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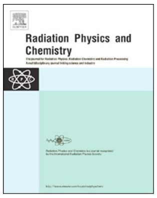

Current response stability of a commercial PIN photodiode for low dose radiation processing applications

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ABSTRACT

This work investigates the on-line response of a thin diode, for monitoring low dose radiation processing, with respect to the linearity between current and dose-rate, the most interesting part being the variation of the current sensitivity with the accumulated dose. The results obtained indicate that the current response of this diode is linear and quite stable with repeatability better than 0.2% and a slight decay of 5% of the current sensitivity (0.28 nA h/Gy) for doses up to 15 kGy. In an attempt to give theoretical support to these results, the radiation induced current is calculated as a function of the dose rate assuming the diode to be thin as compared with the standard values of the minority carrier diffusion lengths in intrinsic silicon. Agreement within 2% is found between calculations and experimental data.

1. Introduction

The increasing interest in low-dose (< 100 Gy) radiation processing applications, as irradiation of blood for transplants (Shastry et al., 2013; ISO/ASTM51939, 2017) and substerilization of insects (Salem et al., 2014; EL-Degwi and Gabarty, 2015), has demanded efforts to develop reliable dosimetry systems with high sensitivity, good spatial resolution, and stable response over the range of 5–100 Gy. Silicon diodes have the clear advantage of providing prompt dose-rate and dose results. However, due to the low radiation tolerance of such dosimeters (Rikner and Grussel, 1983; Lindstrom et al., 1999; Fretwurst et al., 2007), they are rarely employed in radiation processing, where absorbed doses of tens of kGy can be easily reached in regular applications.

Silicon diodes operating in current mode and with no external bias voltage have been widely employed as relative dosimeters in a clinical context for photon and electron beams (Dixon and Ekstrand, 1982; Rikner and Grussel, 1987; Saini and Zhu, 2004; Casati et al., 2005; Griessbach et al., 2005; Bruzzi et al., 2007; Gonçalves et al., 2014; Santos et al., 2014; Nascimento et al., 2018). Even for these low-dose applications, the lifespan of the diode is shortened by the presence of radiation damage effects, which manifest themselves in both a growth of the dark current and a fast drop of their radiation-induced current sensitivities. This effect is physically attributed to the decrease of the diffusion length of minority carriers due to the production of generation-recombination centers in the silicon bulk, leading to a decrease of the sensitive volume of the diode. Indeed, at zero bias voltage, the major contribution to the radiation–induced current is the diffusion of the excess minority carriers (i.e. electrons in the p-side and holes in the n-side) generated within the crystal bulk over a distance of the order of their diffusion lengths (indicated here with L_n and L_p, respectively). These minority carriers diffuse towards the depletion layer and together with the electron-hole pairs herein produced are swept by the built-in voltage (0.7 V) to the electrodes of the diode. Thus, for very thick diodes (i.e. thickness higher than L_n and L_p), the linear extension of the sensitive volume is given by the sum of the diffusion lengths of the excess minority carriers and the depletion layer thickness (w). When no external voltage is applied, w is usually negligible and the sensitive volume of the diode is strongly dependent on the diffusion lengths, which, under irradiation, are continuously reduced by the accumulated dose. Physically, it is possible to mitigate the variation of the sensitive volume, and hence the decay of the current sensitivity, by choosing very thin diodes with thicknesses smaller than the lowest minority carrier diffusion lengths anticipated at the foreseen accumulated dose. On this assumption, a semiconductor dosimeter system has been developed based on a commercial thin photodiode (type SFH206K) with a p-layer/intrinsic/n-layer (PIN) structure operating in short-circuit current mode for low dose gamma radiation processing applications. Nevertheless, questions still remained about the lifespan of these diodes, mainly regarding the stability of the current sensitivity with the

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accumulated dose: a fundamental information to predict the number of times that they can be reused without frequent in-plant calibration procedures. With this aim, the on-line response of this PIN photodiode is investigated in this work with respect to the linearity between current and dose-rate, the most interesting part being the variation of the current sensitivity with the accumulated dose. Theoretical support to the experimental results is given by calculations of the radiation-induced current taking into account the dimensions of the diode, dose-rates and the values of the diffusion lengths available in the literature.

