Diamond & Related Materials 75 (2017) 161–168

Contents lists available at ScienceDirect

Diamond & Related Materials

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

Transient current induced in thin film diamonds by swift heavy ions

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ARTICLE INFO

Keywords:
Diamond crystal
Radiation induced effects
Detectors
Membranes

ABSTRACT

Single crystal diamond is a suitable material for the next generation particle detectors because of the superior electrical properties and the high radiation tolerance. In order to investigate charge transport properties of diamond particle detectors, transient currents generated in diamonds by single swift heavy ions (26 MeV O^{5+} and 45 MeV Si^{7+}) are investigated. Two dimensional maps of transient currents by single ion hits are also measured. In the case of 50 μm-thick diamond, both the signal height and the collected charge are reduced by the subsequent ion hits and the charge collection time is extended. These results are thought to be attributable to the polarization effect in diamond and it appears only when the transient current is dominated by hole current. In the case of 6 μm-thick diamond membrane, an "island" structure is found in the 2D map of transient currents. Signals in the islands shows different applied bias dependence from signals in other regions, indicating different crystal and/or metal contact quality. Simulation study of transient currents based on the Shockley-Ramo theorem clarifies that accumulation of space charges changes distribution of electric field in diamond and causes the polarization effect.

1. Introduction

Diamond is an attractive material for radiation detectors to be used in harsh environments because of its superior electronic properties, such as high carrier mobility, wide bandgap, high radiation tolerance, and high breakdown voltage. Although the study for diamond radiation detectors started in the 1940s [1,2], many problems about the sample preparation, such as availability, crystal quality, and control of impurity, made the development difficult because natural diamonds were used in the earliest years. Since significant improvement has been recently achieved in the crystal growth technology of diamond, research and development for single-crystal diamond radiation detectors has been extensively carried out in recent years and their superior characteristics has been demonstrated [3]. For instance, it has been recently reported that single-crystal diamonds grown by chemical vapor deposition (CVD) showed almost 100% charge collection efficiency and high energy resolution (< 1%) in the detection of 5.486 MeV alpha particles from ^{241}Am [4]. Investigations of photoconductive properties of single-crystal CVD diamonds have been demonstrated the potential for application of UV and X-ray detectors [5,6].

One of the critical issues on diamond radiation detectors is the polarization effect: temporal degradation of signal amplitude during ion irradiation. Being generally known to occur in insulator crystals [7], the polarization effect has been one of the important topics of interest in diamond radiation detectors [8–11]. When charge carriers generated by radiation are trapped in deep levels in diamond, they cannot be released in a short time and give rise to a space charge (internal electric field). The external electric field is screened by the space charge and as a result, the collected charge signal amplitude decreases. The polarization is more pronounced for short range ions, which produce high ionization in a small volume [12]. This is a brief explanation of the polarization effect, and the detail mechanism is still less well understood. It is still unclear how the charge collection process of generated carriers are affected by the polarization effect.

In this study, transient currents in diamond generated by swift heavy ions were measured using Time Resolved Ion-Beam Induced

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[1] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

http://dx.doi.org/10.1016/j.diamond.2017.04.005
Received 15 November 2016; Received in revised form 17 March 2017; Accepted 4 April 2017
Available online 05 April 2017
0925-9635/

Current (TRIBIC) technique [13] in order to investigate the charge collection process in diamonds. Two dimensional distribution of transient currents was also investigated.

2. Experimental

Two samples were used in this study: a single-crystal CVD (sc-CVD) diamond with the thickness of 50 μm and a thin sc-CVD diamond membrane with the thickness of 6 μm. The fabrication method of diamond membrane was reported elsewhere [14]. The detectors were of electronic grade (substitutional nitrogen content [N] < 1 ppb) and optical grade ([N] < 5 ppm), respectively, which were commercially available from Element Six Ltd. Metal electrodes were formed on both sides of the samples to collect charges generated by incident ions: Ti/Pt/Au for the 50 μm-thick diamond and Aluminum for the 6 μm-thick diamond membrane. The metallization on the 50 μm-thick diamond was performed by Diamond Detectors Ltd. Current-voltage (IV) and capacitance-voltage (CV) characteristics under dark conditions were investigated prior to TRIBIC measurements in order to evaluate leakage current and electric field distribution in the samples. CV measurement was performed at the frequency of 1 MHz and the signal amplitude of 20 mV.

The experimental setup of TRIBIC measurement is illustrated in Fig. 1. Comparing to conventional Ion Beam Induced Charge (IBIC) technique [15], the TRIBIC measurement gives information on time variation of charge collection, i.e. transient current, in addition to generated charge by a single ion incidence. The detail of TRIBIC measurement system was reported elsewhere [13]. The samples were irradiated at normal incidence with a focused microbeam of 26 MeV O^{5+} and 45 MeV Si^{7+} ions at the Sandia National Laboratories (SNL), USA. Ion-induced transient currents generated by single ion hits were measured from the top electrode of sample by the 20 GHz oscilloscope (Tektronix, DPO 72004) via a linear amplifier (Picosecond Pulse Labs, 5840B) and a bias tee. The transient currents and their positional information were measured under dark conditions, and the two dimensional (2D) map of the transient currents was recorded. The spot size of the microbeam was about 1 μm in diameter. The microbeam was scanned once at the rate of 2–3 cps from left to right and from bottom to top, and the scan area was 50 × 50 μm^2. It should be noted that this irradiation condition was chosen to intentionally induce the polarization effect. However, no significant displacement damage was expected to be introduced into diamond during TRIBIC measurements, since < 2000 ions hit within 50 × 50 μm^2 for one microbeam scan and it corresponds to the fluence of 8×10^8 cm^{-2}. A bias voltage ranging from − 50 V to + 50 V was applied to the top electrode of sample (the same side as ion incidence) and the bottom electrode was grounded. The variation of transient currents due to applied bias voltages was also investigated.

