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Calibration coefficients of epitaxial diodes used in diagnostic radiology and computed tomography beams

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Abstract: The assessment of the calibration coefficients of an epitaxial diode, previously characterized for diagnostic radiology (RQR qualities) and computed tomography (RQT qualities) dosimetry, is reported in this work. The diode, with an n-type epitaxial layer (50 µm) grown on a thick (300 µm) Czochralski silicon substrate, is directly connected to an electrometer Keithley 6517B in the photovoltaic mode and exposed to X-ray beams from a Pantak/Seifert generator, model Isovolt 160 HS. Under this operational condition, the dosimetric quantity is the dose rate correlated with the output current signal from the diode when exposed to radiation. The corresponding collected charge (the integral of the current signal) is proportional to the dose. The repeatability of the current signals and the dose response of the diode are investigated in several RQR and RQT beam qualities spanning from 50 kV to 150 kV. The calibration coefficients (N_k) are assessed by linking the diode readings to those from the standard ionization chambers for reference beam qualities (RQR-5 and RQT-9) following the formalism recommended by Technical Reports Series No. 457. To take into account the variations of the X-ray beams related to the correspondent reference beam qualities, the correction factors are also calculated. Despite being close to 1, they evidence the energy dependence of the EPI diode for voltages above 100 kV.

Keywords: Epitaxial Diode, Rad-hard Si diode, Dosimetry, Calibration coefficients.

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Coeficientes de calibração de diodos epitaxiais utilizados em feixes de radiologia diagnóstica e tomografia computadorizada

Resumo: A avaliação dos coeficientes de calibração de um diodo epitaxial, previamente caracterizado para dosimetria de raios X de radiologia diagnóstica (qualidades RQR) e tomografia computadorizada (qualidades RQT), é relatada neste trabalho. O diodo, com uma camada epitaxial tipo n (50 µm) crescida em um substrato de silício Czochralski espesso (300 µm), é conectado diretamente a um eletrômetro Keithley 6517B no modo fotovoltaico e exposto a feixes de raios X de um gerador Pantak/Seifert, modelo Isovolt 160 HS. Nesta condição de operação, a grandeza dosimétrica é a taxa de dose correlacionada com o sinal de corrente de saída do diodo quando exposto à radiação. A carga coletada correspondente (a integral do sinal de corrente) é proporcional à dose. A repetibilidade dos sinais de corrente e a resposta à dose do diodo são investigadas em diversas qualidades de feixes RQR e RQT abrangendo o intervalo de 50 kV a 150 kV. Os coeficientes de calibração (Nk) são avaliados relacionando as leituras do diodo àquelas das câmaras de ionização padrão para qualidades de feixe de referência (RQR-5 e RQT-9), seguindo o formalismo recomendado pelo *Technical Reports Series* nº 457. Para considerar as variações dos feixes de raios X relacionados com as qualidades dos feixes de referência correspondentes, os fatores de correção também são calculados. Apesar de estarem próximos de 1, os fatores de correção evidenciam a dependência energética do diodo EPI para tensões acima de 100 kV.

Palavras-chave: Diodo Epitaxial, Diodo de Si resistente à radiação, Dosimetria, Coeficientes de calibração.

1. INTRODUCTION

Silicon diodes have been widely used in photon and electron beam dosimetry, usually at null bias in the short-circuit mode. When exposed to radiation, its operating condition allows real-time acquisition of induced currents, linearly depending on the dose rate. Offline integration of the current signals provides the corresponding absorbed dose. This easy operation, ruggedness, high sensitivity, and immediate readout are the main advantages of diodes over other available dosimeters. However, to be used as dosimeters, they must be calibrated to link the diode reading to the true absorbed dose or dose rate, chiefly measured with a standard ionization chamber under reference conditions (20ºC, 101.3 kPa). The calibration coefficient (N_k) of the dosimeter, defined as the ratio of the conventional true value of the quantity to be measured to the indication of the instrument to be tested, can be assessed through a formalism based on standards of air kerma (K_a) as recommended in Technical Reports Series No. 457 [1]. The value of the air kerma, K_a, at a reference point in the air for a reference beam of quality Q_0, is related to the reading M of the dosimeter under the reference conditions used in the standards laboratory according to:

