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Cd(Zn)Te semiconductor-based diodes for detection of X- and gamma-ray photons with high energy resolution and imaging formation

[1] Organization

Project Leader: *Volodymyr Gnatyuk*, Ph.D., Assoc. Prof., Senior scientist (V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine)

Representative at RIE: *Toru Aoki*, Ph.D., Prof.) Research Institute of Electronics, Shizuoka University, Japan).

Participants:

Oleksandr Vlasenko (Dr., Prof., Head of laboratory (V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Ukraine).

Sergiy Levytskyi, M.Sci., Junior research scientist (V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Ukraine).

Kateryna Zelenska, M.Sci., Engineer (Taras Shevchenko National University of Kyiv, Ukraine).

[2] Progress of Scientific Activity

The CRP participants actively collaborated through electronic media and face-to-face at the meetings when Prof. Toru Aoki and his students visited Ukraine in Sep. and Oct., in particular to attend The 12th Intern. Conf. on Correlation Optics and The 16th Intern. Young Scientists Conf. "Optics & High Technology Material Science" SPO-2015, respectively, and when the Ukrainian scientists (V.G. and K.Z.) visited Hamamatsu in Sep. (14th Intern. Conf. on Global Research & Education: Inter-Academia-2015) and Nov.-Jan. 2016 (research visits owing to CRP). They reported achieved results, exchanged ideas about join work in frames of cooperative projects, and discussed further cooperation between the institutions.

Apart from achieving the research results, described in the next section, the CRP team members were involved in the organization of several international scientific forums, workshops and meetings in Ukraine to discuss the work concerning the project topics and general cooperation.

✓ Dr. *V. Gnatyuk* was a member of the International Committee, and Prof. T. Aoki and Ms. *K. Zelenska* were members of the Organizing Committee of The 16th Intern. Young Scientists Conf. "Optics & High Technology Material Science" SPO 2015 held at the Faculty of Physics of Taras Shevchenko National University of Kyiv (22-25 Oct. 2015, Kyiv, Ukraine).

✓ Dr. *V. Gnatyuk* presented the project-related results at The 14th Intern. Conf. on Global Research & Education: Inter-Academia-2015) held at Shizuoka University (28-30 Sep. 2015, Hamamatsu, Japan).

✓ Prof. *T. Aoki* and his students presented the project-related results at The 16th Intern. Young Scientists Conf. "Optics & High Technology Material Science" SPO 2015 held at the Faculty of Physics of Taras Shevchenko National University of Kyiv (22-25 Oct. 2015, Kyiv, Ukraine).

[3] Research Results

The main purpose of the project is the development of effective techniques and technological procedures for creation of Cd(Zn)Te-based X/gamma-ray detectors, which allow us to design various devices for imaging formation with high energy resolution and stable electrical and spectral characteristics.

Nowadays, the bottleneck in manufacturing Cd(Zn)Te-based detectors is pre-treatment of the crystal surface and formation of electrical contacts with desired and predicted properties. Therefore, the main attention in our project work was devoted to the elaboration of efficient methods and techniques of surface processing of Cd(Zn)Te crystals, including chemical etching, thermal annealing and laser irradiation, to obtain the surface states with the corresponding band bending or a thin surface layer with the modified structure and electrical parameters (including doping layer), and finally to form Ohmic or barrier contacts using different electrode metals, deposition procedures and following treatments [1-14].

