East Eur. J. Phys. Vol.1 No.1 (2014) 47-52

PACS: 71.55.-i, 71.55.Gs, 72.20.-i, 72.20.Jv

EFFECT OF IRRADIATION ON PROPERTIES OF CdTe DETECTORS

A.I. Kondrik
National Science Center «Kharkov Institute of Physics and Technology»
1, Academicheskaya str., Kharkov, 61108, Ukraine
E-mail: kondrik@kipt.kharkov.ua
Received February 7, 2014

A comparative analysis of published experimental data about the concentration, capture cross section and type of traps in CdTe: Cl has been carried out. Based on the performed analysis an identification of registered levels on acceptor and donor type was realized. The numerical simulations have been performed to study the effect of radiation defects arising under the influence of hard X-ray irradiation on the electrical and detector properties of cadmium telluride. The role of radiation-induced and background defects has been determined for the processes of degradation of the spectroscopic characteristics of CdTe:Cl detectors operated under conditions of ionizing radiation.
KEYWORDS: detectors, radiation-induced defects, simulation, CdTe

ВПЛИВ ОПРОМІНЕННЯ НА ВЛАСТИВОСТІ CdTe ДЕТЕКТОРІВ

О.І. Кондрик
Національний науковий центр «Харківський фізико-технічний інститут»
вул. Академічна 1, 61108 Харків, Україна

Проведено порівняльний аналіз опублікованих експериментальних даних про концентрацію, переріз захвату і тип пасток в CdTe:Cl. На основі аналізу здійснена ідентифікація зареєстрованих рівнів по акцепторному та донорам типу. Методом чисельного моделювання виконано дослідження впливу радіаційних дефектів, які виникли під дією жорсткого рентгенівського опромінення, на електрофізичні та детекторні властивості телуриду кадмію. Визначена роль радіаційних і фонових дефектів у процесах деградації спектроскопічних характеристик CdTe:Cl, що експлуатуються в умовах іонізуючих випромінювань.
КЛЮЧОВІ СЛОВА: детектори, радіаційні дефекти, моделювання, CdTe

ВЛИЯНИЕ ОБЛУЧЕНИЯ НА СВОЙСТВА CdTe ДЕТЕКТОРОВ

А.И. Кондрик
Национальный научный центр «Харьковский физико-технический институт»
ул. Академическая 1, 61108 Харьков, Украина

Проведен сравнительный анализ опубликованных экспериментальных данных о концентрации, сечении захвата и типе ловушек в CdTe:Cl. На основе анализа осуществлена идентификация зарегистрированных уровней по акцепторному и донорному типу. Методом численного моделирования выполнено исследование влияния радиационных дефектов, возникших под воздействием жесткого рентгеновского облучения, на электрофизические и детекторные свойства теллурида кадмия. Определена роль радиационных и фоновых дефектов в процессах деградации спектроскопических характеристик CdTe:Cl, эксплуатируемых в условиях ионизирующих излучений.
КЛЮЧЕВЫЕ СЛОВА: детекторы, радиационные дефекты, моделирование, CdTe

The primary requirements to the materials of the detector used in spectroscopy of high energy ionizing radiation are the high resistivity and low concentration of free carriers traps. Detectors of gamma and X-ray radiation based on CdTe and $Cd_{1-x}Zn_xTe$ usually work in hostile radiation environment. Thus arisen electrically active radiation defects make an appreciable impact on the conditions of compensation which determines the resistivity and processes of carrier capture by deep levels. Under the influence of radiation exposure the energy resolution deteriorates also, and peaks positions shift in spectra, the leakage current increases, and such important parameter as charge collection efficiency degrades. Irradiation of CdTe with X-ray flux of high intensity, used to enhance the detector performance in imaging application, can cause a significant polarization of the semiconductor and failure of the device structure [1, 2]. To control performance of detectors it is necessary to get accurate quantitative data on deep levels in CdZnTe. In a number of works the parameters of levels defined by the producing conditions of detector materials as well as radiation defects arising under the influence of radiations during operation were investigated, and the effect of these levels on the transport properties of CdTe and CdZnTe was studied also [2–11].

