Detectors for fast X-ray timing and spectroscopy

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The High Time Resolution Spectrometer (HTRS) on board the International X-ray Observatory (IXO) is dedicated to the physics of matter at extreme density and gravity and will observe the X-rays generated in the inner accretion flows around the most compact massive objects, i.e. black holes and neutron stars. As these are the brightest objects in the X-ray sky the HTRS has to work at extreme count rates and is therefore based on a Silicon Drift Detector (SDD). The SDD is an X-ray sensor combining a large sensitive area with a small output capacitance. It uses fast signal charge collection on an integrated amplifier by a focusing internal electrical field and is optimised for high resolution spectroscopy at high count rate. The HTRS sensor is a monolithic array of Silicon Drift Detectors (SDDs) with 31 cells in a circular envelope and a sensitive volume of 4.5 cm^2 x 450 μm. It is specified to provide energy spectra with a resolution of 150 eV (FWHM at 6 keV) at high time resolution of 10 μsec and with high count rate capability up to a goal of $2 \cdot 10^6$ counts per second, corresponding to a 12 Crab equivalent source. As the HTRS is a non-imaging instrument and will target only point sources it is placed on axis but out of focus so that the spot is spread over the array of 31 SDD cells.

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1. Introduction

The International X-ray Observatory (IXO) [1] is a joint high-energy mission of the US-American, European, and Japanese space agencies with a projected launch in 2021. To address some of the fundamental questions in contemporary astrophysics and cosmology (matter under extreme conditions, formation and evolution of galaxies, clusters and large scale structure, life cycles of matter and energy) IXO requires high sensitivity and high spatial resolution over a broad energy band with excellent energy and time resolution. Therefore, IXO combines a large aperture X-ray mirror (collecting area 3 m², focal length 20 m, angular resolution 5 arcsec) with a set of six specialized complementary sensor systems focal plane sensors.

The High Time Resolution Spectrometer (HTRS) [2] is the only focal plane instrument matching the IXO top level requirement to observe a bright X-ray source of the intensity of one Crab with less than 10 % dead time. The HTRS science will focus on matter under extreme conditions, by simultaneous fast X-ray timing and high-resolution spectroscopy measurements of compact objects (black holes, neutron stars) powered by accretion. As the sources to be observed by HTRS are the brightest in the X-ray sky the instrument design is driven by the capability to operate at extremely high count rates. The only available sensor concept that is able to cope with the HTRS requirements summarized in table 1 is the Silicon Drift Detector (SDD). It combines a large sensitive area with an extremely small readout capacitance and is therefore predetermined for high-rate high-resolution X-ray spectroscopy. The HTRS instrument is based on a monolithic array of 31 SDD cells. As HTRS is a non-imaging instrument and will target only point sources it is placed on axis but out of focus so that the intense photon flux is spread evenly over the array of 31 SDD cells.

energy range	0.3 - 15 keV	
time resolution	10 µsec	
energy resolution (-40 °C)	150 eV	goal at beginning of lifetime
FWHM @ 5.9 keV	≤ 200 eV	requirement at beginning of lifetime
	≤ 300 eV	requirement at end of lifetime
count rate capability	> 10 Crab	1 Crab ≈ 170.000 photons/sec
deadtime & pile-up	< 2% @ 1 Crab	

Table 1.   The sensor requirements of the IXO High Time Resolution Spectrometer

2. Silicon Drift Detector

A Silicon Drift Detectors (SDD) is a large volume of a high resistivity semiconductor, in our case n-type silicon, which is depleted by a small sized n^+-bulk contact reverse biased with respect to p^+-junctions covering both surfaces of the structure. The p^+-junctions are strip-like segmented and biased in such a way that an electric field parallel to the surface exists [3]. Electrons released within the depleted volume by the absorption of ionizing radiation or by thermal generation drift towards the n^+-substrate contact, which acts as collecting anode and is connected to an amplifier. The generated holes are drained away by the p^+-junctions.

