Influence of the thickness of a crystal on the electrical characteristics of Cd(Zn)Te detectors

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ABSTRACT

We studied the electrical characteristics of Cd(Zn)Te detectors with rectifying contacts and varying thicknesses, and established that their geometrical dimensions affect the measured electrical properties. We found that the maximum value of the operating-bias voltage and the electric field in the detector for acceptable values of the dark current can be achieved when the crystal has an optimum thickness. This finding is due to the combined effect of generation-recombination in the space-charge region and space-charge limited currents (SCLC).

Keywords: Cd(Zn)Te, detectors, electrical characteristics, I-V curves, SCLC.

1.   INTRODUCTION

X-ray and nuclear-radiation detectors based on wide band-gap semiconductors find practical applications in industry and medicine, dosimetry, radiology, space research, radio astronomy, and other areas [1]. Cadmium telluride (CdTe) and solid solutions based on Cd(Zn)Te are the most important materials today for spectrometer-type X/γ-radiation detectors working without cryogenic cooling, particularly at photon energies above 30-50 keV [2,3]. A lower density of defects and somewhat wider energy gap of Cd(Zn)Te allowed us to grow single crystals of nearly stoichiometric composition with an electrical resistivity at room temperature close to 10^{11} Ohm×cm [4].

The resolution of CdTe and Cd(Zn)Te detectors can be considerably improved [5,6] if one of the ohmic contacts is replaced by a Schottky contact, an approach that has been used advantageously since the late 1990s. By using a structure with a rectifying contact instead of ohmic, we can increase considerably the intensity of the electrical field created across the detector crystal. Nevertheless, the effects of the crystal's thickness on the detector's electrical parameters have received little attention.

We studied bulk crystals of $Cd_{1-x}Zn_xTe$ ($0 \leq x \leq 0.1$) grown from a melt of a stoichiometric composition and doped with indium during their growth. For the range of typical ambient temperatures, all the crystals weakly expressed electron conduction (i.e., n-type); their resistivity was a function of $x,$ and varied within 10^9-10^{10} Ohm·cm. We note that nowadays such materials are the basis for X-ray and γ-radiation detectors that are widely used in science, technology, medicine, and other fields [1].

2.   EXPERIMENTAL

For our electro-physical investigations, we made both ohmic- and rectifying-contacts for crystals of different thickness. For our experiments the crystal area was fixed at 5x5 mm^2; under this area metal contacts were attached to the crystals. The thickness of the crystals under study varied from 0.5 to 5.0 mm. Preparation of the crystal's surface included high-quality mechanical treatment with diamond paste, and chemical treatment in a bromine-methanol solution. Immediately prior to depositing the metal, the crystal's surface was processed for 10-15 minutes in an argon plasma (300-350 V and 35-50 mA) to create an ohmic contact, and to 350-500 V and 10-15 mA for creating a rectifying contact. Contact metal was applied by thermal evaporation in a vacuum. Indium was used for the ohmic contact and chromium for the rectifying one. These

metal contacts, 4x4 mm^2, were sized by molybdenum masks. In/Cd(Zn)Te/In and Cr/Cd(Zn)Te/In structures also were created this way. For comparison, Au/Cd(Zn)Te/In and Au/Cd(Zn)Te/Au structures also were formed. Gold was applied by a chemical-deposition method. Fig. 1 shows typical current-voltage (I-V) curves.

