Multi-linear silicon drift detectors for X-ray and Compton imaging

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Abstract

Novel architectures of multi-anode silicon drift detectors with linear geometry (Multi-Linear Silicon Drift Detectors) have been developed to image X-rays and Compton electrons with excellent time resolution and achievable energy resolution better than 200 eV FWHM at 5.9 keV. In this paper we describe the novel features of Multi-Linear Silicon Drift Detectors and their possible operating modes highlighting the impact on the imaging and spectroscopic capabilities. An application example of Multi-Linear Silicon Drift Detectors for fast 2D elemental mapping by means of K-edge subtraction imaging is shown. The charge deposited by Compton electrons in a Multi-Linear Silicon Drift Detector prototype irradiated by a $^{22}$Na source has been measured showing the possibility to clearly resolve the 2D projection of the ionization track and to estimate the specific energy loss per pixel. The reconstruction of Compton electron tracks within a silicon detector layer can increase the sensitivity of Compton telescopes for nuclear medicine and γ-ray astronomy.

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1. Introduction

In the last decade silicon drift detectors (SDDs) [1] have extended their field of application from particle tracking [2–4] to X-ray spectroscopy. To this aim circular topologies with central anode and on-chip JFET have been designed and tested [5,6]. Monolithic arrays of SDD cells [7] have been successfully tested to improve active area and detection rate with negligible effects on signal-to-noise ratio. However the achievable position resolution with these detectors is limited by the size of each cell (of the order of 2 mm).

In order to overcome the limitation in the achievable peak-to-background ratio (of the order of 1500 with standard 5 mm$^2$ SDDs having symmetric round shape and concentric drift rings, and of 3000 with 10 mm$^2$ SDDs) novel asymmetric topologies (similar to a droplet) with the anode and the JFET shifted to the side of the structure have been proposed [8]. The asymmetric anode layout has a two-fold advantage as it allows to shield the readout section from irradiation and to optimize the anode-JFET design. Excellent results have been obtained with this detector both in terms of energy resolution (128 eV FWHM at the Mn K$_\alpha$ line at $-15^\circ$ C with a 5 mm$^2$ detector) and of peak-to-background ratios (about 7000 for 5 mm$^2$ detector and 10,000 for 10 mm$^2$ detector). However it is difficult to develop large monolithic matrixes with minimized dead area using a Silicon Drift Detector droplet as the basic...
In this paper, we present novel architectures of multi-anode silicon drift detectors with linear geometry (Multi-Linear Silicon Drift Detectors—ML-SDDs) [9] optimized to image X-rays and Compton electrons with spectroscopic-grade energy resolution and microsecond-scale time resolution. The linear structure naturally accounts for the optimization of the anode capacitance and JFET structure but it also allows the development of large area multi-channel detectors where the readout section is at the side of the active area and can be easily shielded to avoid deteriorating the peak-to-background ratio.

The innovative features of ML-SDDs with respect to conventional silicon drift detectors are described in Section 2. Section 3 presents a complete characterization of the 2-D imaging and spectroscopy capabilities of ML-SDDs showing examples of both transmission images and K-edge subtraction images. Section 4 is devoted to the discussion of the Compton electron tracking capabilities of this kind of detector. Section 5 illustrates the design of a novel large area prototype together with the first successful experimental tests.

2. Innovative features of the ML-SDD

A substantial evolution in the starting material, process complexity as well as in the detector architecture (e.g. availability of grown or high-energy implanted epitaxial layers, n-type and p-type deep implants, entrance window optimization below 1 keV, on-chip JFET) have led to significant performance improvements with respect to the classical silicon drift detector design introduced 1983 by Gatti and Rehak [1]. We focus our attention on the innovative aspects of ML-SDDs that open new fields of applications.

In these detectors the signal electrons generated by the interaction are confined within parallel drifting columns and transported towards point-like anodes by the electrostatic field as schematically shown in Fig. 1. The multi-linear transport mechanism based on electron drift accounts for a dramatic reduction in the number of channels required for true 2D position sensing (i.e. number of channels equal to the square root of the pixels). Moreover, it naturally allows placing the front-end electronics at the side of the detector chip thus simplifying the interconnection issue and it leads to readout times of only few microseconds. The deposited energy can be measured with spectroscopic resolution at (or very close to) room temperature thanks to point-like anodes of very low capacitance (<100 fF) with on-chip JFETs.

