INFLUENCE OF RADIATION-INDUCED DEFECTS ON CdTe AND CdZnTe DETECTORS PROPERTIES

A.I. Kondrik
National Science Center «Kharkov Institute of Physics and Technology», Kharkov, Ukraine
E-mail: kondrik@kipt.kharkov.ua

The correlation between radiation-induced defects, arising in CdTe:Cl and CdZnTe after the hard X-ray irradiation, and charges collection efficiency of detectors based on these materials has been investigated by means of computer simulation method. The role of radiation-induced defects during degradation of CdTe:Cl detector performance has been determined. An attempt to explain the reasons for higher radiation resistance of CdZnTe compared with CdTe:Cl has been made.

PACS: 71.55.GS, 72.20.JV

INTRODUCTION

CdTe and $Cd_{1-x}Zn_xTe$ detectors of gamma and X-ray radiation usually work in hostile radiation environment. Thus arisen electrically active radiation defects influence appreciably on the electrical compensation, which determines the material resistivity and ionization of deep levels capturing the free charge carriers. The basic requirements to detector materials are the high resistivity and low concentration of free carriers traps.

High-resistive semiconductors CdTe and CdZnTe are in strongly compensation state at room temperature when concentration of free electrons n and holes p is about six orders of magnitude lower than concentration of ionized impurities and defects N_i. With decreasing temperature, the difference between n, p and N_i increases even more. Under these conditions, the strong electric fields arise around the ionized local centres, so that the areas with violation of electroneutrality appear in a lattice, and the crystal defect structure can vary greatly. In strongly compensated semiconductor the system of free carriers and fixed ionized centres is in nonequilibrium state, thus any external action can modify the electronic structure of defects and affect on their interaction with free electrons and holes. As a result, the lattice defects have no fixed states and they have to be rearranged under the influence of such external factors as temperature, pressure, electric fields, etc., and each quasi-equilibrium state of the lattice corresponds to only the certain states of defects and positions of their levels in the band gap. In turn, the capture cross sections of free charge carriers by local centres depend on the positions of deep levels corresponding to these centres. In other words, the parameters of deep levels of CdTe and CdZnTe depend on compensation degree of these detector materials and on experimental conditions. A theory of deep levels in strongly compensated semiconductors is not yet created. The exact knowledge about such important parameters as the concentration of deep levels is of particular interest also. Due to the high resistivity of CdTe and CdZnTe and because of the above considerations, the definition of the parameters of deep levels traditionally encounters great difficulties. The differences in measurement of concentrations can reach two or three orders in absolute value, there are also some differences in the measurements of the energy levels positions in the band gap [1–13]. There is still the problem of correct identification of the deep levels determining the operation of detectors. The specific cause for degradation of the detector registering properties under the influence of ionizing radiations also remains as a free-answer question. Thus, it is necessary, in addition to experimental methods, to apply a computer simulation for investigating the dependence of required electrophysical and detector properties of CdTe and CdZnTe on the levels parameters for the materials that were exposed to irradiation.

The aim of this work was to study the impact of radiation defects on the characteristics of detectors based on CdTe:Cl and CdZnTe. The study was carried out by computer simulation using published experimental data about the parameters of defects in initial and irradiated materials.

1. INITIAL DATA AND MODELS

The models and a computer program described in [14, 15] have been used for quantitative research of electrophysical and detector properties of CdTe and CdZnTe. The basis for the program is the well-tested physical models of compensation and electron scattering in relaxation time approximation to calculate specific resistance ρ and electron mobility, respectively. Specific resistance was determined by numerical solution of electric neutrality equation. Shockley-Read-Hall theory, applied to calculate the lifetime τ of nonequilibrium charge carriers, well proven mainly for nondirect band semiconductors, e. g. Si. However, in our case of strongly compensated CdTe and CdZnTe the concentration of ionized deep centres of recombination exceeds the concentration of free charge carriers by six orders of magnitude at room temperature. For this reason, one was decided in the study to neglect the band-to-band recombination and apply the above-mentioned model of electron-hole recombination at the deep levels. To assess the registering properties of detector the simulation of charges collection efficiency was applied for initial and irradiated materials with application of Hecht equation [16] where the calculated values of electron mobility and lifetime of nonequilibrium charge carriers were used. Despite the fact that the Hecht equation is not quite correct to describe the charges collection, however, it allows an indication of the degradation of detector ability to register γ- and X-rays. The thickness of plane

detectors based on CdTe and CdZnTe was assumed equal to 5 mm, and the electric field within interelectrode gap – 1000 V/cm.

