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Current mode response of phototransistors to gamma radiation

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HIGHLIGHTS

- Current mode response of four commercial phototransistors to gamma radiation was investigated.
- Dose rate dependence of the current response followed a power law for dose rates from 0.65 Gy/h to 32.1 Gy/h.
- Significant current degradation was observed during continuous irradiation up to the dose of 20 Gy.
- Relation between absorbed dose and induced charge was fitted with a second order polynomial.
- Only one of the investigated phototransistors may be applicable as a gamma radiation dosimeter.

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ABSTRACT

This paper investigates the current mode response of four commercial NPN phototransistors under gamma radiation exposure from Co-60 source, with the aim to evaluate their applicability for gamma radiation dosimetry. The radiation-induced collector current was measured while the phototransistors were successively biased with 10 V and 20 V between collector and emitter. The main aspects analyzed in the experiment were the stability of the induced current, dependence of the induced current with respect to dose rate, short-term repeatability of the induced current and relation between the induced charge and the absorbed dose. The current response of all samples was stable during the 2-min irradiation sessions at the dose rates from 0.65 Gy/h to 32.1 Gy/h, with the relative uncertainty less than 5% in all cases, and the variation of the mean effective current as a function of dose rate was well fitted with the standard power relation. During the three consecutive 2-min irradiation sessions at the dose rate of 32.1 Gy/h, the repeatability of the induced charge was very good for all samples with the relative uncertainty below 3%. However, for continuous irradiation up to the absorbed dose of 20 Gy (10-min irradiation at the dose rate of 60 Gy/h), all samples exhibited significant current fall which can be attributed to the radiation-induced current gain degradation. As a result of the current degradation, the relationship between the induced charge and the absorbed dose was non-linear and it was demonstrated that the second order polynomial can be used as a calibration equation for determination of absorbed dose. The obtained results have shown that only one of the examined phototransistors may be a suitable candidate for gamma radiation dosimetry employing Co-60 source, since it has exhibited the highest current sensitivity, best linearity of the induced current with respect to dose rate and smallest dose rate dependence of the charge sensitivity.

1. Introduction

Semiconductor ionizing radiation dosimeters operating in the current mode are particularly useful for real-time measurement of dose rate and absorbed dose in radiation fields employed in applications such as medical therapy, industrial processing and high energy physics experiments (Barthe, 2001; Knoll, 2000; Rosenfeld, 2007). The current mode dosimeters provide the current response proportional to the radiation dose rate, and the integration of the induced current over the exposure time gives the value of the accumulated charge which is proportional to the absorbed dose (Knoll, 2000). Besides, other important requirements that must be satisfied by the current mode dosimeters include good stability and repeatability of the radiation-induced current response. The most common types of semiconductor-

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based current mode ionizing radiation dosimeters are the silicon PN and PIN diodes/photodiodes (Lanza, 1979; Ferreira et al., 2009; Andjelković and Ristić, 2013; Aoyama et al., 2002; Romei et al., 2015). However, numerous studies have also reported favorably on the current mode dosimetric performance of diamond detectors and SiC Shottky diodes (Bertuccio et al., 2014; Metzger et al., 2002; Pini et al., 2003; Marczewska et al., 2004; Spadaro et al., 2013). As an alternative solution, the commercial phototransistors have been proposed as current mode dosimeters for various medical applications (Dhole and Bhoraskar, 1994; Santos et al., 2006, 2002, 2008; Magalhaes et al., 2012; Paschoal et al., 2011).

The most significant results on the use of commercial phototransistors as current mode dosimeters have been reported by Dhole et al. (Dhole and Bhoraskar, 1994) and by Santos et al. (Santos et al., 2006, 2002, 2008; Magalhaes et al., 2012; Paschoal et al., 2011). Both groups have analyzed the collector current as the dosimetric parameter. Dhole et al. have shown that the phototransistors can be used for measuring doses from 1 Gy to 1 kGy for 1 MeV electron radiation. They have measured the collector current at various bias voltage levels between collector and emitter, for different fluences of electron irradiation, and have observed that the radiation-induced collector current decreases with increase of radiation dose delivered to the phototransistor. On the other hand, Santos et al. have analyzed the commercial phototransistors as current mode dosimeters for radio-diagnostic applications employing low energy x-ray radiation, as well as for radiotherapeutic applications utilizing high energy photon beams from linear accelerators. They have demonstrated that the phototransistors have good read-out stability for low energy irradiation, but exhibit significant sensitivity loss during high energy irradiation up to the dose of 100 Gy. Furthermore, Santos et al. have shown that the phototransistors have higher sensitivity in comparison to PIN photodiodes due to current gain, but exhibit faster sensitivity loss with respect to absorbed dose as a result of gain degradation.

