Title:

Transient Current Induced in Thin Film Diamonds by Swift Heavy Ions

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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 (less than 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 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 $[\text{N}] < 1$ ppb) and optical grade ($[\text{N}] < 5$ 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 $50 \times 50 \mu m^2$. 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 less than 2000 ions hit within $50 \times 50 \mu m^2$ for one microbeam scan and it corresponds to the fluence of $8 \times 10^8 cm^{-2}$. 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 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.

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.

3. Results and Discussion

3.1. TRIBIC signals of 50 μm -thick diamond

Figure 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 (less than 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).

Figure 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. Figure 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 CCE was higher at positive bias than at negative bias; 86.2 % at +10 kV/cm and 60.4 % at -10 kV/cm. This trend corresponds to the results reported elsewhere [4, 12] and the relatively lower CCE at -10 kV/cm is thought to be related to the larger leakage current (-75 pA at -50 V in Fig. 3(a)). It should be noted that the typical uncertainty of CCE

values, which is shown by an error bar in Fig. 5, is larger than that obtained from conventional IBIC technique, since the fluctuation of baseline is generally large in the TRIBIC measurement and the longer decay component (above 10 ns) was not included in the calculation of CCE values. According to the Shockley-Ramo theorem [19], in the case of charge generation near one electrode, CCE as a function of applied electric field can be explained by a single-carrier Hecht equation:

$$\text{CCE} = \frac{(\mu\tau)E}{W} \left\{ 1 - \exp\left(-\frac{W}{(\mu\tau)E}\right) \right\} \quad (1).$$

Where W , E , and $\mu\tau$ are the thickness, the electric field, and the mobility-lifetime product, respectively. A uniform electric field in the diamond is assumed in Eq. (1). The fitting result is shown as the red line in Fig. 5. The values of $\mu\tau$ product were $(1.8 \pm 0.2) \times 10^{-6}$ cm²/V for holes and $(6.4 \pm 0.8) \times 10^{-7}$ cm²/V for electrons. These values are substantially lower than the values reported elsewhere [4, 12, 20, 21], which can be explained as follows. Since density of electron-hole (e-h) pairs generated by swift heavy ions is much higher than that of light ions (protons and alpha particles) and some carriers recombine promptly after generation, the value of CCE for swift heavy ions are generally lower than that for light ions [22]. As a result, the lower value of $\mu\tau$ product was obtained from the CCE for heavy ions than the reported values.

Fig. 3. Current-voltage characteristics of (a) the 50 μm -thick diamond and (b) the 6 μm -thick diamond membrane under dark conditions.

Fig. 4. Typical TRIBIC signals of the 50 μm -thick diamond generated by a single 26 MeV O^{5+} ion hit. The applied electric fields were +10 kV/cm (black), -10 kV/cm (red), and +4 kV/cm. The linear amplifier was not used for this measurement.

Fig. 5. Variations of peak height of TRIBIC signal (closed squares) and charge collection efficiency (CCE, red open circuits) of the 50 μm -thick diamond due to 26 MeV O^{5+} ion hits as a function of electric field. The line in red are the fitting curve of CCE by Eq. (1). The typical uncertainty of CCE values is also shown by an error bar.

Fig. 6. (a) Two dimensional maps of peak height of TRIBIC signals in the 50 μm -thick diamond and (b) collected charge induced by 45 MeV Si^{7+} ion hits. The applied bias was +50 V (+10 kV/cm) and the irradiation area was $50 \times 50 \mu\text{m}^2$. (c) Variations of the peak height (black) and the collected charge (red) as a function of number of single ion hits. (d) TRIBIC signals at the positions of A to F shown in (b). The number of detected signals at A to F are listed in the right table. A typical TRIBIC signal at the bias of -50 V (-10 kV/cm) is also shown in (d).

The TRIBIC measurement results of the 50 μm -thick diamond by 45 MeV Si^{7+} ion hits at +10 kV/cm are summarized in Fig. 6. Since the linear amplifier was used, the signal heights were much larger than the signals by 26 MeV O^{5+} ions in Fig. 4. Figs. 6(a) and (b) show the 2D maps of signal heights and collected charges of TRIBIC signals, respectively. Fig. 6(c) shows the variation of peak height and collected charge as function of number of single ion hits. Fig. 6(d) shows typical TRIBIC signals at different XY positions and also the typical TRIBIC signal at -10 kV/cm (dashed line in black). These signals are identified by the letters of A to F and A', and their XY positions and the number of hits are

shown in Figs. 6(b) and (c), respectively. These data were obtained by taking the average of ten TRIBIC signals around the number of hits shown in the table in the upper right of Fig. 6.

