Convertor of ionizing radiation into electric power based on the synthetic diamond

N.B. Rodionov, V.N. Amosov, S.A. Meshchaninov, R.N. Rodionov, A.F. Pal and A.G. Trapeznikov

Abstract— Converter of ionizing radiation into electrical power based on the synthetic diamond has been studied. p-i-structure is a IIa-type diamond CVD film with 50 mkm thickness deposited on p-type HPHT-diamond substrate heavily doped with boron. Au, Pt or Al metal contacts were deposited on the surfaces of the structure. The technology of semitransparent contact fabrication was used to manufacture semitransparent entrance window of convertor.

Current-voltage characteristics of photoelectric convertor of alpha-, X-ray, UV-radiations were examined. Comparison of current-voltage characteristics of p-i-structures with solid and semi-transparent contacts made of Pt, Au or Al has been performed. Obtained experimental data allowed to estimate efficiency of ionizing radiation conversion into electrical power. Conversion efficiency for alpha-, x-ray and UV radiation were 5,9%, 8,6% and 22 %, respectively.

Keywords— boron-doped diamond, CVD diamond, ionizing radiation convertor, semi-transparent contacts.

I. Introduction

THE development of devices that converts radiative decay and UV-radiation energy into electric power is one of the most promising directions of design of compact energy sources, capable to operate for a long time autonomously. Several possibilities of conversion of UV-radiation and radiative decay energy to electric current exist [1]. The basic elements of such devices are ionizing radiation source and radiation-hard semiconductor intended to convert radiation energy into electric power. Simple and compact energy source capable to work for a dozen years will be possible to be constructed on the base of those elements, and it could find applications in such devices as cell phones, cardio stimulators, remote control systems, space satellites and so on. Proposal of using wide band-gap semiconductors such as doped synthetic diamond gives extra capabilities of nuclear energy source characteristics improvement [2]. A photovoltaic effect is used to convert radiation energy into electric power in diamond [3]. A basis of such devices is semiconductor structure with embedded electric field area, where separation of non-equilibrium charge carriers occurs. The advantages of diamond-based photo convertors are radiation hardness, high operating temperatures (up to 2500C), high thermal conductivity and chemical inertness. On the base of such elements it is possible to create simple and compact energy source capable to operate for a dozen years in extremely hard environment.

The sensitivity of the diamond detector in pulsed and current modes to various radiation types (UV, x-ray, charged particles, fast neutrons) was determined in work [4]. Voltage-current curves were measured. These curves have diode shape with photovoltaic shift 1.6 V. This effect is induced by boron-doped substrate and deposited IIa-type CVD film interface, while high charge carrier mobility provides low loses during charge collection. Mentioned properties allow creation photoelectric convertors of various types. In paper [5] measurement of characteristics of convertors with semitransparent contacts was carried out, and UV-radiation energy to electric current conversion efficiency was shown to increase 4 times in this case.

Present work devoted to the development of synthetic diamond based ionizing radiation convertor (IRC). Synthetic diamond thin film p-i-structures are considered as IRC. Investigation of IRC with contacts made of various metals is performed. The technology of semitransparent contact fabrication was developed to provide durable entrance of UV-radiation into convertor's volume.

II. (P-I)-Structure

A (p-i)-structure for photovoltaic cell is a substrate with deposited CVD diamond film. The substrate is HTHP IIb-type diamond highly doped with boron (p-type) that has very good hole conductivity. Substrate dimensions were 4x4x0.5 mm3. Samples of the substrates, and structures based on them, used in the experiment had a working designation Br40 and Br03. Nitrogen concentration was less than 1 ppm. Boron concentration was less than 100 ppm. CVD IIa-type diamond film with 50 mkm thickness was deposited on the substrate after substrate annealing in the high temperature oven RD-G WEBB-117. Afterward continuous and semitransparent contacts made from Au, Pt or Al were deposited on the sides of fabricated p-i-structure. Typical scheme of p-i-structure based PEC is represented in fig. 1. Arrows show direction of incident radiation. Working volume of the convertor is IIa-type

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diamond layer directly adjacent to the substrate.

