Microbeam Irradiation Effects on Transmission Diamond Detector

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Abstract

Response of thin film CVD diamond to the ionized particle irradiation was investigated for the utilization as a transmission detector in the end-station of the microbeam line connecting to the AVF cyclotron at JAEA/Takasaki. A spectroscopy-grade 50 μm-thick film Single Crystalline CVD diamond was characterized using Ion Beam Induced Charge (IBIC) and Transient Ion Beam Induced Current (TIBIC) systems. Significant decrease in IBIC signals was observed temporally during a microbeam irradiation period. Peak degradation was easily recovered in a short time by release of biases thus it seems to be caused by the polarization effect due to charge-capture by defects in the surface layer of diamond.

1. Introduction

Diamond is a kind of wide band-gap semiconductor as a promising candidate of radiation sensors with advantage in Signal to Noise (S/N) ratios [1,2]. The diamond detector is expected to have high charge collection efficiency, good thermal stabilities, and excellent radiation hardness [3,4]. Various researches had been already reported on the development of the radiation detectors of diamond [5, 6]. It was quite stable and several of them reached energy resolution better than 1% and transient time response of several nanoseconds.

On the other hand, focused high-energy heavy ion irradiation technique requires durable and sensitive transmission detector, at the same time, for single-ion-hits, such as 260 MeV Ne, 520 MeV Ar, or 220 MeV C from the AVF Cyclotron facility at Takasaki Advanced Radiation Research Institute (TARRI), Japan Atomic Energy Agency (JAEA) [7,8]. This is a new single-ion-hit detector for practical applications such as biological cell irradiation [9,10], fabrication of new materials enhancing polymer [11,12] or test of semiconductor devices [13,14].

Techniques of single MeV ion detection using CVD diamond film or other bulk scintillator were achieved through the measurement of secondary electrons and ion beam-induced photons [15,16]. These techniques are quite effective to detect the incident position of the ionized particle but they still have issues to be improved in their resolutions in energy and timings. Recent progresses in Chemical Vapor Deposition (CVD) process of diamond have enabled thin Single Crystal (SC) CVD diamond films with thickness under 50 μm and with quite low impurities [17]. With these progresses, a transmission high-energy particle detector made of a thin SC-CVD diamond film came to in a futuristic design of beam extraction window for the high-energy heavy ion microbeam line of AVF cyclotron at JAEA/Takasaki. The diamond is durable to mechanical stress and vibrations even in the thin film-form with thickness under 10 μm. Theoretically, thin diamond films under 10μm could still be operated as transmission radiation sensors. Great effort had been paid for the development of thin film diamond detector to use it in spectroscopic purpose [18]. However, there are still very few studies on the irradiation effects and radiation hardness on the intense ion microbeam irradiations.

In this research, transmission particle detectors using thin-film diamond were newly evaluated for the individual detection of single-hit of MeV ions. At first, this paper describes the preparation of SC-CVD diamond film detectors with thickness around 50 μm and the first trial of irradiation experiment of focused MeV ionized particles. To obtain the energy-response of the detectors, microbeam irradiation experiment was executed on Ion Beam Induced Charge (IBIC) and Transient Ion Beam Induced Current (TIBIC) systems at the heavy ion microbeam system on the tandem accelerator of JAEA [19]. It was experimentally examined the response to the MeV ions through energy spectrum and pulse signals.

2. Materials and Methods

2.1 Preparation of the diamond transmission detector

The high-purity spectroscopic-grade SC-CVD diamond films were provided and prepared as a body of transmission detector for heavy ions by Diamond detector ltd. A wafer with size of 4.6 × 4.6 mm^2 of one SC-CVD diamond film was grown in thickness of 50 μm. Metalized layers of Ti/Pt/Au were evaporated with thickness of approximately 50 nm on both side of the detector bodies of SC-CVD diamond films as an ohmic-contact electrodes. Leakage current was measured to be under 10^{-11}A at biases up to ± 70 V.

