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# Evaluation of epitaxial silicon diodes as dosimeters in X-ray mammography

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## HIGHLIGHTS

- Mammography X-ray dosimetry using epitaxial silicon diodes.
- Charge-dose response linear and independent on energy and dose rate.
- Good sensitivity for low-energy X-rays until accumulated dose of 200 kGy.
- Dosimetric parameters of diodes meet the requirements of IEC 61674 norm.

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## ABSTRACT

In this work we report on results obtained with 2 rad-hard n-type epitaxial silicon diodes in mammography X-ray dosimetry. One sample was not irradiated before using as a dosimeter, while the other received a $^{60}$Co gamma-ray pre-dose of 200 kGy. Both unbiased devices operated in a short-circuit mode as on-line radiation dosimeters for quality assurance in medical imaging dosimetry. The irradiation was performed using 28 kV and 35 kV X-ray beams from a Pantak/Seifert generator, previously calibrated by standardized ionization chamber. The dosimetric response of these devices was investigated with respect to the repeatability, long term stability, sensitivity dependence on energy and dose-rate, charge-dose linearity and directional response. The calibration coefficients of each diode, in terms of air kerma, were also determined. These dosimetric parameters of both diodes fully meet the requirements of IEC 61674 norm, confirming their use as a reliable alternative choice for mammography photon dosimetry within the dose range of 60 μGy-10 Gy (unirradiated EPI diode); for the pre-irradiated EPI diode upper limit of dose was not reached up to now. Nevertheless, it still remains to be investigated whether or not the pre-irradiation procedure influences on the response long-term stability of EPI devices. These studies are under way.



## 1. Introduction

Semiconductor devices have been used for photon and electron beams dosimetry mainly in the field of radiation protection, medical imaging and radiation therapy (Khoury, 1999; Grussel and Medin, 2000; Pavel, 2002; Griessbach et al., 2005; Rosenfeld, 2007). One of the major interests in using semiconductor dosimeters is their higher sensitivity per unit of volume in comparison with ionization chambers. Other advantages of Si diodes include their fast processing time, small sensitive volume, excellent repeatability, good mechanical stability and high spatial resolution. However, the most important constraint against the widespread use of silicon devices in medical dosimetry is their low radiation hardness (Rikner and Grussel, 1983; Lindstrom et al., 1999; Pini et al., 2003; Casati, 2005), responsible for long-term sensitivity decay with increasing accumulated dose. As a consequence, the routinely use of silicon diodes in hospitals demands periodic recalibration of the dosimeter, which is timing consuming. Considerable effort has been made to mitigate this sensitivity loss by developing radiation tolerant silicon detectors for applications in High Energy Physics experiments (Candelori, 2006; Harkonen et al., 2007). The performance of some of these rad-hard diodes operating in the photovoltaic mode as on-line gamma radiation

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dosimeters has been investigated in our group (Camargo et al., 2007, 2008) mainly in radiation processing dosimetry. Despite of the higher radiation tolerance of these devices, our results have still shown a sensitivity decay, attributed to the reduction of the minority carrier diffusion length with accumulated dose.

A new proposal (Lindstrom et al., 2006; Bruzzi et al., 2007; Fretwurst et al., 2007; Aldosari, A.H. et al., 2013) has been recently introduced in order to achieve sensitivity independence on accumulated dose: keeping constant the active volume of silicon devices, based on standard materials and processing techniques. This condition can be established by defining the active area of the devices through the use of a grounded guard-ring structure and limiting its depth by implanting the junction on a thin epitaxial (EPI) layer. It is quite feasible that thin silicon diodes based on epitaxial technology can be applied in on-line X-ray dosimetry without the drawbacks of significant energy dependence and current sensitivity drop with the accumulated dose (Talamonti et al., 2007, 2011; Santos et al., 2001). Indeed, thin depletion region and negligible entrance dead layer are the uttermost characteristics of epitaxial devices for detection of low-energy photons.

