Form 1

2019 Report Form for Collaboration with Research Center for Biomedical Engineering

Year/month/date	
Number	

Day/Month/Year
Date: 13/03/2020

To Chairman, Board of Directors, Research Center for Biomedical Engineering

Applicant

Affiliation: V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine
Title: Ph.D., Senior Scientist
Name: Volodymyr GNATYUK
Address: Prospekt Nauky 41, Kyiv 03028, UKRAINE

Phone: +380 44 5258437
Fax: +380 44 5258342
E-mail: gnatyuk@ua.fm

Report Form for Collaboration Research

Research Theme	Development of Cd(Zn)Te-based X/gamma-ray detectors with high resolution for security and diagnostics instruments
Research Area	1. Biomaterials 2. Bioengineering 3. Functional molecules 4. Chemistry/Electrical Engineering/Mechanical Engineering/Materials Science
Research Period	From: Day/Month/Year 14/05/2019 To: Day/Month/Year 31/03/2020

Applicant Organization			
Name	Department	Title	Role
Volodymyr GNATYUK	Department of Physics of Optoelectronic Devices, V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine	Ph.D., Senior Scientist	Leader
Sergiy LEVYTSKYI	Department of Physics of Optoelectronic Devices, V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine	Ph.D., Senior Scientist	Participant
Vitaliy VELESCHUK	Department of Physics of Optoelectronic Devices, V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine	Ph.D., Senior Scientist	Participant
Kateryna ZELENSKA	Faculty of Physics, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine	Ph.D., Junior Scientist	Participant
Collaboration Partners in the Research Center	Toru AOKI, Ph.D., Professor Research Institute of Electronics, Shizuoka University, Japan		

Research Results (Including Purpose, Results, Figures, etc.)

1. *Introduction*

Owing to the support of the Cooperative Research Project (No 2022) of the Research Center of Biomedical Engineering, we performed the research and obtained interesting and important results which were presented at 10 International Meetings and reflected in the abstracts {1-13} (in List of Presentations). Moreover, the project results have been published in 6 articles cited by Scopus [1-6] (in List of Publications). All the publications were published during the period of implementation of this project (05.2019-03.2020). The articles [1-6] contain acknowledgments to the Cooperative Research Project of the Research Center of Biomedical Engineering.

2. *Project purpose and research objectives*

The *purpose* of the project was to develop Cd(Zn)Te-based X/γ-ray detectors with high energy resolution for security and diagnostic instruments. The research *objectives* were the study of Cd(Zn)Te properties and elaboration of two techniques of fabrication of Cd(Zn)Te-based diode-type detectors: (i) creating a *p-n* junction and (ii) forming a Schottky barrier. The first technique included the doping of the thin semiconductor region with an In impurity by backside laser irradiation, creation of a *p-n* junction and, thus In/CdTe/Au diode structures. The second one consisted of formation of Schottky and Ohmic contacts by vacuum deposition of Cr and Au electrodes onto the CdTe(111) crystal surfaces pre-treated with Ar-ion bombardment in different regimes.

To elaborate the techniques of fabrication of X/γ-ray detectors as In/CdTe/Au *p-n* junction diodes or Cr/CdTe/Au Schottky diodes with low reverse dark currents in both the cases, some important semiconductor properties were investigated, different surface treatments (chemical etching, ion bombardment, laser irradiation, plasma processing, etc.) of CdTe crystals were studied and efficient methods of formation of electrical contacts and electrodes (vacuum evaporation, chemical deposition, etc.) were developed.

3. *Semiconductor samples*

Detector-grade (111) oriented CdTe semiconductor single crystals, grown by the THM by Acrorad Co., were used in our research [1-6]. Semi-insulating Cl-compensated CdTe showed weak *p*-type conductivity with a specific resistivity of 4×10^9 Ω·cm at T = 300 K that was close to the intrinsic value [1]. Parallelepiped-like CdTe(111) wafers with a surface area of 5×5 mm^2 and different thicknesses (0.5 mm, 0.75 mm, 1.0 mm and 2.0 mm), preliminary polished by the manufacturer, were employed [1-6]. Before the experimental procedures, all CdTe samples were subjected to chemical surface processing for cleaning from contaminants [1-46,].

4. *Investigation of some properties of CdTe crystals*

The photothermal transformation in the CdTe crystals w studied using the photoacoustic gas-microphone technique, in particular the thermal conductivity was evaluated [4]. The experimental amplitude-frequency and phase-frequency dependences of the photoacoustic response, obtained by optical irradiation of the reference Si and investigated CdTe samples, were approximated by the calculations [4]. The qualitative coincidence of the theoretical curve`s amplitude with the experimental result for the CdTe sample occurred when its thermal conductivity value as a fitting parameter was equal to 3.7 ± 0.7 W/(m·K). This value was used for the calculations of the CdTe melting thresholds under pulsed laser irradiation [4].

