Available online at www.sciencedirect.com
SCIENCE DIRECT®

Applied Radiation and Isotopes 61 (2004) 1343–1347

Applied Radiation and Isotopes

www.elsevier.com/locate/apradiso

Response of PIN diodes as room temperature photon detectors

C.C. Bueno[a,b,*], J.A.C. Gonçalves[a,b], R.R. de Magalhães[a], M.D.S. Santos[a]

[a] *Centro de Tecnologia das Radiações, IPEN-CNEN/SP, Caixa Postal 11049, São Paulo 05422-970, Brazil*
[b] *Depto. de Física, Pontifícia Universidade Católica de São Paulo, São Paulo, Brazil*

Received 18 December 2003; received in revised form 1 March 2004; accepted 2 March 2004

Abstract

In this work we have studied the direct detection and spectrometric capabilities of low-cost commercial silicon photodiodes for X- and γ-rays (energies from 10 up to 80 keV) envisaging their use in characterization of porous microstructures by X-ray microtomography. The best values of the energy resolution for the 59.5 keV ^{241}Am γ-ray line, measured at room temperature, were found to be 2.1 and 1.8 keV for SFH00206 K (Siemens) and S2506-04 (Hamamatsu) PIN diodes, respectively.

Keywords: X-ray spectrometry; Silicon detectors; PIN diodes

1. Introduction

Silicon diodes offer a number of advantages as low energy electromagnetic radiation detectors for many applications in several branches of science (Cesareo et al., 1999; Grybos et al., 2000; Kirkland et al., 1988; Mali et al., 2001; Murty and Devan, 2001; Pavel, 2002; Snider, 1995; Trombka et al., 1999). Standard silicon photodiodes exhibit low leakage current, moderate capacitance and thin dead layers, which make them suitable for ionizing radiation detection with a very good energy resolution, even at room temperature. On the other hand, as these devices also feature a high active area to volume ratio, they are preferable in compact arrangements. Earlier studies performed in our laboratory (Bueno et al., 1996; Magalhães et al., 2000) on the performance of a Siemens photodiode (SFH00206 K) for charged particles and X-ray spectrometry encouraged us to optimize its operational conditions envisaging its application for characterization of porous microstructures by X-ray microtomography (Appoloni et al., 2002). With this aim, we also investigated the response of some commercial photodiodes in order to select those that match the requirements of low price, long-term stability and moderate efficiency for energies up to 80 keV.

We report here a comparison between the response of two PIN diodes, Siemens SFH00206 K and Hamamatsu S2506-04, for direct detection of X- and γ-rays from ^{109}Cd, ^{133}Ba, ^{152}Eu and ^{241}Am radioactive sources. The effect of the reverse bias on energy resolution and efficiency of both photodiodes was studied as well as their stability. The best values of energy resolution for the 59.5 keV γ-ray line from ^{241}Am, measured at room temperature, were found to be 2.1 keV (SFH00206 K) and 1.8 keV (S2506-04).

2. Experimental setup

Two types of low-cost (about US$10.00) PIN photodiodes were investigated in this work: Siemens SFH00206 K and Hamamatsu S2506-04, with active areas of 7.34 and 7.50 mm^2, respectively. Measurements of leakage current densities (current per unit of useful area) and capacitances of these devices as a function of

*Corresponding author. Centro de Tecnologia das Radiações, IPEN-CNEN/SP, Caixa Postal 11049, São Paulo 05422-970, Brazil. Tel.: +55-11-3816-9292, 248; fax: +55-11-3816-9186.

E-mail address: ccbueno@ipen.br (C.C. Bueno).

0969-8043/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apradiso.2004.03.064

reverse bias voltage are presented in Figs. 1 and 2. For both diodes the leakage current densities grow linearly with the voltage but, even when 30 V is applied, their values never exceed 0.7 nA/mm^2. The diodes capacitances, measured with a frequency of 1 MHz, decrease with the polarization bias as a result of the depletion layer growth. Indeed, the effect of reverse voltage on the depletion region depths of the photodiodes (estimated from capacitance measurements) is evidenced in Fig. 3.