The outstanding rad-hard properties of these diodes have stimulated us to investigate their potential for application in medical imaging X-ray dosimetry. In this context, some relevant dosimetric parameters of EPI junctions were evaluated for mammography X-ray beams of 28 kV (RQR-2M) and 35 kV (RQR-4M) radiation qualities, taking into account the IEC 61674 norm (International Electrotechnical Commission, 2012). The results so far obtained are presented in this work.

## 2. Materials and methods

The diodes used (25 $mm^2$ active area) were processed at University of Hamburg (Lindstrom et al., 2006) on n-type 50 μm thick epitaxial silicon layer with a nominal resistivity of 50 Ω cm, grown on a highly doped n-type 300 μm thick Czochralski (Cz) silicon substrate. For comparison purposes, one sample (EPI-A) received a gamma pre-dose of 200 kGy (based on previous results obtained with EPI diodes in radiation processing dosimetry) from a $^{60}Co$ Gammacell irradiator with a dose rate of 42 Gy/min, while the other (EPI-B) was not previously irradiated. The devices were fixed on a ceramic plate ($20 \times 25 \times 0.6$ $mm^3$) using a conductive epoxy paint; after then, they were housed in a black polymethylmethacrylate PMMA probe (Fig. 1) with an entrance window of 8.3 mg/$cm^2$ thick paper to provide protection from mechanical stress, light and moisture, without reducing significantly the X-ray beam intensity. The planar pad ($p^+$) signal electrode of each device was directly connected through low-noise Lemo® coaxial cable to the input of a Keithley® 6517B electrometer in the photovoltaic mode; their backplane were grounded. The $p^+$ type guard ring structure is composed by an inner most guard ring (100 μm width and the distance between the guard and the pad is 10 μm) and thirty small guard rings (10 μm width). All guard rings and the signal electrode alike were left floating.

**Table 1**
Mammography X-ray Qualities from Pantak-Seifert 160HS Isovolt generator implanted at LCI (IPEN-CNEN/SP).

| Mammography qualities (unattenuated beams) | | | | |
|---|---|---|---|---|
| Quality | kV | mA | Filtration (mm) | Air Kerma rate (mGy/min) |
| RQR-2M | 28 | 10 | 0.07 Mo | 13.0 (3) |
| RQR-4M | 35 | 10 | 0.07 Mo | 19.2 (4) |

The dosimetric parameters of the EPI samples were evaluated for mammography X-ray beams of 28 kV and 35 kV energy, unattenuated radiation qualities, from a Pantak-Seifert generator located at the Laboratório de Calibração de Instrumentos of IPEN-CNEN/SP. The radiation beams of this X-ray system was previously standardized by a Radcal RC6M (9231 series) ionization chamber, calibrated at the *Physikalisch-Technische Bundesanstalt* (PTB) with a standard deviation of 0.96%. Table 1 presents the air kerma rates and reference parameters of the X-ray beams used. Irradiations were carried out with the diodes positioned at 1 m from the X-ray tube (focal spot), where the field size was of 12 cm diameter, with 99% homogeneity.

The current measured as a function of time, i.e. the current response curve, was related to the dose rate which enabled to verify the stability of the system during the process. The dose–response curve of the EPI diodes were achieved through the integration of the current signals versus time as a function of the accumulated dose.

The current response repeatability of both devices was evaluated for 28 kV and 35 kV energy beams by registering five consecutive current signals for the same radiation dose, switching the beam on and off. The repeatability parameter was evaluated here by the coefficient of variation (CV), defined as the standard deviation of a set of readings expressed as a percentage of the mean value of these readings (International Electrotechnical Commission, 2012). The long term stability was checked for EPI-A/B by making measurements under reference conditions (28 kV RQR-2M X-ray beam) at one month intervals over a period of not less than six months at 13.0 mGy/min dose rate. During this period, the detector assemblies were stored under standard test values of temperature (20 °C–25 °C) and humidity (30%–75%).

