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Response of a rad-hard silicon diode for charged particles

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Abstract

In this paper, we describe the preliminary results about the response of an ion-implanted diode (Al/p^+/n/n^+/Al), developed in the framework of R&D programs for the future CMS experiment at Large Hadron Collider (LHC), for detection and spectrometry of alpha particles, internal conversion electrons and minimum ionizing particles (MIPs) envisaging its application to isotopic analysis of heavy elements. The effects of reverse bias voltage on capacitance and leakage current of the diode, as well as on its energy resolution, were also studied at room temperature. In spite of having a thick (650 nm) frontal layer of SiO_2, responsible for an important straggling in the energy of the incident heavy charged particles, the results demonstrate that the diode under investigation has good performance for alpha spectrometry (FWHM = 18.8 keV for 5.486 MeV alpha particles from ^{241}Am), comparable to those obtained with ordinary surface barrier detectors. Furthermore, internal conversion electrons with energies up to approximately 350 keV could be detected with a reasonable good energy resolution (FWHM = 6.6 keV for 320.32 keV electrons from ^{133}Ba).

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Keywords: Alpha spectrometry; Internal conversion electrons spectrometry; Silicon detectors

1. Introduction

Although the development of semiconductor detectors has been driven by elementary particle and nuclear physics, their use in other branches of science has increased in the last decades [1–9].

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However, since radiation damage of silicon detectors imposes constraints on their wider applicability, there has been a great effort to improve the radiation tolerance of silicon devices [10–17]. The detector under investigation is an ion-implanted diode, developed in the framework of R&D programs for the future CMS experiment at Large Hadron Collider (LHC), which bears excellent timing properties and high radiation hardness that fulfill the requirements from this accelerator environment. These characteristics encouraged us to study the response of this diode (since now referred as CERN diode) for alpha and internal conversion electrons spectrometry, envisaging its application to isotopic analysis of heavy elements as described by DeVol et al. [18].

In this paper, we report preliminary results obtained with the CERN diode for detection and spectrometry of alpha particles, internal conversion electrons, minimum ionizing particles (MIPs) and low-energy electromagnetic radiation. The effects of reverse bias voltage on capacitance and leakage current of the diode, as well as on its energy resolution, were also studied at room temperature.

2. Experimental arrangements

The diode used in this work, with an active area of 2.5 mm^2, was an Al/p$^+$/n/n$^+$/Al implanted silicon detector processed out of 300 μm thick float-zone substrates with a resistivity of about 3.0 kΩ cm [19]. The thickness of Al (maximum 2 nm) and SiO_2 (650 nm) front layers of the diode were measured by the Rutherford Backscattering Spectrometry (RBS) technique at the Laboratory of Material Analyses by Ion Beams (LAMFI) of São Paulo University. 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 rings connections.

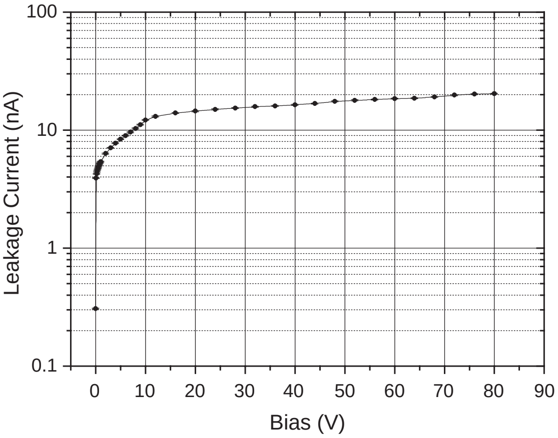

Fig. 1. Leakage current of the diode as a function of bias voltage.

The current–voltage characteristics of the detector were measured with a Semiconductor Parameters Analyzer (HP4156C) adjusted to a maximum current of 1 mA. The results obtained, presented in Fig. 1, showed a typical diode behavior with leakage currents increasing from 0.3 to 20 nA at a voltage range between 0 and 80 V. The dynamic diode capacitances, measured at a frequency of 1 MHz by means of a computer-based Capacitance Measurements System (Keithley K182CV), decrease with the polarization bias as a result of the depletion layer growth. However, as can be seen from Fig. 2, the bend at the depletion voltage does not appear as sharp as it used to be in certain diodes. This behavior is justified by the fact that the exponent 2 in capacitance is not exact for all types of diodes, but, on contrary, it strongly depends both on their construction and junction characteristics. Besides this, the software used in the Capacitance Measurement System (Keithley K182CV) is optimized to a simple junction, what it is not our configuration. Taking into account the inflexion point of the $1/C^2$ vs V curve, we observe that for voltages above 40 V the capacitance of the diode does not increase significantly; as a consequence, the same behavior is expected for the diode's depletion thickness.

