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Semiconductor drift detectors for X- and gamma-ray spectroscopy and imaging

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Abstract

The semiconductor drift detectors (SDDs) show basic advantages, in terms of spectroscopic resolution and detection rate, with respect to other semiconductor detectors. These advantages are strictly related to the very low values of the output capacitance of these devices. In this paper the working principles and the performance of the SDDs are presented and the most recent devices ("droplet type" SDDs and monolithic arrays of SDDs) are introduced. The requirements of front-end electronics for the readout of the SDDs signals are then discussed and the most recent implementations (pulsed-reset preamplifiers, multi-channel ASIC readout circuits) are introduced. Some relevant applications of SDDs in the field of X-ray spectroscopy for material analysis and for nuclear physics experiments, and in the field of gamma-ray imaging, are presented as a conclusion.

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1. Introduction

The silicon drift detector (SDD), introduced by E. Gatti and P. Rehak in 1983, is a detector of ionizing radiation characterized by a very low electronics noise. Since its invention, the SDD has been developed in a large variety of topologies for applications either in the field of high-energy physics and in the field of X-ray spectroscopy and imaging. The SDD has been also recently employed in γ-ray spectroscopy and imaging. In this case the SDD is used as photodetector of the light emitted by scintillators.

The SDD is a fully depleted, usually n-type, semiconductor device where an electric field parallel to the surface of the wafer is superposed to the depletion field by suitably biasing arrays of pn junctions. The electric field component parallel to the surface forces the electrons generated by the radiation drifting towards a very small collecting anode [1]. The basic advantage of the SDD with respect to a conventional pn diode of equivalent active area and thickness is the low value of the capacitance of the small collecting anode, which is of the order of 100 fF. This value is clearly independent of the active area of the device. This feature turns out to reduce the effects of the white and flicker series component of the electronics noise [2] with an overall benefit in terms of energy resolution. Moreover, due to the reduction of the series noise effects, which are inversely proportional to the processing time of the detector signals, the SDD allows to operate with low electronics noise at high counting rates.

Originally, the SDDs were designed to be used as position sensitive detector for high-energy physics experiments [3]. In fact, the drift time of the electrons during their travel from the interaction point to the anode may be used to measure the distance of the interaction point from the collecting anode. The second coordinate can be given by a suitable segmentation of the collecting anode.

To fully exploit the benefit in terms of energy resolution and short shaping time arising from the low output

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capacitance typical of the SDD, both preamplifier input capacitance and stray capacitances of the connection between detector and preamplifier have to be kept as small as possible. This goal can be partially achieved by a very careful choice of the front-end transistor of the readout electronics and of its mounting on the detector, or nearly completely achieved by integrating the front-end transistor directly on the detector wafer [4–7]. The first solution takes advantage from the better performance of the discrete transistors, while the second solution takes advantage from a more effective reduction of the strays and from an easier approach to the ideal capacitive matching conditions ($C_{\text{detector}} = C_{\text{FET}}$). The latter solution seems to be the only one practical in the case of large arrays of monolithically integrated SDDs.

A typical integrated front-end in a SDD is based on a non-conventional n-channel JFET, designed to be operated on completely depleted high resistivity silicon [8]. In a SDD with circular geometry, the JFET is integrated inside the ring-shaped collecting anode placed in the centre of the detector. The discharge of the leakage current from the detector and of the signal charge accumulated on the anode can be performed either in a continuous mode [9] or in a pulsed-reset regime [10].

In recent years, SDDs and monolithic arrays of SDDs have been successfully employed in the development of detectors for gamma-ray spectroscopy and imaging based on scintillators. As replacement of the conventionally used photomultiplier tube, the SDD offers better quantum efficiency at the wavelengths of the scintillation light, excellent electronics noise, better compactness and intrinsic immunity to magnetic fields. In this research, state-of-the art performance in gamma-ray spectroscopy has been achieved. When used in an Anger camera configuration, a position resolution of few hundred microns has been achieved in gamma-ray imaging. This opens the opportunity to use this detector in many applications in astrophysics and in the medical imaging field.

In the following sections of the paper the structure, the working principles and the performance of advanced types of SDDs are presented. The most recent implementations of the readout electronics are introduced. Some relevant applications of SDDs in the field of X-ray spectroscopy, nuclear physics experiments and gamma-ray imaging are presented as a conclusion.

2. SDDs for X-ray spectroscopy

The low electronics noise achievable with a SDD, thanks to the low value of output capacitance, has made them ideal for high-resolution X-ray spectroscopy. In order to enhance their quantum efficiency in the soft X-ray region, particular care has to be used in the design of the radiation entrance window [8,11–13]. At high energy, the X-ray detection efficiency of the SDDs, limited by the total thickness of the wafer, which is now typically about 450 μm, is larger than 90% up to 10 keV.

State-of-the art energy resolutions in X-ray spectroscopy at room temperature or with moderate cooling (with a Peltier cooler) can be reached with SDDs. Using a SDD of 10 mm^2 of circular geometry with an integrated JFET, a typical energy resolution at the Mn Kα line (5.898 keV) of 135 eV FWHM −20 °C can be now achieved. The short value of shaping time used to reach the best energy resolution (of the order of one microsecond) makes the SDD the fastest X-ray spectroscopy detector when compared with conventional systems, i.e. Si(Li) and Ge cryogenic detectors and PIN diodes (of the order of ten microseconds). This feature makes this detector very attractive in those applications where a good energy resolution is required at high counting rates, like, for instance, in Scanning Electron Microscopy.

A new SDD, characterized by a non-cylindrical geometry, optimizes the peak-to-background ratio and further improves energy resolution [14]. In this SDD, named Droplet SDD because of the characteristic shape of its active area (Fig. 1), the anode and the integrated JFET have been placed at the margin of the active area (in the more convex part of the drop) where they can be easily shielded from direct irradiation by means of a simple cylindrical collimator (centred in the less convex part of the drop) thus avoiding that photons interacting in the region between the anode and the integrated JFET generate a charge that can be randomly split between the anode and the transistor. The peak-to-background value is in this way enhanced to values higher than 6000. Moreover, because in the Droplet SDD, with collimator, the signal electrons reach the anode coming just from one side, the JFET can be integrated on the other side with respect to the anode. The anode, which has not to "contain" the transistor like in the case of a classical cylindrical SDDs, can be smaller

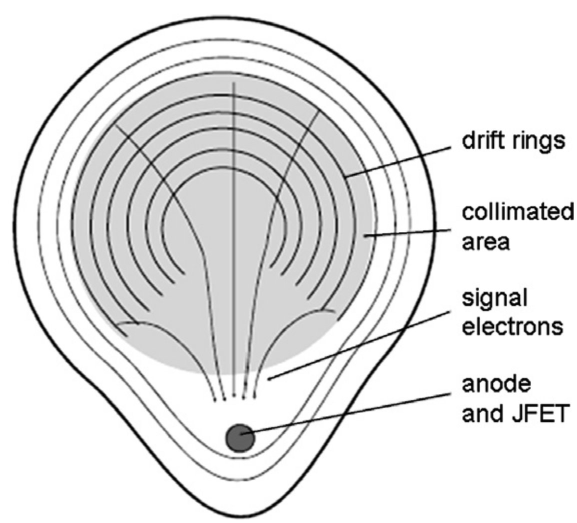

Fig. 1. Layout of the SDD Droplet (SDD^3) detector. The paths of the signal electrons towards the anode placed at the border of the detector are shown. The inner circle in the figure represents the region where the irradiation of the detector can be shielded to improve the peak-to-background ratio.