Due to high specific resistance of material the determination of deep levels concentration in it traditionally encounters great difficulties, and, as it was shown from the analyses of published papers, a discrepancy in measurements can be two or three orders of magnitude. Besides, there are some differences in measurements of positions of the energy levels in the band gap. It is impossible to guarantee also that in a material all levels defining parameters of the detector are correctly identified. There is a free-answer question about the specific causes of degradation of registering properties of detector under the influence of ionizing radiation. In this regard it is expedient to apply additional methods of computer simulation to investigate the dependence of required electrophysical properties and detector characteristics of CdTe on the parameters of the levels measured experimentally in materials which were exposed to irradiation.

The aim of this work was through modeling method to establish a correlation between the characteristics of the

CdTe: Cl detector and defects which experimentally registered in unirradiated material as well as in one irradiated with X-ray. The correlation was carried out for real operation condition of the detector.

MODEL AND INITIAL DATA

The models and a computer program described in [12] were used for quantitative simulation of electrophysical and detector properties of CdTe and CdZnTe. The basis for the program are the well-tested models of compensation, electron scattering in relaxation time approximation, statistics and Shockley-Read, Hecht equation, that compute values of resistivity, electron mobility, lifetime of nonequilibrium charge carriers and charge collection efficiency for initial and irradiated detector material.

The concentrations of electrically active deep and shallow levels in CdTe:Cl before and after its X-ray irradiation with the dose of 260 kGy have been measured in [2]. The sample CdTe:Cl was grown by traveling heater method, and its resistivity was $2\cdot10^9$ ohm·cm. To obtain reliable data about the concentration of deep centers in such high-resistivity material, it was carried out a comparison of the results of two mutually complementary techniques: photo induced current transient spectroscopy [13] and space charge limited current analyses [3]. This material and results of its properties measurements were taken in this paper as a pattern to study the influence of X-ray irradiation on the detector characteristics of CdTe:Cl.

Problem of the identification of defects and related deep and shallow levels in CdTe and CdZnTe was discussed in several papers [9,12,14–19]. It was considered proven that the energy interval from the valence band top E_V of the concrete level is the same in CdTe as in CdZnTe. Difficulties arose not only during correct determination of the concentration but also at identifying recorded levels, and sometimes even the acceptor or donor type of defect was unknown. The capture of electrons or holes by the same level in different materials depends on the degree of filling or ionization that is determined by the position of Fermi level. In turn, the Fermi level depends on the temperature, the ratio between the concentrations of technology defects and the doping level, and for CdZnTe it depends on the molar fraction of the zinc. On the other hand the strict control of composition in the technology of high-resistivity cadmium telluride production is very difficult.

By comparing the results of the experiments described in [2, 14 –18], the work has been carried out to determine the composition and characteristics of levels in CdTe:Cl, both for the unirradiated material and irradiated with X-ray. The analysis was performed with use of approach expounded in [19] and the result presented in the Table. The levels are assumed to be shallow acceptor (A) or shallow donors (D), if under considered conditions they are completely ionized in contrast to the deep acceptor (DA) or deep donor (DD), which are ionized partially. The levels A00, A0, A and A1 are shallow acceptors and relate to the so-called A-centers [20, 21]. Cl dopant forms a level of shallow donor, located below the bottom of the conduction band at 0.014 eV. The belonging of other levels still remains a subject for debate. A1 and Z are the radiation-induced levels of defects, and they appear only after irradiation.

Table.

Defect level parameters measured in CdTe:Cl

Level*	Energy, measured from the valence E_V or conduction band E_C, eV	Concentration of levels, cm^{-3}		Capture cross-section, cm^{-2}	Type of level** and its charge state
		Initial	Irradiated with the dose of 260 kGy		
A00	$E_V + 0.06$	$2.6\cdot10^{12}$	$2.6\cdot10^{12}$	$1\cdot10^{-16}$	A^-
A0	$E_V + 0.12$	$2.8\cdot10^{12}$	$2.8\cdot10^{12}$	$2\cdot10^{-16}$	A^-
A	$E_V + 0.15$	$3\cdot10^{12}$	$3\cdot10^{12}$	$1\cdot10^{-16}$	A^-
A1	$E_V + 0.16$	0	$1\cdot10^{12}$	$4\cdot10^{-17}$	A^-
X	$E_V + 0.36$	$3.5\cdot10^{11}$	$1\cdot10^{12}$	$2\cdot10^{-15}$	DA^{2-}
Z	$E_V + 0.47$	0	$3\cdot10^{12}$	$1\cdot10^{-14}$	DA^+
J	$E_V + 0.53$	$4.5\cdot10^{11}$	$2.5\cdot10^{12}$	$1\cdot10^{-15}$	DA^-
H	$E_V + 0.76$	$2.4\cdot10^{12}$	$6\cdot10^{12}$	$1\cdot10^{-15}$	DA^-
H1	$E_C - 0.79$	$3\cdot10^{13}$	$5\cdot10^{13}$	$1.5\cdot10^{-15}$	DD^+
I	$E_C - 1.0$	10^{14}	$1.6\cdot10^{14}$	$1.3\cdot10^{-12}$	DD^+
Cl	$E_C - 0.014$	$1.2\cdot10^{13}$	$1.2\cdot10^{13}$	$1\cdot10^{-16}$	D^+

