Continuous Observation of Polarization Effects in Thin SC-CVD Diamond Detector designed for Heavy Ion Microbeam Measurement

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Abstract:

Continuous irradiation effects on a thin-film diamond detector were investigated for the utilization of these films as a detector for heavy ion microbeams. Temporal signal degradation in the energy spectrum was frequently observed during the focused heavy ion microbeam irradiation. To measure the temporal response to the each ion incidents, focused heavy ion microbeam with different beam fluence rates were irradiated to a Single Crystal (SC)-CVD diamond film detector with thickness of 50 μm . The responses to each ion were continuously observed and characterized by ion beam-induced charge (IBIC) measurement system. Heavy ions with short penetration path in diamond generate the large difference in mean path of electrons and holes, which is inverted by changing bias polarity. Signal degradation condition was relied on the bias polarity under the irradiation of heavy ions with short penetration length in the diamond. The continuous observation of IBIC signals revealed that temporal degradation in pulse height of signals, so called polarization effects, seems to be mainly caused by the hole trapping in this diamond crystal.

Keywords — diamond; polarization effect; microbeam; beam focusing effect; IBIC;

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1. Introduction

Radiation detectors based on diamond have been attracting many interests among the researchers for its excellent electrical property, thermal stability, and radiation hardness [1-3]. Progress in Chemical Vapor Deposition (CVD) procedure brought high purity in the wafer of diamond allowing them to achieve energy resolutions of less than 1% and high-speed timing responses [4, 5]. Several applications of the diamond detector were already demonstrated for the measurement of high-energy photons or particles [6, 7]. On the other hand, particle detector for focused heavy ion microbeam is now under development at the Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency (TARRI/JAEA). It requires durable, sensitive particle detectors especially for individual heavy ion irradiation experiment of 260 MeV Ne, 520 MeV Ar, or 220 MeV C from the azimuthally varying field (AVF) cyclotron accelerator [8, 9]. In-situ detection techniques for these heavy ions were required for the precise evaluation of the single-hit experiments used for single living-cell irradiation [10, 11], surface modification of polymers [12, 13], and testing semiconductor devices [14, 15]. It is desired to have thin diamond detector on the beam axis that is durable on the heavy ion irradiation for in-situ qualification [16, 17]. Thin diamond films with thicknesses of even less than 50 μm could theoretically stand durable under mechanical stress and not strongly deteriorate quality of microbeam [18]. However, there are few evidence that single-crystal diamond will be sustained its electrical quality in such thin-film form where the deposited energy of ions was expected to be strongly limited compared to that of thick diamond detectors [19]. The radiation hardness of CVD diamond film is required to be tested with several ions with focused microbeam irradiations [20-22]. There is also report on the temporal signal degradation during the irradiation of ion beam, so called polarization effect [23-27]. Investigations on the irradiation effects under both short- and long-period will be quite important to understand its behavior as a detector of focused microbeam.

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3 In this study, 50- μm -thick SC-CVD diamond detector was employed for the continuous irradiation
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5 of heavy ion microbeam. To characterize short-period signal degradation behavior of thin-film CVD
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7 diamond detectors, beam fluence rate of focused heavy ion microbeam was precisely controlled
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9 during the irradiation. The pulse signals from the diamond were continuously obtained by ion
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11 beam-induced charge (IBIC) measurement system and the enhancement of signal degradation was
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13 characterized with different microbeam irradiation conditions.
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19 2. Materials and Methods

20 2.1 Diamond detector

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22 A high-purity spectroscopic grade Single Crystalline (SC-) CVD diamond was employed as
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24 particle detector for the focused heavy ion microbeam irradiation experiment. A SC-CVD diamond
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26 wafer with size of 4.6 mm $\times$ 4.6 mm with a thickness of 50 μm was grown by Diamond Detectors,
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28 Ltd [28]. The typical leakage current was observed through I-V measurements to be less than 10^{-11} A
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30 by applying bias voltages up to ± 70 V on metalized Ti/Pt/Au electrodes deposited on both sides of
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32 the SC-CVD diamond.
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38 The diamond detector was preliminary irradiated with 5.5 MeV alpha particles from ^{241}Am
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40 radiation source and 3 MeV H^+ microbeam from 3 MV single-ended accelerator in Takasaki Ion
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42 Accelerators complex for Advanced Radiation Application (TIARA), JAEA [29, 30]. The ranges of
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44 alpha particles and protons were calculated by SRIM code as 14.3 μm and 43 μm respectively [31].
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46 The Charge Collection Efficiency (CCE) was evaluated with both particles as nearly equal to 1 with
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48 bias voltage higher than ± 10 V. Bias polarity had small effects on differences in CCE. Also IBIC
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50 spectra were well obtained with a full width at half-maximum (FWHM) of 2%, which had almost
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52 uniform distribution by scanning proton microbeam over the whole detector [32].
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2.2 Heavy Ion Irradiation Experiment

Focused heavy ion irradiation experiment was then performed on the microbeam line of a tandem accelerator [33]. Heavy ion microbeam of 15 MeV-O, 15-MeV Ni or 8 MeV-C was used for IBIC measurement [32]. The count rate was precisely evaluated using Si Surface Barrier Diode (SBD) detector placed in front of the SC-CVD detector on a linear drive and controlled from approximately 20 cps to 10^5 cps by installing attenuator [34]. The diamond detector was fixed on the movable stage to control the irradiation position. An electrode on the diamond film directed to the beam was used as signal collection electrode. The bias voltage up to ± 70 V was applied through a charge sensitive amplifier (CSA), whereas the other side of the detector was grounded. The output of the CSA was transmitted to a chain of gate and trigger electrical signal processing circuits as shown in Fig.1 to obtain the IBIC signal responses continuously. The IBIC signals were analyzed by a digital signal processing system based on National Instruments LabVIEW software system.

