Use of a Rad-Hard Silicon Diode for Photon Spectrometry

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Abstract--**In this paper we describe the performance of an ion-implanted diode (Al/p$^+$/n/n$^+$/Al), developed in the framework of R&D programs for the future CMS experiment at LHC, for detection and spectrometry of X-and γ-rays envisaging its use in characterization of porous microstructures by X-Ray microtomography. The effects of the reverse bias on both the electronic noise and the diode energy resolution were studied using ^{57}Co, ^{133}Ba and ^{241}Am radioactive sources at room temperature. In the energy range between 30 and 360 keV, it was obtained reasonable good energy resolution (e.g., FWHM = 4.2 keV for 121.6 keV gamma ray from ^{57}Co). In the same energy range, measurements of full-energy peak efficiencies were carried out and compared with the theoretical values. The results have demonstrated that this diode is appropriate for direct detection of low energy electromagnetic radiation.**

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]. However, due to the low atomic number of silicon and the finite thickness of the diode depletion region (typically below 500 μm) an effective use of these standard devices for electromagnetic radiations is limited to the energies up to 100 keV. For higher energies, there are two effects that should be taken into account: (i) the reduction of the detection efficiency due to the scattering phenomena and the fall of the photoelectric cross section, (ii) the increase of the photoelectron escape fraction. Both effects worsen the energy resolution and diminish the full energy peak efficiencies. Therefore, two important issues to be considered when using silicon diodes for detection of X- and γ-rays are the energy range and the variation of the detection efficiency with the energy of the incident radiation. Furthermore, other properties of the diode such as energy resolution, rate capability and radiation hardness may become important depending on the application envisaged.

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In this work, we present the preliminary results about the response of a rad-hard silicon diode for detection and spectrometry of X- and γ-rays envisaging its use in the characterization of porous microstructures by X-ray microtomography [6]. The detector under investigation [7], developed in the framework of R&D programs for the future CMS experiment at Large Hadron Collider (LHC), features excellent timing properties, high radiation hardness and depletion layer thickness that fulfill the requirements of X-ray microtomography techniques.

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 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 kΩ.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 80V. The results described elsewhere [8] showed that at 80 V the leakage current density was lower than 8 nA/mm^2 and the diode was fully depleted, what make available a sensitive volume of the whole wafer thickness (300 μm).

In order to use this diode as a detector, the guard rings were grounded, while the n+ side was reverse biased via a 100 MΩ resistor. The p+ collecting anode was directly coupled to a field effect transistor (2SK152) in the first stage of a tailor made charge sensitive preamplifier based on the hybrid circuit A250 (Amptek) [9]. This solution minimizes the stray capacitance and reduces the sensitivity to microphonic noise.

The diode and preamplifier assembly was housed in a stainless steel chamber under a pressure of 10^{-6} Torr, at room temperature (about 293 K). The pulses from the preamplifier were shaped and amplified by an ORTEC-572 amplifier with adjustable time constant. The pulse height distributions were measured 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 spectra recorded at room temperature, the best results were obtained with the radioactive sources 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. 1) 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 of 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 Figure 1. It should be mentioned that the peak of the silver X-ray line was probably originated from the contacting material of the diode.

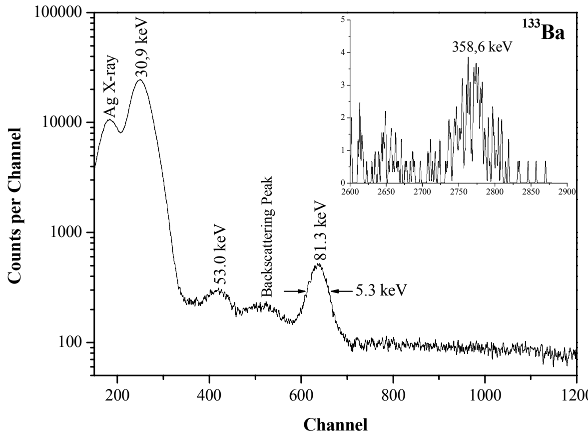

Fig. 1 - Pulse height distribution of ^{133}Ba measured at room temperature with the source placed at 1.5 cm from the diode . The gamma ray of 358.6 keV, detected with a very small efficiency, is shown on the top right-hand corner of the plot. (V= 80 V; 2 μs time constant).

The pulse height spectrum for ^{57}Co is depicted in Fig. 2, 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 total noise of the system, measured by injection of a pulse generator line at the input of the preamplifier, was 2.3 keV (FWHM).

