Review the Space Radiation CVD Diamond Multi-layer Detector.

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***Abstract* — the review highlights the parameters of multilayer diamond detector for monitoring space radiation based on CVD diamond technique. The paper specifies the results of measuring charge output spectrum of single and double layer diamond detectors. Diamond detector serves to on-board radiation monitoring systems of spacecraft having lifetime increase in up to 20 - 25 years. The use of a diamond detector multi-layer structure makes it possible to enhance the amplitude of charge output spectrum, to expand the detector dynamic range, as well as to improve the accuracy and information content of radiation monitoring systems.**

Keywords — diamond detector; space radiation; spacecraft; radiation situation; linear energy transfer.

I. INTRODUCTION

Today, the radiation situation detectors have become an integral part of spacecraft performance on-line analysis and control systems. The radiation situation detectors provide continuous monitoring for spacecraft brain box burn-up life that allows one to hold the optimal satellite replacements in constellations. The radiation situation detector outputs a control signal to switch the spacecraft equipment to the radiation-resistant operation mode when it comes to a sharp increase in the cosmic ray flux.

In view of spacecraft lifetime extension up to 20 - 25 years, there appear good reasons for applying radiation-resistant detectors to execute control over space radiation parameters (SR). Therefore, the development of satellite airborne radiation sensors based on ionizing radiation diamond detectors becomes problem number one at present [1].

The ionizing radiation diamond detectors (DD) are highly resistant to radiation up to 5 Mrad [2], and, that is to say, able to operate at temperatures as high as 200°C [3]. At the same time, the use of diamond plates as an active element of ionizing radiation detector shows a number of features. Thus, to assure the complete collection of the charge generated in the diamond plate while detecting an ionizing particle, many normally select the diamond plate within the limits of 0.3 to 0.5 mm thick. One derives it from the fact that the electric field of at least 0.5 - 1.0 V/μm provides for the effective charge collection in the diamond plate. Based on the above stated, if the diamond plate thickness amounts to 0.5 mm, we should apply the bias voltage higher than 300 - 500 V, which results in significant leakage currents over the diamond plate surface and, thus, in increasing the detector noise. On the other hand, the diamond detector small thickness makes for that while ionizing particle is passing through the detector, it absorbs only a small part of ionizing particle energy, and, hence, the amplitude of detector output signal is small enough.

Nowadays, various configurations of diamond detectors are widely investigated all over the world to obtain the required parameters of diamond detectors [4 - 12].

II. OBSERVING THE USE OF DIAMOND DETECTOR MULTILAYER STRUCTURE TO DETECT THE ELECTRON COMPONENT OF SPACE RADIATION

The present study investigates the possibility of using the diamond detector multilayer structure to detect the cosmic radiation electron component. The authors have applied to a detector double-layer structure, shown in Figure 1.

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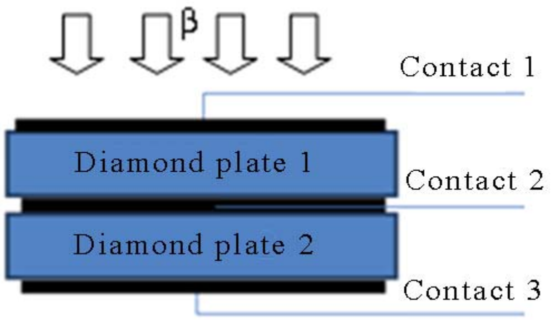

Fig. 1. Double-layer diamond detector to measure space radiation (SR).

Diamond detector consists of two diamond plates 1 and 2. Metal contacts are deposited on the flats of the plates. The plates are arranged one above the other, so that the stream of ionizing particles passes through both diamond plates. The conductors connect contact layers of each plate to the detection electronic circuit. When connecting contacts 1 and 3 to a bias voltage source, and contact 2 to the input of charge sensitive amplifier, then charges generated in the upper and lower plates will start being accumulated. Consequently, it makes possible to increase the detector effective thickness and, respectively, to enhance the DD output signal amplitude, wherein the bias voltage applied to each plate, will not exceed 300 V. Figure 1 shows the DD structure, comprising two diamond plates.

The expressions as follows describe the DD functioning composed of two diamond plates.

