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The performance of low-cost commercial photodiodes for charged particle and X-ray spectrometry

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Abstract

The energy response of a low-cost commercial silicon photodiodes detectors for alpha particles, fission fragments, internal conversion electrons and X-rays was studied. An alpha energy resolution of 16.7 keV (FWHM) was obtained for 5.486 MeV α-particles from ^{241}Am which is comparable in performance with the best surface barrier detectors available, that are considerably more expensive.

1. Introduction

In recent years, the widespread use of silicon photodiodes in the spectrometry of charged particles [1–5] has shown that it is possible to reach energy resolutions comparable with – or better than – those obtained from surface barrier detectors. Their low cost, ruggedness and simplicity of operation are factors which have influenced their increasing use as a research tool both in the laboratory and in industrial applications [6] such as the measurement of the isotopic ratios between $^{241}Am/^{238}Pu$ and $^{234}U/^{233}U$. For such determinations the use of alpha particles spectrometry provides results better than those obtained with the conventional mass-spectrometry techniques.

In order to employ this technique in studies related to reactor fuel elements fabrication and their properties after irradiation in our institute, a careful study of the properties and characteristics of silicon photodiodes (Siemens – SFH00206) for alpha particles spectrometry was made.

Since such commercial photodiodes are surrounded by a plastic cover of 0.7 mm of thickness, a technique was developed to remove such layer without affecting the sensitive surface of the diode, and thus avoiding an increase both in its intrinsic noise and leakage current.

In this paper the results obtained with those PIN photodiodes for the detection and spectrometry of alpha particles from ^{241}Am, ^{239}Pu and ^{244}Cm are described. The effect of the reverse-bias on the leakage current of the detector on the energy resolution was studied and has shown a value of 16.7 keV (FWHM) for the ^{241}Am 5.486 MeV alpha particles when the diode was biased with 28 V at a temperature of 20°C. The influence of the lowering the diode temperature down to −30°C on the energy resolution was studied.

The results obtained with those photodiodes both for the detection and spectrometry of fission fragments, internal conversion electrons and X-rays are presented.

2. Experimental arrangements

In our experiments, a Siemens SFH00206 PIN photodiode was used: with a useful area of 7.34 mm^2 and a capacity of 72 pF (at 0 V), they show a leakage current smaller than 5 nA. After being disencapsulated (through the use of a solvent for the plastic covering layer), it was fixed in the interior of the cover of a stainless steel vacuum chamber and directly connected to a charge sensitive pre-amplifier (ORTEC-142A) in order to decrease the effect of the parasitic capacity. The photodiode was polarized through a 100 MΩ resistor placed inside the pre-amplifier which was also provided with a BNC connector to allow the connection of a pulse generator for the measurement of the electronic noise. The pulses from the pre-amplifier were shaped and amplified by an ORTEC-572 amplifier with the time constant adjusted to 2 μs and fed to an ORTEC Spectrum Ace (8k) multi channel analyzer.

The leakage current from the photodiode, as a function of the polarization voltage, represented in Fig. 1, is smaller than 5 nA even when 28 V is applied as a reverse bias, showing that the removal of the plastic layer did not change its surface electrical properties. The total noise of

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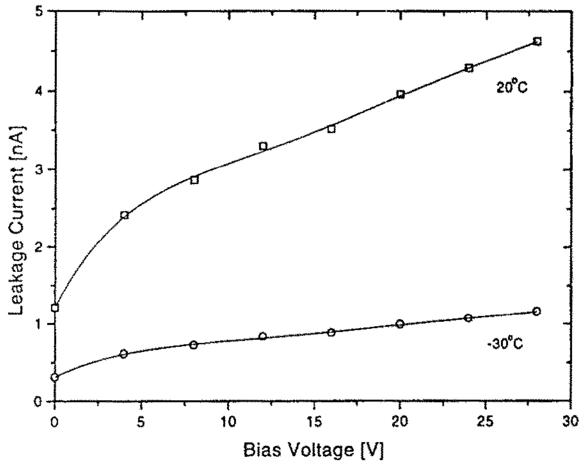

Fig. 1. The leakage current from the photodiode as function of the polarization voltage at 20 and −30°C.

the system, including the photodiode, (Fig. 2), was measured by injection of pulses from an ORTEC 448 precision pulse generator at the input of the preamplifier and the best result (FWHM = 3.65 keV) was obtained for a 28 V bias voltage (at 20°C).