2. Materials and methods

Three commercial photodiodes (SFH206K supplied by Osram) with full wafer thickness of (230 ± 5) µm and square-shaped active area of 7.02 mm^2 have been used in this work. To ensure that they have similar electrical characteristics, the corresponding I-V and C-V curves have been previously measured with a semiconductor device analyzer (Keysight, model B1500). Variations among these curves are less than 3%.

The average thickness of the depletion layer of these diodes at 0 V and at the full depletion voltage (30 V), calculated from the C-V measurements by considering the diode as equivalent to a plane capacitor, are (10.0 ± 0.1) µm and (85.7 ± 0.9) µm, respectively. The latter value corresponds to the thickness of the intrinsic layer of the PIN structure since, under reverse bias, the width of the depletion zone extends across the intrinsic region and, at maximum reverse bias (30 V), the diode is fully depleted. In such a condition, the thickness of the depletion layer is almost equal to the thickness of the intrinsic layer of the diode. To be used as a dosimeter without external bias voltage, the diode is assembled in a light-tight probe and directly connected in short-circuit mode to an electrometer (Keithley, model 6517B). Irradiations have been performed in two small-scale ^{60}Co facilities: a Gammacell-220 irradiator type I (Atomic Energy of Canada Limited), used to preirradiate the diodes under a dose rate of 662 Gy/h to reduce the exposure time, and a Panoramic irradiator type II (Yoshizawa Kiko Co, Ltd) with dose-rate varying from 3.9 to 55.6 Gy/h by changing the diode-source distance from 66 to 16 cm. Dose rate calibrations were previously obtained through standard reference alanine dosimeters with an expanded uncertainty of 1.7% (k = 2) traceable to the secondary standard laboratory at the International Atomic Energy Agency (IAEA). Unless otherwise stated, the on-line characterization of the diodes has been performed in the Panoramic facility under geometry and dose rates quite similar to those routinely used in low-dose radiation processing applications.

The current response stability of the diode is indirectly assessed through measurements of the current sensitivity factor (S_c), given by the slope of the current versus dose rate plot, as a function of the accumulated dose. In this work, the experimental approach adopted is to preirradiate the same diode with fractioned doses of 5 kGy and evaluate its dose rate response before and after each exposure to quantify the variation in the current sensitivity with the accumulated dose. The same procedure is followed to monitor the presence of radiation damage effects by measuring dark current versus reverse bias after each step of irradiation. The influence of the accumulated dose on the repeatability of the current signals, measured at the same dose rate and exposure time, is also evaluated through the coefficient of variation CV (sample standard deviation expressed as a percentage of sample average value, ISO/ASTM 51707, 2015) of five current signals recorded in successive steps of irradiation by switching on and off the source. This procedure is in accordance with the recommendations for clinical dosimetry of photon and electron beams and it is applied here due to the lack of protocols for dosimetry with diodes in radiation processing. For the same reason, the assumptions made to predict the lifespan of the diode and its reusability as online dosimeter are based on McLaughlin and Desrosiers (1995), Chu et al. (2008), ISO/ASTM 51702 (2013) and ISO/ASTM 52628 (2013), that recommend expanded uncertainties of less than 5% in the response of most dosimeters routinely used in radiation processing.

