The evaluation of radiation damage parameter for CVD diamond

V. Grilj*[1], N. Skukan[1], M. Jakšić[1], M. Pomorski[2], W. Kada[3], T. Kamiya[4], T. Ohshima[4]

[1]Division for experimental physics Ruđer Bošković Institute, 10000 Zagreb, Croatia
[2]CEA-LIST, Diamond Sensors Laboratory, Gif-sur-Yvette F-91191, France
[3]Division of Electronics and Informatics, Faculty of Science and Technology, Gunma University, Kiryu, Gunma 376-8515, Japan
[4]Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency (JAEA), Takasaki, Gunma 370-1292, Japan

Abstract

There are a few different phenomenological approaches that aim to track the dependence of signal height in irradiated solid state detectors on the fluence of damaging particles. However, none of them are capable to provide a unique radiation hardness parameter that would reflect solely the material capability to withstand high radiation environment. To extract such a parameter for CVD diamond, two different diamond detectors were irradiated by proton beams in MeV energy range and subjected afterwards to IBIC analysis. The change in CCE due to defects produced was investigated in context of a theoretical model that was developed on the basis of the adjoint method for linearization of the continuity equations of electrons and holes. The agreement of theory and measured data resulted with the first known value of the $k\sigma$ product for diamond. As discussed in the text, this quantity could be considered as a true radiation damage parameter.

Keywords: radiation hardness, CVD diamond, detector irradiation

*Coresponding author: Veljko Grilj, e-mail: vgrilj@irb.hr, mob: +385996136649

1. Introduction

Radiation hardness studies of semiconductor detectors investigate the change in detector properties after exposing it to a known amount of damaging particles such as ions, neutrons, muons, etc. The reduction of charge collection efficiency (CCE) is commonly reported either as a function of particle fluence (Φ) or displacement damage dose (D_d). The later represents the total energy of incident particle spent on the non-ionizing processes per unit mass of detector material and equals:

$$D_d = \Phi \cdot NIEL_{av}, \quad (1)$$

where $NIEL_{av}$ stands for the average non-ionizing energy loss [1] of one damaging particle. The concept of displacement damage dose allows for the prediction of the reduction of detector signal for any type and energy of damaging radiation from data obtained for just one type and energy of particles. This assumption is also known as the NIEL scaling approach defined at the US Naval Research Laboratory [2]. In the low damage regime, the CCE decrease could be written as [3]:

$$CCE = 1 - K_{ef} \cdot D_d. \quad (2)$$

K_{ef} is usually called the equivalent damage factor. However, the change of detector properties depends not only on the total number and type of damaging particles but also on detector geometry and working conditions (e.g. applied bias voltage), depth distribution of stable defects created by irradiation and depth ionization profile of the probing ions. It is important to stress that calculations based on (2) yield a damage factor that is valid for one particular detector under particular experimental conditions and cannot be assigned as a pure material property. Our goal is to define a device independent parameter that would indicate a specific response of chemical vapour deposited (CVD) diamond to primary defects introduced by radiation. This task requires a detailed modelling of the CCE degradation in irradiated detector.

The paper is structured as follows. Chapter 2 provides the information on the detectors that were irradiated and the ion beams that were used for damaging and analysis of damaged areas. Chapter 3 deals with the CCE degradation model that was later used to fit the measured data and extract the value of $k\sigma$ product. Results, followed by a discussion are presented in chapter 4 while the conclusions given at the end of the paper summarize the main aspects covered.

2. Samples and methods

Radiation hardness tests were carried out on two diamond detectors: a commercial, 50 μm thick, single crystal CVD (scCVD) diamond detector purchased from Diamond Detectors Ltd. company in 2012 and less than 6 μm thick scCVD diamond membrane detector described in [4]. The schematics of both detectors are shown in figure 1. Several small (100×100 μm^2) detector areas were selectively irradiated with different fluences of accelerated protons at Zagreb nuclear microprobe facility [5]. Spatial resolution of the proton microbeam was of the order of 1 μm. Based on the SRIM simulations, the energy of protons was tuned to produce an almost homogeneous depth distribution of vacancies. In the case of the 50 μm thick detector 4.5 MeV protons were used, each proton creating in average 0.08 vacancies per micrometer of its path through the detector. Protons with energy of 1.3 MeV were used in the case of 6 μm thick detector resulting with an average depth distribution of 0.26 vacancies per micrometer. Total fluence was measured by the off-axis aligned silicon surface barrier detector that was first calibrated by simultaneous counting of the ions in diamond detector at beam currents of a few thousand protons per second. After the calibration, detectors were grounded and the beam current was increased to a few hundreds of thousands protons per second.

