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A COMPARISON BETWEEN RAD-HARD FLOAT ZONE SILICON DIODES AS GAMMA DOSIMETER IN RADIATION PROCESSING

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ABSTRACT

In this work, we report on the results obtained with rad-hard Standard Float Zone (STFZ) and Diffused Oxygenated Float Zone (DOFZ) silicon diodes in radiation processing dosimetry. The dosimetric probes were designed to operate in the direct current mode, as on-line radiation dosimeter. The irradiation of the samples was performed using a ^{60}Co source with a dose rate of almost 2.4 kGy/h. The current response of each diode was measured as a function of the exposure time in steps from 5 kGy up to 50 kGy to achieve a total absorbed dose of 275 kGy. In this dose range it is observed a significant decrease in the photocurrent generated in both devices due to gamma radiation defects produced in their active volumes. To mitigate this effect, the samples were pre-irradiated with ^{60}Co gamma rays at 700 kGy. Despite of being less sensitive, these devices presented stable and reproducible current signals with a relative sensitivity decrease of about 19% within the whole range of dose studied. The dose-response curves of the pre-irradiated diodes showed quadratic behavior with correlation coefficient higher than 0.9999 for total absorbed dose up to 275 kGy. The comparison of the FZ and DOFZ responses evidenced that the latter was slightly superior to the first. However, it is important to note that all pre-irradiated diodes can be used as gamma dosimeters in radiation processing applications.

1. INTRODUCTION

The use of silicon diodes as on-line gamma dosimeters in radiation processing is a big challenge due to the radiation damage effects suffered by semiconductor devices, such as: sensitivity dependence on dose-rate and the decrease of sensitivity with accumulated dose, the main restriction to their application in high dose dosimetry [1]. On the other hand, semiconductor devices have been widely used for photon and electron beams dosimetry, mainly in the field of radiation protection, medical imaging and radiation therapy [1-5], where the doses are considerably lower than those delivered in some typical radiation processing applications, that can easily reach 30 kGy or more [6].

Nevertheless, developments of rad-hard silicon diodes for high energy physics experiments have been changed this reality, allowing the use of these devices in applications under severe radiation environment [7, 8]. Among several defect engineering technologies used to decrease the radiation damage, one is to diffuse oxygen into the float zone Si bulk, increasing the oxygen concentration when compared with the standard float zone diode. This technology has shown a substantial improvement in radiation hardness, mainly when the diodes are irradiated with gamma rays [9].

In this work, we report the results of the comparison between rad-hard Diffused Oxygenated Float Zone (DOFZ) and Standard Float Zone (STFZ) silicon diodes in radiation processing dosimetry as on-line radiation dosimeter. The main advantage of recording real time currents, and consequently dose rates, is to provide continuous data of the dose delivered to the product for quality assurance in radiation processing.

2. EXPERIMENTAL APPARATUS

The $p^+/n/n^+$ junction devices used were produced on rad-hard float zone Si wafers of 300 μm thickness, active area of 25 mm^2 (surrounded by a multiple guard ring structure), resistivity about 1.4 kΩ·cm and oxygen concentration $< 10^{15}$ cm^{-3}. Additionally, the DOFZ wafer was passivated by oxygen diffusion into the bulk, reaching an oxygen concentration $\approx 10^{17}$ cm^{-3}. Both diodes were manufactured by Okmetic Oyj (Finland) and processed by the Microelectronics Center of Helsinki University of Technology [10] in the framework of the CERN RD50 Collaboration. Two samples of each diode (STFZ and DOFZ) with similar characteristics related to I/V and C/V standard measurements, hereafter referred as STFZ#54, STFZ#75, DOFZ#2 and DOFZ#6, were used in this work. The samples STFZ#54 and DOFZ#2 were not irradiated before using as a dosimeter, while the diodes STFZ#75 and DOFZ#6 received a gamma ray pre-dose of 700 kGy.

Figure 1 shows the dosimetric probe, a PolyMethilMetacrylate (PMMA) box, which protected the diodes from moisture, light and mechanic vibrations. All guard rings of the diodes were left floating, while the back plane (n^+) of each device was properly grounded. The p^+ front electrode was directly connected, via a 2 m long 50 Ω coaxial cable, to a Fluke 189 multimeter with time resolution of 4 s. The photocurrents as a function of time were acquired with the FlukeView Forms® software.

