Investigation on the priming effect of a CVD diamond microdosimeter

LU Rong-Rong, QIU Hui-Yuan, JIANG Da, LI Xiao-Lin, ZHU Jie-Qing

(Shanghai Institute of Nuclear Research, the Chinese Academy of Sciences, Shanghai 201800)

Abstract CVD diamond microdosimeter is an ideal substitute of common Si, GaAs detector for extremely strong radiation experimental environment due to its high band gap energy, fast charge collection, low dielectric constant and hardness. In order to improve its character, a CVD diamond microdosimeter was irradiated by a proton dose of 46 Gy, and a lateral micro-ion beam induced charge (IBIC) technique was utilized to characterize it in low beam current (~fA). It was clearly shown that charge collection efficiency and energy resolution were greatly improved after proton irradiation of that dose. Moreover, the homogeneities of both its counting performance and collection efficiency were enhanced. Proton irradiation of 46 Gy has been proved to be an effective way to prime a CVD diamond.

Keywords CVD diamond microdosimeter, Collection efficiency, Lateral micro-ion beam induced charge

CLC number O474 A

1 INTRODUCTION

Solid state tracking devices have become one of the mainstays of general purpose high energy physics detectors. In the future, detectors for a large hadron collider or new synchrotron will be exposed to high radiation levels in the beam interaction region. For example, detectors at the Large Hadron Collider at CERN are expected to receive a fluence of above 10^{15} particles/cm^2 in the beam interaction area during 10 years of its operation. Therefore, research on the advanced detector technology is becoming an emergent field for high energy physics.

In comparison with the properties of silicon and gallium arsenide (in Table 1), diamond provides fast charge collection due to its high electron and hole mobilities. The high band gap energy of diamond results in a negligible intrinsic carrier density and thus in a very low bulk current. This allows the detector operation of undoped material with Ohmic contacts. Furthermore, its low dielectric constant reduces the detector capacitance and its low leakage current leads to a good noise performance of the detector system.

Manuscript received date: 2002-02-20

These behaviors of diamond have been arosed great interest for physicists to exploit on its synthesization, characterization and its priming effect[1] in order to realize it as an ideal detector for high energy physical experiments.

Table 1 Different quantities of diamond, Si and GaAs

Quantity	Diamond	Si	GaAs
Atomic number	6	14	31,33
Density ($g \cdot cm^{-3}$)	3.51	2.33	5.32
Relative dielectric constant	5.7	11.9	13.1
Band gap energy (eV)	5.47	1.12	1.42
Electron mobility ($cm^2V^{-1}s^{-1}$)	1800	1350	8500
Hole mobility ($cm^2V^{-1}s^{-1}$)	1200	480	400
Energy to create e-h pair (eV)	13.2	3.6	4.3

Chemical vapor deposition (CVD) is an attractive method in diamond synthesization[2] due to its facileness and low price. CVD synthesized diamond displays its feature of columnar structure with its grain size increasing along its growth direction. The grain size is intimately correlated with the performance of CVD diamond.

The performance of CVD diamond is primarily judged by charge collection efficiency and its homogeneities. In addition to improving the chemical conditions during its growth process, there exist two additional approaches to prime diamond. One way is to lap away the low quality material on the substrate. However, this is restricted because the lapped sample is thinner than before. Another effective way is to "pump-up" the diamond by exposing it to radiation. It has been adopted by the RD42 research group of CERN using a standard priming treatment with irradiation dose from 10–100 Gy of x-rays or electrons.[3] In this paper, CVD diamond was irradiated by a 46 Gy proton beam. A lateral micro-ion beam induced charge (micro-IBIC) technique, in which a micro-beam radiates the sample in the direction parallel to the electrode surface (see Fig.1), was introduced to study the priming effect of CVD diamond by comparing the IBIC results with or without irradiation to the diamond sample.

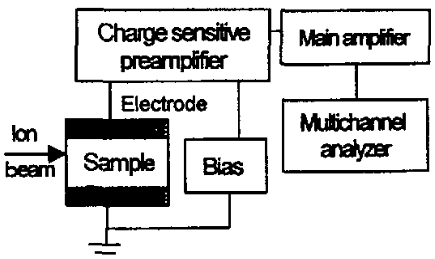

Fig.1 Experimental setup for lateral micro-ion beam induced charge (micro-IBIC)

2 EXPERIMENTAL

IBIC measurements were carried out at the microbeam facilities of Shanghai Institute of Nuclear Research and the Ruder Boskovic Institute of Zagreb (Croatia). It is of great importance to keep the beam current as low as the level of fA to avoid saturation of the electronic chain and space charge creation.[4] A suitable procedure for production of a beam current of about 1 fA is as follows:

(1) The Si surface barrier detector is shielded from the beam (by moving it off the beam axis or using a shutter arrangement) and a beam current of ~100 pA is used to focus the beam by observing the beam spot on a fluorescent material with a stereo zoom optical microscope.

(2) The object aperature is closed to reduce the beam current from 100 pA to ~1 pA.