The influence of introduced defects on transport properties of charge carriers was investigated by the ion beam induced charge (IBIC) technique. Probing was done with the same proton microbeams that were previously used for damaging. The bias voltage on detectors was adjusted by the high voltage power supply. Signals were guided through the standard electronic chain which consisted of a charge sensitive preamplifier, a shaping amplifier and an analogue-to-digital multichannel analyzer. Data acquisition was performed on the personal computer by the in-house developed system SPECTOR [6].

3. Modelling of CCE

The presence of charge carriers traps, both those that originate in the material and those that are introduced by irradiation, is evident through the lifetime τ of charge carriers. According to Shockley-Read-Hall model [7], it can be written as:

$$\tau(x,\Phi) = \frac{\tau_0(x)}{1+k\cdot vac(x)\cdot\Phi\cdot\sigma\cdot v_{th}\cdot\tau_0(x)}. \qquad (3)$$

In the above equation σ and v_{th} are the capture cross section and thermal velocity of charge carriers, $\tau_0(x)$ stands for their intrinsic (virgin) lifetime, while $vac(x)$ presents the depth distribution of vacancies produced by one impinging ion as simulated by SRIM [8]. The meaning of the k factor is the average number of electrically active traps that are associated with one primary created vacancy. By ploting the dependance of the lifetime on the irradiation fluence of damaging ions (Φ), $k\sigma$ product can be determined directly from fit to equation (3).

The same product appears also in the CCE degradation model presented in [9], where for the starting point Vittone used a general expression for the CCE profile that was analytically obtained by solving the adjoint equations [10]. Under the assumption of a low damage regime and with lifetime expressed according to (3), the model gives a simplified form for the CCE profile:

$$CCE(x,\Phi) \cong 1-\Phi\cdot\left[\frac{k_e\cdot\sigma_e\cdot v_{th}}{d}\cdot\int_x^d dy\cdot\int_x^y \frac{vac(z)}{v_e(z)}dz + \frac{k_h\cdot\sigma_h\cdot v_{th}}{d}\cdot\int_0^x dy\cdot\int_y^x \frac{vac(z)}{v_h(z)}dz\right]. \qquad (4)$$

In the last equation, $CCE(x,\Phi)$ is the charge collection efficiency of the sensing electrode for a point charge generated at distance x from that electrode in a detector that was previously irradiated by fluence Φ of damaging particles, d is the thickness of the detector drift region and $v_{e,h}$ are drift velocities of electrons/holes. For a probing ion that enters the detector through one of the electrodes with energy E_{ion}, the $CCE(\Phi)$ is given by the convolution of the $CCE(x,\Phi)$ and the normalized ionization energy loss profile of the probing ion. In the present case, vacancy and ionization depth profiles of proton beams that were used for damaging and IBIC probing were both quite homogeneous, which facilitates solving of the integrals in (4). The resulting expression for $CCE(\Phi)$ states:

$$CCE(\Phi) = 1-\Phi\cdot\frac{\overline{vac}\cdot d\cdot v_{th}}{6}\cdot\left[\frac{k_e\cdot\sigma_e}{v_e}+\frac{k_h\cdot\sigma_h}{v_h}\right], \qquad (6)$$

with $\overline{vac}$ being the average number of vacancies produced per 1 μm.

4. Results and discussion

The choice of transmitting protons for IBIC analysis was made in order to exclude the influence of polarization [11] effect on incomplete charge collection. However, a general drawback of using transmitting probes is the impossibility to differentiate signal contributions between electrons and holes. This could be achieved with short range probes, when one carrier species travels a negligible distance inside the detector in comparison to the other carrier species. A single carrier Hecht equation can be applied then to fit the dependence of the CCE on the electric field [12]. Therefore we also tried to use 1.8 MeV carbon ions whose range in diamond is around 1 μm, but a progressive degradation of signal amplitude inside the damaged areas started after only several ions have entered the sample. This behaviour could be attributed to polarization, i.e. a breakdown of the electric field due to the space charge accumulation at deep level traps throughout the bulk of the detector. In the case of carbon ions, enough counts to extract the peak positions of unpolarized Gaussian signal height distributions were recorded only at the highest bias voltages of ±70 V applied to the thin membrane detector. Such extremely high electric field was able to overcome the polarization effects long enough to collect a few hundred counts in each damaged region. There was no significant difference in signal heights between the positive (holes dominated signal) and negative (electron dominated signal) polarities which led to a conclusion that both charge carriers were trapped with equal probability, a fact that will be highly important for calculating the average $k\sigma$ product.