The directional response of the diodes was studied considering the rotation of the devices related the incident beam. For this purpose, the probe was coupled to a commercial goniometer with 1° resolution. In order to fulfill the requirements of the IEC 61674 norm, all measurements were performed at constant room temperature (23 °C) and air humidity (50%). The experimental

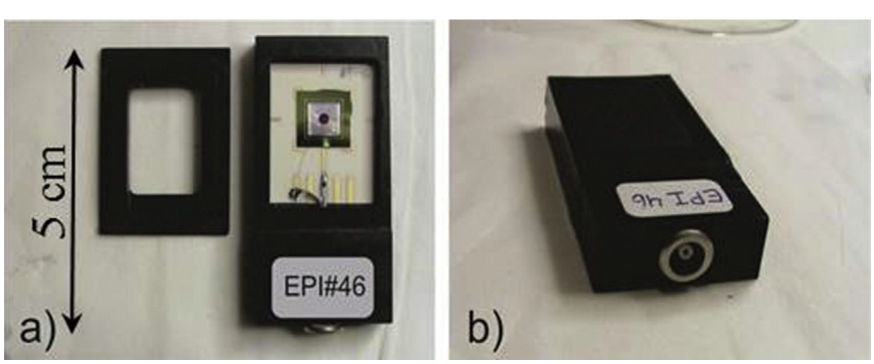


**Fig. 1.** (a) EPI diode housed in the PMMA probe and (b) with a black paper entrance window.

uncertainties of the results (1.7%) were restricted to the electrometer precision (1%), thermometer (0.01%), distance source-detector (0.05%), standardized ionization chamber (0.96%) and stability of the X ray generator current (1.0%). Otherwise pointed on contrary, in this work experimental combined uncertainties are expanded to $k = 2$ (confidence level of 95%).

## 3. Results and discussion

### 3.1. Repeatability

The irradiations were carried out with 13.0 and 19.2 mGy/min dose rates, respectively. The current signals related to subsequent irradiations (60 s each) are shown in Fig. 2 for the EPI-A/B diodes. About 120 acquisitions were performed during each irradiation, which are averaged to obtain the mean current.

As can be seen in Fig. 2, the responses of both diodes were quite stable. The dark currents of the diodes (≅ 0.4 pA for EPI-A and ≅ 0.3 pA for EPI-B) were acquired when the beam was just switched off just to check whether some radiation damage was produced in the device. During these measurements, the dark currents were kept constant and almost four orders of magnitude smaller than the photocurrents generated in the sensitive volume of the devices. For the mammography radiation qualities studied, the diodes presented CV values: 0.27% (EPI-A) and 0.26% (EPI-B), confirming their excellent short-term response. In the range of accumulated dose and dose rate investigated, the repeatability was not influenced by variations of sensitivity with accumulated dose.

### 3.2. Long term stability

Until now, the accumulated dose on the dosimetric probes was about 6.5 Gy and 49.15 Gy for EPI-A and -B diodes, respectively. A decrease not greater than 2% was observed in the current readings of EPI-B for an accumulated dose of 10Gy, reaching undesirable 8% for 49.15 Gy. The corresponding values of charge sensitivity of EPI-A and -B diodes for 6.5 Gy and 49.15 Gy accumulated doses are 4.62 nC/mGy and 9.62 nC/mGy, respectively. This result of the unirradiated EPI diode was already expected, otherwise, it is important to note that 10 Gy is the maximum dose registered without recalibration for most commercially available pre-irradiated silicon dosimeters. For the pre-irradiated diode, no significant variation of response was measured (only 0.07%) in the dose range studied (6.5 Gy). Further studies on long-term stability are under way in order to extend the evaluation of this parameter to higher doses.