In order to reduce the electronic noise of the detection system, the photodiode was refrigerated down to −30°C through the use of a Peltier cell, heated by means of a highly filtered DC current provided with a special system for the rejection for both low and high frequency noise. The decrease of the electronic noise as a function of the temperature for a reverse bias of 28 V (Fig. 3) shows that for a temperature of −30°C the value of the FWHM falls down to 2.57 keV, due to the decrease of the detector leakage current.

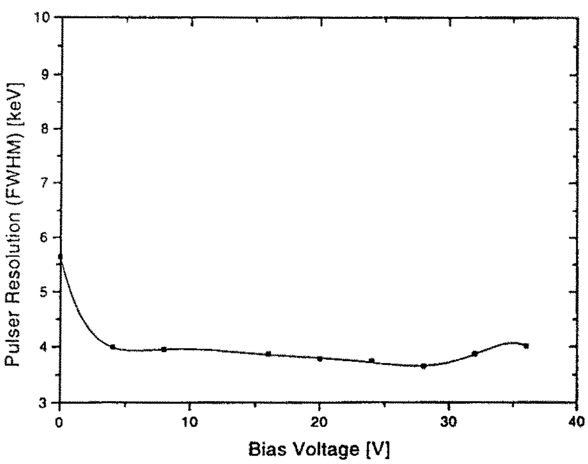

Fig. 2. Energy resolution (FWHM) of the pulse generator with the photodiode coupled to the preamplifier input as function of the bias voltage.

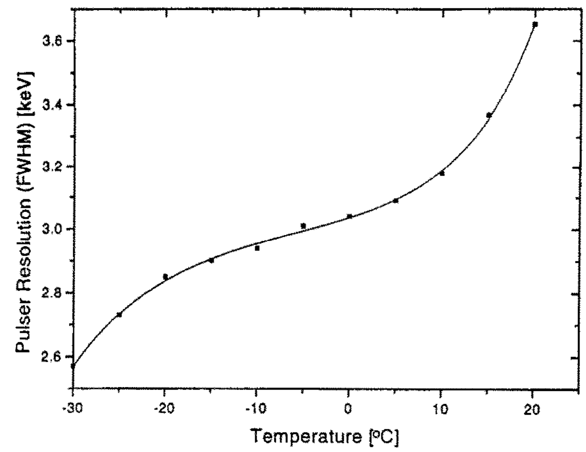

Fig. 3. Energy resolution (FWHM) of the pulse generator line, with the photodiode coupled to the preamplifier input, as function of the temperature. The bias voltage amounts to 28 V.

3. Obtained results

3.1. Alpha particles

A 5.55 kBq mixed nuclide alpha source of ^{239}Pu, ^{241}Am and ^{244}Cm deposited on a stainless disk was placed at 2.0 cm from the diode in a stainless steel vacuum chamber under a pressure of 10^{-5} mmHg. The relative efficiency of the diode for these alpha particles was measured as a function of the reverse bias voltage: the results show that the counting rate is practically independent of the polarization voltage. One can conclude, therefore, that the thickness of the depletion layer of the diode is large enough to absorb practically all the energy of the incoming alpha particles.

In order to evaluate the influence of the bias voltage on the photodiode energy resolution for alpha particles from ^{239}Pu, ^{241}Am and ^{244}Cm, several spectra were recorded. The experimental results show that, even at room temperature and without reverse bias, the alpha particles of the principal group of each isotope are clearly observed. The fine structure lines of each isotope cannot be inferred from those measurements – a fact which is due to the partial collection of the charges liberated in the depletion zone and to the fairly large capacity (72 pF) shown by the diode under those experimental conditions. Since an increase of the polarization voltage leads to a decrease of the diode capacitance and since this phenomenon is accompanied by an increasing value of the leakage current, one should expect that there is a value of the applied potential difference which corresponds to an optimum value of the relation between the signal and the noise and, therefore, to a better energy resolution of the detector. The best mixed alpha source spectrum recorded is represented in Fig. 4, under a bias of 28 V. An analysis of the intensity of the