The experimental results, published in [1–3], allow with use of preliminary calculations to determine the properties of the defect levels arising in the studied materials. Table 1 lists the defects and their parameters for initial CdTe:Cl and for material subjected to X-ray irradiation with the dose of 260 kGy [3]. Levels A00, A0, A and A1 are shallow acceptors and relate to the so-called A-centres [17, 18]. Cl dopant forms a level of shallow donor. The belonging of other levels remains a subject for debate. A1 and Z are the radiation-induced defects and appear after exposure only, while the concentration of J increases almost by order of magnitude. As noted, the characteristics of levels depends on the experimental conditions, so defects parameters measured for different samples and by different researches vary significantly, and their reliable definition in the strongly compensated semiconductors is complicated. For this reason, the capture (recombination) cross sections of levels J, H and H1 were taken as such magnitudes, that there has been a compliance between the calculated lifetime of nonequilibrium charge carriers τ and known value $\sim 10^{-6}$ s. The preliminary simulation discovered that for the resistivity of the initial material ($\rho = 2 \cdot 10^9$ Ω·cm) the concentration of chlorine $8.25 \cdot 10^{12}$ cm^{-3} is required providing that the concentrations and energies of other levels are equal to values shown in Table 1. However, in this case we have an electronic conductivity of CdTe:Cl, that is contrary to experimental data and operating conditions of detectors. Thus, an exact measurement of the defects concentration encounters above objective reasons. If to increase an order of magnitude the concentration of shallow acceptor, for example A0, i. e. N(A0)9999/Y4=$2.8 \cdot 10^{13}$ cm^{-3} (see Table 1), we obtain p-type material with $\rho \sim 10^6$ Ω·cm, and its doping with chlorine to the concentration of $1.38 \cdot 10^{13}$ cm^{-3} gives the desired value of resistance $\rho = 2 \cdot 10^9$ Ω·cm. At this ρ the concentration of free holes p_0 is higher than the concentration of free electrons n_0 by two orders of magnitude 4RE, that is a good characteristic for the detector material. Looking ahead, we note that the main results of this work for CdTe:Cl does not depend on the mentioned exact values of A0 and Cl concentrations.

Table 1

Defect level parameters measured in CdTe:Cl before and after irradiation [1–3]

Level [a]	Energy of level, eV	Concentration of levels, cm^{-3}		Capture cross-section, cm^{-2}
		Initial sample	Irradiated sample	
A00	E_V [b] + 0.06	$2.6 \cdot 10^{12}$	$2.6 \cdot 10^{12}$	$1 \cdot 10^{-16}$
A0	E_V +0.12	$2.8 \cdot 10^{12}$ ($2.8 \cdot 10^{13}$)	$2.8 \cdot 10^{12}$ ($2.8 \cdot 10^{13}$)	$2 \cdot 10^{-16}$
A	E_V +0.15	$3 \cdot 10^{12}$	$3 \cdot 10^{12}$	$1 \cdot 10^{-16}$
A1	E_V +0.16	0	$1 \cdot 10^{12}$	$4 \cdot 10^{-17}$
X	E_V +0.36	$3.5 \cdot 10^{11}$	$1 \cdot 10^{12}$	$2 \cdot 10^{-15}$
Z	E_V +0.47	0	$3 \cdot 10^{12}$	$1 \cdot 10^{-14}$
J	E_V +0.53	$4.5 \cdot 10^{11}$	$2.5 \cdot 10^{12}$	$1 \cdot 10^{-15}$
H	E_V +0.76	$2.4 \cdot 10^{12}$	$6 \cdot 10^{12}$	$1 \cdot 10^{-15}$
H1	E_C [c] – 0.79	$3 \cdot 10^{13}$	$5 \cdot 10^{13}$	$1.5 \cdot 10^{-15}$
I	E_C – 1.0	10^{14}	$1.6 \cdot 10^{14}$	$1.3 \cdot 10^{-12}$
Cl	E_C – 0.014	$8.25 \cdot 10^{12}$ ($1.38 \cdot 10^{13}$)	$8.25 \cdot 10^{12}$ ($1.38 \cdot 10^{13}$)	$1 \cdot 10^{-16}$

[a] Conventional signs of levels were adopted in [3] and other papers.
[b] Top of valence band.
[c] Bottom of conduction band.

Table 2 shows the characteristics of levels in CdZnTe before and after X-ray irradiation with a dose of 260 kGy. Defects A00, D and J are radiation-induced ones. Concentration of H1 level increase by an order of magnitude after irradiation, considerably affecting thereby the properties of irradiated detector. The characteristics of levels, presented in Table 2, correspond to the experimentally measured data [1–3], taking into account of which the calculated values of mobility (1050 cm^2/(V·s) and the lifetime of nonequilibrium charge carriers ($\tau \sim 10^{-6}$ s) agree with well known parameters of CdZnTe. It was specified in [3] that the measured resistivity of $Cd_{0.9}Zn_{0.1}Te$ equalled to $1 \cdot 10^{11}$ Ω·cm at room temperature. However, preliminary simulation showed that the band gap must be 1.77…1.8 eV for cryogenic temperature (T→0) in such material in order to achieve the specified ρ at T = 300 K. Such band gap corresponds to $Cd_{0.8}Zn_{0.2}Te$.

Table 2

Defect level parameters measured in CdZnTe [1–3]

Level	Energy of level, eV	Measured concentration of levels, cm^{-3}		Capture cross-section, cm^{-2}
		Initial sample	Irradiated sample	
A00	E_V + 0,06	0	$1{,}4\cdot10^{12}$	$1\cdot10^{-16}$
A1	E_V +0,16	$1\cdot10^{12}$	$1\cdot10^{12}$	$4\cdot10^{-17}$
K	E_V +0,26	$2\cdot10^{12}$	$2\cdot10^{12}$	$5\cdot10^{-16}$
D	E_V +0,41	0	$9\cdot10^{10}$	$8\cdot10^{-16}$
J	E_V +0,53	0	$1.4\cdot10^{11}$	$1\cdot10^{-15}$
Y	E_V +0,64	$1.3\cdot10^{11}$	$1.3\cdot10^{11}$	$1\cdot10^{-14}$
W	E_V +0.71	$1.7\cdot10^{11}$	$1.7\cdot10^{11}$	$1{,}5\cdot10^{-14}$
H1	E_C –0,79	$2\cdot10^{12}$	$1.5\cdot10^{13}$	$4\cdot10^{-14}$
I	E_C –1,0	$1\cdot10^{14}$	$1.6\cdot10^{14}$	$9\cdot10^{-11}$
Nd	1.66 (E_C – 0.014)	$2.5\cdot10^{12}$	$2.5\cdot10^{12}$	$2\cdot10^{-16}$