With respect to conventional drift detectors the generated signal electrons can be confined along the detector depth (z-coordinate) few micrometers from the detector surface. This is possible due to the presence either of a low-resistivity epitaxial layer grown on the detector substrate [10] or of a high-energy phosphorus implantation locally increasing the substrate doping at a depth of 7–8 μm from the detector front surface [11].

Charge spread into adjacent channels can be suppressed or strongly reduced by means of a suitable pattern of deep p-implants (array of channel-stops [12]) and/or by a sawtooth geometry of the p+ field electrodes [13]. The ionized dopants of the deep implants generate a potential perturbation along the surface that propagates in the volume of the detector with characteristic length related to its surface pitch. The amplitude of the confining potential that can be obtained is determined by the properties of the deep implant, by the doping of the material and by the depth of the potential minimum [12]. In order to reduce the sensitivity of the drift velocity to surface properties [14] and to field strip quantization, an array of phosphorus implants (of tailored energy and dose) are added in the middle of each drift channel [15]. In this way typical drift velocity of about 0.46 cm/μs can be achieved at 400 V/cm drift field. Moreover such n-implants...
in combination with the channel-stops increase the amplitude of the confining barriers.

The p+ back electrodes are designed to pick-up the fast induction pulse of the signal electrons and holes [16,17]. During the initial charge separation a current pulse, lasting few nanoseconds or more (depending on substrate resistivity and on the ionization profile), is induced on the p+ back electrode that collects the holes. The induced charge after hole collection is yet lower than the generated charge due to electron storage in the drift channel (with the potential minimum in the middle of the wafer this accounts for a signal loss of 50% or more depending on the type of ionization). The potential minimum at few µm from the anode-surface makes this signal loss negligible (about 3% for a 300 µm-thick detector and about 1.8% for a 450 µm thick detector) and independent on the ionization profile. As a result a much more reliable timing of the interaction with nanosecond resolution can be obtained.

The measurement of the electron drift time gives the interaction coordinate along the drift channel. The problem of determining the start time of the electron drift is solved in two ways. The detector can be operated in integrate-readout mode (idea of the Controlled Drift Detector [18,19]): the voltages of the p+ strips of the front-side are switched from the integration bias scheme, that produce a matrix of potential wells for charge integration, to the readout bias scheme which activates the drift field to move the electron packets to the readout nodes. Here the precision of the drift time is fully defined by the measurement of the arrival time at the low capacitance anode which allows high resolution. On the other hand to operate the detector in continuous readout mode the start-time is obtained from the back electrodes and the stop-time from the arrival-time of the signal at the anode (i.e. self-timing SDD). Here the time (and spatial) resolution is generally dominated by the noise of the back electrodes, due to their larger capacitance, that also introduces an energy threshold typically of a few keV. However, the absence of the integration phase has a two-fold advantage: it allows reaching a higher event rate with respect to the integrate-readout mode as well as better room temperature energy resolution, since less leakage current is integrated together with the signal.

With a proper design the detector can be operated in either of the two operating modes and the operating mode can be changed without switching off the detector thus offering a high degree of flexibility in the experimental phase.

3. X-ray imaging and spectroscopy with ML-SDDs

The simultaneous measurement of the energy and position information offered by ML-SDDs both in continuous-readout and in integrate-readout mode allows performing high-resolution X-ray imaging in conventional transmission-mode setups at synchrotron sources and in the laboratory. Moreover it opens to advanced imaging techniques like K-edge subtraction imaging and Diffraction-Enhanced Imaging. [20,21].

3.1. Transmission X-ray imaging

As an example of the imaging capabilities of this kind of detector Fig. 2 shows the acquired X-ray image of a lizard. Due to the small dimensions of the ML-SDD prototype used in the measurements (about 1.6 mm x 1.7 mm) the detector was panned to scan the entire object.

This measurement was carried out at ELETTRA Sincrotrone Trieste (SYRMEP beamline) at room temperature with the detector operated in the Controlled-Drift mode at 100 kHz frame frequency. The energy of the incident beam was set to 15 keV, high enough to pass through the lizard’s organs.

