A monolithic array of silicon drift detectors coupled to a single scintillator for γ-ray imaging with sub-millimeter position resolution

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Abstract

In this work, we present a monolithic array of 19 silicon drift detectors (SDDs) used as photodetectors of the scintillation light in position sensitive gamma-ray detectors. In this array, having a total sensitive area of about 1 cm^2, each SDD has a front-end JFET directly integrated on the detector chip, close to the collecting anode. The low electronic noise offered by each single unit allows to reach a sub-millimeter position resolution by coupling the SDD array to a single CsI(Tl) scintillator crystal in a "mini"-Anger camera scheme. In the paper, a detection module based on the SDD array is described and the noise performances are reported. Moreover, the results in terms of position resolution obtained with the "mini" Anger Camera realized with the SDD module are presented

Keywords: Silicon Drift Detectors, Gamma-ray Imaging, Silicon Detectors Arrays

1. Introduction

The development of gamma-ray imaging detectors with a resolution in the sub-millimeter range is required for different nuclear medicine applications, like breast tumor imaging [1], radioassisted oncological surgery [2] or small animal imaging. In such applications, in fact, more compact gamma-ray imagers characterized by a better resolution with respect to the conventional Anger cameras would present many operative and diagnostic advantages. A possible approach to this goal has been recently

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shown by the development of detectors based on scintillators coupled to arrays of silicon photodiodes (PDs) instead of conventional photomultiplier tubes (PMTs) [3].

Alternatively to PDs, silicon drift detectors (SDDs) have recently shown to achieve excellent performances in scintillation light detection [4]. The SDD is in fact characterized by a very low value of output capacitance, typically of the order of 0.1 pF, which is moreover independent from the active area of the device. When compared with a PD of equivalent area and thickness, the SDD then presents a lower value of electronic noise.

In a first prototype of gamma-ray detector for position measurements, based on a single CsI(Tl) crystal 1.4 mm thick coupled to an array of seven individual SDDs having a sensitive area of 5 mm^2 each, a position resolution of about 0.6 mm FWHM and an energy resolution of 16% FWHM have been measured at 122 keV by using a 0.3 mm collimated ^{57}Co source [5]. Nevertheless, relevant distortions of the images, mostly due to border effects related to the small size of the detector, were observed with this prototype. In the perspective of the realization of gamma cameras of larger active areas (few cm^2) for nuclear medicine applications, we have considered therefore necessary to evaluate the imaging capability of a new prototype of larger area with respect to the previous one.

In this work we present a detection module based on monolithic array of 19 hexagonal SDDs, which is characterized by a total sensitive area of about 1 cm^2. The electronics noise of all units have been measured by means of direct X-ray irradiation without the scintillator. A prototype of “mini” Anger camera have been then obtained by coupling the non-structured entrance window of the SDD array to a single CsI(Tl) scintillator crystal. The performances of the gamma camera, in terms of position and energy resolution, have been determined for different scintillator thickness and working temperatures.

2. The monolithic array of SDDs

A monolithic array of 19 hexagonal SDDs, arranged in a honeycomb configuration, as shown in Fig. 1, has been realized at the Semiconductor Laboratories of the Max Planck Institut (Munich, Germany) [6]. Each SDD has an inner diameter of 2.4 mm and an area of 5 mm^2, leading to an array total area of 95 mm^2. A front-end JFET is directly integrated on each individual SDD chip. This solution reduces the stray capacitance of the connection between detector and electronic with a benefit in terms of electronics noise. Moreover, this

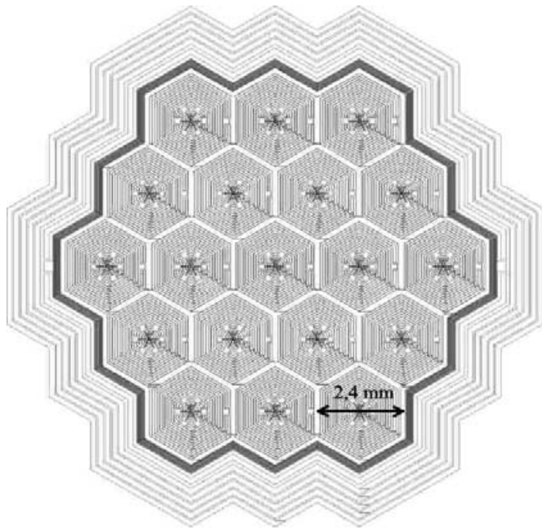

Fig. 1. Layout of the monolithic array of 19-SDDs. The detector side where the drift rings and the front-end JFET are integrated is shown. The scintillator is coupled to the opposite side of the detector.

solution minimizes the cross-talk and simplifies the readout of the multi-element detector signals, with respect to a solution based on external transistors. This is a relevant practical advantage, especially in the perspective of the fabrication of arrays with larger number of units.

