Rad-Hard Silicon Diode Response for Photon Spectrometry

J. A. C. Gonçalves, F. Camargo, M. M. R. Fraga, J. K. C. Pinto, and C. C. Bueno

***Abstract*—In this Paper we describe the performance of a rad-hard diode (Al/p$^+$/n/n$^+$/Al), developed in the framework of research and development programs for the future CMS experiment at LHC, for detection and spectrometry of X-and γ-rays envisaging its use in characterization of porous structures by X-ray tomography. The diode's response was studied using ^{57}Co, ^{133}Ba, and ^{241}Am radioactive sources at room temperature. A reasonable good energy resolution was obtained in the energy range between 30 and 360 keV ($\mathrm{FWHM} = 5.2$ keV and 5.7 keV, respectively). In the same energy range, measurements of full-energy peak efficiencies were carried out and compared with the theoretical values. For 59.5 keV photons the angular dependence of the efficiency was also measured. The results have demonstrated that this diode is appropriate for direct detection of low energy electromagnetic radiation.**

***Index Terms*—Microtomography, rad-hard silicon detectors, X-ray spectrometry.**

I. INTRODUCTION

SILICON diodes have been widely used for X-rays detection in many applications for which portable systems are needed or at least useful [1]–[5]. In addition, for most of present applications it is expected that the silicon devices show a good spectrometric performance for X-rays even at room temperature, a short time response and a high resistance to radiation damage. While the two former requirements can be achieved with ordinary silicon diodes [6], [7], the increase of the radiation tolerance demands efforts to improve both the silicon crystal growth technique and the device manufacturing. Significant progress has been made during the last few years in the radiation hardness of Si diodes mainly driven by the demands of high energy physics experiments [8]. As a result of these efforts, one type of a rad-hard silicon diode was developed in the framework of research and development programs for the future CMS experiment at Large Hadron Collider (LHC) [9]. The fast timing response, low noise and small leakage current of these devices allied with its spectrometric capabilities for charged particles [10] encouraged us to study its performance for X-ray detection envisaging tomography purposes [11].

The first characterization studies of this diode as an X-ray detector with respect to the main properties (energy resolution, linear response, detection efficiency and angular dependence) of interest for a large field of applications is presented in this work.

The article is outlined as follows: the experimental setup and procedure utilized to study the response of the diode for detection and spectrometry of low energy electromagnetic radiation from ^{57}Co, ^{133}Ba and ^{241}Am radioactive sources at room temperature are described in Section 2. The results of the measurements and discussion about calculations of the full-energy peak efficiency as a function of photon energy and angular dependence of the diode are presented in Section 3. The last section is reserved for conclusions.

II. EXPERIMENTAL SETUP

The ion-implanted diode (Al/p$^+$/n/n$^+$/Al) used in this work has an active area of 2.5 mm^2 and it was processed out of 300 μm thick float-zone substrates with a resistivity of about 3.0 k$\Omega\times$cm. The insensitive entrance window of this device, constituted by Al (2 nm) and SiO$_2$ (650 nm) layers, was measured by Rutherford Backscattering Technique. The dynamic measurements of both leakage current and capacitance of the diode were previously carried out at a voltage range between 0 and 80 V. The results described elsewhere [10] showed that at 80 V the leakage current density was lower than 8 nA/mm^2 and the diode was fully depleted, which makes available a sensitive volume of the whole wafer thickness (300 μm).

In order to use this diode as a detector, its guard rings were grounded, while the n$^+$ side was reverse biased via a 100 MΩ resistor. The p$^+$ collecting anode was directly coupled **(DC)** to a field effect transistor (2SK152) in the first stage of a tailor made charge sensitive preamplifier based on the hybrid circuit A250 (Amptek) [12]. This solution minimizes the stray capacitance and reduces the sensitivity to microphonic noise.

The diode/preamplifier assembly and the radioactive source were housed in a stainless steel chamber as can be seen in Fig. 1. The pulses from the preamplifier were shaped and amplified by an ORTEC-572 amplifier with adjustable time constant. The pulse height distributions were measured at room temperature with a computer-based multichannel analyzer (ORTEC Spectrum Ace-8k).