One may use the following formula to express the DD total output charge, accumulated in two diamond plates while detecting ionizing particle:

$$Q_v = Q_{v1} + Q_{v2}, \quad [C] \tag{1}$$

where Q_v stands for the DD total output charge; Q_{v1}, Q_{v2} are the charges, accumulated within the diamond plates 1 and 2, respectively.

whereas, the formulas (2, 3) [14-15] determine the charges Q_{v1}, Q_{v2}:

$$Q_{v1} = \Delta E_1 \times \frac{k_1 \times e}{E_0} \times \alpha_1, \quad [C] \tag{2}$$

$$Q_{v2} = \Delta E_2 \times \frac{k_2 \times e}{E_0} \times \alpha_2, \quad [C] \tag{3}$$

where ΔE_1, ΔE_2 stand for energy transferred to the diamond plates 1 and 2 by charged particle;

k_1, k_2 are the charge collection efficiencies in diamond plates 1 and 2, respectively (with diamond plates of electronic quality at electric-field strength more than 0.5 V/μm k~0.9);

e is the elementary charge (1,6x10^{-19} [C]); E_0 is the energy required for the formation of one electron-hole pair in a diamond crystal (13,2 [eV]), α_1, α_2 are the constants determining whether a diamond plate is connected to the preamplifier output (connected $\alpha = 1$, not connected $\alpha = 0$).

The ionizing particle transfers energy to a diamond plate as [4]:

$$\Delta E_1 = \int_0^{z_1} \rho \times L(E)_1 \times dz, \quad [eV] \tag{4}$$

$$\Delta E_2 = \int_0^{z_2} \rho \times L(E)_2 \times dz, \quad [eV] \tag{5}$$

where $L(E)_1$, $L(E)_2$ stand for linear energy transfer (LET) by charged particles in the material, [MeV/(g/cm^2)]; ρ is the diamond density, 3,5 [g/cm^3]; $z_{1,2}$ – diamond plate thickness.

One may put down a new formula by combining the expressions (1 – 5):

$$Q_v = \left(\frac{k_1 \times e}{E_0} \times \alpha_1 \times \int_0^{z_1} \rho \times L(E)_1 \times dz_1\right) + \left(\frac{k_2 \times e}{E_0} \times \alpha_2 \times \int_0^{z_2} \rho \times L(E)_2 \times dz_2\right), [C] \tag{6}$$

Approximating the constancy of LET value, ($L(E)_1 = L(E)_2 = \frac{dE}{dl} = const$), which is valid when detecting SR by thin detectors, (6) is converted to (7)

$$Q_v = \left(\left(\frac{k_1 \times e \times \rho \times L(E)_1 \times \alpha_1}{E_0}\right) \times z_1\right) + \left(\left(\frac{k_2 \times e \times \rho \times L(E)_2 \times \alpha_2}{E_0}\right) \times z_2\right), [C] \tag{7}$$

The expression (7) shows that the total charge Q_v, resulting from a double-layer diamond detector is proportional to the total thickness of detector diamond plates $z_1 + z_2$.

To validate the efficiency of double layer DD experimentally the simulator consisting of plates dimensioned to 2x2x0.35 mm (plate 1) and 2.5x2.5x0.18mm (Plate 2) has been developed. Each plate side includes Ti/Al contact layers of 50/100 nm in thickness deposited by magnetron sputtering in Ar medium at 10 mTorr pressure. A gold conductor calibrated to 40 microns outputs electrical contact (pin 1, pin 2, and pin 3) from the each plate contact layer. We use the ultrasonic unit for welding process. In addition, we use silver paste for increasing the displacement volume by fastening the flats of the plates to each other. The epoxy lacquer closes the plate edges.

Experimental investigation of double-layer DD simulator has been carried out using a measure test bench, comprising the shielding shell, where the double-layer DD simulator, β radiation source, spectrometric preamplifier are installed. The spectrometric preamplifier output signal arrives at 1024 channel spectrometer input. One has applied the bias voltage to the DD equal to 100V.