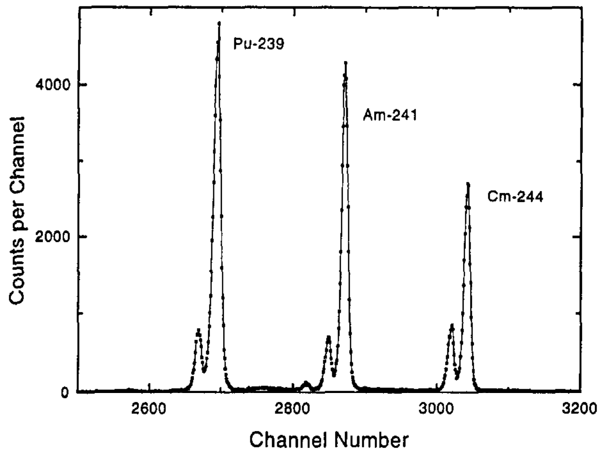

Fig. 4. Pulse height spectrum of ^{239}Pu, ^{241}Am and ^{244}Cm mixed source, recorded at a temperature of 20°C and a bias voltage of 28 V.

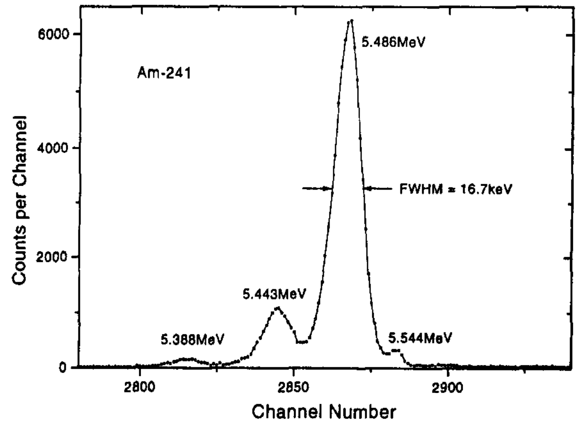

Fig. 5. Expanded view of the ^{241}Am spectrum.

alpha particles from ^{239}Pu, ^{241}Am and ^{244}Cm has shown that the observed values agree, within the experimental error, with the values quoted in the literature (Table 1). Fig. 5 shows an expanded view of the ^{241}Am spectrum where an energy resolution of 16.7 keV (FWHM) for the 5.486 MeV line was found.

One should expect that a further decrease of the energy resolution (FWHM) should be observed by lowering the photodiode temperature – what was accomplished by inserting a Peltier cell. Special care was taken both to avoid the formation of microscopic ice crystals on the diode surface (due to thin layers of adsorbed water on the chamber walls) as well as in the elimination of any high frequency noise that might be picked up from the DC source used in the Peltier cell. For that purpose, a special filter was built which eliminated all the noise, in the range from DC to about 10 GHz, of the DC source. Under these conditions, the energy resolutions measured for the 5.486 MeV α-particles did not show any improvement, although the total noise observed was reduced by a factor of 1.4. We believe, therefore, that the limitation in the energy resolution observed is due to the intrinsic characteristics of the radioactive source used and should be attributed to self-absorption, back-scattering and side scattering of the source, due to the 0.5 mm thickness of the stainless steel on which the active material was deposited.

It should be pointed out, however, that the observed resolution (FWHM = 16.7 keV), is better than those obtained with surface barrier detectors and is compatible with the results obtained with special photodiodes commonly used in alpha particles spectrometry [1,6]. In addition, it is noteworthy to mention that the edge effects encountered by some authors [1,2] which gave rise to "ghost" peaks in alpha spectra recorded with Hamamatsu (S1790-01) photodiodes are totally absent with the Siemens (SFH00206) devices even without collimation.

Table 1
Comparison of published alpha energies and branching ratios [12] with those measured in this work

Isotope	Alpha energy [keV]	I [%]	I [%] this work
^{244}Cm	5 804.96	76.4	76.8±0.7
	5 762.84	23.6	23.2±0.5
^{241}Am	5 544.25	0.34	0.5±0.2
	5 511.61	0.20	not resolved
	5 485.70	82.2	84.5±0.8
	5 443.01	12.8	12.5±0.3
	5 388.40	1.4	1.6±0.2
^{239}Pu	5 155.5	73.2	87.4±0.8
	5 142.8	15.1	
	5 104.7	10.6	12.6±0.3

3.2. Fission fragments

The energy spectrum of fission fragments from ^{252}Cf was measured with the detector using 36 V of polarization in order to warrant its saturation condition; the ^{252}Cf source was constituted by a very thin deposit on a stainless steel disk which was placed at 2.0 cm from the detector. Fig. 6 represents the experimental results and shows clearly the peaks corresponding to the heavy and light fragments.