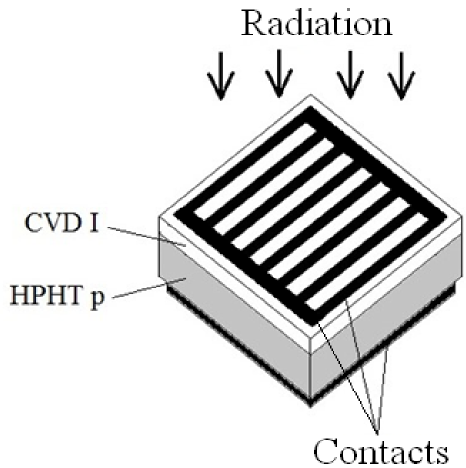


Fig. 1. Photovoltaic element based on p-i-structure: HTHP diamond substrate (p-type) with deposited IIa-type diamond film of 50 mkm thickness

The process of homoepitaxial diamond film deposition requires careful substrate surface preparation. As mentioned above boron doped HTHP-diamond substrate was annealed in vacuum high-temperature oven. The purpose of annealing is reduction of defect concentration in the substrate before CVD-film deposition. Meanwhile major supervised characteristics of the substrate were its absorption spectra for UV- and IR-radiation and electrical resistance at room temperature. Also intensities of cathode-luminescence and roentgen-fluorescence were measured during annealing process. Absorption spectra were measured during sequential annealing of diamond in the temperature range from 1000 to 15000C with step 1000C. After every annealing step chemical cleaning of sample surface was performed because annealing process partially graphitize diamond surface.

Cathode-luminescence images of substrate after annealing at 1100 and 1500^0C obtained by the scanning electron microscope are shown in fig. 2. These images discover samples to have areas with increased concentration of defects which correspond to zonal nonuniformity of the substrate. During annealing process cathode-luminescence intensity was decreasing while heating temperature increasing. This means that annealing decreases concentration of defects in crystals. X-ray luminescence measurements showed that annealing leads to luminescence contrast and brightness decreasing, and respectively, decreasing of defect concentration in the substrate.

Substrate electrical conductivity was monitored by dark current-voltage curves. Current-voltage characteristics were measured in the temperature range from 1100^0C to 1500^0C. Significant reduction of Br03 crystal electrical resistance started after annealing at 1300^0C and during subsequent annealing stages the resistance value decreased almost ten times. Electrical resistance of Br40 crystal was decreasing monotonically during whole annealing cycle except the last stage at 1500^0C and reached the value of 50 Ohm, which is 2.3 times less than initial value. Resistances of crystals versus annealing temperature are summarized in table I.

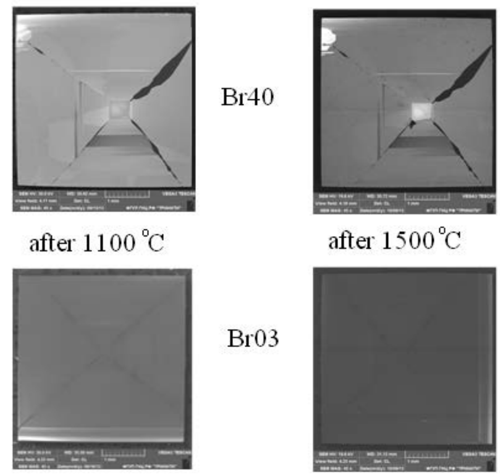


Fig. 2. Cathode-luminescence of diamond crystals after annealing at 1100 and 1500^0C

Table I. Electrical resistance(Ohm) of Br03 and Br40 crystals versus annealing temperature (ºC)