Following the reported results on the phototransistors' sensitivity under electron and x-ray exposure, this work was conducted with the aim to investigate the current mode dosimetric properties of commercial phototransistors under gamma radiation which is also widely used in medical treatment. The four key aspects have been analyzed in this work: stability of the current read-out during irradiation, reproducibility of the current read-out for multiple irradiation sessions, variation of the induced current with respect to dose rate, and variation of the induced charge with respect to absorbed dose. In this regard, the current mode response (collector current) of four low cost commercial NPN phototransistors was analyzed under continuous gamma radiation exposure from Co-60 source, for 10 V and 20 V bias between collector and emitter. The induced current was measured during the experiment and the accumulated charge was analytically determined afterwards.

The paper is organized into four main sections. Brief explanation of the phototransistor's structure and its response under ionizing radiation exposure is given in Section 2. In Section 3, the selected test samples and the experimental procedure are described. The results of the pre-irradiation characterization are outlined in Section 4. The experimental results are presented and discussed in Section 5.

2. Effects of ionizing radiation on phototransistors

The phototransistors are optoelectronic devices consisting of two *p*–*n* junctions: *n*–*p* (collector–base) junction and *p*–*n* (base–emitter) junction. They are available in two versions: with two terminals (collector and emitter) and with three terminals (collector, emitter and base). The typical cross-section of a tree-terminal NPN phototransistor is illustrated in Fig. 1. The two-terminal devices have the same structure but without the base contact. The phototransistors are normally operated in biased mode with positive voltage applied between collector and emitter, whereas the base terminal (if it exists) is often left floating. In that way the collector–base junction is reverse biased and the base–emitter junction is forward biased. The collector–base junction is the sensitive volume of the phototransistor and it is deliberately made larger than the base–emitter junction to achieve high sensitivity to the incident radiation.

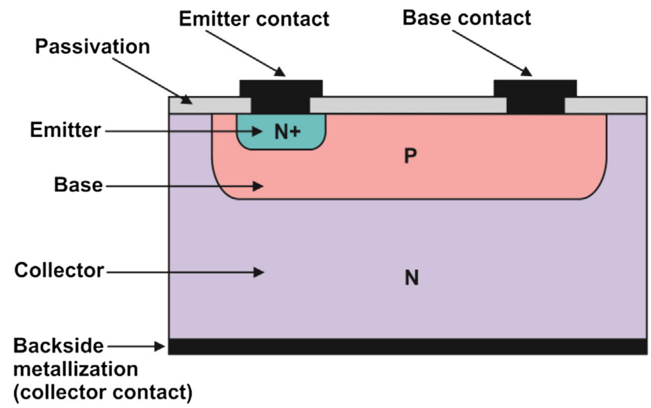

Fig. 1. Typical phototransistor cross-section.

Basically, the response of the phototransistors under ionizing radiation exposure is similar to the response of other semiconductor current mode dosimeters such as PN and PIN diodes/photodiodes. The exposure to ionizing radiation results in the creation of electron–hole pairs within the whole phototransistor. While most of the induced electron–hole pairs recombine immediately, those induced in the depletion layer across the reverse biased collector–base junction and within the diffusion length of minority charge carriers in P and N layers are collected by the electric field in the device, resulting in the current flow. By applying higher bias voltage between collector and emitter, the charge collection efficiency can be enhanced leading to higher current.

In principle, the main advantage of the phototransistors over photodiodes is the inherent current gain which brings the benefit of higher sensitivity to incident radiation (Santos et al., 2008; Spezzigu, 2010). Typical current gain for phototransistors ranges from hundred to several thousands, implying that the phototransistor which is several times smaller than a photodiode might have several times higher sensitivity. The gain of a phototransistor is defined as $h_{FE} = I_C/I_B$, where I_C is the collector current and I_B is the base current, while the emitter is grounded. The phototransistor can be considered as a photodiode connected between the collector and the base of a bipolar transistor, such that the current induced in the photodiode is fed to the base of the bipolar transistor (Spezzigu, 2010). Hence, the induced current acts as the transistor's base current and due to amplification the collector current is significantly higher than the original radiation-induced current.

Provided the dose rate of the incident radiation is sufficiently high, the collector current during radiation exposure will be stable and proportional to the dose rate. Therefore, measurement of the induced collector current gives the information on the dose rate and current integration gives the value of the absorbed dose. Similarly to photodiodes, the phototransistors are characterized by the collector–emitter dark current which determines the minimum measurable dose rate. The difference between the measured current and the dark current provides the value of the effective radiation-induced current. Because the dark current varies due to