Nuclear Instruments and Methods in Physics Research A 784 (2015) 147–150

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Radiation hardness of a single crystal CVD diamond detector for MeV energy protons

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ARTICLE INFO

Available online 18 December 2014

Keywords:
Plasma diagnostics
Diamond detector
Single-crystal CVD diamond
Radiation hardness

ABSTRACT

We have fabricated a particle detector using single crystal diamond grown by chemical vapor deposition. The irradiation dose dependence of the output pulse height from the diamond detector was measured using 3 MeV protons. The pulse height of the output signals from the diamond detector decreases as the amount of irradiation increases at count rates of 1.6–8.9 kcps because of polarization effects inside the diamond crystal. The polarization effect can be cancelled by applying a reverse bias voltage, which restores the pulse heights. Additionally, the radiation hardness performance for MeV energy protons was compared with that of a silicon surface barrier detector.

1. Introduction

The ability to detect deuterium–tritium (D–T) neutrons and charged particles such as deuterons and alpha particles escaping from thermonuclear plasmas in future tokamaks such as NSTX, JT-60U, and the large helical device (LHD) is very important, and is essential for monitoring the energy balance in these plasma devices [1,2]. The detection must be carried out in a harsh environment (at high nuclear radiation fluxes, high temperature, etc.), which limits the use of common semiconductors such as silicon for use in particle detection devices.

Diamond crystal has many superior properties for use as a particle detector substrate for plasma diagnostics. The higher electrical resistivity and band gap energy of diamond crystal compared with those of silicon make it possible to operate with low noise performance [3,4]. Fast signals for particle detection and high rate counting can be obtained using diamond crystals because of their high breakdown electric field strength and high carrier saturation velocities [5–8]. Furthermore, diamond crystal detectors have a higher displacement energy than those made of silicon, which gives them superior radiation hardness when used to fabricate radiation detectors [9]. With these advantages, it is expected that particle detectors made of diamond crystal will maintain their operating characteristics in the harsh environments of high temperatures and high-dose radioactive conditions in plasma devices, where the spectroscopic performance of silicon detectors deteriorates.

The use of natural diamond crystal, i.e., natural diamond detector (NDD) for such application has been carried out [10]. For instance, previous NDDs showed 2–3% energy resolution (FWHM) as D–T neutron spectrometers [11]. The charge collection efficiency of the IIa-group natural diamond crystals is sufficient to allow their usage as particle detectors for high resolution particle spectrometry. However, the use of NDD is limited by the availability of type IIa natural diamond crystals, which have superior electrical properties. The latest generations of diamond particle detectors are made using high purity synthetic single crystal (sc) grown by chemical vapor deposition (CVD) [12].

In a previous study, the detection of 14.2 MeV fast neutrons with a sc-CVD diamond detector was performed at FNS/JAEA. The CVD diamond single crystal used for fabrication of the detector was grown on HP/HT type IIa substrates using a microwave plasma-assisted CVD device (SEKI TECHNOTRON CORPORATION, AX5250) at Hokkaido University. The final crystal dimensions were 5 mm × 5 mm × 60 μm. The growth conditions were as follows: substrate temperature, 850 °C; gas pressure, 110 Torr; methane concentration, 1%; and RF power, 1000 W. The energy peak resulting from the $^{12}C(n,\alpha)^{9}Be$ reaction under 14.2 MeV neutron irradiation was clearly observed and an energy resolution of approximately 3.5% (FWHM) was achieved, as

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http://dx.doi.org/10.1016/j.nima.2014.12.036
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shown in Fig. 1. In this experiment, no performance degradation in the energy resolution was observed after 6 h at a low-counting rate of ~20 cps irradiation.

On the other hand, investigation of the radiation hardness under high-counting rate conditions is necessary for applications in harsh environments such as those required for plasma diagnostics. In this work, we fabricated a sc-CVD diamond detector and measured the irradiation dose dependence of the output pulse height of the diamond detector using 3 MeV protons at 1.6–8.9 kcps counting rates. We also compared the radiation hardness performance toward MeV energy protons to that of a silicon surface barrier detector. Additionally, we comment on the effect of polarization inside the diamond crystal on the output pulse height from the sc-CVD diamond detector.

2. The experimental set-up and measurements

The detector was made from the sc-CVD diamond fabricated at Hokkaido University and described in detail elsewhere [13]. Fig. 2 provides a schematic of the diamond detector and a diagram of the electronic circuit used in the investigation of the radiation hardness for MeV energy protons.

