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Latest Results on the Radiation Tolerance of Diamond Detectors

The RD42 Collaboration

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We have measured the radiation tolerance of chemical vapor deposition (CVD) diamond against protons and neutrons. The relative radiation damage constant of 24 GeV protons, 800 MeV protons, 70 MeV protons, and fast reactor neutrons is presented. The results are used to combine the measured data into a universal damage curve for diamond material.

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1. Introduction

Radiation tolerant sensors are essential in many modern high energy physics applications. Diamond is an interesting candidate for a radiation tolerant detector material due to its large displacement energy [1]. The RD42 collaboration has developed and studied chemical vapor deposition (CVD) diamond as a detector material for a number of years [2, 3].

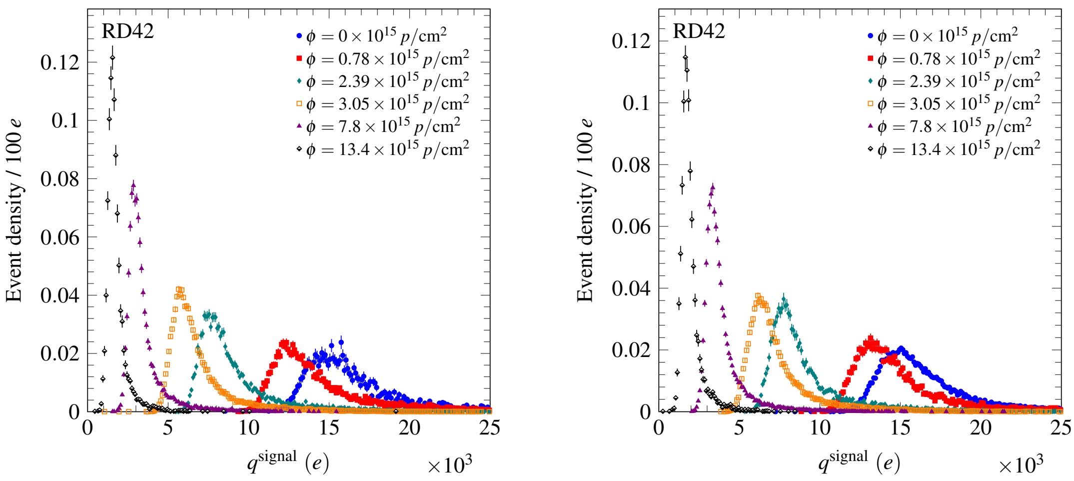
For experiments at future accelerators, such as the High Luminosity LHC (HL-LHC), the innermost tracking layers must be able to tolerate a particle fluence of $>10^{16}$ particles/cm^2 [4]. The RD42 collaboration has quantified the radiation tolerance of CVD diamond against 800 MeV and 24 GeV protons [5]. The same analysis method was used to measure the radiation tolerance of CVD diamond against 70 MeV protons and fast reactor neutrons. The derived radiation damage coefficients were compared to the 800 MeV and 24 GeV proton data. Preliminary results of this analysis are presented in this article.

2. Radiation Tolerance

To characterize the radiation tolerance of CVD diamond, the RD42 collaboration irradiated a series of diamond samples in steps with protons and neutrons. Both, single-crystalline CVD (scCVD) diamond and poly-crystalline CVD (pCVD) diamond devices were tested. The devices were characterized in beam tests to measure the effect of the irradiation on the signal response to 120 GeV/c charged particles (roughly minimum ionizing).

Three samples were irradiated with 24 GeV protons at the IRRAD proton facility at CERN [6]. Four samples were exposed to 800 MeV protons at the Los Alamos Neutron Science Center (LANSCE) [7]. The results obtained with these samples have been published in Ref. [5]. For this work, we extended this study with two pCVD diamond samples irradiated at the Cyclotron and Radioisotope Center of Tohoku University (CYRIC) [8] with 70 MeV protons up to a particle fluence of 8.8×10^{15} p/cm^2 and two pCVD diamond samples irradiated with fast reactor neutrons ($>$100 keV) up to a total dose of 1.3×10^{16} n/cm^2 at the TRIGA reactor of the Jožef Stefan Institute (JSI) [9].

Before and after each irradiation step a 50 µm pitch strip detector was fabricated on each diamond. The strip pattern was metallized on the front side of the diamond and each strip was wire bonded to an individual VA2.2 readout channel [10]. On the back side a single metal pad electrode was metallized. Typically, the detectors were operated at an electric bias field of 1 V/µm and 2 V/µm. The strip detectors were tested in a secondary beam line of the Super Proton Synchrotron (SPS) at CERN to measure the signal response to 120 GeV/c hadrons. A beam telescope [11] was used to provide tracking information with a precision at the device under test (DUT) of roughly 2 µm [12] and measure the signal response of the DUT as a function of predicted track position. The signal response was constructed from the five highest adjacent strips within ten strips around the predicted track position. In Figure 1 the signal response distribution of an scCVD diamond sensor is shown before and after various 800 MeV proton irradiations. At all stages, the signal response is Landau-distributed convoluted with a Gaussian due to noise components. A detailed description of this analysis may be found in Ref. [5, 12, 13].