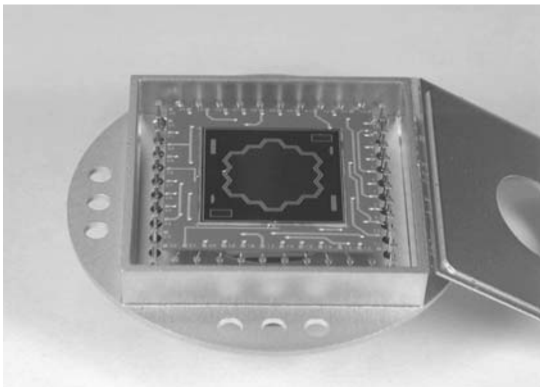

Fig. 2. The detection module based on the 19-SDD array.

Fig. 2 shows the SDD array mounted in a metallic housing which also includes a Peltier stage for detector cooling. The assembly and bonding of this detection module has been carried out by the company KETEK (Munich, Germany).

An experimental set-up has been realized to carry out either the characterization of the array stand-alone and the gamma-ray position measurements when the array is coupled to the scintillator crystal. The front-end readout system consists of 19 low-noise voltage preamplifiers mounted close to the SDD module and connected to the integrated JFETs, operated in a source- follower configuration. The electronic noise of each SDD has been first evaluated at different peaking times by means of a commercial semi-gaussian shaping amplifier (Tennelec TC244).

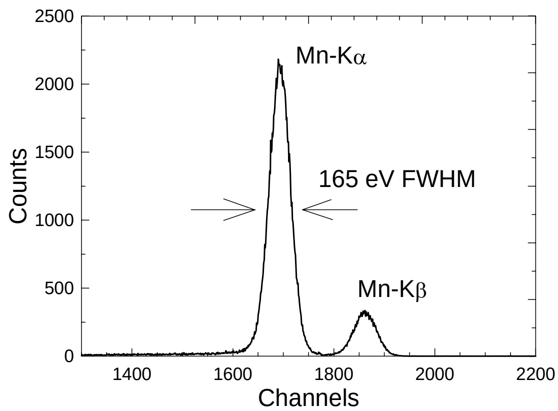

Fig. 3. Spectrum of the ^{55}Fe source measured at 0°C with the best unit of the 19-SDD detector, with a peaking time of 2 μs (TC244 shaping amplifier).

For gamma-ray measurements, in which all the 19 channels have to be readout simultaneously, a multi-channels electronic system has been employed [5]. This system includes RC-CR^2 shaping amplifiers, peak stretchers, discriminators, ADC, control logic and a data transmission stage to a PC, where the analysis of each individual gamma-ray event is carried out. The position of interaction and the photon energy are retrieved for each event by suitably analyzing the signals from the different units which have overcome a given noise threshold.

3. Experimental results

3.1. Noise performances of the SDD array

The electronic noise of each individual unit of the SDD array has been determined by irradiating the array alone (without scintillator) with a ^{55}Fe source at a temperature of 0°C. The ^{55}Fe energy spectrum measured at 2 μs of peaking time (TC244 shaper) with the best element of the array is shown in Fig. 3.

