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The RD42 Collaboration

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Abstract. Diamond is used as detector material in high energy physics experiments due to its inherent radiation tolerance. The RD42 collaboration has measured the radiation tolerance of chemical vapour deposition (CVD) diamond against proton, pion, and neutron irradiation. Results of this study are summarized in this article. The radiation tolerance of diamond detectors can be further enhanced by using a 3D electrode geometry. We present preliminary results of a poly-crystalline CVD (pCVD) diamond detector with a 3D electrode geometry after irradiation and compare to planar devices of roughly the same thickness.

1. Introduction

As high energy experiments are upgraded to operate at higher energies and larger intensities, the innermost detector layers will be exposed to new extremes of particle fluence. As a result, there is a flurry of research to search for detector materials and geometries that can withstand the expected extreme conditions. Diamond is a promising candidate as detector material due to its large displacement energy [1]. Over the last two decades, chemical vapour deposition (CVD) diamond has been developed and characterized as detector material by the RD42 collaboration [2, 3]. Moreover, CVD diamond has been used as part of the abort system and/or luminosity system by a number of experiments [4–7].

The RD42 collaboration has measured the radiation tolerance of CVD diamond against protons, pions, and neutrons of various energies [8, 9]. These results are summarized in section 2. To enhance the radiation tolerance of diamond detectors further, the RD42 collaboration has investigated detectors with a 3D electrode geometry [10, 11]. In section 3, we present preliminary results of a 3D device after 800 MeV proton irradiation.

2. Radiation tolerance

The RD42 collaboration irradiated a series of single-crystalline CVD (scCVD) and poly-crystalline CVD (pCVD) diamond samples with protons, pions, and neutrons to characterize the radiation tolerance of CVD diamond [8, 9]. After each irradiation the samples were metallized to fabricate strip detectors with a 50 µm pitch. The detectors were tested before and after irradiation in a 120 GeV/c hadron beam. A first order model was used to describe the decrease of mean drift distance, λ, with fluence in diamond. The first order damage model is given by [12]

$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi \tag{1}$$

Table 1. Relative damage constants for 24 GeV protons, 800 MeV protons, 70 MeV protons, 200 MeV pions, and fast reactor neutrons [8, 9].

Particle species	κ
24 GeV protons	1.0
800 MeV protons	1.67 ± 0.09
70 MeV protons	2.60 ± 0.29
200 MeV pions	3.2 ± 0.8
Fast neutrons	4.3 ± 0.4

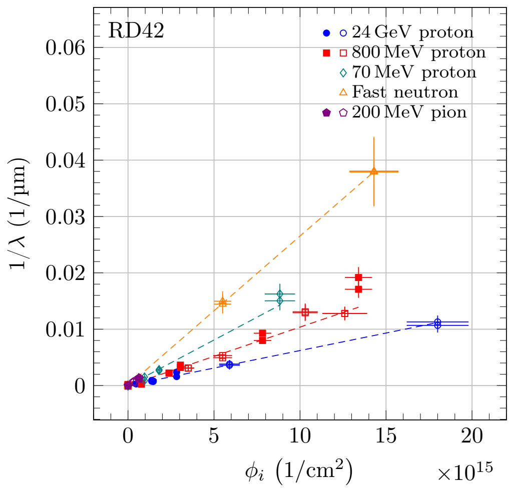

Figure 1. The $1/\lambda$ for scCVD (solid markers) and pCVD (open markers) diamond as a function of particle fluence [9]. Data points of sample j are shifted by $1/\lambda_{0,j}$ to account for the initial collection distance of the sample.

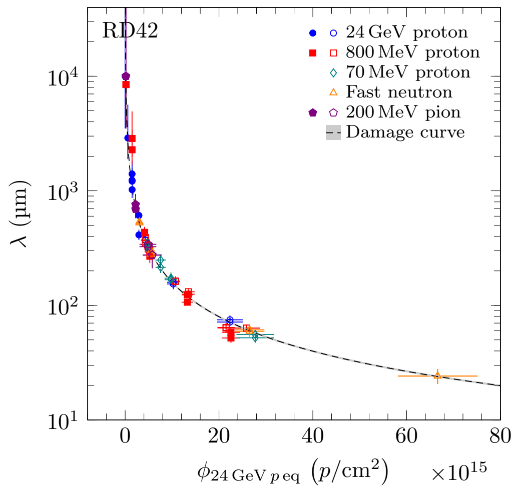

Figure 2. The λ for scCVD (solid markers) and pCVD (open markers) diamond as a function of 24 GeV proton equivalent fluence [9]. Data points of sample j are shifted by the offset, $\phi_{0,j}$, of sample j in 24 GeV proton equivalent fluence space.