The measurements have been conducted for three configurations of picking-up signal from diamond plates. Configuration 2_1 - bias voltage is applied to pin 2, pin 1 is connected to the charge sensitive amplifier input (the upper plate operates in a double-layer DD). Configuration 2_3 - bias voltage is applied to pin 2, pin 3 is connected to the charge sensitive amplifier input (the lower plate operates in a double-layer DD). Configuration 2_1,3 - bias voltage is applied to pin 2, both pin 1 and pin 3 are connected in parallel to the charge sensitive amplifier input (two plates operate in a double-layer DD). Such embodiment represents the detector output signal as the sum of upper and lower plate signals, namely, realizing the multilayer DD configuration.

The graphs in Figure 2 show the multi-layer DD output charge spectra during detecting β-particles for various signal pickup configurations.

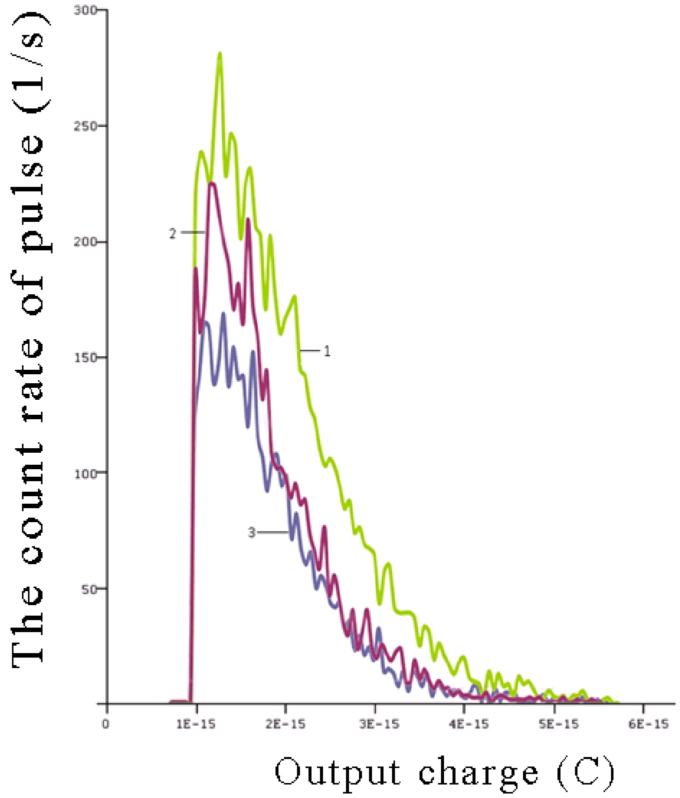

Fig. 2. The multilayer DD output charge spectrum. 1 – signal pickup configuration 2_1.3; 2 – signal pickup configuration2_3 и 3 – signal pickup configuration 2_1.

The graphs in Figure 2 show where two diamond plates operate in parallel (signal pickup configuration 2_1.3), the double layer DD output charge spectrum shifts to the right. The case indicates an increase in the output charge amplitude of multi-layer DD, when compared with one diamond plate DD (signal pickup configuration 2_1 and 2_3)

In order to analyze the amplitude values of output charge signal of multi-layer DD, one needs to compare the output charge values of multi-layer DD in three configurations at a β-particles fixed counting rate. We explain such approach to the output charge analysis of multilayer DD in various configurations, because the β-particle energy spectrum in the first approximation represents the exponential dependence of particle fluence rate on particle energy. With this in mind, the particle-counting rate of DD decreases as far as the particle energy and the DD output charge signal increase, correspondingly. Equation (7) shows that the output charge signal of multi-layer DD is proportional to the particle LET, which further depends on the particle energy. Naturally, there is a need to analyze the response of multi-layer DD to a narrow energy range particles in view of comparing the efficiency of different multilayer DD configurations. Since the particle-counting rate relates uniquely to the particle energy, then analyzing the multi-layer DD responses within the given range of β-particles counting rate we, thereby, will analyze the DD multilayer output charge for particles of the same energy. Such approach provides for a correctness of quantitative analysis of amplitude values of DD multilayer output charge signal.

Let us suppose that β-particle count rate is equal to 100 pulses per second for analyzing the output charge signal of multi-layer DD of different configurations. This count rate corresponds to the average β-particle energy.