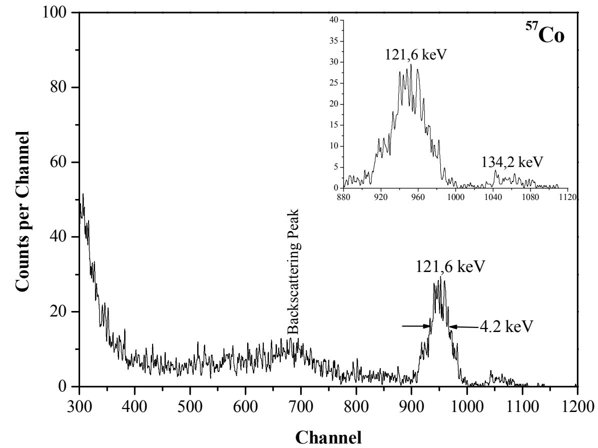

Fig. 2 - Pulse height distribution of gamma rays from ^{57}Co measured at room temperature with the diode under a bias voltage of 80 V. The 121.6 keV γ-ray was detected with an energy resolution (FWHM) of 4.2 keV. The weak peak of 134.2 keV is also identified. (Distance source detector = 1.5 cm, 2 μs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

It is noteworthy to mention that both spectra were recorded without any collimation, so the diode was irradiated over its entire volume. In this case, there is a source of peak broadening due to those events that originate near the edges of the active volume, where the local electric field is below normal. This effect is more important for low energy photons, what can be confirmed in the pulse height distribution of X- and γ-rays from ^{241}Am presented in Figure 3.

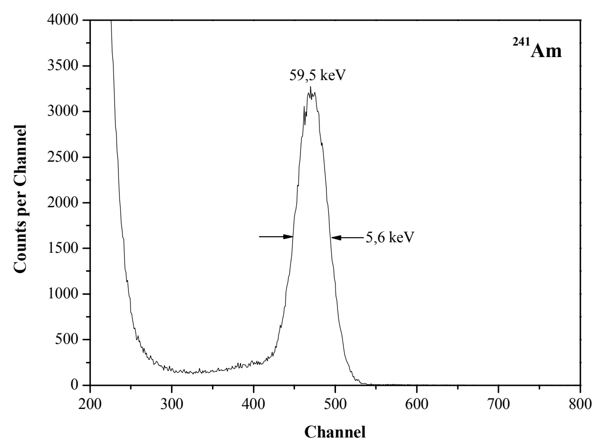

Fig. 3 - Energy spectrum of ^{241}Am recorded at room temperature with the diode fully depleted (V = 80 V). The counts in the lowest channels have been suppressed in order to emphasize the peak line of 59.5 keV (FWHM = 5.6 keV). Distance source detector = 1.5 cm, 2 μs time constant.

The ^{237}Np X-ray lines and 26.3 keV gamma ray were not identified as they appeared superimposed on a continuum due to 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 were 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 Figure 4.

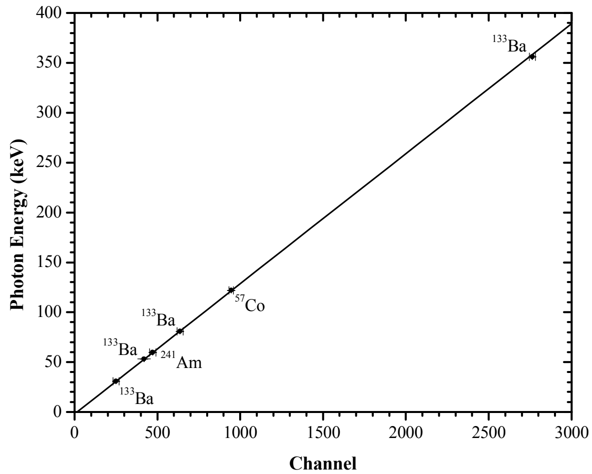

Fig. 4 - Experimentally determined linearity between pulse height and γ/X-rays energies for the diode. Spectra of ^{57}Co, ^{133}Ba and ^{241}Am radioactive sources were recorded at room temperature (V = 80 V).

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 [10-11]. Taking into account the values of f_e quoted from the published data [11], theoretical values of full-energy peak efficiencies were calculated by the photoelectric efficiency, η_p, as following:

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

where μ_p and μ_T are the photoelectric and the total attenuation coefficients [12] of the incident photons in Si and t is the depletion region thickness of the diode.

Figure 5 shows the experimental (points) and theoretical (continuous line) values of intrinsic full-energy peak efficiencies as a function of photon energy. Excellent agreement was noticed between the experimental data and corresponding values from calculations what indicates that our assumptions were reasonable.

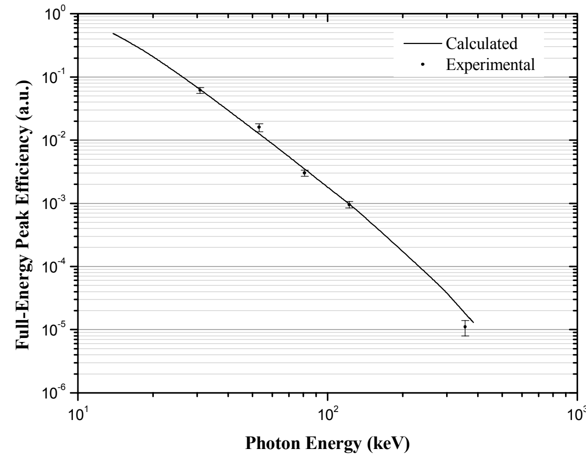

Fig. 5 - Experimental (points) and calculated values (continuous line) of full-energy peak efficiencies of the diode as a function of photon energy (V = 80 V).

IV. CONCLUSIONS

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 limit of energy 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 %, what indicates that this diode is suitable for its application in the field of X-ray microtomography.

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