(3) The aperature is closed so that no beam at all is entering the microprobe chamber.

(4) The detector is placed on the beam axis, and any shutter arrangement is opened.

(5) The aperature is slowly opened until ~1000 ions per second are being recorded by the detector by obversing the count rate on a rate meter connected to the amplifier.

(6) Finially the detector is replaced by the analyzed sample.

The CVD diamond samples were supplied by Norton Diamond Co. (Ma). A typical sample cross section of 200 μm×500 μm area with 200 μm thickness, clamped with two Ti/Au electrodes on both the growth and substrate side, was firstly studied by micro-IBIC technique. Then the sample was irradiated by a 46 Gy proton beam and later analyzed by micro-IBIC technique again. For a good comparision of IBIC results between nonirradiated and irradiated diamond, the electrode on the growth side was added by a fixed bias of −300 V, the other one referenced to the ground and IBIC measurements were maintained in the same experimental conditions. The charge pulse was generated by the motion of the charge carriers towards the electrodes due to the presence of the applied electric field. The charge pulse and its corresponding beam hit position were recorded in a list mode by a data acquisition system.[5] To evaluate the charge collection efficiency (CCE), defined as the ratio between the charge collected on the electrodes and the charge generated inside the sample, charge pulse was normalized to the response of a Si surface barrier detector (nominal 100% CCE) on the basis that the energy for creating a electron-hole pair is 3.6 eV in Si and 13.2 eV in diamond. CCE maps and counts distribution maps were obtained by means of off-line data processing.

3 RESULTS AND DISCUSSION

Fig.2 displays CCE maps for a nonirradiated (top left) and irradiated sample with 46 Gy dose (top right) under the bias of −300 V, respectively. The pixel size in maps is 4 μm×4 μm. The left side of CCE maps is the growth one of diamond and the opposite side is the substrate one. Charge collection efficiency range is shown on the right of CCE maps in % unit. The darker the pixel in CCE maps displays, the higher the CCE in the maps is. It is obvious that after 46 Gy proton irradiation the CVD diamond is more homogeneous with higher CCE. Counts maps are also shown at the bottom of Fig.2.

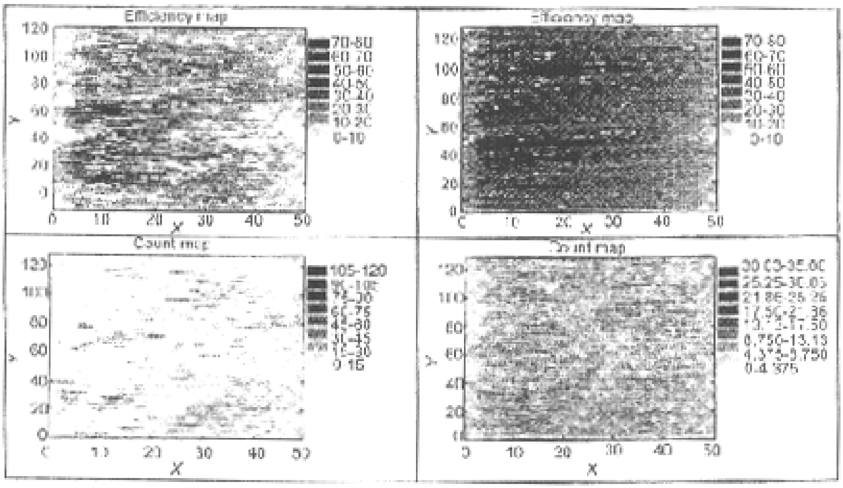

Fig.2 IBIC experimental results for nonirradiated and irradiated CVD diamond
Top: Collection efficiency map, Bottom: Count map

In order to see how the grain affects CCE, CCE maps are projected onto the Y axis. Here we took a bin box with 200 μm by 4 μm, which divided 500 μm into 128 bin columns. CCE profile along the Y direction can be obtained by averaging CCE in each bin box. Fig.3 gives a figure of the CCE profile along Y axis of CCE maps, where the solid circle curve is for the nonirradiated sample and the open circle curve for the irradiated sample. By taking a 0.02 efficiency interval to count column numbers, Fig.3 can be transformed to Fig.4 which exhibits a diagram of column numbers at certain efficiency intervals versus CCE for the nonirradiated and irradiated sample. It is of interest to note that the solid circle curve can be fitted by a continuous line with the addition of two dot Gaussian curves with two CCE centers (their corresponding amplitudes) of 0.15 (18.61) and 0.29 (3.62); in the irradiated case it is enough to fit the experimental data of an open circle curve by a dash Gaussian curve with its center of 0.29 and its amplitude of 17.19. It really seems that in the irradiated case the peak with an average value of 0.15 CCE disappears and it is "transferred" to the peak at 0.29 CCE. In other words, it could be concluded that priming cancels out the "phase" of the moderate CCE in CVD diamond by "transforming" it into a high CCE "phase". Taking into account only the most prominent peaks in Fig.4, energy resolution improves from 50% in the nonirradiated case to 33% in the irradiated one according to the energy resolution definition.

