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Effect of temperature and charged particle fluence on the resistivity of polycrystalline CVD diamond sensors

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ABSTRACT

The resistivity of polycrystalline chemical vapor deposition diamond sensors is studied in samples exposed to fluences relevant to the environment of the High Luminosity Large Hadron Collider. We measure the leakage current for a range of bias voltages on samples irradiated with 800 MeV protons up to 1.6×10^{16} p/cm^2. The proton beam at LANSCE, Los Alamos National Laboratory, was applied to irradiate the samples. The devices' resistivity is extracted for temperatures in the -10 °C to $+20$ °C range.

1. Introduction

Polycrystalline chemical vapor deposition (CVD) diamond [1–4] is presently used in particle physics experiments for beam monitoring [5,6], and it is being further developed [7] for use in vertexing and tracking detectors planned for the challenging radiation environment of the inner layers of High Luminosity Large Hadron Collider (HL-LHC) detectors. At distances shorter than about 24 cm from an LHC collision (i.e., the regime covered by inner pixel detectors), the dominant source of radiation damage is charged particles. Any effect of radiation damage upon the resistivity of the detection material will, if uncompensated, propagate to the leakage current; the result would be that all assessments of the material properties that depend upon leakage current measurement, including active volume and charge collection distance, would be impacted. Accordingly we have studied the resistivity of polycrystalline CVD diamonds as a function of temperature and proton fluence. The 800 MeV proton beam at LANSCE, Los Alamos, was used in the irradiation. This study was carried out in the framework of the RD42 Collaboration at CERN.

2. Method

The devices (see Table 1), manufactured by Element Six [8], are polycrystalline and structured with metalized pads and backplane. The cleaning and metalization process is based on a technique in Ref. [9]. That process begins with the application of three heavily oxidizing acids to remove all organic residues and leave the surface oxygen terminated. The sequence is HCl–HNO_3 (3:1), H_2SO_4 (3:2), then H_2SO_4–H_2O_2 (1:1). This is followed by an oxygen plasma etch for 4 min. After the high energy sputter by composite TiW, the contacts are annealed for another 4 min at 450 °C in an inert atmosphere.

The device thicknesses were measured with an Eichhorn and Hausmann Contactless Wafer Thickness and Geometry Gauge (model MX 203-6-33) and confirmed optically with a microscope; their lengths and widths were measured optically. These diamonds are taken from the same series, number 1006115, produced in 2008. As the results from the two devices are consistent, for clarity the graphs in this paper display the 1006115-36 data unless otherwise indicated (these are indicated in the legends of the graphs as "15–36"). Device 1006115-36 was exposed to fluences 3.85×10^{15}, 1.11×10^{16}, 1.36×10^{16}, and 1.63×10^{16} p/cm^2. Device 1006115-46 (indicated in the graphs as "15–46") was exposed to fluences 2.76×10^{15} and 7.5×10^{15} p/cm^2.

Resistivity ρ is computed as

$$\rho = AR/d, \tag{1}$$

where R is the inverse of the slope of a linear fit to a graph of leakage current versus bias voltage (IV); A is the area of the sensor under test; and d is the sensor thickness. Two slightly different setups, see Fig. 1, were used for the IV measurement in order to quantify systematic uncertainty associated with the instrument configuration. With ground applied to the detector back side and high voltage applied to the front, the bulk leakage current data are

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acquired by the Keithley 237 source measure unit in Setup 1 and by the Keithley 617 electrometer in Setup 2. The advantage of Setup 1 is its simplicity: a single instrument is used to measure the sourced current. The advantage of Setup 2 is the fact that the measurement is made instead on the returned current (so sourced current that did not cross the bulk is excluded); the disadvantage is that this setup requires two instruments, each with its own intrinsic contribution to measurement uncertainty. Dry N_2 is applied continuously to the environment to prevent condensation. The sensor temperature is maintained at approximately -10 °C, 0 °C, 10 °C or 20 °C by the thermal chuck on which the sensor rests. Relative humidity is less than 5% for all measurements below 20° and less than 35% for room temperature measurements. Bias voltage is ramped over the range from -500 V to $+500$ V with confirmation measurements in both directions. Data taken with positive and negative voltage are fitted separately for voltages with a magnitude of 200 V and higher. (We exclude data for voltages in the realm of 100 V, as these currents are comparable to the intrinsic accuracy of the Keithley devices which is 100 fA.) The separate fits are consistent, and the slope R is their average.

