Diamond & Related Materials 31 (2013) 65–71

Contents lists available at SciVerse ScienceDirect

Diamond & Related Materials

journal homepage: www.elsevier.com/locate/diamond

Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions

Ivana Zamboni [a,*], Željko Pastuović [b], Milko Jakšić [a]

[a] Laboratory for Ion Beam Interactions, Division of Experimental Physics, Ruđer Bošković Institute, P.O. Box 180, HR-10002 Zagreb, Croatia
[b] Centre for Accelerator Science, Institute for Environmental Research, Australian Nuclear Science and Technology Organisation, Locked bag 2001, Kirrawee DC NSW 2232, Australia

ARTICLE INFO

Article history:
Received 20 January 2012
Received in revised form 7 November 2012
Accepted 7 November 2012
Available online 14 November 2012

Keywords:
Single crystal CVD diamond detector
Radiation hardness
Ion micro-beam
IBIC
Charge collection efficiency

ABSTRACT

The spectroscopic properties of a commercial high purity single crystal diamond detector (1 mm^2 area, 500 μm thickness) have been studied using focused ion beams (H, He and C ions) in the MeV energy range. A measured relative energy resolution of 1.3% (FWHM = 25 keV) for the detection of 2 MeV protons demonstrated a good spectroscopic performance of the CVD diamond device, which makes it useful for the detection of light ions or atoms. To test the radiation hardness of the diamond detector, it was selectively irradiated with a 6.5 MeV focused carbon beam up to a fluence of 10^{11} ions/cm^2. Reliable measurement of the ion fluence was accomplished by means of the microprobe single ion technique IBIC (ion beam induced charge). After irradiations that produced selectively damaged regions in the diamond detector, low current mode IBIC microscopy has been performed to measure the degradation of the charge collection efficiency (CCE). In order to get a better understanding of the detector performance after irradiation, different ions with the end of a range smaller, equal and larger than the extend of the damaged layer were used as IBIC probes. The same experimental procedure of irradiation and IBIC microscopy has been performed on a detector grade silicon PIN diode in order to directly compare the radiation hardness of diamond and silicon. The presented results show that the single crystal CVD diamond is less radiation hard for the spectroscopy of short range heavy ions compared to the high resistivity silicon, which is contrary to the results obtained for diamond detectors exposed to the high energy particles.

1. Introduction

Synthetic diamond presents a promising material in many advanced electronic applications where the usage of wide band gap semiconductor/insulator devices could be advantageous, ranging from ionizing radiation detection to microelectronics, optoelectronics and quantum computing [1,2]. Its unique properties have been well known for many years, but the most recent developments in crystal growth techniques have allowed the production of high quality single crystal materials with outstanding electronic and optical properties [3,4]. The high electrical resistivity of diamond at room temperature, as a consequence of the wide band gap, results in a negligible leakage current, which is a source of undesirable noise for radiation detection applications. In respect to silicon devices, faster signals for particle detection and triggering can be obtained with diamond detectors due to the higher breakdown electric field strength and higher carrier saturation velocities in diamond. Moreover, the low dielectric constant reduces the capacitance of a circuit formed with a diamond device, which is also a very important property in some applications.

The latest generation of high purity single crystal diamond particle detectors is produced by a chemical vapor deposition (CVD). They show good energy resolution and superior timing properties due to the excellent crystal uniformity [5,6]. These devices should maintain their characteristics in harsh environments (e.g. at high temperatures, under mechanical stress, at excessive radiation levels, etc.), and therefore could be used in different applications where either silicon detectors cannot operate or their spectroscopic performance deteriorates quickly [7]. Possible application areas for these detectors in ion beam analysis (IBA) include: i) the scanning transmission ion microscopy (STIM) as well as tomography of very thin samples where a primary focused ion beam is detected after transmission through a sample; ii) the elastic recoil detection analysis (ERDA) microscopy and elastic scattering coincidence spectroscopy using fast timing measurement between the primary scattered particle in forward direction and the recoiled particle. In both cases the radiation hardness of detectors, which are exposed to excessive fluences of short range ions (energies typically close to or below 1 MeV/u) is of the high importance. The radiation hardness of detectors determines their lifetime and the reliability/repeatability of acquired data. When ionizing radiation detection applications are considered, the most important detector properties are: detection efficiency, energy resolution and rise time, as well as deterioration rate of these properties after

* Corresponding author. Tel.: +385 1 4571227; fax: +385 1 4680239.
E-mail address: izamboni@irb.hr (I. Zamboni).

0925-9635/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.diamond.2012.11.002

exposure to excessive radiation fluences. It is well known that ions produce damage by nuclear collisions displacing atom from a lattice site and thereby creating vacancies and interstitials. Some of them recombine or rearrange leaving stable defects which have energy levels in the forbidden energy gap of the detector material. An excessive exposure yields a sufficiently high defect concentration which increases the leakage current and the capacitance of the detector, and decreases the charge collection efficiency (CCE) [8,9].