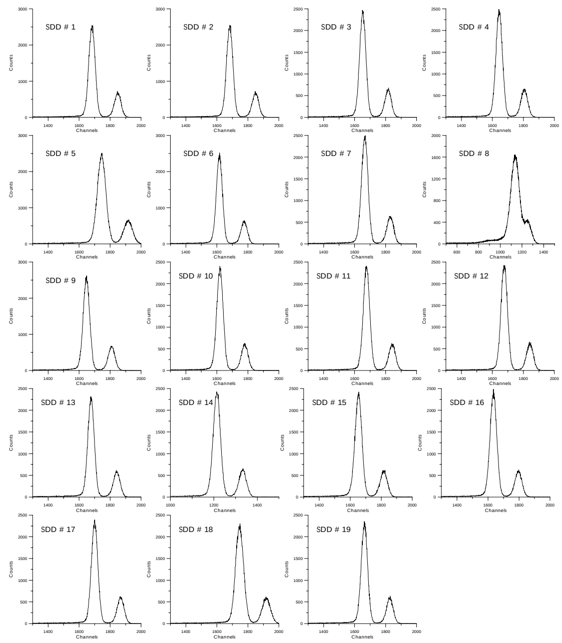

Fig. 4. ^{55}Fe spectra recorded with all 19 units of the array at 2 μs of peaking time.

From the measured energy resolution of 165 eV FWHM at 5.89 keV, a corresponding electronic noise of 13.5 electrons rms has been determined. The electronic noise of this unit rises to 16.9 e- rms and 19 e- rms, respectively at 6 μs and 8 μs peaking time, because of the increase at longer shaping times of the parallel noise contribution due to the SDD leakage current. Despite the worsening of the electronics noise, a peaking time of 6 μs has been chosen to detect the CsI(Tl) scintillation signal (main fall time of about 1 μs) without a relevant ballistic deficit.

The ^{55}Fe individual energy spectra, measured with the 19 SDD units at 2 μs of peaking time, are shown in Fig. 4. All units achieve a rather good energy resolution, with the exception of unit #8 which is characterized by much worse performances, probably due to a damage during bonding of the device. This unit has been therefore excluded in the subsequent measurements. The electronic noise of the other 18 SDDs ranges from 13.5 up to 18.0 e- rms with an average value of the order of 15.9 e- rms.

As mentioned in the previous section, in order to readout all 19-channels in gamma-ray measurements a custom electronic system has been employed. To optimize the readout of the CsI(Tl) scintillation light, the RC-CR^2 shaping amplifiers have been set with a peaking time of 6 μs. The electronic noise of the 18 *good* SDD units, as measured with this electronic system, ranges from 21.2 up to 34.2 e- rms with an average value of the order of 26.1 e- rms.

3.2. Performances of the CsI(Tl)-SDD detector

A CsI(Tl) crystal, completely covering the active area of the SDD array, has been coupled to this device by means of a layer of Bicron BC-637 optical interface 0.5 mm thick and a thin layer of optical grease. A photograph of the CsI(Tl)-SDD detector assembly is shown in Fig.5. Two different crystal thickness of 2 and 3 mm were used during the tests, corresponding to a detection efficiency of respectively 60 % and 75% at 140 keV. All crystal surfaces have been polished. In order to enhance the light collection on the SDD array, a Millipore paper reflector was applied on the top of the crystal. A system gain of 15.4 e-/keV has been measured with this configuration.

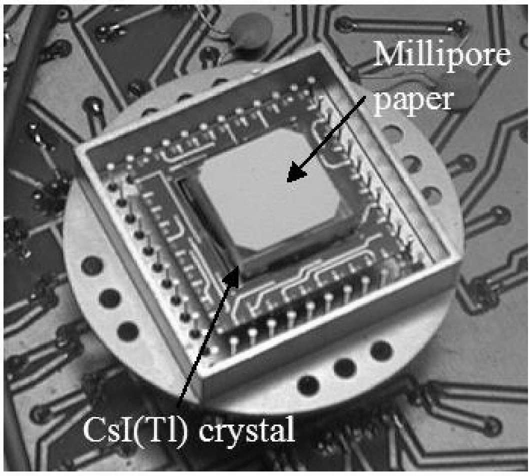

Fig. 5. Photograph of the scintillator/SDD array assembly.

The position of interaction of a gamma-ray photon inside the scintillator was determined by using a maximum likelihood algorithm. This algorithm first calculates analytically the signals collected by each unit for a generic position of interaction (X,Y) of the γ-ray in the crystal. Then it determines the point (X,Y) which maximizes the join probability that the calculated signals for all units correspond to the measured values. With respect to a simple centroid finding algorithm, used in previous measurements [5], this method allows to calculate the position of interaction over the full active area of the detector with much reduced non-linearities.