The treatment features of CdTe under laser irradiation with different wavelengths (λ = 300-800 nm) and pulse durations (τ_p = 7 ns – 1 ms) were studied [4]. Simulations of the melting thresholds I_{th} were performed by the three-stage model of laser-induced excitation and relaxation. Such processes were considered: (i) rapid interband thermalization, (ii) nonradiative interband and (iii) nonradiative surface recombination. The laser intensity I_0 required to heat the semiconductor surface from an initial temperature T_0 to a temperature T_f was estimated as:

$$I_0 = \frac{1}{\tau_p} \int_{T_0}^{T_f} \frac{dTc\rho}{(1-R)\alpha} \left[\eta_T / (L_T\alpha + 1) + \eta_B^{NR} / (L_T\alpha + L_D\alpha + 1) + \eta_S^{NR} / L_T\alpha \right]^{-1}, \quad (1)$$

where c is the specific heat, ρ is the density, R is the reflectivity coefficient, α is the absorption coefficient, $\Delta T = T_f - T_0$ is the temperature rise, $L_D = (D\tau_B)^{1/2}$ is the free carrier diffusion depth, D is the ambipolar carrier diffusion coefficient, τ_B is the bulk carrier recombination lifetime, $L_T(T)$ is the thermal diffusion depth. The parameters η_T, η_B^{NR} and η_S^{NR} are the fractions of the laser energy which go into the thermalization of nonequilibrium excess carriers immediately (1 fs – 1 ps) after excitation (interband relaxation), into both nonradiative interband (bulk) and surface recombination with surface lifetime $\tau_S = L_D/S$, where S is the surface recombination velocity.

The description of the processes under heating of the CdTe surface by nanosecond laser pulses is complicated because of temperature dependences of the thermal and optical parameters, and concentration of photoexcited nonequilibrium excess carriers. In the calculations, we took the parameters of detector-grade CdTe [4], which was used to create Cr/CdTe/Au Schottky and In/CdTe/Au *p-n* junction diodes as X/γ-ray detectors [1-3, 6].

Fig. 1(a) demonstrates the melting thresholds I_{th} calculated by (1) under pulsed laser irradiation within the wavelength region λ = 300–800 nm for different pulse durations τ_p. An increase in τ_p leads to a sensitivity decrease of I_{th} on the excitation wavelength λ. At τ_p = 7 ns, the threshold laser intensity increases by ΔI_{th} = 5.6 MW/cm^2 (from 4.7 MW/cm^2 to 10.3 MW/cm^2) with a variation of λ from 300 nm to 800 nm (Fig. 1(a), curve 1). While, at τ_p = 1 μs, the melting threshold changes only by ΔI_{th} = 0.045 MW/cm^2 (curve 5). Such decrease in ΔI_{th} with increasing τ_p can be explained by the fact that the thermal diffusion depth L_T increases with rising τ_p and becomes much larger than $1/\alpha$, therefore I_{th} becomes less dependent on the optical absorption coefficient $\alpha(\lambda)$ [4].

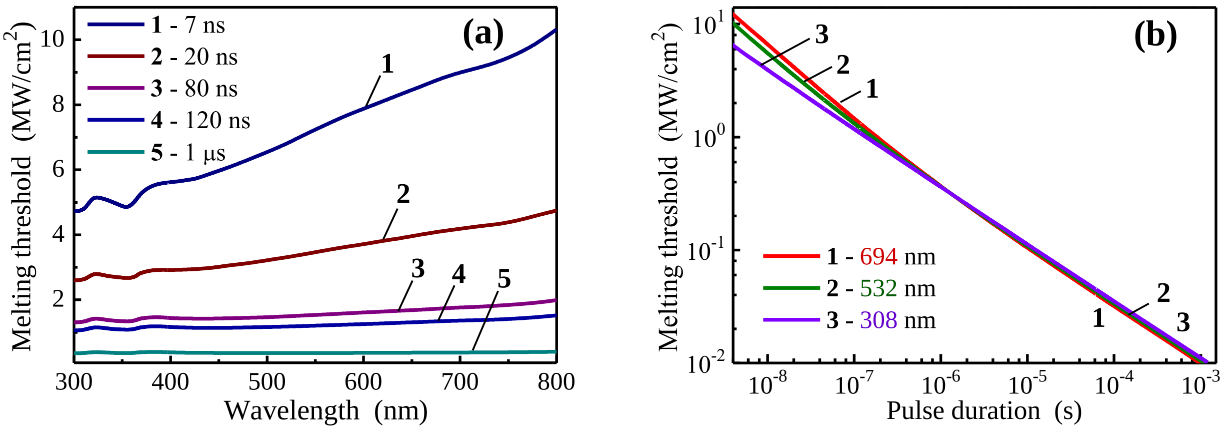

Fig. 1. Dependences of the CdTe melting I_{th} on laser threshold wavelength for different pulse durations (a) and on pulse duration for different wavelengths (b).

