resistivity CdTe ($\rho = 10^4$–10^6 Ω·cm) provides a low-leakage (dark) currents comparable with those in a-Se photoconductors ($\rho = 10^{12}$ Ω·cm at 300 K). In a CdTe diode structure, virtually full charge collection occurs independently of the applied voltage at the carrier lifetime $\tau > 10^{-7}$ s and uncompensated impurity concentration higher than 10^{14} cm^{-3}. Electric field concentration in the space charge region of a barrier structure eliminates the problem of the collection of charge generated by X-ray photon absorption (there is no need to increase the operating voltage up to several kiloelectronvolts as in the case of a-Se photoconductors).

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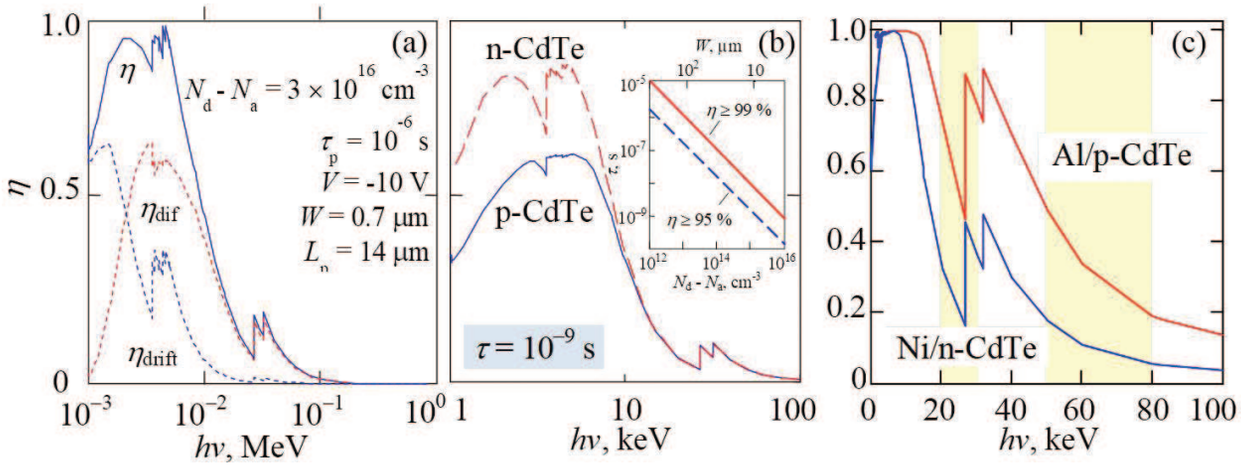

Figure 7. (a) The drift η_{drift} and diffusion η_{dif} components of the detection efficiency in the Schottky diode and their sum η. (b) Comparison of the total detection efficiency of the n- and p-CdTe-based Schottky diodes with the carrier lifetime 10^{-9} s. The inset shows the correlation between the charge-carrier lifetime τ and concentration of uncompensated donors $N_d - N_a$ at which the collection of 99 and 95% charge carriers photogenerated at the interface between the depleted region and neutral part of the diode structure ($x = W$) is achieved at $V = -100$ V. (c) The detection efficiency of the Ni/n-CdTe and Al/p-CdTe diodes calculated for the uncompensated impurity concentration of 10^{16} cm^{-3} and carrier lifetime $\tau = 3 \times 10^{-6}$ s. The photon energy ranges which are used for diagnostics of breast and chest are shown by shading.

7. Conclusions

1. The unconventional peculiarities, which are important from scientific and practical points of view, have been revealed by the experimental studies of the temperature dependences of resistivity and Fermi level energy of semi-intrinsic $Cd_{0,9}Zn_{0,1}Te$:In and CdTe:Cl crystals used for fabrication of X/γ-ray detectors: (i) the material can be semi-insulating when the compensation degree of a deep impurity level located near the middle of the band gap is around 0.5 (in this case, the Fermi level is pinned); (ii) if the impurity level is not close to the middle of the band gap, the semi-insulating condition is reached at low or high compensation degree (in this case, the Fermi level position strongly depends on the temperature T and activation energy ΔE can be significantly higher than one-half of the band gap at $T \to 0$ K as it takes place in an intrinsic semiconductor). Among other things, this can lead to inversion of the conductivity type of the semiconductor as the temperature varies during climatic operation of a device that leads to qualitative changes of the electric properties of both Schottky and Ohmic contacts in X/γ-ray detectors.