The majority of publications on radiation hardness of the diamond detectors are based on experiments performed with gamma rays [10], electrons [11], neutrons [12–14] and GeV energy protons [15–17]. High energy gamma rays, neutrons, pions and protons penetrate through the whole test device losing just a small portion of their initial energy. The result of such irradiation is a homogeneous distribution of defects across the whole thickness of the tested device. Reducing the energy of incident proton from GeV range down to the MeV (and even keV) range results in a significant increase of the defect concentrations in crystalline material. Moreover, in the case of low energy and consequently short range ions, the primary single vacancy defect depth profile is no longer homogenous. The total energy loss rate of a non-relativistic ion strongly depends on its velocity (energy). The non-ionizing energy loss due to displacement of the target atoms prevails over the electronic losses for the slow moving ions that have sufficient energy above the threshold displacement energy, i.e. close to the end of the ion range in solids. Under these lower energy irradiation conditions, the previously reported superior radiation hardness of diamond for GeV protons cannot be simply extrapolated to the lower MeV and keV energy range. The low energy particle interaction with detectors is also important at high energy hadron colliders, where secondary interactions in the detector material produce a significant fraction of particles in this energy range. Systematic studies of diamond detectors exposed to various types of ionizing radiation are required to prove the radiation hardness in different energy ranges.

The IBIC microscopy is a powerful tool to measure the CCE and investigate the charge transport properties at microscopic level with a high spatial resolution and a well-defined (and tunable) penetration depth [18]. We have already successfully demonstrated the use of the IBIC microscopy for silicon radiation hardness testing [19] at the Zagreb heavy ion microprobe facility [20]. Therefore in the present work we systematically investigate the CCE deterioration rate in diamond detector and make a direct comparison with silicon diode under the same experimental conditions. The variation of the CCE values obtained by IBIC testing is reported as a function of particle fluence and applied bias to detectors.

2. Experimental

2.1. Diamond detector (spectroscopy)

The device tested in this work was a single crystal CVD (scCVD) diamond detector with 1 mm^2 active surface area and 500 μm thickness, supplied by Diamond Detectors Ltd. Its novel ohmic electrical contact consists of a very thin (1–3 nm) diamond-like carbon (DLC) film, that acts as an interface layer between the platinum/gold layers and the diamond and results in better adhesion to the diamond surface [21]. The improved contact quality is very important because a previously applied contact fabrication technology often resulted in a poor mechanical adhesion of the metal contact to the scCVD surface. The poor adhesion caused both spatial and temporal inhomogeneities of the electric field distribution in the bulk material due to space charge accumulated at the metal–diamond interface. The overall result was poor and unstable CCE in diamond detector [1,22,23].

The diamond detector was placed inside a hollow aluminum frame mounted on the sample holder, with the rear side electrode connected to the shielded (grounded) metallic detector box. The front contact electrode was biased and connected to a conventional external charge-sensitive electronic chain. A weak current signal is induced by the drift of charge carriers in the region with external applied electric field [18]. After signal amplification in a spectroscopic amplifier, the pulse height and position information of the beam were recorded using the Spector data acquisition software [24]. The total induced charge is proportional to the energy of an incident ion. The pulse height for a pristine (un-irradiated) detector is used as the normalization value for the calculation of the CCE. In the case of a selectively irradiated detector area, the induced charge decreases due to the presence of defects that trap moving charge carriers.

Spectroscopic performance of the pristine diamond detector has been tested over its whole active area using a broad 2 MeV proton beam elastically scattered from 0.1 μm thick gold foil in the forward direction. The detector positioned at 45° angle with respect to the incident beam direction was supplied with a positive or negative DC bias in the 100–400 V range. As it is seen from Fig. 1, the FWHM value of the measured peak decreases with the applied bias voltage, i.e. the detector energy resolution is improving, especially for positive biases. For negative biases the measured resolution is generally better across the bias range, although the resolution improvement with increasing bias is less pronounced. The best resolution value of 25 keV (1.3%) in the diamond detector, was obtained for a bias of −400 V.

2.2. Irradiation and IBIC protocol

The ion microprobe facility at the Ruđer Bošković Institute, which is described in detail in Ref. [20], has been used for micro-beam irradiations and IBIC measurements. The 1 MV Tandetron accelerator provided proton beams, while the 6 MV Tandem Van de Graaff accelerator provided C and He ion beams. H and He ion beams were focused by a triplet, while the carbon beam was focused with a quintuplet microprobe configuration. The spot sizes of the focused ion beams were in all cases equal to or better than 1 μm.

In order to study the influence of ion beam induced radiation damage on charge collection properties of the scCVD diamond detector, we have selected carbon ions as damaging particles. The advantage of using carbon ions is to avoid the implantation of foreign atoms and production of foreign atom related defects in diamond. As simulated by the SRIM code [25] 6.5 MeV C ions have a short range of approximately 3 μm (Fig. 3a). Compared with the diamond detector thickness of 500 μm, it is clear that the produced defects are confined to a shallow layer just below the front contact.

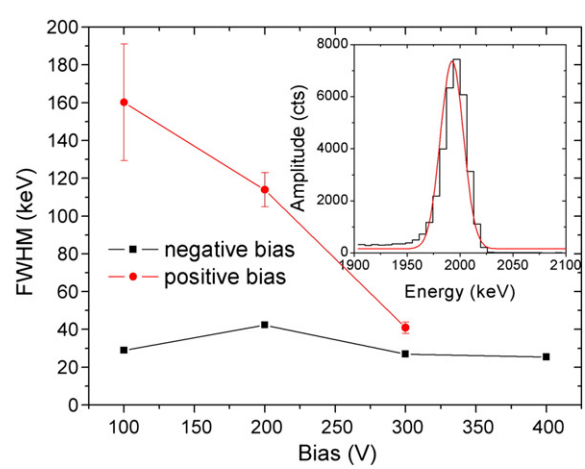

Fig. 1. The measured energy resolution for the detection of the forward scattered 2 MeV protons from a thin gold foil obtained by the pristine diamond detector is shown as a function of applied voltages. The insert shows the energy spectrum obtained at −400 V. The depicted uncertainties correspond to fitting error.

