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Charge collection properties of a CdTe Schottky diode for x- and γ-rays detectors

L A Kosyachenko[1], O L Maslyanchuk[1], V A Gnatyuk[2], C Lambropoulos[3], I M Rarenko[1], V M Sklyarchuk[1], O F Sklyarchuk[1] and Z I Zakharuk[1]

[1] Chernivtsi National University, 2 Kotsyubinsky St., 58012 Chernivtsi, Ukraine
[2] V.E. Lashkaryov Institute of Semiconductor Physics of National Academy of Sciences of Ukraine, 41 Prospekt Nauky, Kyiv 03028, Ukraine
[3] Technological Educational Institute of Halkis, Psahna, Evia, GR 34400, Greece

E-mail: lakos@chv.ukrpack.net

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Abstract
The electrical characteristics of x-ray and γ-ray detectors with Schottky diodes on the basis of CdTe crystals of n-type conductivity with a resistivity of 10^2–10^3 Ω cm (300 K) are investigated. The necessary parameters of the diode structures are determined to interpret the detection characteristics of the detectors. The dependences of the charge-collection efficiency in the detectors on the carrier lifetime and concentration of uncompensated donors are obtained and the conditions for the total collection of charges generated by the photon absorption are established. Taking into account drift and diffusion photocurrent components, the spectral distribution of the quantum detection efficiency is calculated. The comparative analysis of the detection efficiency of Schottky diodes based on low-resistivity p-CdTe and n-CdTe shows the advantages of the latter, especially in a low x-ray energy region.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

During the last few decades, cadmium telluride (CdTe) has become an important material for semiconductor x-ray and γ-ray detectors widely applied in science, engineering, medicine and other fields. Owing to large atomic numbers of the compound components (48 for Cd and 52 for Te), the operation range of CdTe detectors extends to a higher photon energy region (up to 1 MeV) in comparison with Si detectors, and at the same time the wider band gap (1.46 eV at 300 K) provides the operation of CdTe detectors without cryogenic cooling. For the total collection of charge generated by the absorbed x-ray or γ-ray quantum, the following conditions are necessary: (i) the bias voltage applied to a CdTe single crystal of several millimetres thickness should be not less than several hundreds of volts (in doing so, the conductivity of the semiconductor should be close to the intrinsic one) and (ii) the charge-carrier lifetime should not be less than several microseconds (record values of this parameter in the most pure and perfect CdTe single crystals). The fabrication of homogeneous CdTe single crystals with both semi-intrinsic conduction and high carrier lifetime meets a lot of technological problems.

As early as the 1960s, a real opportunity to create spectroscopic CdTe detectors with a surface barrier for γ-ray radiation operating at the room temperature was shown [1, 2]. This opportunity was repeatedly supported and discussed [3, 4]; however, the interest in these developments was lost after the commercial fabrication of detectors based on homogeneous single crystals of CdTe and then $Cd_{1-x}Zn_xTe$ with two ohmic contacts which showed characteristics acceptable for practical use. A return to developing CdTe detectors with a surface-barrier structure occurred at the end of the 1990s when the results were presented in series of publications [5–7]. These results indicated that the problems of obtaining high charge collection with low dark current in CdTe detectors could be overcome if a Schottky contact instead of an ohmic contact is formed on one of the surfaces of a semi-insulating crystal. This opened an opportunity for the fabrication of high-energy radiation detectors on the basis of p-CdTe with extreme energy resolution [8]. For the fabrication of such detectors, single crystals with a resistivity $\rho \sim 10^9$ Ω cm were used. To accomplish this, it is necessary to introduce in CdTe a compensating impurity (for example,

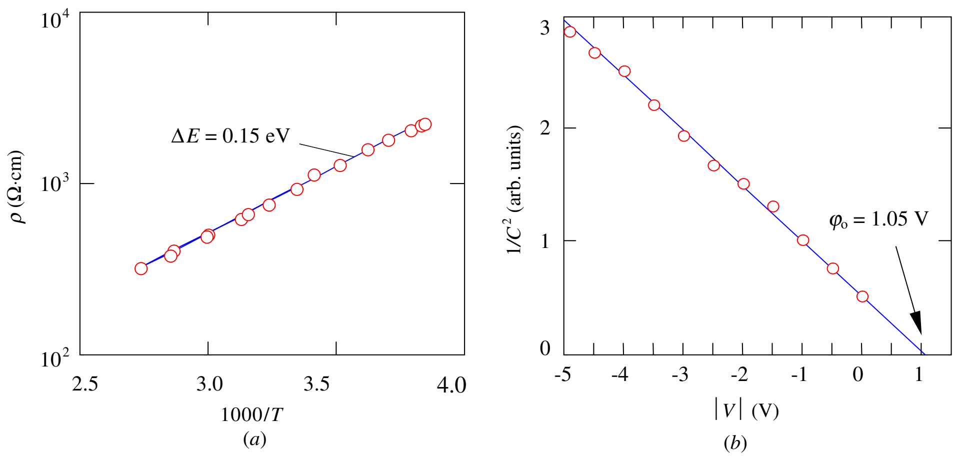


Figure 1. (*a*) The temperature dependence of the resistivity of the n-CdTe single crystal and (*b*) the *C*–*V* characteristic of the Schottky diode based on this material.