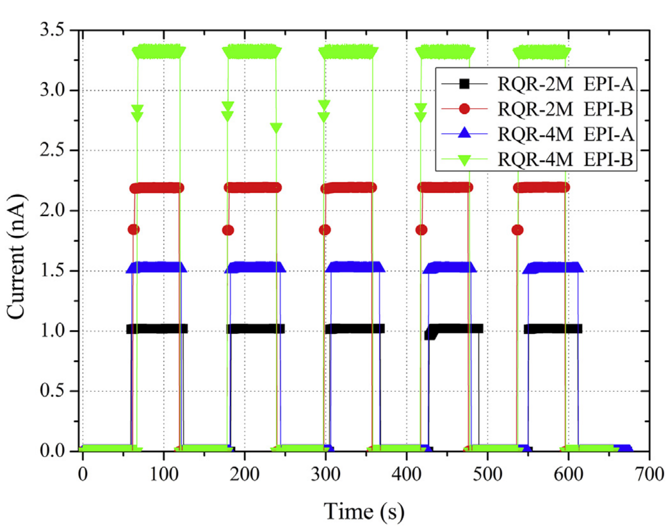


**Fig. 2.** Typical current response of EPI diodes for 28 kV (RQR-2M) and 35 kV (RQR-4M) X-ray beams. Dose rates are the same as indicated in Table 1. The experimental uncertainties are smaller than the symbols size.

### 3.3. Linearity of dose rate response

The linearity between current and dose rate was assessed for RQR-2M quality beam in the range from 2.6 up to 38.4 mGy/min by varying the X-ray generator current from 2 mA up to 20 mA. As depicted in Fig. 3, the pre-irradiated diode (EPI-A) is less current sensitive than the other one by almost a factor 2 (0.09 nA min/mGy against 0.16 nA min/mGy for EPI-B). Similar results were obtained with RQR-4M X-ray beam.

However, EPI-B exhibited energy dependence (<5%), mainly in the region of dose rates higher than 10 mGy/min, possible due to the instantaneous radiation damage effects. Indeed, for EPI-A these effects were mitigated with the pre irradiation procedure.

### 3.4. Charge-dose response and sensitivity

The dose–response of the EPI diodes were investigated by plotting the charge generated (integration of the current signal versus time) as a function of the accumulated dose for mammography radiation qualities, at dose rates pointed out in Table 1. These results, presented in Fig. 4, are well fitted by a linear function (correlation coefficients ≅ 0.999). The charge sensitivity values gathered from Fig.4 and presented in Table 2, evidencing no significant energy dependence. In Fig. 5 is shown the charge sensitivity as function of dose rate in the range studied for both diodes, which clearly indicates that the sensitivity is independent of the dose rate.

### 3.5. Angular dependence

The angular dependence of EPI-A/B diodes evaluated for the reference mammography RQR-2M beam is shown in Fig. 6. The angular response of both diodes are not greater than 3% within an angle range of ±30° from the normal direction of incidence. This result fulfill the requirements from IEC 61674 norm (limit of

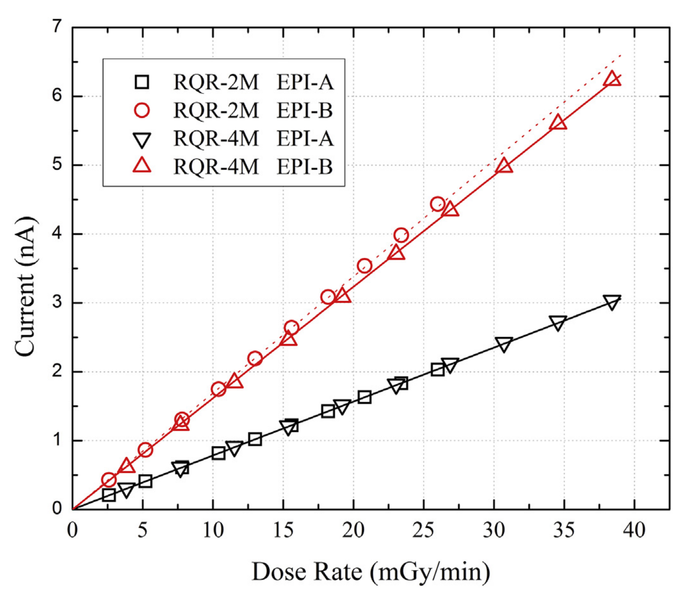


**Fig. 3.** Linearity of dose rate response for EPI-A/B diodes irradiated with 28 kV (RQR-2M) and 35 kV (RQR-4M) X-ray beams under reference conditions in the range from 2.6 up to 38.4 mGy/min by varying the X-ray generator current. The experimental uncertainties are smaller than the symbols size.