2.2 Irradiation Experiments

The SC-CVD diamond film detectors were first evaluated with alpha particles from ^{241}Am standard radiation source. One side of the detector faced to the source was connected to the Ortec 710 high voltage bias power supply and Charge Sensitive Amplifier (CSA) via SMA through, while the another side of the detector was terminated to the ground. The output of CSA was transmitted to the Ortec 572 shaping linear amplifier and Pulse Height Analyzer (PHA). Bias voltage was applied to the diamond films with maximum voltage of ±70 V.

Figure 1 shows the energy spectrum of 5.5 MeV alpha particles from ^{241}Am. The relations between the applied bias voltages and charge collection efficiency and counting-rate efficiency were also obtained with the same condition. Alpha particles were irradiated to the detector with an average density of 10 [particles/mm^2/s]. Irradiation was continuously performed for the evaluation of the durability in the energy-resolution of the detector. 2% in Full Width Half Maximum (FWHM) was sustained as the total fluence was reached to the 10^9 [ions/cm^2].

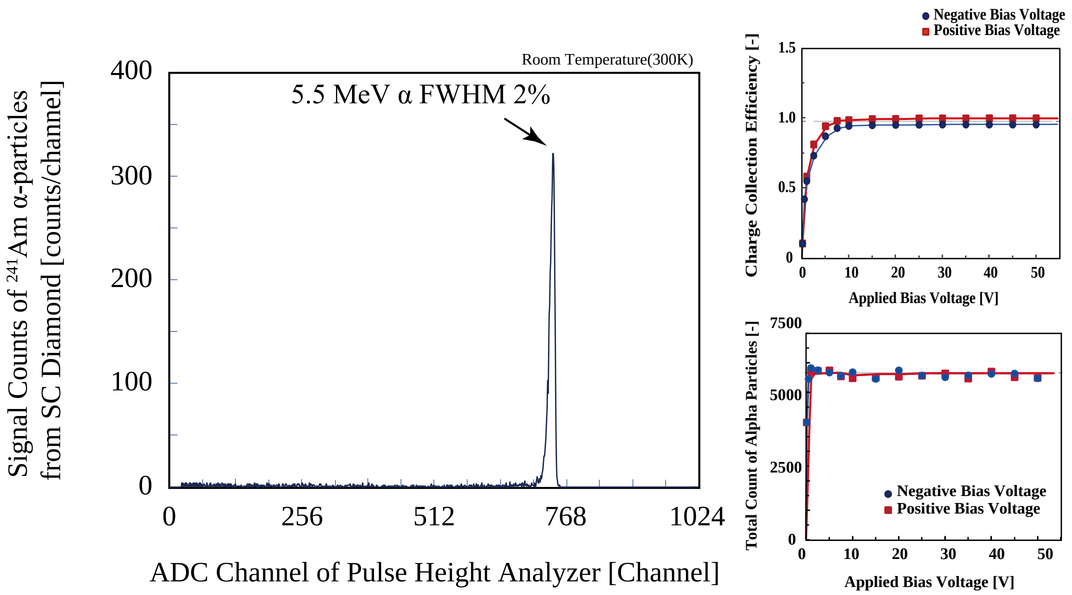

Fig. 1. (left) The energy spectrum of 5.5 MeV alpha particle obtained by the SC-CVD diamond detector. (right)The dependencies of Charge collection efficiency and counting rate efficiency to the applied bias voltages

Then the microbeam irradiation experiments were performed on the microbeam lines of single-ended and tandem accelerators at Takasaki Ion-accelerators for Advanced Radiation Application (TIARA), JAEA. Microbeam of 3 MeV H^+ and 15 MeV O^{4+} were irradiated into the SC-CVD diamond detector with beam current of approximately 100 cps by scanning microbeam probe with maximum area of 800 μm × 800 μm.

