

Recent Results on Diamond Radiation Tolerance

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ABSTRACT: Results are presented on two topics associated with prediction and measurement of the radiation hardness of diamond sensors in environments relevant to detector tracking systems at the HL-LHC. In the first suite of studies, diamond sensors are exposed to particle beams of a variety of energies and species. The damage incurred is compared to predictions by the Monte Carlo simulation package FLUKA incorporating the number of displacements per atom (DPA) according to the model by Norgert, Robinson, and Torrens. In the second study, the resistivity of polycrystalline chemical vapor deposition diamond sensors is inferred from measurements of the leakage current for a range of bias voltages on samples irradiated with 800 MeV protons up to 1.6×10^{16} p/cm². The devices' resistivity is extracted for temperatures in the -10°C to $+20^\circ\text{C}$ range and found to be independent of fluence and temperature over the ranges studied.

KEYWORDS: Diamond, LHC, Radiation, Particle tracking.

1. Overview of diamond and radiation damage issues for the LHC

Chemical vapor deposition (CVD) diamond holds promise as a radiation tolerant substrate for detecting particles close to an interaction point at the LHC. This promise derives from its large band gap (5.5 eV, to be compared to silicon's 1.1 eV) and minimum lattice displacement energy of 43 eV (to be compared to silicon's 25 eV). Positive consequences of these features include negligible leakage current (leading to low readout noise and relaxed demands for cooling); the opportunity to simplify or eliminate sensor guard rings (and thus lower capacitance); fast signal collection; and, given its 50% longer radiation length than silicon's, reduced material per radiation length. The principal challenge with this technology stems from the fact that the average energy needed to liberate an electron-hole pair is 13.1 eV (to be compared with silicon's 3.6 eV), leading to a smaller signal before irradiation.

The inner tracking detectors in the LHC Upgrade era must withstand fluences greater than 10^{16} 1-MeV n_{eq}/cm^2 . Damage to the detectors will be caused by a mixture of species, but below about 24 cm radius from the interaction region, the damage arises primarily from charged pions. The pion spectrum peaks at about 2 GeV with full width at half maximum from 300 MeV to 6 GeV. It is important to model the damage mechanism, to predict detector lifetime and operational conditions. The CERN PS beam (with 24 GeV protons) and Los Alamos LANSCE beam (with 800 MeV protons) bracket this energy and provide especially important benchmarks.

2. Investigation of the application of the FLUKA DPA model to diamond

The CERN RD42 collaboration is studying the ability of FLUKA DPA to describe damage in diamond for a range of beam types and energies. FLUKA [1] is a Monte Carlo simulation package that provides a general tool for calculations of particle transport and interactions in matter. An important addition to FLUKA, DPA, predicts [2] that diamond damage will vary by 20% across the range 800 MeV to 24 GeV. DPA, an abbreviation for "displacements per atom," is a measure of the amount of damage caused by all particles in a hadronic cascade. One DPA signifies that each atom of the material has been displaced from its site within the lattice an average of one time. DPA is calculated from the expression $DPA = \frac{1}{\rho} \sum_i N_i N_f^i$, where ρ is the density in atoms/cm³, N_i is the number of particles per interaction channel i , and N_f^i is the number of Frenkel pairs (compound defects combining an adjacent interstitial and vacancy). N_f^i is given by the expression $N_f^i = K \frac{\xi(T)T}{2E_{th}}$, where $K = 0.8$ is the displacement efficiency, and the difference from 1.0 reflects the forward scattering. T is the kinetic energy of the primary knock-on atom; $\xi(T)$ is the Lindhard partition function [3] that gives the fraction of stopping power that goes to non-ionizing energy loss (NIEL) [4]; and E_{th} is the damage threshold energy for the crystal, that is, the minimum energy needed to produce a defect, averaged over all crystallographic directions.

RD42 has undertaken a study of damage factors in single-crystal (sc) and polycrystalline (pc) diamond exposed to five beam conditions. The figure of merit used is the mean free path $\lambda_{e/h}$ of the charge carriers (electrons and holes). This is given by $\lambda_{e/h} = v_e \tau_e + v_h \tau_h$, where v is velocity and τ is lifetime. Damage in diamond typically follows a curve of the form [5]

$$\frac{1}{\lambda_{e/h}} = \frac{1}{\lambda_0} + k\Phi, \text{ where } \Phi \text{ is fluence and } k \text{ is the damage constant. The } \lambda_0 \text{ is the mean free path}$$

before irradiation, a number that reflects the presence of initial traps and hence the material purity. The goal of this study is to extract the damage constant k for each beam condition and compare it to the FLUKA DPA prediction. In this study, it is assumed that $v_e \tau_e = v_h \tau_h$. This simplification influences the result by a few percent. The value $\lambda_{e/h}$ is obtained by inverting