$$K_a = N_k \,.\, M \,.\, k_Q \,.\, k_T \tag{1}$$

Where k_Q is a correction factor for the effects of the difference between the reference beam quality, Q_0, and the actual quality, Q, during the measurement; k_T is the correction factor for the changes in air density due to changes in the ambient temperature. In this work, the calibration coefficients of a thin epitaxial silicon diode, previously characterized as an online dosimeter in diagnostic radiology (RD) and computed tomography (CT), are assessed considering the RQR-5 and RQT-9 as the reference beam qualities ($k_Q = 1$).

2. MATERIALS AND METHODS

The epitaxial diode used (25 mm^2 active area) is processed on an n-type 50 µm thick epitaxial silicon layer (resistivity of 50 Ω.cm), grown on a highly doped n-type 300 µm thick Czochralski (Cz) silicon substrate [2, 3]. The device is housed in a light-tight probe with a thin (28 mg/cm^2) paper window to avoid significant X-ray beam intensity attenuation. The diode, directly connected to an electrometer Keithley 6517B in the photovoltaic mode, is exposed to X-ray beams from a Pantak/Seifert generator, model Isovolt 160 HS, previously calibrated with Radcal RC6-RD and RC3-CT ionization chambers. Both chambers are calibrated at the *Physikalisch-Technische Bundesanstalt* (PTB) with standard deviations of 0.77% and 1.5%, respectively. Table 1 presents the main characteristics of the diagnostic radiology and computed tomography X-ray qualities used in this work. Irradiations are carried out with the diode positioned at 1 m from the X-ray tube (focal spot), as shown in Figure 1. The repeatability of the current signals and the dose response of the diode are investigated in several RQR and RQT beam qualities spanning from 50 kV to 150 kV.

Five current measurements are consecutively carried out to correlate the averaged current reading to the air kerma rate of each beam quality. With this approach, the repeatability parameter can also be evaluated through the coefficient of variation of the current signals following the IEC 61674 norm [4]. The dose response of the EPI diode, given by the charge produced in its sensitive volume as a function of the absorbed dose, is evaluated for all X-ray beam qualities (Table 1) covering doses up to 1.2 Gy.

The calibration coefficients of the diode, in terms of air kerma rate, are determined for the diagnostic radiology and computed tomography X-ray beam qualities presented in Table 1.

Table 1: X-ray Qualities used from Pantak-Seifert 160HS Isovolt generator.

Quality	kV	mA	Filtration (mm)	Air Kerma Rate (mGy/min)
Diagnostic Radiology				
RQR-3	50	10	2.40 Al	22.4(2)
RQR-5	70	10	2.80 Al	38.6(3)
RQR-8	100	10	3.20 Al	69.3(5)
RQR-10	150	10	4.20 Al	120(2)
Computed Tomography				
RQT-8	100	10	3.2 Al + 0.30 Cu	22.0(7)
RQT-9	120	10	3.5 Al + 0.35 Cu	34.0(1)
RQT-10	150	10	4.2 Al + 0.35 Cu	57.0(2)

Source: Authors.