* Levels notation was adopted in [2] and other papers

**A – acceptor, DA – deep acceptor, D – shallow donor, DD – deep donor.

RESULTS AND DISCUSSION

Fig. 1 (curve 1) shows a dependence of calculated resistivity ρ of non-irradiated CdTe:Cl on the concentration of chlorine dopant. The composition of this sample is presented in the table as the initial one. The material keeps p-type conductivity up to a concentration of chlorine Nd (Cl) = $3{,}3\cdot10^{13}$ cm^{-3}. At the point of maximum resistivity the hole concentration p_0 exceeds the concentration of free electrons n_0 approximately by order of magnitude: $p_0/n_0 \approx 17$. Specific resistance ρ=$2\cdot10^9$ ohm·cm, measured in [2], corresponds to the chlorine concentration Nd(Cl) = $1{,}38\cdot10^{13}$ cm^{-3}

and relation $p_0/n_0 = 440$, that is a good characteristic for the detector material. Curve 2, Fig. 1 shows the dependence of ρ on the concentration of chlorine in the material irradiated with a dose of 260 kGy. Curves 1 and 2 are calculated with taking into account the concentrations and parameters of levels presented in the table. Curve 3 corresponds to irradiated material which lost detecting properties with the concentration of radiation-induced defect of $N(Z)=3\cdot10^{13}$ cm^{-3} (in detail see below). Calculating lifetime of nonequilibrium charge carriers in the sample revealed a value of $\sim10^{-6}$ sec. The calculated electron mobility equaled to 1100 $cm^2/(V\cdot s)$. These values are in good agreement with well known magnitudes.

Fig. 2 shows the charge collection efficiency, η for charge carriers drifting at different distances d_0 from the anode in non-irradiated CdTe:Cl detector with electrode gap of 5 mm. The vertical dashed line indicates the concentration of Cl in the investigated material. The figure shows that the investigated material is characterized by not a very high efficient collection of charges, but for the greater η the ratio p_0/n_0 decreases and the electron component of dark current properly increases and a signal/background ratio significantly decreases, as the electron mobility μ_n = 1100 $cm^2/(V\cdot s)$ is much higher than hole mobility μ_p = 70 $cm^2/(V\cdot s)$.

It was shown experimentally that after the X-ray irradiation with dose of 260 kGy the γ-radiation detector significantly loses its registering properties [2]. A complete degradation of the spectroscopic characteristics occurs after the appearance of radiation-induced defect Z [22]. Nevertheless, simulation with measured parameters of irradiated sample shows that the charge collection efficiency is reduced by no more than 10-15% for carriers drifting from all points of the interelectrode gap (Fig. 3). The reason for this could be an inaccuracy in determining the concentration of levels or their incomplete registration in high-resistivity CdTe. Since the loss of the ability to register radiation is associated with Z level, it was interesting to simulate the effect of this level on η.