As evident from Fig. 1, the Cr/Cd(Zn)Te/In structures possess rectifying properties. At a voltage of ~100 V, the rectification factor was ~10^2. Moreover, Cr/Cd(Zn)Te/In structures had better parameters as detectors. As is evident from Fig. 1, these structures had lower dark currents, especially at high voltages, which is important for detectors of ionizing radiation. So, further studies were performed with Cr/Cd(Zn)Te/In structures. Fig. 2 shows the I-V curves of Cr/Cd(Zn)Te/In structures at forward bias ("minus" the supply sources to the indium contact) made on crystals of different thicknesses. The I-V curves are given both in traditional coordinates I=I(V), and in $\rho_{dif}=\rho_{dif}(V)$. The differential resistance was taken as $\rho_{dif}=dV/dI$. Such a construction is more sensitive to changes in the I-V curves, and hence it can be more informative.
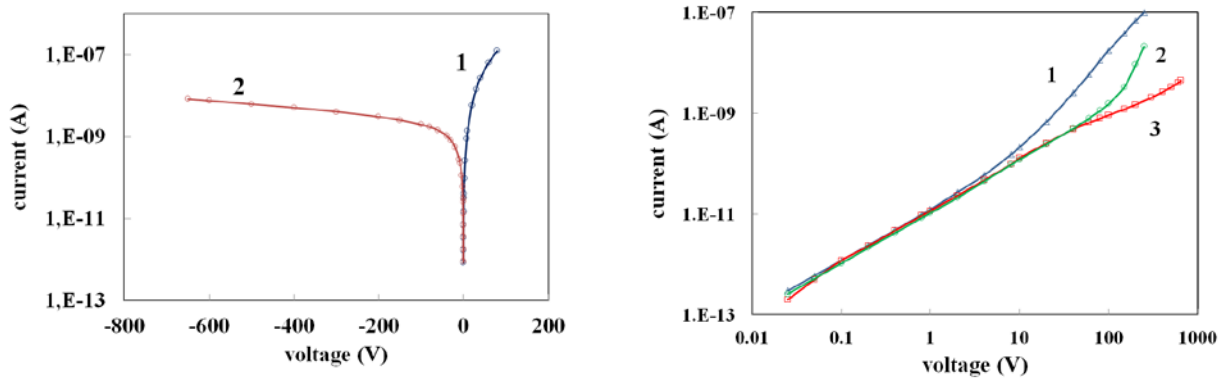

Fig. 1. Left: I-V curves for Cr/Cd(Zn)Te/In structure: 1 - At forward bias, and 2 - reverse biased.
Right: The I-V curves for different structures: 1- In/Cd(Zn)Te/In, 2 - Au/Cd(Zn)Te/Au,
and 3 - Cr/Cd(Zn)Te/In. Crystal thickness - 1.0 mm. Temperature - 293 K.

As shown in Fig. 2, the linear region of the I-V curves (I~V) at a certain voltage V_x becomes quadratic I~V^2. In so doing, the larger that V_x is, the greater is the crystal's thickness. Our investigations established that with a change in crystal thickness within d=0.5 – 5.5 mm, V_x is proportional to d^2. Naturally, we obtained the V_x~d^2 dependence for structures made on homogeneous crystals. Fig. 3 shows I-V curves at reverse bias conditions for the Cr/Cd(Zn)Te/In structure for crystals of different thicknesses.
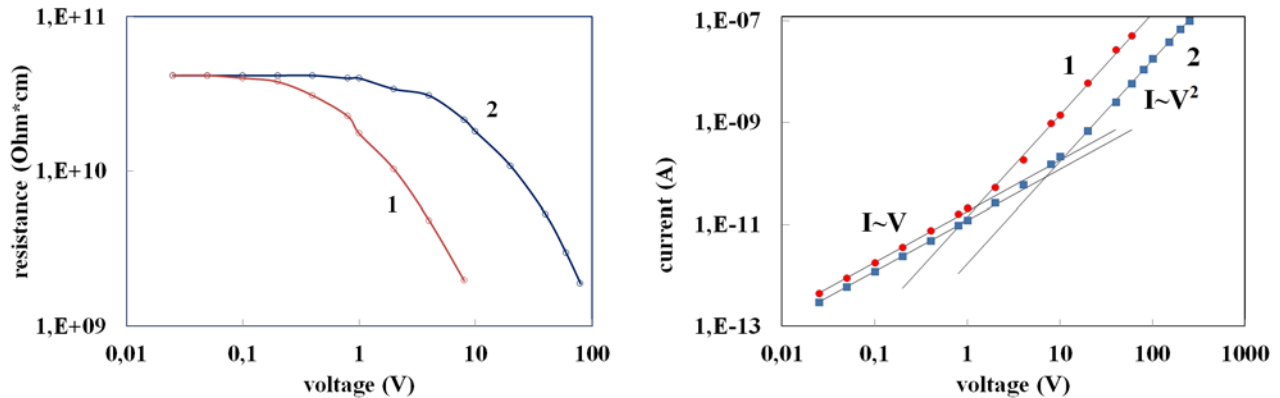