$$\frac{Q_{\text{collected}}}{Q_{\text{ionized}}} = \frac{\lambda_{e/h}}{d} \cdot \left[1 - \frac{\lambda_{e/h}}{d} \left(1 - e^{-\frac{d}{\lambda_{e/h}}} \right) \right], \text{ where } d \text{ is the sensor thickness and } Q_{\text{collected}} \text{ is measured}$$

in the CERN SPS pion test beam. The most probable value of Q_{ionized} is calculated as

$$Q_{MPV} = \xi \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} + \ln \frac{\xi}{I} + 0.2 - \beta^2 - \delta \right], \text{ where } \xi = \frac{KZx}{2A\beta^2} \text{ for a detector of thickness } x, \delta = 1.84 \text{ parameterizes the density effect on the energy loss, } I = 81 \text{ eV is the average ionization energy, and } K = 4\pi N_A r_e^2 m_e c^2.$$

The inverse of the mean free path is graphed versus fluence and fitted to a straight line for each of several diamonds in the same series. The slope gives damage constant k . The fluence offset measures the intrinsic trap density. Unirradiated single crystal diamond is assigned infinite k . The first step of this program to compare diamond sensor data to FLUKA DPA predictions involved irradiation of polycrystalline and single crystal diamond by 24 GeV protons at the CERN PS. A damage constant $k = (0.62 \pm 0.7) \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$ is obtained in this case for both pc and sc, indicating a common damage mechanism for both. This result serves as the normalization for the other beam conditions.

The mean free path has been measured for polycrystalline diamond exposed to 800 MeV protons in Los Alamos. The damage constant extracted is $k = (1.07 \pm 0.05) \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$. This is 1.7 times more damaging than the 24 GeV protons; FLUKA DPA predicts a factor of 1.3 for this case. The mean free path has been measured as well for polycrystalline diamond exposed to 70 MeV protons in CYRIC at Sendai. The damage constant extracted is $k = 1.7 \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$, 2.6 times more damaging than 24 GeV protons. An independent measurement in the 62 MeV proton beam at INFN LNS confirmed this k at $(1.8 \pm 0.3) \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$. The FLUKA DPA model predicts the increase to be a factor of 6. The mean free path in single crystal diamond exposed to 25 MeV protons at Karlsruhe indicates an extracted $k = 2.6 \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$, a number 4 time larger than that for the 24 GeV protons. In this case FLUKA DPA predicts a factor of 8. Lastly, polycrystalline and single crystal diamonds were exposed to 300 MeV pions at PSI, yielding a measured $k = 1.8 \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$, 2.9 times more damaging than 24 GeV protons. The FLUKA DPA prediction for this case is a factor 2.2 increase. There seems to be reasonable agreement between the measurements and predictions in the range 0.07 to 24 GeV. This work is still in progress.

3. Measurement of the relationship between diamond resistivity and proton fluence and temperature

Changes in the resistivity of a diamond substrate propagate to the leakage current. Leakage current is used to infer many properties of a sensor, including its active volume and the charge collection distance. The resistivity of two polycrystalline diamonds was measured before and after exposure to 800 MeV protons at five fluences in the range zero to $1.6 \times 10^{16}/\text{cm}^2$. The resistivity ρ is calculated as $\rho = AR/d$, where d is sensor thickness, nominally 440 microns and measured to 2% precision; A is sensor area, measured optically to 0.2% precision, and R is the inverse slope of a linear fit to a graph of leakage current $I_{leakage}$ to bias voltage V_{bias} . Two measurement setups are used to assess the systematics. In one, ground is applied to the detector's back side, high voltage to the front, and the bulk $I_{leakage}$ is acquired by a Keithley 237 source measure unit. The advantage of this setup is its simplicity: a single instrument measures the sourced current. In the other, ground is applied to the detector's back side, high voltage to the front, and the bulk $I_{leakage}$ is acquired by a Keithley 617 electrometer. The advantage to this setup is that the measurement is made on the returned current, so sourced current that does not cross the bulk is excluded. The diamonds were obtained by Element Six[6]. Figure 1 demonstrates the stability of their operation. Equilibration takes about 30 minutes. Data are acquired beginning 1 hour after installation and continuing for four hours. The sensor represented in Figure 1 was characterized at 20 °C after it had received 1.63×10^{16} p/cm². The slope of the line fitted in the range from 1 to 4 hours is $(-2.29 \pm 1.65) \times 10^{-16}$ A/hr.

