Investigation of the diamond based detectors characteristics with different thickness of the sensor element

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Abstract. This work is devoted to study of the diamond based radiation detectors. Experiments were carried out with two types of detectors: based on a thin diamond film and on a composite diamond plate. The following types of ionizing radiation has been used in experiments: beta radiation of $^{90}$Sr - $^{90}$Y, fission fragments and alpha particles of $^{252}$Cf, and Kr ions obtained at the particle accelerator. It is shown that the developed thin-film diamond based detector effectively registers heavy charged particles, whereas beta, neutron and gamma radiation does not give a significant contribution to the detector signals. Those type of detectors are proposed for measurement of heavy charged particles linear energy transfer in diamond. The multilayer diamond based detector (detector with a composite diamond plate) showed improved charge collection efficiency values in compare with the detection with a single diamond plate.

1. Introduction

The motivation of the work is the need in detectors of ionizing particles with high radiation hardness for long-term space missions. The space ship equipment degradation caused by ionising radiation is known to be the cause of catastrophic failures of onboard spacecraft equipment, and therefore, constant monitoring of the ionizing radiation fluxes passing through the space ship has great importance. Diamond has been chosen as a detector material because of its unique radiation hardness and compactness [1, 2, 3].

The work principle of diamond detector very similar with one of solid state ionization chamber. The thickness of the sensitive layer of the diamond plate is typically less than 0.3 mm. This value of the thickness is determined by the lifetime of charge carriers - electrons and holes. The bias voltage of about 100 V is applied to the electrode on the opposite sides of the diamond plate. When ionizing particle enters the detector, electrons and holes are generated in its entirety. They move to the electrode surface and form the output signal of detector with charge $Q$. The number of electron-hole pairs proportional to the energy $W$ that ionizing particle loses in diamond. Some of the electrons and holes are captured by traps, so the charge collection efficiency CCE (charge collection efficiency) detector is always less than 100% or 1. The captured charge carriers form a polarization field, which further reduces the charge collection efficiency.
and can even make the detector permanently unusable [4]. In this work were made the study of two types of detectors: based on a thin diamond film, and on composite diamond plate (multilayer detector).

2. Thin-film diamond based detector

In theory, radiation detector based on thin diamond film should be insensitive to the penetrating ionizing radiation (neutron, gamma or beta radiation). Accordingly to this, the purpose of this detectors type can be spectrometry and radiometry of heavy ions and short range charged particles. Heavy ions are characterized by their initial energy E and linear energy transfer L. The output signal of the detector is determined by linear energy transfer that changes while the particle passes the active layer. It’s why the energy W deposited in the diamond is not proportional to the initial linear energy transfer of the particle. So the determination of the linear energy transfer becomes a quite hard problem.

To solve this problem the detector with a thin-film active layer has been developed. The active layer has been deposited using CVD technique on the surface of a standard diamond plate. In the beginning of the layer deposition a conductive graphite layer has been formed. Diamond film 10 micron in the thickness has been grown. Metal electrode has been applied on the top surface of the film. The bottom electrode was in contact with the graphite layer. The bias less than 15 V has been applied to the electrodes. Small thickness of the film should provide low energy losses of the ionizing particles and hence the constancy of the linear energy transfer.

Figure 1 shows the key elements of the thin film detector based on the diamond.

![Figure 1](image)

**Figure 1.** Manufacturing technology of thin-film diamond detector for the measurement of linear energy transfer.

To check the proportionality between the output of the detector and linear energy transfer of the ionizing particles the calibration of the detector has been carried out. The output of thin-film detector under action of different ionizing particles has been investigated. The following ionizing radiation has been used: beta-radiation of $^{90}$Sr - $^{90}$Y source, alpha-particles and fission fragments of $^{252}$Cf isotope source and Kr ions obtained in accelerator. The output of the detector...
has been observed using a conventional registering setup. The energy transferred to the diamond by ionizing particles has been calculated using Geant4 simulation.

Figure 2 shows the spectrum obtained by this detector with different radiation sources. The amplitude of the detector output is shown at the horizontal axis and the quantity of the particles detected is at vertical axis.

![Figure 2. Spectrum obtained by thin film diamond detector with next radiation sources: beta-radiation \(^{90}\)Sr - \(^{90}\)Y source, alpha-particles and fission fragments \(^{252}\)Cf isotope source.](image)

Beta radiation of \(^{90}\)Sr - \(^{90}\)Y, source, as well as the gamma and neutron radiation by fission of \(^{252}\)Cf source, did not form noticeable output detector signal. The narrow peak of alpha radiation and a strongly broadened peak of fission fragments of \(^{252}\)Cf isotope are observed. The distance between the \(^{252}\)Cf source and the detector was 1 mm. As the distance has been increased to 10 mm the peak of alpha particles had moved to the lower amplitudes whereas the peak of the fission fragments had disappeared because their free path in air is less than 1 mm.

Figure 3 shows the spectrum of a krypton ion beam accelerator produced by detector. The ion energy was 255 MeV, the average flow on the surface of the detector was 100 ions per second. Green spectrum was obtained for the first 60 seconds of exposure, the shadow spectrum was recorded 15 minutes after irradiation.

As we can see, peak has not shifted so the amplitude of detector output is quite stable. The difference in the number of ions detected is caused by instability of the beam. The detector count rate is close to the ion flow on the surface, which suggests the possibility of using the detector as a sensor of heavy ions with different energies. However, processing of the experimental data showed that the detector signal, that was expressed in the energy transmitted in diamond by
charged particles, was significantly lower than the value of the signal modeled using Geant4. The dependence of the detector output signal from the linear energy transfer values is nonlinear. So the energy equivalent of the output signal under action of $^{252}$Cf fission fragments was about twice lower than the deposited energy whereas the output under krypton irradiation appeared to be only 7 per cent of the value expected. (look in the Table 1).

