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FULL ENERGY PEAK EFFICIENCY OF A RAD-HARD SILICON DIODE FOR X- AND γ- RAYS

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ABSTRACT

The performance of a rad-hard silicon diode (type $Al/p^+/n/n^+/Al$) for detection of electromagnetic radiation with energies from 30 up to 360 keV are reported in this work. In this energy range, the results obtained with the diode totally depleted evidenced a strong photon energy dependence of the full energy peak efficiencies (variation from 6 % to 0,001%). These values agreed within the experimental errors with those calculated from the assumption that the full-energy absorption of an incident photon was caused only by the photoelectric effect.

1. INTRODUCTION

Silicon diodes are widely used for detection and spectrometry of electromagnetic radiation, mainly due to the technology development for processing these devices. New generation of advanced diodes feature low leakage currents, small junction capacitances and thin dead layers, which make possible to detect X- and γ- rays even at room temperature.

However, one important issue to be considered in the field of photon detection is the energy dependence of the full energy peak efficiencies. Since the depletion regions of silicon devices hardly ever exceed 500 μm, the multiple interactions of incident photons with the diodes can be neglected and, consequently, the full energy absorption is caused only by the photoelectric effect. For higher energies, the reduction of the photoelectric cross section and the increase of the photoelectron escape fraction worsen the detection capability of silicon diodes and diminish the full energy peak efficiencies.

In this work, we describe the preliminary results obtained with an ion implanted diode (type $Al/p^+/n/n^+/Al$) [1] for detection and spectrometry of X- and γ- rays from radioactive sources of ^{57}Co, ^{133}Ba and ^{241}Am. This diode was developed in the framework of R&D programs of the European Center for Nuclear Research (CERN) to enhance the radiation hardness of silicon detectors due to the hostile radiation environment that will be encountered at high luminosity accelerators.

The results of the energy resolution and the full energy peak efficiency as a function of the photon energy, measured in the energy range from 30 up to 360 keV, are also reported in this work. In this energy range, theoretical values of full energy peak efficiencies were calculated by the photoelectric and total attenuation coefficients, the depletion region thickness of the diode and the photoelectron fraction escape. The comparison between experimental and theoretical values of full-energy peak efficiencies showed an excellent agreement, even without Compton scattering correction in the low energy region of the spectra.

2. EXPERIMENTAL ARRANGEMENT

The diode used in this work was processed out of 300 μm thick n type substrate with a resistivity of about 3.0 kΩ·cm and an active area of 4 mm^2. The p^+ side of the diode had a multi guard ring structure (10) around the contact pad. The thickness of Al (maximum 2 nm) and SiO_2 (650 nm) front layers of the diode were measured by RBS technique at the Laboratory of Material Analyses by Ion Beams (LAMFI) of São Paulo University.

The dynamic current and capacitance measurements of the device were performed at a voltage range between 0 and 100V. The results obtained showed that the diode was fully depleted at voltages above 40 V, with a leakage current density (current per unit of useful area) smaller than 4.1 nA/mm^2. At this condition, the depletion region depth of the diode was estimated from capacitance measurements as 243 μm.

In order to use the diode as a detector, the silicon slice was mounted on a gold capsule to make its electric leads and guard ring connections. The first guard ring was grounded and the others were left floating, while the bias voltage was applied on the diode's backside (n^+) through a 100 MΩ resistor. The signal from the detector was readout from the p^+ layer, directly coupled to a field effect transistor (FET) in the first stage of a tailor made charge sensitive preamplifier based on the hybrid circuit A250 (Amptek). The pulses from the preamplifier were shaped and amplified by a linear amplifier with adjustable shaping time constant and fed to a multichannel analyzer.

3. RESULTS AND DISCUSSION

First of all, it was studied the influence of the polarization voltage on the diode's response for gamma and X-rays from radioactive sources of ^{57}Co, ^{133}Ba and ^{241}Am placed at 1.5 cm from the diode. Several spectra were recorded at a room temperature and at a voltage range from 0V to 100 V. The results obtained with all radioactive sources evidenced that for low applied bias the energy resolution was strongly limited by the electronic noise generated by the diode's capacitance. Conversely, high voltages also led to poor energy resolution due to the increase of the leakage current of the device. The best compromise between leakage current and diode capacitance was reached at 80 V where the electronic noise of the system, measured by injection of a pulse generator line at the input of the preamplifier, was minimum (FWHM = 2.3 keV).