For application, the dependence of I_{th} on τ_p is also important (Fig. 3(b)). I_{th} falls drastically with an increase in τ_p in accordance with (1) because the heated-up layer volume increases. If τ_p becomes shorter, the rate of laser energy delivery becomes higher. With increasing τ_p by six orders of magnitude, I_{th} decreases by three orders of magnitude, e.g. from 8.7 MW/cm^2 to 10 kW/cm^2 at λ = 532 nm (Fig. (1(b), curve 2). The fact that the curves intersect at τ_p ~ 1 μs is explained by temperature dependences of the optical parameters of the semiconductor [4].

It was revealed that in the range τ_p = 7 ns – 1 μs, I_{th} mainly depends on the absorption coefficient $\alpha(\lambda)$. For τ_p > 1 μs, I_{th} starts to depend also on the reflectivity $R(\lambda)$. The results on determination of I_{th} was used for optimization of the laser-assisted techniques of surface processing and stimulated doping of CdTe crystals [6].

5. In/CdTe/Au p-n junction diode detectors formed by backside laser irradiation doping

Backside laser irradiation of the In/CdTe structures was employed to dope the thin *p*-CdTe region with In atoms (donors), form a shallow abrupt *p-n* junction and create diode-type X/γ-ray detectors [6]. An In dopant film with the thickness of 100 nm was thermally evaporated onto the CdTe(111)B crystal surface (Te-terminated) using a mask of sizes of 4 × 4 mm^2. Then, the In/CdTe structure was irradiated with single pulses of a YAG:Nd laser (λ = 1.06 μm, τ = 8 ns) from the CdTe(111)A (Cd-terminated) side [6].

CdTe semiconductor is transparent for the employed laser radiation wavelength and radiation is strongly absorbed (α ~ 10^9 cm^{-1}) only by a thin In layer at the In/CdTe interface. After backside laser irradiation doping, an Au electrode was deposited on the CdTe(111)A (Cd-terminated) surface with the same technique and thickness as an In one to form a near Ohmic contact at the Au/CdTe interface [6].

Fig. 2(a) shows the *I-V* characteristics of the In/CdTe/Au sample fabricated without laser irradiation of the In/CdTe interface (curve 1) and diode after backside laser doping (curve 2) performed by irradiation of the In/CdTe structure with 50 laser pulses of output energy E = 11 mJ. Reverse current flowed when the In electrode (rectifying contact) was biased positively with respect to the Au electrode (Ohmic contact). As seen, pulsed laser irradiation remarkably shifted the forward branch of the *I-V* characteristics of the In/CdTe/Au structure toward lower voltages (i.e, forward current increased) and reduced reverse current in comparison with the unirradiated sample. High forward current and low reverse one (leakage current) were evidence of formation of a high barrier *p-n* junction as result of backside laser doping of a thin CdTe layer at the In/CdTe interface (Fig. 2(a), curve 2).