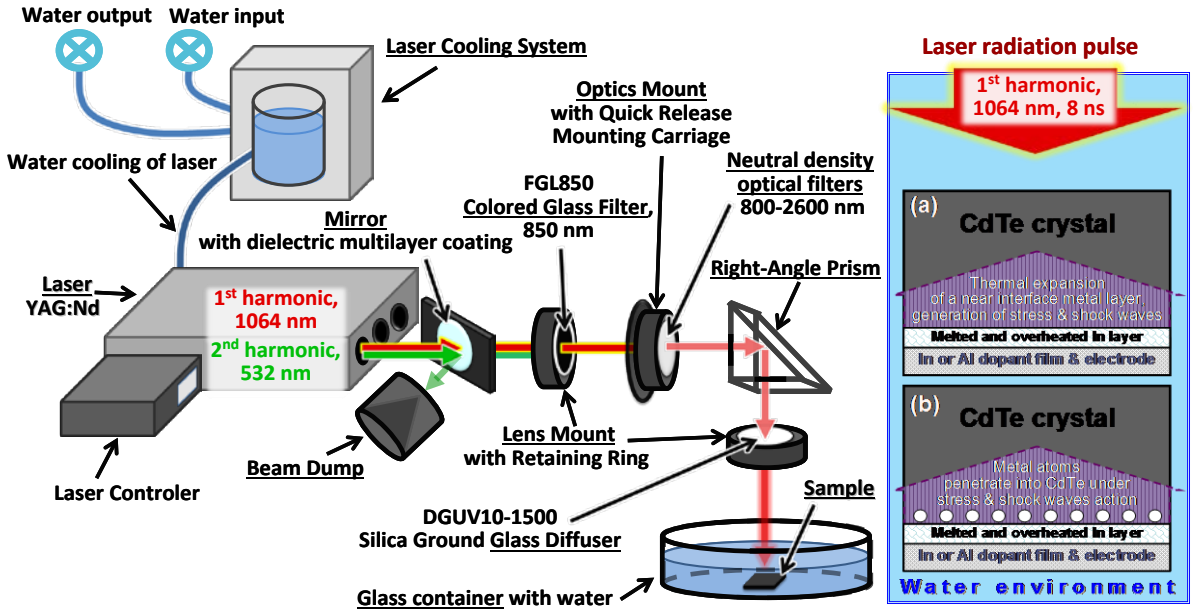

Fig. 1. Experimental setup of the optical equipments for irradiation and laser-induced doping of CdTe samples in water with YAG:Nd laser pulses (λ = 1064 μ, τ = 8 ns). The insert schematically shows laser-stimulated thermal and stress processes (a) and doping of a thin CdTe layer near the CdTe-metal interface with In or Al atoms (b).

We have suggested the principally optimized technique of the laser-induced doping of a thin layer of CdTe crystals and formation of a built-in *p-n* junction by irradiation of the CdTe-metal structure from the CdTe side with YAG:Nd laser pulses (λ = 1064 nm, τ = 8 ns) [1, 2, 7, 8, 11, 14]. The experimental setup for laser treatment has been designed (Fig. 1).

A relatively thick (0.1-2 μm) dopant metal film was deposited in vacuum on the *p*-like CdTe(111)B crystal surface. The whole area of the sample was irradiated from the CdTe side in distilled water. CdTe is transparent for this laser wavelength and it was possible to irradiate the CdTe-metal structure through the CdTe bulk and directly affect the interface (Fig. 1, insert). In or Al was used as a doping source and the metal film also served as an electrode. An Au electrode was evaporated on the opposite side of the sample, i.e. on the CdTe(111)A surface.

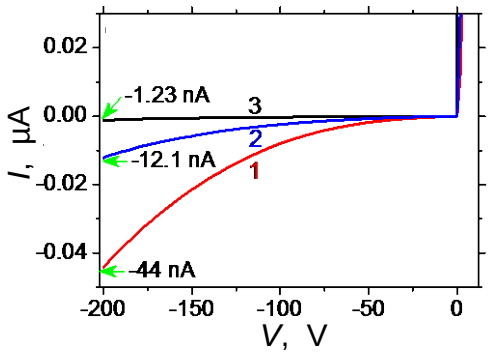

Fig. 2. *I-V* characteristics of the In/CdTe/Au diode before (1) and after (2 and 3) laser irradiation by 10 pulses with intensity F = 5.3 MW/cm^2 (2) and by 50 pulses with F = 1.8 MW/cm^2.

The *I-V* characteristics of the In/CdTe/Au diodes showed that multiple laser irradiation increased forward current and decreased reverse one (Fig. 2). Extreme conditions in the confined area at the CdTe-In interface under irradiation resulted in formation a heavily doped CdTe layer and a high barrier *p-n* junction [7, 8].