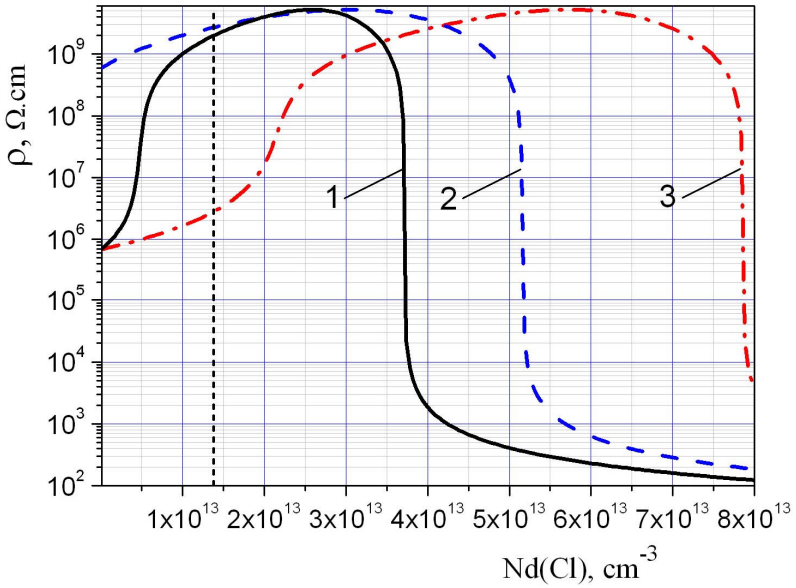

Fig. 1. The dependence of the resistivity of CdTe:Cl on concentration of chlorine dopant.
The vertical dashed line indicates the concentration of Cl dopant in the material; 1 – unirradiated material; 2 –after irradiation with the dose of 260 kGy; 3 – irradiated material which lost detecting properties with the concentration of radiation-induced defect of $N(Z)=3\cdot10^{13}$ cm^{-3}.

Fig. 3 shows the result of calculating the charges collection efficiency depending on the content of radiation-induced defect Z in irradiated detector with the concentrations of other defects listed in table. Comparing Fig. 2 and Fig. 3, we see that the levels with the measured parameters after exposure lead to a loss of detection efficiency not more than 10 - 15%, whereas total loss of spectroscopic properties occur with the content of defect Z · about $3\cdot10^{13}cm^{-3}$, i.e. approximately an order of magnitude larger than concentrations measured experimentally. There is a question about the reason for the observed degradation of detecting characteristics. To answer this question it was carried out a calculation of η dependence on the concentration of the chlorine dopant with content of radiation defect Z, equal to $3\cdot10^{13}$ cm^{-3}, when the degradation occurs according to the evaluation. The result of this calculation is shown in Fig. 4. We see that in the investigated sample the collection efficiency of charges decreased at least an order of magnitude. If in modeling program one substitute the defects Z with radiation defects A1 having the same concentration, the dependences in Fig. 4 will change insignificantly. Based on this, as well as on the comparison of Fig. 2-4 it can be concluded that degradation of detector characteristics occurs mainly due to a shift of η dependence on the concentration of chlorine shallow donor. The simulation showed that the specified shift is proportional to a difference between the concentrations of shallow donors and acceptors.

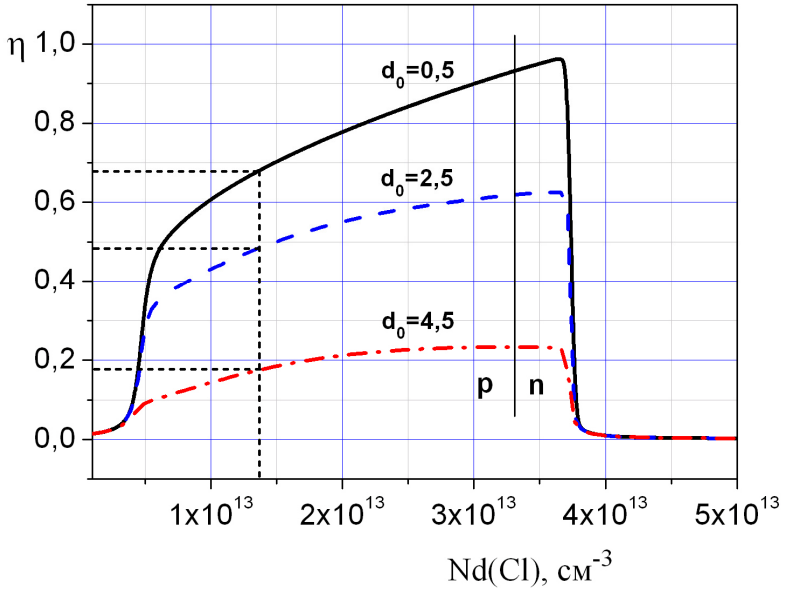

Fig. 2. Charge collection efficiency for carriers drifting from the different distances d_0 from the anode, depending on the concentration of chlorine in the unirradiated detector CdTe:Cl.
The vertical dashed line shows the investigated sample.