2. RESULTS AND DISCUSSION

2.1. DEGRADATION OF CdTe:Cl DETECTOR

Fig. 1 shows the calculated dependence of the charges collection efficiency η on the concentration of the chlorine dopant for initial (non-irradiated) and irradiated CdTe:Cl. The vertical dashed line marks analyzed material, the composition of which was measured in [3], where it was shown experimentally that the γ-radiation detector largely loses its registering properties after X-ray irradiation with the dose of 260 kGy. However, modelling shows (see Fig. 1) that for the measured content of defects the charge-collection efficiency decreases no more than by 10…15%. This discrepancy could be due to inaccuracies in determining the concentrations of levels in high-resistive CdTe for the reasons outlined in the introduction of the paper.

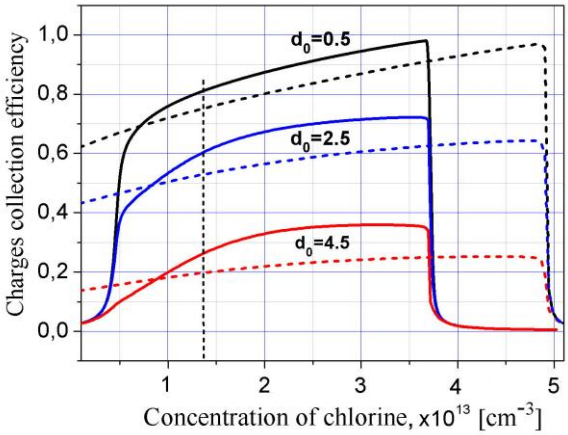

Fig. 1. Charges collection efficiency for carriers drifting from the different distances d_0 from the anode, depending on the concentration of chlorine in the unirradiated (solid curves) and irradiated (dashed curves) CdTe:Cl detector. The vertical dashed line marks the investigated sample

As shown in [19] the complete degradation of detector performance occurs after the appearance of radiation defect Z. Since the loss of the ability to register γ-radiation is associated with Z level, it was interesting to simulate the effect of this level on the charges collection. Fig. 2 shows the result of calculating the charges collection efficiency η depending on the content of radiation-induced defect Z in irradiated detector with the concentrations of other defects listed in Table 1.

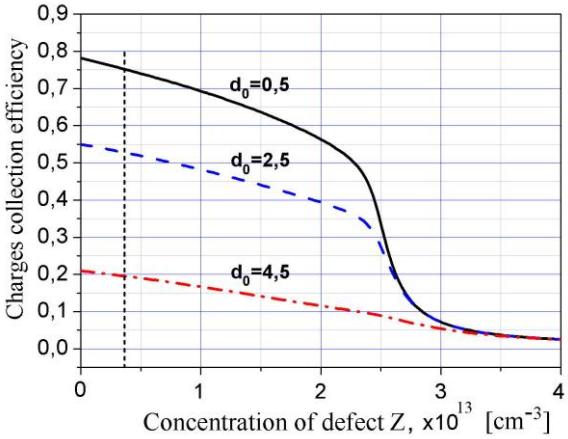

Fig. 2. Charges collection efficiency in irradiated CdTe:Cl-based detector, depending on the concentration of radiation defects Z for charges drifting from different distances d_0 from the anode. The vertical dashed line marks the measured concentration of Z in the investigated sample

It is seen that the total loss of registering properties occurs at the content of defect Z about ~ $4\cdot10^{13}$ cm^{-3}, i. e. approximately by order of magnitude larger than concentrations measured experimentally [3]. For this content of Z the simulation of η depending on concentration of chlorine dopant was carried out. The result of the calculation is presented in Fig. 3 that shows that for investigated sample the charges collection efficiency decreased at least an order of magnitude.

If in modelling program one substitute the defects Z with radiation defects A1 having the same concentration, the dependences in Fig. 3 will change insignificantly. Based on this, as well as on the comparison of Figs. 1–3 it can be concluded that degradation of detector characteristics occurs mainly due to a shift of dependence of charges collection efficiency on the concentration of chlorine shallow donor. The simulation discovered that the specified shift is proportional to a difference between the concentrations of ionized donors and acceptors.

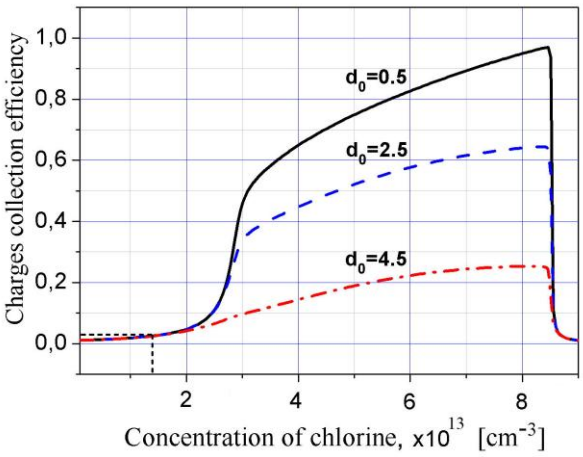

Fig. 3. Charges collection efficiency as a function of the chlorine dopant content in the detector after X-ray irradiation at the concentration of radiation defect Z equaled to $4 \cdot 10^{13}$ cm^{-3}. Vertical and horizontal dashed lines indicate the concentration of Cl and charges collection efficiency in the studied detector, respectively

