Feasibility study of using Epitaxial Silicon Diodes for clinical electron and photon beams dosimetry

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Abstract – **In this work the feasibility of using epitaxial (EPI) silicon diodes for clinical dosimetry was studied with a Siemens Primus Linear Accelerator from Sírio-Libanês Hospital. Three samples of EPI diodes were investigated, concerning the influence of pre-irradiation on their response as on-line clinical photon and electron beam dosimeter. All measurements were performed with the diodes unbiased, operating in the direct current mode and inserted into a PMMA phantom. The dynamic current responses of the diodes under irradiation with electron beams in the energy range of 6 MeV-21 MeV and photon beams of the 6 and 18 MV were measured at different dose-rates. The dose-response curves of the diodes are quite linear in the range of zero up to 29.54 kGy for electrons and evaluated from 63 cGy up to 370 cGy for photon beams. The percentage depth dose profile (PDD) and transversal dose profile (TDP) for both electron and photon beams were also measured in PMMA with the EPI diodes. The results were in excellent agreement with those calculated with Monte Carlo code using the Oncentra MasterPlan® Treatment Planning System (TPS). The TDP was also evaluated with a commercialized array of 2D pixel ionization chambers MatriXX from IBA Dosimetry®.**

I. INTRODUCTION

Semiconductor devices have been used for photon and electron beams dosimetry mainly in the field of radiation protection, medical imaging and radiation therapy [1-3]. One of the major interests in using semiconductor dosimeters is their higher sensitivity per unit of volume in comparison with ionization chamber. Other major advantages of Si diodes are their fast processing time, small sensitive volume, excellent repeatability, good mechanical stability, high spatial resolution 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) [4]. However, ordinary silicon devices present low radiation hardness, being very prone to radiation damage effects [5], responsible for a gradual long-term sensitivity decay, mainly for high energy electron beams irradiation. This is the most important constraint against the widespread use of silicon devices in medical dosimetry [6-9], once their routinely use demands periodic recalibration of the dosimeter due to the drop in sensitivity with the increasing of the accumulated dose. Nevertheless, this drawback has been overcome with the development of radiation tolerant silicon detectors [10] in the framework of High Energy Physics research projects. The performance of rad-hard diodes [11] 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 [12,13]. 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. 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 (EPI) layers with high radiation damage tolerance [14,15].

In this work we present the preliminary results concerned with the influence of gamma and electron pre-irradiation on EPI silicon diodes response as on-line clinical photon and electron beam dosimeter.

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II. MATERIALS AND METHODS

The diodes used, with 25 mm^2 active area, were processed at University of Hamburg [14] on n-type 50 µm thick epitaxial silicon layer (nominal resistivity of 50 Ω.cm), grown on a highly doped n-type 325 µm thick Czochralski (Cz) silicon substrate. Three samples of EPI diodes were investigated: **A** – which was non-irradiated, **B** – which received a gamma pre-dose of 200 kGy from a ^{60}Co irradiator (Gammacel 220, from University of Pernambuco) and **C** – which was pre-irradiated with 200 kGy from a 1.5 MeV electron beam from a DC 1500/25/4 - JOB188 accelerator, located at IPEN-CNEN/SP. In order to use the diodes as a dosimeter, each one was housed in a black polymethylmethacrylate (PMMA) probe to provide protection from mechanical stress, light and moisture. The devices were connected in the photovoltaic mode to the input of a Keithley 6517B electrometer and their dosimetric responses were evaluated for electron beams within the energy range of 6 MeV up to 21 MeV and for photon beams of the 6 and 18 MV from a Siemens Primus Radiotherapy Linear Accelerator, located at Sírio-Libanês Hospital. During all measurements, each diode was held between PMMA plates, placed at the reference depth (z_{ref}) [16] to electron beams studies (or 10.0 cm depth to photon beams) and centered in a radiation field of 10 x 10 cm^2, with the source-to-surface distance (SSD) kept at 100 cm. The short-term repeatability of the EPI diodes was evaluated for all energies by registering five consecutive current signals for the same radiation dose, switching the beam on and off. After each step of irradiation, when the beam was switched off, the leakage currents of the diodes were measured to monitor possible radiation damage effects. Measurements were performed with an average dose-rate of 5.0 cGy/s for the electron beams energies of 6, 9, 12, 15, 18 and 21 MeV and dose-rates of 2.11cGy/s (200 MU/min) and 3.70 cGy/s (300 MU/min) for the photon beam energies of 6 and 18 MV, respectively. The dose-response curves of the devices, i.e, the charge released (obtained via integration of the signal current) as a function of accumulated dose were also studied.