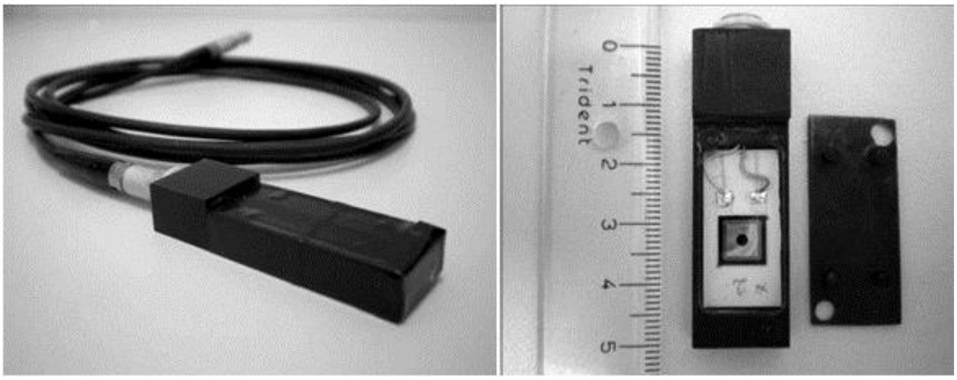
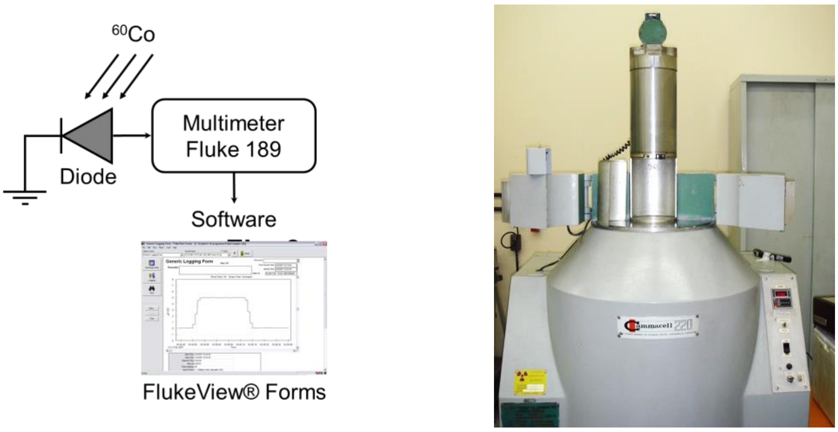


Figure 1: Dosimetric probe based on the rad-hard float zone Si device.

The irradiation was performed at IPEN-CNEN/SP using a ^{60}Co source (Gammacell 220 – MDS Nordion) with traceability through the International Dose Assurance Services (IDAS) from International Atomic Energy Agency (IAEA). Figures 2a and 2b illustrates the experimental setup used to obtain the photocurrents as a function of time.

The dose rates used to irradiate each diode are listed in Table 1. The diodes were placed in the central position of the ^{60}Co irradiation chamber and irradiated in consecutive steps of 5 kGy from 50 kGy. It took more than 110 h irradiation time to achieve an accumulated dose of 275 kGy per diode. After each step, the source was switched off the measurement of the leakage current of the dosimetric probe. The temperature during exposure was typically 25 ± 3 ºC.



(a) (b)

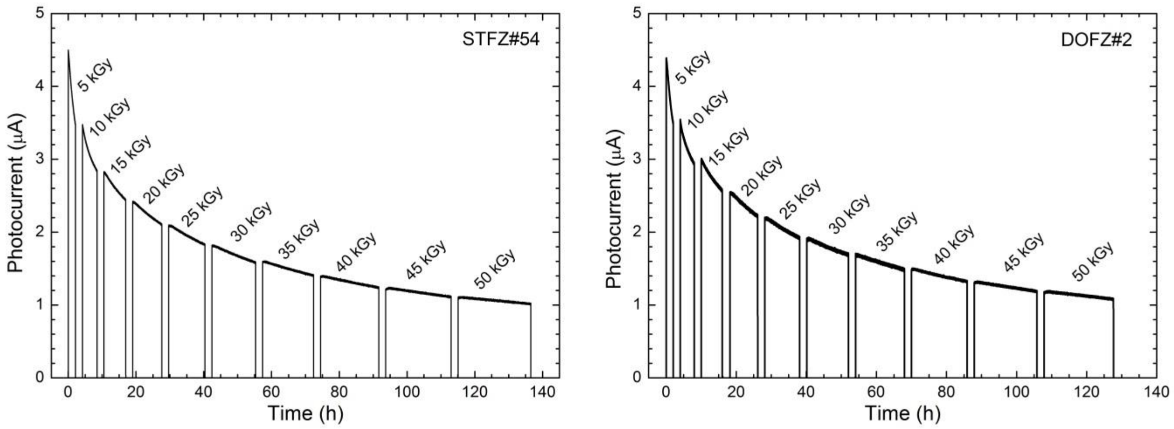
Figure 2: (a) Schematic setup used to obtain the photocurrents as a function of time; (b) Gammacell 220 – MDS Nordion (^{60}Co source).