In order to use the photodiodes as detectors, each device was placed in a stainless-steel vacuum chamber and directly connected (DC coupling) to a homemade charge sensitive pre-amplifier, based on the hybrid circuit A250-AMPTEK. The pre-amplifier output was further shaped and amplified in an ORTEC 672 main amplifier with adjustable time constant. The pulse height distributions were measured with a computer-based multichannel analyzer (ORTEC Spectrum Ace-8k).

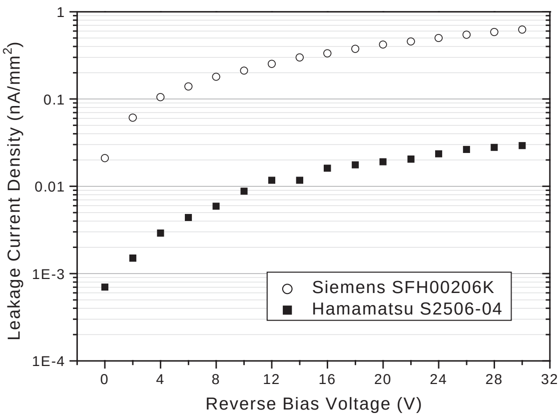

Fig. 1. Leakage current densities (current per unit of useful area) as a function of reverse bias voltage for SFH00206 K and S2506-04 diodes.

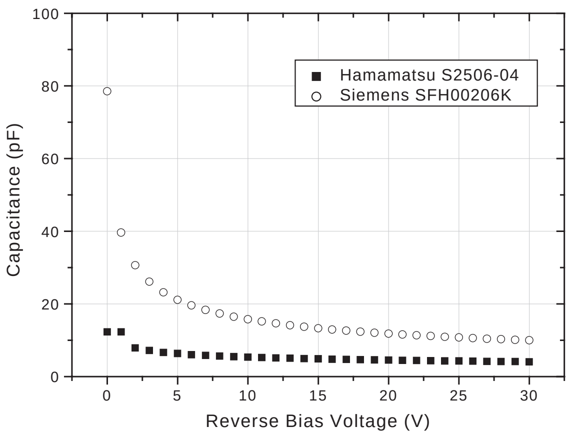

Fig. 2. Capacitances of both diodes as a function of reverse bias voltage.

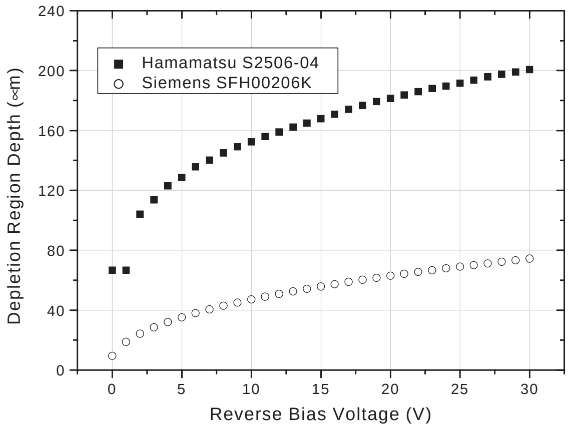

Fig. 3. Depletion region depths of the photodiodes (estimated from capacitance measurements) as a function of reverse voltage.

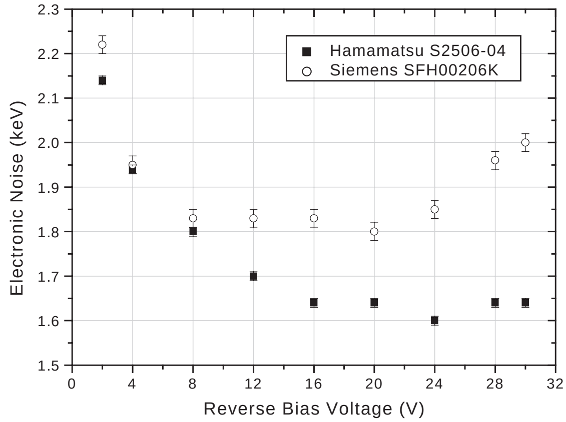

Fig. 4. Electronic noise (FWHM) measured as a function of reverse bias voltage for both diodes.