Percentage depth dose (PDD) measurements were carried out in a PMMA phantom with **B** and **C** diodes at different electron beams energies and **B** diode irradiated with 6 MV and 18 MV photon beam energies. The SSD was kept at 100 cm, changing the depth of the dosimeter from 1 mm to 80 mm with PMMA plates to electron beams and from 5 mm to 200 mm for photon beams. The PDD measurements were repeated from the top to the bottom position in the PMMA phantom. For each position, two signals were consecutively registered. The transversal dose profile (TDP) was measured in PMMA at the reference depths for 12 MeV and 15 MeV electron beams and at 10.0 cm depth for 6 MV and 18 MV photon energies. The TDP data were gathered moving the treatment table across the whole irradiation field (10 x 10 cm^2) crossplane axis.

The PDD and TDP experimental results with electron beam energies were compared with Monte Carlo calculations performed using the Oncentra MasterPlan® Treatment Planning System (version 3.2, algorithm eVMC) from Nucletron®. An additional experimental evaluation was also made with TDP provided by a commercial dosimetry system, which consists of a 2D array of 1020 parallel plates ionization chambers (each one with 0.5 cm diameter and 0.76 cm center to center spacing), called MatriXX, from IBA Dosimetry®. Finally, for photon beams, the PDD and TDP experimental results were compared with calculations provided by Colapse Cone Convolution and Pencil Beam codes using the OncentraMasterPlan® Treatment Planning System (version 3.2, algorithm eVMC).

III. RESULTS

The dynamic current responses of the EPI diodes under irradiation with electron and photon beams are presented in Fig. 1a and 1b. The results obtained evidenced that, for the same average dose rate, the current signals are very stable in both cases, although it was not observed any improvement on the instantaneous stability of the pre-irradiated diode responses. For all energies, data show good instantaneous repeatability of the diodes, characterized by coefficients of variation (CV) better than 2.8% and 0.04% to electron and photon beams, respectively.