Despite the relatively large dimensions of the pixels (120 µm) the details in the lizard body are beautifully reconstructed. The vertebral bones and the ribs can be clearly distinguished and also a faint image of the internal organs like the lungs can be identified. The two black spots in the radiography are due to two small stones that were present in the lizard body. If needed the information about the energy spectrum of the photons collected in each pixel of the digital radiography is available. This feature can be used to exclude inelastic scattered photons that can degrade the contrast of the acquired image.

3.2. K-edge subtraction imaging

The abrupt change of the absorption coefficient of an element around its K-edge allows imaging the 2D distribution of known elements in a sample by subtracting the transmitted image above and below the element’s absorption edge [22]. The same technique can be used to enhance the contrast of selected elements in radiographic imaging.

We have mapped the distribution of silver in a phantom composed of gold, indium, iron and silver. Fig. 3a shows the transmission image of the phantom illuminated by a 26.7 keV X-ray beam, i.e. above the K-edge of silver (25.51 keV). Fig. 3b shows the transmission image when a 24 keV X-ray beam (i.e. below the K-edge of silver) illuminates the phantom. The silver region appears in light gray due to the lower absorption coefficient of silver at this...
energy. Fig. 3c is obtained by taking the difference of the two transmission images. Since the absorption coefficient of all the elements but silver is nearly constant, by changing from 24 to 26.7 keV we can map the silver distribution in the phantom that can be clearly distinguished in the figure. Fig. 3d shows the indium distribution obtained with the same method (K-edge of indium 27.94 keV). A CDD-based system would allow a very fast 2D elemental mapping of square-centimeter area with spatial resolution in the order of 100 μm and is an alternative to XRF techniques.

Profiting from the energy-resolving capability of the CDD the K-edge subtraction imaging technique can be performed also with conventional X-ray generators that provide a broadband spectrum, or with polychromatic sources, instead of the highly monochromatic light coming out from a synchrotron. In the first CDD prototypes, not optimized for spectroscopy applications, we measured an energy resolution at the Mn Kα line of 270 eV FWHM (28 electrons rms) at room temperature and of 198 eV FWHM (19 electrons rms) at −50°C. Implementing into a CDD/ML-SDD the optimized readout section used in SDD cells or in fully depleted charge-coupled devices for X-ray spectroscopy will bring the spectroscopic

![Fig. 3. (a) Radiography of a phantom composed by different elements (silver, gold, iron and indium). The energy of the incident beam was set to 26.7 keV (i.e. above the K-edge of silver, 25.51 keV). (b) Radiography of the same phantom with 24 keV incident-beam energy (below the K-edge of silver). The silver region appears in light gray due to the lower absorption coefficient of silver at this energy. (c) Silver distribution in the phantom obtained as the difference between the two radiographies shown in (a) and in (b). (d) Indium distribution in the phantom obtained as the difference between two radiographies with the incident beam at 26.7 keV (below the K-edge of indium, 27.94 keV) and at 29.1 keV (above the K-edge of indium).](image)

![Fig. 4. Simplified sketch of one ML-SDD layer in which a Compton interaction takes place. E₀ and E₁ are the energies of the incident γ-ray and of the scattered photon, respectively. The detector images the 2D projection of the electron track and samples the deposited charge with spatial resolution in the order of 100 μm.](image)
performance of CDDs/ML-SDDs to a comparable energy resolution [8].

4. Compton electron tracking

The excellent energy resolution and the relatively small Doppler broadening of silicon makes a ML-SDD imager an ideal candidate as scatter detector in Compton telescopes to reconstruct the original location of the gamma-ray with sub-millimeter position resolution [23]. This is of particular interest in the field of small-animal single photon emission computer tomography (SPECT) for in-vivo study of radiopharmaceuticals distribution. In the following we will discuss the first experimental measurements that highlight the capability of this detector in Compton electron tracking.

4.1. Theory

In a Compton telescope the direction of the incident \( \gamma \)-ray is constrained to lie on a cone with aperture equal to the scattering angle and axis given by the measured direction of the scattered photon (see Fig. 4). Electron tracking of the first Compton scatter can significantly increase the sensitivity of Compton telescopes because the estimation of the recoil electron direction restricts the source direction to lie on a small section of the cone.

