Active Pixel Matrix for X-ray Satellite Missions

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Abstract

We present an active pixel matrix for high rate, spectroscopic and imaging X-ray detection. It is foreseen as a wide field imager on the XEUS (X-ray Evolving Universe Spectroscopy) satellite. A 1024 × 1024 pixel device with pixel sizes of 50 – 75 µm shall cover an area of 76 mm × 76 mm.

A single pixel consists of a p-channel DEPFET (DEPleted Field Effect Transistor). It is realized on high-ohmic detector grade silicon allowing the bulk to be fully depleted to achieve high quantum efficiency.

In a matrix arrangement pixels are interconnected in such a way that single rows can be randomly accessed and read-out. Various read-out modes can be realized making this detector an ideal instrument for the high dynamics in the photon flux on XEUS.

A 64 × 64 pixel matrix prototype has been produced at the HLL. We will describe the test system setup, and present measurements, which characterize the expected performance for a focal plane instrument.

I. INTRODUCTION

Current state-of-the-art focal plane instruments for wide field X-ray imaging on satellites are CCDs (Charge Coupled Devices). They combine adequate position, energy (typically 140 eV FWHM at 6 keV) and time resolution (50 µs with pn-CCDs). However, the operating principle of the CCD limits the tolerable rate of photons in single photon counting mode as well as the time resolution. The crucial parameter is the transfer time of the signal charges, which is in the order of few milliseconds for the fastest existing CCDs (pn-CCDs, see [1, 2]).

Table 1. lists several relevant specifications of past, current and future X-ray space observatories. It reflects the development towards higher sensitivity and optical resolution. Higher spectroscopic resolution is a parallel development using dedicated instruments with no or limited imaging capabilities such as grating spectrometers (RGS on XMM [3]) or cryogenic detectors (CIS on XEUS [4]).

The XEUS mission is currently under study by ESA's Horizons 2000 Survey committee. It is an X-ray satellite telescope, which shall be launched in approximately 2010. XEUS wants to look far back in time to study some of the most distant and hence youngest known objects in the universe. This means in particular to search for very faint sources. The large collection area of the X-ray mirrors will bring the faint source limit down to 10^{-18} erg cm^{-2} s^{-1}. This is about a factor of 100 fainter than XMM's limit. This also means that brighter sources will produce high count rates, which the focal plane detector must be able to "digest".

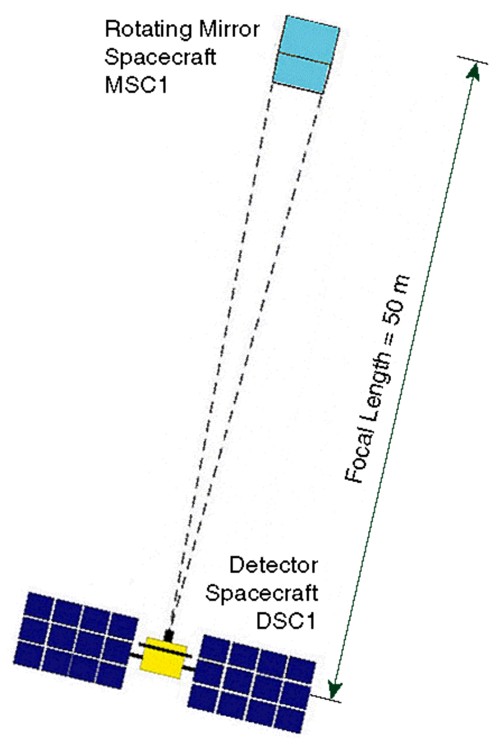

Figure 1: Schematic view of XEUS. The Detector Spacecraft will maintain its position relative to the Mirror Spacecraft's focus within +/- 1 mm³.

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Table 1.
Comparison of X-ray satellite missions' optical properties and derived count rates

	ROSAT	XMM	XEUS I	XEUS II
Launch year	1990	1999	2010?	2015?
Effective area (1 keV)	0.024 m^2	0.2 m^2	6 m^2	30 m^2
Focal length	2.4 m	7.5 m	50 m	50 m
Energy range	100 eV – 2 keV	100 eV – 12 keV	100 eV – 30 keV	100 eV – 30 keV
Resolution (HEW)		15"	2"	2"
Rate in Crab nebula	1 kCts/s	10 kCts/s	300 kCts/s	1,500 kCts/s
Rate in Crab pulsar	0.03 kCts/s	0.3 kCts/s	9 kCts/s	45 kCts/s

Figure 1 shows a schematic view of XEUS. It consists of two modules: the Detector and the Mirror Spacecraft (DSC and MSC). It is planned to launch them into low Earth orbit by a single Ariane V. They will maintain a separation corresponding to the focal length of the mirrors of 50 m. An active range finding system will provide an alignment accuracy of less than one cubic millimeter. In reconstruction the relative position will be known within 100 µm.