An analysis of the parameters associated to this spectrum shows a good agreement with the known data reported previously for surface barrier detectors [7], except for the relations N_L/N_V between the maximum counting rate of the peak corresponding to the light fragments (N_L) and the minimum of the valley which distinguishes both the light and heavy fragments. The expected value for the ratio N_L/N_V is 2.9 whereas our value is 3.3; this dis-

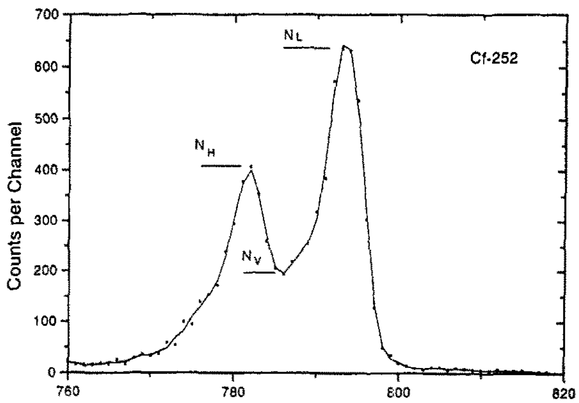

Fig. 6. Pulse height spectrum for ^{252}Cf spontaneous fission fragments. The bias voltage amounts to 36 V in order to warrant the photodiode saturation condition.

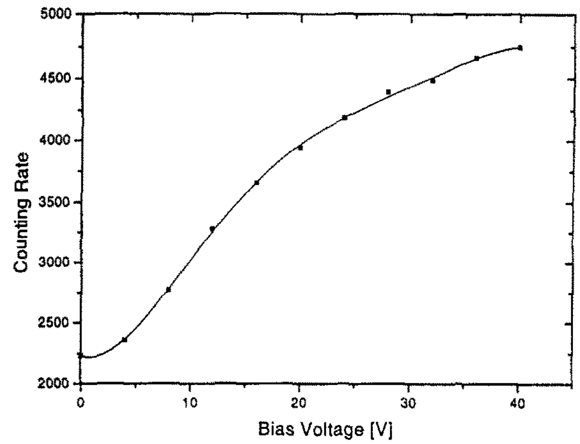

Fig. 7. The relative efficiency of the photodiode for internal conversion electrons as function of the polarization voltage.

crepancy is attributed to the difference in the stopping powers of the light and heavy fragments which traverse the dead layer of our diode. This fact is also confirmed by the value of 1.5 obtained for N_L/N_H (where N_H is the maximum counting corresponding to the peak of the heavy fragments) which is slightly larger than the expected value (1.3). All the other parameters coincide, within the experimental error, with the values quoted in the literature showing that the diodes we used can be utilized for fission fragment spectrometry provided that due attention is paid to the above observations. We made also several measurements with collimators of different diameters placed either on the detector or on the source and results obtained did not differ from those quoted above.

3.3. Internal conversion electrons

Although silicon photodiodes are being used mainly in the spectrometry of heavy particles their application as detectors of low energy electrons has increased in the last years [8–11] due to the simplicity of their use, associated with the fairly good resolution in energy. An important characteristic of these diodes is the low value of the back-scattering of electrons in the sensitive volume of the silicon photodiode (as compared with Ge), which is the main factor responsible for the reduction of the distortions observed in both the beta spectra and in the detection of low energy electrons.

The response of the photodiode for the detection of internal conversion electrons was studied by using a thin open source of ^{133}Ba. The change in the relative efficiency of the photodiode as a function of the polarization voltage was measured and the observed results (Fig. 7) show that the counting rate increases with the applied voltage, as one would expect, as a consequence of the increase of the thickness of the depletion layer of the diode.

A pulse height spectrum for ^{133}Ba internal conversion electrons was obtained with the diode using a bias of 28 V, the gain of the amplifier was increased due to the change in amplitude of the electron pulses which is obviously smaller than those due to alpha particles. The obtained spectrum (Figs. 8 and 9) shows clearly the lines corresponding to the electrons of 17.18, 25.80, 45.01 (FWHM = 4.5 keV), 75.28, 124.63, 154.90, 187.25, 240.41, 266.87 (FWHM = 4.6 keV), 320.32 and 347.87 keV energy. Since electrons of 300 keV have a range of 300 μm in silicon, one can observed that, in this energy region, the detector efficiency for the total absorption of energy is low, due to the small thickness of the depletion layer of the diode. In fact, the broadening of the electron lines is partly due both to the energy loss in the diode dead layer and to the backscattered electrons leaving the photodiode without fully depositing their energy. Nevertheless, the energy resolutions measured are sufficiently good to justify their use in the spectrometry of internal conversion electrons.