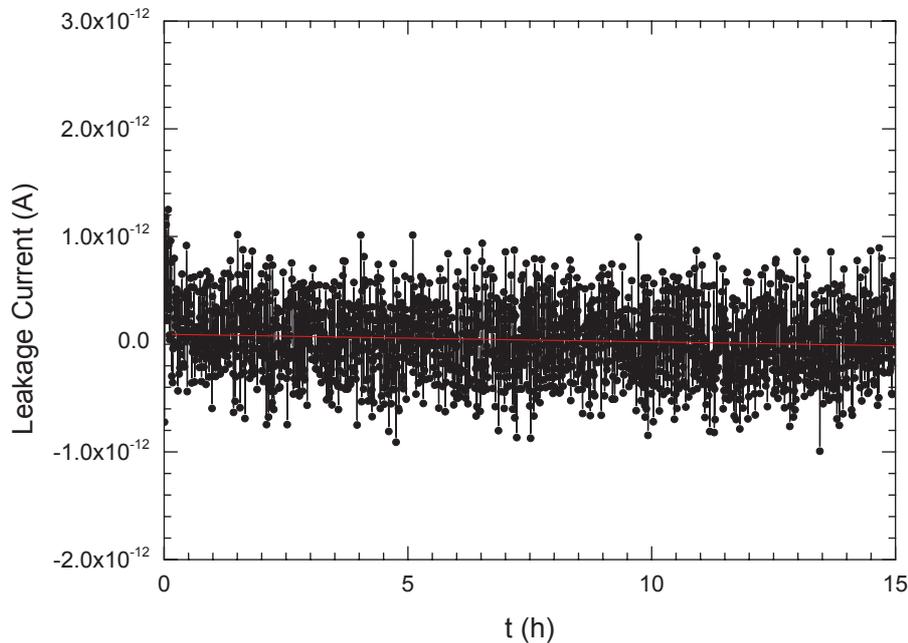


Figure 1. The current versus time characteristic of a diamond in a typical resistivity measurement. These data were taken at 20 °C on a device that had received 1.63×10^{16} p/cm².

Measurements are made at $-10\text{ }^{\circ}\text{C}$, $0\text{ }^{\circ}\text{C}$, $+10\text{ }^{\circ}\text{C}$, and $+20\text{ }^{\circ}\text{C}$ with thermal control through the probe station chuck. Dry N_2 is applied to prevent condensation. The relative humidity is $<5\%$ for all measurements below room temperature, and $<35\%$ for room temperature measurements. The bias is ramped from -500 V to $+500\text{ V}$ and confirmed in both directions. Data taken with positive and negative bias are fitted separately for the range $200 - 500\text{ V}$. The fits are consistent. The slope R is their average. The measurement uncertainties include (1) a statistical error of $[3 - 9] \times 10^{-13}\text{ A}$ on the current, representing the average of 3-5 measurements under identical conditions; (2) a temperature uncertainty $< 0.1\text{ }^{\circ}\text{C}$ per individual measurement; (3) the manufacturer's specifications of $\pm(0.04\% + 240\text{ mV})$ for the Keithley 237 and $\pm(0.3\% + 100\text{ fA})$ for the Keithley 617; (4) uncertainty on the measured dimensions of 2% on thickness and 0.2% on length and width; (5) $10\% - 30\%$ uncertainty on fluences; and (6) 40% uncertainty due to the setup configuration. This last is due to the different intrinsic accuracies of the Keithley 617 (1.6%) and the Keithley 237 (0.3%).

Figure 2 shows the measured resistivity versus temperature, for all fluences and both diamonds. A logarithmic scale is used to capture the full spread of data values. A free linear fit produces an intercept at $(8.37 \pm 0.55) \times 10^{15}\text{ }\Omega\text{-cm}$, with slope $(-0.63 \pm 4.13) \times 10^{13}\text{ }\Omega\text{-cm}/^{\circ}\text{C}$ and $\chi^2/\text{dof} = 0.62$. We conclude that there is no significant dependence of diamond resistivity upon temperature over the range approximately $-10\text{ }^{\circ}\text{C}$ to $+20\text{ }^{\circ}\text{C}$.