Energy depositions and creation of number of electron-hole pairs by incident ions were calculated by SRIM [16]. The calculation results are

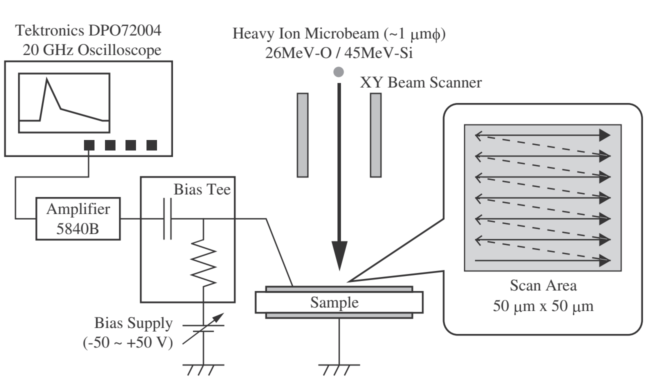

Fig. 1. Experimental setup of TRIBIC measurement.

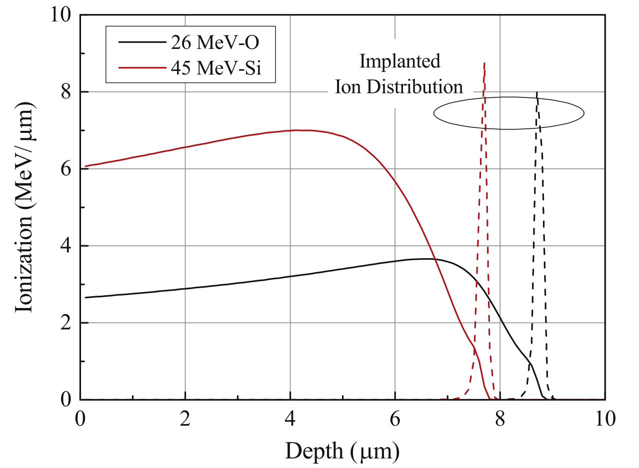

Fig. 2. Implanted ion distributions and deposited energy profiles of 26 MeV Oxygen and 45 MeV Silicon into diamond.

shown in Fig. 2. The projected ranges of 26 MeV-O and 45 MeV-Si in diamond were calculated to be 7.7 μm and 8.7 μm, respectively. Therefore, 45 MeV-Si ions completely pass through the 6 μm-thick diamond membrane and 38.9 MeV (86.4%) of the energy was estimated to be deposited by electronic excitation. The diamond density of 3.515 g/cm^3 and the average ionization (electron-hole pair creation) energy of 13.2 eV [17] were used in these calculations.

3. Results and discussion

3.1. TRIBIC signals of 50 μm-thick diamond

Fig. 3(a) shows the IV characteristics of the 50 μm-thick diamond under dark conditions. The bias voltage was applied from the top electrode and was swept from negative to positive. The leakage current was low enough to investigate transient currents by incident ions (< 100 pA at ± 50 V). However, the IV curves showed asymmetric shape, indicating the Ohmic contacts were incompletely formed. This asymmetry was thought to be due to the difference in junction barrier height of the metal-diamond interfaces [18]. Since the capacitance was 5.35 pF independent of the bias voltage, a uniform external electric field by the bias supply was formed throughout the diamond between the top and bottom electrodes. The 6 μm-thick diamond membrane showed the symmetric IV characteristics, although the relatively large leak current was found (around 500 nA at ± 50 V), as shown in Fig. 3(b).

Fig. 4 shows typical transient currents (TRIBIC signals) at the biases of ± 50 V (± 10 kV/cm) and + 20 V (+ 4 kV/cm) when a single 26 MeV-O ion hit to the 50 μm-thick diamond. The linear amplifier was not used for this measurement. The signals shown in Fig. 4 were obtained by taking the average of ten raw TRIBIC signals to make scattered data more visible. The signals at the positive bias were larger than the signals at the negative bias. Also both the rise and fall times, which are defined as the time intervals between 90% and 10% of peak current of TRIBIC signal, increased with decreasing applied bias; 1.1 and 1.5 ns for + 10 kV/cm, and 1.9 and 2.5 ns for + 4 kV/cm, respectively. Collected charge was obtained by integrating transient current with respect to time and charge collection efficiency (CCE) was also obtained from the collected charge, the deposited ion energy, and the average ionization energy. The charge generated in 50 μm-thick diamond by 26 MeV Oxygen was estimated to be 0.318 pC. Fig. 5 shows variations of the peak heights and CCEs of TRIBIC signals as a function of applied electric field. Histograms for the peak heights and CCEs were produced using more than several hundreds of signals and these mean values were plotted in Fig. 5. Both the peak height and the CCE increased with increasing absolute value of electric field. The value of