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Accumulated dose stability parameters in p-type and n-type silicon diodes

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Abstract: This work investigates the influence of doping type on the dose responses and the accumulated dose stability of n- and p-type silicon MCz diodes. The operating principle of diode-based dosimeters relies on measuring the radiation-induced currents delivered by non-polarized diodes throughout the exposure time. An electrometer promptly reads the current signal, linearly dose rate dependent. The offline integration of the current signal provides the charge generated in the sensitive volume of the diode, expected to be proportional to the absorbed dose. The experimental approach involves analyzing the repeatability of the current signals, the dose responses of both pristine and pre-irradiated diodes, the correspondent charge sensitivities, and the sensitivity decay with increasing doses. For doses up to 175 kGy, the results reveal a linear dose response of the MCz(p) diode, characterized by a charge sensitivity of 3.1 μC/Gy. Within the same dose range, the response of the MCz(n) diode is visibly saturated and given by a fourth-order polynomial function. This saturation effect is likely linked to radiation damage effects manifesting in the current decay with increasing accumulated doses. This surmise is confirmed in this work by a less pronounced drop in sensitivity of the p-type diode than that recorded for the n-type diode when both are subjected to 175 kGy. This behavior is ascribed to the working principle of the diode in the short-circuit current mode and the differences between the diffusion lengths of minority carriers in n- and p-type silicon materials. The diodes' response stability and dose lifespan remain to be further investigated.

Keywords: silicon diodes, rad-hard diodes, radiation processing dosimetry, high-dose dosimetry

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Parâmetros de estabilidade de dose acumulada em diodos de silício tipo p e tipo n

Resumo: Este trabalho tem como objetivo investigar a influência da dopagem (n ou p) nas respostas dosimétricas e da estabilidade da dose acumulada de diodos de Si dos tipos MCz (n) e MCz (p). O princípio de operação dos dosímetros baseados em diodos reside na medida das correntes induzidas pela radiação em diodos não polarizados durante todo o tempo de exposição. Um eletrômetro adquire em tempo real o sinal de corrente, que dentro de certos limites depende linearmente da taxa de dose. A integração do sinal de corrente fornece a carga gerada no volume sensível do diodo, que se espera ser proporcional à dose absorvida. A abordagem experimental adotada envolve a análise da repetibilidade dos sinais de corrente, das respostas de dose para diodos limpos e pre-irradiados, as sensibilidades de carga correspondentes e a queda da sensibilidade com o aumento da dose acumulada para ambos diodos. Para doses de até 175 kGy, os resultados revelam uma resposta linear do diodo MCz(p), caracterizada por uma sensibilidade de carga de 3,1 μC/Gy. Dentro do mesmo intervalo de dose, a resposta do diodo MCz(n) é visivelmente saturada e dada por uma função polinomial de quarta ordem. Este efeito de saturação está provavelmente ligado aos efeitos dos danos da radiação que se manifestam na redução da corrente com o aumento das doses acumuladas. Esta hipótese é confirmada neste trabalho por uma queda menos pronunciada na sensibilidade do diodo tipo p do que aquela registrada para o diodo tipo n quando ambos são submetidos a 175 kGy. Este comportamento é atribuído ao princípio de operação do diodo no modo de corrente de curto-circuito e às diferenças entre os comprimentos de difusão dos portadores minoritários em materiais de silício do tipo n e do tipo p. A estabilidade de resposta e o intervalo operacional dos diodos ainda precisam ser investigadas.

Palavras-chave: diodos de Si, diodos resistentes à radiação, dosimetria de processamento por radiação, dosimetria de altas doses.

1. INTRODUCTION

The development of radiation-hard silicon diodes to face the harsh radiation environment in high-energy physics experiments [1-3] has renewed interest in applying them in gamma radiation processing dosimetry. The operating principle of diode-based dosimeters relies on measuring the radiation-induced currents delivered by non-polarized diodes throughout the exposure time. An electrometer promptly reads the current signal, linearly dose rate dependent. The offline integration of the current signal provides the charge generated in the sensitive volume of the diode, expected to be proportional to the absorbed dose. It holds within a certain dose limit since departures from linearity between charge and dose have been observed for a few tens kGy [4-6]. The origin of such a nonlinear dose-response is related to radiation damage effects that shorten the diffusion length of the minority carriers, reducing the sensitive volume of the diodes. Therefore, different doping types (n or p) must play a meaningful role in the diode's response stability at increasing accumulated doses.