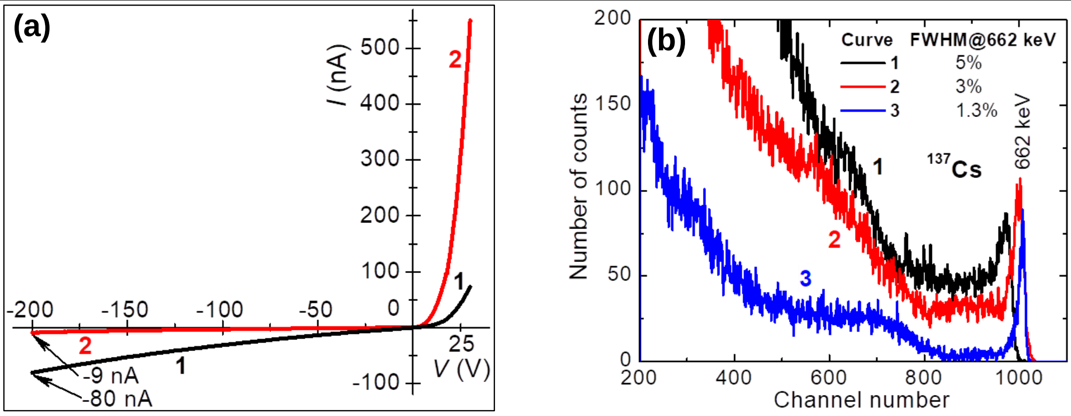

Fig. 2. *I*-*V* characteristics (a) and spectra of a ^{137}Cs isotope (b) obtained from the unirradiated In/CdTe/Au structure (Schottky diode) (curves 1) and In/CdTe/Au *p*-*n* junction diodes formed by the backside laser irradiation doping with laser pulse energy E = 11 mJ (curves 2) and 2 mJ (curve 3).

Both types of In/CdTe/Au diode detectors (with Schottky contact and *p*-*n* junction) were tested for detection of ^{241}Am and ^{137}Cs isotope emissions at T = 300 K [6]. Fig. 2(b) shows the ^{137}Cs isotope spectra taken with three detectors at reverse bias voltage V = 200 V. The unirradiated In/CdTe/Au structure (Schottky diode) detected 662 keV γ-rays with rather low (FWHM = 5%) energy resolution (Fig. 2(b), curve 1). The In/CdTe/Au *p*-*n* junction diodes, formed by backside laser irradiation doping, demonstrated higher energy resolution, more correct peak channel position of the 662 keV line and lower background (Fig. 2(b), curves 2 and 3). Attention is drawn to a significant increase in energy resolution (FWHM = 1.3%) and decrease of the low-energy tail level in the spectrum taken with the In/CdTe/Au *p*-*n* junction diode fabricated by multiple laser irradiation with E = 2 mJ (curve 3). A broad shoulder and tail, extending toward the low-energy side from the 662 keV peak in the spectrum taken with the In/CdTe/Au Schottky diode (Fig. 2(b), curve 1), were due to incomplete charge collection (a part of photogenerated carriers was trapped in the CdTe bulk) along with Compton scattering [6].

6. Cr/CdTe/Au Schottky-diode detectors formed by Ar-ion bombardment

We also developed high energy resolution X/γ-ray detectors as Cr/CdTe/Au Schottky diodes using CdTe wafers with different thicknesses *d*: 0.5 mm, 0.75 mm, 1.0 mm and 2.0 mm. Both the Schottky (Cr electrode) and Ohmic (Au electrode) contacts were formed on the opposite sides of semi-insulating CdTe(111) crystals after preliminary Ar-ion etchings using different parameters of such plasma treatment [1-3]. The *I*-*V* characteristics of the Schottky diodes were measured in dark at T = 300 K. Forward current flowed when the Cr electrode was biased negatively with respect to the Au one. Based on the *I*-*V* measurements, the dominant charge carrier transport mechanisms were determined as: (i) generation-recombination in the space-charge region (SCR) at reverse bias voltages V = 1-100 V, (ii) the charge transport in the conditions when the SCR width W exceeded the semiconductor thickness d at elevated V and, finally (iii) currents limited by space charge at even higher V [2].

The spectroscopic performance of the Cr/CdTe/Au Schottky-diode detectors with different CdTe crystal thicknesses was examined by the measurements of ^{241}Am and ^{137}Cs isotope emissions in dark at T = 300 K without any charge-loss correction or rise-time discrimination electronics [1-3]. The electronic parameters such as the uncompensated impurity concentration N, the SCR width W and thus, the depletion region thickness in the diodes, were calculated based on the comparison of the bias voltage dependences of the photopeak heights in the ^{241}Am isotope spectra excited from the Schottky contact side (Cr) and Ohmic contact side (Au), respectively [1].

The Cr/CdTe/Au Schottky diodes demonstrated steep rectification that made it possible to apply high reverse bias voltages up to V = 1500 V at moderately low dark currents (Table 1). This provided full collection of photogenerated charge carriers and, thus high energy resolution. Fig. 3 shows the ^{137}Cs isotope spectra taken by the Schottky-diode detectors with different CdTe crystal thicknesses d at V = 1200 V (Fig. 3). As seen, the intensity (number of counts) of the 662 keV photopeak in the spectra increases significantly with increasing d.

The CdTe crystal thickness dependences of the photopeak height (curve 1) and energy resolution (curve 2) are shown in Fig. 4. It follows, that the intensity (number of counts) of the 662 keV photopeak in the ^{137}Cs isotope spectra increases approximately in 4 times (curve 1) and energy resolution (FWHM at the 662 keV peak) of the detectors varies from 0.5 % to 3 % (curve 2), when d increases from 0.5 mm to 2.0 mm (Fig. 4). Both the values (height and FWHM) change almost linearly (Fig. 4).