The gamma-ray photon energy was instead assumed to correspond at the simple sum of all signal amplitudes which have overcome a noise threshold.

The position resolution of the detector has been evaluated by moving a collimated ^{57}Co source (122 keV) in different points over the active area of the detection module. The collimator hole diameter was of 0.3 mm.

Fig. 6a shows the 2D position distribution of two irradiation points in the central region of the array, separated by 1 mm. In this measurement, the crystal thickness was of 2 mm and the temperature was held to 0°C. In Fig. 6b, a section of the position distribution, measured along the *X* axis is reported. According to the gaussian fit of the measured distribution, a position resolution of 0.47 mm FWHM has been estimated. Taking into account the collimator aperture of 0.3 mm, an intrinsic resolution of 0.36 mm can be derived for the gamma detector.

Fig. 7a shows the 2D position distribution of two irradiation points separated by 0.5 mm after having cooled the detector, with the same crystal thickness, down to –10°C. The two irradiation points can still be distinguished in the measurement. From the section along the *X* axis, shown in Fig. 7b, a position resolution of 0.38 mm FWHM has been estimated, corresponding to an intrinsic resolution of 0.23 mm, taking into account the collimator aperture.

The performances of the gamma camera have been measured also by using a scintillator thickness of 3 mm, leading to a higher detection efficiency, at a temperature of 0°C. In this case, the performances of

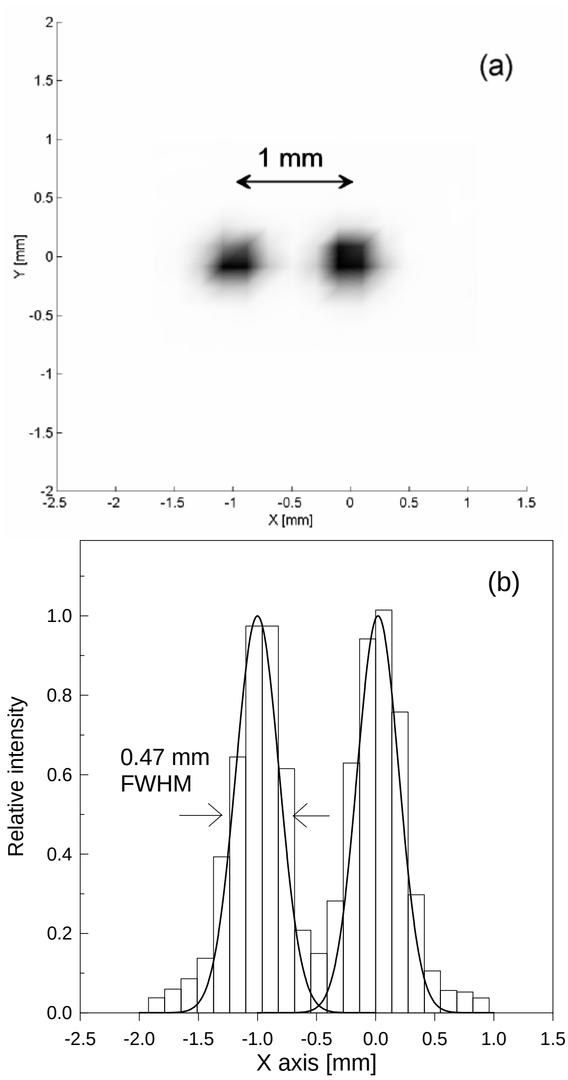

Fig. 6. (a) 2D position distribution of two irradiation points separated by 1 mm. (b) Position distribution of a section along the *X* axis. The crystal thickness is of 2 mm and the temperature is of 0°C. From the measured resolution of 0.47 mm FWHM and taking into account a collimator aperture of 0.3 mm, an intrinsic resolution of 0.36 mm can be derived.

