The Controlled-Drift Detector: a new detector for fast frame readout X-ray imaging☆

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Abstract

The Controlled-Drift Detector (CDD) is a new X-ray imaging detector operated in integrate-readout mode. Its basic feature is the fast transport of the integrated charge to the output electrode by means of a uniform drift field. The energy-resolved X-ray imaging capability of the CDD has been tested at room temperature. The images of a ^{55}Fe source taken with the CDD at different frame rates (up to 10 kHz) are presented and the achieved energy resolution is analyzed. A detector with such features can be of interest in several fields of application like time-resolved X-ray crystallography and astronomy.

1. Introduction

Several applications, such as crystallography [1], medical diagnostic [2] and X-ray astronomy [3] require detectors which combine good energy resolution with position information and feature high frame rate capability. The development of high-intensity synchrotron X-ray sources has made it possible to perform X-ray diffraction and crystallography experiments on time scales sufficiently short (microseconds) that fundamental biological, chemical and physical processes may be probed (time-resolved macromolecular crystallography [4], time-resolved crystallography of a certain class of phase transitions in chemical reactions [5], time-resolved muscle fiber diffraction [6], time-resolved small angle X-ray scattering [7]). Therefore several research groups are currently involved in the development of advanced detectors for the aforesaid applications [8–10]. A second field of application that could benefit from the development of fast frame rate imaging detectors is X-ray astronomy. The 0.25–10 keV X-ray band contains the K-shell lines of all the abundant metals (carbon through zinc), and the L-shell lines of many. In the study of the chemical composition and evolution of the universe X-ray imaging and spectroscopic observations of supernovae and remnants can directly measure the synthesis and distribution of heavy elements [11]. Time-resolved high-resolution iron line spectroscopy will map the innermost regions near black holes and will measure the properties of strongly curved space-time [12]. Finally, X-ray spectroscopy will measure the surface temperature and composition of isolated neutron stars and constrain the nuclear equation of state.

In this paper, we present the results of the experimental characterization of a new X-ray imaging detector that can fulfill the demanding requirements of the aforesaid fields of application. In particular, the images of a ^{55}Fe source registered with the Controlled-Drift Detectors (CDD) at different frame rates (up to 10 kHz) are presented and the achieved energy resolution is discussed.

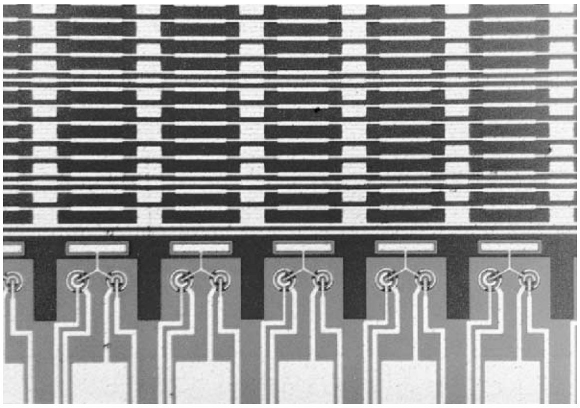

Fig. 1. Microphotograph of the anode side of the Controlled-Drift Detector in the low-voltage region. Five pixel columns are clearly visible, each provided with a readout electrode and on-chip electronics.

2. Basic concepts of the Controlled-Drift Detector

The Controlled-Drift Detector (CDD) [13,14] is a new imaging detector for X-rays in the range 0.25–20 keV. The device is fully depleted and operates by switching between integration and drift mode. The basic idea of the CDD is to generate potential wells in spite of a superposed uniform drift field. The drift field can be high enough to provide fast drift velocity for signal electrons. The time between the removal of the barriers and the arrival of the signal electrons to the collecting anodes gives the position of the illuminated "pixel" in the drift direction. The second coordinate is obtained from the granularity of the anodes. The energy of the X-ray is measured by the signal charge with spectroscopic resolution.

The starting material is a 280 μm thick high resistivity (3 kΩ cm) n-type, detector-grade silicon wafer on which an epitaxial 50 Ω cm n-type layer was grown. During the drift mode the p+ strips of the front side are biased at linear increasing potentials, thus generating a nearly uniform drift field that transports the integrated electrons to the readout anode. During the integration mode the bias of the p+ strips is modified in order to block the drift and fully confine the signal electrons. The new strip potentials are obtained by superposing a perodical bias perturbation to the linear bias in order to generate equally spaced potential wells along the drift coordinate. The pixel size of the CDD is 180 μm × 180 μm given by the pitch of the channel-stops and by the number of field strips (6) used to generate the bias perturbation. The chosen strip pitch of 30 μm also assures acceptable non-uniformity of the drift field during the drift mode [14]. Fig. 1 shows a microphotograph of the anode side of the CDD in the low-voltage region. Five pixel columns are clearly visible, each provided with a readout electrode and on-chip electronics.