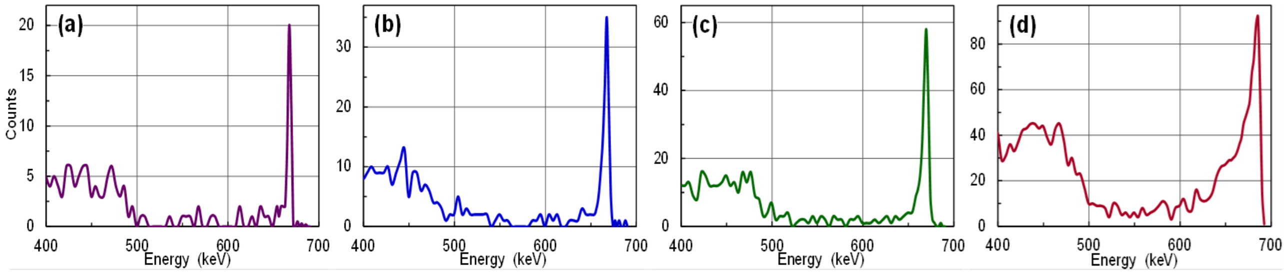

Fig. 3. Spectra of a ^{137}Cs isotope, measured by the Cr/CdTe/Au Schottky-diode detectors with different CdTe crystal thicknesses d at reverse bias voltage V = 1200 V for d (mm): 0.5 (a), 0.75 (b), 1.0 (c) and 2.0 (d).

Table 1. Leakage currents of the Cr/CdTe/Au Schottky-diode detectors with different thicknesses d at different applied reverse bias voltages (T = 293 K).

CdTe crystal thickness d (mm)	Applied bias (reverse) voltage (V)						
	100	200	400	500	600	1000	1500
	Reverse dark (leakage) current (nA)						
0.50	0.58	0.92	1.40	1.72	2.00	2.70	4.60
0.75	0.39	0.60	0.98	1.18	1.40	2.50	3.60
1.00	0.26	0.40	0.72	0.88	1.04	1.60	2.50
2.00	0.26	0.40	0.60	0.75	0.88	1.30	2.10

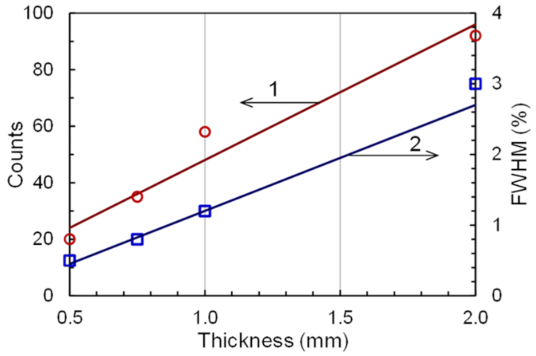

Fig. 4. Thickness dependences of the height (curve 1) and energy resolution (curve 2) of the 662 keV photopeak in the ^{137}Cs isotope spectra (Fig. 3); circles and squares are the experimental data; the curves are linear approximations.

From the comparison of the detection efficiency dependences on the crystal thickness with the corresponding calculated dependences, the uncompensated impurity concentration in CdTe was obtained as $N \approx 4 \times 10^{10}$ cm^{-3} [1, 3]. N determines the SCR width W in Schottky diodes, therefore the effect of this value on the detection efficiency was analyzed [3]. A key feature of the efficiency calculation was the correct evaluation of the electric field strength in the CdTe crystals and using the integration limit d rather than W when $W > d$ [1- 3].

7. Summary

In the frames of the Cooperative Research Project (No 2022, May 2019 – March 2020), we have carried out the investigations according to the research plan, achieved new important results which have been reported at the international meetings {1-13} and published in the articles [1-6]. This is the following.