In an advanced SDD design optimized for applications in photon spectroscopy the p[+]-strip system for the generation of the drift field has the shape of concentric rings. The drift rings and the collecting anode in their centre are placed on one side of the structure, while the opposite surface is covered by a non-structured p[+]-junction acting as homogeneous, thin radiation entrance window [4, 5] (fig. 1). There is no field-free region in the device, and the whole volume is sensitive for the absorption of ionizing radiation. The typical signal charge drift time is of the order of 100 nsec. SDDs of this type do not provide position information but are used as energy dispersive spectrometers, taking advantage of the small value of the anode capacitance, guaranteeing high count rate capability and excellent, CCD-like energy resolution.
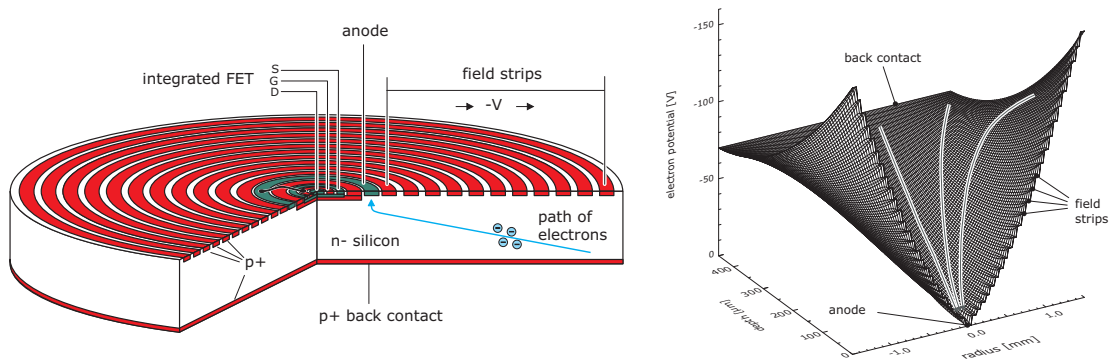

Figure 1.   Schematic view of a cylindrical Silicon Drift Detector and its calculated potential distribution.

An additional gain in high-rate performance and energy resolution is achieved by integrating the first transistor of the amplifying electronics on the SDD chip [6]. That way the SDD also gets robust with respect to microphonic noise and electrical pickup. Due to its minimized overall capacitance in the order of 100 fF the SDD with integrated transistor has its optimum noise figure at extremely short shaping time constants ≤ 1 µsec and it works at photon rates exceeding 10^5 cps (counts per second) without degradation in spectroscopic performance. The low leakage current level obtained by the elaborated process technology allows operating SDDs at room temperature or with moderate cooling, e.g. by a thermoelectric cooler.

SDDs of this type have been produced in large numbers and are available in a multitude of shapes and sizes from 5 mm² up to 1 cm². They are primarily used for X-ray spectroscopy in industrial instrumentation and scientific experiments. SDDs have also gained space experience in the Alpha Particle X-ray Spectrometers on the robotic arms of the NASA Mars Exploration Rovers Spirit and Opportunity [7]. To increase the sensitive area without loss in performance monolithic SDD arrays have been developed [8].

3. SDD for the High Time Resolution Spectrometer

3.1 Layout

The HTRS sensor is a multi-channel SDD consisting of 31 cells in a circular envelope of 24 mm diameter and a total area of 4.5 cm². The central cell has a circular shape. The outer cells have the shape of ring sectors and are arranged in three rings of 1 x 6 and 2 x 12 cells (fig. 2).

All cells have equal areas of 14.6 mm². The thickness of the Silicon wafer is 450 μm. The 31 SDD cells are logically grouped in four 'quadrants' of seven or eight cells. The quadrants are to a large extent electrically independent, including redundant supply and readout electronics. The readout structures of each quadrant's cells are connected to an eight-channel readout chip.

The border lines between the cells' entrance windows is masked by a baffle to inhibit 'split events' caused by photons absorbed along the cell borders. Split events generate signal charges in two or more neighbouring cells and cause false energy information. The baffle has 200 μm wide spokes and covers a 10 % fraction of the total sensitive area, but it increases the spectral quality as the sensor cells will receive the full signal of single events.
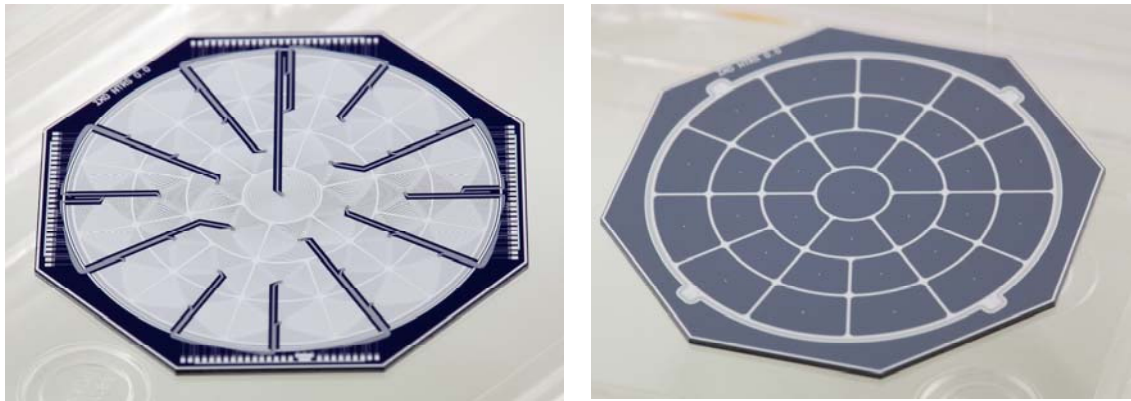