Cl) which creates deep levels in the bandgap; however, this inevitably results in a decrease of the charge-carrier lifetime. An ohmic contact assumes that an enriched layer in the semiconductor is formed, and the injection of carriers from this layer into the bulk part of a diode structure that decreases its resistivity is possible. In the case of a semi-insulating material and high carrier lifetime, the decrease of resistivity is quite essential [9]. Finally, high-resistivity CdTe crystals suffer from significant temperature and uncontrollable time fluctuations of electrical characteristics due to polarization processes which are inherent in the semiconductor.

In the present work, the possibilities of using n-CdTe with a Schottky contact for the development of x-ray or γ-ray detectors are investigated. The electrical properties of the fabricated n-CdTe-based Schottky diodes and charge-collection processes are discussed and the spectral distribution of the detection efficiency, which is one of the most important characteristics of a detector, is also analysed. The obtained results have shown that Schottky diodes fabricated on the basis of relatively low-resistivity n-CdTe (6–7 orders of magnitude lower than that of the semi-insulating material) have the characteristics no worse than those of Schottky diode detectors based on high-resistivity CdTe. The fabrication procedure of detectors on the basis of low-resistivity CdTe is simpler than in the case of high-resistivity CdTe because it is simpler to make non-injecting contacts to the semiconductor. There are also no particular problems to form a rectifying contact with a significant band bending at a semiconductor surface and low reverse currents. The total charge collection at the photon absorption occurs at low reverse bias and an increase in voltage results in only an extension of the active region of a detector. Schottky diodes based on low-resistivity CdTe have higher time stability without any polarization effects and they have weaker temperature variations of the parameters in comparison with diodes based on semi-insulating CdTe single crystals with two ohmic contacts.

2. Characterization of CdTe samples

For the fabrication of Schottky diodes, CdTe single crystals of (1 1 1) orientation grown in quartz crucibles with an internal diameter of 50 mm were used. Wafers of 1.5 mm thickness sliced from a CdTe ingot were ground, polished and then the samples were subjected to chemical etching and were thoroughly rinsed in de-ionized water. Further, in order to create n-type conduction, the wafers were annealed in saturated Cd vapour at a temperature of 850–900 °C for 24 h. After repeated mechanical and chemical treatment, the CdTe wafers of 1 mm thickness were annealed in vacuum at a temperature of 480 °C for 70–100 h, which essentially improves the material uniformity. The resistivity of the n-CdTe wafers ρ at room temperature was 10^2–10^3 Ω cm and the values of the electron concentration and mobility obtained from the measurements of the Hall coefficient and conductivity were equal to 10^{13}–10^{14} cm^{-3} and (1–1.15) × 10^3 cm^2 (V s)$^{-1}$, respectively. Figure 1(*a*) shows the typical temperature dependence of the resistivity of the obtained n-CdTe single crystals ($\rho \sim 10^3$ Ω cm at 300 K).

The Schottky contacts were fabricated by vacuum (10^{-6} Torr) evaporation of a Ni electrode with the area of 3.5 mm^2 and the thickness of 0.1–0.2 μm at the substrate temperature of 150–200 °C. Before the deposition of Ni, the surface of the CdTe wafers was subjected to the chemical treatment with subsequent etching in an argon atmosphere. An ohmic contact was formed by vacuum evaporation of In on the opposite side of the CdTe wafers.

The study of the capacitance characteristics of the Schottky diodes has allowed us to determine the parameters which are practically important in the detector performance: potential barrier height at the contact, concentration of uncompensated donors and space-charge region width, i.e. the width of the depletion layer (barrier region).

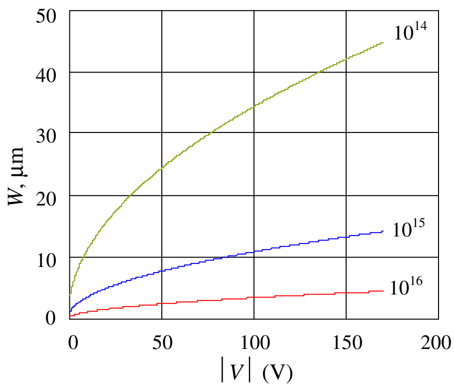


Figure 2. The voltage dependence of the space-charge region width in the n-CdTe-based Schottky diode calculated by equation (2) for different concentrations of uncompensated donors (indicated in cm^{-3} at the curves).

The dependence of the capacitance of a Schottky diode on bias voltage V is described by the expression [10]

$$C(V) = A\sqrt{\frac{\varepsilon\varepsilon_0 q^2(N_\mathrm{d} - N_\mathrm{a})}{2(\varphi_0 - qV)}}, \tag{1}$$

where A is the area of the diode, ε is the relative permittivity of the semiconductor, ε_0 is the permittivity of vacuum, q is the electron charge, $N_\mathrm{d} - N_\mathrm{a}$ is the concentration of uncompensated donors, $\varphi_0 = qV_\mathrm{bi}$ is the barrier height from the semiconductor side and V_bi is the diffusion (built-in) potential.