- ✓ Based on the study of photothermal transformation and features of processing of CdTe crystals by laser irradiation with different wavelengths (λ = 300–800 nm) and pulse durations (τ_p = 7 ns – 1 ms), the CdTe parameters have been evaluated, in particular, the dependencies of the melting threshold on λ and τ_p [4].
- ✓ The controllable technique of solid-phase doping of the thin semiconductor region near the metal-CdTe interface by backside laser irradiation has been elaborated and In/CdTe/Au *p-n* junction diodes have been created for X/γ-ray detectors [6].
- ✓ High energy resolution Cr/CdTe/Au Schottky-diode detectors have been created using the developed Ar-ion bombardment-based technique of semiconductor surface processing to create both the rectifying (Cr/CdTe) and Ohmic (Au/CdTe) electrical contacts [1-3].
- ✓ Studying the effect of CdTe thickness d on the detection efficiency of the Cr/CdTe/Au Schottky-diode X/γ-ray detectors, the uncompensated impurity concentration in the semiconductor was estimated as $N \sim 4 \times 10^{10}$ cm^{-3}. The SCR width at bias voltage V = 0 V is $W \sim$ 0.15 mm that was a significant part of the CdTe crystals and with increasing V, W extends over the entire crystal and can be formally greater than d [1, 3].
- ✓ Quite high energy resolution has been achieved in the developed Cr/CdTe/Au Schottky-diode detectors formed on thin CdTe crystals (FWHM = 0.5 %@662 keV for d = 0.5 mm) and higher detection efficiency at lower resolution has been obtained for the thicker detectors (FWHM = 3.0 %@662 keV for d = 2.0 mm) [3].
- ✓ The elaborated techniques of the formation of Schottky and Ohmic contacts, based on Ar-ion bombardment of the semiconductor crystal surfaces, have also been successfully employed for creation of Schottky-diode IR detectors with low leakage current at high operating voltages [5].

List of Publications Related to the Collaboration Research.

Article with ***acknowledgments*** to the Cooperative Research Project of the Research Center of Biomedical Engineering

[1] V.M. Sklyarchuk, V.A. Gnatyuk, T. Aoki, **Depletion region in CdTe Schottky diode X- and γ-ray detectors**, *IEEE Transactions on Nuclear Science*, Vol. **66**, Issue 9 (Sep. 2019) 2140-2144. DOI: 10.1109/TNS.2019.2935836

[2] V.M. Sklyarchuk, V.A. Gnatyuk, X. Fang, T. Aoki, **Effect of the thickness of CdTe crystals on electrical and detection properties of Cr/CdTe/Au Schottky-diode detectors**, *Proceedings of SPIE*, Vol. **11114**, *Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XXI*, (Sep. 2019) 111141S-1-7. DOI: 10.1117/12.2529965

[3] V.M. Sklyarchuk, V.A. Gnatyuk, T. Aoki, **Effect of CdTe crystal thickness on the efficiency of Cr/CdTe/Au Schottky-diode detectors**, *Nuclear Instruments and Methods in Physics Research A*, Vol. **953** (Feb. 2020) 163224-1-5. DOI: 10.1016/j.nima.2019.163224

[4] V.P. Veleschuk, V.A. Gnatyuk, T. Aoki, Z.K. Vlasenko, S.M. Levytskyi, A.V. Shefer, A.G. Kuzmich, K.V. Dubyk, V.V. Kuryliuk, M.V. Isaiev, **Melting threshold and thermal conductivity of the CdTe under pulsed laser irradiation**, in: A.R. Varkonyi-Koczy (ed.) *Engineering for Sustainable Future. Inter-Academia 2019. Lecture Notes in Networks and Systems (LNNS)*, Vol. **101** (2020) 101-109, Cham: Springer. DOI: 10.1007/978-3-030-36841-8_10

[5] V.M. Sklyarchuk, V.A. Gnatyuk, V. Pylypko, T. Aoki, **Schottky diode detectors with low leakage current at high operating voltage**, in: A.R. Varkonyi-Koczy (ed.) *Engineering for Sustainable Future. Inter-Academia 2019. Lecture Notes in Networks and Systems (LNNS)*, Vol. **101** (2020) 159-167, Cham: Springer. DOI: 10.1007/978-3-030-36841-8_16

[6] **Controllable Doping of CdTe and formation of PN junction diodes by backside laser irradiation**, *2019 IEEE Nuclear Science Symposium and Medical Imaging Conference, 26th International Symposium on Room-Temperature Semiconductor X-Ray and Gamma-Ray Detectors. Proceedings*, (2019) 4 pages, *in press*.

List of Presentations (Conference, Meeting, etc.)

{1} V. Gnatyuk, **CdTe-based diode-type X/γ-ray detectors with high energy resolution and applications,** *The Seminar at Anhui Institute of Optics and Fine Mechanics (AIOFM), Hefei Institutes of Physical Science (HIPS), Chinese Academy of Sciences (CAS)*, 2019, 1 page abstract. (7 May 2019, Hefei, China). (*Invited report*).