3. Results and Discussion

3.1 Focusing Effect of microbeam to the IBIC

The SC-CVD diamond detector was then irradiated with 15-MeV nickel or 8 MeV carbon focused microbeam. The probe had a typical beam size of approximately $2\text{ }\mu\text{m}$ and current down to 10 cps. The IBIC signals were also successfully obtained by applying certain bias voltage as 50 V. Fig. 2 shows the comparison of the pulse height spectra of 15-MeV nickel ion beam between unfocused and focused irradiation condition. On the focused condition, the beam was scanned on the area of $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$, while unfocused condition irradiates the area over $800\text{ }\mu\text{m} \times 800\text{ }\mu\text{m}$. A FWHM better than 10% was obtained for the unfocused beam but not for the focused beam irradiation. This difference must be caused by the differences in the temporal degradation in CCE for both conditions. The distortion in IBIC spectra has been enhanced during the microbeam irradiation.

3.2 Continuous observation of IBIC signals

Continuous measurement of pulse height spectra was then demonstrated to reveal the enhancement of the temporal degradation of the signals. The microbeam of 8 MeV carbon was scanned over the same area of $100 \times 100 \mu\text{m}$ with fluence rate of $4000 [\text{ions}/\text{mm}^2/\text{s}]$. Fig. 3 show the time-differential pulse height spectra of 8 MeV carbon microbeam obtained with negative and positive bias conditions. The positive bias voltage of +50V and the negative bias voltage of -50V were used for the measurement. The IBIC spectra with positive bias condition showed the degradation as the total fluence enhances. On the contrary the signal was not detonated by the beam irradiation with the negative bias voltage. Even the time-differential pulse height spectra of IBIC signal with negative bias voltage have three times longer time span compared to that of positive bias voltage, the signal had small difference as the irradiation progress. These peak degradations were recovered in certain time scale around 10 minutes after releasing the positive bias voltages by grounding the signal electrode. The results indicated that the signal degradation, so called polarization effect, occurred in this diamond detector would be related to the movement of the holes in the crystal while the difference generated by the changing bias brings the changes in the traveling path of the electrons and holes. The temporal degradation in this SC-CVD diamond was probably caused by defects that have longer de-trapping time of holes than their life time.

3.3 Fluence rate dependency

The relation between the fluence rate of the microbeam and IBIC spectra were shown in Fig. 4. The irradiation condition was configured to obtain the different beam fluence rate and the spectra were obtained with both negative and positive bias polarities of 50V. The irradiation was continued as the total fluence to be reached approximately to $10^8 [\text{ions}/\text{cm}^2]$. The significant decrease in the pulse height spectra of the IBIC signals was observed with positive bias application to the surface

electrode, while almost no decreases were obtained in the spectra obtained with negative bias condition. The speed of the degradation enhancement was clearly differed by the fluence rate with positive bias. Fig. 5 shows the relations between the signal degradation and the total fluence. The attenuation factor of the polarization seems to have a dependency to the fluence rate with the positive bias voltage. The results indicate that the hole-trapping defect that causes the polarization effect distributed with the certain density in this CVD diamond crystal.

4. Conclusion

Microbeam irradiation effects on a detector-grade SC-CVD diamond film were investigated under the continuous MeV heavy ion bombardments. The response of the detector for focused heavy ion microbeam was completely different from that for unfocused condition. Temporal signal degradation, so named polarization effect, was observed especially at the microbeam irradiation with higher fluence rates. This temporal decrease seems to be caused by high-density charge generation occurring under intense ion beam irradiation. Signal degradation was strongly deferred by the bias polarity under the irradiation and would be mainly caused by the hole-trapping defects in the crystal. Further research is required to determine the defect level of these hole-trappers at the surface or inside the SC-CVD diamond, while it would require technical development on the measurement to investigate a deep level defect in such wide-band gap semiconductor.

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Figures

Fig. 1 Schematic drawing of electrical chain for continuous IBIC measurement.

Fig. 2 Comparison of IBIC spectra obtained in focused and unfocused conditions.

Fig. 3 Time-differential pulse height spectra of IBIC continuously measured at 8-MeV carbon bombardment with (a) positive and (b) negative bias voltage of 50V..

Fig. 4 Comparison of the total pulse height spectra of IBIC signals obtained with different fluence rates with (right) positive and (left) negative bias voltage of 50V.

Fig. 5 The relation between the total fluence and relative pulse height ratio to the original signals with different fluence rate under positive bias voltage supply.

Figure 1

Figure 2

Figure 3

(a) IBIC spectra obtained with positive bias

(b) IBIC spectra obtained with negative bias

Figure 4

Figure 5