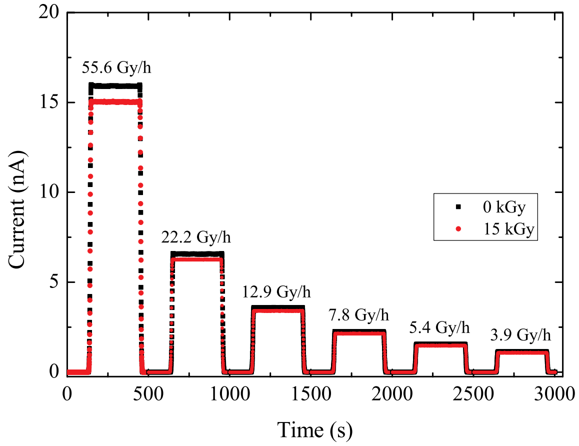

Fig. 1. – Current signals delivered by the diode without bias unirradiated (0 Gy) and irradiated to 15 kGy during its exposure to dose-rates varying from 3.9 to 55.6 Gy/h.

3. Results

Current signals delivered by the same diode during its exposure to dose rates ranging from 3.9 to 55.6 Gy/h have been measured in four steps: with the sample unirradiated (used as reference for 0 Gy) and preirradiated up to 15 kGy fractioned in tree steps of 5 kGy. The current response versus the dose rate has been measured before the irradiation of the diode and after each exposure step. As all of them exhibited the same pattern, to ease the visualization, only those gathered with the unirradiated diode (0 Gy) and preirradiated to 15 kGy are presented in Fig. 1. The correlation between current and dose rate is rather clear as well as the expected drop in the sensitivity of the diode with increasing accumulated doses. For 15 kGy, the percentual decrease in the currents is found to vary from 4.7% to 5.5% for dose rates of 3.9 Gy/h and 55.6 Gy/h, respectively. The agreement of these results, within the experimental error of the current measurements (1.0%), indicates that the sensitivity decrease is almost independent from the dose rate within the range herein covered.

In addition, the study of the repeatability of the five current signals consecutively read out at the same dose rate and accumulated dose, yielded a coefficient of variation (CV) of less than 0.2% even in the worst scenario of irradiation up to the highest dose rate (55.6 Gy/h) and accumulated dose (15 kGy). These results are compared in Fig. 2 with those gathered with the unirradiated diode. In both cases, the signals are very stable despite the current decrease exhibited by the preirradiated diode. It is important to note that the measurements of the dark current carried out between the irradiations (with the source shielded) remain almost constant (≅ 1 pA) regardless of the accumulated dose. Such negligible dark currents, delivered by the very thin diode at 0 V, justify the high current-to-noise ratio ($\geq 10^3$) experimentally found in this work. For example, the induced current reading (1.1 nA) for the lowest dose rate (3.9 Gy/h) at the highest accumulated dose (15 kGy) is three orders of magnitude higher than the dark current.

The current response of the same diode unirradiated and preirradiated to 5, 10, and 15 kGy is obtained by the data on current as a function of the dose rate presented in Fig. 1. The corresponding plots are presented in Fig. 3, where the linearity of the current with the dose rate is clearly visible (the continuous line represents a fit with a straight line), regardless of the accumulated dose. For comparison, calculations (detailed in section 4) of the current generated in the sensitive volume of the unirradiated diode using its dimensions (active area and thickness) and dose-rates are also plotted in Fig. 3. A better agreement

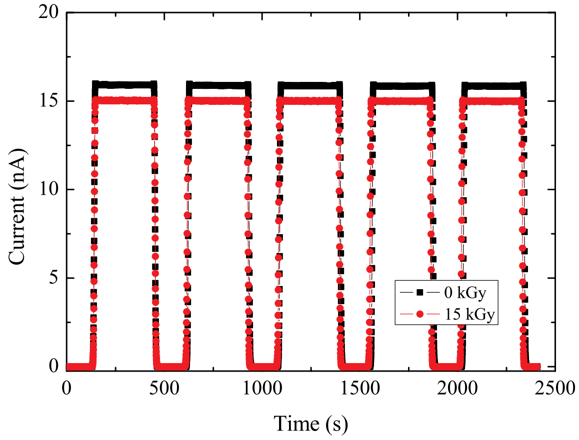

Fig. 2. Repeatability of five current signals consecutively registered by switching on and off the source. Irradiations were performed with a dose rate of 55.6 Gy/h with the same diode unirradiated (0 Gy) and preirradiated to 15 kGy. Experimental uncertainties of the current measurements (1.0%) are smaller than the size of the symbols.