The selective area irradiation was performed by scanning of the focused carbon beam across a 50×50 μm^2 area using varying fluence value in the 10^{10} to 10^{11} cm^{-2} range (Fig. 2). The device was biased and connected to the data acquisition system during the irradiation to allow precise monitoring of the accumulated fluence. The micro-beam was repeatedly scanned over the selected area to achieve the homogenous defect distribution.

For a direct comparison of the radiation hardness of diamond and silicon, we have selected Hamamatsu S-5821 silicon PIN diode. Its configuration, doping profile and electrical characteristics are specified in detail in Ref. [9] and its response to excessive irradiation by different ions has previously been systematically studied using the same experimental protocol [9,19]. This particular device has been selected for our investigation due to its excellent spectroscopic properties: a) low noise, b) high-energy resolution and c) high over-bias capability. One silicon diode has been irradiated with 6.5 MeV C ions as the diamond detector (Fig. 3c), while the other has been irradiated with a carbon beam of reduced energy 2.6 MeV to maintain the same range in silicon as the 6.5 MeV C ions have in diamond (Fig. 3b). In the latter case the damaged layer of the similar thickness is positioned at exactly the same depth with respect to the front contact of the tested device.

In addition to 6.5 MeV C ions, we have also used the shorter range 430 keV and the longer range 2 MeV proton beams to probe damaged regions in the diamond and silicon devices. Their ionization depth profiles (LET) are presented in Fig. 3a and c. In addition to 2.6 MeV C ions, selectively damaged silicon diode was also probed using the shorter (600 keV He) and longer (1.3 MeV H) range ions (Fig. 3b). The geometrical similarities in the studied probe-damage systems are clearly established.

We have performed additional SRIM calculations to separate the influence of metal contact layers of the diamond detector. According to Ref. [21] the total thickness of those layers is approximately 10% of an ion range. The simulated vacancy distribution and ionization depth profiles in such diamond detector configuration are very similar to those obtained from simulations without a front metal contact layers. The surface contact of the silicon photodiode is measured to be 50 nm and is also negligible in that respect.

3. Results and discussion

3.1. IBIC measurements performed on the irradiated scCVD diamond detector

The measured CCE values in the partially damaged scCVD diamond detector decreased with the carbon ion fluence in all studied cases (Fig. 4). For protons the highest CCE value measured at the largest fluence is approximately 0.55 (Fig. 4c). For the carbon probe the highest CCE value at the largest fluence is approximately the same in spite of a significantly wider spread of the individual CCE values obtained for different applied voltages (Fig. 4a and b). For protons (Fig. 4c and d) the deviations between the individual CCE distributions obtained for different bias settings are much smaller. Due to the diamond detector configuration, the path length of a free carrier moving under the applied electric field towards the back (grounded) electrode is much larger compared to the path length of a free carrier with opposite charge state moving towards the front electrode. Therefore, the CCE values obtained by the diamond detector are dominated either by the electron contribution for negative values or by the hole contribution for positive values of applied bias voltages. The hole CCE (Fig. 4d) deteriorates faster than the electron CCE (Fig. 4c) suggesting either more efficient hole trapping by carbon ion produced stable defects or less efficient electron trapping due to the presence of additionally produced donor centers [28].

The irradiated diamond detector showed a sensitivity to visible light, although it should be unaffected by it during operation because of the wide band gap. The priming effect was previously observed in diamond detectors [29] when a positive DC bias was applied to a diamond detector. Since the major contribution to the CCE in this case comes from holes, a visible light illumination might be used to fill the shallow hole traps created by the carbon ion irradiation of diamond and increase the hole lifetime in irradiated material [30]. The consequence is the slight enhancement of signal amplitude recorded by the illuminated irradiated detector in comparison to the same device operated in complete darkness. Besides the priming effect, we have occasionally observed an abrupt decrease of the IBIC signal amplitude during some measurements. A reliable procedure to restore a normal detector operation included grounding the both contacts. We suspect that the polarization took place locally in the biased diamond detector after accumulated trapped charge was sufficient to generate opposing electric field. For IBIC studies of the diamond radiation