Fig. 2. The dependence of the differential resistance, $\rho_{dif,}$ at forward bias (on the left), and the dark current (on the right) for a Cr/Cd(Zn)Te/In structure. Crystal thickness: 1 - 1.0 mm, and 2 - 2.0 mm. T = 293 K.

As we see from Fig. 3, $\rho_{dif}=\rho_{dif}(V)$ dependences are different. For crystals 2.0 mm- and 4.5 mm-thick, for the $\rho_{dif}=\rho_{dif}(V)$ dependence, there is a marked decay in the differential resistance at voltages $V > 1$ V that changes with the increase in ρ_{dif} at higher voltages. For crystals 0.5 mm- and 1.0 mm-thick, no such decay is observed. However, for the latter, the maximum ρ_{dif} value is achieved in a rather wide range of voltage. In our view, the construction of ρ_{dif} dependence on the crystal's thickness d, $\rho_{dif}=\rho_{dif}(d)$, at a constant voltage is informative. Fig. 4 shows such dependence at a reverse voltage of ~150 V.

3. RESULTS AND DISCUSSION

This behavior of the I-V curve of the Cr/Cd(Zn)Te/In structures with change in the crystal's thickness is attributable to the action of two mechanisms during the passage of the dark current: Space-charge-limited currents (SCLC) in the neutral part of the crystal, and a generation-recombination mechanism in the depleted region of the rectifying contact. With an increase in reverse voltage, the depleted region of contact W is increased in the proportion $W \sim V^{1/2}$. The differential resistance of this region essentially is higher than the resistivity of the neutral part of the crystal. However, at low voltages, the resistance of the neutral part can be higher and, accordingly, contribute more to the resistance of the total structure. In this situation, the crystal's thickness plays an essential role: for relatively thick crystals, the resistance of the total structure can be close to the resistance of the neutral crystal part. With a reduction in the crystal's thickness, the situation can change, and the resistance of the depleted region can contribute more to the resistance of the total structure. This, in our view, can explain the increase in ρ_{dif} for the region of voltages 0.1-2.0 V concurrent with a reduction in the thickness of the crystal (Fig. 3). The thicker the crystal, the closer is ρ_{dif} to the crystal's resistivity. With a further voltage increase, the dark current becomes higher. In this case, with crystals of different thicknesses, voltage decay is distributed differently between the neutral part and the depleted layer. When the voltage drop in the neutral crystal part reaches the value V_x, the contribution of SCLC becomes notable. Therefore, the increase in voltage is accompanied by two opposite processes, namely the SCLC mechanisms that tend to reduce the crystal's resistance, and the expansion of depleted region that increases the resistance. Thus, there are "dimples" on $\rho_{dif}=\rho_{dif}(V)$ dependences for crystal of 2.0-mm thick and 4.5-mm thick (Fig. 3), and there is a maximum for the $\rho_{dif}=\rho_{dif}(d)$ dependence at a constant voltage. For the trap mechanism of SCLC, V_x corresponds to the voltage at which the currents of the ohmic and the quadratic regions of I-V curve are equal [7]. In this case, the flight time is calculated by the equation $\tau_{\Pi p}=\tau_M$, where τ_M is Maxwell time of dielectric relaxation. The dielectric relaxation time is $\tau_M = \varepsilon_s \cdot \rho$, where ρ is semiconductor resistivity, ε_s is the product equal to $\varepsilon \cdot \varepsilon_o$ [8], ε is dielectric permittivity, and ε_o is electric constant. It is clear that in our case $\rho \sim 10^{10}$ Ohm·cm; hence, τ_M essentially is larger than the lifetimes τ_n and τ_p of electrons and holes in the semiconductor. Therefore, in the equality $\tau_{\Pi p}=\tau_M$, the Maxwell lifetime must be replaced by τ_n, that is, for an n-type semiconductor:

