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Silicon drift photodetector arrays for the HICAM gamma camera

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ABSTRACT

Silicon drift detectors (SDDs) have shown to be a competitive device for the readout of scintillators with respect to conventional photodetectors, thanks to their high quantum efficiency and low electronics noise. Recently, they have been successfully employed in first small prototypes of Anger cameras to achieve sub-millimeter spatial resolution in gamma-ray imaging. To cover larger formats of Anger cameras, in particular in the framework of the HICAM project, specially focused on human imaging, we have developed new SDD arrays of larger active areas. To assemble photodetector planes of several cm^2, we have designed a basic unit composed by a linear array of 5 SDDs of 1 cm^2 active area each. In this work, we present the results of the experimental characterization of these photodetector arrays in direct X-ray detection to evaluate the electronics noise, as well as gamma-ray detection with a scintillator.

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1. Introduction

The interest in using silicon drift detectors (SDDs) as photodetectors to readout scintillators for different applications (γ-ray astronomy, medical imaging, nuclear monitoring) has recently grown. SDDs show high quantum efficiency and a low intrinsic electronics noise without the need of multiplication, as in PMTs and APDs, therefore avoiding the associated statistical spread of the gain and the sensitivity to temperature and bias shifts. An Anger camera based on SDDs represents a gamma-ray imaging device with several potentialities in the fields of medical imaging and astrophysics. With respect to pixellated gamma-ray detectors, this architecture allows one to obtain a spatial resolution much smaller than the pixel size, roughly one order of magnitude or, for a given spatial resolution, allows a significant reduction of the number of readout channels. A first small prototype of an SDD-based Anger camera has allowed one to obtain an intrinsic spatial resolution of less than 200 μm [1]. Recently, we have developed the DRAGO camera [2], which is a high-resolution Anger camera based on a monolithic array of 77 SDDs, with an active area of 6.7 cm^2, coupled to a 5 mm thick CsI(Tl) scintillator crystal. This camera has shown to reach a spatial resolution between 0.25 and 0.5 mm. $LaBr_3$ scintillators have been also tested as candidate crystals for this kind of cameras with excellent energy resolution [3].

According to the achieved results, we are developing a new Anger camera, in the framework of the HIgh resolution CAMera (HICAM) project [4], supported by the European Community, composed by 100 SDDs of 1 cm^2 each in a 10×10 cm^2 format. This camera is foreseen to be employed in applications in medical imaging where high position resolution and camera compactness are of primary concern. The camera has a modular structure, based on monolithic arrays of five SDDs, cooled by Peltier elements. Each array is placed on a custom designed board and properly connected to an electronics backplane where the detector biasing electronics and the readout ASICs are placed. The system is completed by a data acquisition system and by a suitable mechanical translation arm.

This work reports specifically on the design of the arrays of SDDs photodetectors, the basic sensitive devices of the gamma camera. The design has been carried out on the basis of either required performances, such as electronics noise, quantum efficiency, drift time, and system considerations, such as working temperature, suitable photodetector geometry and others. Taking into account all these constraints, and the need to cover a large photodetector plane with minimal dead area, we have designed a basic chip composed by a linear array of 5 SDDs of 1 cm^2 active area each.

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In this paper, we describe the SDD photodetector array and we present the results of its experimental characterization in direct X-ray detection to evaluate the electronics noise and also in gamma-ray detection with SDD unit coupled to a scintillator.

2. The design of the SDD photodetector array

To cover the large photo-sensitive area of the HICAM camera, arrays of SDDs of large active areas have been designed. The active area of the single SDD unit of the array has been chosen as the best compromise for the sampling of the scintillation flash emitted in occurrence of the gamma-ray interaction in the scintillator crystal, the level of electronics noise necessary to reach the desired performances in the measurement of this scintillation light and other constraints. The electronics noise, in particular, turns out to depend on parameters such as the leakage current at room temperature expected with the production process, the desired working temperature of the photodetector and the choice of the scintillator. A working temperature warmer than $-10\,^{\circ}\mathrm{C}$ would be desirable to keep the power consumption and the related heat transfer by the Peltier reasonably low. The effect of the scintillator decay time on the electronics noise may be calculated according to the following formula:

$$\mathrm{ENC}_{\mathrm{effective}} = \mathrm{ENC}/(1-B_{\mathrm{deficit}})$$

where ENC is the electronics noise, B_{deficit} is the relative reduction (from 0 to 1) of the pulse amplitude due to the ballistic deficit. The amplitude reduction is due to the processing by the preamplifier and filter of a detector current signal characterized by an exponential decay shape instead of the ideal δ-like shape. The formula derives directly from the definition of ENC: to achieve an output signal-to-noise ratio equal to one, a larger input charge ($\mathrm{ENC}_{\mathrm{effective}}$) has to be applied to match a reduced signal amplitude due to the ballistic deficit. Two scintillators have been considered: CsI(Tl) and $LaBr_3$(Ce). CsI(Tl), due to its main scintillation time constant (1 μs), imposes the choice of a long shaping time to reduce the ballistic deficit, thus forcing the photodetector to operate in a shaping time range where the parallel noise due to the leakage current is the dominant contribution. On the other side, CsI(Tl) is not hygroscopic, providing some assembly advantages of the camera. Moreover, the light response of the silicon photodetector can be optimized to well match the emission spectrum of the crystal (wavelength of peak emission at 565 nm). On the contrary, ballistic deficit is not an issue with $LaBr_3$ having a scintillation decay time of 20 ns. Its light output is similar to CsI(Tl), about 60–65 photons/keV. However, this crystal requires to be sealed and its wavelength range of emission (360–380 nm) makes more critical the matching of the silicon photodetector response. We have chosen a required level of electronics noise (effective, according to the previous definition) of $30e^-$ rms to achieve about 1 mm spatial resolution with the HICAM camera. We have calculated that this noise level can be achieved with a 1 cm^2 SDD with an operating temperature of $-10\,^{\circ}\mathrm{C}$ in perspective of a leakage current resulting in about 0.3 and 1nA/cm^2 at room temperature. In the two cases, we consider to use CsI(Tl) and $LaBr_3$ crystals, respectively. foresees the use of a peaking time of 8 and 3 μs, respectively, for the two scintillators.

The ballistic deficit can be in principle influenced also by the drift time of the charge inside the SDD. We have simulated that in the designed 1 cm^2 SDD, a drift time lower than 1 μs can be obtained, not significantly affecting the conclusions regarding the electronics noise reported above for both CsI(Tl) and $LaBr_3$ scintillators.

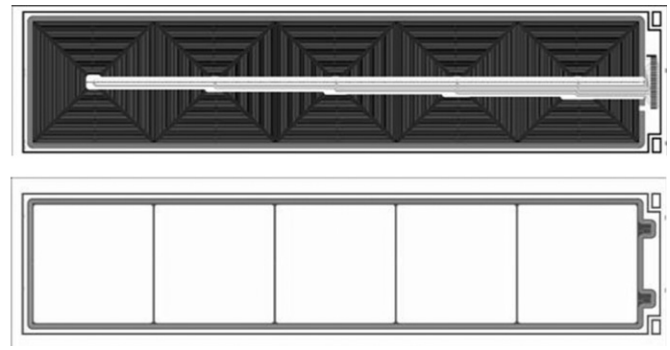

Fig. 1. Layout of the array of SDDs. On the lower section, the side where the scintillator is read out is shown while on the upper side the detector side with the drift rings and the on-chip JFET is shown.

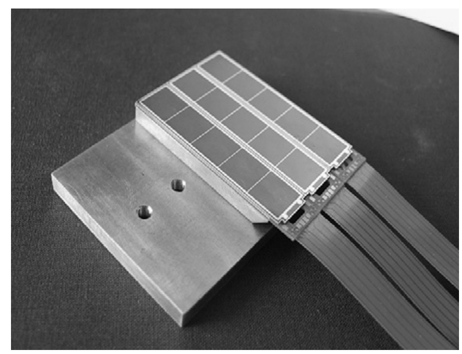

Fig. 2. Photograph of the assembly of 3 monolithic arrays of SDDs.