It was found from Fig. 6(c) that both the signal height and the collected charge decreased gradually with increasing number of hits. The increase in width of the transient current in addition to the decrease in peak height appeared (see the signals A, B, C, and D in (d)). The microbeam was scanned from left to right, and from bottom to top, and the transient current was recorded only when the signal height was higher than a trigger level of the oscilloscope. Therefore, the signal amplitude was reduced gradually from the bottom left to the top right in the 2D maps and eventually the signal height fell below the trigger level. As a result, no signal was observed even if the ions hit, and the blank region appeared at the upper region of 2D maps. After ~1200 hits, strong signals appeared sparsely at the upper region of 2D maps (see the shaded zone in (c)). The typical weak and strong TRIBIC signals were shown as the signals E and F in (d), which were unchanged from the signals D and A, respectively. The strong signal F was most likely caused by stray beams which hit different positions in the diamond. Stray beams are generated by scattering of a main beam with residual gases in vacuum chamber and/or beam line. Generally, the intensity of stray beams are negligibly lower than the main beam in most cases. However, strong signals due to stray beams are detected during a dwell time of signal detection if most of ions within the microbeam do not induce signals above the trigger level of the Oscilloscope.

These results are obviously attributable to the polarization effect. When ion induced

carriers (electrons and holes) are trapped in deep levels in diamond, the trapped carriers interfere with the external electric field and the charge collection is interrupted. The detail of polarization effect is discussed in section 3.2. We therefore conclude that the inhomogeneous 2D maps in Figs. 6(a) and (b) do not indicate the inhomogeneity of crystal quality, but are simply caused by enhancing the polarization effect with increasing number of ion hits. The results of Fig. 6 also indicate that the polarization effect induced by previous ion hits are widely spread bidimensionally and the degradation of signal amplitude occurs even if the position of subsequent ion hits is different from that of precedent ion hits. In addition, the fact the signals degraded gradually with accumulating ion hits indicates that not only the last single ion hit, but also all precedent ion hits contribute to the polarization effect. The signal is affected by the polarization effect of precedent ion hits more prominently as the distance is closer and the time interval is shorter. Since signals at the upper center region were affected by charges generated from the whole bottom region whereas signal at the left (right) side was less affected from the bottom right (left) region, ring-shaped distributions were obtained in Figs. 6(a) and (b). The distance among ion hits in the X-direction was about 2 μm and the spatial distribution of the polarization effect could be estimated to be over the range of microns, although it is difficult to estimate the exact value in this study. On the other hand, the polarization effect is polarity-dependent and the inhomogeneous map was never observed when the negative bias was applied. Also, the signal height at -10 kV/cm, which is shown as the signal A' in Fig. 6(d), was about 60% compared to the signal at +10 kV/cm.

3.2. Analysis of the polarization effect based on the Shockley-Ramo theorem

In order to analyze the signal degradation due to the polarization effect shown in Fig. 6(d),

a simulation of transient currents based on the Shockley-Ramo theorem developed by Li et al. [23] was performed. A one-dimensional model of charge collection in semiconductors can be obtained from the Shockley-Ramo theorem and this is suitable to clarify how the polarization effect affects the charge collection process. Figure 7(a) shows the conceptual diagram of the model proposed in this study. When an incident high energy ion creates a lot of e-h pairs along its ion path, electrons and holes move toward the anode and the cathode, and induce the electron current and the hole current, respectively. The sum of electron and hole currents is observed as a transient current of the incident ion. In this case, the transient current, $i(t)$, is represented by the following equations:

$$i(t) = i_e(t) + i_h(t) \quad (2)$$

$$i_k(t) = \frac{q}{GW} \exp\left[-\frac{t}{\tau_k}\right] \int_0^W \Lambda(x, t) \cdot v_k(x) dx \quad k = e, h \quad (3).$$

Where $i_e(t)$, $i_h(t)$, and t denote the electron current, the hole current, and the time, respectively. q , Λ , G , R , W , τ_e , and τ_h are the electron charge, the electronic energy deposition by incident ions, the average ionization energy (13.2 eV [17]), the projected range of incident ions, the sample thickness, the electron lifetime, and the hole lifetime. The data of $\Lambda(x, t = 0)$ was obtained from Fig. 2. The subscripts, e and h denote electron and hole, respectively. The drift velocity, v is represented by the Canali model [24]:

$$v_k = \frac{\mu_k E(x)}{1 + \frac{\mu_k E(x)}{v_{sk}}} \quad k = e, h \quad (4).$$