First, 3 MeV H^+ microbeam irradiation was performed to evaluate uniformity in the CCE by visualizing Ion Beam Induced Charge (IBIC) images. Same NIM electrical circuit chain for high voltage bias power supply (Ortec 710) and CSA was used for the IBIC signal process. Obtained signal was processed on the MCA system originally developed for Particle Induced X-ray Emission (PIXE) analysis [20]. Beam current was first monitored by faraday cup and count-rate was then decreased by installing the object slit to approximately 100 cps using the output signal from SC-CVD diamond detector.

Following experiment was demonstrated with heavy ion microbeam of 15 MeV O^{4+} at microbeam line of a tandem accelerator. The system equips IBIC analysis system and the Transient Ion Beam Induced Current (TIBIC) collection system [21]. Signal was processed the same NIM electrical circuit chain to obtain IBIC signal responses. Count-rate of the beam was previously controlled by pulse counting from Si Surface Barrier Diode (SBD) detector placed in front of the SC-CVD detector on a linear drive. The transient current was also monitored by a 3 GHz or 15 GHz Digital Storage Oscilloscope (DSO) Tektronix TDS694C via high voltage bias-tee. The transient current signals were stored on real-time by the NI Labview based digital signal processing system in the condition of single ion hit.

3. Results and discussion

3.1 Observation of the uniformity in CCE

Focused proton microbeam of 3 MeV was irradiated into SC-CVD diamond detector with spatial beam spot size of 1 μm with beam current of approximately 100 cps. A photograph of the detector was shown in Fig.2. 4×10^4 [particles/mm^2/s] was the typical density of the proton microbeam irradiation. Approximately 1.8% in Full

Width Half Maximum (FWHM) was obtained in the energy spectra. Several Positions (A)-(E) in the detector were irradiated by the microbeam with scanning area of 100 μm × 100 μm. IBIC images correspond to the area of (A) to (E) were also shown in the figure. Almost homogeneous distributions in charge collection were obtained in the IBIC image induced by 3 MeV proton microbeam. The CCE has decreased on the edge of the wafer in a scale of approximately 5 micrometers from the terminal of the electrode as shown in IBIC image of (D) and (E). The result suggest that this SC-CVD diamond film has uniform response to the ionized particle in its relatively-large detection plane of 4.6 mm × 4.6 mm that is well correspond to the area of beam extraction window on the AVF cyclotron.

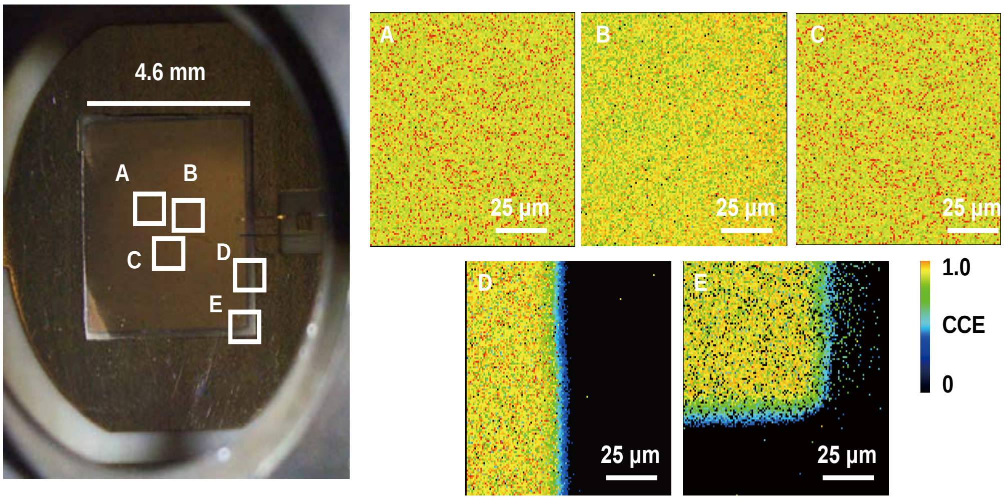

Fig. 2. (left) A photograph of the SC-CVD diamond detector and (right) IBIC images obtained by 3 MeV H+ microbeam in specific area (A) through (E) indicated in the photograph