In order to use this diode as a detector, the guard rings were grounded, while the bias voltage was applied on the n$^+$ side. The signal from the detector was readout from the p$^+$ side by means of a DC coupled field effect transistor (FET) in the first stage of a tailor made charge sensitive preamplifier based on the hybrid circuit A250 (Amptek) [20]. This circuit, originally projected

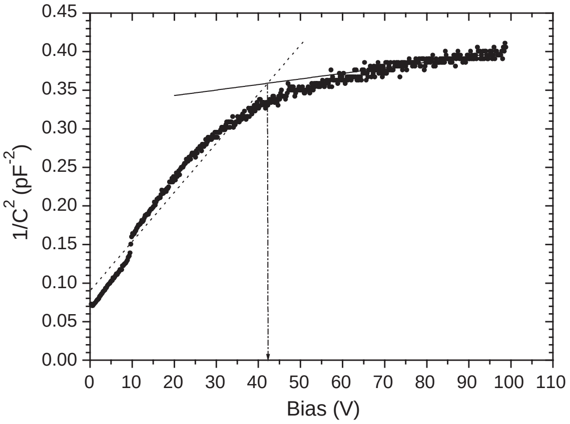

Fig. 2. Capacitance of the diode as a function of bias voltage.

for low energy X-rays, was modified (in terms of its feedback loop) to match the characteristic of higher charge per pulse associated with charged particles. The distance between the diode and the FET was kept as short as possible to minimize the noise contribution originated from parasitic capacitances and both were operated at room temperature. The diode and pre-amplifier assembly was housed in a stainless steel chamber under a pressure of 10^{-6} Torr. The pulses from the pre-amplifier were shaped and amplified by a linear amplifier (ORTEC 572) with adjustable shaping time constant and fed to a multichannel analyzer (ORTEC Spectrum Ace).

3. Results

3.1. Alpha particles

The effect of the applied voltage on the diode detection efficiency and energy resolution capabilities for alpha particles was investigated at different experimental conditions. Measurements of the diode efficiency for alpha particles as a function of the reverse bias, carried out with an ^{241}Am radioactive source, showed that this parameter is constant (100%) regardless of the polarization voltage. As the range of these alpha particles in silicon is about 30 μm, they are fully stopped near the slice front surface (p$^+$) where the electric signal is taken. Therefore, the charge generated is collected, at least partially, even when the diode is unbiased.

In order to evaluate the influence of the bias voltage, shaping time constants and diode–source distance on the alpha energy resolution, several spectra from a mixed source of ^{239}Pu, ^{241}Am and ^{244}Cm were recorded at room temperature. The results showed that, even without bias voltage, it was possible to identify the main alpha group from each isotope although with a poor energy resolution due to both the electron–hole recombination and the diode capacitance. The effect of the reverse bias on the energy resolution measured for the 5.486 MeV alpha particles from ^{241}Am was investigated and presented in Fig. 3. Since an increase of the applied voltage lessens the diode capacitance and, conversely, heightens the leakage current, one should expect that there is one bias voltage value related to a maximum signal to noise ratio and, therefore, better energy resolution. Indeed, from Fig. 3, with the radioactive source placed at 2.0 cm from the diode, the best energy resolution was achieved at 60 V and 1 μs time constant. It is worth noting that the energy loss of about 93 keV for 5.486 MeV alpha particles in 650 nm of SiO$_2$ is one important contribution to the worsening of the spectrometric response of the diode.

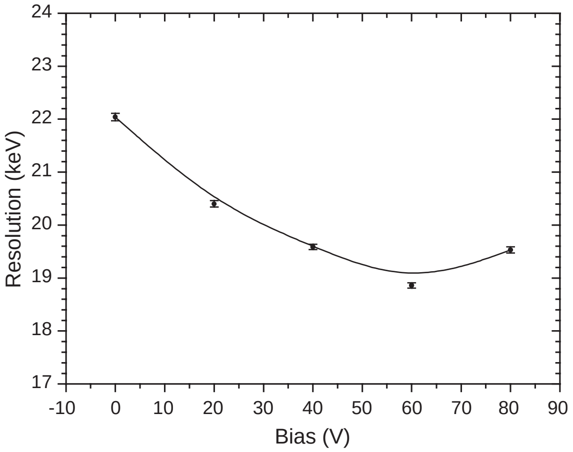

Fig. 3. Energy resolution for the 5.486 MeV alpha particles from ^{241}Am as a function of bias voltage. Source placed at 2.0 cm from the diode and 1 μs shaping time constant.