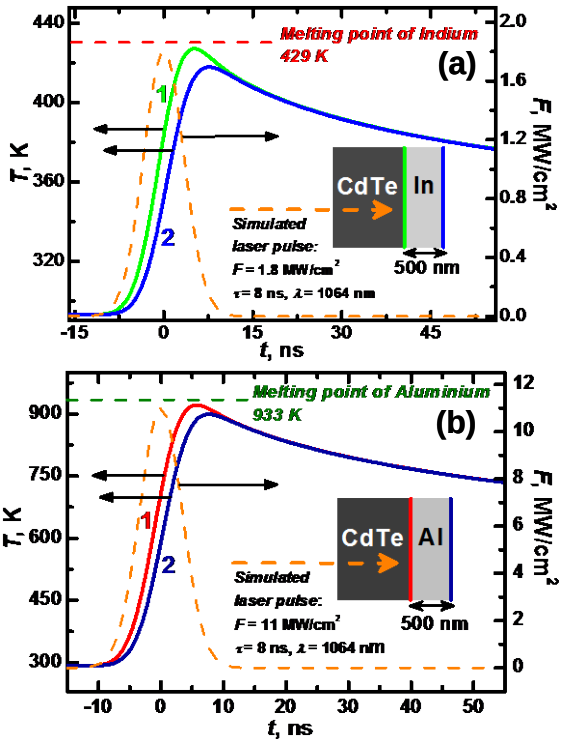

Fig. 3. Time dependences of the temperature at the front (1) and back surface (2) of the In (a) and Al (b) film deposited on the CdTe crystal. The simulated laser pulse and metal melting points are shown by dashed orange curve and red (a) and green (b) lines.

The computer simulation of laser heating and temperature calculations were performed to choose the optimal regimes for achieving the effective doping of thin and thicker CdTe layers under laser irradiation of the CdTe-In and CdTe-Al interfaces through the CdTe bulk [2, 8, 14]. The calculation was based on the thermal conduction equation and it was performed for the three-layer structures of CdTe-In-Water and CdTe-Al-Water. Water and CdTe were assumed as transparent media for the chosen laser wavelength (λ = 1064 nm) and radiation was absorbed only by a thin metal layer adjoining to the CdTe. Temperature distributions inside all the layers were obtained for different laser intensities and metal film thicknesses. The calculated time dependences of the temperature in the CdTe-In-Water and CdTe-Al-Water structures are shown in Fig. 3(a) and (b), respectively. The results were used to find the optimal laser irradiation regimes for effective doping of thin or thicker CdTe layers.

The obtained In/CdTe/Au detectors were tested by radioisotope spectra measurements and demonstrated high sensitivity to X/gamma-rays and satisfactory energy resolution [14].

[4] Publications (*published and submitted by the CRP participants during the project period 29.05.2015-06.03.2016*)