III. RESULTS AND DISCUSSION

The performance of the diode for detection and spectrometry of photons from radioactive sources of ^{57}Co, ^{133}Ba and ^{241}Am was investigated at different bias voltages, distances source-detector and shaping time constants. From several

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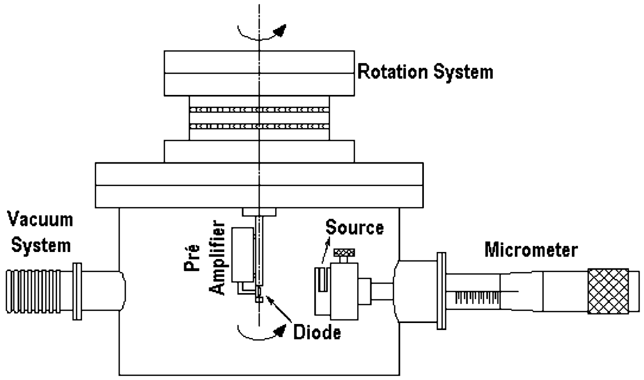

Fig. 1. Schematic view of experimental apparatus.

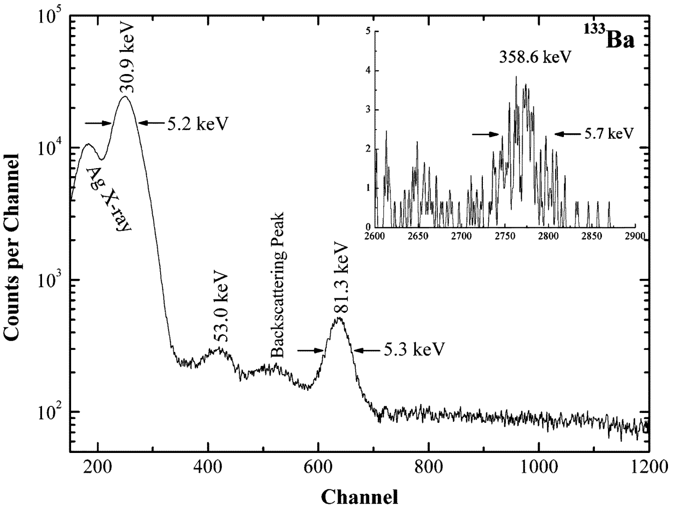

Fig. 2. Pulse height distribution of ^{133}Ba measured at room temperature with the source placed at 1.5 cm from the diode. The gamma ray of 358.6 keV, detected with a very small efficiency, is shown on the top right-hand corner of the plot. ($V = 80$ V, 2 μs time constant, 5.4 h time acquisition).

spectra recorded at room temperature, the best results were obtained with the radioactive source placed at 1.5 cm from the diode, biased at 80 V and 2 μs time constant. Due to the complexity of ^{133}Ba nuclide disintegration scheme, the low energy part of its spectrum (Fig. 2) showed broad full energy absorption peaks due to closely spaced photons energies such as the lines of 30.63 to 30.97 keV and 79.60 to 80.99 keV (FWHM = 5.3 keV). Two weak peaks superimposed on a Compton continuum were identified as the gamma ray of 53.0 keV and the backscatter photons mainly associated with the lines of 79.60 and 80.99 keV. Despite being registered with a very small efficiency, it was possible to detect the gamma ray of 358.6 keV shown on the top right-hand corner of the Fig. 2. It should be mentioned that the peak of the silver X-ray line was probably originated from the contacting material of the diode.

The pulse height spectrum for ^{57}Co is depicted in Fig. 3, where counts in the lowest channels have been suppressed in order to emphasize the peak lines of 121.6 and 134.2 keV. The energy resolution of the 121.6 keV gamma line amounts to 4.2 keV (FWHM) and is dominated by the electronic noise contribution. Indeed, the minimum noise of the system including the diode, measured by applying a voltage step pulse over a precision capacitor at the input of the preamplifier, was 2.3 keV (FWHM). It is important to note that at room temperature, the diode's leakage current is the dominant source of noise (Schott) in this system.