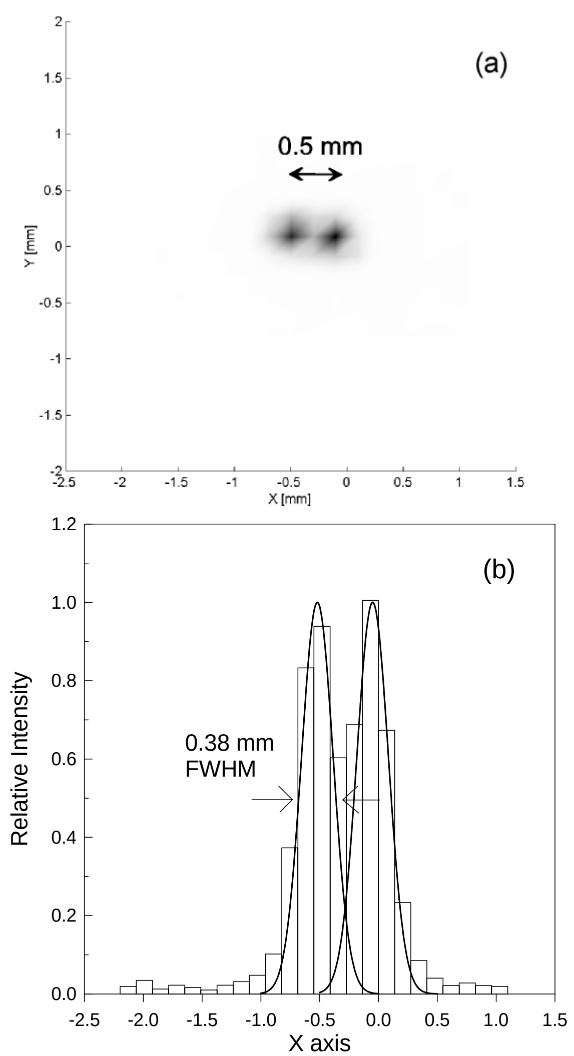

Fig. 7. (a) 2D position distribution of two irradiation points separated by 0.5 mm. (b) Position distribution of a section along the *X* axis. The crystal thickness is of 2 mm and the temperature is of -10°C. From the measured resolution of 0.38 mm FWHM and taking into account a collimator aperture of 0.3 mm, an intrinsic resolution of 0.23 mm can be derived.

the detector have been evaluated also in a extended region of the active area. Fig. 8 shows the 2D position distribution of eight irradiation points separated by 1 mm disposed along the a straight line, crossing an extended region of the array up to its border. In order to evaluate possible non-linearities of the detector, the line direction was chosen not to have any preferential orientation with respect to the symmetry axes of the array. From the figure, the measured position distributions in correspondence of the eight points are clearly distinguishable and disposed satisfactorily along the line without relevant distortions. The measured position resolution ranges from a minimum value of 0.49 mm FWHM, for the irradiation points close to the array centre, up to 0.68 mm FWHM in correspondence of the more external point.

We point out that the sub-millimeter position resolution here reported has been achieved by using a photodetector array having a pixel size of 2.4mm. This result represents a relevant advantage, in terms of either performances and simplicity (number of channels) with respect to ‘discrete’ gamma cameras, based on arrays of scintillator coupled to arrays of photodetectors (PMTs, PDs), which have an intrinsic resolution limited by the pixel size.

Fig. 9 shows the ^{57}Co energy spectrum measured at 0°C with the 3 mm thick scintillator. The measured energy resolution at 122 keV is 17.4 % FWHM. The energy resolution is not as good as the one achieved by using arrays of single CsI(Tl)-PD (see for instance ref. [3]), because in our case the photon energy is determined by summing the signal of all pixels (therefore summing also all the noises) while by using a single CsI(Tl)-PD pixel, only the noise of a single PD contributes to the energy resolution.

Finally, to evaluate the imaging capability of this prototype, a gamma-ray image was obtained from a small opening drilled in a lead layer (2 mm thick) whose shape is shown in Fig. 10. The image of the patterned layer has been obtained by irradiating the detector with a ^{57}Co source through the layer itself. As shown in figure, just obtained from the raw data without any further processing, the present detector is able to image the pattern in all its details without relevant distortions.