1. K.S. Zelenska, D.V. Gnatyuk, T. Aoki, Modification of the CdTe-In interface by irradiation with nanosecond laser pulses through the CdTe crystal, *Program & Technical Digest, LAPM2015 - The 7th Intern. Congress on Laser Advanced Materials Processing*, 2015, Th2-LO-16, 184. (26-29 May 2015, Kitatyushu, Japan).
2. K.S. Zelenska, D.V. Gnatyuk, T. Aoki, Modification of the CdTe-In interface by irradiation with nanosecond laser pulses through the CdTe crystal, *Proceed. of LAMP2015 - the 7th Intern. Congress on Laser Advanced Materials Processing*, (2015) 5 pages.
3. A.I. Vlasenko, V.P. Veleshchuk, V.A. Gnatyuk, S.N. Levitskii, Z.K. Vlasenko, G.D. Ivlev, E.I. Gatskevich, Acoustic response to the action of nanosecond laser pulses on an In/CdTe thin-film heterostructure, *Physics of the Solid State*, **57**(6), (2015) 1089-1094.
4. V.A. Gnatyuk, O.I. Vlasenko, S.N. Levytskyi, T. Aoki, Laser-induced modification of properties of CdZnTe crystals, *Advanced Materials Research*, **1117**, (2015) 15-18.
5. D.V. Gnatyuk, T. Ito, T. Aoki, Photo-luminescence spectra of CdTe single crystals subjected to nanosecond laser irradiation, *Advanced Materials Research*, **1117**, (2015) 102-106.
6. V.A. Gnatyuk, O.I. Vlasenko, S.N. Levytskyi, T. Aoki, Photoconductivity of CdTe-based semiconductor solid solutions subjected to laser irradiation, *The 14th Intern. Conf. on Global Research and Education: Inter-Academia 2015, Extended Abstract Digest*, 2015, 220-221. (28-30 Sep. 2015, Hamamatsu, Japan).
7. D.V. Gnatyuk, T. Aoki, Mechanism of laser-induced doping under direct irradiation of CdTe-In interface through the CdTe crystals, *The 14th Intern. Conf. on Global Research and Education: Inter-Academia 2015, Extended Abstract Digest*, 2015, 166-167. (28-30 Sep. 2015, Hamamatsu, Japan).
8. K.S. Zelenska, D.V. Gnatyuk, T. Aoki, Modification of the CdTe-In interface by irradiation with nanosecond laser pulses through the CdTe crystal, Journal of Laser Micro/Nanoengineering, **10**(3), (2015) 298-303.
9. V.A. Gnatyuk, O.I. Vlasenko, S.N. Levytskyi, T. Aoki, Modification of the surface state of CdZnTe crystals and contact formation, *The 22nd Intern. Symp. on Room-Temperature Semiconductor X-Ray and Gamma-Ray Detectors, 2015NSS/MIC/RTSD, Conf. Program Book*, 2015, Abstract R3A-40. (31 Oct. - 7 Nov. 2015, San Diego, CA, USA).
10. D.V. Gnatyuk, T. Ito, T. Aoki, Photoluminescence of the CdTe single crystal surface layer after nanosecond laser irradiation, *The 22nd Intern. Symp. on Room-Temperature Semiconductor X-Ray and Gamma-Ray Detectors, 2015NSS/MIC/RTSD, Conf. Program Book*, 2015, Abstract R3A-51. (31 Oct. - 7 Nov. 2015, San Diego, CA, USA).
11. K.S. Zelenska, D.V. Gnatyuk, T. Aoki, Formation of diode detectors by laser irradiation of CdTe-In interface from the semiconductor side, *The 22nd Intern. Symp. on Room-Temperature Semiconductor X-Ray and Gamma-Ray Detectors, 2015NSS/MIC/RTSD, Conf. Program Book*, 2015, Abstract R3A-52. (31 Oct. - 7 Nov. 2015, San Diego, CA, USA).
12. V.A. Gnatyuk, O.I. Vlasenko, S.N. Levytskyi, T. Aoki, Modification of the surface state of CdZnTe crystals and contact formation, *2015 Nuclear Science Symposium and Medical Imaging Conference Record (2015NSS/MIC/RTSD)*, (2015), in press.
13. D.V. Gnatyuk, T. Ito, T. Aoki, Photoluminescence of the CdTe single crystal surface layer after nanosecond laser irradiation, *2015 Nuclear Science Symposium and Medical Imaging Conference Record (2015NSS/MIC/RTSD)*, (2015), in press.
14. K.S. Zelenska, D.V. Gnatyuk, T. Aoki, Formation of diode detectors by laser irradiation of CdTe-In interface from the semiconductor side, *2015 Nuclear Science Symposium and Medical Imaging Conference Record*

(2015NSS/MIC/RTSD), (2015), in press.

Traveling Report

Name:	Volodymyr Gnatyuk
Affiliation and address:	V.E. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Prospekt Nauky 41, Kyiv 03028, Ukraine
Period of time:	15 November 2015 – 13 January 2016
Destination:	Research Institute of Electronics, Shizuoka University
Purpose:	Preparation of the experimental setup and carrying out experiments on elaboration of novel methods and techniques of fabrication of effective uncooled Cd(Zn)Te semiconductor-based X/gamma-ray detectors. Participation in scientific forums and meetings at Research Institute of Electronics, Shizuoka University during the staying period. Educational activity with students of the laboratory headed by Prof. Toru Aoki.
Name of receiver:	Prof. Toru Aoki