(a) (b)

Figure 1: Pulse height distribution before and after various 800 MeV proton fluences at an electric bias field of −2 V/µm (a) and +2 V/µm (b) [5].

On average a minimum ionizing particle (MIP) creates 36 electron-hole pairs per micron of path length traversed [14]. We use the term "charge collection distance", *ccd*, defined by

$$ccd = \frac{\overline{q^{\text{signal}}}}{36\,e/\mu\text{m}}, \tag{2.1}$$

to express the average signal response $\overline{q^{\text{signal}}}$. The charge collection distance is related to λ_i, the mean drift distance of electrons and holes in an infinite material, by [15]

$$\frac{ccd}{t} = \sum_{i=e,h} \frac{\lambda_i}{t} \left[1 - \frac{\lambda_i}{t}\left(1 - \mathrm{e}^{-\frac{t}{\lambda_i}}\right)\right] \tag{2.2}$$

where t is the thickness of the material. The mean drift distance is inversely proportional to the number of traps within the material, which increases linearly with particle fluence. Thus, the simplest damage model is given by [16]

$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi \tag{2.3}$$

where k is the radiation damage constant, λ_0 the initial mean drift distance before irradiation, and ϕ the particle fluence.

To derive the damage constant for each irradiation type, the damage model in Eq. (2.3) was fitted to the measured $1/\lambda$ data as a function of particle fluence. Since the results were observed in agreement between scCVD and pCVD diamond, a single damage constant can be quoted for CVD diamond material [5]. The final damage constants normalized to 24 GeV protons are listed in Table 1. The radiation damage constant decreases with rising proton energy. Fast reactor neutrons were observed to cause the most radiation damage.

Particle species	κ	
24 GeV protons	1.0	[5]
800 MeV protons	1.67 ± 0.09	[5]
70 MeV protons	2.48 ± 0.25	
Fast neutrons	4.5 ± 0.4	

Table 1: Relative damage constants for different particle species.

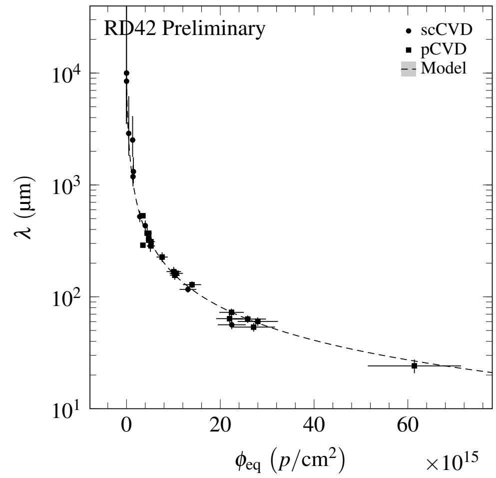


Figure 2: Mean drift distance as a function of 24 GeV proton equivalent fluence. The dashed line indicates a fit of the damage model to the data points.

3. Universal Damage Curve

A consequence of Eq. (2.3) adequately describing the data for different energies, different irradiation species, and different materials is that there should be a transform to combine the data into a universal damage curve. The transform we used is described below. The data points derived with pCVD diamond samples were observed to be offset with respect to the scCVD diamond samples due to the presence of inherent charge traps in poly-crystalline material [5]. Thus, the pCVD diamond data points were shifted by [13]

$$\phi_0 = \frac{1}{\lambda_0 k_j} \tag{3.1}$$

where k_j is the radiation damage constant of irradiation type j. Subsequently, the 24 GeV proton equivalent fluence was calculated by [13]

$$\phi_{\text{eq}} = \kappa_j \phi_j \tag{3.2}$$

where κ_j is the relative damage constant listed in Table 1 and ϕ_j the particle fluence of irradiation type j. Figure 2 shows the mean drift distance as a function of 24 GeV proton equivalent fluence of all tested devices. As expected, the corrected data points fall on a universal damage curve whose shape is determined by Eq. (2.3).

4. Summary

A series of CVD diamond samples were irradiated with protons and neutrons. After each irradiation, the irradiated material was characterized in a beam test. As a result, the radiation damage constant as a function of particle species and energy has been determined. The measured data has been combined in a preliminary universal damage curve for diamond material. The existence of a universal damage curve for diamond material allows predictions to be made for any potential application.

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