{2} K. Zelenska, **Laser-induced incandescence of carbon surface, creation of marks in transparent polymers, formation of CdTe-metal interfaces for diode-type high energy radiation detectors,** *the same as above*, 1 page abstract. (*Invited report*).

{3} T. Aoki, K. Takagi, T. Takagi, T. Terao, H. Kase, V. Gnatyuk, A. Koike, **Photon counting X-ray image sensor by laser doping process**, *XVII International Freik Conference on Physics and Technology of Thin Films and Nanosystems (ICPTTFN-XIVII), Abstract Book*, 2019, 6. (20-25 May 2019, Ivano-Frankivsk, Ukraine). (*Key report*).

{4} J. Nishizawa, V. Gnatyuk, A. Koike, T. Aoki, **Doping of *p-n* junction CdTe diode by backside laser doping**, *Monday Morning Forum, Research Institute of Electronics, Shizuoka University, Program & Abstract*, 2013, 1-2. (27 May 2019, Hamamatsu, Japan).

{5} O.P. Kulyk, V.A. Gnatyuk, K.S. Zelenska, O.V. Podshyvalova, A. Koike, T. Aoki, **High-performance semiconductor X/γ-ray detection system for environment monitoring**, *Proceedings of the International Scientific and Technical Conference "Physical and Technical Problems of Energy and Their Solutions 2019" (ISTCPTPES-2019)*, 2019, 3. (19 June 2019, Kharkiv, Ukraine). (*Plenary report*).

{6} V. Gnatyuk, **Photoelectric properties of semiconductors subjected to laser pulse action**, *International Congress on Advanced Materials Sciences and Engineering 2019 (AMSE-2019)*, Abstract Book, 2019, 43. (22-24 July 2019, Osaka, Japan).

{7} V.M. Sklyarchuk, V.A. Gnatyuk, T. Aoki, **Effect of the thickness of CdTe crystals on the detection properties of Cr/CdTe/Au Schottky diode detectors**, *The conference on Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XXI (Conference OP319), Part of 2019 SPIE Optics + Photonics: Optical Engineering + Applications*, 2019, Abstract No 11114-67, 165. (11-15 August 2019, San Diego, CA, USA).

{8} V.P. Veleschuk, V.A. Gnatyuk, T. Aoki, Z.K. Vlasenko, S.M. Levytskyi, A.V. Shefer, A.G. Kuzmich, K.V. Dubyk, V.V. Kuryliuk, M.V. Isaiev, **Melting threshold and thermal conductivity of the CdTe under pulsed laser irradiation**, *The 18th International Conference on Global Research and Education in Engineering for Sustainable Future, Inter-Academia 2019 (iA-2019)*, Program and Book of Abstracts, 2019, 5. (4-7 September 2019, Budapest and Balatonfüred, Hungary).

{9} V.M. Sklyarchuk, V.A. Gnatyuk, V. Pylypko, T. Aoki, **Schottky diode detectors with low leakage current at high operating voltage**, *the same as above*, 16-17.

{10} J. Nishizawa, H. Nakagawa, V. Gnatyuk, A. Koike, T. Aoki, **Impeccable regulated doping of p-n junction CdTe diode by backside laser doping**, *2019 IEEE Nuclear Science Symposium and Medical Imaging Conference, 26th International Symposium on Room-Temperature Semiconductor X-Ray & Gamma-Ray Detectors, Abstract Booklet*, 2019, Contribution R-10-04, Abstract #2606, 363. (26 October - 2 November 2019, Manchester, United Kingdom).

{11} V. Gnatyuk, **Characterization of $Cd_{1-x}Zn_xTe$ crystals, modification of their properties by surface processing and formation of diodes for X/γ-ray detectors**, *The Seminar at the State Key Laboratory of Solidification Processing, Northwestern Polytechnical University (NPU)*, 2019, 1 page abstract. (28 November 2019, Xi'an, China). *(Invited report).*

{12} K. Zelenska, **Techniques of formation of CdTe-based diode-type for X/γ-ray detectors**, *the same as above*, 1 page abstract. *(Invited report).*

{13} V. Gnatyuk, S. Levytskyi, V. Veleschuk, K. Zelenska, J. Nishizawa, T. Aoki, **Development of Cd(Zn)Te-based X/gamma-ray detectors with high resolution for security and diagnostics instruments**, *The Annual Meeting of 2019 Cooperative Research on Biomedical Engineering, Book of Abstracts*, 2020, Abstract No 1-09. (13 March 2020, Tokyo, Japan), *in press*.

