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Results on radiation tolerance of diamond detectors

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A B S T R A C T

In sight of the luminosity increase of the High Luminosity-LHC (HL-LHC), most experiments at the CERN Large Hadron Collider (LHC) are planning upgrades for their innermost layers in the next 5–10 years. These upgrades will require more radiation tolerant technologies than exist today. Usage of Chemical Vapor Deposition (CVD) diamond as detector material is one of the potentially interesting technologies for the upgrade. CVD diamond has been used extensively in the beam condition monitors of BaBar, Belle, CDF and all LHC experiments. Measurements of the radiation tolerance of the highest quality polycrystalline CVD material for a range of proton energies, pions and neutrons obtained with this material are presented. In addition, new results on the evolution of various semiconductor parameters as a function of the dose rate are described.

1. Introduction

Diamond has some unique characteristics suitable for detector applications in radiation harsh environments such as that of the future HL-LHC [1]. The large band-gap of 5.5 eV implies low intrinsic carrier density resulting in low leakage current and low noise but also roughly half of the signal collected with silicon devices. Other outstanding properties are the large displacement energy, which renders the lattice less prone to radiation damage, the low dielectric constant leading to lower capacitance for similar structure in other material, the high thermal conductivity and the high charge carrier mobilities, which allow fast signal collection. In addition, the low atomic number minimizes the particles scattering and absorption, which is desirable for detectors close to the interaction point. Hence, Chemical Vapor Deposition (CVD) diamond represents an interesting radiation tolerant technology, which may be exploited as sensor material that can be operated without cooling and the need of pn-junction. There are two types of CVD diamond material: single crystalline (scCVD) and polycrystalline (pCVD). scCVD is very pure, expensive and can only be grown on a single crystal seeds. pCVD diamond is cheaper and can be grown in large area wafers. However, it suffers from larger amount of intrinsic charge traps resulting in a smaller collected charge for a given thickness. For more than 20 years the RD42 Collaboration [2,3] has developed CVD diamond detectors and studied their radiation tolerance. The latest results of the collaboration are presented in this article.

2. Device preparation and irradiations

Diamond samples, with a typical thickness of around 500 μm, were cleaned with hot acid and etched with an oxygen plasma, then metallized with a single pad and tested with a source or in a beam test. Before being irradiated, they underwent "pumping" [4] with a ^{90}Sr source to fill the intrinsic diamond traps, then the leakage current was checked to be below 10 nA. One scCVD diamond sample and three pCVD diamond samples were irradiated with 800 MeV protons at the Los Alamos Neutron Science Center (LANSCE) [5] up to a fluence of $(13.4 \pm 0.8) \times 10^{15}$ p/cm^2. Two pCVD diamond samples were exposed to 70 MeV protons at the Cyclotron and Radioisotope Center of Tohoku University (CYRIC) [6] up to a fluence of $(8.8 \pm 0.9) \times 10^{15}$ p/cm^2, and two pCVD diamond samples were irradiated with fast reactor neutrons (>100 keV) at the Jožef Stefan Institute (JSI) TRIGA reactor [7] up to a fluence of $(13.0 \pm 1.3) \times 10^{15}$ n/cm^2. After each irradiation, diamonds were metallized with a 50 μm pitch strip pattern detector on the diamond growth side using a low temperature photolithographic lift-off process to prevent annealing. The substrate side was metallized with a single bias pad. Each of the 128, 25 μm wide, strips was wire-bonded to an individual channel of a low noise front-end, mostly the VA2.2 [8] readout ASIC. The devices were then tested with a 120 GeV/c hadron beam in the H6 secondary beam line of the CERN Super Proton Synchrotron (SPS) [9].

3. Results

For all measurements, the diamond samples were biased with two polarities at ±1 V/μm and ±2 V/μm [10,11]. The amplified signal was calibrated for the conversion from ADC to electrons and corrected for pedestal by subtraction and corrected for common mode noise. The common mode corrected noise was around 80e for each sample. The precise particle position in the diamond samples, approximately 2 μm, was determined with an high precision telescope made of 8 planes of silicon strip detectors plus a plastic scintillator serving as trigger. For each track the analysis looks in the diamond detector and calculates the cluster of the two largest adjacent strips within 10 strips of the projected track. In general the algorithm collects more than 97% of the signal [10].

3.1. Radiation damage

To estimate the damage induced by the radiation in diamond, a simple model is used. This model assumes that the number of radiation induced traps in diamond is linearly proportional to the fluence. This model can be expressed in terms of the mean free path (MFP), which is the average distance traveled by electrons or holes before being trapped, as:

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

where k is the radiation damage constant, which is extracted with a fit to data for each CVD diamond sample then averaged. The initial MFP, λ_0, accounts for the inherent defects present in the pCVD samples and it is measured before the irradiation with a ^{90}Sr source, whereas the MFP, λ, is derived from the average measured pulse heights [10,11]. To evaluate the MFP from the measured pulse height the ratio of electrons and holes MFP is required. The theoretical and experimental value of this ratio does not agree but range from 2/3 (experimental) to 3/2 (theoretical). Since we did not measure this quantity we have used the ratio of 1 and varied the ratio from 2/3 to 3/2 to assign a systemic error to the MFP. The radiation damage constant depends upon the energy and the species of the particles and it has been extracted for the 800 MeV proton irradiations, as shown in Fig. 1a. A similar procedure was used to extract the radiation damage constant for 70 MeV proton irradiations as well as for the fast neutron irradiations. The parallel slopes for pCVD and scCVD diamond samples of Fig. 1a indicate that both CVD species follow the same radiation damage mechanism. The MFP measurements can be compared to those previously measured with 24 GeV proton irradiations [12,13] by refitting that data with the above procedure [11,10]. To do that, the fluences are scaled with:

$$\phi_{eq} = \kappa(\phi_i + \phi_0) \quad \text{where } \kappa \text{ is defined as} \quad \kappa = \frac{k_i}{k_{24GeV\,p}} \tag{2}$$

is the relative radiation damage constant. The initial fluence, ϕ_0, accounts for the initial MFP, λ_0, of pCVD diamonds as:

$$\phi_0 = \frac{1}{\lambda_0 k} \tag{3}$$