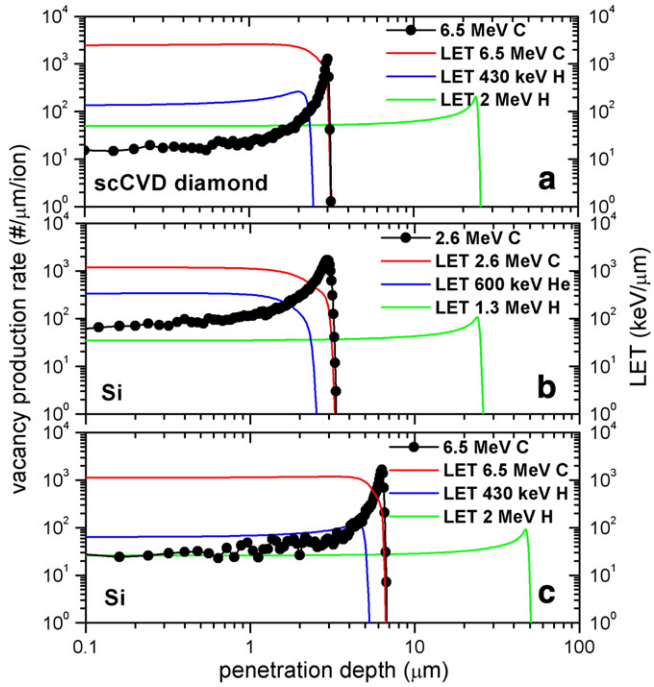

Fig. 3. SRIM simulations for the vacancy production rate (black dots) and linear energy transfer (LET; continuous lines) depth profiles for the different probe-damage systems used for the radiation hardness testing of diamond (a) and silicon (b and c). Vacancy production rates have been calculated with the threshold displacement energy (E_d) value of 21 eV for silicon [26] and 50 eV for diamond [27].

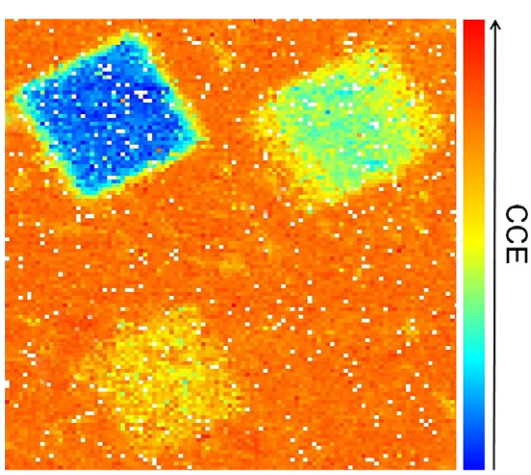

Fig. 2. IBIC pulse height 2D distribution measured with a 430 keV proton probe scanned over the selectively irradiated diamond detector by 6.5 MeV carbon micro-beam. Bias voltage applied to the diamond detector is −500 V. Three damaged areas corresponding to the lower CCE are clearly visible.

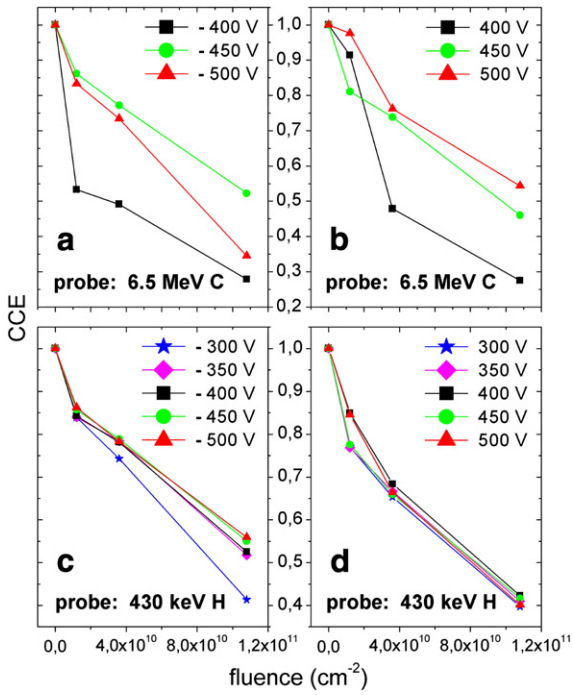

Fig. 4. The CCE distributions as a function of the carbon ion fluence measured with 6.5 MeV C (a, b) and 430 keV H (c, d) ion probes detected by irradiated diamond detector.

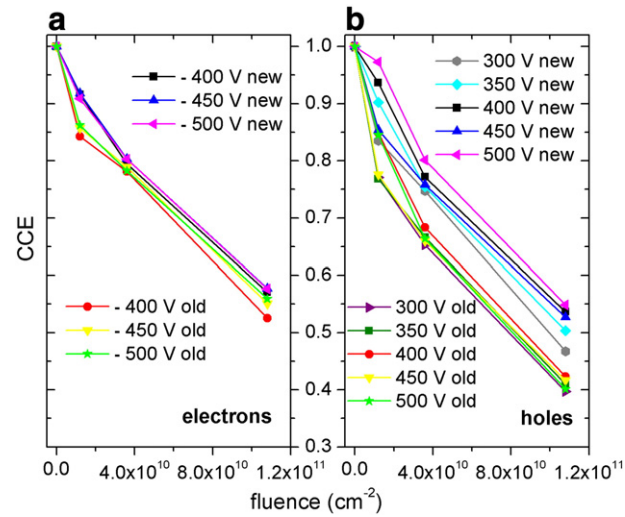

Fig. 5. The CCE distributions as a function of the carbon ion fluence measured with 430 keV H ion probe detected by irradiated diamond detector immediately after irradiation (old) and one year after (new).

hardness both effects are undesirable because they change the CCE value and the spectroscopic response of the tested device by modifying the charge transport properties. However, for the particle detection and spectroscopy using irradiated/damaged diamond detectors, as well as with diamond electronic devices in general [31–33], the priming effect is beneficiary because it helps to avoid or reduce polarization and therefore improves the performance of diamond detector. The IBIC microscopy at positive bias applied to the irradiated diamond detector has been performed under periodically visible light illumination to avoid the polarization effect.