It follows from expression (1) that the voltage dependence C^{-2} is illustrated by a straight line. The barrier height and concentration of uncompensated donors can be determined from the slope of this line and segment intercepted on the x-axis (figure 1(*b*)). The calculated values of φ_0 and $N_\mathrm{d} - N_\mathrm{a}$ for the investigated diode are 1.05 eV and 1×10^{14} cm^{-3}, respectively. Knowledge of these parameters allows us to find the space-charge region width W at voltage V:

$$W(V) = \sqrt{\frac{2\varepsilon\varepsilon_0(\varphi_0 - qV)}{q^2(N_\mathrm{d} - N_\mathrm{a})}}. \tag{2}$$

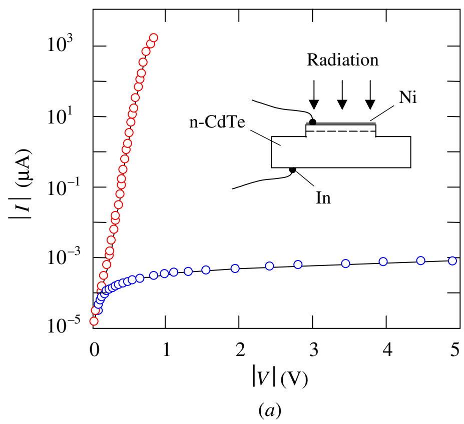
Figure 2 shows the voltage dependence of the space-charge region width W determined by equation (2) at different values of the concentration of uncompensated donors $N_\mathrm{d} - N_\mathrm{a}$. The value of W noticeably increases with a decrease in $N_\mathrm{d} - N_\mathrm{a}$. However, the minimal value of $N_\mathrm{d} - N_\mathrm{a}$ is chosen equal to 10^{14} cm^{-3}, proceeding from the reason that for an effective charge collection in a wide space-charge region, the carrier lifetime should be long (see section 4).

It should be noted that the active region of a detector is determined by both the space-charge region and region-adjoining layer of the neutral part of the diode structure. The effective width of this region equals the diffusion length of minority carriers; in our case it is holes $L_p = (\tau_p D_p)^{1/2}$, where τ_p and D_p are the hole lifetime and diffusion coefficient, respectively. In CdTe $D_p = 2$ $cm^2\ s^{-1}$ and the diffusion length is 1.7–17 μm at $\tau_p = 10^{-8}$–10^{-6} s (the electron diffusion length is several times longer owing to larger mobility).

3. Electrical characteristics of Ni/n-CdTe diodes

The fabricated Ni/n-CdTe diode structures have excellent rectification properties as is evident from the *I–V* characteristic of one of the diodes (figure 3(*a*)). From the practical point of view, it is important that the current is only several nanoamperes ($A = 3.5$ mm^2) at reverse bias $V = -100$ V at room temperature and when the temperature lowers to -25 °C (this is often used in the practical application of CdTe detectors [8]), the dark current decreases up to tenths of a nanoampere (figure 3(*b*)). This fact attracts the attention that the conductivity of semi-intrinsic CdTe varies with temperature practically in the same manner. It is no wonder because, according to the theory discussed below, the reverse current in a Schottky diode is proportional to the intrinsic carrier concentration n_i when levels are located near the middle of the band gap of the semiconductor.

The *I–V* characteristics of CdTe-based Schottky diodes are well described by the Sah–Noyce–Shockley theory for generation recombination of charges [11, 12], according to which the current through the diode is found by integrating the generation–recombination rate over the entire space-charge



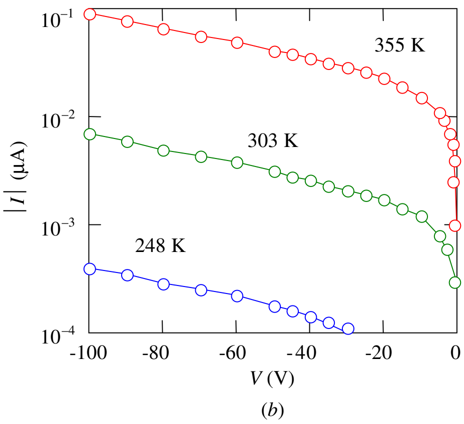


Figure 3. (*a*) The *I–V* characteristic of the Ni/n-CdTe diode in semilogarithmic coordinates (the inset shows a cross section of the diode structure). (*b*) The reverse current through the diode at different temperatures. The area of the Ni contact is 3.5 mm^2.