IBIC maps of irradiated areas are shown in figure 2 for the same electric field of 1 V/μm applied to both detectors. The colour of each pixel in maps corresponds to the average signal height of all events that were recorded in that pixel. The fluence of 4.5 MeV protons in 9 damaged areas on 50 μm thick detector varies from 3.1×10^{12} cm^{-2} to 3.1×10^{14} cm^{-2}. On the other hand, 6 damaged areas were created on 6 μm thick detector with 1.3 MeV proton fluence ranging from 6.9×10^{12} cm^{-2} up to 8.6×10^{14} cm^{-2}. An average CCE value was calculated for every damaged region from a Gaussian distribution containing signal heights of all counts inside that region. Figure 3 shows the reduction in CCE in 50 μm and 6 μm thick detectors with the increase of the proton fluence for several electric fields. As mentioned in the introduction, to compare the irradiation effects of different damaging beams, a displacement damage dose is conventionally used. Hence the results from figure 3 are presented together for both detectors in figure 4a with D_d plotted on the x-axis. It is obvious that a different damage parameter K_{ef}, as defined in (2), corresponds to each set of points that were recorded in a certain diamond detector and under a certain electric field. In other words, for the same amount of non-ionizing energy deposited and under the same electric field, signal loss in the membrane detector is much lower as expected due to the shorter distance that free carriers have to travel before being collected at the electrodes. This is the reason why K_{ef} cannot be considered as a unique, material dependent constant. Instead, a detailed modelling presented in previous chapter has to be utilized.

For a further simplification of the expression (6) we can assume that $k\sigma$ products for electrons and holes are equal ($k_e\sigma_e = k_h\sigma_h = k\sigma$). The justification was found in similar CCE degradation trends in membrane detector obtained at ±70 V with 1.8 MeV carbon ions as short range IBIC probes. Now (6) can be rewritten as:

$$CCE(\Phi) = 1 - D^* \cdot k\sigma, \quad (7)$$

with D^* representing the following:

$$D^* = \Phi \cdot \frac{\overline{vac} \cdot d \cdot v_{th}}{6} \cdot \frac{v_e \cdot v_h}{v_e + v_h}. \quad (8)$$

In order to apply equation (7) to the measured data, a dependence of CCE on D^* is shown in figure 4b. Data sets that were previously separated now converge towards a one single curve, allowing for a simple linear fit to provide the value of the $k\sigma$ product. Only points that fulfill the criteria of having the CCE higher than 85% (low level damage regime) were fitted and $k\sigma$ equal to $(8.8 \pm 0.2) \times 10^{-16}$ cm^{-2} was obtained. For highly damaged detector the violation of linear CCE – fluence relationship is expected and points with lower values of CCE are starting to move away from the fitted line. It is worth to emphasise that D^*, also called the effective fluence, takes into account not only the average number of vacancies produced but also the thickness of the detector and the field dependent drift velocities of charge carriers [13]. Therefore, the $k\sigma$ product reflects solely the material response to damaging radiation. A detailed analysis of the type of electrically active traps produced could yield the value of the capture cross section σ and enable the calculation of the k factor which establishes the relation between the number of traps and the number of primary defects created. However, such a comprehensive study of defects in diamond is beyond the scope of this paper.

As reported in [14], $k\sigma$ product for p^+-n-n^+ silicon diodes irradiated by various ions with energies of about 0.3 MeV/u was found to be $(9 \pm 1) \times 10^{-16}$ cm^{-2}. Almost the same $k\sigma$ values of diamond and silicon imply that CCE reduction in two identical detectors made of these materials would be similar for equal amount of vacancies introduced. Nonetheless, for the same ion species, the number of vacancies produced will always be lower in diamond due to stronger crystal lattice, which followed by somewhat higher drift velocities of charge carriers, favours diamond over silicon in terms of radiation hardness.