3.2 Observation of the durability

The detector was then irradiated with 15 MeV O^{4+} microbeam. The count rate of this heavy ion microbeam was also reached to approximately 4×10^4 [particles/mm^2/s] with a scanning area of 50 × 50 μm^2 and approximately 5% in Full Width Half Maximum (FWHM) was obtained in the energy spectra. The experiment was first performed to reach the total fluence to 10^9 ions/cm^2. As shown in Fig.3, significant decrease of pulse height of IBIC signals was observed between 10^8 ions/cm^2 to 10^9 ions/cm^2, however, this peak degradation easily recovered in a short time by release of bias voltages. This temporal degradation effect was enhanced in areas damaged by previous ion irradiation. It was quite important that we did not obtained such a high temporal decrease with the microbeam of 3 MeV H^+ or higher-energy microbeam irradiation of 260 MeV Ne^{7+}. Therefore, the temporal peak degradation is expected to be caused by the polarization effect due to charge captured by defects in the near surface region of the single crystal diamond.

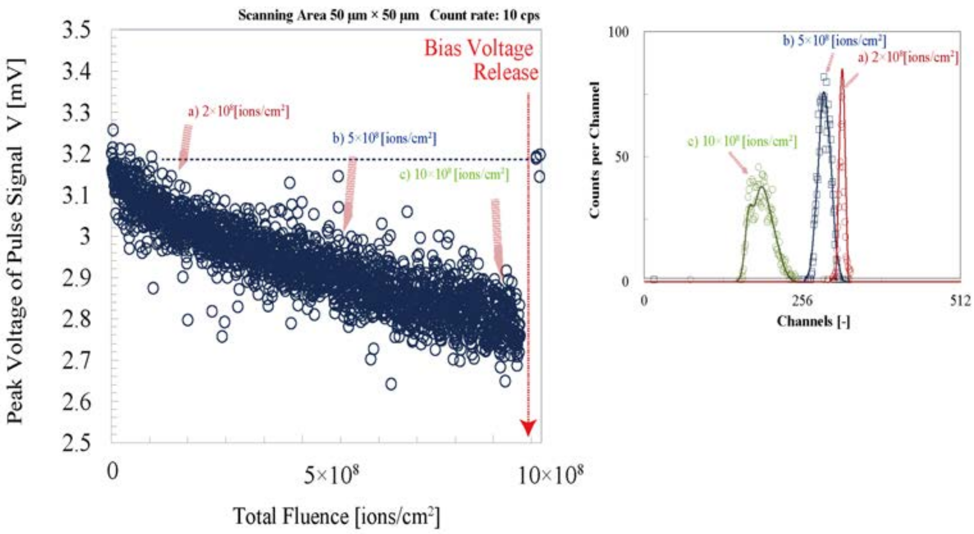

Fig. 3. (left) The decrease in pulse height spectra of IBIC signals with increase of the total fluences (right) IBIC spectra obtained at three different fluences.

4. Conclusion

The transmission particle detectors based on the CVD diamond film substrate were prepared and irradiated with microbeam for the evaluation to the futuristic usage of MeV ion microbeam irradiation. SC-CVD diamond detector with thickness of 50 µm was characterized by using the 241-Am standard alpha source and ion microbeam irradiations. Uniformity of the response of the detector was obtained by the irradiation of 3 MeV proton microbeam and IBIC analysis. Compared with the result of alpha-particles from radiation source, SC-CVD diamond showed totally different response to the irradiation with the 15 MeV O^{4+} microbeam. This temporal decrease of the CCE is quite unique phenomena of the microbeam irradiation where the intense charge generation occurs in high density. Additional experiments are being proceeded to characterize these temporal decreases by changing energy and ion species of the microbeam. It is also need to be take account the analysis and measurement of the defects distribution on the surface of the SC-CVD diamond that is expected to play a key role for the generation of temporal CCE distortion by so named polarization effect.

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