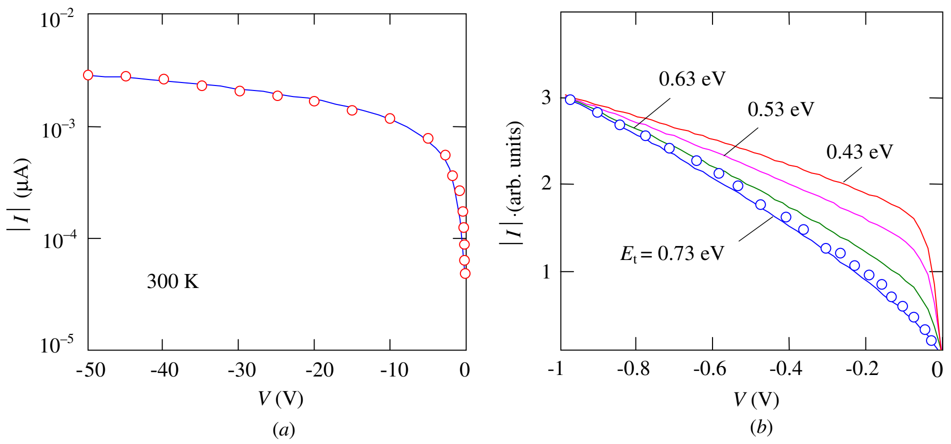


Figure 4. (*a*) Comparison of the measured reverse *I–V* characteristic of the Ni/n-CdTe diode of a 3.5 mm^2 area (circles) with that calculated (solid line) by equation (3) at $E_t = 0.73$ eV. (*b*) The initial sections of the reverse *I–V* characteristic normalized at the voltage $V = -1$ V: measured (circles) and calculated (solid lines) by formula (3) at different values of E_t.

region [13]:

$$I_{g-r} = Aq \int_0^W \frac{n(x, V)p(x, V) - n_i^2}{\tau_{p0}[n(x, V) + n_1] + \tau_{n0}[p(x, V) + p_1]} \, dx, \tag{3}$$

where $n(x, V)$ and $p(x, V)$ are the carrier concentrations in the corresponding bands, and τ_{n0} and τ_{p0} are the effective lifetimes of electrons and holes in the space-charge region. The values of n_1 and p_1 are equal to the equilibrium concentrations of electrons and holes, respectively, under the condition that the Fermi level coincides with the considered level, i.e. $n_1 = N_c \exp(-E_t/kT)$ and $p_1 = N_v \exp[-(E_g - E_t)/kT]$, where $N_c = 2(m_n kT/2\pi\hbar)^{3/2}$ and $N_v = 2(m_p kT/2\pi\hbar^2)^{3/2}$ are the effective state densities in the conduction and valence bands, respectively (m_n are m_p are the effective masses of electrons and holes, respectively), E_t is the energy spacing between the generation-recombination energy level and the bottom of the conduction band.

Calculating the energy from the bottom of the conductivity band in the bulk of the diode structure and the coordinate x from the semiconductor surface, it is possible to write for the concentrations of electron and holes in a point x at voltage V [11]:

$$n(x, V) = N_c \exp\left[-\frac{\Delta\mu + \varphi(x, V)}{kT}\right], \tag{4}$$

$$p(x, V) = N_v \exp\left[-\frac{E_g - \Delta\mu - \varphi(x, V) - qV}{kT}\right], \tag{5}$$

where E_g is the bandgap of the semiconductor, $\Delta\mu$ is the energy difference between the Fermi level E_F and the conduction band edge in the neutral (bulk) part of the diode structure which can be found using the electron concentration as $kT \ln(N_c/n)$, and $\varphi(x, V)$ is the potential energy of electron in the space-charge region:

$$\varphi(x, V) = (\varphi_0 - qV)\left(1 - \frac{x}{W}\right)^2. \tag{6}$$

Figure 4(*a*) shows the results of comparison of the measured reverse current with that calculated by equation (3) in the range of reverse bias voltages 0–50 V. The following parameters were used at calculations**:** $m_n = 0.11m_0$, $m_p = 0.35m_0$ (m_0 is the vacuum electron mass), $\mu_n = 1000$ cm^2 (V s)$^{-1}$, $\varphi_0 = 1.05$ eV, $\Delta\mu = kT \ln(N_c/n) = 0.307$ eV and $N_d = 1 \times 10^{14}$ cm^{-3}. For coincidence of the values of experimental and calculated currents at forward bias, the lifetime was accepted as equal to $\tau_{n0} = \tau_{p0} = 1.2 \times 10^{-9}$ s. As is seen from figure 4, a good agreement is observed between the calculation results and the experimental curve that is evidence of the correctness of the discussed charge transport mechanism in the investigated diodes.

According to the Sah–Noyce–Shockley theory, the value of the reverse current through the diode essentially depends on the position of the generation–recombination level in the band gap of the semiconductor, i.e. on the energy E_t appearing in expressions for n_1 and p_1 in equation (3). At low reverse biases, the shape of the curve $I(V)$ also depends on E_t [11, 12]. This can be used for finding the value of E_t. Comparison of the experimental dependence $I(V)$ with the calculated ones at different E_t is shown in figure 4(*b*) (all curves are normalized by the voltage $V = -1$ V). As seen, a good agreement of the theory and experiment is observed at $E_t = 0.73$ eV, i.e. when the generation–recombination level is located in the middle of the band gap of the semiconductor. It is not surprising because the impurities with just such energy levels are the most effective centres of generation recombination [13], and there is always a rather high concentration of accidental impurities (point defects) which create deep levels in CdTe single crystals [14, 15].

