# Performance of DOFZ Diode as On-Line Gamma Dosimeter in Radiation Processing

F. Camargo, J. A. C. Gonçalves, E. Tuominen, J. Härkönen and C. C. Bueno

***Abstract*–In this work, we report on results obtained with two rad-hard Diffusion Oxygenated Float Zone (DOFZ) silicon diodes as on-line gamma dosimeter in radiation processing. One device was not irradiated before using as a dosimeter, while the other received a gamma pre-dose of 700 kGy.**

**The samples irradiation was performed using a 60Co source at a dose rate of 2.50 kGy/h from 5 kGy up 275 kGy. It was investigated the dosimetric response of these devices, operating in short-circuit current mode, with respect to the sensitivity dependence on dose and charge-dose linearity. Without any pre-dose, the diode exhibited a significant sensitivity decrease due to radiation induced point-defects in the crystal bulk. Conversely, the pre-irradiated device presented very stable current signals with a relative charge sensitivity of 0.9 mC/kGy.**

## I. Introduction

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]. The uttermost characteristic of silicon diodes that make them very attractive for dosimetric purposes, relative to gas-ion chambers, is their high sensitivity which allows reducing the sensitive volume and minimizing the medium perturbation. Furthermore, unlike gas-filled detectors, silicon devices do not require high voltages when operated in short circuit current mode, which great simplifies their utilization. Nevertheless, radiation damage effects, such as the sensitivity dose-rate dependence and the sensitivity decrease with dose suffered by semiconductor devices are the main restriction to their application in high dose dosimetry [1].

However, as radiation tolerance of semiconductor detectors is also an important concern in high-energy physics (HEP) experiments, considerable researches have been dedicated to develop rad-hard Si devices able to operate under severe radiation environment [6,7]. Among several defect engineering technologies to decrease the radiation damage, one is to diffuse oxygen into the float zone Si bulk. Devices developed with this technology, named Diffused Oxygenated Float Zone (DOFZ), have shown a substantial improvement in radiation hardness mainly when they are irradiated with gamma rays [8]. The outstanding rad-hard properties of these diodes have stimulated us to investigate their potential for application in gamma radiation processing dosimetry.

In this work we report on results obtained with DOFZ devices, processed by the Microelectronics Center of Helsinki University of Technology [9], as on-line radiation dosimeter. The main advantage of recording real time currents, and consequently dose rates, is to provide continuous data of dose delivered to the product for quality assurance in radiation processing.

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## II. Experimental Apparatus

The rad-hard diodes used in this work were processed on n-type oxygenated float zone Si wafers of 300 μm thickness and resistivity of about 1300 Ω·cm. The $p^+$-n-$n^+$ junction devices have an active area of 25 $mm^2$ surrounded by a multiple guard ring (MGR) structure. Two diodes with similar characteristics from I/V and C/V standard measurements, hereafter referred as DOFZ#2 and DOFZ#6, were used in this work. The DOFZ#2 was not irradiated before using as a dosimeter, while the DOFZ#6 received a gamma pre-dose of 700 kGy.

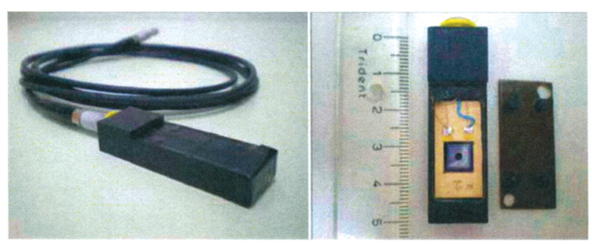

Fig. 1. Dosimetric probe based on the DOFZ device.

Figure 1 shows the dosimetric probe where each diode was put inside a small PolyMethilMetacrylate (PMMA) box to be protected from moisture, light and mechanic vibrations. All guard rings were left floating while the back plane ($n^+$) of the 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 (time resolution of 4 s). The data were acquired with the FlukeView Forms® software.

The irradiation was performed at IPEN-CNEN/SP using a $^{60}$Co source (Gammacell 220 – MDS Nordion) at a dose rate of 2.50 kGy/h with traceability through the International Dose Assurance Services (IDAS) from International Atomic Energy Agency (IAEA). With no bias voltage, the diode was placed in the central position of the $^{60}$Co irradiation chamber and irradiated in consecutive steps from 5 kGy up to 50 kGy to achieve an accumulated dose of 275 kGy. It took approximately 110 h irradiation time to reach the highest dose. After each step, the source was switched off to measure the current noise of the dosimetric probe. The temperature during exposure was typically 25 ± 3 °C.