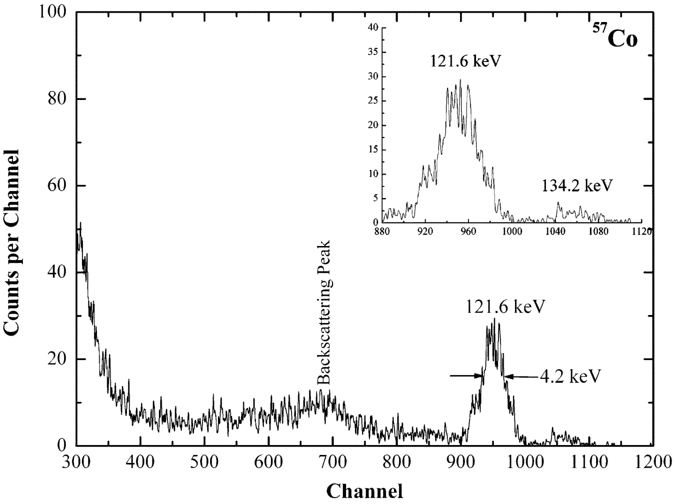

Fig. 3. Pulse height distribution of gamma rays from ^{57}Co measured at room temperature with the diode under a bias voltage of 80 V. The 121.6 keV γ-ray was detected with an energy resolution (FWHM) of 4.2 keV. The weak peak of 134.2 keV was also identified. (Distance source detector = 1.5 cm, 2 μs time constant, 3.6 h time acquisition).

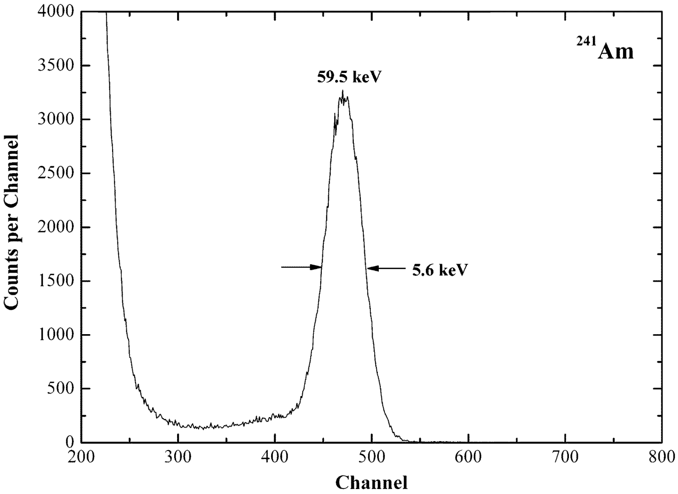

Fig. 4. Energy spectrum of ^{241}Am recorded at room temperature with the diode fully depleted ($V = 80$ V). The counts in the lowest channels have been suppressed in order to emphasize the peak line of 59.5 keV (FWHM = 5.6 keV). Distance source detector = 1.5 cm, 2 μs time constant, 2.5 h time acquisition.

Furthermore, as both spectra were recorded without any collimation, there might be an additional source of peak broadening due to those events that originate near either mechanical or electrically-defined edges of the diode. Since in this region the electric field is below normal, the charge collection efficiency and therefore peak width may be affected. This effect is more important for low energy photons, which can be confirmed in the pulse height distribution of X- and γ-rays from ^{241}Am presented in Fig. 4.

