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The effect of dose enhancement near metal interfaces on synthetic diamond based X-ray dosimeters

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ABSTRACT

This study investigates the effects of dose enhancement on the photocurrent performance at metallic interfaces in synthetic diamond detectors based X-ray dosimeters as a function of bias voltages. Monte Carlo (MC) simulations with the BEAMnrc code were carried out to simulate the dose enhancement factor (DEF) and compared against the equivalent photocurrent ratio from experimental investigations. The MC simulation results show that the sensitive region for the absorbed dose distribution covers a few micrometers distances from the interface. Experimentally, two single crystals (SC) and one polycrystalline (PC) synthetic diamond samples were fabricated into detectors with carbon based electrodes by boron and carbon ion implantation. Subsequently; the samples were each mounted inside a tissue equivalent encapsulation to minimize unintended fluence perturbation. Dose enhancement was generated by placing copper, lead or gold near the active volume of the detectors using 50 kV_p and 100 kV_p X-rays relevant for medical dosimetry. The results show enhancement in the detectors' photocurrent performance when different metals are butted up to the diamond bulk as expected. The variation in the photocurrent measurement depends on the type of diamond samples, their electrodes' fabrication and the applied bias voltages indicating that the dose enhancement near the detector may modify their electronic performance.

1. Introduction

Radiation dosimetry is the measurement and calculation of the radiation dose absorbed in a medium that is exposed to direct or indirect ionising radiation. There is a demand for dosimetric systems that provide excellent spatial resolution, high accuracy and high precision. Diamond is an attractive material for radiation detection when used as solid-state detector due to its small size, radiation hardness, fast response, chemical resilience, small sensitive volume, high spatial resolution and near-tissue equivalence (Cirrone et al., 2006; Mandapaka et al., 2013). The particular interest for medical dosimetry applications originates in the atomic number (Z=6) of diamond, which is closer to the atomic number of human tissue than most other solid-state detector materials (Fidanzio et al., 2005).

Natural diamonds with reproducible electrical properties for dosimetry purposes are rare and difficult to obtain and, therefore, very expensive (Fidanzio et al., 2004). There has been much progress recently in the production of single-crystal and polycrystalline synthetic diamonds by chemical vapour deposition (CVD) (Buttar et al., 1997; Gorka, 2008); these are a good alternative to natural diamonds. The quality of CVD diamonds has been improved by controlling specific properties; such diamonds are now produced at relatively low cost (Fidanzio et al., 2004). The possibility of using CVD diamond detectors for medical physics applications has already been investigated by several research groups (Fidanzio et al., 2004, 2005; Buttar et al., 1997). Some limitations have been reported by several groups regarding their application as medical dosimeters: high leakage currents, priming effects, issues with stabilisation, internal crystal polarisation and limited response reproducibility (e.g. Tromson et al., 2000; Bergonzo et al., 2003, 2007; Gorka, 2008).

All the structure elements of a dosimeter system should have atomic numbers similar to that of tissue, like the diamond bulk. Diamond detectors based on low thickness and low atomic number electrodes are a requirement to maintain tissue equivalence and reduce fluence perturbation and absorption of the incident beam (Das et al., 2002; Long et al., 1982). There are several reports on variations in the performance of diamond radiation detectors caused by metals with high Z being used as metallic electrodes, wires, conductive glue and encapsulation near the diamond bulk material in the dosimeter construction (Fidanzio et al., 2004; Cirrone et al., 2006; Górka et al.,

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2008, Hugtenburg, 2012).

Dose perturbations are significant in the assessment of radiation effects associated with high Z interfaces. For lower energies and high Z, the differences in doses are more obvious (Fleetwood et al., 1988, Das et al., 2002). Studies have revealed dose enhancement at low energies, where there is strong Z dependence, due to interactions with X-rays via the photoelectric effect (Long et al., 1982). Owing to the difference in atomic number between the diamond and the metal, this results in non-equilibrium of radiation caused secondary electrons; the energy deposited by these electrons in low Z material can result in an increase in the energy absorbed in the diamond detector during irradiation. The kilovoltage energy ranges used in this study form part of radiation therapy for superficial treatments. The higher sensitivity of the photoelectric cross-section to small variations in Z at these energy ranges is critical due to considerable variation in the stopping power and mass absorption coefficient ratios. Moreover, the suitability of diamond as a practical detector in these energy ranges requires investigation (Mobit and Sandison, 1999). This phenomenon becomes an issue when testing semiconductor devices to evaluate their response to the lower energy portion of the ionising radiation (Fleetwood et al., 1988).

Studying the interface phenomena inside a CVD diamond detector may be complex due to the small device dimensions; a suitable alternative method involves using Monte Carlo techniques (Berger, 1963). In 1999, Mobit and Sandison used the EGS4 Monte Carlocode to simulate the geometry of PTW natural diamond detectors in therapeutic photon beams without taking the electrodes into account (Mobit and Sandison, 1999). As a consequence, Górke et al. employed the PENELOPE Monte Carlo code to study interface phenomena in the metal-diamond transition zone of diamond detectors (Górka et al., 2006). Excellent agreement of data from simulations was found when using EGSnrc Monte Carlo code compared with data from the published work of Górka et al. (2006) in the investigation of small diamond detectors for physical and dosimetric properties (Baluti et al., 2015). It also showed that the absorbed dose distribution reached at a few micrometers distance from the interface due irradiation from a MV photon beam.