This work aims to check whether this statement holds in high-level dosimetry applications by investigating the dose-response of n- and p-type silicon diodes processed through a similar Magnetic Czochraslki (MCz) technique. The experimental approach is focused on the current sensitivity decay as a function of the accumulated doses for both diodes.

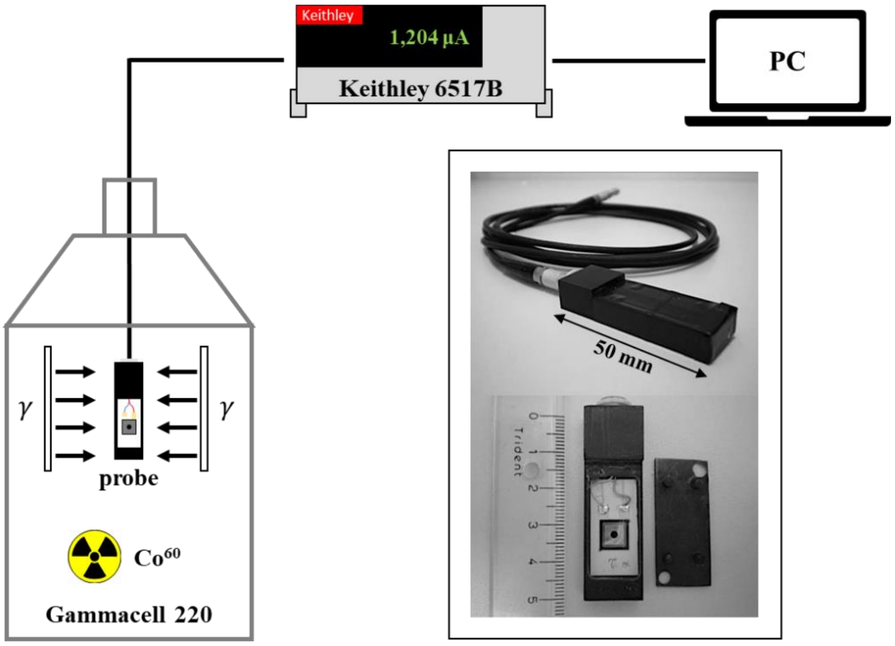
2. MATERIALS AND METHODS

The diodes used in this work are manufactured on silicon wafers made by Okmetic Oy (Vantaa, Finland) and processed in Micronova research infrastructure for micro-and nanotechnology, jointly run by VTT Technical Research Centre of Finland and Aalto

University [7]. The electrical and structural characteristics of these diodes, such as total depletion voltage (VFD), leakage current at total depletion voltage (IF@VFD), useful area (A), chip thickness (d), resistivity (ρ), and type of doping, are presented in Table 1.

Each diode, conductively glued on a ceramic plate, is enclosed in a black acrylic (PMMA) case to be protected against light and mechanical stress. The frontal pad electrode is directly connected, via coaxial cable, to the input of a Keithley® 6517 electrometer to record the output currents from the diode. The short-circuit current mode is achieved with the grounded backplane electrode and the guard ring structure floating. For analysis, the acquired current signals, i.e., current amplitude as a function of the exposure time, are transferred online to a computer with an interface programmed in LabView®. The experimental setup is shown in Figure 1. All experimental procedures are adopted to adhere to the ISO/ASTM 51702 [8] and ISO/ASTM 52628 [9] recommendations.

Figure 1: Experimental setup and details of the dosimetric probe (photo botton right).



Source: Authors.

Irradiations are performed in a Nordion Gammacell 220 at a 1.535 kGy/h dose rate, previously calibrated with standard reference alanine dosimeters (2.75%, k = 2). During the irradiations at a constant dose rate, the basic dosimetric parameter is the prompt-induced current signals delivered by the diode. The corresponding charge produced in the sensitive volume of the diode is assessed offline by integrating these current signals. The corresponding dose response is assessed by plotting the charge as a function of the accumulated dose.

