X-ray imaging and spectroscopy with Controlled-Drift Detectors: experimental results and perspectives

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Abstract

The Controlled-Drift Detector is a fully-depleted silicon detector that allows 2-D position sensing and energy spectroscopy of X-rays in the range 1-30 keV with excellent time resolution. Its distinctive feature is the simultaneous readout of the charge packets stored in the detector by means of a uniform electrostatic field leading to readout times of few µs/cm. At frame rates higher than 60 kHz the achieved room-temperature energy resolution at the Mn Kα line is better than 300 eV FWHM thanks to the short integration time. In this paper we present the characterization of the imaging and timing properties of two CDD prototypes. Time resolved 2-D images in the microsecond range as well as X-ray radiographies will be presented. Details of the design of a new 6×6 mm² prototype will be presented and the preliminary measurements will be discussed.

Keywords: Time resolved X-ray imaging; X-ray radiography; Controlled-Drift Detectors; Energy-resolved X-ray imaging;

1. Introduction

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The Controlled-Drift Detector [1] is a single photon counting 2-D X-ray imager proposed in 1997 [2]. It is built on a fully depleted n-type high-resistivity Silicon substrate with thickness in the range $300 – 500 \mu m$. A lower resistivity layer epitaxially grown on or implanted in the Si substrate is employed as guiding layer to confine the signal electrons at about $10 \mu m$ from the detector front surface. In the normal operating condition the detector is switched between an integration phase and a readout phase. During the integration phase a pixellated structure is generated in the detector volume by creating potential barriers in spite of a superposed electrostatic field pointing parallel to the

![Graph](image-url)

Fig. 1. Scatter plot energy vs drift time of the X-rays of a $^{241}$Am source collected by a column of the CDD at $10$ kHz frame frequency. The integration time was set to $90 \mu s$ and the readout time to $10 \mu s$. The upper inset shows the distribution of the events along the time axis. The inset on the right end shows the total distribution of the event energies (i.e. the spectrum of the $^{241}$Am source collected by all the pixels).
wafer surface. During the drift phase an external control voltage removes the potential barriers preventing the electron drift so that the electrostatic field is free to transport the signal electrons to the readout electrode. The time between the start of the drift phase and the arrival of the signal electrons at the readout electrode gives the position of the irradiated pixel along the drift direction. The second coordinate is obtained providing a separate readout electrode for each pixel column. The amplitude of the charge packet collected at the readout electrode measures the energy of the incident X-ray with spectroscopic resolution.

The main performances of small area CDDs in terms of position and energy resolution have been extensively tested and are reported in [3-4]. The active area of this detector prototype is about 0.7 mm × 2 mm, corresponding to 4 × 11 pixels, 180 µm wide.

Fig. 1 shows the scatter plot energy vs. drift time (i.e. position) of the events detected by a single column when the CDD is operated at 10 kHz frame frequency and exposed to a 241Am radioactive source at room temperature. The detector was operated at such a low frame rate in order to collect enough statistics despite the low intensity of the radioactive source (100 µCi). Moving along the time axis we see that the events are gathered in well separated clusters corresponding to the characteristic lines of the 241Am source (Np Lα, Lβ and Lγ lines can be clearly distinguished as well as the 26.3 keV and 59.5 keV γ-rays) and to the illuminated pixels. The low intensity of the 59.5 keV γ-ray is due to the limited efficiency of the detector at high energy.

The upper inset of Fig. 1 shows the distribution of the events along the time axis. The relative FWHM of the peaks is about 25% showing a margin for reduction of the pixel size along the drift coordinate. The inset on the right end of Fig. 1 shows the total distribution of the event energies (i.e. the spectrum of the 241Am source collected by all the pixels in the column). The energy resolution at the Np Lα line (13.9 keV) is 515 eV FWHM, corresponding to an Equivalent Noise Charge (ENC) of 56.8 electron r.m.s..

When the detector is operated at the maximum frequency of 100 kHz, the achieved energy resolution at room temperature is 277.5 eV FWHM at the Mn Kα line, thanks to the lower contribution of the leakage current integrated in the pixels [5]. These results show the feasibility of X-ray imaging spectrometers based on CDDs and operated at or near room temperature giving energy resolutions close to state-of-the-art X-ray imagers operated at LN.