5. Conclusion

Calculation of unique parameter that characterizes the radiation hardness of a specific material requires a thorough CCE degradation modelling, like the one presented in this work. Gathering of all data points on one degradation line obtained in figure 4b supports the application of (7) over the more usual phenomenological expression (2), when describing the measured radiation induced decrease in CCE. Moreover, the $k\sigma$ product, once determined, makes it possible to predict the behaviour of any detector made of the same material after exposing it to an arbitrary damaging radiation, as long as the type of defects produced remains unchanged. Thus it could be considered as a true radiationl damage parameter. The obtained $k\sigma$ value could be exploited further to estimate the number of stable free carriers' traps per one initially created vacancy. This information would help in resolving the still unclear correlation between the structural defect and electrically active trapping centre.

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References:

[1] S. R. Messenger, E. A. Burke, G. P. Summers, M. A. Xapsos, R. J. Walters, E. M. Jackson, and B. D. Weaver, *IEEE Trans. Nucl. Sci*. **46**, 1595 (1999).
[2] S. R. Messenger, G. P. Summers, E. A. Burke, R. J. Walters and M. A. Xapsos, *Prog. Photovolt. Res. Appl*. **9**, 103 (2001).
[3] S. R. Messenger, E. A. Burke, R. J. Walters, J. H. Warner, and G. P. Summers, *Prog. Photovolt. Res. Appl.* **13**, 115 (2005).
[4] V. Grilj, N. Skukan, M. Pomorski, W. Kada, N. Iwamoto, T. Kamiya, T. Ohshima, and M. Jaksic, *App. Phys. Lett*. **103** 243106 (2013).
[5] M. Jaksic, I. Bogdanovic-Radovic, M. Bogovac, V. Desnica, S. Fazinic, M. Karlusic, Z. Medunic, H. Muto, Z. Pastuovic, Z. Siketic, N. Skukan, and T. Tadic, *Nucl. Instr. Meth. Phys. Res. B* **260**, 114 (2007).
[6] M. Bogovac, I. Bogdanovic, S. Fazinic, M. Jaksic, L. Kukec, and W. Wilhelm, *Nucl. Instr. Meth. Phys. Res. B* **89**, 219 (1994).
[7] W. Shockley and W. T. Read Jr., *Phys. Rev. B* **87** 5 (1952).
[8] J. F. Ziegler, J. B. Biersack, and U. Littmark, SRIM–The Stopping and Range of Ions in Solids (Pergamon Press, New York, 1985).
[9] E. Vittone, IAEA CRP technical report (2012).
[10] T. H. Prettyman, *Nucl. Instr. Meth. Phys. Res. A* ***422***, 232 (1999).
[11] W. Kada, N. Iwamoto, T. Satoh, S. Onoda, V. Grilj, N. Skukan, M. Koka, T. Ohshima, M. Jaksic, and T. Kamiya, *Nucl. Instr. Meth. Phys. Res. B*, **331** 113 (2014).
[12] K. Hecht, *Zum Mechanismus des lichtelektrischen Primarstromes in isolierenden Kristallen* (1932).
[13] M. Gabrysch, S. Majdi, D. J. Twitchen, and J. Isberg, *J. Appl. Phys.* **109** 063719 (2011).
[14] Z. Pastuovic, E. Vittone, I. Capan, and M. Jaksic, App. Phys. Lett. **98** 092101 (2011).

Figures:

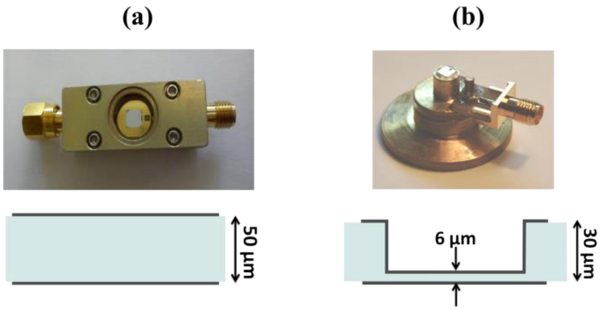

Figure 1. Photographs and schematic side views of detectors used: (a) 50 µm scCVD diamond detector from DDL and (b) homemade 6 µm scCVD diamond membrane detector.