To achieve the optimum electronic noise performance of the detector system, including the diodes, we have investigated the bias voltage and shaping time constant dependence. For that purpose, the FWHM of a pulse generator line injected at the input of the pre-amplifier was measured. The best results, obtained for a 2 μs shaping time constant amplifier, are presented in Fig. 4. Since an increase of the applied voltage lessens the diodes capacitances and, conversely, heightens the leakage current, there is one bias voltage value for which the amount of noise is minimum. In our measurements, this occurs at 24 V (FWHM = 1.6 keV) for S2506-04 and at 20 V (FWHM = 1.8 keV) for SFH00206 K diodes. In these experimental conditions, the voltage drops across the load resistor (100 MΩ) were about 300 mV (SFH00206 K) and 18 mV (S2506-04).

Since in our measurements the total noise of the system included the leakage currents from the diodes, as well as their capacitance effects, the superior noise performance of the S2506-04 compared with that obtained for the SFH00206 K diode is completely understandable.

3. Results

The response of S2506-04 and SFH00206 K photodiodes for detection and spectrometry of low-energy γ and X-rays was studied through the use of a ^{241}Am radioactive source placed inside a vacuum chamber at 2.0 cm from the diodes. In order to evaluate the influence of the bias voltage on the diodes' energy resolution for the 59.5 keV γ-ray, several spectra were recorded at room temperature. Fig. 5 presents the comparative energy resolution of the diodes as a function of the bias voltage; the best results obtained were 1.8 keV at 24 V and 2.1 keV at 20 V for S2506-04 and SFH00206 K, respectively. In such conditions, the pulse height distributions measured using both photodiodes are shown in Figs. 6 and 7, where the low energy part of these spectra are due to ^{237}Np X-ray lines and 26.3 keV γ-ray from ^{241}Am, which are detected with higher efficiency than those for 59.5 keV.

To verify the linearity of both detection systems, energy spectra of γ and X-rays from ^{109}Cd, ^{133}Ba, ^{152}Eu and ^{241}Am radioactive sources were recorded at room temperature and at the same reverse bias applied to each diode. The channel numbers of the fitted peak centroids were plotted versus photons energies from 10 up to 80 keV and the results are presented in Fig. 8. Hereby,

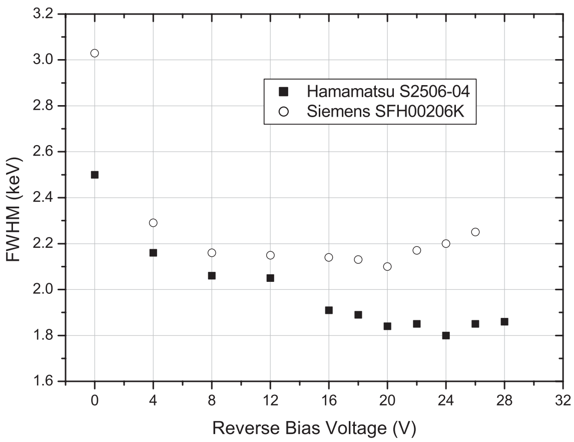

Fig. 5. Comparative energy resolution of the diodes as a function of the bias voltage measured at 59.5 keV γ-ray from ^{241}Am. The shaping time constant was 2 μs and the spectra were recorded at room temperature.