4. Charge-collection efficiency in the depletion region of Schottky diodes

If the effect of detrapping is neglected, the collection efficiency of charge carriers generated as a result of photon absorption in a homogeneous semiconductor is described by the Hecht equation, which in the one-dimensional case has the form [16, 17]

$$\eta(x) = \frac{\lambda_n}{W}\left[1 - \exp\left(-\frac{W-x}{\lambda_n}\right)\right] + \frac{\lambda_p}{W}\left[1 - \exp\left(-\frac{x}{\lambda_p}\right)\right], \quad (7)$$

where W in this case is the distance between the collecting electrodes and λ_n and λ_p are the mean drift lengths of electrons and holes, respectively, where

$$\lambda_n = \mu_n \tau_n E, \quad (8)$$

$$\lambda_p = \mu_p \tau_p E, \quad (9)$$

and where E is the electric field strength, τ_n and τ_p, μ_n and μ_p are the lifetimes and mobilities of electrons and holes, respectively (mobility-lifetime products $\mu_n\tau_n$ and $\mu_p\tau_p$ are the most important parameters characterizing the operation of a semiconductor detector).

Non-uniformity of the electric field in the barrier region of the Schottky diode is described by the formula following from equation (6):

$$E(x) = \frac{2(\varphi_0 - qV)}{qW}\left(1 - \frac{x}{W}\right). \quad (10)$$

Consideration of the non-uniformity of the electric field in expression (7) becomes simpler because according to equation (10) the electric field strength depends linearly on the coordinate x; therefore, the value of E in equations (8) and (9) can be replaced by the average values of the electric field strength in the range (x, W) for electrons E_n and in the range (0, x) for holes E_p (similar to how it is made in the case of diodes Al/p-CdTe [18]). Assuming that the average fields are equal to $(E_{\min} + E_{\max})/2$, the expressions below follow from (10):

$$E_n = \frac{(\varphi_0 - qV)}{qW}\left(2 - \frac{x}{W}\right), \quad (11)$$

$$E_p = \frac{(\varphi_0 - qV)}{qW}\left(1 - \frac{x}{W}\right). \quad (12)$$

Figure 5 shows the coordinate dependences of η at the concentration of uncompensated donors $N_\mathrm{d} - N_\mathrm{a} = 10^{14}$ cm^{-3} and different values of lifetimes of electrons and holes which are accepted to be equal $\tau_n = \tau_p = \tau$. As was possible to expect, the value of $\eta(x)$ depends essentially on the charge-carrier lifetime. It is important for practice that the charge-collection efficiency is quite low when the carrier lifetime is less than $\tau = 10^{-7}$ s. By increasing the concentration of uncompensated donors, the charge-collection efficiency significantly improves owing to the narrowing of the space-charge region and to the consequent increase of the electric field strength. If, for example, $N_\mathrm{d} - N_\mathrm{a}$ is increased from 10^{14} cm^{-3} up to 10^{16} cm^{-3}, the view of figure 5(*a*) is not changed but three bottom curves correspond $\tau = 10^{-12}$ s, 10^{-11} s and 10^{-10} *s* and practically the total charge collection occurs at $\tau > 10^{-9}$ s (instead of $\tau > 10^{-7}$ s at $N_\mathrm{d} - N_\mathrm{a} = 10^{14}$ cm^{-3}).

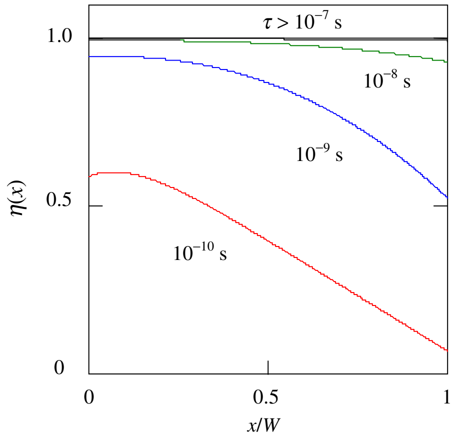


Figure 5. The charge-collection efficiency η in the barrier region of the Schottky diode at $N_\mathrm{d} - N_\mathrm{a} = 10^{14}$ cm^{-3} ($W = 11.4$ μm) and at different values of the charge-carrier lifetime τ.

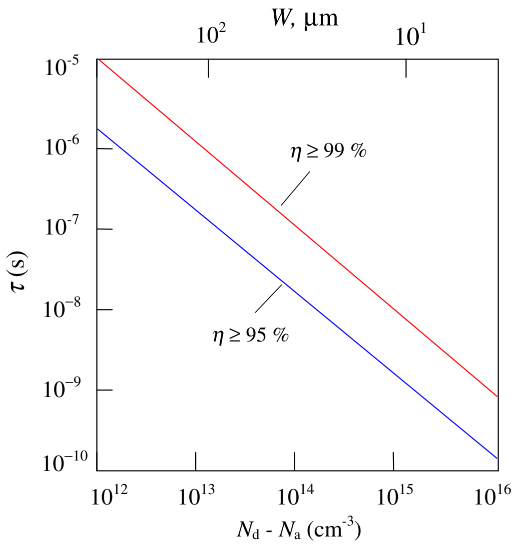


Figure 6. The correlation between the charge-carrier lifetime τ and concentration of uncompensated donors $N_\mathrm{d} - N_\mathrm{a}$ at which the collection of 99% and 95% charge carriers photogenerated at the interface between the depleted region and neutral part of the diode structure ($x = W$) is achieved at $V = -100$ V. The top axis shows the value of W corresponding to the given $N_\mathrm{d} - N_\mathrm{a}$.