The primary dosimetric characteristics of the routine dosimeter response, including repeatability, charge sensitivity, and dependence on the accumulated dose, are investigated for both pristine and pre-irradiated diodes. The best pre-dose value is assessed by continuously irradiating the diode and monitoring the induced current decay below 5% (ISO/ASTM 51702 [8] and ISO/ASTM 52628 [9]).

Table 1: Electrical and structural characteristics of the MCz diodes.

Diode	V_{FD} (V)	$I_F@V_{FD}$ (nA)	A (mm²)	d (μm)	ρ (kΩ.cm)	Type
MCz	350	0.4	25	300	0.9 - 1	n
MCz	117	1.2	25	300	0.9 - 1	p

The repeatability parameter is evaluated using the coefficient of variation (CV), which is the current standard deviation expressed as a percentage of the average value of the current signals delivered by the diode during five consecutive irradiation cycles at 5 kGy each. The charge sensitivities are obtained through the slope of the dose responses, provided they are linear. If not, the charge sensitivity varies with the accumulated dose and is assessed for each point on the dose-response curve. Variations in the repeatability and charge sensitivity with increasing accumulated dose are used to infer the endurance to radiation damage effects of both diodes.

The overall uncertainty of the dose values is assessed by adding all the components (types A and B) of the standard uncertainties in quadrature. As the statistical errors are negligible (≤ 0.15%), the experimental combined uncertainties (3%) are restricted to the electrometer precision (1%), time acquisition (0.005%), and Gammacell calibration (2.75%). The uncertainty values are expanded to k = 2 (confidence level of 95%).

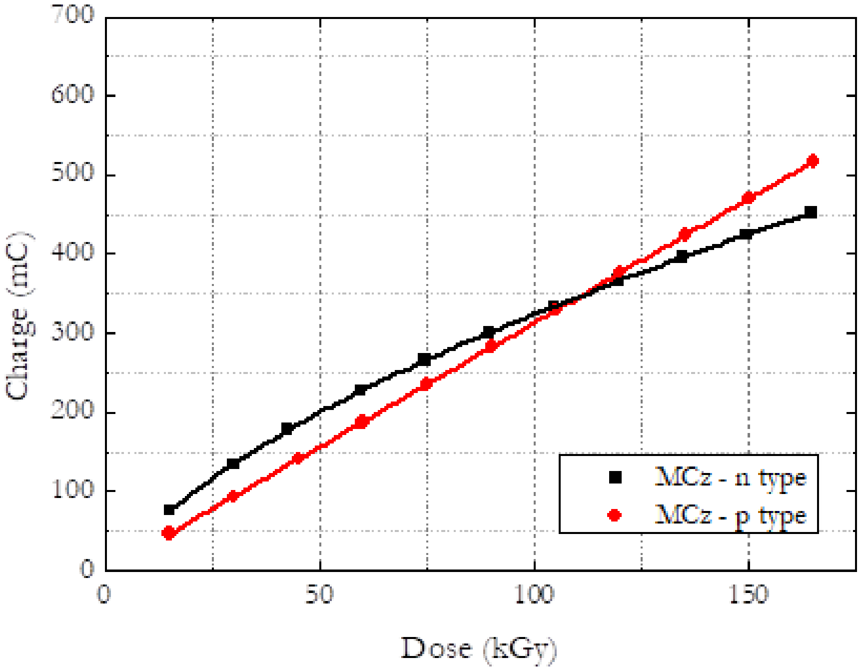
3. RESULTS AND DISCUSSIONS

3.1. Dosimetry response of pristine diodes

The dose response of pristine diodes covering doses up to 175 kGy is presented in Figure 2. The data acquired with the MCz (p) diode is well-fitted (R2 = 0.99999) by a linear function between charge and dose. It enables the charge sensitivity, given by the linear plot slope, to be assessed as 3.13 μC/Gy. Conversely, the response of the MCz(n) diode within the covered dose range is visibly saturated, likely due to the significant current decay with increasing accumulated doses. So, it is impossible to define a single charge sensitivity parameter and a nonlinear function, somewhat arbitrarily capable of reproducing the dose response, is used instead. A fourth-order polynomial function best adjusts the data gathered with the MCz(n) diode, corroborating our previous findings with similar diodes published elsewhere [6]. Furthermore, this result also validates the ICRU Report 80 [10] recommendation to determine the degree of the polynomial response of routine dosimeters established in high-level dosimetry.

