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Evaluation of rad-hard epitaxial silicon diode in radiotherapy electron beam dosimetry

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ABSTRACT

The dosimetric response of an epitaxial (EPI) silicon diode for clinical electron beams was investigated using Siemens KD2 and Primus Linear Accelerators. All measurements were performed with the diode unbiased and operating in the short-circuit current mode using a PMMA phantom. Within the energy range of 6 MeV–21 MeV, the output current signals exhibited good instantaneous repeatability (CV≤2.4%), measured through switching on/off the electron beams. Furthermore, the diode showed a quite linear response, given by the charge versus absorbed dose, with charge sensitivities higher than 0.86 μC/Gy. The percentage depth dose profile (PDD) and transversal dose profile (TDP) were also measured in PMMA. The PDD and TDP results were in excellent agreement with those calculated with Monte Carlo code using the OncentraMasterPlan® Treatment Planning System (TPS). However, despite of showing energy dependence effects, neither dark currents increase nor memory effects were observed in the device response.

1. Introduction

Since the early 1980s, silicon diodes have been used as teletherapy beams dosimeters, mainly due to both their high sensitivity per unit volume and high spatial resolution (Dixon and Ekstrand, 1982). Other major advantages of Si devices are excellent repeatability, good mechanical stability and the energy independence of mass collision stopping powers ratios (between silicon and water for electron beams with energy from 4 up to 20 MeV) (Rikner and Grussel, 1983). However, ordinary silicon diodes are very prone to radiation damage effects which are responsible for a gradual long-term sensitivity decay (Lindstrom et al., 1999; Pini et al., 2003) mainly for high energy electron beams irradiation. In radiation therapy dosimetry, it is important to know the sensitivity decrease with the absorbed dose in order to foresee when re-calibration of the dosimeter should be done. This is the most important constraint against the use of ordinary silicon devices in medical dosimetry. This scenario has changed with the development of rad-hard diodes, based on magnetic Czockralski (MCz), standard and oxygen-enriched float zone (FZ) silicon substrates (Harkonen et al., 2007), which will be used in the tracking system of future colliding beam experiments. The performance of these MCz and Fz diodes operating in the photovoltaic mode as on-line gamma radiation dosimeters has been investigated in our group mainly in the field of radiation processing dosimetry (Bueno et al., 2008; Camargo et al., 2007). Despite of the higher radiation tolerance of these devices, our results have still shown a sensitivity decay, attributed to the reduction of the minority carrier diffusion length, for doses up to 0.5 MGy. So, the use of thinner diodes would improve the sensitivity stability by keeping almost constant the active volume of the device. This assumption motivated us to investigate the dosimetric characteristics of diodes processed on thin n-type epitaxial layers with high radiation damage tolerance (Lindström et al., 2006). In this work we present the preliminary results obtained with an epitaxial (EPI) silicon diode as on-line clinical electron beam dosimeter.

2. Materials and methods

The diode used was processed on n-type 75 μm thick epitaxial silicon layer and nominal resistivity of 50 Ω cm grown on a highly doped n-type, 300 μm thick Czochralski (Cz) silicon substrate (Lindström et al., 2006). This device, with 25 mm^2 active area, was housed in a polymethylmethacrylate (PMMA) probe and connected to a Keithley 6517B electrometer in the photovoltaic mode. During

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all measurements, the diode was held between PMMA plates, placed at the reference depth (z_{ref}) (TRS 398., 2000) and centered in a radiation field of 10 × 10 cm^2, with the source-to-surface distance (SSD) kept at 100 cm. The dosimetric response of the device was evaluated for 6, 9, 12, 15, 18 e 21 MeV electron beams from a Siemens KD2 Radiotherapy Linear Accelerator, located at Sírio-Libanês Hospital. With a constant dose rate of 300 cGy/min, the output current signal of the diode was registered for a fixed 300 monitor unit (MU) as a function of the exposure time during 60 s for each electron beam energy. To study the short term repeatability, five current signals were consecutively registered for the same radiation dose, for all energies, just switching on and off the electron beam. The dose response curve of the EPI diode, given by the charge versus the accumulated dose, was achieved through the integration of the current signals as a function of the exposure time. The charge sensitivity dependence on the electron beam energy was also studied.