The MSC contains two docking ports. DSC – being equipped with an orbital transfer motor – can dock to it and the coupled pair can rendezvous with the International Space Station (ISS) for refurbishing and expansion. After 4 – 6 years of mission duration, it is planned to mount additional mirror modules on the MSC, increasing the initial effective collection area from 6 m^2 to 30 m^2 at 1 keV.

One of the instruments on the DSC will be the Wide Field Imager (WFI). We discuss and propose two detector systems for the WFI, a pn-CCD with a frame store and the active pixel matrix.

II. Focal Plane Detector Considerations

A. CCD based systems

Table 2 compares the pn-CCD on XMM with an advanced pn-CCD incorporating a Frame Store and a DEPFET pixel matrix.

The advantages of the future instruments over the current state-of-the art devices are obvious. An important parameter is the Integration to Read-out time Ratio (IRR), which corresponds to the percentage of out-of-time events. An out-of-time event occurs when a photon hits the CCD during read-out, i.e. during charge transfer. The incident position of this photon is not correctly reconstructed in the dimension of the charge transfer. The current read-out speed of the XMM pn-CCDs is artificially reduced to maintain an acceptable IRR of 11:1. Introducing a Frame Store in the design one can fully exploit the transfer speed of the pn-CCDs. This results in an increase of read-out speed and IRR by a factor of 10 even with about five times more pixels.

Another important value is the precision, to which the incidence time of an X-ray photon can be determined without loss of imaging information. For the CCD based systems the time resolution is equal to the read-out cycle time.

Table 2.
Comparison between focal plane detectors (FF = Full Frame, FS = Frame Store, IRR = Integration to Read-out time Ratio). MOS-CCD based systems are not considered, since their read-out speed is not adequate for high throughput X-ray telescopes (e.g. the MOS-CCDs on Chandra need 3.3 s for a Full Frame read-out).

	XMM	XEUS I	XEUS I/II
Sensor Type	pn-CCD	Pn-CCD (FS)	DEPFET pixel
(FF) read-out cycle	50 ms	5 ms	2 ms
Line transfer time	20 µs	0.1 µs	0
Line readout time	20 µs	10 µs	2 µs
Pixels in focal plane	384 × 400	1024 × 1024	> 1024 × 1024
Pixels per sub-unit	64 × 200	128 × 512	128 × 512
Pixel size	150 µm	50 – 75 µm	50 – 75 µm
Time resolution (FF)	50 ms	5 ms	~20 µs – 2 ms
IRR	11:1	100:1	10:1 – 1000:1

B. Active pixel matrix based systems

A pixel matrix is operated without any transfer of signal charges. The IRR is therefore given by the time to read out a full image divided by the time to read out a line of pixels. In addition the imaging information stays always correct. Depending on when an out-of-time event occurs it will either be suppressed completely (during a clear pulse) or recorded with too low amplitude.

Moreover, since single lines can be randomly accessed, regions where time information is essential (or count rate is high) can be read out more often than the rest of the image. Assuming a minimum IRR of 10:1, a time resolution of 20 µs can be achieved when read-out is restricted to a sub-area of 10 lines. However, also a combined mode is possible: in Full Frame mode, a given sub-region can be read out more often than the rest of the image.

III. DEPFET Pixel Matrix Principle

Figures 2 and 3 relate the layout of a pixel matrix with a schematic cross section as well as with an equivalent electronic circuit.