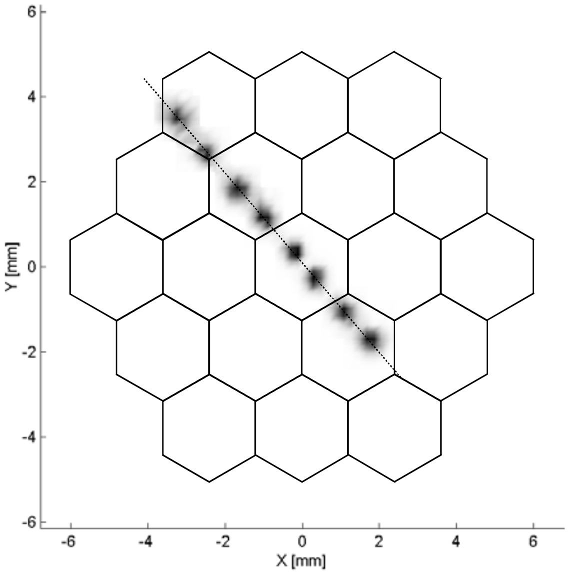

Fig. 8. 2D position distribution of eight irradiation points separated by 1 mm disposed along the dotted line shown in the figure. The line direction has no preferential orientation with respect to the symmetry axes of the array, whose schematic is also reported in the figure. The crystal thickness is of 3 mm and the temperature is of 0°C. The measured position resolution ranges from a minimum value of 0.49 mm FWHM for the irradiation points close to the array centre up to 0.68 mm FWHM in correspondence of the more external point.

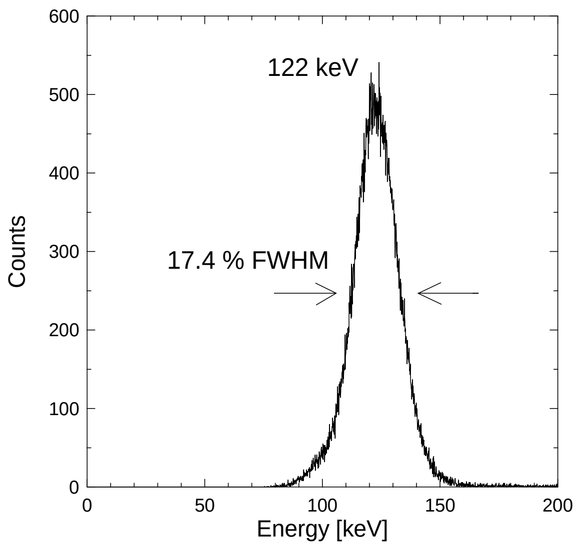

Fig. 9. Energy spectrum of the ^{57}Co source measured with the CsI(Tl)-SDD detector. The crystal thickness is of 3 mm and the temperature is of 0°C.

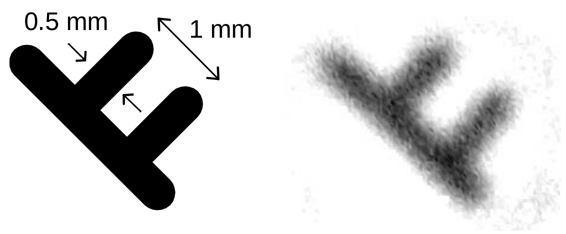

Fig. 10. Image of a small opening drilled in a lead layer, irradiated by a ^{57}Co source.

4. Conclusions

In this work we have presented a monolithic array of 19 SDDs with on-chip JFETs to be used for high-resolution gamma-ray imaging with scintillators. The SDD array is characterized at 0°C by an average electronic noise of 15.9 e- and 26.1 e- measured, respectively, with a peaking time of 2 μs and 6 μs. When coupled to a single CsI(Tl) scintillator 2 mm thick and irradiated by a 0.3 mm collimated ^{57}Co source (122 keV), a position resolution of 0.47 mm FWHM (0.36 mm intrinsic) and 0.38 mm FWHM (0.23 mm intrinsic) have been measured, respectively, at 0°C and –10°C. With a 3 mm thick crystal and at 0°C, a position resolution ranging from 0.49 mm up to 0.68 mm FWHM has been achieved within the full extension of the detector active area. In this last configuration, an energy resolution of 17.4 % FWHM at 122 keV have been also measured.

The achieved results in terms of position resolution are rather relevant if one considers that they have been obtained starting from a pixel size of 2.4 mm. Moreover, performances of similar quality have not been reported yet, to our knowledge, for scintillation-based gamma cameras, either Anger or "discrete" types.

Based on this architecture, larger FOV detectors for medical diagnostic systems as well as for small animal imaging systems are currently under study.

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