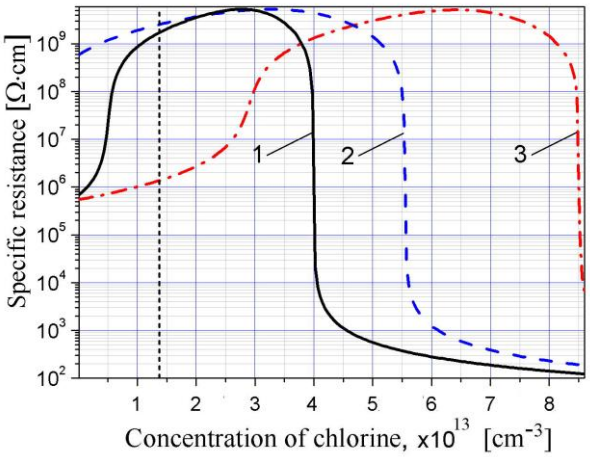

Fig. 4. Dependence of the resistivity of CdTe:Cl on concentration of chlorine dopant. Vertical dashed line indicates the concentration of Cl dopant in investigated material; 1 – unirradiated material; 2 – after irradiation with the dose of 260 kGy; 3 – irradiated material which lost detecting properties at the concentration of radiation-induced defect Z equalled to $4 \cdot 10^{13}$ cm^{-3}

Fig. 4 shows the dependence of the resistivity of CdTe:Cl on the concentration of chlorine for the initial material (curve 1), for the experimentally measured parameters after X-ray irradiation (curve 2) and specific resistance of irradiated material which loses its detector properties (curve 3) according to calculations at $N(Z) = 4 \cdot 10^{13}$ cm^{-3}. In the last case, the resistivity of investigated sample is reduced by three orders of magnitude, which further deteriorates its detector properties, while the resistivity of the irradiated material with experimentally measured parameters even slightly increases. At $N(Z) = 4 \cdot 10^{13}$ cm^{-3} the calculated value of the lifetime of nonequilibrium charge carriers in the irradiated sample under investigation decreased for electrons approximately by two orders of magnitude ($\tau_e \approx 2 \cdot 10^{-8}$ s) and for holes – by three orders of magnitude ($\tau_p \sim 10^{-9}$ s). In this case, the value of electron mobility after irradiation hardly changed. Fermi level for the irradiated material is situated at the value of E_V+0.52 eV, which is close to the position of level Z, as well as of level J, the concentration of which increased significantly after irradiation (Fig. 5).

Thus, the capture of free charge carriers at deep levels of radiation-induced defects Z and J, as well as a significant decrease in resistivity go a long way in the deterioration or significant degradation of the registering properties in the irradiated CdTe:Cl detector.

2.2. RADIATION-RESISTANT CdZnTe DETECTOR

It was found experimentally [3] that CdZnTe-based detector after X-irradiation with the dose of 260 kGy almost does not lose its registering characteristics, unlike CdTe. The reasons for such a high radiation resistance were unexplained. The defects A00 and D (see Table 2), that can not directly affect the drift of free charge carriers, appear in CdZnTe detector after its irradiation. Level A00 is too shallow and its capture cross section is very small, so it hardly captures the free charge carriers drifting within the interelectrode gap. As to the level D, then, it was shown by simulation, the set of parameters such as the concentration ($9 \cdot 10^{10}$ cm^{-3}), position in band gap (E_V+0.41 eV) and capture cross section ($8 \cdot 10^{-16}$ cm^{-2}) also does not allow it to exert significant effect on the drift of free electrons and holes, and hence on the charges collection efficiency.

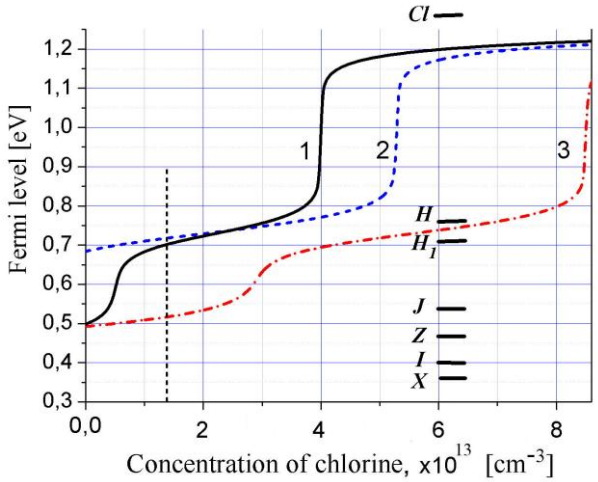

Fig. 5. Behaviour of the Fermi level in the CdTe:Cl, depending on the concentration of the chlorine dopant: 1 – unirradiated material; 2 – irradiated CdTe:Cl with measured parameters of levels; 3 – irradiated CdTe:Cl with calculated concentration of radiation-induced levels, equal to $4 \cdot 10^{13}$ cm^{-3}, where the detector lost its registering properties

Levels H1 and J can be considered as a major reason of possible degradation of the spectroscopic properties of CdZnTe-based detector provided a significant increase in radiation dose above 260 kGy. Depth and capture cross sections of these levels are sufficiently large, their concentrations after irradiation increased by almost an order, reaching the highest value for H1 ($1.5 \cdot 10^{13}$ cm^{-3}) (see Table 2). Based on the above, the impact of radiation-stimulated levels J and H1 on the detector properties of CdZnTe was studied in this work.