Thus, the total charge collection can be achieved by an increase in $N_\mathrm{d} - N_\mathrm{a}$, according to equation (6), by narrowing the space-charge region, i.e. the active region of the detector. Figure 6 shows what $N_\mathrm{d} - N_\mathrm{a}$ and τ should be to achieve practically the total charge collection at $V = -100$ V. As the criterion, the conditions were selected when the charge-collection efficiency $\eta(x)$ was equal to 0.99 at $x = W$, i.e. 99% (the charge-collection efficiency in the range $x < W$ is even higher). It is seen that to achieve such a value of η at the concentration of uncompensated donors $N_\mathrm{d} - N_\mathrm{a} \sim 10^{12}$ cm^{-3}, the carrier lifetime should be equal to a practically inaccessible value 10^{-5} s (the thickness of the active region of the detector is $\sim$400 μm at $V = -100$ V).

If the selected criterion of the charge-collection efficiency is decreased to 95% at $x = W$ (top line in figure 6), the lifetime should be equal to several microseconds, which is a typical case for the best CdTe samples [9, 14]. On the other hand, if $N_d - N_a \approx 10^{16}$ cm^{-3}, the carrier lifetime should exceed 10^{-9} s which is quite real even when a mediocre material is used. In the case of $N_d - N_a \approx 10^{14}$ cm^{-3}, to provide practically the total charge collection (99%) the carrier lifetime should be equal to or exceed $\sim 10^{-7}$ s.

It is necessary to note that the charge-collection efficiency in the space-charge region of a Schottky diode does not depend on the applied voltage V. This is explained by the fact that with increasing V, the space-charge region W extends simultaneously with an increase in the electric field strength. Moreover, as seen from equations (2) and (10), both the values increase proportionally to $(\varphi_0 - qV)^{1/2}$. Owing to this, the transit time of carriers through the space-charge region t_0 does not depend on the applied voltage V. In fact, the average electric field strength in the Schottky diode equals $(\varphi_0 - qV)/qW$ and the average drift velocity, for example, of an electron equals $\mu_n(\varphi_0 - qV)/qW$. Having divided W by the average drift velocity, we obtain the expression for the electron transit time independent of V:

$$t_0 = \frac{2\varepsilon\varepsilon_0}{q\mu_n}\frac{1}{N_d - N_a}. \qquad (13)$$

A similar expression can be obtained for the hole transit time by replacing the electron mobility μ_n in (13) with the hole mobility μ_p. Thus, an increase in the voltage applied to the Schottky diode detector does not improve the charge-collection efficiency (unlike a single crystal with ohmic contacts) and only increases the detection efficiency of photons because the active region W of the detector increases.

5. Spectral distribution of detection efficiency

The number of photons absorbed in a layer of thickness dx at the distance x from the front surface of the detector can be presented as

$$d\Phi = \Phi_0 \exp(-\alpha_{Ni}d_{Ni})\alpha_{CdTe}\exp(-\alpha_{CdTe}x)\,dx, \qquad (14)$$

where Φ_0 is the number of incident photons, d_{Ni} is the thickness of the front electrode, α_{Ni} and α_{CdTe} are the linear absorption coefficients of the electrode material (Ni) and CdTe, respectively. The number of photons absorbed in a layer dx and separated by the electric field is equal to the product of dΦ and $\eta(x)$, and the detection efficiency in the entire barrier region is

$$\eta_{drift} = \frac{1}{\Phi_0}\int_0^W \eta(x)\,d\Phi$$
$$= \exp(-\alpha_{Ni}d_{Ni})\int_0^W \alpha_{CdTe}\eta(x)\exp(-\alpha_{CdTe}x)\,dx. \qquad (15)$$

As we have mentioned in section 2, calculating the detection efficiency, it is necessary to take into account not only the considered drift component but also the *diffusion* one, which is due to the fact that a pulse in the detector circuit is also formed by carriers generated by the photon absorption outside of the barrier region of the detector at a distance from the point $x = W$ no more than the minority carrier diffusion length L_p (holes in a detector based on an electronic semiconductor). Having reached as a result of diffusion the point $x = W$, electrons are captured by the electric field in the space-charge region. The charge-collection efficiency of such a process can be accepted equal to the value of $\eta(x)$ in the point $x = W$. Thus, the expression for the diffusion component of the charge collection can be written as

$$\eta_{dif} = \eta(W)\int_W^{W+L_p} d\Phi, \qquad (16)$$

where

$$\eta(W) = \frac{\lambda_p}{W}\left[1 - \exp\left(-\frac{W}{\lambda_p}\right)\right]. \qquad (17)$$

The total photon detection efficiency of a Schottky diode detector equals the sum of the drift and diffusion components

$$\eta = \eta_{drift} + \eta_{dif}. \qquad (18)$$

The calculation results of the spectral distribution of the detection efficiency of the n-CdTe-based Schottky diode performed by equation (18) by taking into account (15) and (16) are presented in figure 7. At the calculations, we used the tables of absorption coefficients of Cd, Te and Ni of the National Institute of Standards and Technology (NIST), USA [19].