To investigate the energy resolution dependence on shaping time constants and source–diode distance, some alpha spectra were recorded at the same bias voltage (60 V). The results obtained, represented in Fig. 4, showed that the energy resolutions are improved when the source is placed far away from the detector inasmuch as only alpha particles with normal incidence on the diode are registered. The best alpha spectrum, recorded at 60 V, 1 μs time constant and radioactive source far 2.0 cm from the diode, is showed in Fig. 5, where the fine structure lines of each isotope can be evidenced. The intensity of the alpha particles studied agree, within the experimental error, with the values quoted in the literature [21], as can be seen from Table 1.

In spite of the good energy resolution (FWHM = 18.8 keV for 5.486 MeV alpha particles from ^{241}Am), the CERN diode gave rise to some satellite peaks (SP), developed at somewhat lower energies than the main peaks in the spectrum. Since all pulse-height distributions were recorded without any diode collimation, the origin of these satellite peaks is thought to be due not only to incomplete charge collection in weak electric field region around the guard rings, but also with changes on the entrance window absorption near the edge of the diode. This opinion is based on the fact that our previous results [22] obtained with a commercial PIN photodiode devoid of any guard ring (Siemens SFH00206 K) evidenced that the satellite peaks were totally absent, even without the use of collimators. To clear up this problem some measurements are under way.

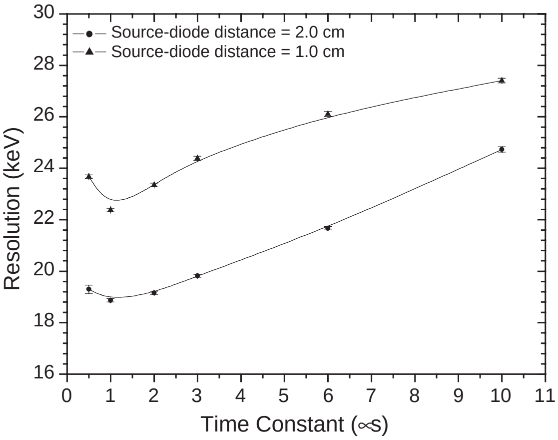

Fig. 4. Energy resolution for the 5.486 MeV alpha particles from ^{241}Am as a function of time constant for different source–diode distances. $V = 60$ V.

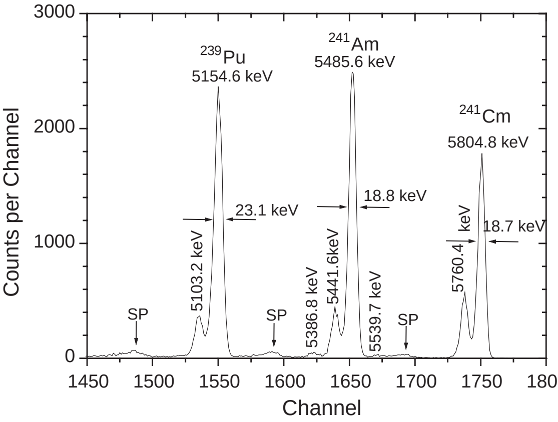

Fig. 5. Alpha particle spectrum recorded at room temperature with the source placed at 2.0 cm from the diode ($V = 60$ V; 1 μs time constant; ADC gain = 8196). Satellite peaks (SP) are evidenced.

3.2. Internal conversion electrons

The diode response for internal conversion electrons was studied by using ^{57}Co and ^{133}Ba radioactive sources, both of them deposited on a 0.4 mm thick polyethylene disk and covered with a thin (about 2 μm) makrofol foil. Many pulse height spectra were recorded to study the effect of the bias voltage, shaping time constant and source–diode distance on the energy resolution. Fig. 6 displays the best result obtained with a ^{57}Co source placed at 2.0 cm from the diode, polarized at 80 V and 2 μs time constant. The pulse height distribution of ^{57}Co shows clearly the peaks related to electrons of 114.95 and 129.36 keV (FWHM = 4.6 keV). Besides the electronic noise, the broadening of the electron lines was probably due to the energy losses in both the makrofol foil and the Al/SiO$_2$ front layers of the diode. Since the mechanism for the electron–hole pair production is the same for photons and electrons, it was possible to estimate these electron energy losses through an energy calibration curve obtained with X- and γ-rays from ^{241}Am, ^{133}Ba and ^{57}Co sources. The energies of these radiations