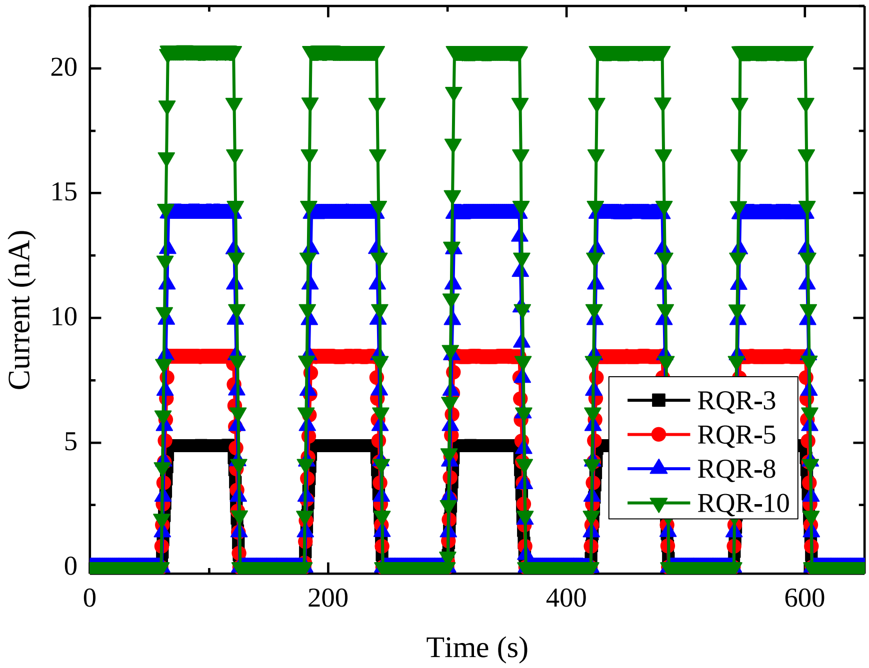
Figure 1: Probe of the EPI diode set at Pantak-Seifert 160HS Isovolt X-ray generator.

Source: Authors.

3. RESULTS AND DISCUSSIONS

Figure 2 depicts the current signals induced for all diagnostic radiology beam qualities. It reveals a stable current response, proved by coefficients of variation (CV) less than 0.3%. Similar results are obtained with the computed tomography qualities.

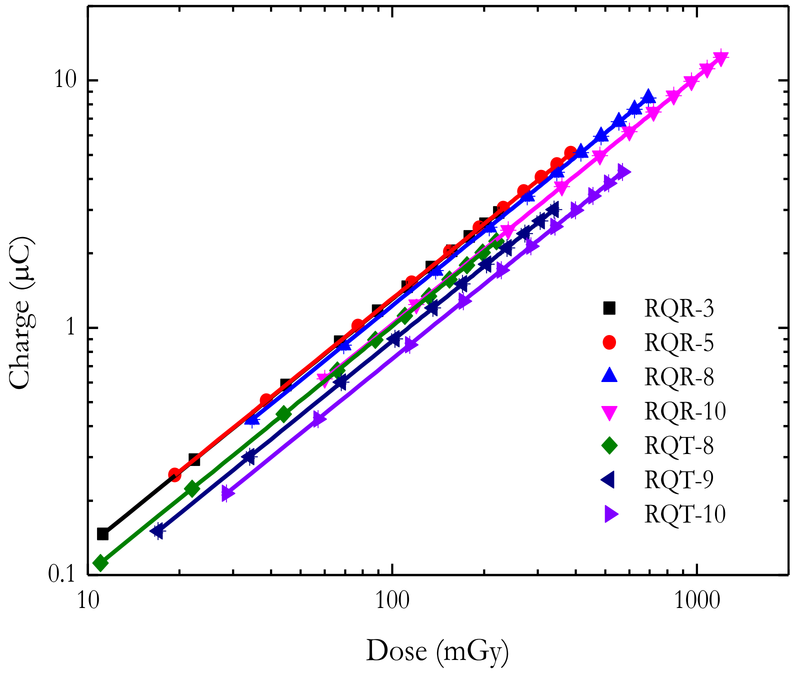
Figure 2: Current signal profiles for RQR-3/5/8/10 X-ray beam qualities. The overall experimental uncertainties (0.8 %) are smaller than the symbols' size.



Source: Authors.

The dose response of the EPI diode, given by the charge as a function of the accumulated dose, for all beam qualities, is shown in Figure 3. The data sets, plotted on a di-log scale for easy viewing, are well-fitted by a linear function (correlation coefficients $R^2 \cong 0.999$) with slightly different slopes compared to those taken as reference (RQR-5 and RQT-9). These discrepancies are physically related to distinct energies deposited by the X-ray beams (50 kV-150 kV) on the active layer (50 μm) of the diode. This hypothesis is supported by the good agreement of dose responses for the RQR-8 and RQT-10 beams, with similar mean energies.