$$\tau_{\Pi p}=\tau_n \tag{1}$$
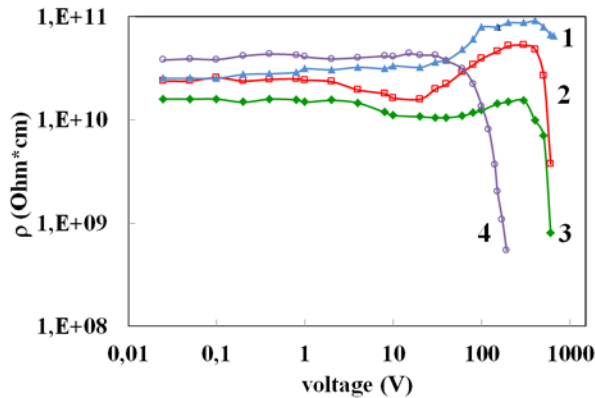

Fig. 3. The dependence of the differential resistance, ρ_{dif}, at reverse bias for the structure Cr/Cd(Zn)Te/In for crystals with different thickness:
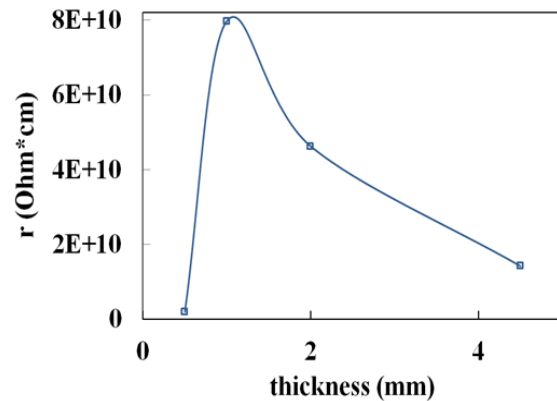1 - 1.0; 2- 2.0; 3- 4.5; 4 - 0.5 mm. T= 293 K.

Fig. 4. Experimental dependence of differential resistance, R_{dif}, at reverse bias versus the crystal's thickness for the Cr/Cd(Zn)Te/In structure. Temperature - 293 K.

The time of flight is equal to $\tau_{np}=d^2/\mu_n E$ [7], where E is the intensity of the electric field, μ_n is the electron mobility, and d is the crystal's thickness. Then, the voltage V_x is equal [7] to

$$V_x = 4d^2/3\rho\mu_n\varepsilon_s . \qquad (2)$$

According to (1) and (2), V_x, with all other parameters constant, will be the larger, and the shorter is the lifetime. This is significant for further analysis of the behavior of the I-V curve.

With the reverse-voltage increasing, the thickness of the depleted area, W, grows and, under certain conditions, may become equal to or bigger than the crystal's thickness, d. Clearly in this case, not only the generation-recombination current increases, but SCLC also does. The value of this current in general depends not only on the thickness of the depleted region and the concentration and energy position of deep impurities, but also on the effective lifetime τ_{n0} [9], which may differ significantly from τ_n in a neutral part of the crystal. Usually, τ_{n0} is at least an order-of-magnitude smaller than τ_n. Therefore, the voltage V_{xo} corresponding to the SCLC mechanism will be significantly bigger than V_x.