As one should expect, the best energy spectra of gamma and X-rays from ^{57}Co, ^{133}Ba and ^{241}Am radionuclides were obtained with the diode polarized at 80 V. To identify all peaks depicted in these spectra, a typical energy calibration curve (photon energy versus channel number of the fitted peak centroid) was plotted with the most intense lines from the three radionuclides cited above. This curve is presented in Fig. 1 where the excellent linearity of the detection system over the full energy range is observed.

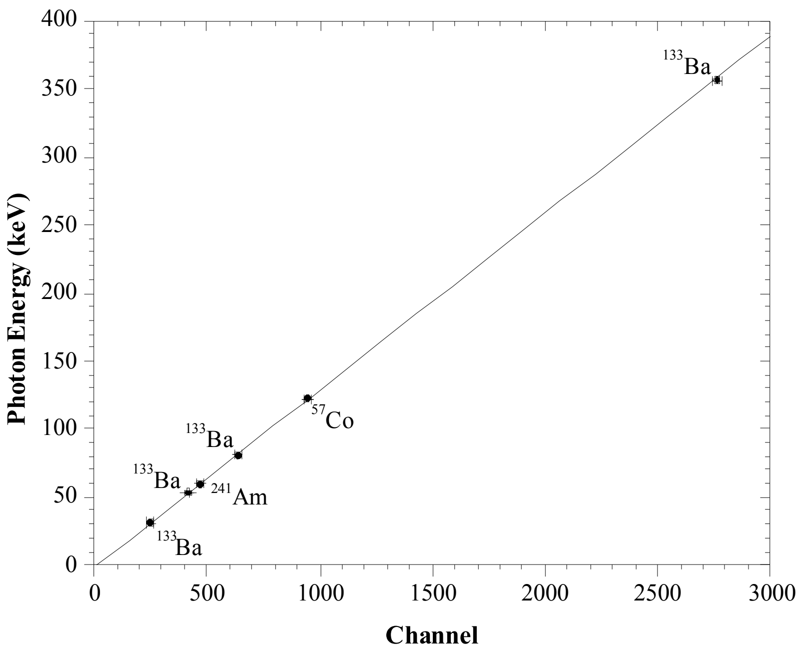

Figure 1. Experimentally determined linearity between pulse height and γ/X-rays energies for the diode. Spectra of ^{57}Co, ^{133}Ba and ^{241}Am radioactive sources were recorded at room temperature (V = 80 V).

Just to illustrate, the pulse height distribution of ^{133}Ba is depicted in Figure 2 in a logarithmic scale to evidence all lines registered, independently of its relative intensity. In the low energy part of this spectrum it can be observed two broad photopeaks: the first one was identified as the silver X-ray line, probably originated from the contact material of the diode and the second peak was due to 30.63 and 30.97 keV photons not resolved with this system. The photopeak of 53.0 keV was evidenced as well as the backscatter peak associated with the lines of 79.60 and 80.99 keV. Since the energies of these last gamma rays are very closed spaced, they originated only one photopeak with 5.3 keV energy resolution (FWHM). It is worth noting that this result was adversely affected by a Compton continuum tail in the spectrum due to higher energy photons. Indeed, the weak full-energy peak of 358.6 keV gamma ray (top right-hand corner of the Fig. 1) evidenced that, in this detector, the probability of full-energy absorption may be very small and consequently, the scattering phenomena predominate in this photon energy region.