Table 1: Dose rate ($\dot{D}$) applied by the Gammacell 220 during samples irradiation.

Pre-Dose	Diode	$\dot{D}$ (kGy/h)
None	DOFZ#2	2.52 ± 0.04
	STFZ#54	2.33 ± 0.04
700 kGy	DOFZ#6	2.49 ± 0.04
	STFZ#75	2.31 ± 0.04

3. RESULTS

The photocurrent response of the STFZ#54 and DOFZ#2 diodes under ^{60}Co gamma radiation with different exposure times is shown in Fig. 3. The sensitivity dependence of the diodes on the dose is clearly evidenced by a fast decay of the photocurrent for accumulated doses of about 30 kGy, followed by a slower decrease at higher doses, as can be seen in the Figure 4. In order to eliminate the influence of dose rate in the generation of the photocurrent, the data in this figure are normalized by the maximum current measured at the beginning of exposition and presented as a function of the accumulated dose.



(a) (b)

Figure 3: Current response of the (a) STFZ#54 and (b) DOFZ#2 diodes for successive exposure times, irradiated at the dose rate of 2.33 and 2.52 kGy/h, respectively.

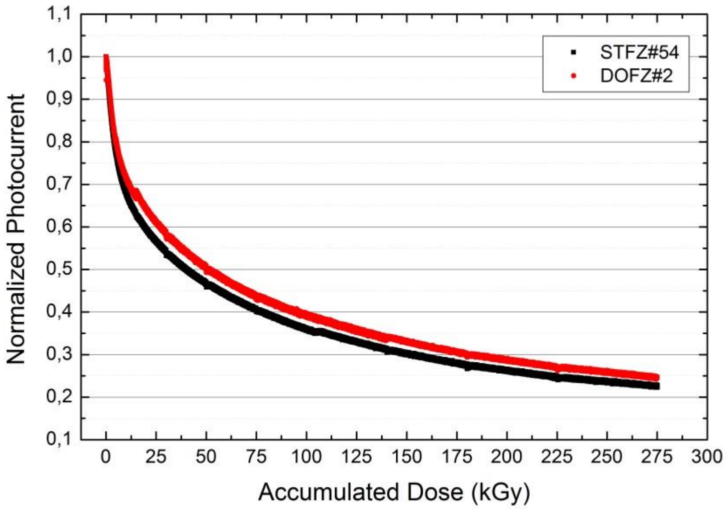
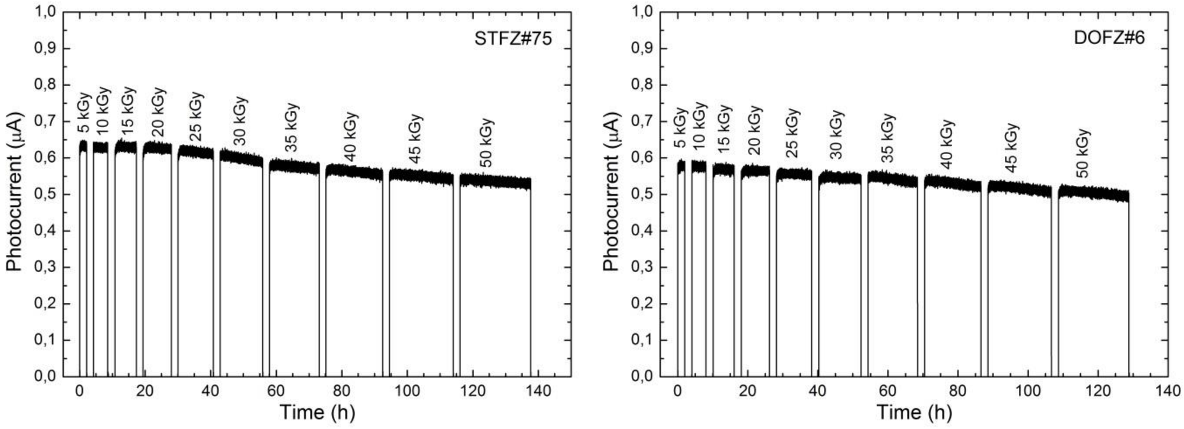


Figure 4: Normalized photocurrent for the STFZ#54 and DOFZ#2 diodes as a function of the accumulated dose.