As is seen from figure 7(*a*), 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 two 'teeth' on the curves correspond to the energy of the absorption edge of electrons on the K-shell in Cd and Te (26.7 keV and 31.8 keV, respectively). In the case of CdTe detectors with a thickness in the order of magnitude of a millimetre without a Schottky barrier, these teeth are not observed (the dashed line in Figure 7(*b*)) because the detection efficiency in this photon energy range is equal to 1. A decrease in the detection efficiency at $h\nu < 10$ keV is due to the photon absorption by a nickel electrode and a weak 'structure' in the range ~3 eV corresponds to the energy of the absorption edge of electrons on the L-shell.

Representation of the detection efficiency spectrum in double logarithmic coordinates allows us to visually reveal its features in the high photon energy range and to compare them with the detection efficiency of the detector with ohmic contacts (figure 7(*b*)). As was possible to expect, the detection efficiency of the detector with a thickness of 1 mm in the photon energy range higher than 50 keV significantly exceeds the detection efficiency of the Schottky diode detector. Let us note that an increase in the bias voltage for the order of magnitude (from 10 to 100 V) leads to an insignificant rise (by 1.6–1.7 times) in the total detector efficiency. This can be explained as follows: firstly, the barrier region of the detector extends proportionally to $(\varphi_0 - eV)^{1/2}$ and, secondly, a significant contribution to the detection efficiency comes from the diffusion component which is determined by the hole diffusion length and does not depend on the voltage. In this connection, it is interesting to consider the p-CdTe-based

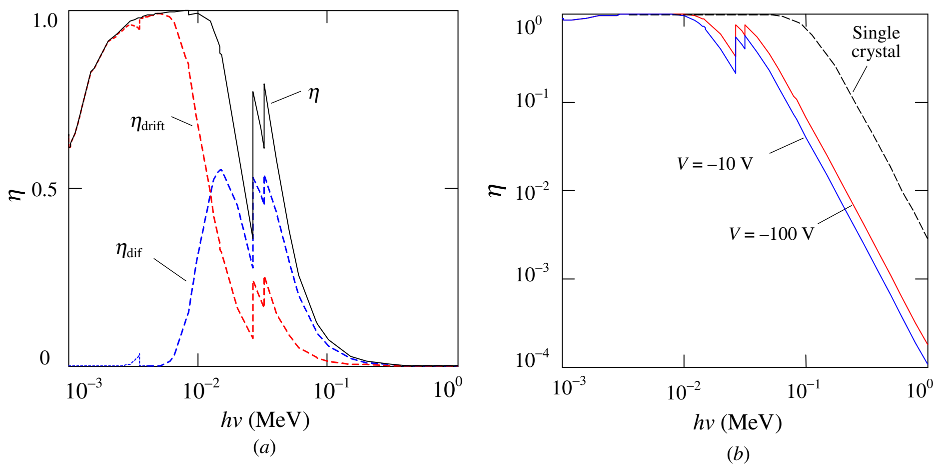


Figure 7. (a) The drift $\eta_{\rm drift}$ and diffusion $\eta_{\rm dif}$ components of the detection efficiency (dashed curves) and also their sum (solid curve) calculated at $N_{\rm d} - N_{\rm a} = 10^{14}$ cm^{-3} and the hole lifetime $\tau_p = 10^{-6}$ s at reverse bias $V = -10$ V ($W = 11.4$ μm). (b) The total detection efficiency spectra of the detector $\eta = \eta_{\rm drift} + \eta_{\rm dif}$ calculated at the same parameters and at reverse biases of -10 V and -100 V. The dashed line shows the detection efficiency for a 1 mm thick single crystal detector with two ohmic contacts at $V = -100$ V (the collection efficiency $\eta = 1$ is assumed).

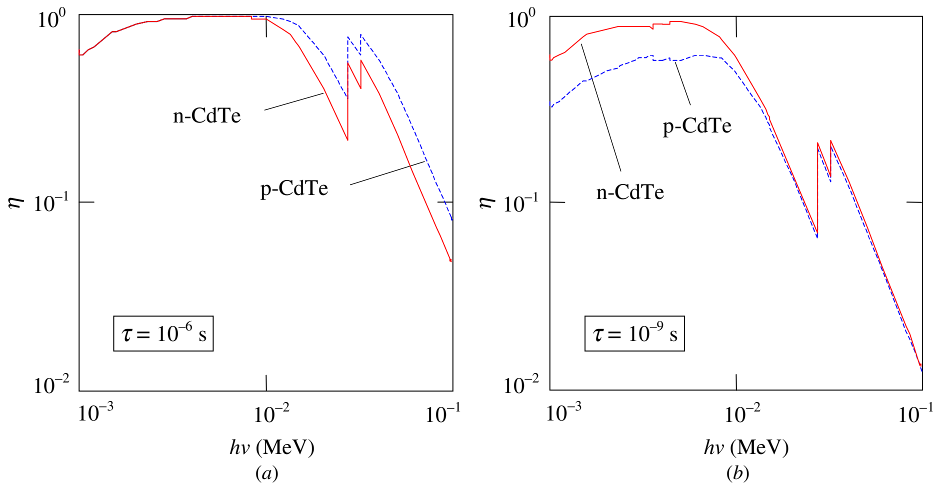


Figure 8. Comparison of the total detection efficiency of the n- and p-CdTe-based Schottky diodes with the carrier lifetimes (a) 10^{-6} s and (b) 10^{-9} s.