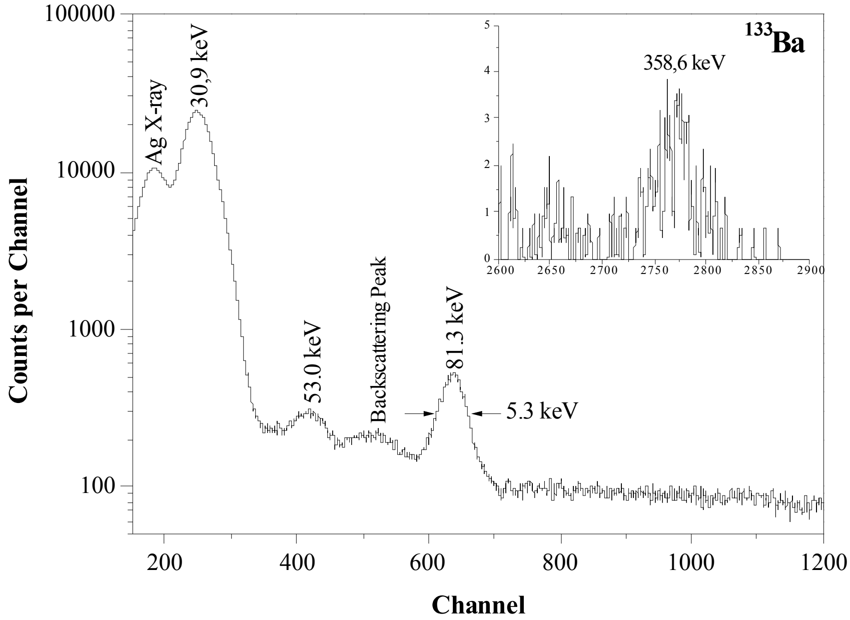

Figure 2. Pulse height distribution of 133Ba measured at room temperature with the source placed at 1.5 cm from the diode. The gamma ray of 358.6 keV, detected with a very small efficiency, is shown on the top right-hand corner of the plot. (V = 80 V; 2 μs time constant).

The full energy peak efficiencies, defined as the ratio of the photopeak area to the number of the incident photons on the diode, were both measured and calculated for photons with energies from 30 up to 360 keV. Experimental results were obtained through the best ^{57}Co, ^{133}Ba and ^{241}Am energy spectra recorded and the photon emission rates of each radionuclide. These rates were corrected by a geometrical factor and beam attenuation in both the dead layer of the diode and the polyethylene film cover of the radioactive sources. These results are presented in Fig. 3, together with the calculated values of the full energy peak efficiencies. Theoretically, we assumed that the total photon energy absorption was only due to the photoelectric effect and neglected the photon multiple interactions in the active volume of the diode. However, since de depleted region thickness is 300 μm, some photoelectrons may escape out of from the detector, carrying part of the incident photon energy. To correct this effect, we introduced a factor (f_e), called photoelectron escape fraction, in the well-known photoelectric efficiency (η_p) formula, as following:

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

where μ_p and μ_T are the photoelectric and total attenuation coefficients [2] of the incident photons in Si and t is the depletion thickness of the diode. With f_e values quoted from the published data [3] it was calculated the full-energy peak efficiency as a function of the photon energy (Fig.3). The agreement between experimental and theoretical values indicates that our assumptions were at least reasonable.

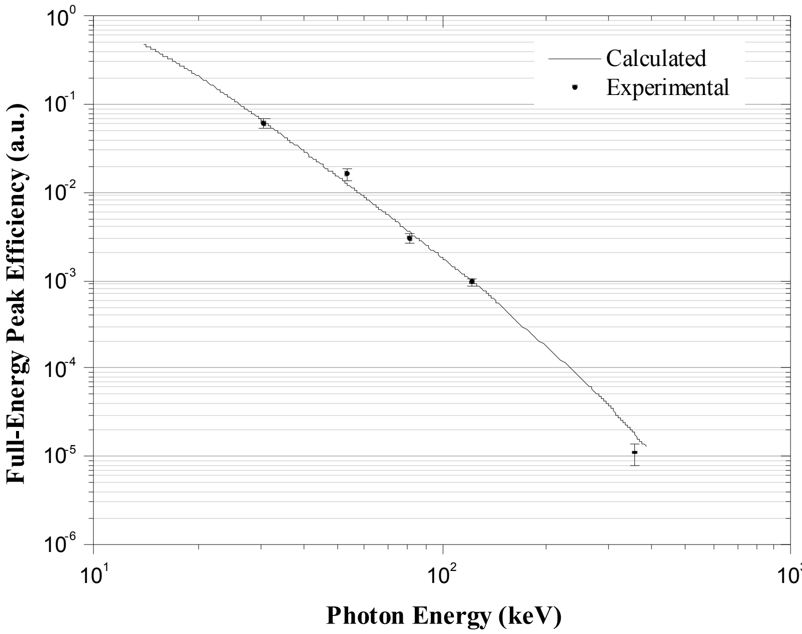

Figure 3. Experimental (points) and calculated values (continuous line) of full-energy peak efficiencies of the diode as a function of photon energy (V = 80 V).

4. CONCLUSIONS

The ion implanted diode studied in this work presents a good performance for both detection and spectrometry of low energy photons, even at room temperature. However, as it could be expected, the photon detection efficiency has a strong energy dependence in the energy range from 30 to 360 keV (variation of 6% to 0.001%, respectively).

The energy resolution of 5.3 keV (FWHM) obtained for 79.60 and 80.99 keV photons from ^{133}Ba shows that this diode can be used for photon spectrometry measurements. Nevertheless, since the total electronic noise is 2.3 keV, we believe that the energy resolution is mainly limited by both the scattering phenomena of higher energy photons and the diode's dead layer.

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