Where μ , v_s , and E are the drift mobility, the saturation velocity, and the electric field. Constant values were used for both the electron and the hole mobilities, and the drift

velocity was changed only by the change in electric field. Values of 1.5×10^7 cm/s and 1.05×10^7 cm/s were used for electron and hole saturation velocities [2], although slightly different values for saturation drift velocities have been reported [25-27]. Finally, the calculated current was convolved with a Gaussian that included all terms of the system resolution, such as stray capacitance, etc. This assumes that a Gaussian shape signal is obtained at oscilloscope when a delta like signal is generated in device. The typical response time, which corresponds to the full width at half maximum of Gaussian function, was 6.5×10^{-10} s for the 50 μ m-thick diamond. This value was determined from the TRIBIC signals by 26 MeV-O ions shown in Fig. 4.

In the case of the 50 μ m-thick diamond, since 45 MeV-Si ions create e-h pairs near the top electrode, the electrons are collected toward the top electrode in a shorter time and the holes are collected toward the bottom electrode in a longer time when positive bias is applied to the top electrode. Therefore, the hole current is more dominant than the electron current in the transient current. In addition, since a part of holes is trapped by deep-levels in the diamond which has a long de-trapping time, they act as space charges which change the distribution of electric field in the diamond. This is generally called polarization effect in diamond. The expected distribution of electric field after accumulation of space charges is shown as the red line in Fig. 7(a). It is assumed in this model that the electric field is reduced to be E_p in the irradiated region and increases linearly in the other region, since space charges are accumulated almost uniformly in the irradiated region and a part of them expands to the other region. The electric potential between the electrodes is determined by the external voltage supply and is unchanged regardless of the polarization. Thus, the electric field at the interface of bottom electrode

is $E_W = \frac{2E_0W - E_F(W+R)}{W-R}$. Initial values of mobility and lifetime were determined from fittings of the signals A and A' in Fig. 6(d), which were the transient currents without the polarization. The obtained values are summarized in Table 1. Both the mobility and the lifetime are substantially lower than literature values obtained by light ion irradiations [25-28] because of the difference of incident ions [22]. The products of mobility and lifetime for electrons and holes in Table 1 were slightly smaller than the $\mu\tau$ products which were obtained in Fig. 5. This is also attributed to the difference of incident ions [22].

In Fig. 7(b), the experimentally obtained transient currents as well as the calculated results are shown. The signal D, which is the transient current after the polarization, was successfully reproduced by considering the electric field was reduced to be +0.30 kV/cm in the irradiated region. This fact indicates that the electric field in the irradiated region is probably reduced to be almost zero as the polarization progresses. The transient current would not be observed in this situation, since the carrier transport in the irradiated region is governed by diffusion rather than drift.

In this model, effect of metallization and interface between metal and diamond were not considered. It has been suggested that there were interface traps between metal and diamond and they had the potential to affect transport properties of charge carriers [21, 27]. Also, it is generally known that electric devices with oxide layers (MOS devices) are strongly affected by the interface traps between oxide layer and semiconductor, which are generated by radiations [29]. It cannot be excluded the possibility that the similar

phenomena could appear in the diamonds. However, the experimental results of this study could not be explained well by assuming that only the electric field in the vicinity of top electrode in diamond (a few nm from the interface) was drastically changed by the interface traps. This is because most of holes, which transport toward the bottom electrode when positive bias is applied, are unaffected by electric fields near the top electrode in this model. We therefore conclude that the polarization effect observed in this study was largely caused by accumulation of holes (space charges) in diamond. On the other hand, holes transport toward the top electrode when negative bias is applied and the hole current might be affected by the interface traps, resulting in the lower CCE values (Fig. 5). Our calculation model has the potential to be improved by taking into account the effect of interface traps in addition to accumulation of space charges in diamond.

Table 1. Parameters used for the simulation of transient currents in Fig. 6(d).

Electron mobility, μ_e (cm ² /Vs)	2.2×10^2
Hole mobility, μ_h (cm ² /Vs)	3.1×10^2
Electron lifetime, τ_e (ns)	2.4
Hole lifetime, τ_{hl} (ns)	5.45
Electric field after polarization, E_p (V/cm)	3.0×10^2

Fig. 7. (a) One-dimensional model of the polarization effect based on the Shockley-Ramo theorem. (b) Calculation results for TRIBIC signals in the 50 μm -thick diamond (red lines). Calculated electron and hole currents for the signal A are drawn as the dashed and dashed-dotted lines, respectively.