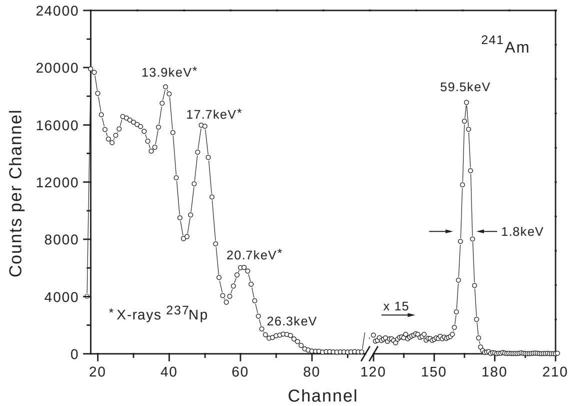

Fig. 6. Pulse height distribution of ^{241}Am measured at room temperature with S2506-04 photodiode under a bias voltage of 24 V. The low energy part of this spectrum is due to ^{237}Np X-ray lines and 26.3 keV gamma line from ^{241}Am.

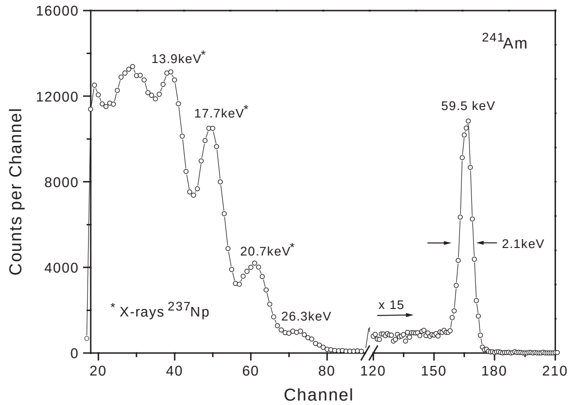

Fig. 7. Energy spectrum of ^{241}Am measured at room temperature with SFH00206 K photodiode polarized at 20 V. The ^{237}Np X-ray lines and 26.3 keV γ-ray from ^{241}Am are evidenced in the low energy part of this spectrum.

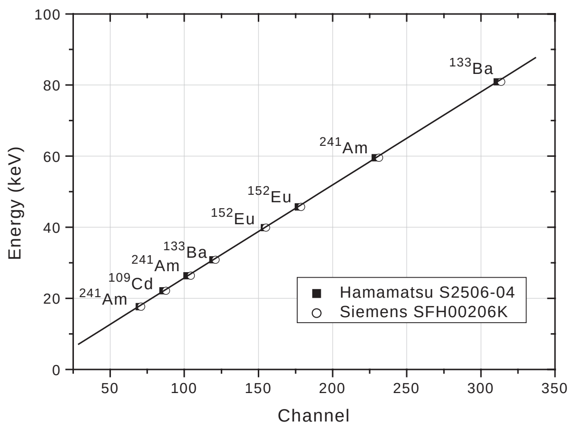

Fig. 8. Experimentally determined linearity between pulse height and X/γ- rays energies for SFH00206 K (20 V) and S2506-04 (24 V) diodes. Spectra of ^{109}Cd, ^{133}Ba, ^{152}Eu and ^{241}Am radioactive sources were recorded at room temperature.

an excellent degree of linearity over the full energy range was observed not only with the S2506-04 (24 V), but also with the SFH00206 K (20 V) diode.

The behavior of the relative efficiencies of the photodiodes as a function of the reverse bias was measured for the full energy absorption of the 59.5 keV γ-ray from the ^{241}Am source. Several spectra were recorded over a fixed time and the full energy peak area versus applied voltage allowed us to obtain the diodes' counting curves. The results presented in Fig. 9 showed an increase of the relative efficiency with the bias voltage as a consequence of the depletion layer growth in the devices. Short plateaus can also be observed at voltages above 20 V, which leads us to expect that both photodiodes were almost totally depleted. The ratio of the full energy peak area measured at any reverse bias to that obtained at the almost total depletion voltage is here defined as relative efficiency of the diodes. Furthermore, calculations and measurements of the full-energy peak efficiencies as a function of photons energy were carried out using calibrated ^{109}Cd, ^{133}Ba, ^{152}Eu and ^{241}Am sources. From spectra recorded with both diodes fully depleted (applied voltage of 28 V), the full-energy peak efficiencies were obtained through the ratio of the measured counting rates under the photo-peaks to the corresponding photon emission rates, normalized by a geometrical factor and corrected for the beam attenuation in the plastic cover of the devices.