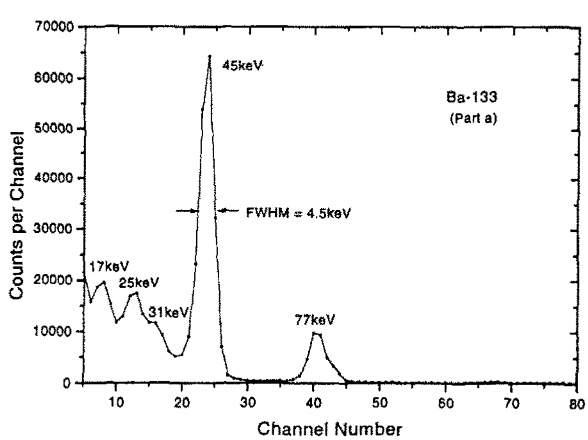

Fig. 8. ^{133}Ba conversion electron spectrum (part a).

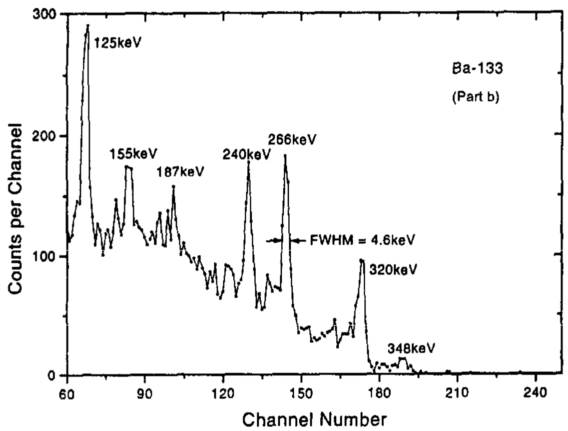

Fig. 9. ^{133}Ba conversion electron spectrum (part b).

3.4. X-rays

The response of the photodiode for the detection and spectrometry of low energy gamma rays and X-rays were determined through the use of ^{133}Ba and ^{241}Am sources. The experimental results obtained with a reverse voltage of 28 V are depicted in Fig. 8, which shows the X-rays of 30.63, 30.97 (unresolved) and 80.99 keV gamma rays (not distinguished from 75.98 and 80.98 keV internal conversion electrons). The pulse height spectrum for ^{241}Am was also obtained (Fig. 10) and the full-energy peak width of 4.0 keV was recorded for 59.5 keV photons. The full energy intrinsic efficiency decreases rapidly above 60 keV, but these photodiodes exhibit useful efficiency below this photon energy. Since in this energy region the largest contribution for the resolution is due to the preamplifier electronic noise, a new hybrid preamplifier is being designed, which will enclose the direct coupling of the photodiode and the simultaneous cooling of the system.

4. Conclusions

The low cost (about U$1.00) commercial photodiode SFH00206 described in this paper can be used with success both for the detection and spectrometry of charged particles such as electrons, alpha particles and fission fragments. The obtained results show that they present a low cost and very precise tool which can substitute advantageously surface barrier detectors frequently used for the spectrometry of these radiations.

Their small size and very good characteristics as detectors, even if inexpensive preamplifier was employed, make them very suitable for building large arrays of detectors.

The results obtained, described in this paper, show that the photodiodes can be used for neutron detection through (n, α), (n, p) and (n, f) processes by the use of the usual converters such as boron 10, fissile uranium nuclei, etc.

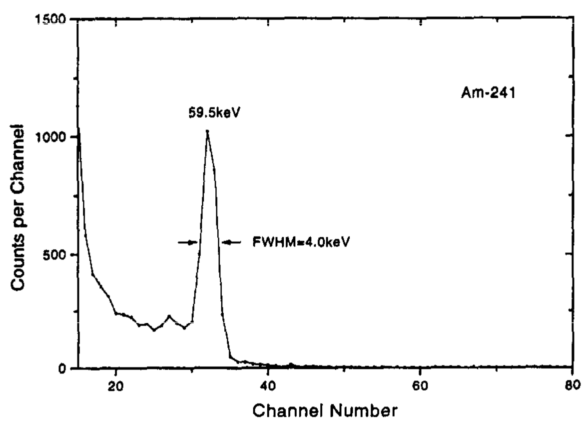

Fig. 10. Energy spectrum of ^{241}Am 59.55 keV γ line.

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