The standard deviation on any measured current varies between 3 and 9 $\times 10^{-13}$ A, depending upon the setup, derived from three to five measurements under identical conditions. The standard deviation is unaffected by the temperature or humidity within the ranges used here. An interval of a few hours is typically allocated to the measurement of a single IV point. After being mounted to the thermal chuck, the diamond's current and temperature are monitored continuously. The temperature of the diamond is recorded through a thermal sensor mounted directly to the thermal chuck. Temperature uncertainty is less than 0.1 °C for any individual measurement and falls in the range 0.2–0.8 °C for the full voltage scan of most devices. Equilibration takes approximately 30 min. An average current and temperature are extracted from data during the period beginning about 1 h after installation and continuing up to 4 h. We do not observe any deviations of the average slope from flatness during these intervals. Fig. 2 demonstrates the stability of the current at a typical

Table 1
Dimensions and features of the diamond sensors used in this study. Representative uncertainties on these lengths are 0.002 cm on the transverse dimensions and 10 μm on the thickness.

Diamond sensor	Dimensions (cm × cm × μm)
1006115-36	1.016 × 1.017 × 440
1006115-46	1.007 × 1.008 × 432

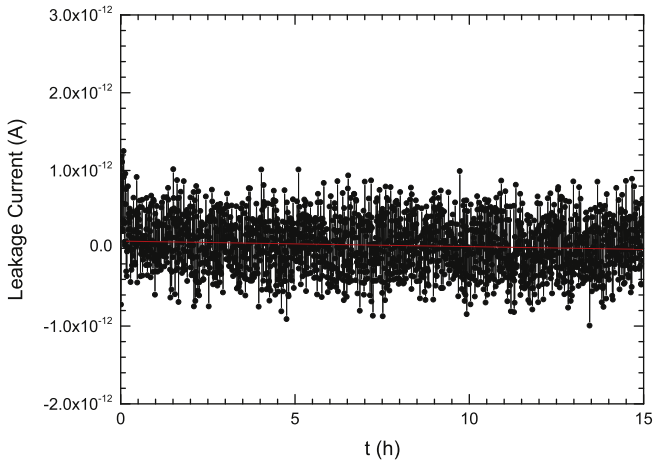

Fig. 2. This current versus time graph for a typical measurement illustrates the stability of the current. Measurements commence about 1 h after the change in bias voltage and are recorded every 30 s thereafter. These data were taken at 20 °C on device 1006115-36 after it had received a fluence of 1.63×10^{16} p/cm^2.

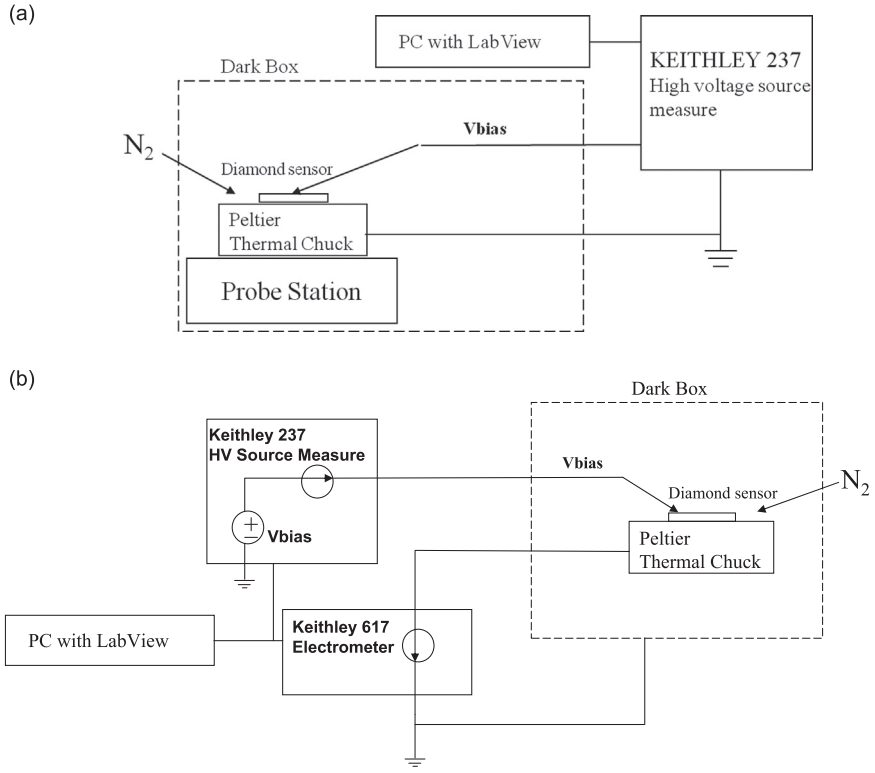

Fig. 1. The experimental setups for measuring leakage current as a function of bias voltage. (a) Measurement configuration 1. (b) Measurement configuration 2.