In this paper we present the results of the characterisation of the imaging and timing properties of two CDD prototypes. The X-ray radiography of a wasp as well as the first time-resolved 2-D image in the microsecond range carried out with the small area CDD will be presented. The last section of the paper is devoted to the design and preliminary characterisation of a new generation of CDDs of larger area.

2. X-ray radiography

We have tested the imaging capabilities of the CDD by radiographing different objects with synchrotron light in the range 8.5 keV – 30 keV [6]. The CDD was operated at frame frequencies in the range 10 kHz – 100 kHz according to the transmitted intensity of the beam.

Fig. 2 shows the radiography of a wasp. The detector was operated at 100 kHz frame frequency (9 µs integration time and 1 µs drift time). The energy of the incident beam was set to 10 keV in order to optimise image contrast. Due to the small dimensions of the CDD prototype used in this measurement the
detector was panned to cover the entire object. Despite the relatively large dimensions of the pixel, significant details of the wasp body (e.g. antennas and legs) can be clearly distinguished.

3. Time-resolved 2-D imaging

We tested the performances of the CDD in time-resolved 2-D imaging in the sub-millisecond range. The experimental apparatus built for this purpose is shown in Fig. 3a. A 50 µm diameter pinhole has been fixed to a loudspeaker by means of a light arm. The system has been irradiated with a 650 nm DC laser. Fig. 3b shows two recorded images one with the loudspeaker off and the other with the loudspeaker driven by a 106 Hz sinusoidal wave. This frequency was chosen to bring the system into resonance to obtain a larger displacement of the spot on the detector. When the loudspeaker is off we obtain the still image of the pinhole, having a diameter of the order of 250 µm on the detector. When the loudspeaker is on, the acquired image shows that the achieved displacement of the laser spot is of the order of 1 mm.

The detection system has been synchronised with the input sine wave driving the loudspeaker. A time stamp for each image frame has been obtained by digitizing the input sine wave.

A time resolution of 50 µs has been chosen to obtain time-sliced images. Fig. 4 shows one every ten time-sliced images to cover the full oscillation period. The sinusoidal-like displacement of the laser spot is beautifully reconstructed. By trading off between time resolution and statistics, time resolution can be improved down to 20 µs as the CDD was operated at 50 kHz frame frequency.

The capability of the CDD to perform time-

![Fig. 3. a) Experimental setup used for time-resolved imaging of a repetitive process. b) Image (540 µm × 1980 µm) of the pinhole mounted on the loud speaker without any time slicing when the loud speaker is off and when the loud speaker is driven at 106 Hz. The CDD was operated at 50 kHz frame frequency.](image)

![Fig. 4. Time sliced images (50 µs) of the pinhole mounted on the loud speaker driven at 106 Hz. The sinusoidal-like displacement of the pinhole is beautifully reconstructed.](image)
resolved X-ray images of repetitive processes with sub-millisecond resolution can be of great interest in the industrial and medical fields [7]. In fact tomographic reconstructions can be performed by rapidly rotating the sample under test and keeping fixed the detector/source system. In this way also time dependent changes in the sample structure can be studied with the required time resolution. Detector frame frequencies higher than 10 kHz can be of interest also in time-resolved diffraction studies [8] in which the sample can be continuously rotated.

4. Towards large area Controlled-Drift Detectors

A second generation of Controlled-Drift Detectors has been designed and was recently produced at the Halbleiterlabor of the Max Planck Institut, München, Germany [9].

The designed prototype, to be used as a demonstrator in imaging applications, has an active area of 6 mm × 6 mm. The pixel size (180 µm × 180 µm) and the shape of the potential perturbation superposed to the linear bias of the field strips during the integration mode are the same of the previous prototype. The metalization mask of the designed detector is shown in Fig. 5. Several improvements have been introduced with respect to the previous prototype. In order to improve electron transport during the drift mode, properly tailored deep n-implants have been added along the drift direction [10]. In order to reduce the risks of damage of the integrated dividers during the bonding of the detector, the bonding pads have been placed in a lateral area not overhanging the resistive implant of the dividers. The width of the guard regions is 1/6 of the drift length (in the previous prototype the ratio was 1/3).