Schottky detector with the minority carrier (electron) diffusion length which is approximately 3.5 times more in comparison to that in n-CdTe. Calculating the drift component of the detection efficiency of the p-CdTe-based Schottky detector, we should modify equation (7) because in this case an electron photogenerated in a point x passes a way from x to 0 and a hole from x to W. Calculating the diffusion component of the detection efficiency, it is necessary to set the upper integration limit in equation (16) equal to $W + L_{\rm n}$ and replace $\lambda_{\rm p}$ with $\lambda_{\rm n}$ in equation (17).

Figure 8 shows the detection efficiency spectra of the n- and p-CdTe-based diodes calculated at the same parameters: barrier height (1 eV), uncompensated impurity concentration (10^{14} cm^{-3}) and bias voltage (-10 V).

As seen, in the case of $\tau = 10^{-6}$ s, the detection efficiency in the high energy range for the Schottky diodes based on p-CdTe is approximately two times more than that of the n-CdTe-based Schottky diodes (figure 8(a)). This is due to a longer diffusion length of electrons ($\sim$50 μm) compared with holes ($\sim$14 μm). This advantage of the p-CdTe-based detector is lost when the carrier lifetime equals 10^{-9} s. In this case, the diffusion lengths of electron and holes decrease to 1.6 μm and 0.4 μm, respectively, that resulted in a decrease in the diffusion component of the detector efficiency. As a result, the detection efficiencies of the detectors based on n- and p-CdTe semiconductors almost coincide in the high-energy range (figure 8(b)).

However, charge-collection losses in the space-charge region become essential at the carrier lifetime $\tau = 10^{-9}$ s (figure 5) which leads to a decrease in the detection efficiency in the low energy range (figure 8(b)). This is the reason that, for the fabrication of Schottky diode detectors, n-type CdTe is the preferred semiconductor because it operates even at relatively low carrier lifetimes (up to 10^{-9} s).

The sensitivity of a CdTe Schottky diode detector in the high-energy spectrum range can be increased using several diodes stacked together [20]. For example, the calculations performed for $N_d - N_a = 10^{14}$ cm^{-3}, $\tau = 10^{-6}$ s and $V = -100$ V show that in the photon energy range $h\upsilon > 50$ keV, the detection efficiency of the ten-stage detector approaches the efficiency of the single crystal detector of 1 mm thickness with ohmic contacts.

Let us once again note that requirements for material quality in the case of a Schottky diode detector are less stringent and material resistivity can be lower by many orders of magnitude in comparison with a detector with two ohmic contacts. The charge-carrier lifetime can also be smaller by 1–2 orders of magnitude because it is much easier to achieve the total charge collection in a thin barrier region than in a thick detector with ohmic contacts; moreover, it can be made without electronic devices eliminating the influence of low mobility holes in CdTe.

6. Conclusions

The investigation of the electrical properties, charge-collection processes and spectral distribution of the detection efficiency of x-ray and γ-ray detectors with Schottky contacts based on relatively low-resistivity n-CdTe crystals have showed that in many respects their performances are not inferior to those of more technologically complicated Schottky diode detectors based on semi-insulating CdTe. Reverse leakage current of the investigated Schottky diodes is determined by the generation in the space-charge region and its density is as low as 0.3 nA mm^{-2}.

The charge-collection efficiency in x-ray and γ-ray detectors with a Schottky diode essentially depends on the carrier lifetime τ and uncompensated donor concentration $N_d - N_a$. In the case of $N_d - N_a \approx 10^{14}$ cm^{-3}, to provide practically the total charge collection (99%) the carrier lifetime should be equal to or exceed $\sim 10^{-7}$ s. If $N_d - N_a \approx 10^{16}$ cm^{-3}, the carrier lifetime should exceed 10^{-9} s, which is quite realistic when even a mediocre material is used.

The photon detection efficiency in x-ray and γ-ray detectors with a Schottky diode is determined not only by the drift component but also by the diffusion one which is due to the absorption of photons outside of the space-charge region of the diode structure. The contribution of this component to the total detector efficiency is quite essential at the minority carrier lifetime $\sim 10^{-6}$ s and it becomes dominant in the photon high-energy range. From the point of view of a high detection efficiency, for the x-ray spectrum range $h\upsilon < 50$ keV n-type CdTe is preferred in comparison with p-CdTe. The use of several cascades of CdTe detectors (stacked detectors) with a Schottky diode allows us to considerably increase the detection efficiency of the device in the high-energy range of the spectrum.

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