In order to monitor the long term room temperature stability of defects induced in diamond by carbon irradiation and to eliminate a possible presence of the long term polarization, the 430 keV proton measurements were repeated one year after the carbon irradiation was performed. In the meantime the detector was held at standard temperature and pressure (STP). Again it was necessary to periodically illuminate the diamond detector during measurements in order to prevent the polarization effect. The repeated IBIC results obtained with the proton probe are presented in Fig. 5 together with the old results obtained a year ago. New results show almost the same behavior for both electrons (Fig. 5a) and holes (Fig. 5b). The previously measured lower CCE values for the collection of holes compared to the higher values of repeated IBIC measurements (positive applied bias; Fig. 5b) may be explained by slightly different conditions during measurements (e.g. difference in the illumination intensity used), polarization effects or possible spontaneous defect annealing. Otherwise, in both cases (positive biases—hole contribution and negative biases—electron contribution) there is no strong CCE dependence on the applied bias voltage.

3.2. Diamond radiation hardness comparison to silicon

In the case of ion energies in the MeV/u range, the highest concentration of defects per impinging ion is produced at the end of its trajectory, which is well within the sensitive volume of the tested device. Two possible experimental approaches to compare the radiation hardness of diamond with silicon will be either:

1) The measurement of the CCE or the equivalent damage factors [9,19] for the exactly same damaging and probing ion combination or,
2) The measurement of the CCE for different energy ions under exactly the same conditions in terms of the energy loss rate in the different materials.

In the first approach a focused 6.5 MeV C beam was used for selective area irradiation of both the diamond detector (Fig. 3a) and the silicon PIN diode (Fig. 3c). The second approach, i.e. the introduction of defects at the same depth (3 μm), was realized by irradiation of the diamond detector with 6.5 MeV C ions (Fig. 3a) and of the silicon PIN diode with 2.6 MeV C ions (Fig. 3b), respectively. Since the reverse bias polarity of the silicon PIN diode is negative and the CCE distributions of diamond detectors biased with the same voltage but opposite polarity are very similar, the comparison between diamond and silicon is shown only for the negative polarity bias voltages (−100 V for the Si PIN diode and −450/−500 V for the scCVD diamond detector respectively). In the case of the shallow probes the CCE distributions are dominated by the electron contribution. The deep proton probe is an exception because both electrons and holes contribute to the total CCE.

Results using the first approach comparing the radiation hardness of silicon and diamond for the 6.5 MeV C beam are shown in Fig. 6. The high sensitivity of the CCE response to the produced radiation damage (i.e. the high CCE deterioration rate), was obtained for short range ion-probes having the end of range smaller (430 keV H; Fig. 6b) or equal (6.5 MeV C; Fig. 6a) to the position of the induced damage. The CCE values obtained for the detection of utilized shallow IBIC probes by the irradiated silicon detector are significantly higher than the CCE values obtained for the irradiated diamond detector. In such experimental arrangement the majority of electrons, which substantially contribute to the total induced charge value, have to pass through the damaged layer. The higher CCE values and the lower CCE deterioration rate obtained for silicon diode over the entire carbon ion fluence range suggest the less efficient electron trapping and the better radiation hardness of the silicon diode compared to the diamond detector. In the case of the deep IBIC probe (2 MeV protons; Fig. 6c) the influence of the shallow damaged region on the collection of electrons and holes is less pronounced and the CCE degradation rate is much smaller. However, even in this case the CCE values obtained for 2 MeV H probe detection in the silicon PIN

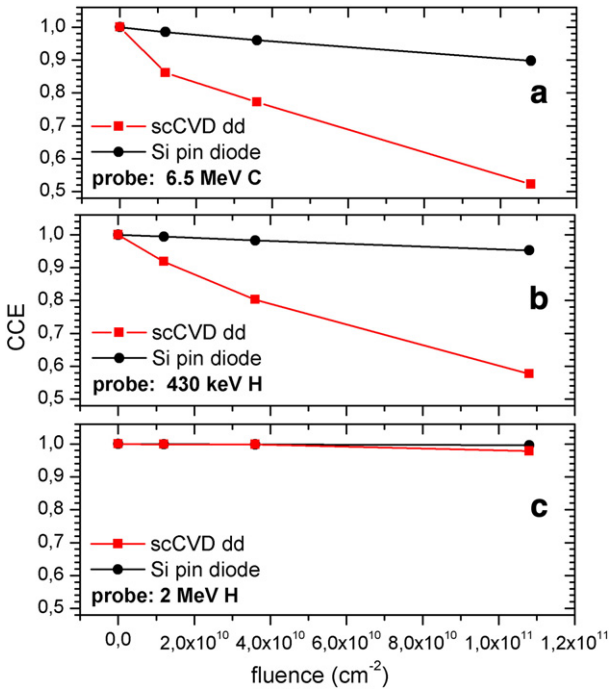

Fig. 6. Comparison of the CCE distributions obtained by IBIC microscopy performed on the selectively irradiated scCVD diamond detector (squares) and silicon PIN diode (circles) by focused 6.5 MeV C ion beam.