The detector has a layered structure of Pt (50 nm)/sc-CVD diamond (90 μm)/Ti (50 nm)/Au (50 nm), and the TiC layer was created at the boundary region between the diamond crystal and the Ti electrode layer. The 90 μm-thick sc-diamond was grown under the same growth conditions described in the introduction. A Pt Schottky contact and a Ti/Au Ohmic contact were fabricated as electrodes on the diamond crystal by vacuum evaporation. Sintering of the evaporated Ti on the diamond crystal was carried out at 400 °C for 1 h to create a TiC layer. The Pt electrode was circular with a 3 mm diameter. On the other side of the crystal, the Ti/Au contact covered the entire surface of the crystal. The diamond detector was housed within an aluminum box, and the diameter of an entrance aperture on the aluminum box was the same as the diameter of the Pt electrode, 3 mm. During operation, the Pt electrode and the Ti/Au electrode were set at ground and −100 V voltage levels, respectively. Incidentally, the output pulse height showed saturation under the bias voltage from −80 V to −100 V, and the leakage current at −100 V was approximately 0.3 pA, which is plotted in the current–voltage (*I*–*V*) curve of the diamond detector as shown in Fig. 3.

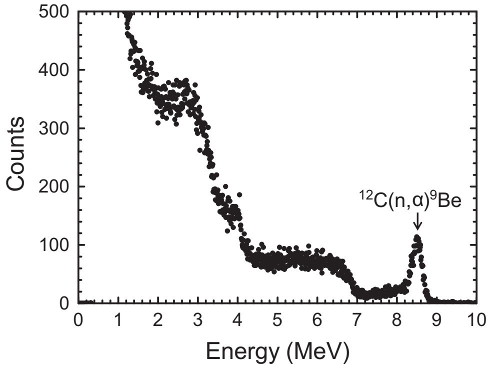

Fig. 1. Energy spectrum under 14.2 MeV neutron irradiation measured with a sc-CVD diamond detector. Applied bias voltage was set to +200 V.

Incident protons were generated and accelerated using the pelletron accelerator (National Electrostatic Corp. 5SDH-2) operated by RIKEN Atomic Physics Laboratory. The total kinetic energy of the accelerated protons was 3 MeV, incident onto the Pt electrode side of the detector. Horizontal and vertical slits with 50 μm width were placed in front of the detector. Ion-induced pulses were read out from the Ti/Au electrode using a charge-sensitive preamplifier (TENNELEC TC 171), and the preamplifier outputs were shaped by a shaping amplifier (CANBERRA 2024). The shaping time of the amplifier was set to 4 μs. Pulse height spectra for the incident protons were measured using a multichannel analyzer (MCA: CAEN N957), and the number of incident protons was also recorded using a scaler (REPIC RPN-031). The proton count rate during the experiment was set to 1.6–8.9 kcps. The pressure in the beamline vacuum duct was about 7×10^{-7} Torr, which was sufficient to keep energy loss induced by collisions with residual gas molecules was negligible.

3. Results and discussion

The pulse height spectra for 3 MeV protons were measured and the energy peak was clearly observed. However, the output pulse height decreased with proton irradiations, as can be seen in Fig. 4. Fig. 4(a) shows the peak channel number as a function of the number of incident 3 MeV protons. The vertical axis shows the peak channel number normalized by that obtained at the start of irradiation. The count rate at each measurement period in this experiment is also shown in the upper part of the figure. These values show the range of the fluctuation of the count rate due to the instability of the ion-beam intensity.

Additionally, Fig. 4(b) shows the pulse height spectra measured with sc-CVD diamond detector under various 3 MeV proton fluences. The capital letters (A)–(F) labeling each spectrum correspond to the measurement times indicated in Fig. 4(a), respectively. The peak width increased by approximately twice at incident rates above ~7 kcps compared with that observed at the start of irradiation because of pile-up events, as shown in panels (E) and (F).

The phenomenon of output pulse height decreasing with radiation irradiation is likely to be caused by polarization effects, which are well known in compound semiconductor radiation detectors such as cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe) detectors [14,15]. A quantitative dynamical model, based

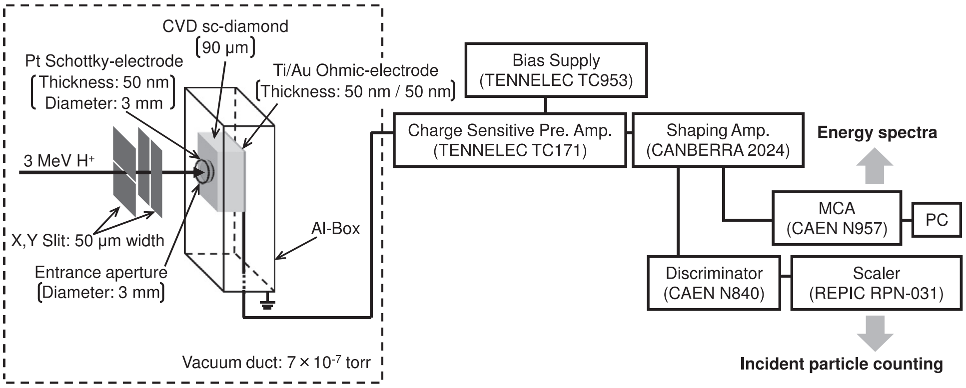

Fig. 2. Schematic of the diamond detector and block diagram of the electronic circuit used in 3 MeV-proton measurements. MCA stands for multi-channel analyzer.