Owing to important aspects of the interface phenomena, therefore, the effects of these phenomena on the detector performance remain to be investigated experimentally for the CVD diamond detector with small dimension. Hence, this paper reports a preliminary study of dose enhancement effects from the interface between different metals and CVD diamond detectors with carbon based electrodes to improve understanding of the dose enhancement effect on the detectors' photocurrent performance, with the aim of developing a synthetic diamond radiation detector for medical X-ray dosimetry. For this purpose, Monte Carlo (MC) simulations and experimental measurements were employed to determine the effect of dose enhancement at the diamond-metal interface.

2. Theory of radiation characterisation techniques

2.1. Alpha particle spectroscopy

The expected performance of detectors was evaluated using alpha particles. The induced signal in each sample due to alpha particles irradiation has been characterised for electron and hole transport separately by changing the applied bias voltage polarity to the irradiated surface. Due to the shallow depth of penetration of the alpha particles compared to the thickness of the diamond bulk, a positively biased surface will mostly collect electrons while a negatively biased surface will mostly collect holes. The charge collection efficiency (CCE) is the ratio of the induced charge at the contact, Q, and the charge created as electron-hole pairs by a particle in the detector, Q_0. The average electron-hole pair creation energy (W_{ehp}) is 13.2 eV in diamond (Canali et al., 1979). Detection properties of diamonds under irradiation by alpha particles and X-ray show that the CCE is dependent on the concentration of defects in the device (Tromson et al., 2000, 2001).

2.2. Dose rate and linearity

A linear current against dose rate dependence is equivalent to a charge-dose response independent of dose rate. In the case of solid state detectors, the Fowler relation is often used to describe the relationship between the photocurrent (I) and the dose rate (D) (Fowler, 1966):

$$I = I_{\text{dark}} + \mathrm{RD}^{\Delta} \tag{1}$$

where I_{dark} is the dark current, R and Δ are fitting parameters, where R is the sensitivity and the exponent Δ the linearity index which is a constant that describes the deviation from linearity for values unequal to 1. This index can also be interpreted as a measure of the homogeneity of traps within the crystal structure assuming Ohmic contacts. In the case of trap free crystals, the model predicts Δ=0.5. This makes such a detector very dose-rate dependent. If the trap distribution limiting the charge carrier lifetime is uniform it leads to Δ=1, and if there are traps in the crystal and all have the same capture cross section Δ falls between 0.5 and 1. If the value is 1, then the integrated photocurrent has no dependence on dose rate, so will be directly related to the integrated dose on the detector, a highly desirable behaviour for a dosimeter. The Fowler expression and in particular the linearity index are often reported in the literature for diamond dosimeters (Lansley et al., 2009; Górka et al., 2008; Cirrone et al., 2006; Buttar et al., 2000), despite the fact that different Δ values are reported for the same bulk materials, indicating that the bulk trap distribution interpretation is not applicable in all cases, including studies that used continuous X-ray generators similar to the ones employed in this work. (Abdel-Rahman et al., 2011, 2012).

There is no consensus in the literature on how Δ values change with the bias voltage. Planskoy (1980) studied the dose rate dependence of some natural diamond detectors and concluded that Δ is independent of some variables such as bias voltage (Planskoy, 1980). The variation of Δ with electric field has been reported by Fidanzio et al. (2004) and similar variations were related by Abdel-Rahman et al. (2012) to the signal to noise ratio (SNR) due to increase in leakage current (Abdel-Rahman et al., 2012). Ade and Nam (2015) studied the influence of the bias voltage on the dose rate dependence of the several diamond detectors and concluded that Δ could vary with bias voltage dependent on the concentration of the traps which develop the polarisation effect which cause a sub-linear dose rate response even at higher voltages (Ade and Nam, 2015). However, Ramkumar et al. (2001) explained that Δ decreases with increase in applied voltages due to a reduction in carrier lifetime with increase in electric field which could also be caused by polarisation effects (Ramkumar et al., 2001).

3. Experimental procedure

For this study, two commercial single crystalline (SC) and one polycrystalline (PC) CVD diamond samples were procured from Element Six Ltd, UK (with dimensions 5×5 mm^2, 0.3 mm thick). Boron ion implantation (60 keV) was used to fabricate the carbon based electrodes to one PC (B) and one SC (B) diamond samples (Sellin and Galbiati, 2005). In addition, one SC (C) diamond sample was fabricated using carbon ion implantation (100 keV, to implant at the same depths as the boron of about 100 nm). This produced conducting electrodes on both sides of the samples that are adequately tissue equivalent (Albarakaty, 2011).

3.1. Alpha particle spectroscopy

For alpha particle irradiation, a ^{241}Am radio isotope alpha source