The ^{237}Np X-ray lines and 26.3 keV gamma rays were not identified as they appeared superimposed on a continuum due to

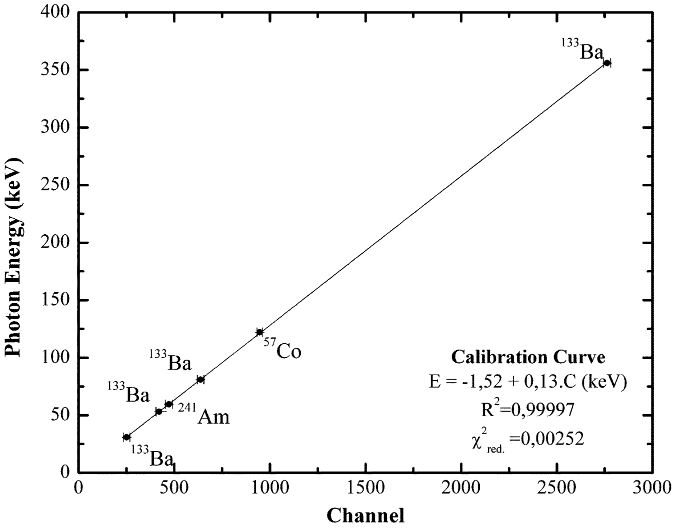

Fig. 5. Experimentally determined linearity between pulse height and γ/X-rays energies for the diode. Spectra of ^{57}Co, ^{133}Ba, and ^{241}Am radioactive sources were recorded at room temperature (V $=$ 80 V).

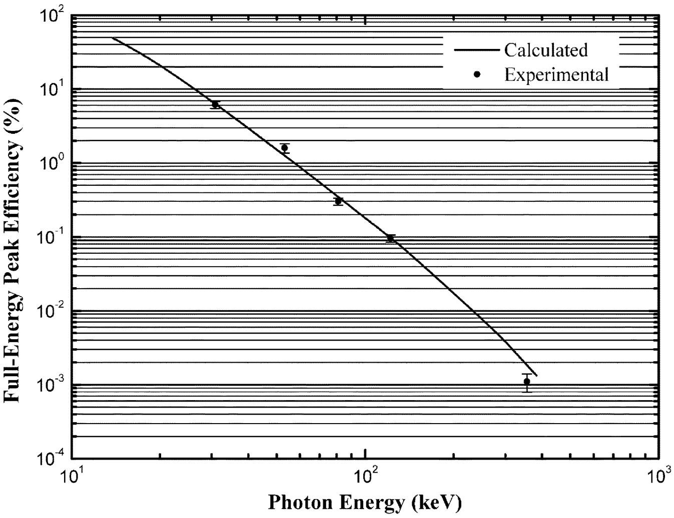

Fig. 6. Experimental (points) and calculated values (continuous line) of full-energy peak efficiencies of the diode as a function of photon energy (V $=$ 80 V).

both Compton scattering and electronic noise. We also believe that, for low energy photons, the detector dead layer of SiO_2 is responsible for a small straggling in the energy deposited by the photoelectrons in the depleted region of the diode.

The linearity of the detection system was verified through the energy spectra of X- and γ-rays from sources listed above, recorded at room temperature, at the same reverse bias of 80 V. Photons energy from 30 up to 360 keV was plotted versus the channel numbers of the fitted peak centroids. Hereby, an excellent degree of linearity over the full energy range was observed, as can be seen from Fig. 5.

Measurements of the intrinsic full-energy peak efficiencies, defined as the ratio of full-energy peaks counts to the number of photons incident on the diode, were carried out using the available calibrated sources of ^{57}Co and ^{133}Ba. The photon emission rates were normalized by a geometrical factor and corrected for the beam attenuation in the Al (2 nm) and SiO_2 (650 nm) front layers of the diode and the polyethylene (3 mm thick) cover of the radioactive sources.

Theoretical values of full-energy peak efficiencies of the diode as a function of photon energy were also calculated. As the depleted region of the diode is 300 μm, we assumed that the incident photons rarely undergo multiple interactions in the active volume of the diode. Hence, the full-energy absorption was considered as caused only by photoelectric interaction, where the effect of silicon's K escape (about 1.84 keV) was neglected. However, since this diode features a high active area to volume ratio, not a few electrons created by the photoelectric effect may escape out from the detector carrying part of the incident photon energy. The probability of this photoelectron escape (f_e), called photoelectron escape fraction, has been calculated using a Monte Carlo method for various detector sizes and energy ranges [13], [14]. Taking into account the values of f_e quoted from the published data [14], theoretical values of full-energy peak efficiencies were calculated by the photoelectric efficiency, η_p, as following:

$$\eta_P = \left[\frac{\mu_P}{\mu_T} \cdot \left(1 - e^{-\mu_T t}\right)\right] \cdot (1 - f_e),$$

where μ_p and μ_T are the photoelectric and the total attenuation coefficients [15] of the incident photons in Si and t is the depletion region thickness of the diode.