To interpret the mechanisms of charge transfer in a wide range of current-voltage (I-V), it is useful to introduce the characteristic in double logarithmic coordinates, as shown in Fig. 5.
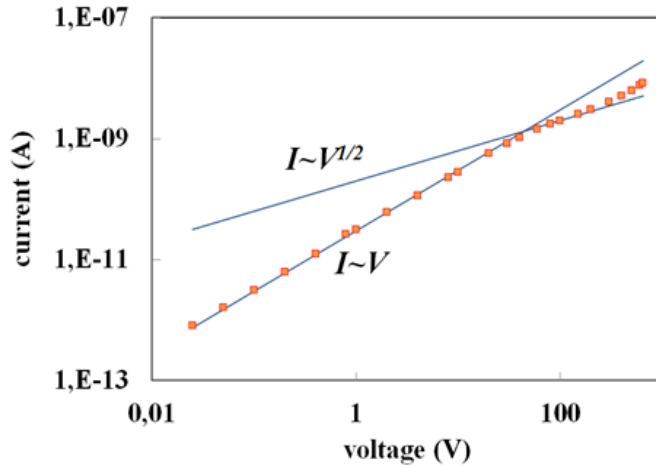

Fig. 5. I-V curves for Cr/Cd(Zn)Te/In structure under reverse bias: Open circles - experiment, solid lines - approximation of linear and square-root dependences of current versus voltage. Crystal thickness: 1.0 mm. T - 293 K.

As shown, the linear dependence of I vs. V is observed in the range of voltages from 0.05 V to ~30 V; the current is controlled mainly by neutral part of the crystal in this range. In the voltage range from ~40 to 200 V, the square-root dependence of I vs. V clearly is visible. This is completely understandable because, according to the Sah-Noyce-Shockley theory of generation in the SCLC [9], when qV is much bigger than kT, the multiplier $[\exp(qV/2kT) – 1]$ at a reverse displacement does not show itself, and the dependence of I vs. V is the square root ($I\sim V^{1/2}$). However, at a bias above ~200 V, the charge transfer mechanism in a Cr/Cd(Zn)Te/In structure changes, and in the voltage range from ~200 to 600-700 V, the dependence I vs. V again becomes close to linear (I ~ V), as demonstrably is manifested in the constant differential resistance in this range (see Fig. 3). This behavior of the I-V characteristic can be explained by the fact that at voltages above ~200 V, the width, W, of the SCLC is more than the thickness of the crystal, while at V > 500 V, the field strength at a crystal of 1.0-mm thick is approximately equal to ~ 10^4 V/cm. Herewith, the charge carrier mobility in

Cd(Zn)Te reaches saturation at the level of $\sim 10^7$ cm/s [10]. Finally, at an even bigger voltage, the SCLC mechanisms become connected. In this case, at V > 900-1000 Volts, the current becomes proportional to the square of the voltage (I~V^2) (not shown in Fig. 5), i.e., the Mott-Gurney law is realized [7,8]. As discussed, SCLC's width, W, is equal to

$$W = \sqrt{\frac{2\varepsilon\varepsilon_o(\varphi_o - qV)}{q^2 N}}\,, \tag{3}$$

where φ_o is the height of the potential barrier on the semiconductor side, and N represents the concentration of uncompensated impurities.

Measurements of the spectra from irradiating the Cr/Cd(Zn)Te/In structure with [241]Am isotope both from the rectifying side and the ohmic contacts' side were carried out to assess N - an important parameter of the crystals. Our choice of the [241]Am isotope for such measurements reflects the relatively large attenuation coefficient, α_γ, of Cd(Zn)Te, which is equal to approximately 40 cm^{-1}. In this case, the effective penetration depth of the radiation is equal to $\sim$ 250 microns, and at the crystal's thickness, $d = 0.5$ mm, the radiation weakens approximately 7 times according to $\exp(\alpha_\gamma d)$. We expect that with such a non-homogeneous generation of electron-hole pairs, the I_{sh}/I_{ohm} relation should depend on the applied voltage to the detector, especially if the SCLC occupies only part of the crystal's thickness. The peak heights in the spectrum are marked through I_{ohm} and I_{sh}, when Cd(Zn)Te detector is irradiated, respectively, from the side of ohmic- and the rectifying-contact. The voltage was changed in the range from 5 to 1000 V. The results obtained are shown in Fig. 6.