## III. Results

The current response of the DOFZ#2 diode under $^{60}$Co gamma radiation within different exposure times is shown in Fig. 2. The sensitivity dependence on the dose is clearly evidenced by a fast decay of the diode's photocurrent for accumulated doses of about 30 kGy, followed by a slower decrease at higher doses.

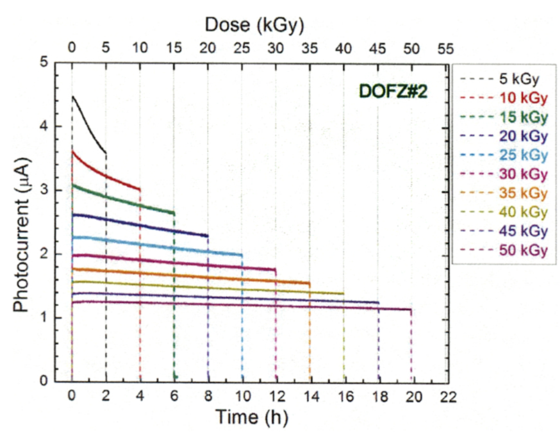


Fig. 2. Current response of the DOFZ#2 diode for successive exposure times. For comparison, each current signal was shift to the origin of the time axis.

From Fig.2, it was expected a less pronounced sensitivity decay at accumulated doses higher than approximately 300 kGy. In order to improve the diode response stability, by reducing its sensitivity dependence on the dose, the DOFZ#6 sample was pre-irradiated with $^{60}$Co gamma rays with a dose of about 700 kGy.

Indeed, in Fig.3, the current response of the DOFZ#6 diode, evaluated for accumulated doses up to 275 kGy, presents very stable current signals. For a dose rate of 2.50 kGy, the average photocurrent value was about 0.6 μA. It is important to note that, even being less sensitive, the unbiased diode photocurrent to dark current ratio is about $10^3$.

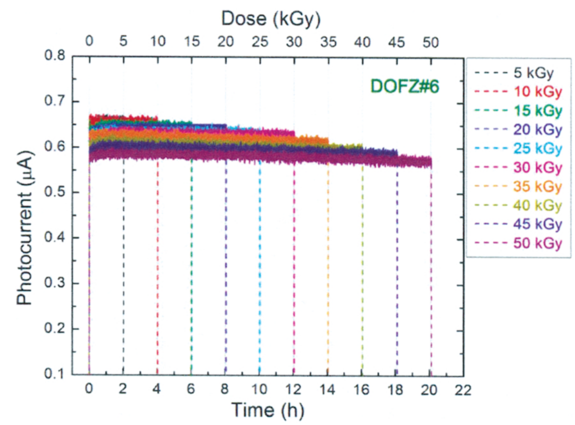


Fig. 3. Current response of the DOFZ#6 for successive exposure times. For comparison, each current signal was shift to the origin of the time axis.

To compare the stability response of the DOFZ#2 and DOFZ#6 devices, the average current signals of each exposure, normalized to the average current at 5 kGy of both diodes, are plotted in Fig.4 as a function of the accumulated dose up to 300 kGy. Within this dose range, the sensitivity decrease of DOFZ#6 was only 10%, against 70% for DOFZ#2.

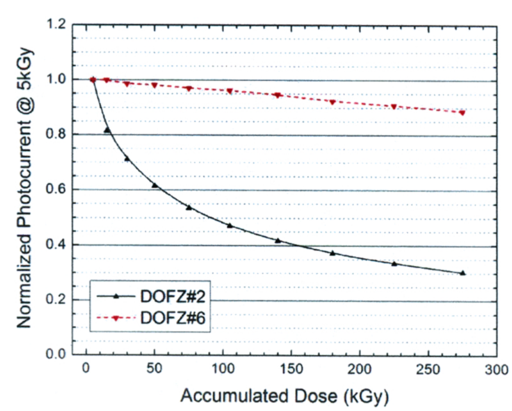


Fig. 4. Average current signals of each successive exposure, normalized to the average current at 5 kGy of both diodes, as a function of the accumulated dose.

This stability is also evidenced in Fig. 5 which shows the released charge in both 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 the DOFZ#2 shown a significant saturation, probably due to point defects created in its volume by the gamma radiation. Conversely, within the whole dose range it was observed a linear response of the DOFZ#6 device with a correlation coefficient ($R^2$) of 0.9998 and a charge sensitivity of (0.899 ± 0.004) mC/kGy. These results suggested that preirradiation with 700 kGy was enough to achieve the stable response of this device.