Sample	Electrical resistance, Ohm					
	After 1000 °C	After 1100 °C	After 1200 °C	After 1300 °C	After 1400 °C	After 1500 °C
Br03	88,8	71	75,2	39,6	30	9,3
Br40	117	104	80,8	65,8	49,9	50,05

After annealing at 1500^0C the homoepitaxial layer of extremely pure IIa-type diamond was deposited on the substrate. The thickness of the layer was about 50 mkm. The continuous contact was deposited on the substrate side while semitransparent contact was deposited on the CVD layer. Semitransparent contact was formed from parallel metal stripes with 50 mcm width and 60 mcm distance between them. Two additional stripes perpendicular to the others were deposited at the edges of crystal to provide electrical connection between stripes. The thickness of contacts was about 35 mcm. Various combinations of metals were considered as materials for contacts from substrate and CVD-film sides: Al-Au, Al-Al, Au-Au, Pt-Al and so on, where in every pair first metal is material for substrate side contact while the last – for the CVD-film side. DESK V magnetron deposition installation was used for contacts fabrication. Copper masks were used to provide semitransparent contact deposition. Masks were cut out from copper plates by laser cutting system DIAMAX. Finally P-I structure with contacts was mounted in a housing with 3 mm diameter aperture.

III. THE EXPERIMENT

Electrometer Keithley-6517B was used to measure current-voltage characteristics under various irradiation conditions. Variation of the bias voltage of investigated sample was performed by controlled electrometer built-in power supply source.

Spectral sensitivity characteristic of the samples was measured by optical complex based on scanning monochromator MDR-23 and electrometer Keithley-6517B.

Measurements of amplitude spectra of p-i-structure irradiated by alpha-particles emitted by Am-241 source were carried out in order to estimate charge collection efficiency. In this case spectrometric electronic setup consisting of CanBerra 2001A charges sensitive preamplifier, shape amplifier BUI-14P and ADC ”Parsek” was used.

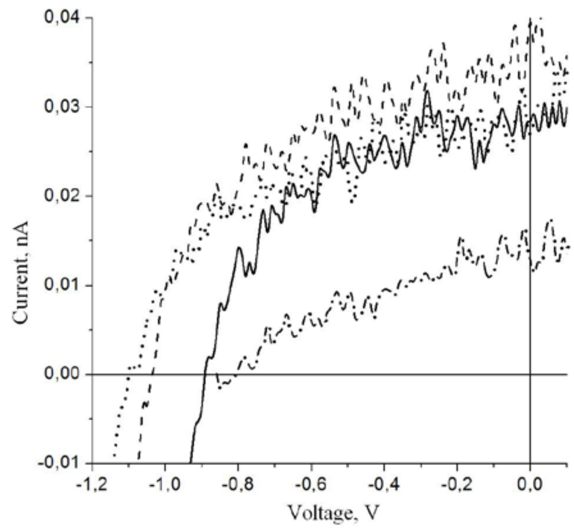
IV. RESULTS OF EXPERIMENTS AND DISCUSSION

IRC was tested under various types of irradiation to investigate the conversion of UV-, alpha- and x-ray radiation into electric current.

The charge collection efficiency of convertor with continuous contacts was estimated to be greater than 90% and almost equal 100% if electric field in the film is greater than 500 V/mm.