Percentage depth dose (PDD) measurement was carried out in a PMMA phantom. The SSD was kept at 100 cm, changing the depth of the dosimeter from 1 mm to 80 mm with PMMA plates. For each position, two signals were consecutively registered during 20 s. The measurements were performed for 9 and 18 MeV electron beams from the Siemens Primus Linear Accelerator and repeated from the top to the bottom position in the PMMA phantom. The transversal dose profile (TDP) was measured in PMMA at a depth of 2.5 cm, in a 12 MeV electron irradiation field size of 10 × 10 cm^2. The data were collected by moving the treatment table across the whole irradiation field cross plane axis.

The PDD and TDP experimental results were compared with Monte Carlo calculations performed using the OncentraMasterPlan® Treatment Planning System (version 3.2, algorithm eVMC).

3. Results

The current response of the diode irradiated with 21 MeV electron beam, at a dose rate of 300 cGy/min, is presented in Fig. 1. As can be seen, the 5 signals consecutively registered during 60 s, switching on/off the beam, evidence that the diode has good short term repeatability with coefficient of variation (CV) of 2.4%. It is worth noting that the output current was almost five orders of magnitude higher than the dark current (≅ 27 pA) of the diode. Similar CV results obtained with electron beams from 6 up to 18 MeV are presented in Table 1.

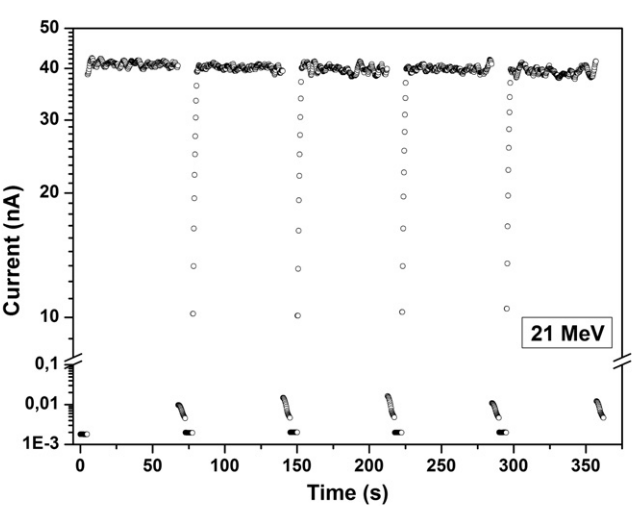

Fig. 1. Short term repeatability of the EPI diode for 21 MeV electron beam energy (Siemens KD2 Radiotherapy Linear Accelerator).

Table 1
Coefficient of variation (CV) and charge sensitivities of the diode for all electron beam energies studied (Siemens KD2 Radiotherapy Linear Accelerator).

Energy (MeV)	C.V. (%)	Sensitivity (μC/Gy)
6	1.5	1.31
9	2.4	1.08
12	1.3	0.93
15	1.4	0.89
18	1.1	0.87
21	2.4	0.86

Fig. 2 shows the charge generated in the sensitive volume of the diode as a function of the absorbed dose within the range from 3 to 16 Gy. For electron beam energies from 6 MeV up to 21 MeV, the dose response of the diode are quite linear (correlation coefficients of about 0.9999) with charge sensitivities higher than 0.86 μC/Gy (Table 1).

Nevertheless, the results of charge sensitivity plotted in Fig. 3 show the dependence of the EPI diode response on the electron beam energy, mainly in the region of low energy. Indeed, the charge sensitivity of 6 MeV electron beam is almost 34% higher than that obtained for 21 MeV electron beam. To clarify the origin of this energy dependence Monte Carlo simulations were performed using the CASINO® code, considering electron beams of 6 and 21 MeV energies with 200,000 incident electrons each. The results obtained show the deposited energy by the 6 MeV electrons in EPI diode is 31% higher compared to the 21 MeV energy electrons. Although the CASINO is a code specifically designed for low energy beam interaction, the agreement with our experimental results was reasonable.