Anti-reflective coatings (ARCs) have been designed in order to keep an efficiency higher than 80% in the range between 360 nm ($LaBr_3$) and 550 nm (CsI(Tl)), as a compromise solution to read out both scintillators.

In view of the assembly of a 10×10 cm^2 photodetector array for the HICAM camera, we have chosen a design of monolithic arrays of 5 SDDs of 1 cm^2 each. This turned out to be an intermediate solution between a fully monolithic array, which poses severe yield requirements, and an array of single 1 cm^2 SDDs, which implies a more complicated packaging. The layout of the array is shown in Fig. 1. Each unit includes an input JFET integrated in the detector itself. The signal and bias lines from all 5 units are grouped in the central region of the array and are externally accessible with bonding pads placed at one side of the layout (on the right in Fig. 1).

Each array is packaged in a single module with a rigid-flex PCB. The rigid part is used for mechanical handling and for heat transfer to a copper holder. The flex part is used to transfer signal and bias lines to the external electronics board. A set of five modules is assembled on a common copper carrier, which is then cooled by a Peltier element. A photograph of three SDD arrays mounted on the carrier is shown in Fig. 2.

3. Experimental results

We have made a first experimental characterization of single SDDs of the arrays to find the optimum common bias point. This is mandatory to have all SDDs operating with the smallest number of bias voltages. In order to operate all SDDs with good performances in terms of electronics noise and charge collection, the voltage to the back electrode is common for the five SDDs of a single chip (but different from chip to chip) and voltages for the first drift ring are all independent. The need to apply independent voltages for the first ring is imposed by the fact that a specific voltage to this electrode allows one to optimize the signal charge collection of the specific SDD. To achieve a good collection of the charge for all five SDDs in a single array, the first ring voltages may need to be set in a range from −25 to −7 V. All other voltages can be common to all SDDs and all chips.

Thanks to a successful technological processing of the photodetectors, a single device is characterized by a very low level of leakage current, between 100 and 200 pA/cm^2 for all SDDs. For radiation measurements, a pulsed-reset charge preamplifier has been adopted. The pulsed reset regime allows to keep at the minimum the parallel noise contribution, which would be twice as high in noise spectra density if using a continuous reset through the JFET electrodes.

To asses the achievable electronics noise, a single SDD of one monolithic array has been irradiated with a Fe^{55} source and spectroscopy measurements have been carried out at different temperatures and shaping times with conventional electronics (Tennelec TC244 shaping amplifier). The best spectrum of the Fe^{55} source measured at −20 °C is shown in Fig. 3. The satisfactory electronics noise obtained also with moderate cooling makes this device very promising in view of its implementation in the gamma camera. Spectroscopy measurements carried out on the other units of the same array have shown similar results.

A custom designed 25-channel ASIC is dedicated to read out 5 arrays of SDDs [5]. The ASIC implements all analog electronics necessary for the proper preamplification, filtering, multiplexing and buffering of the signals read from the photodetectors. The ASIC is able to process the signals at different peaking times. The spectra of a Fe^{55} source irradiating a module composed of 5 SDD chips (25 SDD units) is reported in Fig. 4 with respect to a photodetector map. The detector is cooled down to −10 °C. The adopted peaking time in this measurement is 5.5 μs. All 25 units provide homogenous spectra, as confirmation of the validity of the biasing procedure explained at the beginning of this section. The average energy resolution at 6 keV is 179 eV FWHM, with minimum and maximum values of 167 and 197 eV FWHM, respectively. The plot of the electronics noise calculated from the spectroscopy measurements taken at four different peaking times is plotted in Fig. 5. The electronics noise, even at the longest available peaking time, is well below the specified value of 30e$^-$ taken as reference in the design of the HICAM camera.