The working principle of the CDD has been verified with a signal charge of 24 000 electrons for drift fields in the range 100–400 V/cm [14]. The non-linearity of the drift time vs. incident position is 1% of the pixel length at 300 V/cm. This assures safe reconstruction of the position information from the measurement of the drift time. At 300 V/cm the measured drift speed of the charge packet is 0.35 cm/μs. Charge handling capability exceeding 10^5 electrons is reached with 2.1 V amplitude of the surface perturbation at a drift field of 400 V/cm while the same charge handling capability is obtained at 250 V/cm with 1.44 V [15].

3. Time-resolved X-ray imaging

We tested the imaging capability of the detector and its spectroscopic resolution when operated in integrate-readout mode. The output of the preamplifier shaper ($\tau_{sh} = 250$ ns) was fed to an 8-bit digitizer controlled by a PC that acquires the output waveforms, subtracts the background and computes the amplitude and the arrival time of each pulse. We performed several images of ^{57}Co and ^{55}Fe with the CDD operated at room temperature at different frame rates (up to 10 kHz). We present here the image of a ^{55}Fe source obtained with the CDD operated at 10 kHz frame rate. The readout time was set to 10 μs, enough to include electron drift and signal processing, and the integration time to 90 μs. The operating drift field was 200 V/cm and the amplitude of the surface perturbation was 2 V. A scatter plot of the obtained X-ray image is shown in Fig. 2. Moving along the vertical axis we see that the events are clearly gathered in clusters centered at about 6 keV corresponding to the K_α and K_β lines. Moving along the time axis the clusters are well separated indicating the illuminated pixels. A more detailed analysis is obtained by plotting the measured events against one parameter at a time. Fig. 3 shows the distribution of the events along the time axis. The peaks of the drift-times are clearly visible and are in close agreement with the drift-time measurement made with the laser spot in the preliminary characterisation. Fig. 4 shows the total distribution of the events along the energy axis that corresponds to the spectrum of the ^{55}Fe source collected by all the pixels. The energy resolution at the K_α line (5.899 keV) is 837 eV FWHM, corresponding to an Equivalent Noise Charge (ENC) of 98 electron r.m.s.. The noise analysis shows that the main

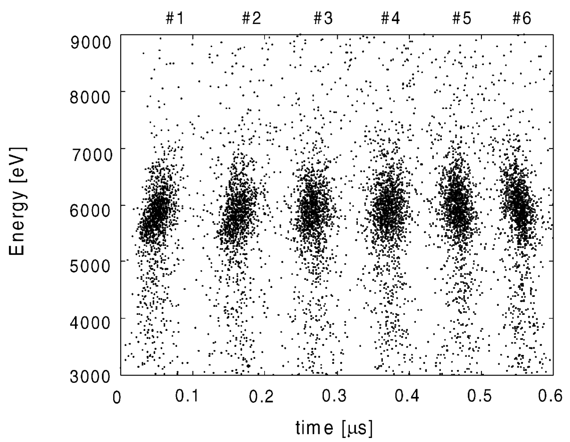

Fig. 2. Scatter plot in energy and drift time of the X-ray image of a ^{55}Fe source collected by a column of the CDD. The measurement was carried out at room temperature. The readout and integration times are 10 and 90 μs, respectively.

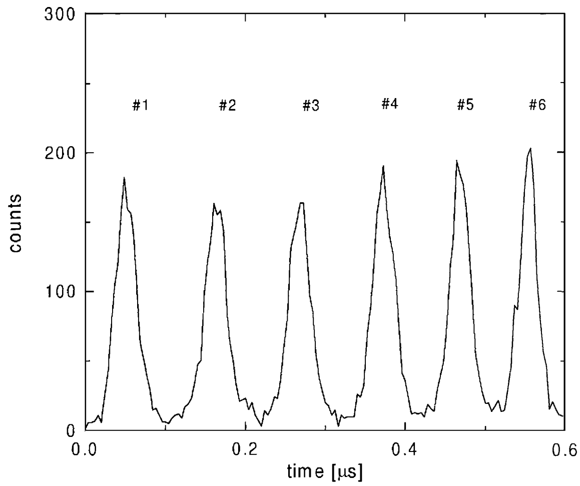

Fig. 3. Distribution of the events of Fig. 2 along the drift time (equivalent to the drift coordinate).