From Fig. 4, it was expected a less pronounced sensitivity decay at accumulated doses higher than approximately 300 kGy. Therefore, in order to improve the diode response stability, by reducing its sensitivity dependence on the dose, the STFZ#75 and DOFZ#6 samples were pre-irradiated with ^{60}Co gamma rays with a dose of about 700 kGy.

Indeed, in Fig. 5, the photocurrent response of the STFZ#75 and DOFZ#6 diodes, evaluated for accumulated doses up to 275 kGy, presents very stable and reproducible current signals at all doses studied, as can be seen by the normalized photocurrent as a function of the accumulated dose (Fig. 6). This fact can be attributed to the saturation of the traps generated in the sensitive volume of the devices by the radiation and is confirmed by the average photocurrent values and the sensitivity for the pre-irradiated devices showed in Table 2. It is important to note that, even being less sensitive after the high pre-dose, the signal to dark current ratio is about more than 10^3 [11], allowing the safe use of these diodes as dosimeters.



(a) (b)

Figure 5: Current response of the (a) STFZ#75 and (b) DOFZ#6, with a pre-dose of 700 kGy, irradiated at the dose rate of 2.31 and 2.49 kGy/h, respectively.

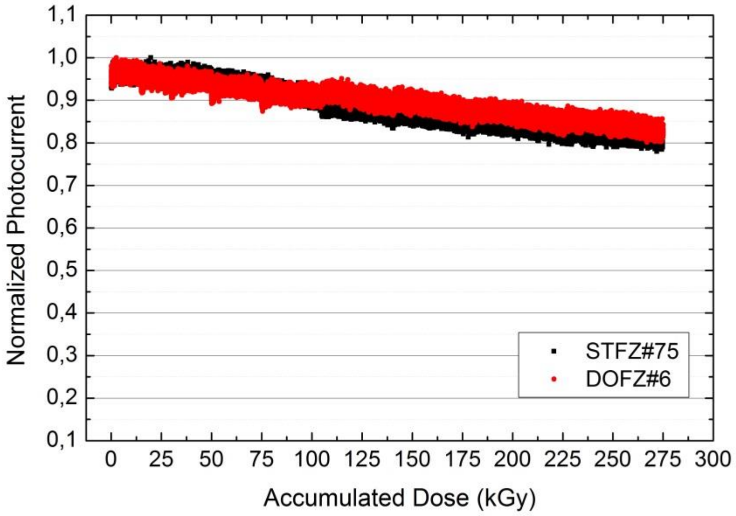


Figure 6: Normalized photocurrent for the STFZ#54 and DOFZ#2 diodes as a function of the accumulated dose.

Table 2: Average photocurrent ($\overline{I_F}$), sensitivity (S) and charge sensitivity (S_q) for the pre-irradiated diodes.

Sample	$\dot{D}$ (kGy/h)	$\overline{I_F}$ (μA)	S (μAh/kGy)	S_q (mC/kGy)
STFZ#75	2.31 ± 0.04	0.60 ± 0.03	0.26 ± 0.01	0.92 ± 0.05
DOFZ#6	2.49 ± 0.04	0.55 ± 0.02	0.22 ± 0.01	0.79 ± 0.04

Analyzing the results presented in Tab. 2, it is possible to conclude that the STFZ diode is more sensible than the DOFZ diode.

To compare the stability response of the devices, the average current signals of each exposure, normalized to the average current at 5 kGy for each diode, are plotted in Fig. 7 as a function of the accumulated dose up to 275 kGy. Within this dose range, the sensitivity decreases about 18% and 19% for the DOFZ and STFZ diodes, while for the non-irradiated diodes, for the same accumulated dose, the sensitivity in current reduced to 77% (STFZ) and 75% (DOFZ) respectively.