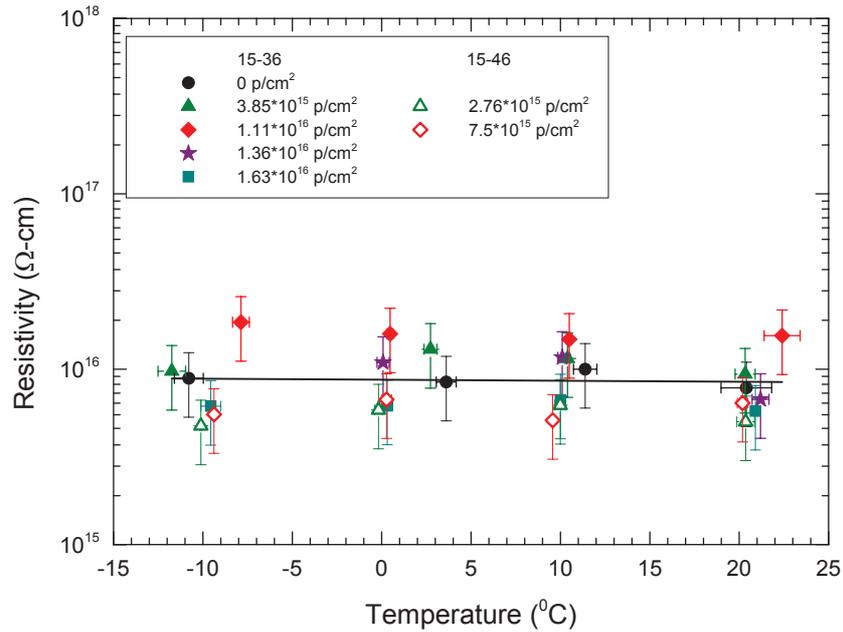


Figure 2. The resistivity of the diamond sensors as a function of temperature, for fluences ranging from 0 to $1.63 \times 10^{16}\text{ 800-MeV-protons/cm}^2$. The parameters of the fitted line are described in the text.

Figure 3 shows the measured resistivity versus fluence for all temperatures and both diamonds. A logarithmic scale is used to capture the full spread of data values. A free linear fit produces an intercept of $(8.01 \pm 0.81) \times 10^{15}\text{ }\Omega\text{-cm}$, with slope $(0.49 \pm 8.54) \times 10^{-2}\text{ }\Omega\text{-cm}$.

cm/(p/cm²) and $\chi^2/\text{dof} = 0.62$. We conclude that there is no significant dependence of diamond resistivity upon proton fluence over the range 0 to 1.6×10^{16} 800-MeV-p/cm² (0 to 1.13×10^{16} 1-MeV-n_{eq}/cm²).

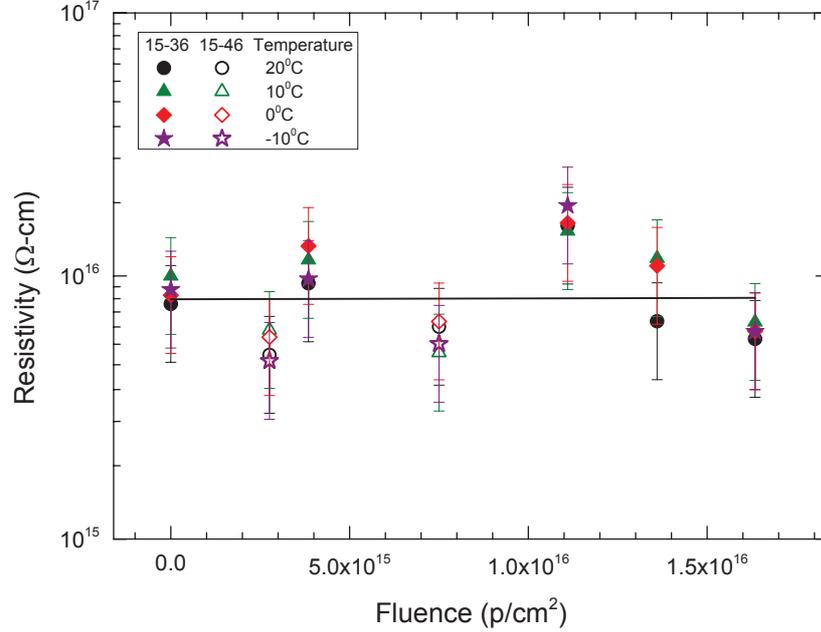


Figure 3. The resistivity of the diamond sensors as a function of fluence, for temperatures ranging from -10 °C to +20 °C. The parameters of the fitted line are described in the text.

4. Summary and conclusions

Damage constants for single crystal and polycrystalline diamond have been measured in 5 different beam conditions and compared to predictions from FLUKA DPA. The study is still ongoing but seems to indicate reasonable agreement between data and theory that improves with energy. All measurements conform to the equation $\frac{1}{\lambda_{e/h}} = \frac{1}{\lambda_0} + k\Phi$ to better than 2 standard deviations, demonstrating a common radiation damage mechanism in CVD diamond.

The resistivity of polycrystalline diamond has been found to be independent of temperature and fluence over the ranges -10 °C to +20 °C and zero to 1.63×10^{16} 800-MeV-p/cm².

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