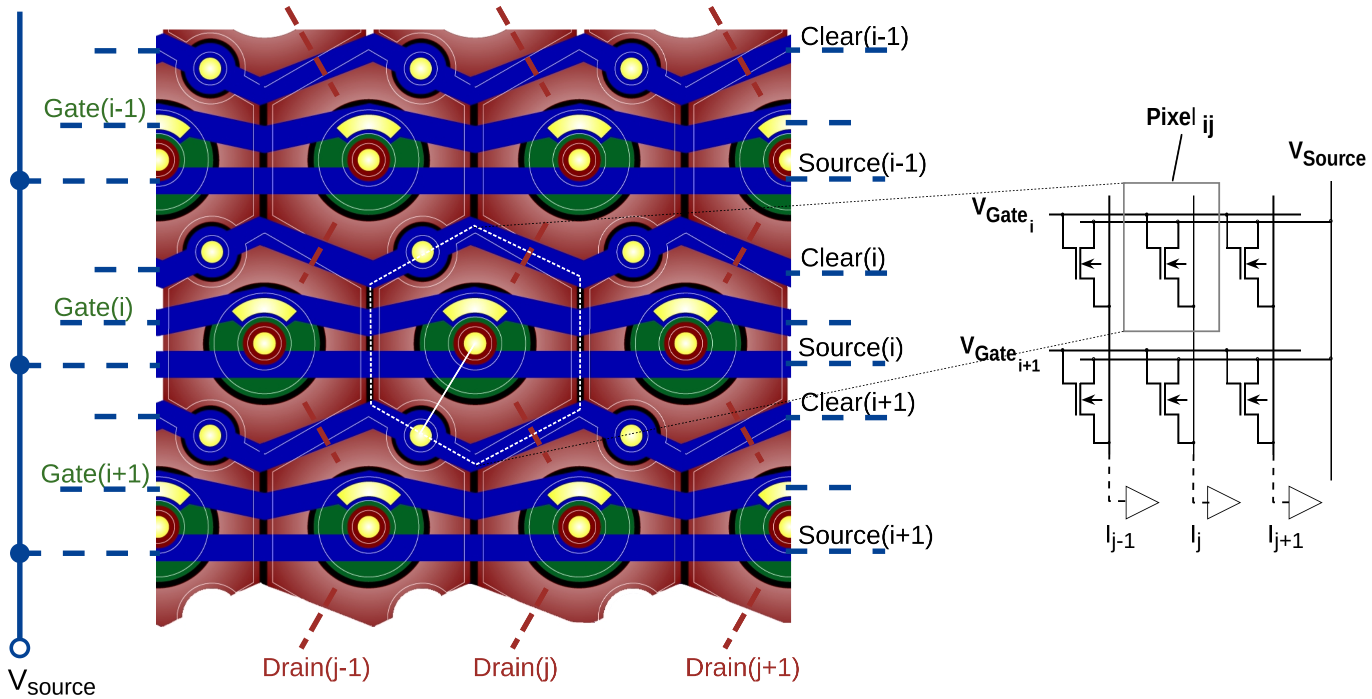

Figure 2: DEPFET pixel matrix layout and schematics. The dashed white line indicates the outline of one single pixel, the solid white line the location of the cross section in Figure 3. Dark dashed lines show how the drains are interconnected.

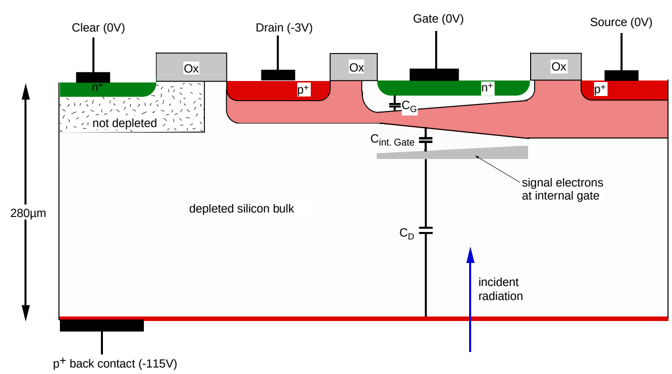

Figure 3: Schematic cross section through a single DEPFET pixel. Voltages apply for read-out phase.

Each pixel is formed by a p-channel DEPFET [5, 6], built on a high-ohmic, n-type silicon wafer. The DEPFET structure is realized by ion implantation. A ring-shaped n+ gate surrounds the circular p+ source. Both are embedded in the p^+ drain. High-energy implants are used to produce the transistor channel and to "configure" the potential inside the pixel in such a way that a potential minimum for electrons is present. This potential minimum is located under the n^+ gate and electrons collected there will influence the transistor current. We therefore refer to this potential minimum also as the *internal* gate and to the n^+ ring as the *external* (accessible) gate.

The silicon bulk is fully depleted via a large area p^+ back contact (common for all pixels in a matrix). It simultaneously works as an entrance window for incident radiation. A production process has been developed to minimize the dead-layer of X-ray CCDs and spectroscopic Silicon Drift Detectors [7, 8].