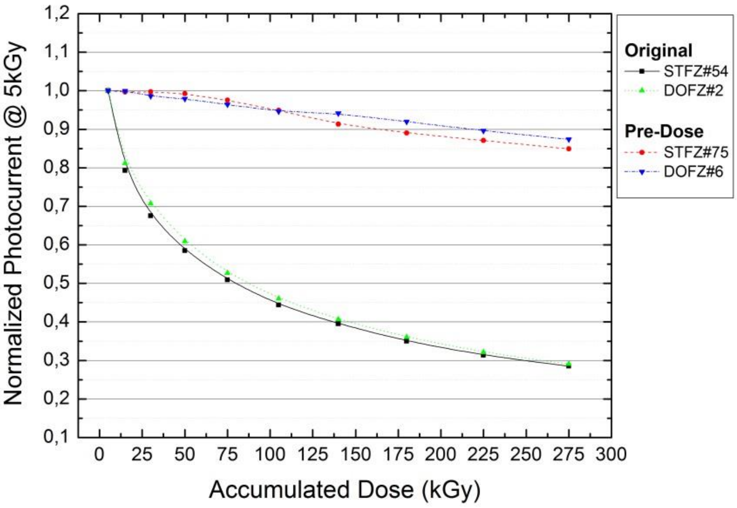
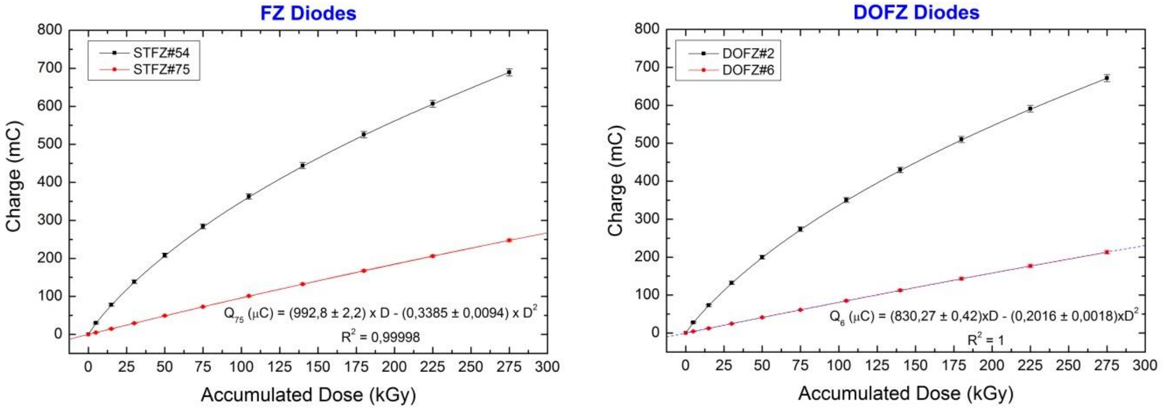


Figure 7: Average current signals of each successive exposure, normalized to the average current at 5 kGy of respective diode, as a function of the accumulated dose.

This stability is also evidenced in Fig. 8 which shows the charge released in different types of devices, obtained by integrating the current signals over the exposure times, as a function of the accumulated dose. As can be seen, for doses higher than 30 kGy, diodes without pre-dose shown a significant saturation, probably due to point defects created in their volume by the gamma radiation. Conversely, within the whole dose range studied it was observed a quadratic response of the pre-irradiated diodes with a correlation coefficient (R^2) more than 0.999. These results suggested that pre-irradiation with 700 kGy was enough to achieve the stable response of these devices.



(a) (b)

Figure 8: Charge as a function of the accumulated dose for diodes (a) without (STFZ#54 and DOFZ#2) and (b) with pre-dose (STFZ#75 and DOFZ#6).

4. CONCLUSION

Rad-hard float zone diodes have been characterized as on-line ^{60}Co gamma radiation dosimeters from 5 kGy up to 275 kGy. In this dose range, the sensitivity decrease of diodes without pre-dose (STFZ#54 and DOFZ#2) was about 77%, leading to a significant saturation on their charge versus dose response. This effect, due to gamma radiation induced point-defects in the crystal bulk, was reduced by pre-irradiating the diodes (STFZ#75 and DOFZ#6) with a gamma ray dose of 700 kGy. Despite of being less sensitive, these devices presented stable and reproducible current signals with a relative sensitivity decrease of about only 19% within the whole range of dose studied. The calibration curves of the pre-irradiated dosimeters showed quadratic responses with correlation coefficient higher than 0.9999 for total absorbed dose up to 275 kGy. The comparison of the dosimetric response among the diodes studied evidenced that the best result was achieved with the DOFZ, which exhibited higher sensitivity and stability than the FZ devices. However, it is important to note that all pre-irradiated diodes can be used as gamma dosimeters in radiation processing applications.

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