Fig. 6 shows the experimental (points) and theoretical (continuous line) values of intrinsic full-energy peak efficiencies as a function of photon energy. The excellent agreement between the experimental data and corresponding values from calculations indicates that our assumptions were reasonable.

The angular dependence of the full-energy peak efficiency was measured for 59.5 keV photons from ^{241}Am with the diode completely depleted (V $=$ 80 V). For simplicity reasons, the efficiency values presented in Fig. 7 were relative to that obtained at photon incident direction perpendicular to the diode surface (0°). Due to the constraints imposed by the diode assembly, it was not possible to carry out the efficiency measurements for angles greater than 60°. In spite of this experimental limitation, the results showed that the diode has nearly zero angular dependence as predicted by our theoretical model. Indeed, since the multiple interactions were ignored, the relative efficiency (ε_r) was obtained by the following ratio:

$$\varepsilon_r = \frac{\cos\theta \left(1 - e^{-\mu_T t/\cos\theta}\right)}{1 - e^{-\mu_T t}}$$

where θ is the angle between the perpendicular to the diode's surface and the photon incident direction. For comparison, the calculated values obtained for the depletion layer thickness (t) of 300 μm and the total attenuation coefficient (μ_T) of 59.5 keV photons in silicon are also presented (continuous line) in Fig. 7. For angles higher than 30°, there is a small discrepancy between

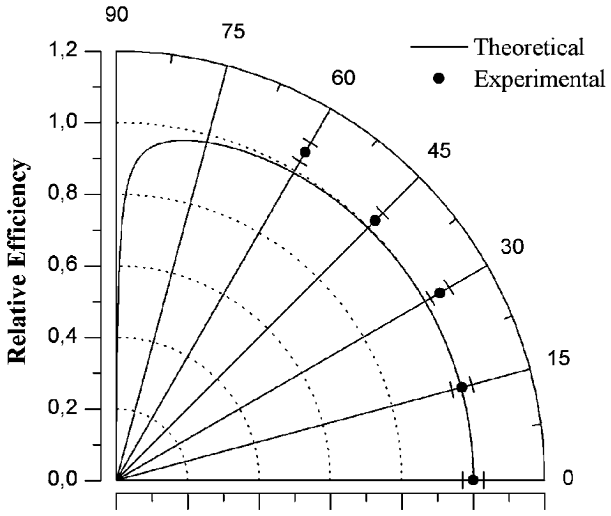

Fig. 7. Angular dependence of the relative full-energy peak efficiency for 59.5 keV photons.

experimental and theoretical efficiency values. Since in our calculations we considered that the radioactive source was punctual, it seems that there is a geometrical factor affecting the measurements due to both the finite source-detector distance and the diode's useful area. However, for angles smaller than 60°, theoretical and experimental values of the relative full energy peak efficiency show a similar angular dependence.

IV. CONCLUSION

It has been shown that the ion-implanted diode (Al/p^+/n/n^+/Al) used in this work is appropriate for direct detection of X- and γ-rays in the energy range from 30 keV to 360 keV with a reasonable energy resolution, even at room temperature. The lower energy limit was defined by the signal-to-noise ratio and the upper limit by the intrinsic full-energy peak efficiency. Since the electronic noise of the preamplifier does not exceed 2.3 keV, we believe that the edge effect of the diode is an important source of energy straggling and set the limit on detector performance.

The measured values of the full-energy peak efficiency show excellent agreement with the theoretical ones. In the energy range studied the full-energy efficiency varies from 6 % to 0.001 %. Besides, for 59.5 keV photons the angular dependence of the measured efficiencies is isotropic. These results indicate that this diode is suitable for its application in the field of X-ray tomography.

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