3.3. TRIBIC signals of 6 μm -thick diamond membrane

The TRIBIC signals of the 6 μm -thick diamond membrane by 45 MeV Si^{7+} ion hits were measured with different applied biases. Figures 8(a), (b), (c), and (d) show the 2D maps of collected charge of TRIBIC signals at the biases of +30 V (+50 kV/cm), -30 V (-50 kV/cm), +3 V (+5 kV/cm), and -3 V (-5 kV/cm), respectively. The 2D maps of peak heights are not shown here since they were qualitatively no different from that of peak heights. Typical TRIBIC signals in these conditions are shown in Fig. 9. Almost

homogeneous distributions were found in the higher bias conditions and the signal height at -50 kV/cm was about 90% compared to the signal at +50 kV/cm. Slightly lower signals were found in the left below and the right below. This “island” structure appeared prominently in the lower bias conditions (Figs. 8(c) and (d)). The intensity of signals at the islands showed a different trend from the other region, suggesting the existence of dislocation, inclusion, grain boundary, or an imperfect metal contact. The difference of bias polarity dependence might be due to the difference of crystal quality in the islands. In the case of lower applied bias (± 3 V), however, the expected applied field in the diamond membrane was so low that the signals could have been affected by a small barrier between the metal (Al) and the diamond. It is unclear at the present stage whether the island structure was formed during crystal growth or during the RIE etching for the fabrication of membrane structure.

Rise and fall times of TRIBIC signals in Fig. 9 are shown in Table 2. Whereas the rise time decreased with increasing applied electric field, interestingly, the fall time was almost unchanged (about 7.8 ns). This fact indicates that the charge collection time was dominated by different factor(s) from electric field and carrier mobilities. We speculate a small barrier and/or interface traps between the metal and the diamond might contribute to the extension of fall time. The effect of metal-diamond interface on charge collection process should be investigated.

Fig. 8. Two dimensional maps of collected charge (pC) of TRIBIC signals in the 6 μm -thick diamond membrane due to 45 MeV Si^{7+} ion hits. The applied electric field was (a) +50 kV/cm, (b) -50 kV/cm, (c) +5 kV/cm, and (d) -5 kV/cm.

Fig. 9. Typical TRIBIC signals in the 6 μm -thick diamond membrane induced by 45 MeV Si^{7+} ion hits. Black, red, green, and blue lines show TRIBIC signals at the electric field of +50 kV/cm, -50 kV/cm, +5 kV/cm, and -5 kV/cm, respectively.

Table 2. Rise and fall times of TRIBIC signals of the 6 μm -thick diamond membrane (Fig. 9).

Applied electric field (kV/cm)	Rise time (ns)	Fall time (ns)
+50	0.24	7.7
-50	0.24	7.9
+5	0.50	7.8
-5	0.70	7.7

4. Conclusion

Transient currents (TRIBIC signals) of diamonds induced by single swift heavy ion hits and their 2D maps were investigated in this study. Variations of TRIBIC signals and CCEs due to different diamond thicknesses, applied biases, and bias polarities were clarified. Change in the TRIBIC signals by subsequent ion hits was also investigated.

From the results of TRIBIC measurements in the 50 μm -thick diamond by irradiated by 45 MeV-Si ions, the temporal signal degradation originating from the polarization effect were observed. At positive bias, signals were drastically degraded by the subsequent ion hits. An increase in the charge collection time in addition to the decrease in signal height were observed. The spatial distribution of the polarization effect could be estimated to be in the range of microns. At negative bias, on the other hand, no signal degradation appeared with the subsequent ion hits. The signal height at negative bias was about 60% compared to the signal height at positive bias. In the case of the 6 μm -thick diamond membrane by 45 MeV-Si ions, island structure was found in the 2D maps and signals in the islands showed different trend from the other regions. The inhomogeneity is thought to be caused by the presence of dislocation, inclusion, grain boundary in diamond, or imperfect metal contact. The fall time of TRIBIC signals was unchanged by applied electric field.

Also, simulation study based on the Shockley-Ramo theorem was performed to understand the observed polarization effect. A relatively simple model was proposed and explained well the transient currents of polarized diamond. This indicates that space charges are generated by heavy ion hits and change the distribution of electric field in the

diamond. Nature of space charges are thought to be holes trapped by deep-levels which has an extremely long de-trapping time. Information regarding the deep-level hole traps (trap energy, capture cross section, trap density etc.) which contribute to the polarization effect should be clarified. The influence of incident ions and electric field strength on the polarization effect should also be investigated in order to develop a more detailed model.

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Graphical Abstract

Degradation of transient currents caused by the polarization effect of subsequent single ion hits.