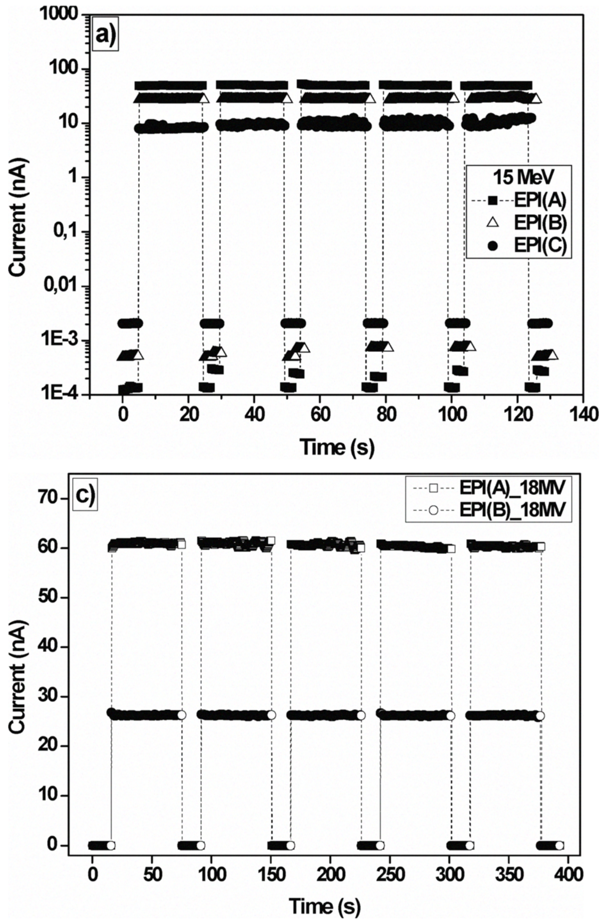

Fig. 1. Five signals consecutively registered with the diodes under irradiation with: (a) 15 MeV electron beam irradiation at 5.0 cGy/s dose rate; (b) 18 MV photon beam at 3.70 cGy/s dose rate.

However, it is worth to note that even for the **C** diode, the current signal was almost four orders of magnitude higher than the dark current of the diode (≅ 2.5 pA), acquired after each step of irradiation when the electron beam was just switched off.

The dose-responses of the devices, given by the curves of the charge as a function of the accumulated dose (Fig. 2a, 2b) are quite linear (correlation coefficients of about 0.9999), with charge sensitivities better than 0.21 μC/Gy and 1.60 μC/Gy to electron (Fig. 3) and photon (Table I) beams energies, respectively. Besides of being more sensitive, the non-pre-irradiated diode exhibited minimum dependence on the electron beam energy in comparison to the others EPI diodes studied. In the case of photon beams, both diodes used presented a similar energy dependence, which might be attributed to the structure and small dimensions of the devices. Some studies are under way to clarify the origin of this effect.

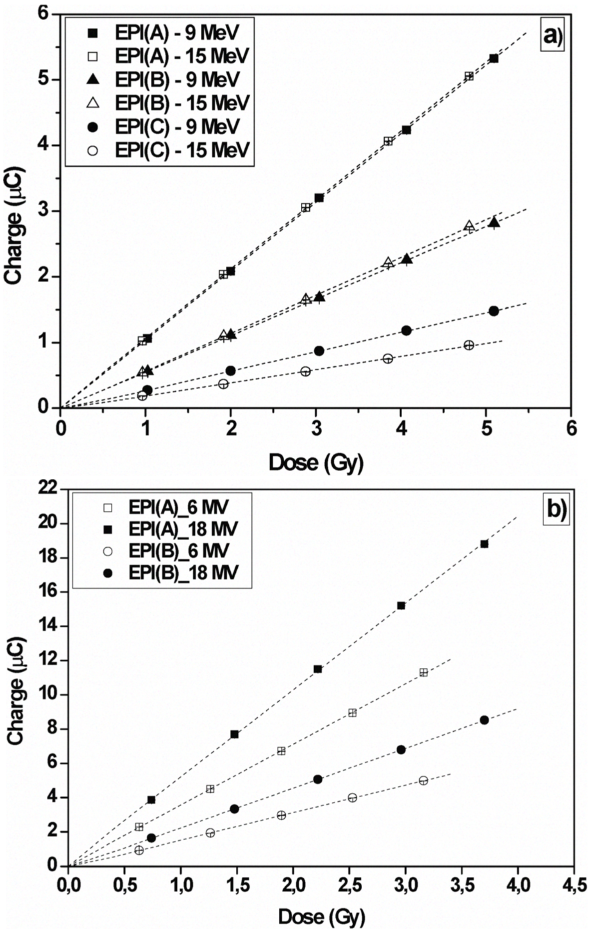

Fig. 2. Dose-Response curves of EPI diodes for: (a) 9 and 15 MeV electron beam energies; (b) 6 and 18 MV photon beam energies. Experimental uncertainties are smaller than the symbols size in both figures.

Table I: Charge sensitivities of EPI diodes for 6 and 18 MV photon beam energies.