Fig. 6 shows the dependences of charge collection efficiency of the detector at different concentrations of defects J and H1 depending on the start coordinates of free charge carriers drifting toward the electrodes. Fig. 6,a demonstrates the influence of the defect J on the charges collection. For an upper curve the concentration of defect H1 equals to its initial magnitude in the non-irradiated sample, and N(J) = 0. For all other dependencies, the concentration of H1 is equal to $1.5 \cdot 10^{13}$ cm^{-3} that corresponds to the value measured after irradiation. For comparison, Fig. 6,b shows the similar dependence for almost exactly the same concentrations of J, but at different content of H1 which increases up to $1.5 \cdot 10^{15}$ cm^{-3} during the irradiation process. It can be seen from Figure 6a that for measured concentration of H1 the total degradation of detector properties occurs at $N(J) = 2 \cdot 10^{13}$ cm^{-3}. The complete degradation is not observed at the same concentration of J and for the content of H1 increased by two orders of magnitude (see Fig. 6,b). Comparing the curves in Fig. 6 it could also be concluded that the decisive contribution to the deterioration of registering properties of detector is made by the level J. This conclusion is illustrated by a Fig. 7 that clearly shows also that the presence of the defect H1 partially neutralizes the negative impact of J level on the detector properties. It is one of the reasons for higher radiation resistance of CdZnTe-based detector compared with CdTe detector. To explain this effect we can consider the influence of J and H1 levels on the behaviour of Fermi level *F*. Fig. 8 shows the dependence of the Fermi level position in the band gap on the concentration of J at different content of defect H1, as well as locations for the levels J, Y, W and H1.

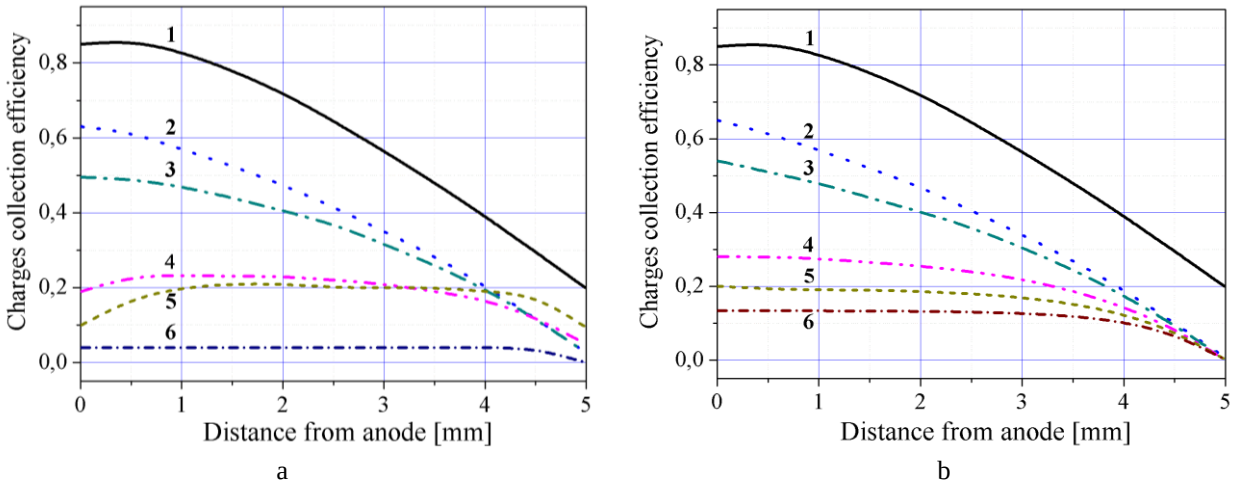

Fig. 6. Charges collection efficiency for free carriers drifting from different coordinates of the interelectrode gap of CdZnTe detector.

a – At increasing concentrations of J and measured (fixed) concentration of H1: in initial sample and after the irradiation, cm^{-3}: 1 – N(J)=0, $N(H1)=2 \cdot 10^{12}$; 2 – $N(J)=4.5 \cdot 10^{11}$, $N(H1)=1.5 \cdot 10^{13}$ for curves 2–6; 3 – $N(J)=2.5 \cdot 10^{12}$; 4 – $N(J)=8 \cdot 10^{12}$; 5 – $N(J)=1.3 \cdot 10^{13}$; 6 – $N(J)=2 \cdot 10^{13}$.

b – At proportional increasing concentrations of J and H1 during irradiation, cm^{-3}; 1 – N(J)=0, $N(H1)=2 \cdot 10^{12}$; 2 – $N(J)=5 \cdot 10^{11}$, $N(H1)=1.5 \cdot 10^{13}$; 3 – $N(J)=2.5 \cdot 10^{12}$, $N(H1)=2 \cdot 10^{14}$; 4 – $N(J)=8 \cdot 10^{12}$, $N(H1)=8 \cdot 10^{14}$; 5 – $N(J)= 1.3 \cdot 10^{13}$, $N(H1)=1.3 \cdot 10^{15}$; 6 – $N(J)=2 \cdot 10^{13}$, $N(H1)=1.5 \cdot 10^{15}$

It follows from a Fig. 8, increasing the concentration of H1 elevates the Fermi level, while the increase of defect J content leads to lowering of *F* to energies which are close to J level. Comparing Figs. 6, 7 it can be concluded that the degradation of registering properties of the CdZnTe detector can occur through the capture of free charge carriers by J level when its concentration is greater by two orders of magnitude than value measured after X-ray irradiation with the doze of 260 kGy. Increase of H1 content pulls the Fermi level to the middle and upper part of band gap, weakening thereby the processes of capture of free electrons and holes by the J level.