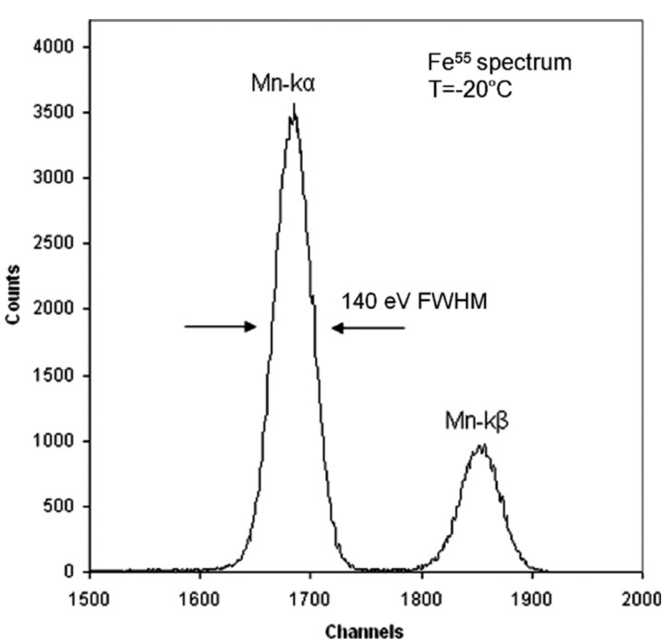

Fig. 3. Energy spectrum of a Fe^{55} source measured at −20 °C and a shaping time of 2 μs.

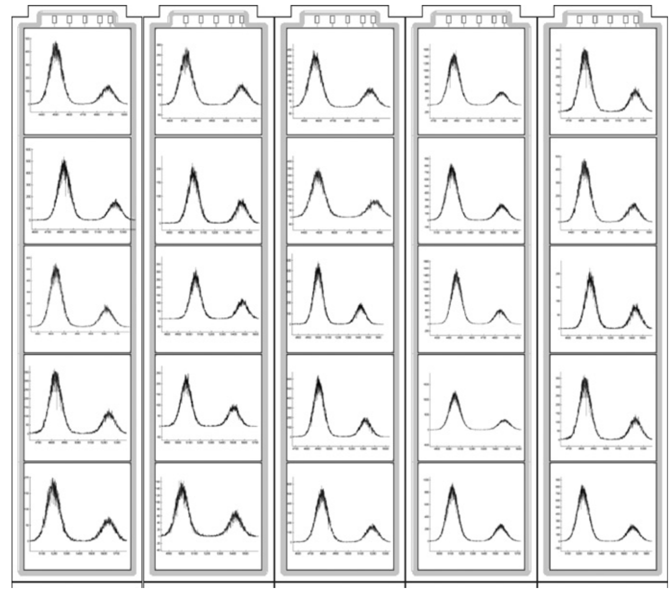

Fig. 4. Energy spectrum of a Fe^{55} source measured at −10 °C and with a peaking time of 5.5 μs.

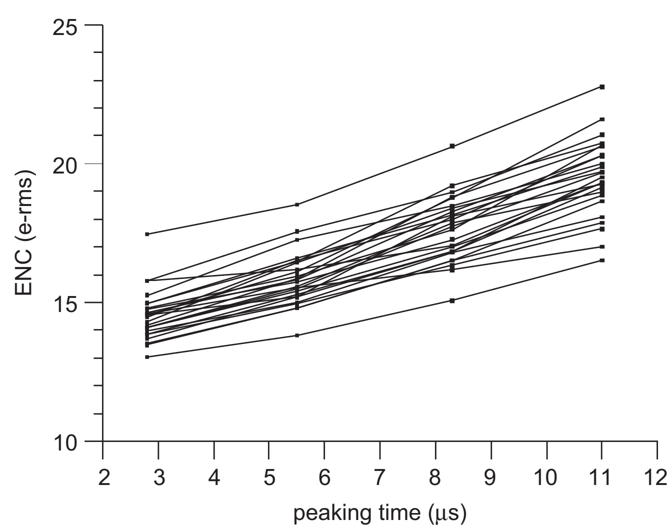

Fig. 5. Electronics noise measured for the 25 SDDs at −10 °C and at different peaking times provided by the ASIC.