As is evident in Fig. 6, I_{sh} exceeds I_{ohm} in all voltage ranges. For n-type conductivity, the crystal's reverse bias corresponds to positive voltage on the ohmic contact. Therefore, the conditions in low-mobility holes will be better for collecting the charge from irradiation by [241]Am isotope from the side of rectifying contact. These holes will move to the negative electrode over a shorter pathway than the electrons.

To assess the value of N, we compared the experimental results to the calculated ones, which had a value, N, as a fitting parameter. The Hecht equation and the Bugger law were used to take into account recombination losses in calculating the detector's efficiency.

If we neglect surface recombination on the crystal's front surface, then the drift component of efficiency detection of the Schottky diode for photons energies of $\sim$ 60 keV can be represented by the expression:

$$\eta_{sh}^{drift} = \int_0^W \alpha_\gamma \exp(-\alpha_\gamma \cdot x)\,\eta_H(x)dx\,, \tag{4}$$

where α_γ is the linear component of the photoelectric absorption X/γ-radiation coefficient.
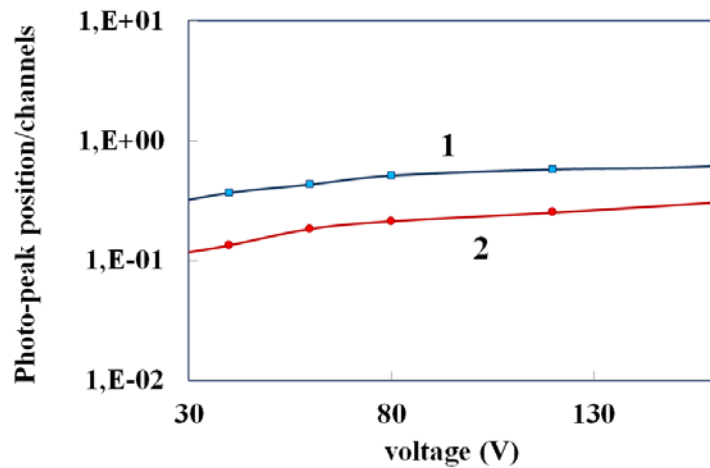

Fig. 6. Dependence of the amplitude of the photo-response to irradiation of the structure Cr/Cd(Zn)Te/In by Am-241: 1 – from the side of rectifying contact (Chrome); 2 - from the side of ohmic contact (Indium). Circles - experiment, solid lines - calculations. Crystal's thickness - 1.0 mm. T= 293 K. N $\sim 2\times 10^{11}$ cm^{-3}.

Recombination (capture) of photo-generated charge carriers can be considered using the Hecht equation for n-type semiconductors [11]:

$$\eta_{\mathrm{H}}(x) = \frac{\lambda_{\mathrm{n}}}{W}\left[1 - \exp\left(-\frac{x - W}{\lambda_{\mathrm{n}}}\right)\right] + \frac{\lambda_{\mathrm{p}}}{W}\left[1 - \exp\left(-\frac{x}{\lambda_{\mathrm{p}}}\right)\right], \tag{5}$$