Energy (MV)	Sensitivity (μC/Gy)	
	EPI A	EPI B
6	3.54	1.60
18	5.08	2.32

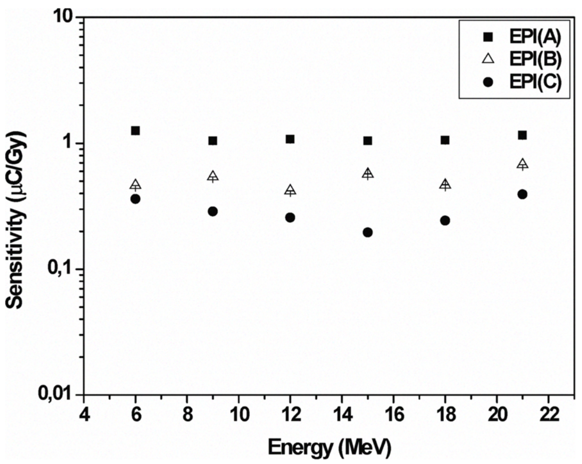

Fig. 3. Charge sensitivities of EPI diodes as a function of the electron beam energy. Experimental uncertainties are smaller than the symbols size.

The measurements of the percentage depth dose profile (PDD) in PMMA are presented in Fig. 4(a) and 4(b) for samples at different beam energies together with the theoretical values obtained through the Oncentra MasterPlan® (OMP) planning system. The good agreement between the experimental and simulation results evidences that the EPI diodes, even the pre-irradiated ones, can be used for measuring PDD profiles. Fig. 5(a) and 5(b) depict the transversal dose profile (TDP) measurements performed in PMMA with the **B** EPI diode in both type of irradiation. The experimental results plotted agree with the TDP simulation performed with the OMP Monte Carlo code and the measurements performed with MatriXX® for 15 MeV electron beam. The results for 6 MV photon beam were in excellent agreement with those calculated using Colapse Cone Convolution and Pencil Beam codes, confirming the excellent spatial resolution of the EPI diodes.

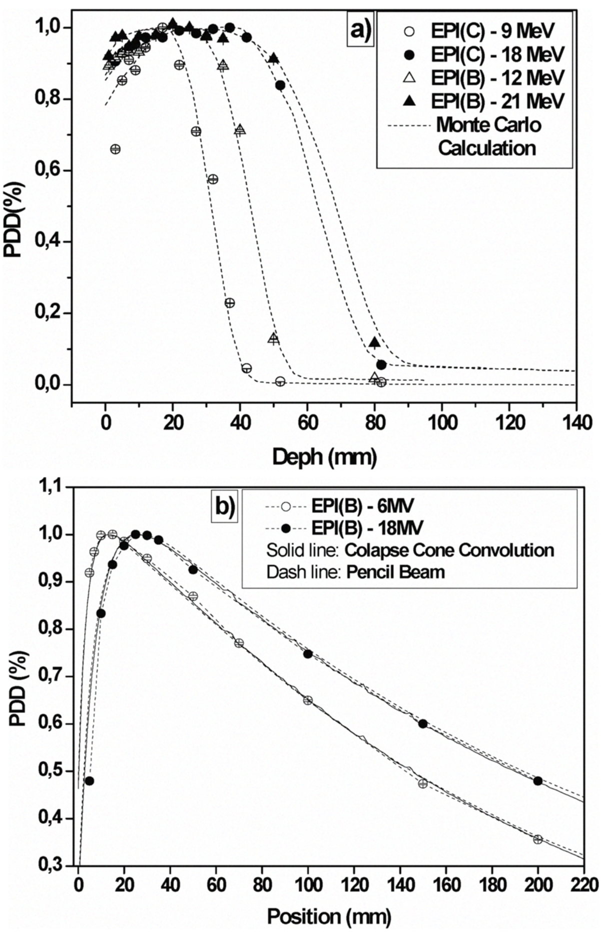

Fig. 4. PDD profiles in PMMA under irradiation with: (a) 9, 12, 18 and 21 MeV electron beams; (b) 6 and 18 MV photon beams. Monte Carlo (lines), Colapse Cone Convolution (solid line) and Pencil Beam (dash line) calculations are presented for comparison. Experimental uncertainties are smaller than the symbols size.