As a preliminary test of one single unit (1 cm^2) SDD with a scintillator, a Co^{57} spectrum has been measured by coupling the SDD to a cylindrical CsI(Tl) scintillator with 8 mm diameter and 10 mm of thickness. The measurements have been carried out at +15 °C. The energy spectrum is reported in Fig. 6. A shaping time of 12 μs has been adopted in this measurement (using the TC244 shaping amplifier). The CsI crystal has been wrapped with a Millipore paper and coupled to the SDD by means of an optical grease. An energy-to-charge conversion factor of 53e$^-$/keV has been obtained in the measurements at the mentioned temperature and shaping time. Considering an estimated value of the emitted photons of 65 ph/keV, the result of the measurement corresponds to about 80% of conversion of the

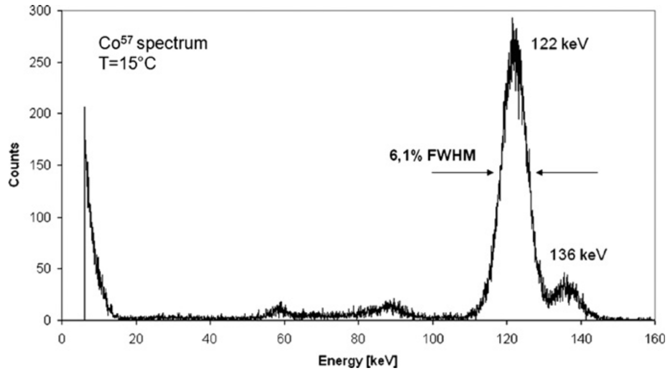

Fig. 6. Energy spectrum of a Co^{57} source measured at +15 °C with a 10 mm thick CsI(Tl) scintillator coupled to the SDD unit. The shaping time of the measurement is 12 μs.

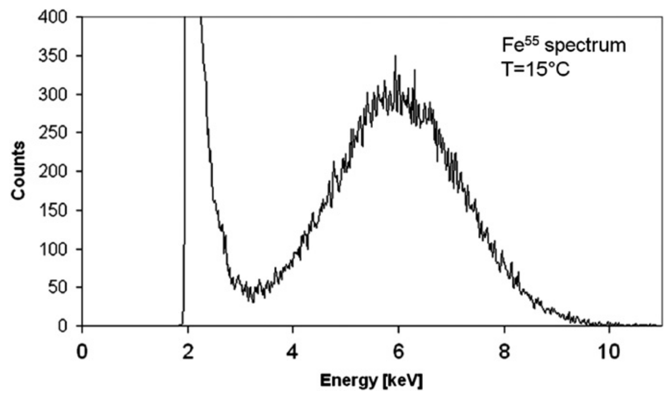

Fig. 7. Energy spectrum of a Fe^{55} source measured at +15 °C with the CsI(Tl) scintillator coupled to the SDD unit. The shaping time of the measurement is 2 μs.

photons into electrons. The energy resolution at 122 keV is 6.1% FWHM, among the best measurements with CsI(Tl) at this energy.

To evaluate the low energy threshold detectable with this configuration, we made also a measurement with the Fe^{55} (now detected with the scintillator-SDD detector). The spectrum is reported in Fig. 7. The shaping time here adopted was 2 μs. It can be seen that the 5.9 keV peak can be well distinguished from the noise. This is a quite remarkable result with a scintillation detector kept close to room temperature.

4. Conclusions

SDDs arrays have been designed for the $10 \times 10\,cm^2$ Anger camera under development in the framework of the HICAM project. The $1 \times 5\,cm^2$ SDD basic module shows already excellent performance in terms of low noise and high quantum efficiency and therefore appears suitable as the basic photodetector element for the camera. 5 modules have been already assembled to realize a first test prototype of the gamma camera and show a satisfactory electronics noise and homogeneity of performances.

Acknowledgment

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