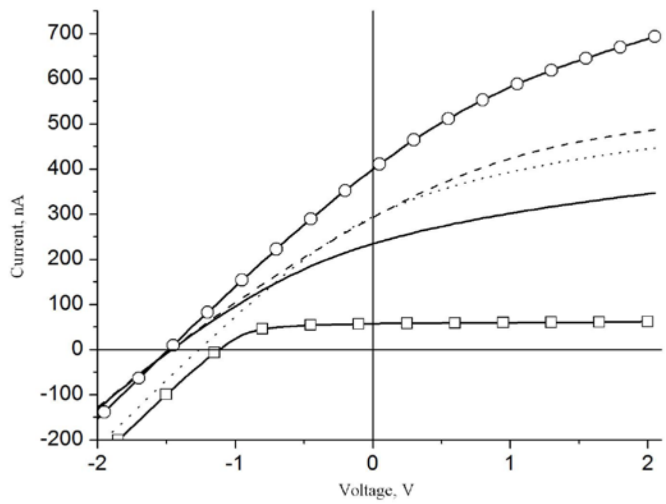
The study of energy conversion of alpha-particles emitted by Am-241 source into electric current was performed. Fig. 3 demonstrates measured current-voltage characteristics (CVC) of photo convertors with various contacts on the substrate and CVD-film: Al-Au, Au-Al, Au-Au. Also the current-voltage curve for continuous contact on the CVD-film side is shown in fig. 3. CVCs for Al-Au and Au-Al contacts are slightly different. The photovoltaic shift of CVC in case of different material of contacts (Al-Au, Au-Al) is greater by 0.3 V than for the case of identical contacts (Au-Au), and short circuit current is greater by 15% than in the case of Au-Au contacts. Short circuit current of Br40 sample was the same as for Br03 sample, but photovoltaic shift was less by 0.3 V.

Fig. 4 shows current-voltage characteristics of photo convertor irradiated by deuterium UV lamp for various combinations of contacts (Al-Au, Au-Al, Au-Au, Al-Al). Also current-voltage characteristic of convertor with continuous contact on the CVD side is shown in Fig. 4. These curves show that short circuit current for aluminum contacts is two times greater than for gold contacts, and short circuit current for Al-Au and Au-Al contacts is greater two times. All curves have clear photovoltaic shift ~ 1.5 V. Semitransparent contact allow to increase converter efficiency almost twice with respect to continuous contacts.



Solid curve – Au-Au contacts, dots – Au-Al, dashed – Al-Au, dot-dashed – both continuous Au-Au.

Fig. 3. Current voltage characteristics of p-i-structure irradiated by alpha-particles



Solid line – both contacts are gold, dashed – Au-Al, dots – Al-Au, circles – Al-Al, squares – both continuous contacts Au-Au

Fig. 4. Current-voltage characteristics of convertors irradiated by deuterium UV lamp

Fig. 5 shows current-voltage characteristics of convertor irradiated by deuterium UV lamp for contacts combinations: Au-Pt and Al-Al for Br40 sample. Pare of Au-Pt contacts looks more promising for the converter because of larger photovoltaic shift.

Pt-Au contacts along with Al-Al contacts allow acquiring short circuit current up to 400 nA.

For the case of x-ray irradiation current-voltage characteristics varied slightly (about 15%) for different materials of contacts.

Conversion of radiation energy into electric power can be described by the following characteristics: current sensitivity S_I (ratio of electric current and irradiation dose, A/W), photovoltaic shift U_{OC} (V) and energy conversion efficiency æ ≈ $Uoc*S_I/P$, where P-radiation power. We consider that the measured photovoltaic shift is equal to convertor photo-voltage i.e. ratio of maximum power of photo converter to $U_{OC}*S_I$ equals 1.

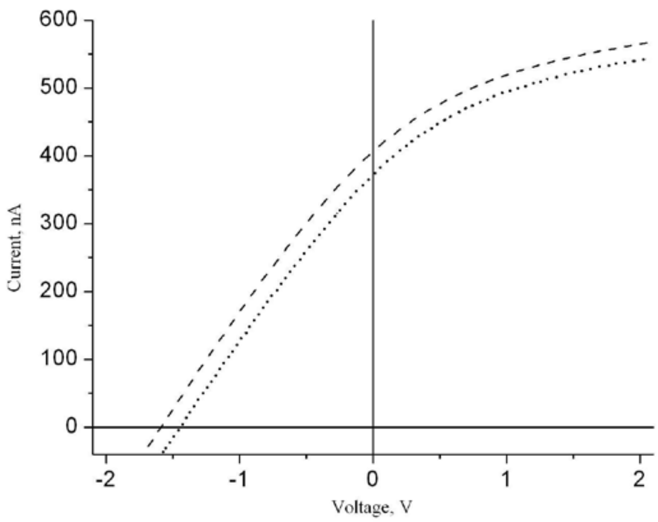


Fig. 5. Current voltage characteristics of convertor irradiated by deuterium UV lamp. Dashed – Au-Pl, dots – Al-Al