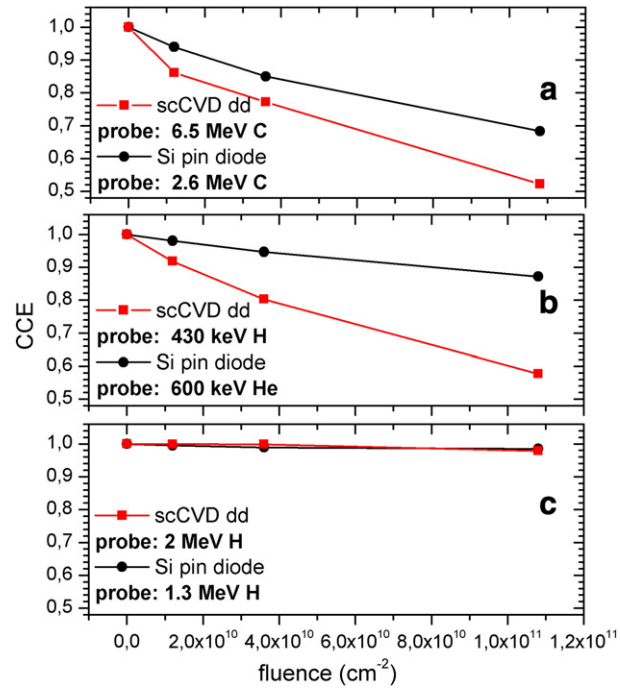

Fig. 7. Comparison of the CCE distributions obtained by IBIC microscopy performed with different ion probes on the partially damaged scCVD diamond detector selectively irradiated by focused 6.5 MeV C ion beam (squares) and partially damaged silicon PIN diode selectively irradiated by focused 2.6 MeV ion beam (circles).

diode are slightly higher than those obtained in the diamond detector for the highest fluence values.

The results for the CCE values obtained by IBIC utilizing the second approach are shown in Fig. 7. Similarly to the results of the first approach, the CCE values obtained for the partly damaged silicon detector are higher than those for the irradiated diamond detector across the fluence range. Moreover, the measured CCE distributions have similar deterioration rates for individual cases when the probe end of a range is equal, shorter, or larger than the depth of the damaged layer. The only observed significant difference between the two approaches is the higher CCE deterioration rate for the Si PIN diode irradiated with shorter range 2.6 MeV C and probed with the same ions (Fig. 7a) compared to the silicon diode irradiated and probed with 6.5 MeV C ions (Fig. 6a). The total number of vacancies according to SRIM simulations is approximately 10% higher for the 6.5 MeV C ion having 7 μm range in silicon (Fig. 3c), as opposed to 2.6 MeV C having 3 μm range only (Fig. 3b). Therefore, we can conclude that a higher average concentration of the vacancy related defects in the damaged volume is created for the irradiation with 2.6 MeV C (Fig. 3b). The higher trap concentration reduces the carrier lifetime and results with shorter drift length of free electrons moving through the damaged layer towards the sensing electrode. Consequently induced charge at the sensing electrode of the Si PIN diode and measured CCE value is lower in a sample with a higher trap concentration, which is the one irradiated with 2.6 MeV C (Fig. 7) compared to the sample irradiated with 6.5 MeV C (Fig. 6).

IBIC results for the CCE deterioration rate, which can be attributed to the radiation hardness of individual tested materials, obtained in both experimental approaches, strongly suggest that the tested low doped n-type silicon diode is more radiation hard than the tested scCVD diamond detector. An understanding of the lower diamond radiation hardness in the presented experimental arrangement can be related to:

1) *Inhomogeneous defect production*. In our radiation hardness experiment performed at MeV energies, electrically active defects (traps) have been produced in a very small bulk volume at the end of the ion range much closer to the front biased contact in respect to the grounded back contact. The result is significantly higher local defect concentration in small bulk volume, which decreases the carrier lifetime by increasing trapping probability. Locally decreased lifetime could significantly influence the CCE of irradiated detector compared to the reported results obtained with homogeneous irradiation using high energy particles, even for several orders of magnitude higher fluencies [15].
2) *Defect production by secondary particles*. At high projectile energies dominant damage is produced by nuclear fragments. For silicon many heavier nuclear recoils can be created (the most important are Mg and Al), while in diamond most of the secondary particles are less damaging light He nuclei [17]. The heavier fragments displace lattice atoms more efficiently creating cascades along fragment and recoil tracks.
3) *Mobility of defects*. The outcome of this study is quite surprising because 6.5 MeV C ions create on average four times more vacancies in silicon than in diamond according to SRIM simulations. The possible explanation for lower radiation hardness of diamond could be the significantly higher mobility of primary point defects in silicon compared to their mobility in diamond at room temperature. Lower mobility and recombination rate of primary induced point defects in diamond can result in the higher net concentration of electrically active traps.
4) *Higher sensitivity to imperfections in subsurface layers*. The inadequate electrode fabrication and diamond crystal impurities may have influenced our radiation hardness results as well.