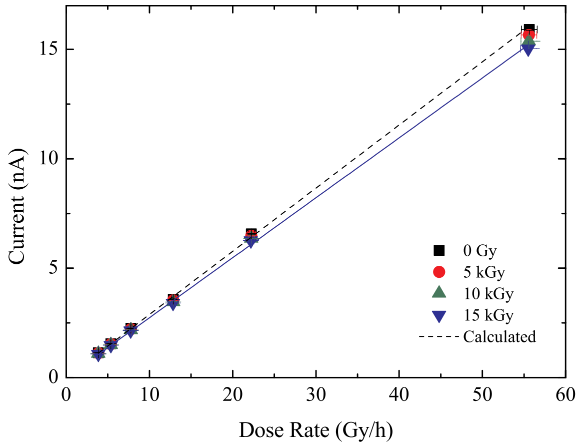

Fig. 3. – The induced current as a function of the dose rate with the same diode unirradiated (0 Gy) and preirradiated to 5, 10, and 15 kGy. The continuous line represents a linear fit to the measured values. The calculated curve (dashed line) is obtained as discussed in the text.

Table 1
– Current Sensitivity (*Sc*) of the same diode unirradiated and irradiated to 5, 10, and 15 kGy. The calculated value is obtained as explained in the text.

Accumulated Dose (kGy)	Current Sensitivity (nA.h/Gy)
0	0.288 ± 0.006
5	0.284 ± 0.006
10	0.278 ± 0.006
15	0.274 ± 0.006
Calculated	0.289 ± 0.008

between theoretical and experimental results obtained with the unirradiated diode is visible. Furthermore, in the same figure, it can be seen that the current sensitivity (S_c) of the diode, assessed through the slope of the linear fit of the current data versus dose rate, is slightly dependent on the accumulated doses. In the case of the calculated sensitivity, the uncertainty is due to the uncertainties on the dose rate (1.7%) and the thickness of the diode (2.2%) combined in quadrature. However, all values of S_c presented in Table 1 agree within the expanded uncertainty (2.2%) despite of the visible downward trend of the current sensitivity with accumulated dose. This behavior is also observed in Fig. 4, where the data on the current sensitivity of the preirradiated diode, normalized to that gathered before the irradiation, are presented as a function of the accumulated dose. These results clearly demonstrate a progressive decrease of the current sensitivity with the accumulated dose reaching almost 5% at 15 kGy.

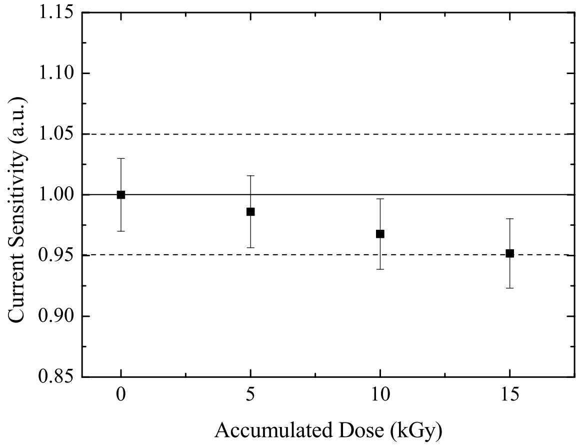

Fig. 4. – Current sensitivity of the preirradiated diode normalized to that gathered before the irradiation, as a function of the accumulated dose.

Another qualitative information, that can be drawn from the results presented in Fig. 4, is that the lifespan of the diode is 15 kGy, i.e. this is the maximum accumulated dose that the diode can withstand and still comply with the requirements of ISO/ASTM 51702 (2013) and ISO/ASTM 52628 (2013) to be used as routine dosimeter in radiation processing. In the case of diodes, the main concern is to guarantee that variations in their current response are less than 5% to prevent frequent and time consuming in-plant calibrations. Based on the lifespan of 15 kGy, it is possible to infer that this dosimetry system can be reused almost 150 times in low-dose (≤100 Gy) radiation processing applications.