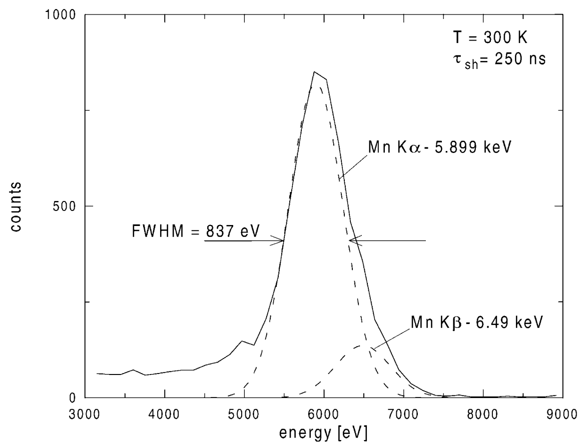

Fig. 4. Distribution of the events of Fig. 2 along the energy.

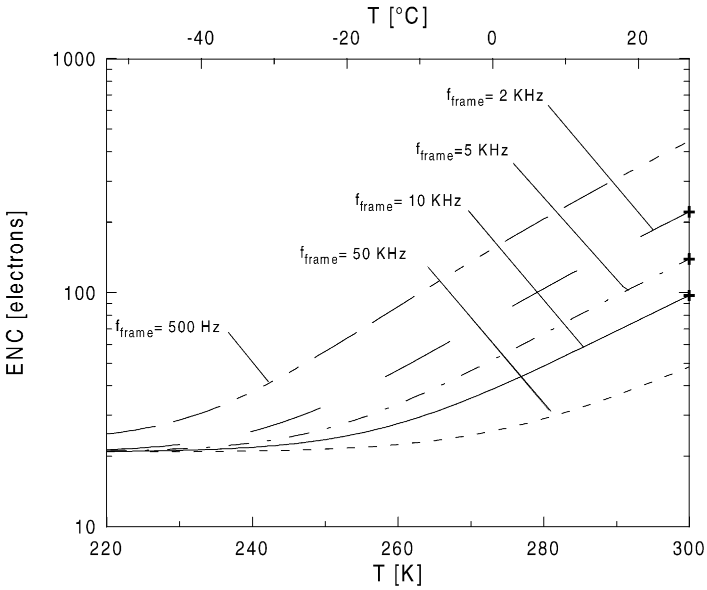

Fig. 5. Expected equivalent noise charge vs. temperature for different frame rates. The crosses are the experimental points.

contributions are from the noise of the electronic chain (20 electrons r.m.s.), the quantization noise of the 8-bit ADC converter (12 electron r.m.s.) and the parallel noise due to the leakage current (about 40 pA/channel) integrated in the pixels during the 90 μs integration time (95 electrons r.m.s.). As the dominant contribution in the achieved energy resolution is the parallel noise due to the integrated leakage charge ways to reduce such contribution are discussed. One way is to cool down the detector in order to reduce the thermally generated current. A second possibility is to shorten the integration time in order to reduce the amount of leakage charge that accumulates in the pixels. Assuming a fixed time ratio between integration and readout to minimize out-of-time events, this requires to increase the frame rate. In fully depleted pn-charge-coupled devices [16] the duration of the readout time is limited by the shaping time to the millisecond range and the only way to reach maximum performances is to cool down the detector. In the CDD the readout time is ultimately limited by the time needed to drift the integrated signal electrons to the anode, that is about 2–3 μs for a 1 cm-long detector. Therefore higher frame rate of the order of 30–50 kHz are expected to be achieved with the CDD. An estimation of the achievable energy resolution as a function of the operating temperature and of the frame rate is shown in Fig. 5. It is clear from Fig. 5 that the lower contribution of the thermal noise at higher frame rates (i.e. shorter integration times) brings the room-temperature energy resolution close to the one obtainable at cryogenic temperatures and lower frame rate. Energy resolutions close to present state-of-the-art X-ray imagers are expected to be obtained with Peltier-cooled CDD systems.

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