3.3. The influence of damage introduction rate on the degradation of scCVD diamond detector

The measured differences between radiation hardness of silicon and diamond might be also influenced by the primary vacancy damage

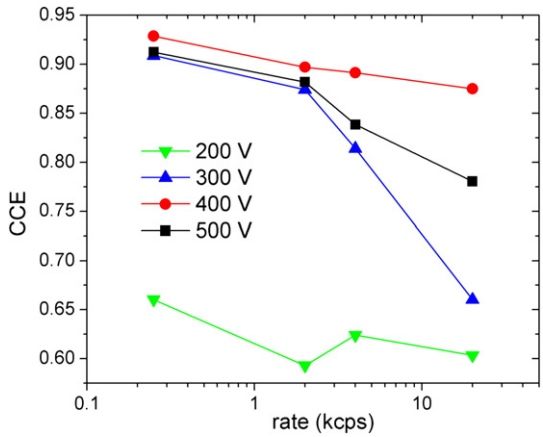

Fig. 8. Deterioration of the CCE as a function of beam rate obtained by 430 keV H IBIC microscopy performed on scCVD diamond detector irradiated with 8 MeV C ions and biased at different voltages.

introduction rate [34], since different currents, focusing and scanning parameters have been used. In order to investigate the beam rate influence on the CCE properties of tested diamond detector, we have additionally irradiated different pristine surface areas of diamond detector with the same ion beam fluences but at different irradiation beam rates. Four selected areas 80×80 μm^2 were irradiated with 8 MeV C at 0.25, 2, 4 and 20 kcps beam rates to the same total fluence of 5.1×10^{10} ions/cm^2. The detector was biased during irradiations at 500 V in order to avoid long term detector polarization and recombination effects. Fluence values were determined by measuring secondary electron response with the Channeltron particle detector because at very high beam rates the IBIC signal was not reliably measured.

Obtained results shown in Fig. 8 confirm our expectations that higher rates of focused heavy ion beams accelerate the CCE deterioration rate, especially above 2000 ions/sec beam rates. We speculate that an increased density of overlapping individual ion cascades increases the amount of simultaneously produced primary defects in a very small implantation volume at the end of ion range. The higher micro-beam rate generates the higher net point defect concentration and increases the probability of the final stable electrically active defect formation by the rearrangement of primary defects. The net effect is the increased trap concentration, shorter carrier lifetime and consequently the faster CCE value deterioration rate at the same fluence values. It is worth to mention that the accelerated CCE deterioration rate could not have influence on the presented results for the diamond radiation hardness because irradiations of the diamond detector prior to the performed IBIC measurements were performed utilizing the low carbon beam rate of 80–350 ion/sec.

4. Conclusions

The previously reported high radiation hardness of single crystal diamond detectors exposed to GeV energy protons (as well as to the gamma, neutron, electron and positron radiation) in high energy particle experiment environment was put to the test on the almost opposite side of the energy spectrum of ionizing radiation. We investigated the radiation hardness of the simple planar diamond particle detector to short range ions with ~0.5 MeV/u in order to test the CCE degradation of these devices in an environment common to IBA and similar applications. The CCE values were obtained by IBIC microscopy performed on the high purity monocrystalline CVD diamond particle detector selectively irradiated with focused 6.5 MeV carbon ion beam up to 10^{11} particle/cm^2 integral fluence. Moreover, the same procedure has been repeated on the detector grade silicon PIN diode in order to make a comparison following two experimental approaches: (i) introduction of defects by the same ions in both devices (6.5 MeV C); and (ii) introduction of defects at the same depth in respect to the sensitive electrode of each device (3 μm obtained by 6.5 MeV C in diamond and 2.6 MeV C in silicon).

In all the studied probe-damage cases the CCE value decreases as the ion fluence increases. The CCE values obtained for studied short range particle detection, by the irradiated silicon detector, are significantly higher than the values obtained by the diamond detector. Even in case of damage regions produced at the approximately same depth in both diamond and silicon detectors, the obtained CCE values are higher for silicon than for diamond. Detection of significantly higher energy (larger range) probing ions (in our case 1.3 and 2 MeV protons) has shown negligible sensitivity to the shallow damaged region in both detectors.

The comparison of CCE vs. fluence distributions obtained for oppositely biased diamond detector shows similar distributions for both electron (negatively) and hole contributions (positively biased front contact). Detection efficiency of ions with high rates (>1 kcps) was significantly reduced due to polarization appearance in diamond. Effects of visible light priming, i.e. the improvement of the CCE and the uniformity of the diamond detector response were observed for holes only.

Presented results do not confirm better radiation hardness of the tested diamond material in comparison to the low doped n-type silicon commonly used in devices for the detection of short range ions in IBA applications. Although 6.5 MeV C ions create four times more vacancies in silicon than in diamond according to SRIM simulations, the outcome of the presented study is strongly suggesting that the silicon diode is more radiation hard than the tested diamond detector for low energy ions having energies around ~0.5 MeV/u. Possible explanation for those results could be the much higher mobility of defects in silicon and their recombination that decreases the net concentration of permanent defects when compared to diamond. Alternative explanation may be the much stronger influence of polarization effects in significantly damaged regions of diamond.

Prime novelty statement

This work is the first systematic ion beam induced charge (IBIC) study of the radiation hardness of commercial single crystal diamond detector for the detection of short range ions (1 MeV/u or less). The main aim of this work is to investigate the influence of radiation damage produced by MeV heavy ions on the charge collection efficiency (CCE) of the diamond detector and to make a direct comparison with the detector grade low doped n-type silicon PIN diode performance under the same conditions common to ion beam analysis (IBA) applications.

Therefore we are certain that this paper represents novelty in an area of a diamond application as a radiation detector.

Acknowledgments

This work has been partly supported by the European Community as an Integrating Activity “Support of Public and Industrial Research Using Ion Beam Technology (SPIRIT)” under EC contract no. 227012.

