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Real-time high intensity X-ray dosimetry diamond monitors: Response simulations compared to silicon sensitivities

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Abstract

This paper deals with the use of diamond detectors operating in the current mode, i.e. in particularly high-intensivity fields of X- and γ-rays. It is concerned with the monitoring of broad photon energy spectra close to radiation plans. The discussions are supported by numerical response simulations of diamond detectors foreseen to control real-time absorbed or ambient dose rates. The collected charges and the current delivered by the irradiated detectors are analysed to propose stacks of materials with less than 30% measurement uncertainty in an unknown 20 keV–1.5 MeV photon (X- or γ-rays) field. Single-sensor monitors show sensitivities sufficient for X-ray manipulation alarm dosimetry.

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Keywords: Diamond; Silicon; Real-time dosimetry; Room-temperature X-ray detector; Absorbed dose; Ambient dose; Angular dependence; Survey dosimetry

1. Introduction

In the frame of personal dosimetry, we have recently explored proposals using diamond sensors measuring low X-ray doses [1]. The sensitivity achieved in a digital pulse-height counting mode has been compared to similar silicon diode responses. In this paper another approach is evaluated based on the analysis of the current delivered by detectors working like ionisation chambers, the measured current being associated to the irradiating dose rate. The current measurement usually favours high fluence controls since the response has to overcome dark currents, often present in most of the junctions. Previous papers studied dose rate detection thresholds expected for silicon and CdTe sensors in the field of γ or neutron dosimetry [2,3]. Several authors have published proposals and experimental results based on current measured by γ-ray or particle-irradiated

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diamond monitors [4–8]. Due to their good stability, diamond detectors are well suited for high γ-ray fluence facilities as, for instance, in medical radiotherapy [9–12]. However, techniques for medical irradiation control, which need accurate adjustments of the absorbed doses inside human body tissue using well-defined energies (delivered by accelerators), are not considered in this paper which is mainly concerned with unknown γ-ray environmental energy spectra monitoring.

Both natural diamond as well as CVD crystals possess interesting low-leakage currents reduced by several orders of magnitude as compared to CdTe or Si diodes [4,13,14]. Consequently, a lower dose rate detection threshold for these sensors can be expected. A second advantage of diamond material compared with silicon is a lower atomic number, close to that of human body tissue, so that it can work more easily as a dose-equivalent monitor. Then, it is interesting to study its application in an ambient dose-equivalent survey for instance in endoscopic surgery under X-ray illumination. In this frame work, our simulations compute the charges delivered by various irradiated diamond layers. The dose–response dependence of the sensors as a function of X-ray beam energy is discussed. The interaction volume as well as several other parameters are considered, and the performances, such as sensitivities and confidence levels, are compared to those of silicon monitors. The numerical simulations are planned for biomedical fields of interest. The studied energy interval is limited to within 20 keV and 1.5 MeV proposing detector configurations able to monitor X-ray doses in an unknown photon energetic field spectrum. The selection criterion is that of a personal (or patient) dosemeter response with less than 30% dispersion around the mean value, following the actual ICRP recommendations [15]. (N.B.: This accuracy is less critical as for radiotherapy where well-defined energies are used.)

2. Brief recall of the calculation method

Diamonds belong to the category of room-temperature detectors, with a large resistivity; even at a low bias voltage, an electric field is developed through the whole volume. Also former investigations [4] showed a non-uniformity of the electric field distribution due to charge trapping making the sensor work in a manner similar to CdTe surface barrier detectors. We propose a method to calculate the output signal similar to that of CdTe sensors [16–18], its processing being only presented briefly here.

2.1. The current generation

The detector is assimilated to planar stacked matter layers which are assumed to be irradiated by mono-energetic X-ray beams. Each stack is composed of various metallic filters covering the diamond. The numerical simulation is a Monte Carlo computing method which follows the interaction and cascade particle production induced by each individual incident photon crossing the different material components. The interaction probabilities follow the cross-section values [19,20]. During these interactions, secondary electrons are generated, leaving their energy along their trajectory. The energy deposited inside the detector is stored and analysed event by event. Different Monte Carlo codes available can simulate this kind of interaction mechanism [21,22]. The originality of our MCGET1 code is the individual treatment of each interacting photon response. It presents the advantage of a more accurate signal analysis compared to a simple energy deposit calculation. The characteristics and operation of the sensor are taken into account to extract the final output response. It takes into account a free produced carriers local charge collection distance inside the detector, following Hecht Schubweg [23]. The energy deposited in the detector is stored in meshes of equal width in which the amount of free carriers is calculated for the $w = 13.25\,\text{eV}$ ionisation energy. In addition, the amount of carriers produced can be assumed as having a Gaussian dispersion weighted by a Fano factor (here equal to 0.5). The presence of the electric field inside the biased sensor acts on the free electron–hole pairs. Inside each mesh, the carrier clusters begin to move towards the corresponding electrode. The displacement of each bunch of carriers from mesh to mesh is followed