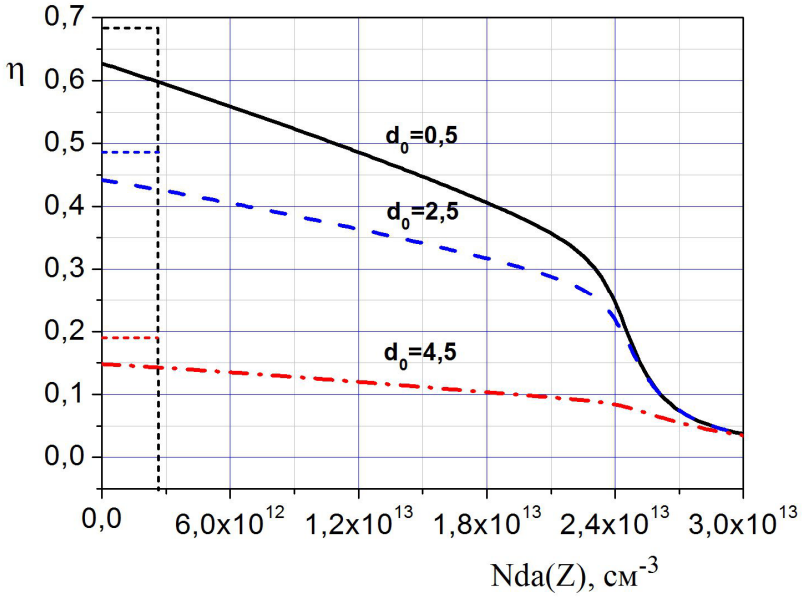

Fig. 3. Charge collection efficiency in irradiated CdTe:Cl detector, depending on the concentration of radiation defects Z for charges drifting from different distances d_0 from the anode.
The horizontal dashed lines represent η of unirradiated detector, and the vertical line marks the measured concentration of Z.

Returning to Fig. 1 and comparing the curves 1 and 2, we see that for measured parameters of the irradiated material the resistivity even increased compared with ρ of non-irradiated CdTe:Cl. Curve 3 in Fig. 1 was calculated for the concentration of defect Z, equal to $3 \cdot 10^{13}$ cm^{-3}, i.e., for the case where according to the calculations there is a complete loss of the detector performance. It can be seen that the reduction of resistivity ρ by about three orders of magnitude takes place, besides the significant decrease of η, which leads to further deterioration in the registering characteristics of the detector. For this case, 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 ($\tau_e \approx 2 \cdot 10^{-8}$ sec) and for holes — three orders of magnitude ($\tau_p \sim 10^{-9}$ sec). 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 + 0.55 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 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 due to lowering of Fermi level.

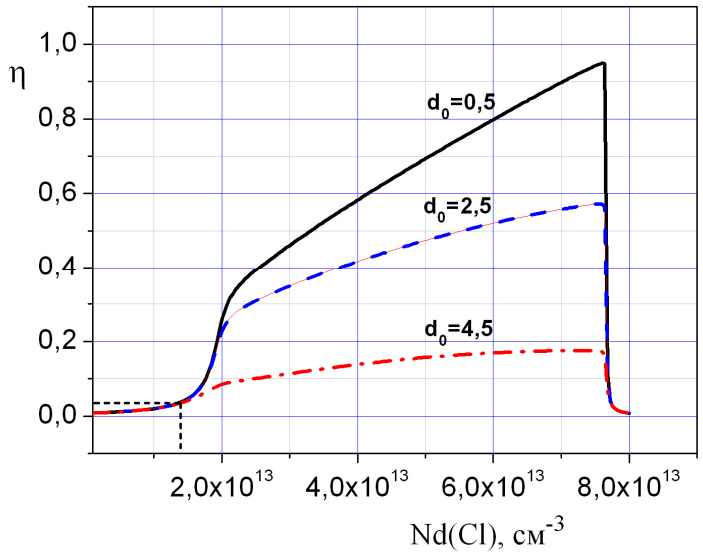

Fig. 4. Charge collection efficiency as a function of the content of chlorine dopant in the detector after X-ray irradiation with the dose of 260 kGy at a concentration of radiation defect Z, equal to $3 \cdot 10^{13}$ cm^{-3}.
The vertical and horizontal dashed lines indicate, respectively, the concentration of Cl and collection efficiency η in the studied detector.