Preliminary tests of the electron transport over the 6 mm drift length have been carried out by operating the CDD in continuous readout mode. An infrared pulsed laser (904 nm) has been focused on the front side of the detector in the middle of one drift channel to generate a signal charge of about 15,000 electrons. Drift fields from values as low as 25 V/cm up to 400 V/cm have been tested. In all these cases the potential minimum was located at about 8 µm from the front surface within the high-energy n-type implanted layer. A pseudo-gaussian shaping with 250 ns time constant was used for the measurements. For drift fields of 50 V/cm or smaller a longer shaping time of 3 µs has been used. In fact as the drift time increases the electron cloud broadening becomes comparable to the shaping time (at 50 V/cm the contribution of thermal diffusion to the electron cloud broadening is larger than 500 ns r.m.s.). The laser spot was displaced by 30 µm steps (equal to the pitch of the field strips) along the drift direction. Fig. 6 shows the drift time as a function of the drift coordinate with the CDD biased at 300 V/cm. The measured non linearity error is below 40 ns and is mostly due to an accidental damage in the integrated divider at about 1/3 of the active area.

Fig. 7 shows the average drift velocity as a function of the applied drift field. It has been derived from the linear fit of the measured drift times versus the drift coordinate. At 300 V/cm the average drift velocity is 0.35 cm/µs. Proper electron drift is possible even at 25 V/cm and the achieved average drift velocity is 0.026 cm/µs. The solid line shows the ideal bulk velocity \( v_{\text{drift}} = \mu_n \times E_{\text{drift}} \) where we arbitrarily assumed \( \mu_n = 1400 \text{ cm}^2/(\text{Vs}) \) for the electron bulk mobility. The average drift velocity shows a reduction of about 17% with respect to the ideal drift velocity.
In order to verify the effectiveness of the combination of deep n- and p-implants in achieving the lateral confinement of the signal charge the laser spot was focused in the middle of a drift strip at about 6 mm far away from the collecting electrode and displaced by 5 µm steps along the lateral coordinate. The corresponding amplitude at the output electrode was measured. As shown in Fig. 8 for three neighbor channels, the deep implanted doping profile effectively confines the signal charge within one drift channel.

Finally we biased the detector in integrate-readout mode at a drift field of 200 V/cm and repeated the measurement shown in Fig. 6. Fig. 9 shows the expected ‘staircase’ dependence of the drift time vs. the drift coordinate as within the same pixel length the signal charge starts drifting from the same integration minimum. The nearly abrupt change of the measured drift time occurs when the laser spot crosses the saddle point defining the border between adjacent pixels of the same column.

The same measurement was repeated for drift fields in the range 150 V/cm – 300 V/cm. In Fig. 10 the measured drift time normalised to the drift time

Fig. 6. Drift time vs. drift coordinate measured at 300 V/cm in continuous readout mode using a focused pulsed laser beam. The non-linearity visible at 1/3 of the drift length is due to a damage in the integrated voltage divider.

Fig. 8. Normalized amplitude as a function of the lateral coordinate at about 6 mm from the collecting electrodes. Three adjacent channels are shown.

The same measurement was repeated for drift fields in the range 150 V/cm – 300 V/cm. In Fig. 10 the measured drift time normalised to the drift time
from the last pixel is shown as a function of the drift coordinate. For all experimented drift fields the non-linearity of the drift time vs. incident position is negligible compared to the pixel length apart from a small region around the already mentioned damage.

**Acknowledgement**

This work was supported by INFN, Istituto Nazionale di Fisica Nucleare – Sezione di Milano, by the Italian Space Agency (ASI) and by the US Department of Energy under contract number DE-AC02-98CH10886. Accordingly, the U.S. Government retains a non-exclusive, royalty free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

The authors gratefully acknowledge E. Gatti for many fruitful discussions and P. Holl and the staff of the MPI Halbleiterlabor for the detector production. We are specially indebted to S. Masci for careful bonding of the detector chip. We also acknowledge RTM of Vico Canavesi (Italy) for the laser drilling of the chip holder. A. Castoldi, A. Galimberti and C. Guazzoni would like to thank R. Menk and F. Arfelli for the kind hospitality at the SYRMEP beamline (Sincrotrone Trieste).

**References**