It is evident from a comparison of Tables 1 and 2 that the concentrations of radiation-induced defects A00 and D in CdZnTe are considerably less than content of radiation defects A1 and Z in CdTe. That is also a reason for higher radiation resistance of irradiated detectors based on CdZnTe, since levels of defects A00 and D involved in the compensation processes and their low concentration has a little effect on the position of Fermi level and on resistivity of the material. Fig. 9 shows the behaviour of the resistivity depending on the concentrations Nd of alloying shallow donors with increasing concentration of radiation-induced defects J and H1 and proportional increase in the content of radiation defects A00 and D during irradiation. The figure show that after irradiation with the dose of 260 kGy (curve 2), the resistivity of an investigated sample is slightly reduced compared to the non-irradiated state (curve 1). Further increasing concentration of H1 and J defects causes gradual decrease of ρ at approximately twice (curves 3–6). The simulation revealed that the proportional increase in the concentration of radiation-induced defects A00 and D during irradiation does not affect appreciably on the sample resistivity. In other words, these levels do not affect the drift of free charge carriers within an interelectrode gap, and they do not decrease the specific resistance of CdZnTe by engaging in the processes of compensation.

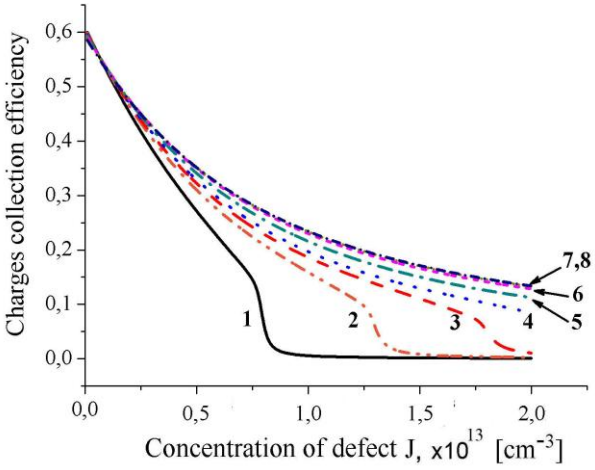

Fig. 7. Charges collection efficiency of irradiated CdZnTe-based detector in dependence on the content of defect J at the different concentrations of defect H1. Concentration of H1, cm^{-3}: 1 – $1 \cdot 10^{13}$; 2 – $1.5 \cdot 10^{13}$; 3 – $2 \cdot 10^{13}$; 4 – $2.5 \cdot 10^{13}$; 5 – $5 \cdot 10^{13}$; 6 – $2 \cdot 10^{14}$; 7 – $8 \cdot 10^{14}$; 8 – $3 \cdot 10^{15}$. Concentrations of other levels are listed in the Table 2 for irradiated sample

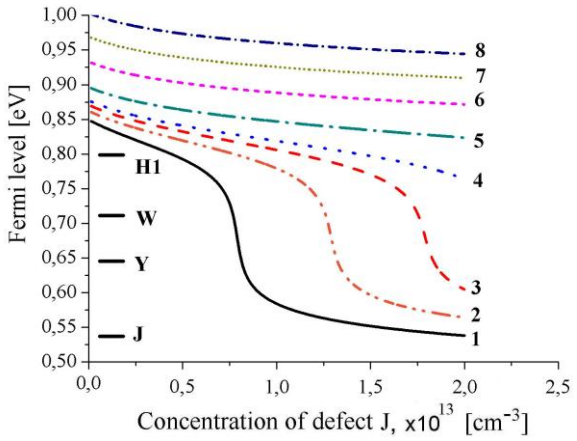

Fig. 8. Behaviour of Fermi level in the band gap of CdZnTe depending on the content of defects J and H1. Different concentrations of H1, corresponding to curves 1–8, are the same as on the Fig. 7

Level H1 has an appreciable influence on the position of Fermi level and thus significantly affects on the resistivity of the CdZnTe material. Fig. 10 demonstrates the influence of H1 concentration on ρ. Increasing the H1 content improves the resistivity. Thus, at $N(J)=2 \cdot 10^{13}$ cm^{-3}, where the detector significantly loses its registering properties, increase in the content of H1 defect by an order from $1 \cdot 10^{13}$ to $1 \cdot 10^{14}$ cm^{-3} elevates the resistivity by five orders of magnitude (see Fig. 10, curves 6 and 1). The positive impact of the H1 level on radiation resistance of CdZnTe detector is manifested in this also.

In conclusion, it should be noted that presented dependences, which obtained on the basis of well-tested physical models, make possible to describe mainly qualitatively the effect of radiation-induced levels on the properties of detectors based on CdTe and CdZnTe.

