Towards large area X- and gamma-ray imagers based on Controlled Drift Detectors

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Abstract

The design solutions of a new generation of Controlled Drift Detectors (CDD) with larger area and flexible pixel size are discussed. The experimental results show that the active areas of few square centimetres and pixel sizes ranging from 50 to 180 μm can be safely designed keeping the readout time within few microseconds. Large-area CDD with excellent energy resolution and fast readout opens a variety of new biological, medical and industrial applications. Application examples to microsecond-scale time-resolved imaging of periodical processes, 2D/3D energy-weighted tomography and Compton telescope for γ-ray imaging with sub-millimeter resolution are proposed.

1. Introduction

The distinctive feature of the Controlled Drift Detector (CDD) is the simultaneous readout of the signal charge packets stored in each pixel by means of an electrostatic field in few microseconds [1]. The detector is built on a fully depleted high-resistivity silicon wafer that assures a good quantum efficiency for X-ray detection from about 0.5 up to 20 keV. To operate as a 2D spectroscopic imager the CDD is run in integrate-readout mode. During the integration phase suitably engineered potential wells confine the signal electrons in spite of the presence of a uniform electrostatic field. At the transition to the drift phase the potential wells are destroyed and the electric field moves simultaneously the electrons' packets towards the anodes. On-chip n-channel JFETs allow low-noise measurement of the drift time and of the total charge of each electron packet giving, respectively, the position information along the drift coordinate and the X-ray energy. The segmentation of the anodes allows to measure the orthogonal coordinate.

Extensive tests carried out on CDD prototypes of small area ($\sim 1\,mm^2$) successfully proved the working principle [2, 3]. Measured drift velocities are in the range 0.2–0.5 cm/μs confirming that readout times of 2–5 μs for a 1-cm-long detector are feasible. The measured energy resolution at the

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Mn Kα line (5.9 keV) is better than 300 eV FWHM at room temperature and it is expected to drop to about 150 eV with moderate (Peltier) cooling.

The excellent performances measured up to now have pushed the development of a second generation of CDDs with larger area and different pixel sizes to cope up with the requirements of applications. Section 2 discusses the design issues and the experimental characterization of two new CDD prototypes. Section 3 reviews some field of applications that will benefit from the time/energy resolution of the CDD.

2. Second generation of CDDs

Let us analyze the factors that limit the pixel size of a CDD. In the direction orthogonal to the drift the pixel size is defined by the pitch of the "channel-stop" implants that create the drift channels. This size can be easily tailored to the experimental needs down to a size 50 μm [4, 5]. In the direction along the drift the pixel length is strictly related to the layout of the p+ strip of the anode side. In the first CDD design one pixel was made by a cell of 6 strips corresponding to a pixel length of 180 μm. In order to change the pixel length either the number of strips per pixel or the strip pitch or both must be changed. A new CDD prototype has been designed with a pixel length of 120 μm corresponding to a cell of 4 strips. The corresponding voltage pattern during integration is shown in the inset at the lower right of Fig. 1. The potential barrier separating adjacent wells is a critical issue because a shorter pixel generates a less penetrating perturbation which eventually requires a larger voltage change ΔV to switch between integration and drift. To compensate for these effects in the new design the potential minimum for the electrons was placed closer to the surface (at a depth of 7 μm instead of 15 μm). This prototype was successfully tested and Fig. 1 shows the 'staircase' behaviour that confirms the correct quantization of the measured drift times. The charge handling capability (inset at the upper left of Fig. 1) is slightly better than for the 6-strip case [6] due to the reduced distance from the surface. Fig. 2 shows the flat image of a ^{241}Am

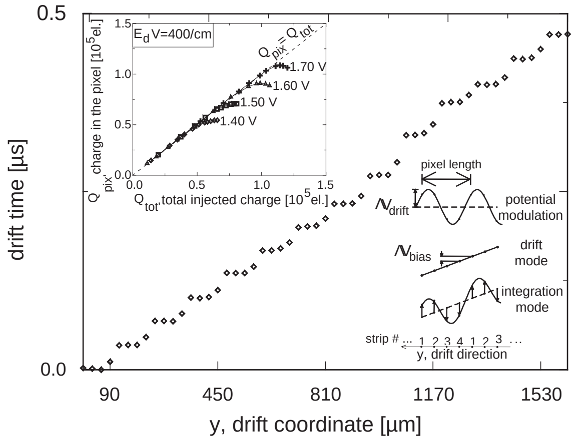

Fig. 1. Drift time vs. drift coordinate in the detector with 120 μm pixels. The 'staircase' behaviour confirms the correct quantization of the measured drift times. The inset at the lower right shows the voltage pattern during drift and integration. The inset at the upper left shows the charge handling capability at a drift field of 400 V/cm.

source recorded by the new 120 μm-pixel CDD at room temperature. The frame frequency is 100 kHz (9 μs integration, 1 μs drift). For each of the 13 drift channels, the scatter plot energy-drift time is reported in the energy range 10–30 keV.