Let's estimate characteristics of conversion x-ray and alpha radiation into electricity. Count rate of the alpha-particles on the photo converter surface was 700 s^{-1}, that corresponds to absorbed power of P=0.62 nW. Maximum current sensitivity of photo converter for x-ray and alpha radiation can be estimated as energy that is necessary for electron-hole pair creation in the crystal: for diamond it equals Sia=0.075 A/W. The estimation of current sensitivity of diamond convertor for the case of alpha particle irradiation, obtained in this article is 0.056 A/W (Fig.3). Taking into account that the maximum electric current power was reached for convertor with Al-Au contacts (Uoc=1.05, Isc=0.035 nA) the alpha-radiation conversion efficiency can be estimated: æ ≈ $U_{OC}\ I_{SC}/P \approx 5.9\%$. Maximum photovoltaic shift obtained for the case of alpha irradiation in the present work was 1.05 V.

When intensity of x-ray radiation was ~ 2 Rad/s, absorbed power in CVD film was P=3.14 nW. In this case current sensitivity of diamond converter was about 0.066 A/W. Taking into account photovoltaic shift which is about 1.3 V, x-ray energy conversion efficiency can be estimated to be ~ 8,6%.

Let's estimate efficiency of UV-radiation conversion into electric power. Maximum current sensitivity in the UV range can be estimated through band gap width: for diamond Sia=0.18 A/W. UV radiation power measured by reference detector AXUV-HS5 at the aperture of housing was 2.6 mkW. So current sensitivity for UV-radiation reached 0.15 A/W, energy conversion efficiency ~22 %, photovoltaic shift was 1.5 V.

Important advantages of diamond ionizing radiation convertor are diamond radiation hardness, small cross section of neutron transmutations, chemical inertness and mechanical strength. For example, critical fluence for diamond is more than two orders of magnitude greater then the one for silicon. Diamond radiation hardness for gamma-radiation reaches 1 Grad. Another advantage of diamond is wide band gap. During photo convertor operation it will be heating. In work [5] it is shown that with temperature increasing silicon-converter efficiency is decreasing (band gap is 5 times less than diamond band gap). In the case of diamond heating effect, which leads to decreasing of photo-voltage and short circuit current, will influence weaker because of wide band gap.

Proposed diamond structure is shown to operate as radiation to electric power convertor, moreover application of semitransparent contacts on the CVD side and optimal material selection allowed increasing UV-energy conversion efficiency almost by an order of magnitude. Ionizing radiation energy conversion efficiency depends on homoepitaxial film quality. Crystal defects of the film reduce average lifetime of charge carriers. Further improvement of p-i-structure will be possible after substrate quality enhancement as long as its surface preparation before deposition. Photovoltaic convertor with large working surface area and great efficiency could be easily created by joining elements into parallel net.

V. Conclusion

Diamond p-i-structure was shown to operate as convertor of ionizing radiation energy into electric power. The technology of semitransparent contacts fabrication was developed. Diamond photo element with continuous and semitransparent contacts was manufactured. Ionizing radiation convertor was tested. Photovoltaic voltage shift for alpha-, x-ray and UV radiation were 0.62 V, 1.5 V and 1.1 V respectively. Conversion efficiency for alpha-, x-ray and UV radiation were 5,9%, 8,6% and 22 %, respectively.

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