References

[1] C. Manfredotti, Diamond Relat. Mater. 14 (2005) 531–540.
[2] J. Isberg, J. Hammersberg, D.J. Twitchen, A.J. Whitehead, Diamond Relat. Mater. 13 (2004) 320–324.
[3] J. Isberg, J. Hammersberg, E. Johansson, T. Wikström, D.J. Twitchen, A.J. Whitehead, S.E. Coe, G.A. Scarsbrook, Science 297 (2002) 1670–1672.
[4] R.S. Balmer, et al., J. Phys. Condens. Matter 21 (2009) 364221.
[5] M. Pomorski, E. Berdermann, A. Caragheorgheopol, M. Ciobanu, M. Kiš, A. Martemiyanov, C. Nebel, P. Moritz, Phys. Status Solidi A 203 (2006) 3152–3160.
[6] P. Bednarczyk, et al., Acta Phys. Pol. B 38 (2007) 1293–1296.
[7] M. Pomorski, E. Berdermann, W. de Boer, A. Furgeri, C. Sander, J. Morse, Diamond Relat. Mater. 16 (2007) 1066–1069.

[8] M. Jakšić, Z. Medunić, N. Skukan, M. Bogovac, D. Wegrzynek, IEEE Trans. Nucl. Sci. 54 (2007) 280–283.
[9] Ž. Pastuović, M. Jakšić, G. Kalinka, M. Novák, A. Simon, IEEE Trans. Nucl. Sci. 56 (2009) 2457–2464.
[10] T. Behnke, M. Doucet, N. Ghodbane, A. Imhof, C. Martínez, W. Zeuner, Nucl. Instrum. Methods Phys. Res. A 489 (2002) 230–240.
[11] C. Grah, et al., IEEE Trans. Nucl. Sci. 56 (2009) 462–467.
[12] A. Oh, M. Moll, A. Wagner, W. Zeuner, Diamond Relat. Mater. 9 (2000) 1897–1903.
[13] P. Lardon, et al., Diamond Relat. Mater. 15 (2006) 815–821.
[14] M. Angelone, et al., Nucl. Instrum. Methods Phys. Res. A 595 (2008) 616–622.
[15] D. Meier, et al., Nucl. Instrum. Methods Phys. Res. A 426 (1999) 173–180.
[16] W. Adam, et al., Nucl. Instrum. Methods Phys. Res. A 447 (2000) 244–250.
[17] W. de Boer, J. Bol, A. Furgeri, S. Müller, C. Sander, E. Berdermann, M. Pomorski, M. Huhtinen, Phys. Status Solidi A 204 (2007) 3004–3010.
[18] M.B.H. Breese, E. Vittone, G. Vizkelethy, P.J. Sellin, Nucl. Instrum. Methods Phys. Res. B 264 (2007) 345–360.
[19] Ž. Pastuović, E. Vittone, I. Capan, M. Jakšić, Appl. Phys. Lett. 98 (2011) 092101.
[20] M. Jakšić, et al., Nucl. Instrum. Methods Phys. Res. B 260 (2007) 114–118.
[21] A. Galbiati, et al., IEEE Trans. Nucl. Sci. 56 (2009) 1863–1874.
[22] C. Manfredotti, A. Lo Giudice, E. Vittone, F. Fizzotti, Y. Garino, E. Pace, Diamond Relat. Mater. 15 (2006) 1467–1471.
[23] C. Manfredotti, et al., Diamond Relat. Mater. 16 (2007) 940–943.
[24] M. Bogovac, in: Data acquisition for X-ray microprobe, Computer Manual Series No.17IAEA, Vienna, 2002.
[25] J.F. Ziegler, J.P. Biersack, M.D. Ziegler, SRIM — the stopping and range of ions in matter, Ion Implantation Press, Annapolis, USA, 2008. (www.srim.org).
[26] S.M. Sze, Physics of semiconductor devices, second ed. John Wiley and Sons, Hoboken, New Jersey, USA, 1981.
[27] W. Wu, S. Fahy, Phys. Rev. B 49 (1994) 3030–3035.
[28] R. Kalish, A. Reznik, S. Prawer, D. Saada, J. Adler, Phys. Status Solidi A 174 (1999) 83–99.
[29] P. Bergonzo, D. Tromson, C. Descamps, H. Hamrita, C. Mer, N. Tranchant, M. Nesladek, Diamond Relat. Mater. 16 (2007) 1038–1043.
[30] M. Bruzzi, F. Hartjes, S. Lagomarsino, D. Menichelli, S. Mersi, S. Miglio, M. Scaringella, S. Sciortino, Phys. Status Solidi A 199 (2003) 138–144.
[31] C. Manfredotti, E. Vittone, F. Fizzotti, A. Lo Giudice, C. Paolini, Diamond Relat. Mater. 11 (2002) 446–450.
[32] C. Manfredotti, F. Fizzotti, Y. Garino, Diamond Relat. Mater. 15 (2006) 1362–1368.
[33] P.J. Sellin, A. Lohstroh, A.W. Davies, A. Galbiati, J. Parkin, S.G. Wang, A. Simon, Nucl. Instrum. Methods Phys. Res. B 260 (2007) 293–298.
[34] S. Libertino, S. Coffa, A. La Magna, Nucl. Instrum. Methods Phys. Res. B 186 (2002) 265–270.