A second CDD prototype having 180 μm pixels and $6 \times 6\,mm^2$ active area was designed with deep n-implants in the middle of the drifting channels to enhance the electron velocity [7]. At a drift field of 400 V/cm, the electron velocity achieved with the deep n-implants is about 0.46 cm/μs to be compared with 0.35 cm/μs obtained without deep n-implants. Moreover, a moderate cooling determines a significant increase of the electron mobility (about 1% increase every 1°C near 300 K [8]) which helps to compensate the increase of the drift time with the drift length.

3. Fields of application

Time-resolved structure research with X-rays has several applications in biological, medical and industrial fields. By periodically stimulating morphological changes in the sample (e.g. with laser excitation, electricity, temperature or pressure variations) a wide number of phenomena can be

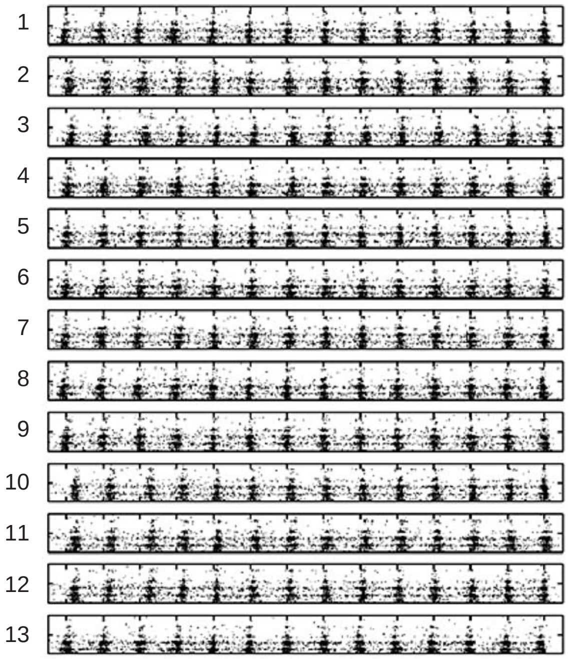

Fig. 2. Flat image of a ^{241}Am source collected by the new 120 μm-pixel CDD prototype at room temperature. The frame frequency is 100 kHz (9 μs integration, 1 μs drift). For each of the 13 drift channels, the scatter plot energy-drift time is reported in the energy window 10–30 keV.

probed in the microsecond scale by employing a CDD (pump and probe technique). Time-resolved images of a vibrating pinhole were successfully recorded with a CDD with 20 μs time resolution [9].

X-ray computed tomography is a well-assessed technique to view features in the interior of a wide range of materials (e.g. rock, bone, ceramic, metal and soft tissue). The use of an X-ray detector with excellent energy and time resolution, as a CDD, can increase the sensitivity and power of this technique. The contrast between different materials having similar absorption coefficients (μ) can be maximized in a suitable energy window. When using a polychromatic X-ray source, energy-weighting techniques can be used to obtain the elemental mapping of the sample. Corrections of beam-hardening artefacts can be obtained approaching the same quality of monochromatic illumination. The time resolution of CDDs (some tens of microseconds) can be used to perform 3D tomographic measurement of rapidly rotating objects. This will also allow to select the angular slices after the measurement in order to optimize statistics and angular precision.

Several stacked layers of CDDs constitute a very promising scatter detector for a Compton telescope for γ-ray imaging. Thanks to the high-energy resolution of a CDD imager and to the relatively small Doppler broadening in silicon the original location of the γ-ray can be reconstructed with sub-millimeter position resolution. This is of particular interest in the field of small-animal SPECT for in vivo study of radiofarmaceuticals distribution. The fast trigger, needed for event coincidence, can be obtained from the signals induced on the CDD back electrodes by the initial separation of the electron–hole track generated by the recoil electron [10].

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