**Table 1.** The difference between the experimental and theoretical values of the energy lost by the charged particles in the detector.

| Heavy particle         | $W_{\text{theor}}, \text{MeV}$ | $W_{\text{exp}}, \text{MeV}$ | $W_{\text{exp}}/W_{\text{theor}}$ |
|------------------------|---------------------------------|-------------------------------|-----------------------------------|
| $\alpha$               | 5.8                             | 5.50                          | 0.93                              |
| $^{252}$Cf fission      | from 25                         | from 10                       | 0.4                               |
| fragments              | to 105                          | to 40                         |                                   |
| $Kr^+$                 | 250                             | 183                           | 0.07                              |

We assume the polarization to be responsible for low amplitude of the detector output. The previous investigations of diamond polarization have shown that the polarization becomes noticeable when ionizing particles have transferred to the diamond about 180 GeV. Under action of alpha radiation the time needed for the polarization rising is about 1700 s. For high-energy krypton ions this time is only 7 seconds. So we can conclude that in the case of krypton irradiation the detector has operated under conditions of strong polarization. This explains...
unexpected low output of the detector. To improve the detector output further investigations of diamond polarization especially under action of high-energy ions are necessary.

In spite of polarization we can see that the output of the detector increases monotonically with linear energy transfer of the particle detected. The irradiation of different particles with close values of linear energy transfer leads to close amplitudes of detector output. So we conclude that the detector developed is perspective for measuring of linear energy transfer of heavy ions.

3. Detector based on a composite diamond plate (multilayer detector)

The diamond based detector with increased sensitivity volume was made. The detector consists of two CVD IIa type diamond plates. Size of the first plate is 2x2x0.35 mm and size of the second plate is 2.5x2.5x0.18mm. The wide verges of plates is coated with metal contact layer. The plates are arranged one above the other, so that the stream of ionizing particles passed through the both diamond plates. Thus the sensitive volume of the detector has increased. The contact layers of each plate is connected to the electronic circuit reception. In sum, the detector has three electrical contacts. First and third one is on opposite detector verges, and second one is on the electric contact between diamond plates. If contacts 1 and 3 are connected to a bias voltage source, and contact 2 is connected to the input of the amplifier, the charge generated in the upper and lower plate and added together. Thus, it is possible to increase the effective thickness of the detector, respectively, to increase the detection efficiency of the detector.

Experimental studies of the detector were conducted on a special measuring stand, using a source of β radiation, a metal low-noise housing, charge sensitive amplifier and signal amplitude analyzer based on the SBS-77 processor. Value of the bias voltage is equal to 100V.

The wiring diagram of the detector bias voltage source and the amplifier is shown on figure 4. Also in this figure can be seen the detector parts, which are active in the ionizing radiation registration process for each connection.

![Figure 4. The wiring diagram of the detector bias voltage source and the amplifier.](image)

In this experiment the diamond based detector has been irradiated by the beta-particle from $^{90}\text{Sr} - ^{90}\text{Y}$ source. The spectra of beta radiation were recruited for three different wiring diagrams of the detector (see. figure 4). Each spectrum was 300 seconds long. The data obtained is plotted as dependence of the number of pulses from the amount of charge that is fed to the detector. This dependence is shown on the figure 5.

We can see noticeable increase of the count rate of the signal with the same amplitude in the multilayer detector mode. This result is quite expected. At the same time there is a noticeable lack of real-spectrum of the $^{90}\text{Sr} - ^{90}\text{Y}$ beta-source, because its maximum energy value of the beta particles is about 2.5 MeV, and the total thickness of the multilayer detector is about 500 microns. Beta particles of $^{90}\text{Sr} - ^{90}\text{Y}$ could completely lose their energies in diamond, if its...
Figure 5. Dependence of the number of pulses from the amount of charge that is fed to the detector.

A thickness value is not less than 3300 microns. For an average thickness of the one diamond plate, that had been used in this experiment, it is necessary to use about ten diamond single crystals, similar to those used in this study.

4. Conclusion

The efficiency of the developed thin-film diamond detector tested using isotope sources and heavy ion accelerator. The detector can measure flow of heavy ions and it is insensitive to radiation with a low linear energy transfer (beta, gamma and neutron radiation). Nonlinear dependence of the detector output signal from the linear energy transfer values has been noticed. The probable cause of non-linearity is the polarization of the diamond sensor element under the action of high-energy ions. In further studies should be optimized depolarization process for the preparation of detectors for use in real devices.

Also the practical test of the possibility of creating a multi-layer diamond based detector were made in this work. The detector based on a composite diamond plate, showed an increase in detection efficiency of beta radiation from $^{90}$Sr - $^{90}$Y source by about 25% in compare to single diamond layer detector. These results show the fundamental possibility of creating multi-layered radiation detection patterns based on the diamond. Further it is planned to carry out an experiments on the registration of low energy gamma-ray with a multi-layer diamond based detector, as well as study the possibility of creating a beta-spectrometer with the multi-layer diamond based detector.

References

[1] E Berdermann et al. 2010 Diam. Relat. Mater. 19 358
[2] Davydov L et al. 2012 Proc. of the SPIE 8507 85071N
[3] Conte G et al. 2015 Nucl. Inst. and Meth. A 799 10
[4] Tyurin E et al. 2016 JPCS 675(3) 0320010