The measurements of the percentage depth dose profile (PDD) for 9 and 18 MeV electron beams in PMMA are presented in Fig. 4 together with the theoretical values obtained through the Oncentra Master Plan® planning system based on Monte Carlo code. The good agreement between the experimental and simulation results evidences that the EPI diode can be used for measuring the PDD profile. These results can be considered also as a first hint that the diode may not present dose rate dependence, at least within the range from 1.73 cGy/s to 8.25.10^{-3} cGy/s. However, this fact need to be confirmed with further experiments, once the influence of the

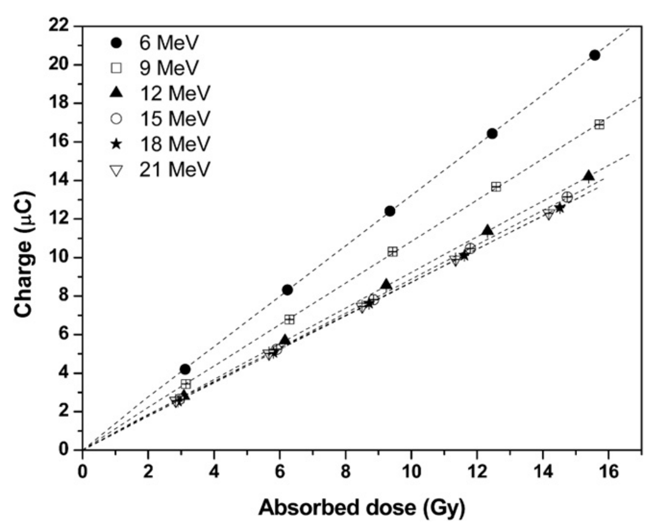

Fig. 2. Dose Response curve for the EPI diode for the electron beam energies studied (Siemens KD2 Radiotherapy Linear Accelerator). Experimental uncertainties are smaller than the symbols size.

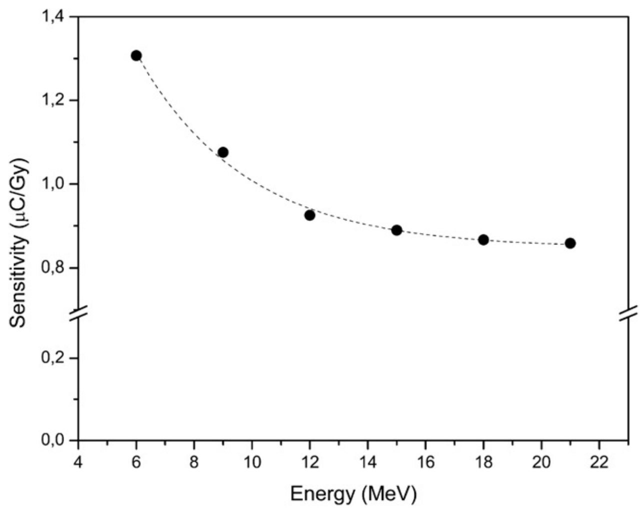

Fig. 3. Charge sensitivities as a function of the electron beam energy (Siemens KD2 Radiotherapy Linear Accelerator). Experimental uncertainties are smaller than the symbols size.

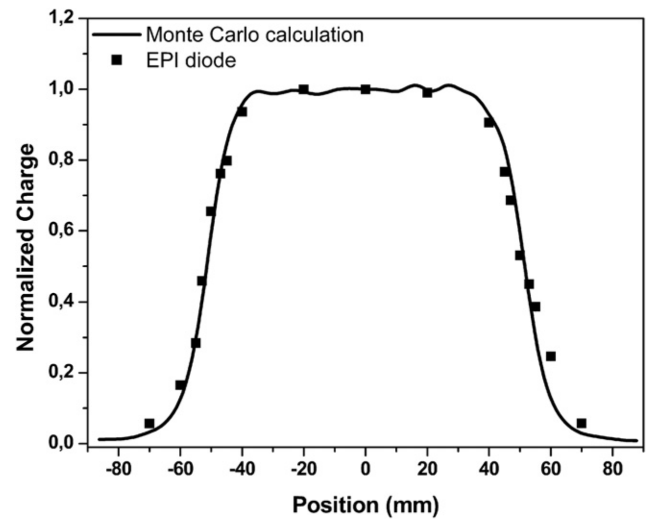

Fig. 5. Transversal dose profile (TDP) measurements performed in PMMA with the EPI diode placed at z_{ref} for 12 MeV electron beam irradiation (Siemens Primus Linear Accelerator). Experimental uncertainties are smaller than the symbols size.