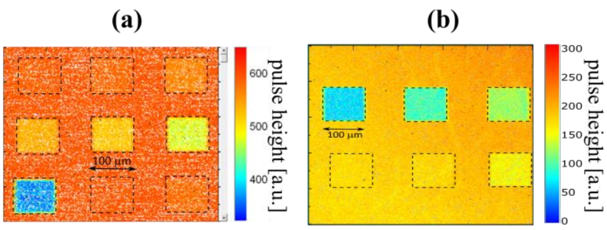

Figure 2. IBIC maps recorded by 4.5 MeV and 1.3 MeV protons showing (a) 9 damaged regions in 50 µm thick diamond detector and (b) 6 damaged regions in 6 µm thick diamond detector.

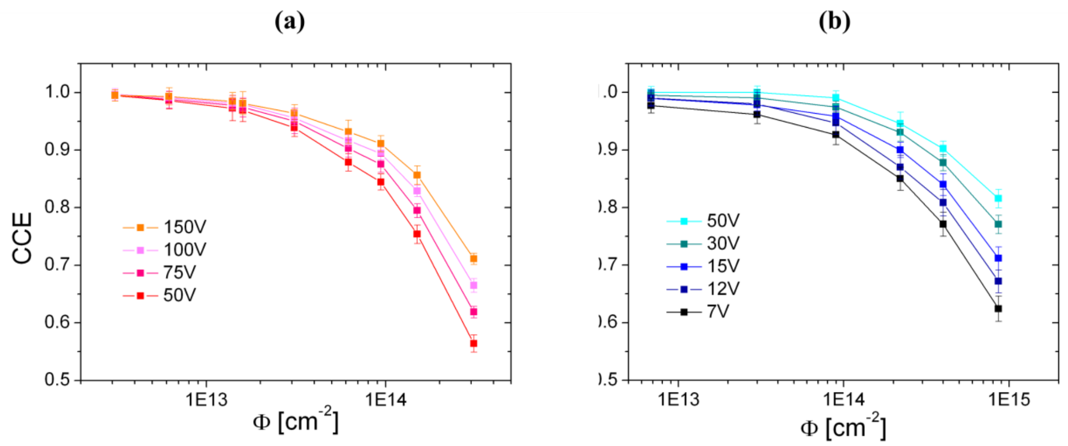

Figure 3. Degradation of CCE with the increasing fluence of (a) 4.5 MeV protons in 50 μm thick detector and (b) 1.3 MeV protons in 6 μm thick detector for various applied bias voltages.

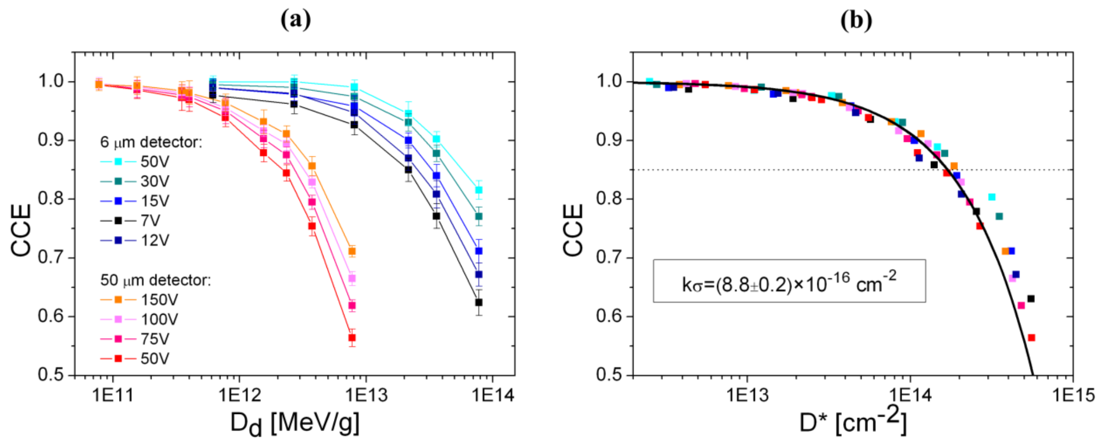

Figure 4. (a) Degradation of CCE for both diamond detectors shown as a function of displacement damage dose D_d. (b) All data from (a) shown as a function of the effective fluence D* defined by expression (8). Thick black line in (b) presents a linear fit (scale is logarithmic) of data above the dashed horizontal line which is defined by CCE equal to 0.85.