As the depleted regions of the diodes are thinner than 200 μm, we assumed for the calculations that the incident photons rarely undergo multiple interactions in the active volume of these detectors. 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. Under these

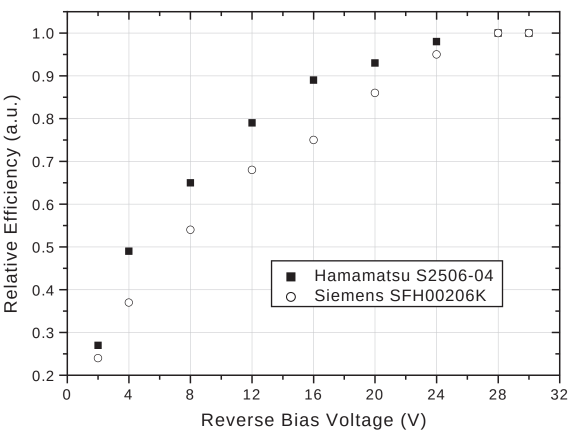

Fig. 9. Relative full-energy peak efficiency of 59.5 keV γ-ray from ^{241}Am of both diodes as a function of reverse bias voltage. The relative efficiency is here defined as the ratio of the full energy peak area measured at any reverse bias to that obtained at the almost total depletion voltage.

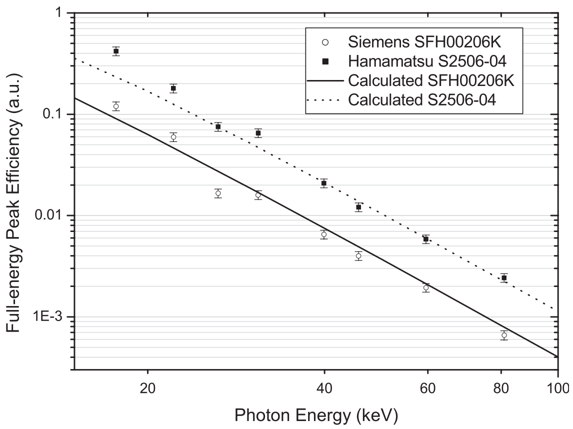

Fig. 10. Experimental and calculated full-energy peak efficiencies of both diodes as a function of photons energy.

assumptions, theoretical values of full-energy peak efficiencies were calculated by the photoelectric efficiency, η_p, as follows:

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

where μ_p and μ_T are the photoelectric and the total attenuation coefficients of the incident photons in Si, t is the depletion region thickness of the diodes (75 and 200 μm for the SFH00206 K and S2506-04 diodes, respectively) and f_e is the photoelectron escape fraction. The need of taking into account the f_e factor in the calculation of the full-energy peak efficiency was based on the fact that, for example, the range of 60 keV photoelectrons in Si (about 33 μm) cannot be neglected in comparison with the intrinsic layers of the diodes; as a consequence, not a few photoelectrons produced in these thin depletion layers may escape out from the diodes. This effect was studied by some authors (Pani et al., 1987; Aoki and Koyama, 1989) and the values of f_e used in this work were quoted from the published data (Aoki and Koyama, 1989). Fig. 10 presents the experimental and calculated full-energy peak efficiencies of SFH00206 K and S2506-04 diodes as a function of photons energy. As can be seen, there was a good agreement, within the experimental error, between the theoretical and measured results, what indicates that our assumptions were reasonable. It is important to note that no corrections were introduced for the distortion in the spectra due to Compton continuous, what justifies the higher values obtained for the experimental data below 20 keV photons.