Table 1
Comparison of published alpha energies and branching ratios [21] with those measured in this work

Isotope	Alpha energy (keV)	*I* (%)	Alpha energy (keV) this work	*I* (%) this work
^{244}Cm	5762.70 (3)	23.60 (20)	5760 (2)	24.64 (44)
	5804.82 (5)	76.40 (20)	5805 (8)	75.36 (92)
^{241}Am	5388.23 (13)	1.60 (20)	5387 (8)	2.36 (11)
	5442.80 (13)	13.23 (60)	5442 (2)	14.39 (28)
	5485.56 (12)	84.50 (10)	5486 (8)	82.27 (83)
	5511.47 (13)	0.22 (3)	Not resolved	—
	5544.50 (16)	0.34 (5)	5540 (5)	0.98 (7)
^{239}Pu	5105.50 (80)	11.50 (80)	5103 (4)	13.56 (27)
	5144.30 (80)	15.10 (80)	Not resolved	—
	5156.59 (14)	73.30 (80)	5155 (9)	86.44 (86)

The number in brackets defines the uncertainty in the last digit given in the value.

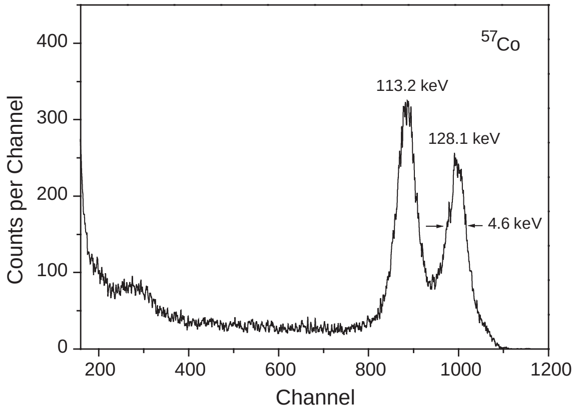

Fig. 6. Energy spectrum of internal conversion electrons from ^{57}Co recorded at room temperature. Source is placed 2.0 cm from the diode ($V = 80$ V; 2 μs time constant; ADC gain = 8196).

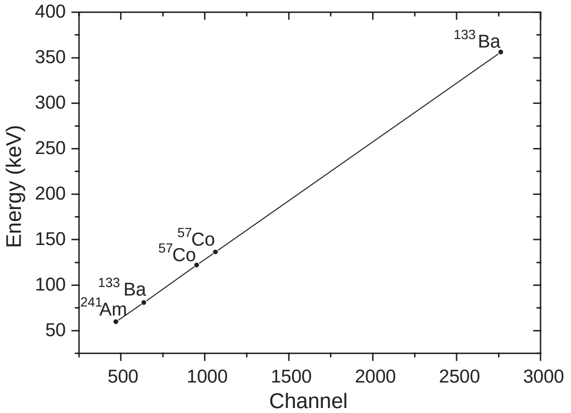

Fig. 7. **C**alibration curve obtained with X- and γ-rays from ^{241}Am, ^{133}Ba and ^{57}Co sources ($V = 80$ V; 2 μs time constant; ADC gain = 8196).

plotted against their pulse height guided to the straight line presented in Fig. 7, from what it was possible to determine the energy deposited by the electrons on the diode depletion region. The results obtained showed that the pulse amplitudes for the incident electrons of 114.95 and 129.36 keV correspond to photon energies of 113.19 and 128.06 keV, respectively. These values agree, within the experimental error, with the deposited energy estimated (113.57 and 128.07 keV) from the data of stopping power of electrons [23] took into account the energy losses in the makrofol covering of the source and in the SiO_2 layer.