According to the graphs we obtain the following values of multi-layer DD output charge signal in three signal pickup configurations: configuration 2_1 - Q_{v1} = 1,90 · 10^{-15} C; configuration 2_3 Q_{v1} = 1,95 · 10^{-15} C: configuration 2_1,3 Q_{v1} = 2,51 · 10^{-15} C. Like so, the amplitude of double layer DD output charge signal as compared to the amplitude of single layer DD output charge signal increases 1.3 times. This is slightly less than the estimated amplitude value of output charge signal by reference to the formula (7). Many may explain the discrepancy between the analytical and experimental calculation results because the experiment involves β-rays with β-particle energies no more than 2.5 MeV. With a view to such energies and with a view to diamond plates used in testing, the assumption of LET constancy in the process of particle passing through the detector volume may be flexible enough.

By means of GEANT 4 program, we have performed the simulation of β-particle passing through a double-layer DD structure for calculating more accurately the theoretical value of energy dissipated by β-particle when passing through the multilayer diamond detector, taking into account the nonlinear dependence of particle LET on the detector thickness. We have obtained the spectra of multilayered DD output charge signal shown in Figure 3 as well.

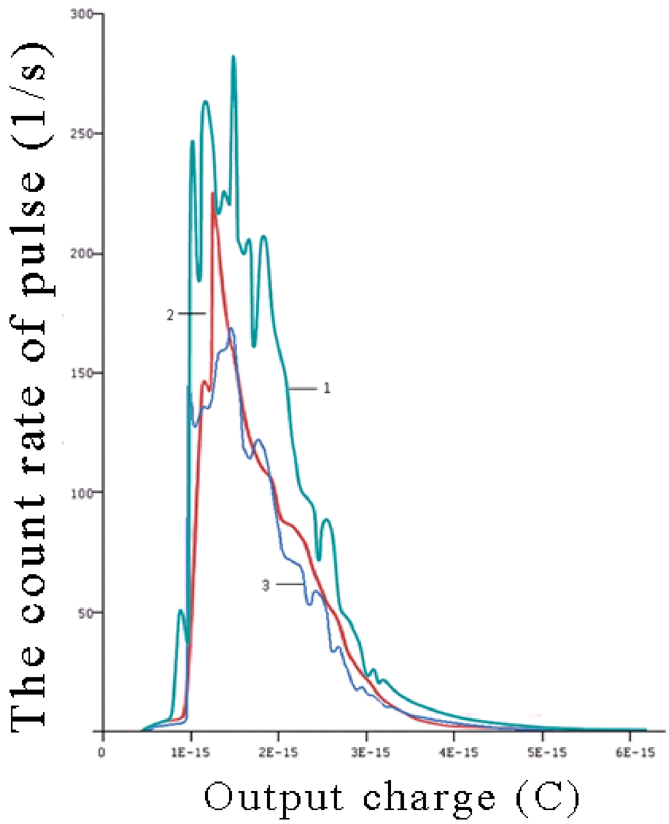

Fig. 3. Simulated output charge spectrum of multilayer DD. 1 – signal pickup configuration 2_1,3; 2 – signal pickup configuration 2_3 и 3 – signal pickup configuration 2_1.

Table 1 summarizes the experimental values of DD output charge signal and the values of output charge signal obtained by GEANT 4 program simulation.

TABLE 1.

Signal Pickup Configuration	**DD Output Signal Experimental Value × 10^{15} (C)**	**DD Output Signal Value × 10^{15}, obtained by GEANT 4 Program Simulation (C)**
1_2 signal picked up from upper plate	1,90±0,06	1,92±0,06
2_3 signal picked up from the lower plate	1,95±0,06	1,91±0,06
2_1,3 signal picked up from both plates	2,51±0,09	2,36±0,08

III. CONLUSIONS

As Table 1 shows, the results of double-layer DD mathematic simulation and the experimental data coincide within statistical error limits. Analysis shows that the amplitude of DD output charge signal of test model, when picking up signal from two diamond layers, is 1.25 times greater than when picking up signal from one layer. Therefore, the use of double-layer structure makes it possible to expand the dynamic range of cosmic radiation particles LET measurements, by at least 25%.

Note that one may extend the results of DD double-layer structure performance analysis to the DD structure with a larger number of layers. We admit the effective use of 3-5 layer detectors for monitoring high-energy ionizing radiation.

So, the review has shown the multi-layer diamond sensing structures to be promising particle detectors for applications in the field of high-energy cosmic radiation monitoring.

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