4. Conclusions

It has been shown that low-cost commercial PIN photodiodes (type Hamamatsu S2506-04 and Siemens

SFH00206 K) are appropriate for detection and spectrometry of 10–80 keV photons at room temperature, even when they are coupled to an inexpensive pre-amplifier. Comparative studies have revealed that the performance of S2506-04 is slightly better than that obtained with the SFH00206 K diode. However, they can be considered a low budget alternative, good enough for many applications.

Since in the X- and γ-ray energy range studied the largest contribution to the resolution is the electronic noise, our next step will be the construction of a charge pre-amplifier where we can directly mount the diodes, minimizing the stray capacitance. This assembly will also enable us to easily change the FET's, feedback resistors and the connection (AC/DC) between the diode and the first stage of the amplifier. Considering that the minimum electronic noise of the hybrid circuit A250 (including a 100 pF input capacitance) is about 1 keV, we expect to reach with this new prototype a better performance in terms of energy resolution at room temperature.

Acknowledgements

The authors acknowledge to FAPESP for supporting this research (contracts 96/5923-2 and 97/12485-4) and for awarding a scholarship to one of us, R.R. Magalhães. Thanks are also due to the Siemens manufacturer in Brazil for the free supply of the photodiodes.

References

Aoki, K., Koyama, M., 1989. Measurement of diagnostic X-ray spectra using a silicon photodiode. Med. Phys. 16 (4), 529–536.

Appoloni, C.R., Macedo, A., Fernandes, C.P., Philippi, P.C., 2002. Characterization of porous microstructure by x-ray microtomography. X-ray Spectrom. Westsussex UK. 31 (2), 124–127.

Bueno, C.C., Gonçalves, J.A.C., Santos, M.D.S., 1996. The performance of low-cost commercial photodiodes for charged particle and X-ray spectrometry. Nucl. Instrum. Methods A 371, 460–464.

Cesareo, R., Gigante, G.E., Castellano, A., 1999. Thermoelectrically cooled semiconductor detectors for non-destructive analysis of works of art by means of energy dispersive X-ray fluorescence. Nucl. Instrum. Methods A 428, 171–181.

Grybos, P., Bialas, W., Cabal, A., Dabrowski, W., Giubellino, P., Idzik, M., Magana-Mendoza, L., Ramello, L., Szczygiel, R., Wheadon, R., 2000. Characterization of silicon strip detectors with a binary readout chip for X-ray imaging. Nucl. Instrum. Methods A 454, 214–220.

Kirkland, J.P., Jach, T., Neiser, R.A., Bouldin, C.E., 1988. PIN diode detectors for synchrotron X-rays. Nucl. Instrum. Methods A 266, 602–607.

Magalhães, R.R., Bueno, C.C., Gonçalves, J.A.C., Santos, M.D.S., 2000. Espectrômetro de Radiação Eletromagnética com Fotodiodos de Si. In: V National Meeting on Nuclear Applications, Rio de Janeiro, CD-ROM Proceedings.

Mali, T., Cindro, V., Mikuz, M., 2001. Silicon microstrip detectors for digital mammography—evaluation and spatial resolution study. Nucl. Instrum. Methods A 460, 76–80.

Murty, V.R.K., Devan, K.R.S., 2001. On the suitability of Peltier cooled Si-PIN detectors in transmission experiments. Radiat. Phys. Chem. 61, 495–496.

Pani, R., Laitano, R.F., Pellegrini, R., 1987. Diagnostic X-ray spectra measurements using a silicon surface barrier detector. Phys. Med. Biol. 32, 1135–1149.

Pavel, N.A., 2002. Particle detectors for biomedical applications—demands and trends. Nucl. Instrum. Methods A 478, 1–12.

Snider, R.T., 1995. Active silicon X-ray filter for measuring electron temperature. Rev. Sci. Instrum. 66 (1), 546–548.

Trombka, J.I., Evans, L.G., Starr, R., Clark, P.E., Floyd, S.R., 1999. Future planetary X-ray and gamma-ray remote sensing system and in situ requirements for room temperature solid state detectors. Nucl. Instrum. Methods A 428, 199–208.