The basic approach in present Compton telescopes relies on tracking Compton electrons in successive layers of silicon detectors until they are fully absorbed. However the determination of the initial electron direction from the first two interaction layers is basically limited by multiple Coulomb scattering in silicon and does not apply to low \( \gamma \) energies (\(<\)0.5 MeV) due to the short electron range [24]. The availability of good energy resolution (500 eV) and position resolution (100 \( \mu \)m) in ML-SDDs gives the possibility to resolve the Compton electron track within one silicon layer, therefore also in the case when the Compton electron is fully absorbed in the first interaction layer. Fig. 4 shows a simplified sketch of one ML-SDD layer in which a Compton interaction takes place. The detector images the 2D projection of the electron track and samples the deposited charge with spatial resolution in the order of 100 \( \mu \)m. The (projected)
initial direction of the recoil electron and the vertex of the interaction can be therefore better estimated for a wider range of Compton electron energies and with less impact of multiple electron scattering. Additional information can be obtained by estimating the specific energy loss per pixel. The comparison of the data with the known theoretical curve (dE/dx versus E) allows us to derive a least-square estimate of the recoil electron energy (T_e) and of the escape energy for those electrons escaping from the interaction layer.

The lack of the depth-of-interaction (DOI) information affects the estimation of dE/dx and limits the accuracy of this analysis. It must be pointed out however that the shape of the induced signals on the segmented back electrodes could also be used to provide DOI information at the expense of a more sophisticated signal processing.

4.2. Experimental results

A small-area ML-SDD prototype having 13 120µm-wide drift channels was operated at room temperature in continuous readout mode and irradiated with a 22Na source to image Compton electron tracks. The induction signal picked up at the uniform back contact provided the interaction time (and the start of the electron drift) with a measured time jitter of about 6 ns FWHM.

Figs. 5a,b,c, show selected examples of recorded tracks. In each figure the left inset shows the pixellated (120 × 120 µm pixel size) image of the electron ionization track. Pixel gray levels correspond to the deposited energy (in keV) according to the shown grey-scale. The right inset shows the estimated specific energy loss after least-square-fit to the theoretical curve (solid line) which gives the initial Compton electron energy. Fig. 5a shows the case in which a 415 keV electron is fully absorbed in the silicon detector. The marked increase of the deposited energy near the end of the track is clearly visible. Fig. 5b shows the case in which the ionization track appears inside the detector volume and stops at the edge of the active area or beyond it with partial charge loss. Fig. 5c shows a different case in which an energetic electron (∼960 keV) crosses the detector thickness and escapes through the surface with a residual energy of about 760 keV.

Although more refined data analysis can be performed these examples already show how ML-SDDs can add direct ‘true imaging’ capability to Compton telescopes which is an attractive way to significantly reduce background and increase sensitivity.
5. The new generation of Multi Linear Silicon Drift Detectors

Newly designed prototypes of a 3 × 1 cm² linear drift detector were recently produced at the Halbleiterlabor of the Max-Planck-Institut in cooperation with PN Sensor GmbH. Fig. 6 shows the metallization mask of the detector anode-side. The detector has 240 anodes with 120 μm pitch and a maximum drift length of about 1 cm. The p⁺ junction on the backside has been segmented in 15 strips. The detector design allows operation either in continuous-readout mode, using the induction signal from the back as a self-trigger to measure the drift time, or in integrate-readout mode (i.e. as a Controlled Drift Detector) thanks to the presence of two different voltage dividers to bias the field strips [25].

The detector was mounted and electrical tests were carried out. Fig. 7a shows the output characteristics of one of the 240 on-chip JFETs. Figs. 7b and c show the DC (saturation current and pinch-off voltage) and the small signal (transconductance and output resistance) parameters for all the different channels. The spread of the parameters is below 3%. The output resistance of some channels was not measured due to a problem in the detector prototypes by S. Masci is deeply acknowledged. A.C., A.G. and C.G. wish to thank R. Menk and F. Arfelli for the kind hospitality at the SYRMEP beamline (Sincrotrone Trieste).

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