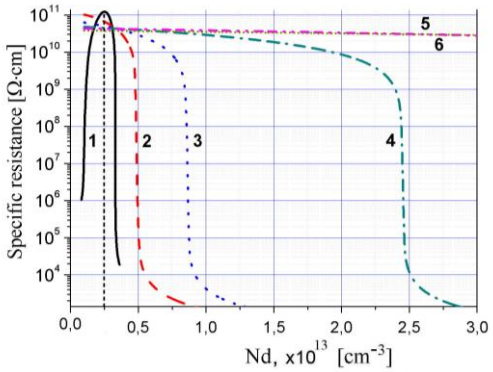

Fig. 9. Resistivity change depending on concentration of shallow donors Nd for the increasing concentrations of radiation-induced defects J, H1, A00, D, cm^{-3}. 1 – unirradiated sample ($N(J)=0$, $N(H1)=2 \cdot 10^{12} cm^{-3}$); 2 – $N(J)=1{,}5 \cdot 10^{11}$, $N(H1)=1.5 \cdot 10^{13}$, $N(A00)=1.4 \cdot 10^{12}$, $N(D)=9 \cdot 10^{10}$; 3 – $N(J)= 5 \cdot 10^{11}$, $N(H1)=5 \cdot 10^{13}$, $N(A00)=4.5 \cdot 10^{12}$, $N(D)=3 \cdot 10^{11}$; 4 – $N(J)=2 \cdot 10^{12}$, $N(H1)= 2 \cdot 10^{14}$, $N(A00)=1.8 \cdot 10^{13}$, $N(D)=1.2 \cdot 10^{12}$; 5 – $N(J)=8 \cdot 10^{12}$, $N(H1)=8 \cdot 10^{14}$, $N(A00)=7.0 \cdot 10^{13}$, $N(D)=4.8 \cdot 10^{12}$; 6 – $N(J)=1{,}3 \cdot 10^{13}$, $N(H1)=1{,}3 \cdot 10^{15}$, $N(A00)=1.0 \cdot 10^{14}$, $N(D)=7.2 \cdot 10^{12}$

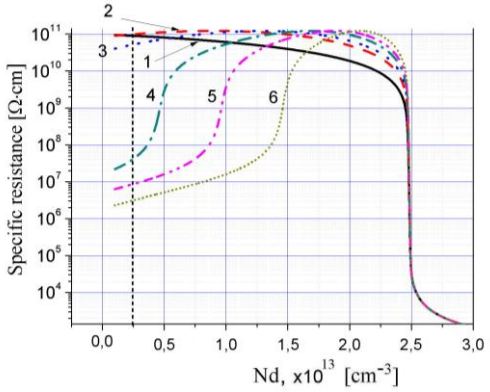

Fig. 10. Resistivity of CdZnTe depending on Nd at fixed concentrations of radiation defects J, A00, D (cm^{-3}): $N(J) = 2 \cdot 10^{13}$, $N(A00)=1.4 \cdot 10^{12}$, $N(D)=9 \cdot 10^{10}$ and different concentrations of the defect H1, cm^{-3}. 1 – $N(H1)=1.0 \cdot 10^{14}$; 2 – $N(H1)=4.0 \cdot 10^{13}$; 3 – $N(H1)=3.0 \cdot 10^{13}$; 4 – $N(H1)=2.0 \cdot 10^{13}$; 5 – $N(H1)=1.50 \cdot 10^{13}$; 6 – $N(H1)=1.0 \cdot 10^{13}$.

CONCLUSIONS

Experimentally measured parameters of deep levels in strongly compensated CdTe:Cl and CdZnTe do not allow reproduce properly the resistivity and registering properties of these materials. To resolve the long-time problem of identification of deep levels in CdTe and CdZnTe and reliable measuring their parameters it is necessary developing the theory of deep levels in the strongly compensated semiconductors.

The reduction in resistivity by three orders of magnitude, as well as the capture of free charge carriers at the radiation-induced deep levels Z and J located above the valence band by 0.47 and 0.53 eV, respectively, mainly lead to the degradation of the CdTe:Cl-based detector properties during operating under hard radiation exposure. Average drift time of nonequilibrium charge carriers within interelectrode gap before their capture at deep levels of radiation-induced defects decreases for electrons by two orders and for holes – by three orders of

magnitude. The significant degradation of registering properties of CdTe:Cl-based detector occurs at the J and Z concentrations of about by an order of magnitude more than the experimentally measured values.

The experimentally observed greater radiation resistance of CdZnTe detectors compared with CdTe detectors could be explained by the following reasons. First, the concentrations of radiation defects A00, D, and J arising during irradiation of CdZnTe are relatively small. Secondly, only defect J has a significant influence on the capture of free charge carriers, but its negative impact is compensated to some degree by defect H1, the concentration of which increases considerably during irradiation. Increment of H1 content highly increases the resistivity of CdZnTe and reduces the capture of carriers by the level J and, thus, diminishes the degradation of charges collection efficiency.

REFERENCES

1. D.M. Hofmann, W. Stadler, P. Christmann, B.K. Meyer. Defects in CdTe and $Cd_{1-x}Zn_xTe$ // *Nucl. Instrum. Methods Phys. Res.* 1996, v. A 380, p. 117-20.

2. A. Castaldini, A. Cavallini, B. Fraboni. Deep energy levels in CdTe and CdZnTe // *J. Appl. Phys*. 1998, v. 83, p. 2121-2126.

3. B. Fraboni, L. Pasquini, A. Castaldini, A. Cavallini, and P. Siffert. X-ray irradiation effects on the trapping properties of $Cd_{1-x}Zn_xTe$ detectors // *J. Appl. Phys.* 2009, v.106, p. 093713.