decrease in the mean electrons energy with the depth must be taken into account.

Fig. 5 depicts the transversal dose profile (TDP) measurements performed in PMMA with the EPI diode placed at the reference depth (2.5 cm) for 12 MeV electron beam irradiation. Within the field size of 10×10 cm^2, the charge measured in each position of the field cross plane axis was normalized to that registered with the diode centered in the irradiation field (0 mm). The experimental results plotted in Fig. 5 agree with the TDP simulation performed with the Oncentra Master Plan® Treatment Planning System (solid line), confirming thus the expected good spatial resolution of the EPI diode. The overestimation of the penumbra is due to the finite size of the diode, which causes an averaging effect (TG 106., 2008) that blurry the steep dose gradient at the edge of the field. Although punctual differences between the measurements and the calculation can be up to 10% (at 60 mm), the distance-to-agreement at this point is just 3 mm. Nevertheless, the average difference between the measurements and the calculation is 2.6%.

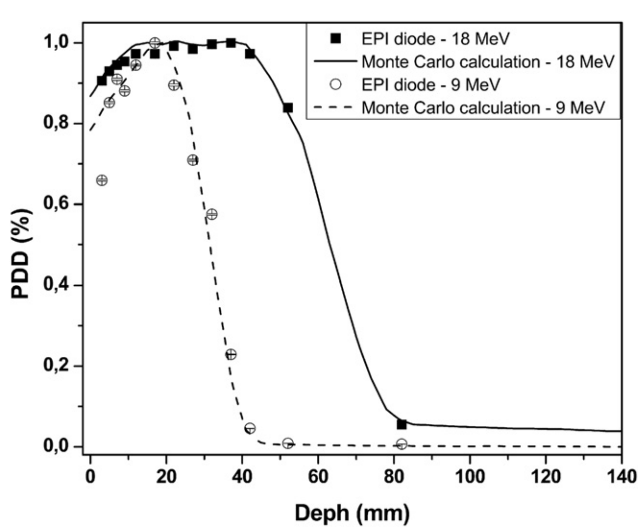

Fig. 4. Percentage depth dose profiles in PMMA under irradiation with 9 and 18 MeV electron beams (Siemens Primus Linear Accelerator). For comparison, EPI diode measurements (symbols) are presented with Monte Carlo calculations (lines). Experimental uncertainties are smaller than the symbols size.

4. Conclusions

The dosimetric characteristics of an epitaxial silicon diode for clinical electron beam irradiation were investigated in the 6–21 MeV energy range. The results showed that the current response of this device, operating in a photovoltaic mode, is quite stable with good short term repeatability (CV≤2.4%). It was also observed that the charge produced in the sensitive volume of the EPI diode increases linearly with the absorbed dose. Despite of these good results, charge sensitivity measurements evidenced that the dose response of the diode is slightly dependent on the electron beam energy. To clarify the origin of this effect some Monte Carlo calculation is under way. It is worth noting that, despite of showing energy dependent effects, neither dark currents increase nor memory effects were observed in the device response.

The percentage depth dose profile (PDD) and transversal dose profile (TDP) results, that are in excellent agreement with Monte Carlo simulation, also demonstrates that the investigated device can be used as an on-line radiotherapy electron beam dosimeter. Furthermore, it is expected that this device is suited for mapping dose distributions of teletherapy beams, as well as to routinely monitor the constancy of the output of clinical linear accelerators. Further investigation will be undertaken regarding energy dependence and long-term reproducibility of the EPI diode studied in this work.

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