The repeatability parameters, characterized by the coefficient of variation (CV) of five consecutive current signals of 5 kGy each, are 1.8% and 15% for the MCz(p) and MCz(n) diodes, respectively. These results demonstrate that the p-type diode, in addition to meeting the stringent repeatability condition of better than 2.0% in the medical field [11], can be used without any prior conditioning, unlike the n-type diode.

Figure 2: Charge dose response for pristine diodes MCz (n) and MCz(p).



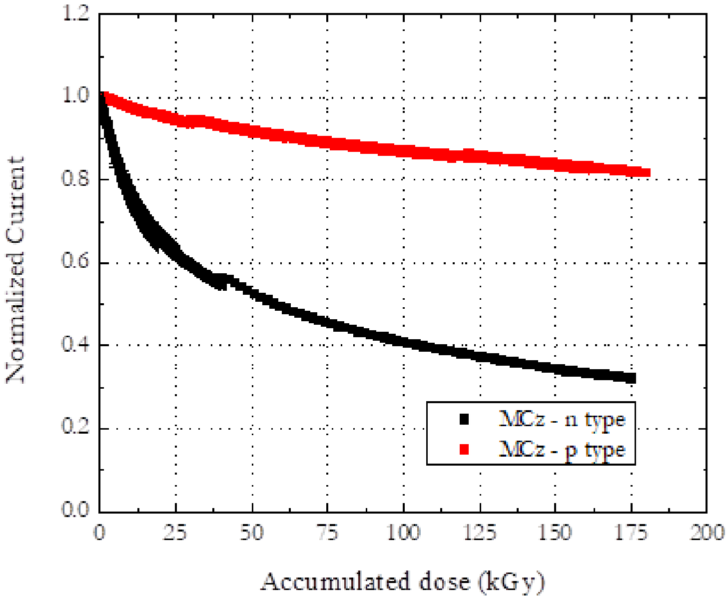
Source: Authors.

3.2. Dosimetry response of pre-irradiated diodes

Pre-irradiating a diode involves introducing numerous defects into its silicon bulk. This process ensures that when the diode is exposed to radiation later, any resulting changes in the current signals are minimal and can be neglected. For the diode to function effectively as a routine online dosimeter, the current variations must remain below 5% to adhere to the recommendations set by ISO/ASTM 51702 [8] and ISO/ASTM 52628 [9].

The correlation between the dose response saturation and the current decay with increasing accumulated doses might be inferred from the data plotted in Figure 3. It shows the output currents continuously delivered by MCz (p) and MCz (n) diodes when irradiated up to 175 kGy. The currents are normalized to those acquired at the beginning of irradiation to ease the visualization of the two independent data sets. When the irradiation starts, the current signal is maximum but rapidly diminishes by almost 5% (p-type) and 38% (n-type) at 25 kGy. However, the relative decrease in sensitivity slowly tends to saturate throughout the irradiation.

Figure 3: Normalized current as a function of accumulated dose for diodes MCz (n) and MCz(p).

