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ABSTRACT

Using the advantage of the high spatial resolution of the Ruđer Bošković Institute (RBI) ion microprobe, small areas of a thin membrane single crystal chemical vapor deposition (scCVD) diamond detector were intentionally damaged with a high-intensity 26-MeV oxygen ion beam at various fluences, producing up to ~10^{18} vacancies/cm^3. The response of the detector was tested with the ion beam-induced charge technique (IBIC) using a 2-MeV proton beam as a probe. The signal amplitudes decreased down to approximately 50% of the original value at low electric fields (<10 V/μm) inside the detector. However, the increase of electric field to values of ~100 V/μm completely recovers the signal amplitude. The results presented herein can facilitate the development of true radiation hard particle detectors.

The behavior of thin single-crystal chemical vapor deposition (scCVD) diamond radiation detectors[1] under extreme conditions of high electric field is further explored in this work. Recently, we demonstrated charge multiplication in electrical pulses formed upon the impact of ions at MeV energies;[2] herein, we investigate the influence of high electric fields on the radiation hardness of these thin membrane diamond detectors. Radiation hardness of particle detectors is a very important parameter for complex detector systems used in high-energy physics.[3,4] It was previously shown[5] that chemical vapor deposition (CVD) diamond-based detectors show superior radiation hardness compared to standard Si-based detectors when detecting high-energy particles.

In our present work, we use a 6.15-μm-thin self-supported membrane, produced from <100> oriented single crystal "standard grade" CVD diamond (<1 ppm N concentration according to the producer Element Six Ltd) to make a thin membrane particle detector. The manufacturing steps for the detector production were explained elsewhere.[6] Al strip electrodes (300 μm wide) were PVD sputtered on the membrane area free of large structural defects. This area was selected under birefringence microscopy observation, in which large structural lattice defects like bundles of dislocation or inclusions can be easily detected due to the strain formation and appearance of light contrast. The overlap area of the electrodes is rhombus-shaped, with the total active area being approximately 300x300 μm^2. To test the behavior and then the response to high irradiation fluences, we intentionally damaged five areas of a 6.15-μm-thin diamond detector with 26 MeV oxygen ions. This particular ion and energy were chosen because the damage profile in the 6.15-μm membrane is relatively homogenous, according to the SRIM code simulation.[7] Additionally, an oxygen ion creates a large number of vacancies per volume compared to light ions. Thus, we could reach an extremely high concentration of radiation-induced defects in a relatively short time. The irradiation was carried out at the ion microbeam setup at the Ruđer Bošković Institute accelerator facility.[8]

Prior to the high fluence irradiation, the whole active area of the detector was scanned with the ion beam induced charge (IBIC) technique[9] to assure a homogenous response of the detector and a charge collection efficiency of close to 100%. A low current (<fA) of 26 MeV oxygen ions has been used for that purpose. The high fluence irradiation using the same beam (and higher currents) has been performed at areas in lateral size from 30x30 μm^2 to approximately 100x100 μm^2. After the damage creation, the same beam was used to perform IBIC scan at the electric field of 10 V/μm. Proton

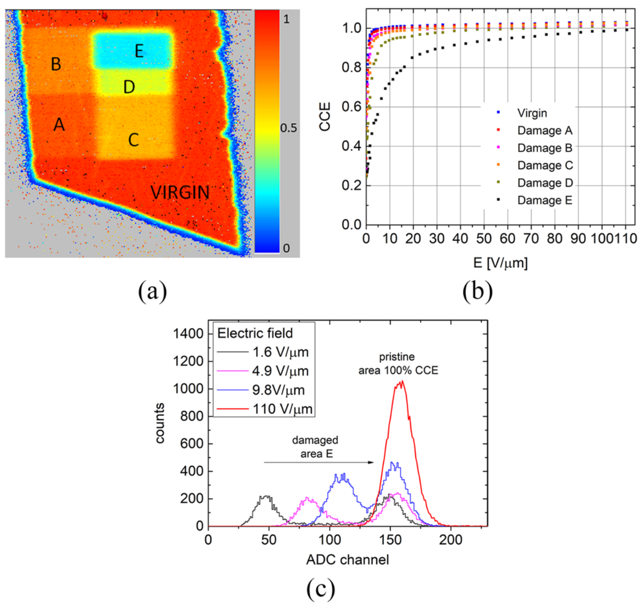

FIG. 1. (a) Map of the damaged and virgin areas of the detector with 26-MeV oxygen beam at electric field 10 V/μm. (b) CCE vs electric field plots for five different damage areas and the virgin part of the detector using a 2-MeV proton beam. (c) IBIC pulse-height spectra of the virgin and "E" damaged area at E=1.6, 4.9, 9.8, 110 V/μm (see text for selection criteria).