Figure 2.   Mechanical sample of the HTRS sensor, readout side (left) and radiation entrance window side (right).

3.2 Performance

At the HTRS conditions, i.e. sensor temperature -40 °C and short signal processing time for high count rate handling, the SDD energy resolution will be ≤ 150 eV FWHM at 5.9 keV at the beginning of the lifetime. The energy resolution is stable within 2 % and the gain variation is less than 2 ‰ even at count rates $> 10^5$ photons per second and SDD cell, corresponding to a source intensity > 10 Crab (fig. 3). The SDD's quantum efficiency is above 90 % in the energy band from 0.5 to 10 keV. Photons at higher energies are increasingly transmitted through the bulk thickness of 450 μm without interaction. At low energies the quantum efficiency is limited by the entrance window's Si dead layer and by a thin Al layer deposited on the window.

SDDs processed in the HTRS-like technology have proven to be radiation hard with respect to X-rays up to 10^{13} absorbed photons (Mo-K, 18 keV) without degradation of the energy resolution. This figure would theoretically allow for a ten years' continuous observation of a bright source with an intensity of several Crabs. In addition to photon irradiation the HTRS sensor will be exposed to $2·10^9$ ($5·10^9$) protons (10 MeV equivalent) per cm² in a 5 (10) years mission, assuming an effective shielding represented by 15 mm of Aluminium. Protons create defects in the bulk, which are generation centres for leakage current. Based on experimental data [9] this non-ionizing radiation effect has been modelled to cause an additional leakage current of $2.43·10^{-17}$ A at room temperature per 10 MeV proton. The corresponding deterioration of the energy resolution is ≤ 250 eV FHWM at 5.9 keV towards the end of the mission lifetime, still meeting the system specifications within a sufficient margin.

3.3 Readout

The first FET integrated on the SDD chip is configured as a charge sensitive amplifier (CSA, fig. 3) [10]. For the capacitive feedback the parasitic capacitance of the reverse biased junction between the charge collecting anode and a guard ring is used, its value is about 30 … 35 fF. The leakage current and the signals are integrated on this feedback capacitance C_{fb} generating a voltage ramp with superposed steps at the pre-amplifier output. Whenever the output voltage exceeds a preset threshold value the readout chip produces a signal which is used to trigger an external reset circuit discharging the SDD. For this purpose a p^{+}-doped reset diode is integrated directly in the anode. The reset diode is reverse biased (-15 V) during signal integration and pulsed to forward bias (+7 V) for the reset with a pulse duration of 300 … 500 nsec. The reset signal is common for all channels of a quadrant, and so the average reset period is determined by the channel with the highest sum of leakage and signal currents.