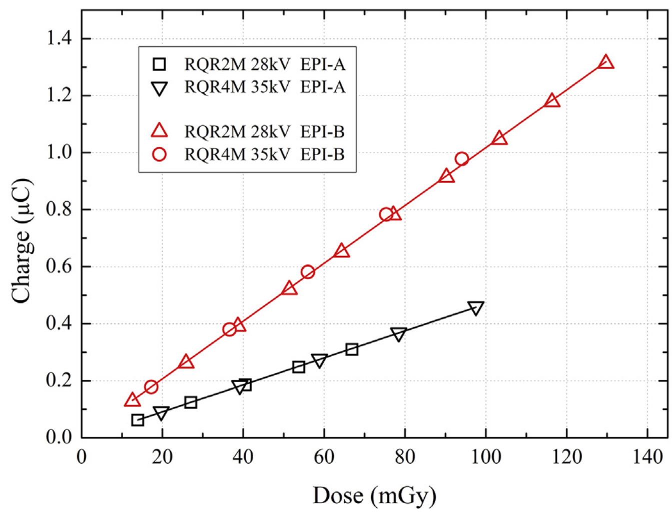


**Fig. 4.** Charge-dose response of EPI diodes for 28 kV (RQR-2M) and 35 kV (RQR-4M) unattenuated mammography X-ray beams. The experimental uncertainties are smaller than the symbols size.

**Table 2**
Charge sensitivities of EPI-A/B diodes for the mammography X-ray qualities. Values gathered from Fig. 4 with data fitted separately and with one linear function.

| Beam quality | EPI-A | EPI-B |
|---|---|---|
| | Sensitivity (nC/mGy) | Sensitivity (nC/mGy) |
| RQR-2M 28 kV | 4.72 (3) | 10.41 (7) |
| RQR-4M 35 kV | 4.67 (3) | 10.12 (7) |
| (RQR-2M + RQR-4M) | 4.73 (3) | 10.14 (7) |

variation $\leq$ 3% within an angle range of $\pm 5°$ from the normal direction of incidence) allowing their use in the dosimetry procedures involving rotational treatments.

### 3.6. Calibration coefficient, $N_k$

According to the Technical Reports Series No. 457 (International Atomic Energy Agency, 2007), the determination of dosimetry

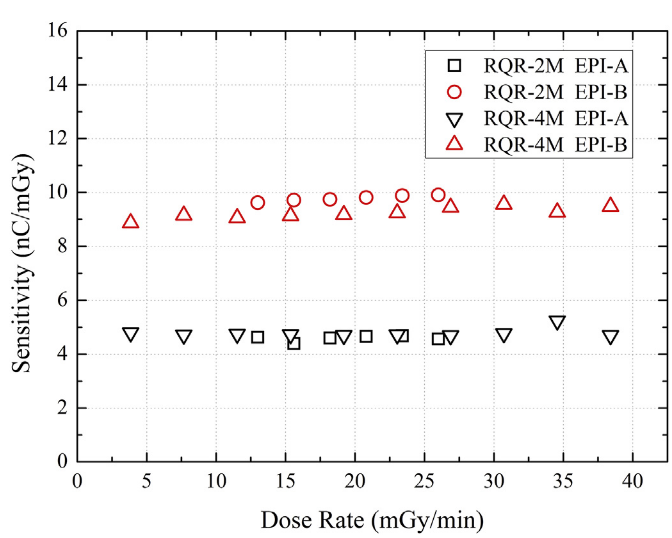


**Fig. 5.** Dependence of the dosimetric probes sensitivity on the dose rate for 28 kV (RQR-2M) and 35 kV (RQR-4M) unattenuated X-ray beams under reference conditions. The experimental uncertainties are smaller than the symbols size.