where x is the coordinate where the electron-hole pair creation appears, the average drift length for electrons is $\lambda_{\mathrm{n}} = \tau_{\mathrm{n}}\mu_{\mathrm{n}}E$ and holes $\lambda_{\mathrm{p}} = \tau_{\mathrm{p}}\mu_{\mathrm{p}}E$, E is the electric field's intensity in SCLC, τ_{n} and τ_{p} are the electrons and holes lifetimes in the SCLC, and μ_{n} and μ_{p} are the electrons and holes mobility, respectively. In a diode of a metal-semiconductor type (Schottky contact), the electric field is not homogeneous, but considering that the heterogeneity is simplified because the field's intensity decreases linearly with the x coordinate, i.e., in the $(0,x)$ and (x,W) areas, the field intensity in the expressions for λ_{n} and λ_{p} can be replaced by the variables $(\varphi_{\mathrm{o}} - q)(2 - x/W)/q$, and $(\varphi_{\mathrm{o}} - q)(1 - x/W)/q$ correspondingly [12].

For the irradiation of the ohmic contact, recombination on the surface adjacent to the Schottky contact can be neglected, which is why the efficiency equation for detecting drift components can be written similarly as in (4-3), but replacing x by $(d - x)$:

$$\eta_{\mathrm{ohm}}^{\mathrm{drift}} = \int_0^W \eta_{\mathrm{H}}(x)\alpha_{\gamma}\exp[(-\alpha_{\gamma} \cdot (d - x)]dx, \tag{6}$$

The calculations show that the contribution of the diffuse component is important only in the voltage range of ~ 0 to 1 V. To simplify the calculations, starting from voltages of ~ 10 V, the contribution of the diffusion component can be neglected. The following values were taken in the calculations: $\mu_{\mathrm{n}} = 900$ V^{-1}·s^{-1}·cm, $\mu_{\mathrm{p}} = 80$ V^{-1}·s^{-1}·cm, $\tau_{\mathrm{n}} = 0.6 \cdot 10^{-7}$ s, $\tau_{\mathrm{p}} = 0.6 \cdot 10^{-7}$ s, and $\varphi_{\mathrm{o}} = 0.4$ eV. The lifetimes were found from measuring the α-spectra. The solid lines in Fig. 6 depict the results of these calculations. Clearly, a value proportional to the effectiveness is constructed on the vertical axis. Therefore, the results of calculation and experiment were "stitched", but only for the top curve. A good coincidence between the experiment and calculation is observed at N ~ 1-2×10^{11} cm^{-3}. At such value of N, even at V = 0 V, W is ~ 70 microns, and at a voltage of 500 V, W ~ 1.6 mm.

CONCLUSIONS

In this paper, we detail our findings on the influence of the crystal's thickness on the detectors' I-V curves for a detector with a metal-semiconductor-type contact. Cd(Zn)Te crystals, doped by indium in the growth process, had weakly expressed n-type conductivity, and a high resistivity of $\sim 10^{10}$ Ohm·cm at 300 K. Particularities in the manufacturing technology of rectifying contacts provided the opportunity for the structure to work at high reverse-bias voltages (up to 900-1000 V) in a relatively thin crystal, ~ 1.0-1.1 mm, with moderately low reverse currents (leakage currents).

It was established by our experimental and technological studies that the I-V curves of the structures, which were made on crystals with the same concentration of uncompensated impurities, but different thicknesses, significantly differ. Our research refutes the prevailing opinion that in order to reduce dark current, it is necessary to produce thicker crystals. Optimization of the thickness of the crystal substantially changes the I-V curve characteristics. For optimal crystal thickness, the dark currents become noticeably reduced in the range of important detector voltages, and, very importantly, the maximum voltage that can be applied to the detector significantly increases. It leads to an increase in the intensity of the electric field and undoubtedly improves not only the energy resolution, but also the reliability and stability of the device performance. The range of voltage change becomes substantially extended. This is because the dark current is formed by two mechanisms: one generation-recombination

in the depleted area of reversely-biased rectifying contact structure, and one by currents limited by space charge in the neutral part of the crystal.

ACKNOWLEDGEMENTS

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