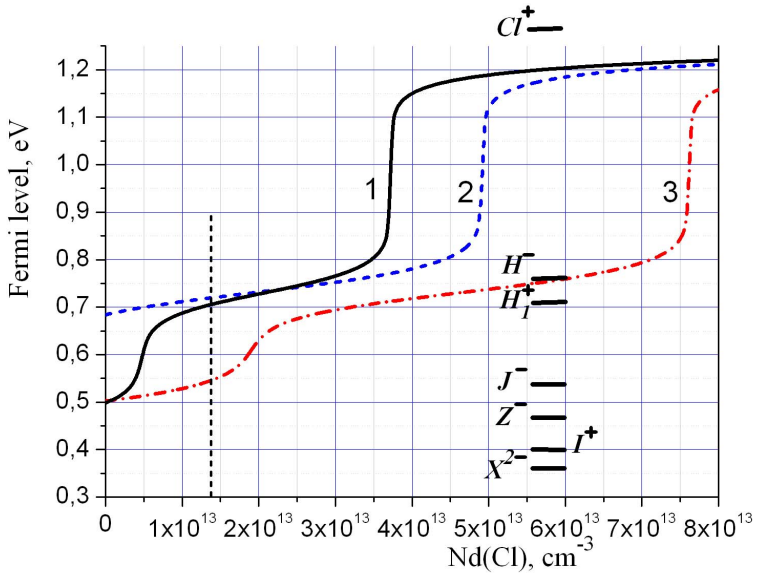

Fig. 5. The behavior of the Fermi level in the CdTe:Cl, depending on the concentration of the dopant;
1 – unirradiated material, 2 – irradiated CdTe:Cl with measured parameters of levels; 3 – irradiated CdTe:Cl with calculated concentration of radiation-induced levels where the detector lost its registering properties.

CONCLUSION

The analysis of published experimental results of measuring characteristics of deep and shallow levels in CdTe:Cl was carried out, and a concrete variant to parametrize the recorded levels was suggested together with determination of their concentrations, capture cross-sections, donor or acceptor types. Proposed parametrization is valid for any CdTe:Cl material having the energy levels as in the table. Accepted parameters of deep levels provide a good agreement of calculated electrophysical properties: resistivity, electron mobility and lifetime of nonequilibrium charge carriers with measured or well known values for the unirradiated material.

The main contribution to the degradation of the detector properties of CdTe:Cl during operating under hard radiation exposure gives a reduction in the resistivity by three orders of magnitude, as well as the capture of free charge carriers at the radiation-induced levels Z and J allocating above the valence band by 0.47 and 0.53 eV, respectively. Average drift time of nonequilibrium charge carriers in detector before their capture at these levels decreases for electrons by two orders and for holes - three orders of magnitude.

For significant degradation of registering properties of CdTe:Cl detector the concentration of J and Z defects plus the total concentration of shallow acceptors or the difference between the total concentration of ionized acceptors and

donors should be approximately an order of magnitude more than the experimentally measured values.