List of Awards

Owing to the results obtained in the frame of the Cooperative Research Project of the Research Center of Biomedical Engineering (Project No 2022), the Ukrainian leader and participants were awarded by three research grants (international projects were adopted):

A. Short-term Recruitment Program of Foreign Experts in Anhui (APFEP-2019, China). The research topic: "*Development of perovskite single crystal X/gamma-ray detectors for environmental radioactive contamination monitoring*".

B. Program of the Ukraine -The People's Republic of China scientific and technical collaboration for the period of 2019-2020 adopted by the Ministry of Science and Technology of The People's Republic of China (Grant No CU03-15). The research topic: "*Exploring novel perovskite single-crystal based gamma-ray detector for trace environmental radioactivity monitoring*".

C. The Fundamental Research Funds for the Central Universities, (Grant No 3102019ghxm015, 2019-2020, China). The research topic: "*Fabrication and characterization of high energy resolution CdZnTe detectors for radiation detection applications*".

In the frame of Program (A), the project leader Dr. Volodymyr Gnatyuk and participant Dr. Kateryna Zelenska were awarded by travel grants to report the project-related results at the seminar in Anhui Institute of Optics and Fine Mechanics, Hefei Institutes of Physical Science, Chinese Academy of Sciences (Hefei, China) in May 2019 {1, 2}.

In the frame of Program (B), Dr. Volodymyr Gnatyuk was awarded by the two month fellowship (Oct.-Dec. 2019) to implement the project-related results at the institution mentioned above.

In the frame of Program (C), Dr. Volodymyr Gnatyuk and participant Dr. Kateryna Zelenska were awarded by travel grants to report the project-related results at the seminar at State Key Laboratory of Solidification Processing, Northwestern Polytechnical University (Xi'an, China) in Nov. 2019 {11, 12}.

Totally, 5 travel grants (in frames of Programs (A-C)) were received to present the project related results.

Registration of research-theme continuation for next year. Prior consent from the collaboration partner in the Research Center is necessary.	**Yes**	No

Research plan for the next year (from April 1, 2020 to March 31, 2021), if the collaboration research is continued.

Due to high interest of the scientific community to our research results obtained under implementation of the present project (No 2022), that is confirmed by a large number of our publications, presentations (6 articles and 13 abstracts/reports) and received awards (3 research grants (projects) and 5 travel grants) during less than one year, we have concluded that the investigated research field is very important, the achieved results are interesting and promising, thus the collaborative project work should be undoubtedly continued in the next year.

The project purpose for the next year is development of the laser and ion-plasma techniques for efficient surface processing of Cd(Zn)Te semiconductor crystals to provide modification of the surface state, formation of Ohmic and Schottky contacts, doping of a surface layer and creation of a *p-n* junction, and thus to create room temperature Cd(Zn)Te-based X/γ-ray detectors with low leakage current, high detection efficiency and energy resolution, which will be well suitable for using in various security and diagnostic instruments.

Our main idea in the development and fabrication of Cd(Zn)Te-based X/γ-ray detectors, designed as diode structures, is to overcome the general problem concerning charge losses caused by incomplete collection of photogenerated charge carriers. Our brief research plan is the following.

- Theoretical study and computer simulation of the processes which take place under different chemical, laser and ion-plasma treatments of the surface of Cd(Zn)Te semiconductor crystals.
- Elaboration of efficient chemical-based techniques for preliminary surface processing (cleaning, etching, polishing) of Cd(Zn)Te crystals and surface passivation of the created detector structures.
- Investigation and selection of the most suitable materials (metals, carbon compounds, etc.) for electrical contacts to Cd(Zn)Te crystals.
- Development of methods of electrical contact formation and electrode deposition techniques to form a high-barrier Schottky contact and Ohmic contact on the Cd(Zn)Te crystal surfaces.
- Elaboration of techniques of creation of CdTe *p*-*n* junction diode detectors by frontside and backside laser irradiation doping.
- Development of plasma-assisted techniques of formation of CdTe Schottky-diode detectors in particular using ion-bombardment etching of the semiconductor surface.
- Fabrication of Cd(Zn)Te Schottky and *p*-*n* junction diodes using the developed techniques of semiconductor surface processing and electrical contact formation.
- Characterization of Cd(Zn)Te diode-type X/γ-ray detectors by measurements of their electrical, photoelectric and spectroscopic properties.
- Simulation of the electronic transport and photogenerated processes in the developed Cd(Zn)Te diodes and evaluation of optimal conditions for detector fabrication.
- Testing of Cd(Zn)Te diode X/γ-ray detectors in devices for detection and identification of ionization sources.
- Application of Cd(Zn)Te X/γ-ray detectors with high energy resolution for security diagnostic instruments.