Figure 3: Charge as a function of the accumulated dose for all RQR and RQT beam qualities. The overall experimental uncertainties (0.8 %) are smaller than the symbols' size.



Source: Authors.

The calibration coefficients (N_k) of the EPI diode, in terms of the air kerma rates given in Table 1, link the diode reading to the true absorbed dose measured with the standard reference ionization chambers (Radcal RC6-RD and RC3-CT) under reference conditions (20°C, 101.3 kPa). Calibration certificates from the PTW laboratory provide the respective N_k values ($7.606 \cdot 10^4$ Gy/C, Radcal RC6-RD, and $1.130 \cdot 10^5$ Gy/C, Radcal RC3-CT).

The calibration coefficients are calculated considering RQR-5 and RQT-9 as the reference ($k_Q = 1$) and a room temperature of 21°C. These data are summarized in Table 2, along with the correction factors for temperature variation (k_T) and beam qualities (k_Q). Changes in air pressure and humidity are neglected.

Table 2: Calibration coefficients and correction factors for the diagnostic radiology and computed tomography X-ray qualities. N_k uncertainty equals 0.8% (RQR) and 1.5% (RQT).

Beam Quality	$N_k = 7.606 \cdot 10^4$ Gy/C	
	k_Q	$k_{\square}$
RQR-3	1.006	1.005
RQR-5	1	1.005
RQR-8	1.071	1.005
RQR-10	1.271	1.005
	$N_k = 1.130 \cdot 10^5$ Gy/C	
	k_Q	$k_{\square}$
RQT-8	0.871	1.005
RQT-9	1	1.005
RQT-10	1.181	1.005

From the data shown in Table 2, the temperature correction factor is almost negligible, unlike those correction factors due to variations in the X-ray beams for the reference ones ($k_Q = 1$). It corroborates the data in Figure 3 concerning the energy dependence of the EPI diode, mainly for the RQR-10 and RQT-10 energy ranges. Indeed, as the active layer of the diode is very thin (50 μm), the energy deposited by the diagnostic radiology and computed tomography beams, within the range from 50 kV to 150 kV, can vary significantly.

4. CONCLUSIONS

This work reports on the assessment of the calibration coefficients and correction factors of an epitaxial diode intended for diagnostic radiology and computed tomography dosimetry. The formalism adopted based on the air kerma rate proved suitable for precisely linking the diode readings to the standard reference ionization chambers. Despite being close to 1, the correction factors due to variations of the RQR-10 and RQT-10 X-ray beams related to the correspondent reference qualities evidence the slight energy dependence of the EPI diode for voltages above 100 kV.

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CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

All authors declare that they have no conflicts of interest.

REFERENCES

[1] IAEA, INTERNATIONAL ATOMIC ENERGY AGENCY. Dosimetry in diagnostic radiology - An international code of practice. **Technical Reports Series 457**, Vienna: IAEA, TRS-457, 2007.

[2] Lindström, G.; Dolenc, I.; Fretwurst, E.; Hönniger, F.; Kramberger, G. Epitaxial silicon detectors for particle tracking – Radiation tolerance at extreme hadron fluencies. **Nucl. Instrum. Methods Phys. Res. Sect. A**, v. 568, p. 66-71, 2006.

[3] Gonçalves, J. A. C.; Mangiarotti, A.; Antonio, P. L.; Caldas, L. V. E.; Bueno, C. C. Dosimetric parameters and radiation tolerance of epitaxial diodes for diagnostic radiology and computed tomography beams. **Radiat. Phys. Chem.**, v. 223, p. 111926-33, 2024.

[4] IEC, INTERNATIONAL ELECTROTECHNICAL COMMISSION. Medical diagnostic X-ray equipment Medical electrical equipment - Dosimeters with ionization chambers and semiconductor detectors as used in X-ray diagnostic imaging. Geneva, **IEC 61674**, 2024.

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