2. The features of operation of X/γ-ray detectors based on Cd(Zn, Mn)Te crystals with two Ohmic contacts have been established and ways to improve their energy resolution have been determined by comprehensive investigation of the electrical characteristics and quantum efficiency of detectors: (i) in the CdTe detector a rapid rise of the current with increasing voltage higher than 6–8 V for the crystal thickness of 1 mm is caused by the SCLC. A distinctive feature of the current is its temperature independence because the mechanism of injection of charge carriers is tunneling through the thin insulating film between the crystal and metal contact; (ii) thermoelectric cooling, commonly used for CdTe Schottky diode detectors, does not provide the desired result since it leads to a decrease in leakage

current no more than 2–3 times when the temperature lowers from 300 to 260–270 K, and further cooling loses its meaning; (iii) with thinning the semiconductor crystal, the ratio between the carrier drift length and crystal thickness increases that improves the efficiency of charge collection at relatively low bias voltage; (iv) in the CdZnTe and CdMnTe detectors under study, a rapid rise of the current with increasing voltage and temperature due to injection of charge carriers is observed, so these crystals are not suitable for fabrication of X/γ-ray detectors; (v) a significant increase in the energy resolution can be achieved by improving the quality of Cd(Zn, Mn)Te crystals and, as a result, increasing the charge carrier lifetime.

3. The key results have been obtained from the investigation of the electrical characteristics of the Ni/CdTe/Ni structures with a Schottky contact based on CdTe:Cl crystals with nearly intrinsic conductivity: (i) the *I-V* characteristics of the Schottky diode structure with low reverse leakage current at high-bias voltages can be quantitatively described in terms of the known physical models: the generation-recombination in the SCR, the processes under conditions of strong electric fields and currents limited by space charge; (ii) a rapid rise of the current at high direct voltages due to injection of minority carriers from the Schottky contact to the neutral part of the crystal and the modulation of its conductivity; (iii) at relatively high reverse bias, the processes in the "Ohmic" contact on the opposite side of the crystal affect the reverse-biased Schottky contact.

4. The investigation results, obtained for Schottky diode detectors based on CdTe and $Cd_{0.9}Zn_{0.1}Te$ crystals with high resistivity (~10^9–10^{10} Ω·cm) and minority carrier lifetime (~10^{-6} s) and demonstrating significant differences in detection of the spectra from ^{241}Am, ^{57}Co, ^{133}Ba and ^{137}Cs isotopes, have shown a correlation between the low concentration of uncompensated donors and poor detection efficiency of the $Cd_{0.9}Zn_{0.1}Te$ detectors with quite acceptable resistivity and carrier lifetime. The conducted measurements and calculations show that the concentration of uncompensated impurities in the range from 3×10^{10} to 3×10^{12} cm^{-3} is yet another obligatory condition for effective operation of X/γ-ray Schottky diode detectors based on CdTe and $Cd_{1-x}Zn_xTe$ crystals.

5. The important conclusions about application of the CdTe layers with a Schottky contact in direct-conversion flat-panel X-ray image detectors have been established based on the research results of the electrical and detection characteristics of the fabricated diode structures: (i) the highly developed technology of the deposition of polycrystalline CdTe layers of large area with a surface-barrier structure in solar cells can be adapted to the fabrication of flat-panel X-ray image detectors. The presence of a barrier structure in the relatively low resistivity CdTe (ρ = 10^4–10^6 Ω·cm) provides low-leakage (dark) currents comparable with those in a-Se photoconductors (ρ = 10^{12} Ω·cm 300 K); (ii) electric field strength in the space charge region of a barrier structure eliminates the problem of the collection of charge generated by X-ray photon absorption. In a CdTe diode structure, virtually full charge collection occurs independently of the applied voltage at the carrier lifetime $\tau > 10^{-7}$ s and uncompensated impurity concentration higher than 10^{14} cm^{-3}; (iii) the detection efficiency of X-rays in the Al/p-CdTe diode structure at the maximum possible electron lifetime (a few microseconds) is 50–70 and 20–40% in the photon energy ranges

of 20–30 and 50–80 keV, respectively. Such characteristics seem to be acceptable for mammography and chest radiography.

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