At the same experimental conditions, further measurements were carried out with a ^{133}Ba radioactive source. The best energy spectrum is displayed in Fig. 8, hereby the lines corresponding to the electrons of 124.63, 154.90, 187.25, 240.41, 266.87, 320.32 (FWHM = 6.6 keV) and 347.87 keV energy are showed. Nevertheless, peaks corresponding to low energy electrons (17.18, 25.80 and 45.01 keV) are hardly identified as they are superposed to both electronic noise and a significant higher energy electrons backscattering tail. On the other hand, electrons of 75.98 and 80.98 keV were undistinguished and detected at

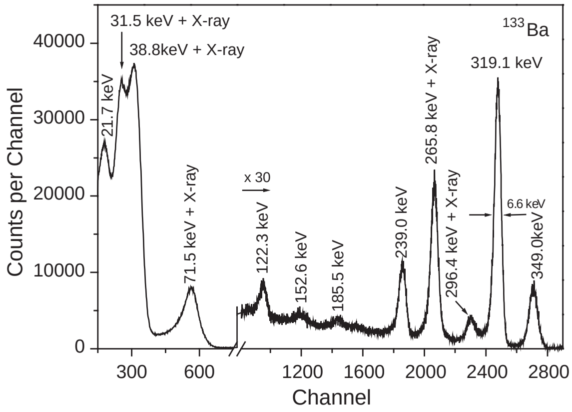

Fig. 8. Pulse height distribution of internal conversion electrons from ^{133}Ba. Source far 2.0 cm from the diode. Spectrum recorded at room temperature ($V = 80$ V; 2 μs time constant; ADC gain = 8196).

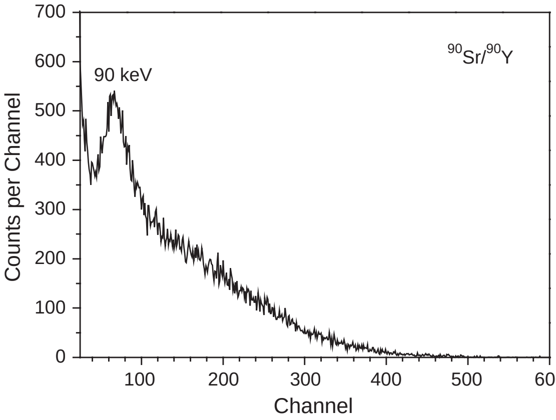

Fig. 9. Pulse height distribution of minimum ionizing particles from a collimated ^{90}Sr/^{90}Y source covered with 630.0 mg/cm^2 Al absorber. Spectrum recorded at room temperature ($V = 80$ V; 2 μs time constant; ADC gain = 1024).

the same peak with a poor energy resolution. Despite the complexity of the ^{133}Ba disintegration scheme, it was possible to identify the peaks energies deposited in the depletion region by the calibration curve presented in Fig. 7. Although the electron energy losses in both makrofol foil and SiO_2 layer were small, they contributed to the worsening of the energy resolutions that can be achieved with this diode.

3.3. Minimum ionizing particles (MIPs)

The response of the CERN diode to MIPs was investigated using a ^{90}Sr/^{90}Y radioactive source whose spectrum of high–energy electrons from ^{90}Y was enriched by an Al absorber of 630 mg/cm^2 density. The emergent beam was collimated by a Pb collimator with a diameter of 1 mm. Pulse height distributions of these electrons were recorded with the diode biased at 40 and 80 V and time constant of 2 μs. The spectra obtained showed asymmetric peaks, corresponding to the minimum ionizing particles, followed by a continuous distribution due to beta particles with lower energies than those of MIPs. The comparison of these spectra, whose shape can be described by the Landau function, evidenced that the position of the MIP peak does not change significantly. Indeed, Fig. 9 displays the results obtained with the diode polarized with 80 V where a MIP's peak was found (by the gamma and X-rays calibration curve with the same ADC gain) to correspond an energy loss of 90 keV, what is higher than the expected energy loss (80 keV) of minimum ionizing particles in 300 μm of silicon, using an approximation of the Landau theory, in the limit of thin absorbers [24]. This discrepancy could be attributed to the fact that our source does not deliver a pure MIP spectrum.

4. Conclusion

The results presented in this paper demonstrate that the diode under investigation has good performance for charged particles spectrometry. In spite of having a thick frontal layer of SiO_2, responsible for an important straggling in the energy of the incident heavy charged particles, it was possible to achieve energy resolutions comparable to those obtained with ordinary surface barrier detectors. However, since this diode was used without any collimation, satellite peaks are believed to be an edge effect. Furthermore, internal conversion electrons with energies up to approximately 350 keV could be detected with a reasonable good energy resolution (FWHM = 6.6 keV for 320.32 keV electrons from ^{133}Ba).

On the other hand, it remains to be investigated whether these results can be optimized through reducing the temperature of both the diode and the first stage of the preamplifier by means of a cold finger, using diode or/and source collimators and trying other solutions in order to improve the diode's response. Work in this direction is currently in progress.

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