4. B. Fraboni, D. Cavalcoli, A. Cavallini, P. Fochuck. Electrical activity of deep traps in high resistivity CdTe: Spectroscopic characterization // *J. Appl. Phys.* 2009, v. 105, p. 073705-06.

5. V. Babentsov, J. Franc, R.B. James. Compensation and carrier trapping in indium-doped CdTe: Contributions from an important near-mid-gap donor // *Appl. Phys. Lett*. 2009, v. 94, p. 052102.

6. G.A. Carini, A.E. Bolotnikov, G.S. Camarda, et al. Effect of Te precipitates on the performance of CdZnTe detectors // *Appl. Phys. Lett*. 2006, v. 88, p. 143515.

7. R. Gul, K. Keeter, R. Rodriguez, A.E. Bolotnikov, et al. Point defects in Pb-, Bi-, and In-doped CdZnTe detectors: deep-level transient spectroscopy (DLTS) measurements // *J. Electr. Mat.* 2012, v. 41, p. 488-493.

8. A. Cavallini and B. Fraboni. Defective states induced in CdTe and CdZnTe detectors by high and low energy neutron irradiation // *J. Appl. Phys.* 2003, v. 94, p. 3135-3142.

9. E. Belas, R. Grill, J. Franc, P. Hlídek, V. Linhart, T. Slavíček, P. Höschl. Correlation of electrical and optical properties with charge collection efficiency of In-doped and In+Si co-doped CdTe // *Nucl. Instrum. Methods Phys. Res.* 2008, v. A 591, p. 200-202.

10. R. Gul, A. Bolotnikov, H.K. Kim, R. Rodriguez, K. Keete, Z. Li, G. Gu, and R.B. James. Point Defects in CdZnTe Crystals Grown by Different Techniques // *J. Electr. Mater*. 2011, v. 40, p. 274-79.

11. A. Cavallini, B. Fraboni, W. Dusi, M. Zanarini, M. Hage-Ali, and P. Siffert. Defects introduced in cadmium telluride by γ irradiation // *J. Appl. Phys.* 2001, v. 89, p. 4664-4666.

12. B. Fraboni, A. Cavallini, N. Auricchio, W. Dusi, M. Zanarini, and P. Siffert. Time and thermal recovery of irradiated CdZnTe detectors // *Semicond. Sci. Technol*. 2006, v. 21, p. 1034.

13. A. Cavallini, B. Fraboni, W. Dusi, M. Zanarini, and P. Siffert. Deep levels and compensation in gamma-irradiated CdZnTe // *Appl. Phys. Lett.* 2000, v. 77, p. 3212-3214.

14. A.I. Kondrik. Modelirovanie svoistv CdZnTe i parametrov detektorov γ-izlucheniya na ego osnove // *Tekhnologiya i konstruirovanie v elektronnoi apparature.* 2004, N 6, p. 17-22 (in Russian).

15. A.I. Kondrik. Effektivnost' sbora zaryadov v datchikakh γ-izluchenia s razlichnoi konfiguratsyei elektrodov // *Tekhnologiya i konstruirovanie v elektronnoi apparature.* 2012, N 4, p. 47-51 (in Russian).

16. W. Akutagawa, K. Zanio. Gamma response of semi-insulating material in the presence of trapping and detrapping // *J. Appl. Phys.* 1969, v. 40, p. 3838-3854.

17. W. Stadler, D. Hofmann, H. Alt, T. Muschik, et al. Optical investigations of defects in $Cd_{1-x}Zn_xTe$ // *Phys. Rev*. 1995, v. 51, p. 10619-30.

18. J.W. Allen. Spectroscopy of lattice defects in tetrahedral II-VI compounds // *Semicond. Sci. Technol.* 1995, v. 10, p. 1049-1055.

19. B. Fraboni, A. Cavallini, W. Dusi. Damage induced by ionizing radiation on CdZnTe and CdTe detectors // *IEEE Trans. Nucl. Sci*. 2004, v. 51, p. 1209-1215.

Статья поступила в редакцию 11.12.2014 г.

ВЛИЯНИЕ РАДИАЦИОННЫХ ДЕФЕКТОВ НА СВОЙСТВА ДЕТЕКТОРОВ НА ОСНОВЕ CdTe И CdZnTe

А.И. Кондрик

Методом компьютерного моделирования проведено исследование корреляции между радиационными дефектами, возникшими в CdTe:Cl и CdZnTe после жесткого рентгеновского облучения, и эффективностью сбора зарядов детекторов на их основе. Определена роль радиационных дефектов в процессах деградации детекторных характеристик CdTe:Cl. Сделана попытка объяснить причины более высокой радиационной стойкости CdZnTe по сравнению с CdTe:Cl.

ВПЛИВ РАДІАЦІЙНИХ ДЕФЕКТІВ НА ВЛАСТИВОСТІ ДЕТЕКТОРІВ НА ОСНОВІ CdTe ТА CdZnTe

О.І. Кондрик

Методом комп'ютерного моделювання проведено дослідження кореляції між радіаційними дефектами, які виникли в CdTe:Cl та CdTe після жорсткого радіаційного опромінення, і ефективністю збору зарядів детекторів на їх основі. Визначена роль радіаційних дефектів у процесах деградації детекторних характеристик CdTe:Cl. Зроблена спроба пояснити причини більш високої радіаційної стійкості CdZnTe у порівнянні з CdTe:Cl.