4. Calculations and discussion

In this work, a thin photodiode is proposed as on-line dosimeter, envisaging to increase the dose threshold for the onset of the current sensitivity drop with increasing accumulated dose. The experimental data presented in Section 3, namely a stable and linear current response with current sensitivities almost constant (0.28 nA h/Gy) up to 15 kGy and repeatability of the current signals better than 0.2%, indicate that the main goal of this work is achieved. In an attempt to give theoretical support to these results, the radiation induced current can be calculated as a function of the dose rate, using the expression for the current generated by irradiation of a p-n junction available in the literature (Osvay and Tárczy, 1975). The assumptions made to calculate the current are: i) the diode is thin as compared with the values of the diffusion lengths for electrons and holes in intrinsic silicon; ii) the contribution of the diffusion current to that produced in the depletion layer (10 μm at 0 V) of the diode is absent, thus the current is not affected by the reduction of the diffusion length with accumulated dose; iii) the sensitive volume of the diode at 0 V is constant within the dose range 0–15 kGy. If these assumptions hold true, the current can be calculated taking into account the thickness and active area of the diode and the generation rate of electron-hole pairs per unit of volume of the diode. A correction for the difference between the air kerma and the energy deposited per unit mass in silicon has also been applied. The theoretical current response is presented in Fig. 3, where a good agreement among different sets of experimental data is found. As expected, the calculated current sensitivity (0.289 nA h/Gy) agrees, within the experimental errors, with that measured with the unirradiated diode and preirradiated to 5, 10, and 15 kGy, see Table 1.

To check the validity of the above assumption of a negligible contribution of the diffusion current, an equation by Osvay and Tárczy (1975), that takes into account the effect of the diffusion of electrons and holes, can be used to estimate the current and, by comparison with the previous value, to manifest whether a reduction of the effective volume (thickness) of the diode is present or not. As the relevant technical information about the PIN structure of the SFH206K diode is not disclosed by the manufacturer, the values (640 µm for electrons and 380 µm for holes) of the minority carrier diffusion length (L) are estimated using equation $L = (D\cdot\tau)^{1/2}$, where D is the diffusion coefficient and τ the minority carrier lifetime. The first parameter is calculated considering the electrical properties of intrinsic silicon, i.e. electron and hole mobilities at 300 K (Gildenblat et al., 1996). With regards the lifetime, it is estimated from the dark current measurements performed at room temperature ($\approx$ 300 K) with the diode fully depleted (reversely biased at 30 V) following the method adopted by Kitaguchi et al. (1996). Using these values of the diffusion lengths, a total thickness of the diode of 230 µm and, due to the lack of technical information of the PIN structure, an equal thickness of the p-type and n-type layers, the correction to the effective depletion zone (or alternatively of the generated current) due to a better account of diffusion is estimated to be around 2%, below present experimental uncertainties. Such a conclusion is not significantly altered if the p-type and n-type layers do not have equal thicknesses. Moreover, this is also an indirect confirmation that, at least in absence of radiation damage, the detector is indeed thin as compared to the minority carrier diffusion lengths.

5. Conclusions

The current response stability of a thin diode has been investigated in this work focusing on the variation of the current sensitivity with accumulated dose. The results obtained indicate that the current response of this diode is linearly dependent on the dose rate and quite stable, being characterized by a repeatability better than 0.2% and a slight decay of 5% of the current sensitivity (0.28 nA h/Gy) for doses up to 15 kGy. Theoretical support for these results is given by the good agreement between calculations of the proportionality coefficient between current and dose rate and the corresponding experimental value. All these results lead us to conclude that this diode is a reliable alternative choice for low dose radiation processing dosimetry.

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