where k is the radiation damage constant, λ_0 represents the initial mean drift distance before irradiation, and ϕ the particle fluence. Figure 1 shows the $1/\lambda$ damage curves for 24 GeV proton, 800 MeV proton, 70 MeV proton, 200 MeV pion, and fast reactor neutrons. The measured relative damage constants are listed in table 1. The one-parameter description of the data lends itself to a universal damage curve. To combine the data, the fluences were normalized by [9]

$$\phi_{24\,\mathrm{GeV}\,p\,\mathrm{eq}} = \kappa_i \times \phi_i \tag{2}$$

where $\kappa_i = k_i/k_{24\,\mathrm{GeV}p}$ is the relative damage constant of irradiation species i. Figure 2 shows the resulting universal damage curve. At a fluence of $10^{17}/\mathrm{cm}^2$ a mean drift distance of $\lambda \approx 16\,\mu\mathrm{m}$ is predicted.

3. 3D detectors

The mean drift distance of electrons and holes in an infinite material decreases as a function of particle fluence [12]. After a fluence of $10^{17}/\mathrm{cm}^2$ all detector materials will be trap limited and diamond has a predicted mean drift path approximately $20\,\mu\mathrm{m}$ in the present $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$

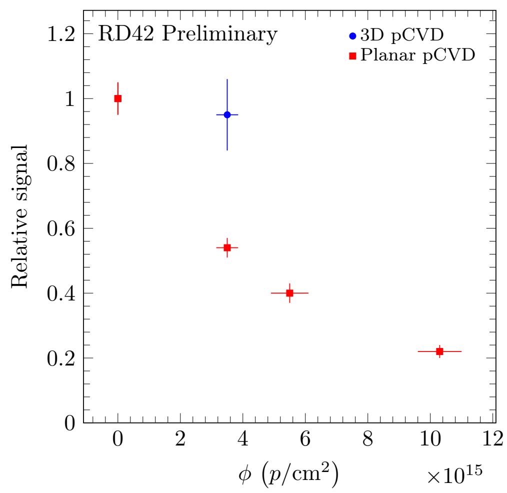

Figure 3. Relative signal response of 3D (blue) and planar (red) pCVD diamond detectors as a function of 800 MeV proton fluence. The signal response is normalized to the signal response of the unirradiated detectors.

cells. In a detector device with a 3D electrode geometry, the electrodes are located in the bulk material [13]. This electrode geometry reduces the necessary drift path of an electron-hole pair created by a minimum ionizing particle (MIP) to create the same signal compared to an equally thick planar detector but with roughly 1/20th the drift distance to the readout electrode. The RD42 collaboration has successfully demonstrated the feasibility of the 3D diamond detector concept in 2015 [10, 11]. In this work we present the preliminary results of a 3D detector based on pCVD diamond irradiated with 800 MeV protons.

A femtosecond laser was used to fabricate the column electrodes in the diamond bulk [14]. The columns were drilled in a pattern to form 50 µm × 50 µm cells. A cell consists of four bias columns and one readout column in the centre. The bias columns were connected to the metallization on the bottom and the readout columns to the metallization on the top.

The 3D detector was tested in a 120 GeV/c hadron beam and compared to planar devices of the same thickness from section 2. The measured signal was normalized to the signal before irradiation for the 3D and the planar device, respectively. In figure 3 the relative signal response of a 3D and planar device as a function of 800 MeV proton fluence is shown. We note that an unirradiated 3D device in diamond has roughly twice the signal size of an equally thick planar device and this factor has been removed in the present comparison. After a fluence of $3.5 \times 10^{15}\ p/\mathrm{cm}^2$ a reduction in signal of $(45 \pm 5)\,\%$ was observed for the planar detector, while the signal of the 3D detector was reduced by $(5 \pm 10)\,\%$. In addition to the smaller reduction of signal the extra observed unirradiated charge can also be viewed as additional radiation tolerance for the 3D devices compared to planar devices.

4. Summary and future plans

The mean drift path of diamond after a fluence of $10^{17}/\mathrm{cm}^2$ was estimated and is roughly comparable with the drift distance in a 25 µm × 25 µm 3D cell. Preliminary results of a 3D diamond detector after irradiation were presented. The results are very promising in comparison to planar devices. Further measurements with larger fluences in both 50 µm × 50 µm 3D cells and 25 µm × 25 µm 3D cells are planned to derive the appropriate damage curves necessary for more precise predictions.

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