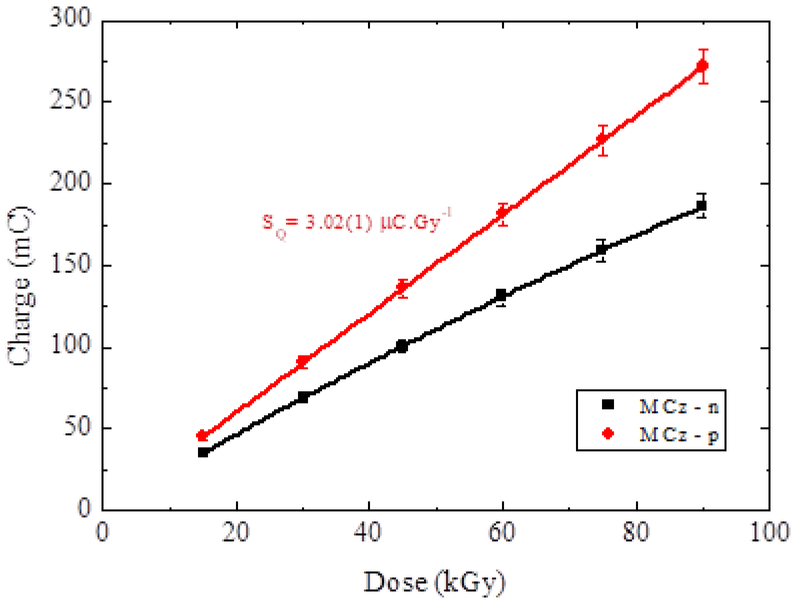


Source: Authors.

Regardless of the doping type, both diodes suffer from radiation damage effects that manifest in a current drop with increasing accumulated doses. However, the p-type doping favors the radiation tolerance of the MCz (p) diode with a sensitivity drop of 20%, well below that achieved by the MCz (n) diode (65%) at 175 kGy. Analyzing the current data in the saturation region depicted in Fig.3 and setting the limits of sensitivity variation to less than 5%, the optimal pre-irradiation dose is 100 kGy. This dose is expected to balance enhanced response stability and a minimal current sensitivity decay. Indeed, repeatability parameters are improved with this condition, with CV values of 1.6% for MCz (p) and 5.8% for MCz(n).

The beneficial effect of pre-irradiating the diodes is evidenced in the dose responses shown in Figure 4. The linear relationship between charge and absorbed dose in the MCz(p) diode is confirmed; however, the charge sensitivity (3.02 μC/Gy) is slightly lower than before irradiation (3.13 μC/Gy). The dose-response of the MCz(n) diode is best described by a second-order polynomial function, which indicates a relative reduction in the saturation of current signals and, consequently, in the charge produced in the diode as the accumulated doses increase.

Figure 4: Charge dose response for pre-irradiated diodes MCz (n) and MCz(p).



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For comparison purposes, all relevant dosimetric parameters gathered with both diodes are shown in Table 2. An analysis of the data on charge sensitivities, dose linearity, and repeatability parameters reassures the better dosimetric performance of the MCz (p) diode.

Table 2 – Relevant dosimetric parameters of MCz (p) and MCz(n) diodes.

Diode	Pre dose (kGy)	Best fit	S_Q (kGy)	CV (%)
MCz - p	0	linear	3.13 ± 0.03	1.6
	100	linear	3.02 ± 0.03	1.4
MCz - n	0	Polynomial 4th order	---	14.5
	100	Polynomial 2nd order	---	1.9

These overall results corroborate the greater radiation endurance of p-type diodes reported in the literature about diode-based dosimeters applied in medical dosimetry [12-15]. In these applications, similar to the one herein described, the diodes operate without externally applied voltage. Under this condition, the diffusion current due to the excess minority carriers produced on each side of the junction greatly contributes to the output current signal. For this, each minority carrier (electrons on the p-side and holes on the n-side) diffuses toward the depletion zone and, if it reaches the junction edge, is swept by the built-in potential and collected. Physically, only minority carriers produced outside the junction at a distance from its edge equal to or less than their diffusion length can be collected. So, the sensitive volume of the diode depends on the minority carrier diffusion length, which is strongly affected by radiation damage effects. As the diffusion length of electrons (p) is much greater than that of holes (n), the sensitive volume changes with increasing accumulated dose might be, comparatively, smaller. Consequently, the p-type diode response is expected to be more stable.

4. CONCLUSIONS

A comparative investigation concerning the doping type influence on the accumulated dose stability of MCz(p) and MCz(n) diodes is reported in this work. The experimental approach involves analyzing their dose responses, the correspondent charge sensitivities, the repeatability parameters, and the sensitivity decay with increasing doses. Mitigation of this decay is achieved by pre-irradiating the devices to 100 kGy.

The results evidence both a better repeatability parameter and a less pronounced drop in sensitivity of the p-type than that recorded for the n-type diode. This behavior can be ascribed to the working principle of the diode in the short-circuit current mode and the differences between the diffusion lengths of minority carriers in n- and p-type silicon materials. The response reproducibility (or long-term stability) and the dose lifespan of these diodes remain to be further investigated.

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CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

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