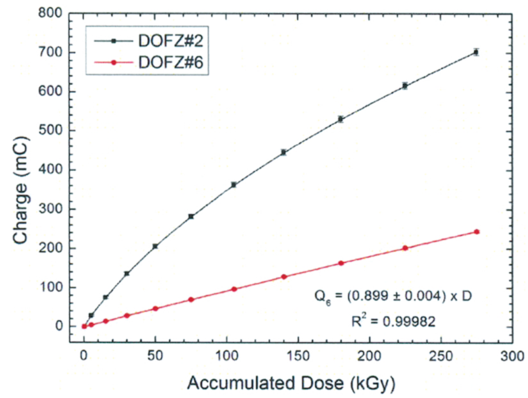


Fig. 5. Dosimetric response of DOFZ #2 and #6 devices as a function of the accumulated dose.

## IV. Conclusions

Rad-hard DOFZ 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 the DOFZ#2 diode was about 70% which led to a significant saturation on its charge versus dose response. This effect, due to gamma radiation induced point-defects in the crystal bulk, was reduced by pre-irradiating the DOFZ#6 diode with a gamma dose of 700 kGy. With this device, it was observed stable and reproducible current signals with a sensitivity decrease of about 10% within the whole range of dose studied. Furthermore, the DOFZ#6 diode exhibited a linear dosimetric response with a charge sensitivity of 0.9 mC/kGy.

Despite of being preliminary, these results have shown that pre-irradiated DOFZ devices can be used as on-line gamma dosimeter in radiation processing applications for doses up to 275 kGy.

It still remains to be investigated the annealing influence on both sensitivity and stability response of pre-irradiated DOFZ devices.


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## References


[1] Jean Barthe, "Electronic dosimeters based on solid state detectors," *Nucl. Instr. and Meth. Section B*, vol. 184, pp. 158-189, May 2001.

[2] Anatoly B. Rosenfeld, "Electronic dosimetry in radiation therapy," *Radiation Measurements*, vol. 41, pp. S134-S153, 2007.

[3] M. Casati, M. Bruzzi, M. Bucciolini, D. Menichelli, M. Scaringella, C. Piemonte, and E. Fretwurst, "Characterization of standard and oxygenated float zone Si diodes under radiotherapy beams," *Nucl. Instr. and Meth. Section A*, vol. 552, pp. 158-162, Jul. 2005.

[4] D. Menichelli, M. Bruzzi, M. Bucciolini, C. Talamonti, M. Casatia, L. Marrazzo, M. Tesi, C. Piemonte, A. Pozza, N. Zorzi, M. Brianzi, and A. De Sio, "Design and development of a silicon-segmented detector for 2D dose measurements in radiotherapy," *Nucl. Instr. and Meth. Section A*, vol. 583, pp. 109-113, Aug. 2007.

[5] F. Camargo, J. A. C. Gonçalvesa, H. J. Khoury, C. M. Napolitano, J. Härkönen, and C. C. Bueno, "MCz diode response as a high-dose gamma radiation dosimeter," *Radiation Measurements*, vol. 43, pp. 1160-1162, 2008.

[6] RD50 Status Report 2006 - Radiation hard semiconductor devices for very high luminosity colliders, *CERN-LHCC-2007-005 and LHCC-RD-013*.

[7] J. Härkönen, E. Tuovinen, P. Luukka, H. K. Nordlund, and E. Tuominen, "Magnetic Czochralski silicon as detector material," *Nucl. Instr. and Meth. Section A*, vol. 579, pp. 648-652, 2007.

[8] E. Fretwurst, G. Lindström, J. Stahl, I. Pintilie, Z. Li, J. Kierstead, E. Verbitskaya, and R. Röder, "Bulk damage effects in standard and oxygen-enriched silicon detectors induced by $^{60}$Co-gamma radiation," *Nucl. Instr. and Meth. Section A*, vol. 514, pp. 1-8, 2003.

[9] J. Härkönen, E. Tuominen, E. Tuovinen, K. Lassila-Perini, P. Mehtälä, S. Nummela, J. Nysten, P. Heikkilä, V. Ovchinnikov, M. Palokangas, M. Yli-Koski, L. Palmu, S. Kallijärvi, T. Alanko, P. Laitinen, A. Pirojenko, I. Riihimäki, G. Tiourine, and A. Virtanen, "The Effect of Oxygenation on the Radiation Hardness of Silicon Studied by Surface Photovoltage Method," *IEEE Trans. Nuclear Science*, vol. 49, no. 6, pp. 2910-2913, Dec. 2002.