CVD diamond priming also includes the homogeneities of CCE and counts distribution. By grouping now the columns in bins of different sizes, it is possible to obtain the homogeneity of CCE and of count as a function of the bin size ν_j by the following equation:

$$h_i = 1 - \frac{\sqrt{\sum_i N_{i,j}(\eta_{i,j} - <\eta>)^2 / \sum_i N_{i,j}}}{<\eta>},$$

where $<\eta>$ is the overall average CCE, $\eta_{i,j}$ is the average CCE of the bin i with the bin size indicated by j, $N_{i,j}$ is the number of bins with the bin size indicated by j which have an average CCE $\eta_{i,j}$.

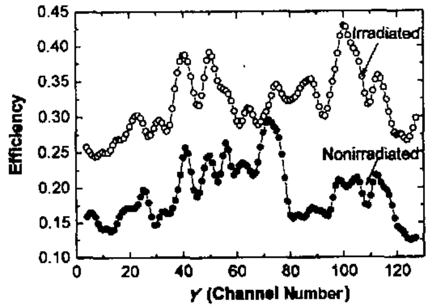

Fig.3 Collection efficiency profile along Y direction for nonirradiated and irradiated CVD diamond

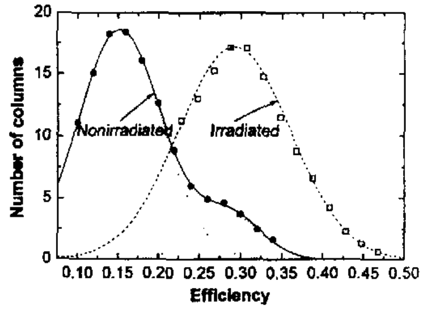

Fig.4 Collection efficiency profile versus bin size at a certain collection efficiency

The results of this analysis is shown in Fig.5 both for the nonirradiated (solid circle) and irradiated case (open circle): particularly in the latter case the uniformity is already good just at lower bin sizes, for example, at the bin size of 24 μm CCE uniformity has reached up to 85%, but it does not go to the value of 100% even at a bin size of half of the region width. Anyway, at the same bin size the homogeneity of CCE is improved after the irradiation of diamond. Data reported in Fig.5 qualitatively agree with analogous data experimentally obtained with the strip detectors.[3] Same conclusions can be drawn with respect to the counts homogeneity. Fig.6, which is analogous to Fig.5, shows the counts homogeneity behaviour as a function of bin size obtained from counts maps of Fig.2. It can be clearly seen that in the irradiated case it overcomes 90% just at the smallest bin size while it is very low for the nonirradiated case even up to very large bin sizes. It can be concluded that the improvement of the homogeneities due to priming has its major effects in counting homogeneity more than in the CCE homogeneity, as can be observed from Fig.5 and Fig.6.

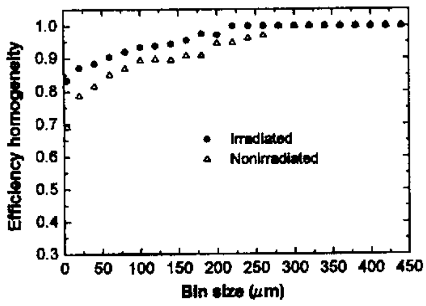

Fig.5 Profile of collection efficiency homogeneity versus bin size

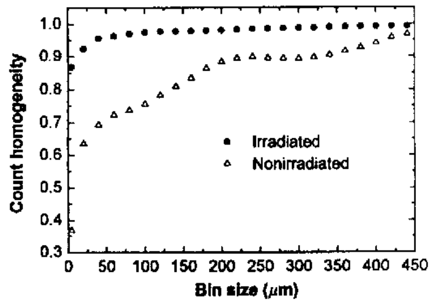

Fig.6 Profile of counts homogeneity versus bin size

4 CONCLUSION

Some conclusions can be made through the analysis mentioned above:

(1) Lateral micro-ion beam induced charge technique is an effective method to analyze the electrical properties of semiconductors materials.

(2) The charge collection efficiency and energy resolution of CVD diamond were greatly improved after 46 Gy proton beam irradiation to the sample.

(3) In addition, the homogeneities of collection efficiency and counts were increased after the irradiation. Especially for the counts homogeneity, even at lower bin size it reaches over 95%.

In summary 46 Gy proton irradiation to CVD diamond is an effective way to prime the sample.

References

1 The RD42 Collaboration, R and D proposal, Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC. DRDC/P56, CERN/DRDC 94-21, May. 1994
2 St Gobain/Norton Diamond Film, Goddard Road, Northboro, Ma 01532, USA
3 Meier D. CVD diamond sensors for particle detection and tracking, inaugural dissertation. Physics Department of Heidelberg University, Dusseldorf, 1999
4 Breese M B. J Appl Phys, 1993, 74(6):15
5 Zhu J Q. Trend Nucl Phys (in Chinese), 1992, **9**(1):50