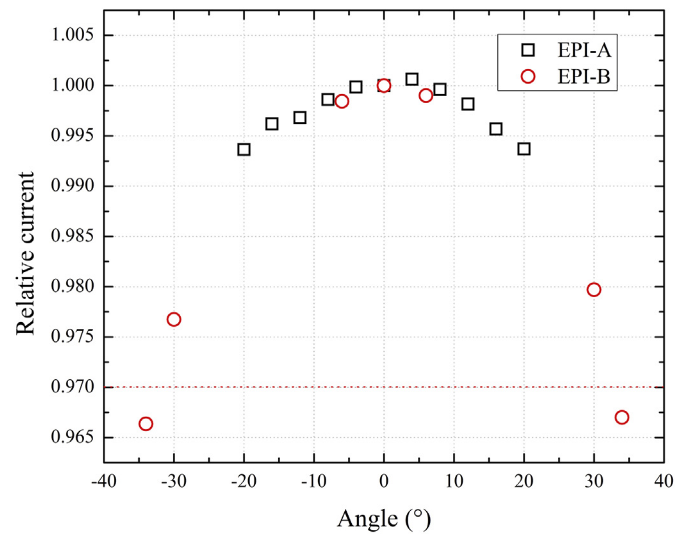


**Fig. 6.** Directional response of the EPI-A/B diodes for RQR-2M X-ray beam. The red dashed line shows the angle range ($\pm 30°$) within the limit of variation ($\lesssim$3%) required by IEC 61674. The experimental uncertainties are smaller than the symbols size. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

quantities used in diagnostic radiology is based on standards of air kerma, $K_a$, named $N_k$ formalism. The calibration coefficient of the dosimeter, $N_k$, refers to reference conditions used at the laboratory and is defined as the ratio of the conventional true value of the quantity to be measured to the indication of the instrument to be tested. In this way, the value of the air kerma, $K_a$, at a reference point in 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:

$$K_a = N_k \cdot M \cdot k_Q \cdot K_\rho$$

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; $k_\rho$ is the correction factor for the changes in air density due to changes in the ambient temperature. Once the mammography X-ray beams were previously established with the secondary standard reference ionization chamber (Radcal RC6M), the calibration coefficients of the diodes, in terms of the air kerma given in Table 1, could be determined considering the RQR-2M as the reference beam quality ($k_Q = 1$). These data are summarized in Table 3 for the EPI diodes used in this work.

## 4. Conclusions

The dosimetric response of unbiased EPI diodes were evaluated for RQR-2M (28 kV) and RQR-4M (35 kV) standard quality mammography beams. The devices alike delivered current signals quite stable. The results evidenced very good linearity between current and dose rate from 2.6 up to 38.4 mGy/min. The charge-

**Table 3**
Calibration coefficients and corrections factors of EPI diodes for the mammography X-ray qualities. Uncertainties on $N_k$ are equal to 1.7%.

| | EPI-A | | EPI-B | |
|---|---|---|---|---|
| Beam Quality | $N_k = 197{,}345 \times 10^3$ Gy/C | | $N_k = 80{,}165 \times 10^3$ Gy/C | |
| | $k_Q$ | $k\rho$ | $k_Q$ | $k\rho$ |
| RQR-2M | 1 | 1.092 | 1 | 1.087 |
| RQR-4M | 0.972 | 1.090 | 0.951 | 1.085 |

dose curves are linear and independent on energy and dose rate for both diodes. Within the rated range of 10 Gy, the unirradiated diode exhibited a drop in the current sensitivity of only 2%. Despite of being less sensitive (by a factor of 2), the pre-irradiated EPI diode showed a sensitivity almost independent on accumulated dose. The directional response of EPI-A/B devices was 0.1% within an angle range of $\pm 5^\circ$. The dosimetric parameters investigated meet the requirements of IEC 61674 norm, confirming the use of both diodes as a reliable alternative choice for mammography photon dosimetry within the dose range of 60 μGy-10 Gy (unirradiated EPI diode). Note that for the pre-irradiated EPI diode upper limit of dose was not reached up to now. Nevertheless, it still remains to be investigated whether or not the pre-irradiation procedure influences on the response long-term stability of EPI devices. These studies are under way.

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