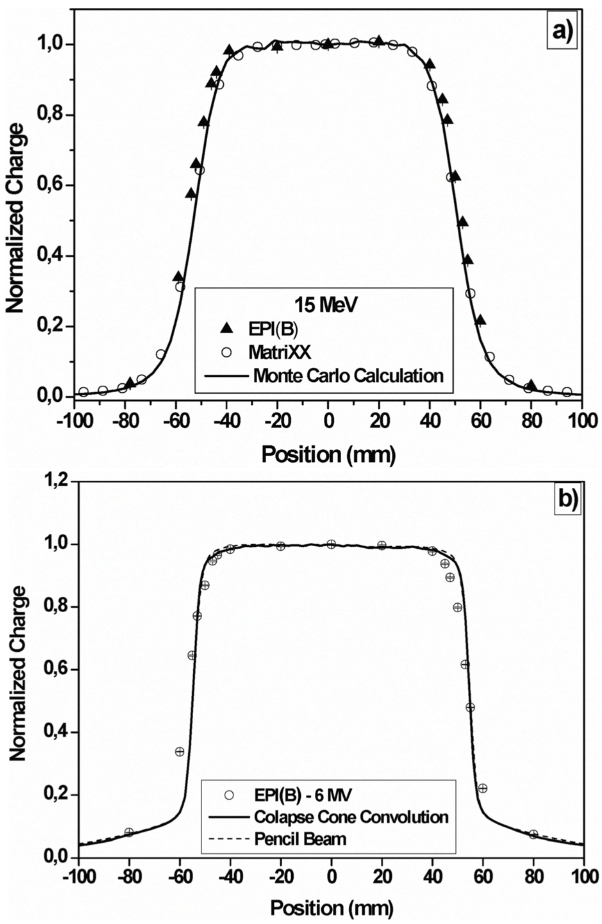

Figure 5: TDP measurements performed in PMMA with the EPI diodes for: (a) 15 MeV electron beam irradiation; (b) 6 MV photon beam irradiation. For comparison, Colapse Cone Convolution (solid line) and Pencil Beam (dash line) calculations are presented. Experimental uncertainties are smaller than the symbols size.

IV. CONCLUSIONS

The influence of pre-dose on epitaxial silicon diodes envisaging their application in on-line clinical electron and photon beam dosimetry was investigated in the 6 - 21 MeV electron energy range and in the 6 and 18 MV photon energies. The results indicate very good instantaneous repeatability of these devices to electron and photon beams operating in photovoltaic mode, mainly for the non-pre-irradiated EPI diode. As expected, the highest sensitivity was achieved with the **A** EPI diode also. It was observed that the charges produced in the sensitive volume of all samples increase linearly with the absorbed dose (correlation coefficients better than 0.9999). Indeed, the pre-irradiation with electrons makes the dose response of the **C** diode slightly dependent on the electron beam energy, what it was not observed with A and B diodes. However, the responses of these later devices were dependent on the photon beam energy. Further studies and Monte Carlo calculation are demanded to clarify the origin of these effects.

The PDD profile and TDP results for both electron and photon beams are in excellent agreement with Monte Carlo simulation and with calculations performed using OncentraMasterPlan® Treatment Planning System to photon beams. Based on these results, one can conclude that the investigated devices can be used as an on-line radiotherapy electron and photon dosimeter for beam scanning purposes and relative dosimetry. It worth noting that these results are preliminary and still remains to be investigated the long term stability and the radiation hardness of these diodes for absorbed doses higher than investigated in this work. All these studies are under way.

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