beam of 2 MeV, was afterwards used for IBIC scans, varying detector bias from 0 to 680 V, which corresponds to a 0-110.5 V/μm electric field. Figure 1a shows IBIC scan of whole active area after the damage creation, using 26 MeV oxygen and 10 V/μm). Table I shows the fluences for five damaged areas and the corresponding number of created vacancies, as simulated with SRIM in a detailed cascade calculation mode. The highest fluence (E) is the equivalent of $5{\cdot}10^{15}$ of 10 MeV protons/cm^2, or $6.8{\cdot}10^{16}$ fluence of 24 GeV protons.[6,10]

The pulse-height spectra for damaged parts were extracted from the central parts of the damaged areas, while the pristine region pulse-heights were taken from the lower right part of the active area marked in Figure 1a. The charge collection efficiency (CCE) in diamond was calibrated using a standard Si PIPS detector taking into account electron-hole creation energies of 3.6 eV for Si and 12.8 eV for diamond.[11] Figure 1b shows the CCE vs. electric field responses

TABLE I. Irradiation fluences and their corresponding vacancy densities for five damaged regions of the detector according to SRIM.[7]

Region	F [cm-2]	VAC [cm-3] (SRIM)
A	1.50E+11	1.90E+16
B	4.40E+11	5.40E+16
C	1.10E+12	1.35E+17
D	2.30E+12	2.80E+17
E	8.00E+12	9.90E+17

for five different damaged areas as well as the response of the pristine part of the detector for a 2-MeV proton beam. Because the material used to produce the detector was of standard grade, the charge carriers were expected to have a shorter lifetime compared to a purer electronic grade material. Therefore, a relatively high electric field of approximately 5 V/micron is needed to reach the plateau of CCE even for the pristine areas of the detector. Unexpectedly, the CCE curves for damaged areas reach almost full efficiency at a sufficiently high electric field. Signals, except for the most damaged "E" area recover to above 95% of the original pulse height at approximately 13 V/μm, while at fields above 100 V/μm the most damaged area reaches a recovery of approximately 99%. Notably (Figure 1b), the charge collection efficiency slowly increases with increase of electric field for the virgin and all the damaged parts. The reported value of 12.8 eV for electron-hole pair creation is valid for low and moderate electric fields, while it decreases slightly at high fields. Figure 1c shows the amplitude spectra for the virgin (peaks to the right) and the "E" damaged part (peaks to the right) at electric fields of 1.6, 4.9, 9.8, 110 V/μm respectively. It is clear, however, that at lower fields the two peaks of different CCE merge into one of CCE ~100% at 110 V/μm electric field without significant broadening of the peak.

Signal-to-noise (S/N) ratio is an important aspect of the signal amplitude recovery. In the ideal case, when increasing the detector bias and for detectors with low or zero leakage current, the noise level should remain constant, and therefore, S/N ratio improves with the amplitude increase. Figure 2 shows the FWHM to CCE (FWHM/CCE) ratio of the corresponding peaks as a function of the electric field for the virgin, "D" and "E" damage areas. FWHM of the peak is an indication of the noise in the measurement. The behavior of the FWHM/CCE, which is the relative resolution, follows the trend of recovery of the signal; and at high electric fields, it reaches a minimum value of approximately 16% for both the damaged and virgin parts of the detector. Considering that the 2-MeV proton beam traverses through the 6.15-μm-thick diamond material, it deposits only a fraction of its energy of approximately 330 keV in the detector. Therefore, the effect of energy straggling is significant. According to the SRIM simulation,[7] the straggling contribution for

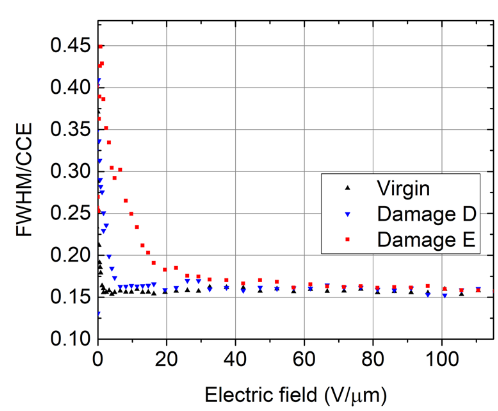

FIG. 2. Peak width (FWHM) divided by CCE vs electric field for the virgin part of the detector and the two highest damage areas (D and E).

that particular case is approximately 11.5% of the total deposited energy. Approximately 11% contribution to the total FWHM is the electronic noise from the detector chain which remains constant.

In conclusion, we have shown that the resistance of single-crystal CVD diamond detectors to radiation damage could be significantly improved if high electric fields (up to 100 V/μm) are used. The signal amplitude can be recovered almost completely in severely radiation-damaged diamond detectors having defect concentration levels of damaging ions that cannot work at all, if standard (1-10 V/μm) electric fields are being used. In addition, it has been shown that by increasing the electric field, the signal-to-noise ratio improves as well. Finally, it has been observed that the electron-hole pair creation energy slightly decreases by increasing of the electric field. Although these findings have been performed in relatively small detector volumes, advantages of the high electric fields are evident and give new insight into the possible application as an extreme-radiation hard detector that can be used in high-energy physics experiments or other very high radiation conditions (e.g., fusion reactors).

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