REFERENCES

1. Derek S. Bale, Csaba Szeles Nature of polarization in wide-bandgap semiconductor detectors under high-flux irradiation: Application to semi-insulating $Cd_{1-x}Zn_xTe$ // Physical Review B.– 2008. – Vol. 77. – Issue 3. – P. 035205-1–035205-16.
2. Fraboni B., Pasquini L., Castaldini A., Cavallini A., Siffert P. X-ray irradiation effects on the trapping properties of $Cd_{1-x}Zn_xTe$ detectors // Journal of Applied Physics. – Vol. 106. – 2009, No.9. – P. 093713.
3. Fraboni B., Cavalcoli D., Cavallini A., and Fochuck P. Electrical activity of deep traps in high resistivity CdTe: Spectroscopic characterization // Journal of Applied Physics. – 2009. – Vol. 105. – P. 073705–6.
4. Babentsov V., Franc J., James R.B. Compensation and carrier trapping in indium-doped CdTe: Contributions from an important near-mid-gap donor // Applied Phys. Letters Vol. 94.– 2009. – P. 052102.
5. Carini G.A., Bolotnikov A.E., Camarda G.S. Effect of Te precipitates on the performance of CdZnTe detectors // Applied Physics Letters.– 2006. – Vol. 88. – P.143515-1 – 143515-3
6. Gul R., Keeter K., Rodriguez R., Bolotnikov A.E. at al. Point defects in Pb-, Bi-, and In-doped CdZnTe detectors: deep-level transient spectroscopy (DLTS) measurements // Journal of Electronic Materials. – 2012. – Vol. 41, No. 3. – P. 488-493.
7. Cavallini A., Fraboni B. Defective states induced in CdTe and CdZnTe detectors by high and low energy neutron irradiation // Journal of Applied Physics. – 2003. – Vol. 94, No.5. –P. 3135-3142.
8. Belas E., Grill R., Franc J., Hlídek, P. Linhart V., Slavíček T., Höschl P. Correlation of electrical and optical properties with charge collection efficiency of In-doped and In+Si co-doped CdTe // Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. – 2008. – Vol. 591. - Issue 1. - P. 200–202.
9. Gul R., Bolotnikov A., Kim H.K., Rodriguez R., Keeter K., Li Z., Gu G., James R.B. Point Defects in CdZnTe Crystals Grown by Different Techniques //Journal of Electronic Materials. – 2011. – Vol. 40, No. 3. – P. 274–279.
10. Cavallini A., Fraboni B., Dusi W., Zanarini M., Hage-Ali M., Siffert P. Defects introduced in cadmium telluride by γ irradiation // Journal of Applied Physics. – 2001. – Vol. 89, No. 8. – P. 4664–4666.
11. Fraboni B., Cavallini A., Auricchio N., Dusi W., Zanarini M., Siffert P. Time and thermal recovery of irradiated CdZnTe detectors // Semiconductor Science and Technology. - 2006. - Vol. 21.– No.3. – P. 1034-1040.
12. Kondrik A.I. Modelirovanie svoistv CdZnTe i parametrov detektorov γ-izlucheniya na ego osnove // Tekhnologiya i konstruirovanie v elektronnoi apparature. – 2004. – No.6. – S. 17-22.
13. Tapiero M., Benjelloun N., Zielinger J.P. Hamd S.E., Noguet C. Photoinduced current transient spectroscopy in high-resistivity bulk materials: Instrumentation and methodology // Journal of Applied Physics. – 1988.– Vol. 64. – P.4006-4012.
14. Cavallini A., Frabony B., Dusi W. Compensation processes in CdTe-based compounds // Nuclear Science, IEEE Transactions. – 2005. – Vol. 52. – Issue 5. – P.1964-1967.
15. Fraboni B., Cavallini A., Auricchio N., Bianconi M. Deep traps induced by 700 keV protons in CdTe and CdZnTe detectors // Nuclear Science Symposium Conference Record. (Oct. 29 – Nov. 1 2006). San Diego, Canada. – IEEE. – 2006. – P. 3594-3597.
16. Hofmann D.M, Stadler W., Christmann P., Meyer B.K. Defects in CdTe and $Cd_{1-x}Zn_xTe$ // Nuclear Instruments and Methods in Physics Research. – Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. – 1996. – Vol. 380. – Issues 1-2. – P. 117-120.
17. Castaldini A., Cavallini A., Fraboni B. Deep energy levels in CdTe and CdZnTe // Journal of Applied Physics. – 1998. – Vol. 83, No. 4. – P. 2121-2126.
18. Castaldini A., Cavallini A., Fraboni B., Fernandez P., Piqueras J. Midgap traps related to compensation processes in CdTe alloys // Phys. Rev. B. – 1997. – Vol. 56, No. 23. – P. 14897-14900.
19. Kondrik A.I. Effektivnost' sbora zaryadov v datchikakh γ-izluchenia s razlichnoi konfiguratcyei elektrodov // Tekhnologia i konstruirovanie v elektronnoi apparature. – 2012. – No.4. – S. 47-51.
20. Stadler W., Hofmann D., Alt H., Muschik T., Meyer B., Weigel E., Mueller-Vogt G., Salk M., Rupp E., Benz K. Optical investigations of defects in $Cd_{1-x}Zn_xTe$ // Physical Review B. – 1995.– Vol. 51, No. 16. – P. 10619-10630.
21. Allen J.W. Spectroscopy of lattice defects in tetrahedral II-VI compounds // Semiconductor Science and Technology. – 1995.– Vol. 10, No. 8. – P. 1049-1055.
22. Fraboni B., Cavallini A., Dusi W. Damage induced by ionizing radiation on CdZnTe and CdTe detectors // Nuclear Science, IEEE Transactions. – 2004. – Vol. 51. – Issue 3. – P. 1209-1215.