The readout configuration with CSA and pulsed reset has been tested using a 5 mm² SDD and conventional discrete components for the electronic chain. The spectroscopy performance is almost independent of the input count rate up to 10^{5} cps: the energy resolution (FWHM at 5.9 keV) is stable on the 1 % level and the peak position is stable on the 0.1 % level (fig. 3).
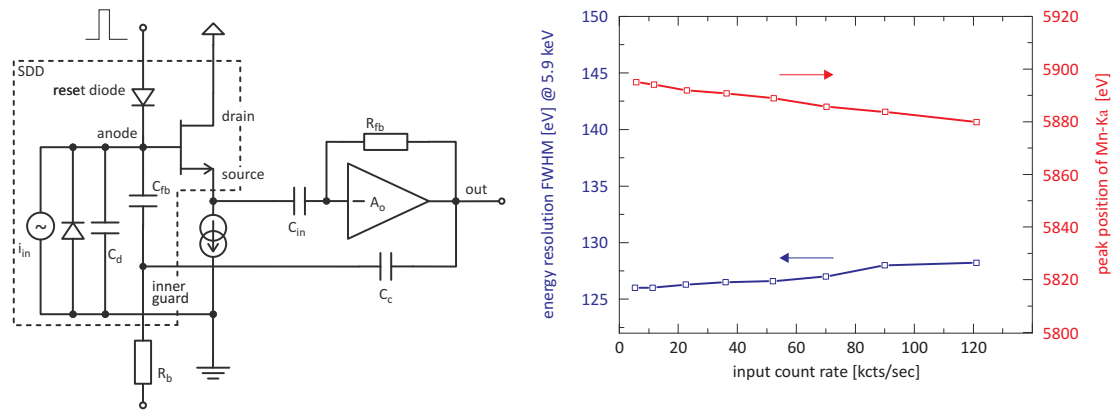

Figure 3. Charge sensitive amplifier configuration of the integrated FET (left)
and measured high rate performance of a 5 mm² SDD (right).

The baseline implementation of the readout electronics is an analog chain integrated in an 8-channel ASIC. It includes a pre-amplifier, a filter with 600 nsec peaking time, a baseline holder, an event trigger, a peak stretcher, and a fast (200 nsec) shaper channel for pile-up detection and rejection. The analog amplitudes of the eight channels and the channel addresses are delivered to an external ADC by an 8/1 analog multiplexer operating at 10 MHz.

As an alternative a digital readout chain is under study. In the digital option the configuration and operation mode of the integrated first FET is unchanged. The readout chip includes eight pre-amplifiers only. The pre-amplifier output signals of each channel are sampled by a fast (150 MHz) 14 bit ADC and filtered by software filter functions with effective time constants comparable to the analog shaper. The digital option is of great flexibility, as its function is mainly based on software which can be developed and adapted even after the launch.

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3.4 Focal Plane

As HTRS is a non-imaging instrument operating at high count rates the sensor is displaced from the focal plane to distribute the photon flux over the 31 SDD cells. With the actual mirror design (3 m² at 1.25 keV) the out-of-focus distance is 11.3 cm. The out-of-focus distance is chosen such that with the given SDD format 99.9 % of the incoming photons fall into the sensor area even in the worst case misalignment scenario. The thermal, mechanical and electrical interface to the HTRS sensor is given by the sensor hybrid. To keep the quadrant philosophy an individual hybrid is assigned to each sensor quadrant. Per quadrant there is one power flex-lead connected to the electronics box and carrying the sensor supply voltages and one signal flex-lead connected to the readout board and including the signal, feedback and trigger lines. To keep the setup compact the active components of the readout electronics are placed on a readout board separated from the sensor by a graded shield plate. Both the sensor hybrid and the readout board are enclosed by an Al box acting both as radiation shield and thermal interface (fig. 4).
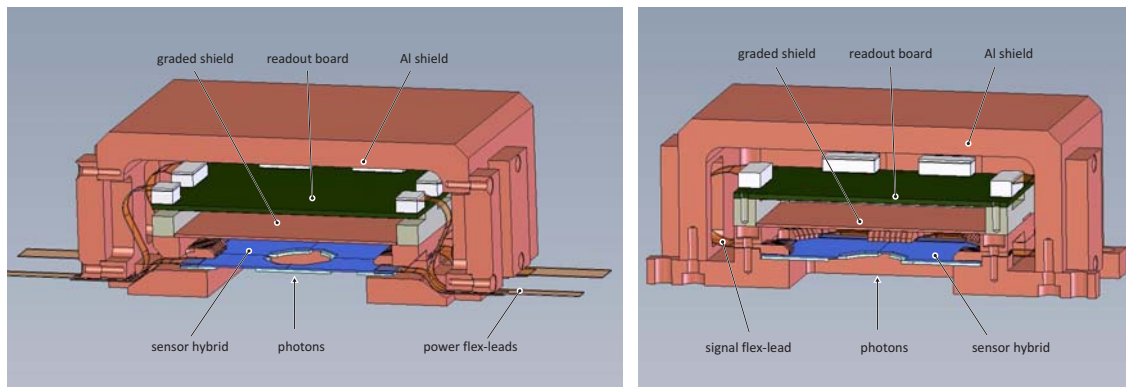

Figure 4. Two perpendicular cross sections of the HTRS sensor assembly.

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