The DEPFET pixel is operated in three states:

1. Signal charges are collected in the integration phase. A positive voltage at the external gate inhibits the transistor current and puts the pixel in an inactive (though sensitive) state.
2. During read-out an appropriate voltage on the external gate switches on the DEPFET's current. The modulation of this current due to signal charges stored in the internal gate is amplified and recorded. The read-out is non-destructive.
3. The pixel has to be cleared periodically to remove charges generated by signals or leakage current from the internal gate. This is done in the third phase by applying a positive voltage to the n^+ clear contact.

In a matrix arrangement all pixels of one row are simultaneously controlled (i.e. deactivated, read-out or cleared). Two interconnections per row, one between all gates and the other between all clear contacts realize this. The control voltages are supplied by a pair of ASIC chips, the so-called Switchers [9]. Each of their outputs is connected to one row of either gates or clear contacts. Up to four DC voltages (max. 25 V) can be selectively applied to choose one of the three above operating states.

The read-out signal is picked up by a multiplexing preamplifier ASIC (e.g. the CARLOS chip [11]). Its input channels are connected to the drains of the pixel matrix. The drains are common to one column of pixels. However, since only one row is active at a time an unambiguous correlation between a signal and the originating pixel is guaranteed. A possible layout for a full-scale focal plane system is shown in Figure 4.

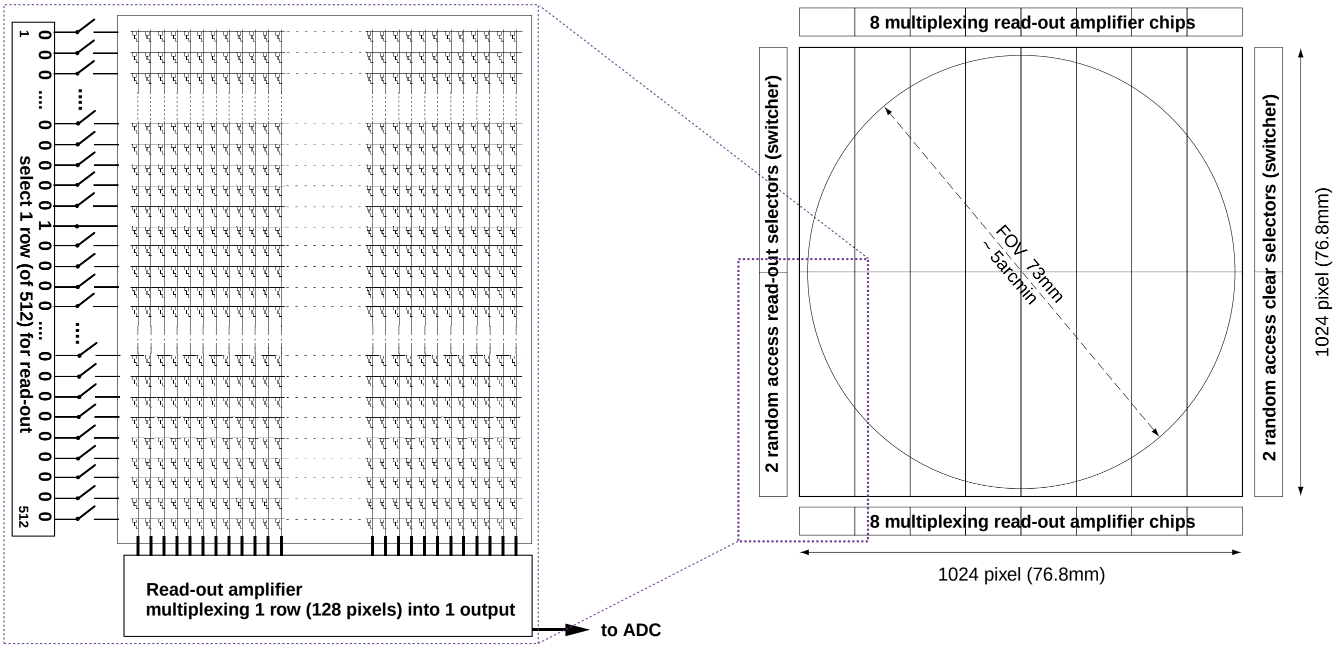

Figure 4: Layout of a focal plane matrix system, consisting of the detector chip, read-out and control electronics. The figure shows the sensitive area and its logical division.

The detector chip is logically divided into 16 sub-units of 128 × 512 pixels. Each sub-unit is read out by one amplifier chip. One pair of switcher controls all 1024 pixels per row. Still, due to the non-destructive character of the read-out, sub-regions can be selected. Such a system has been suggested as a wide field imager for the XEUS mission [10].

V. Measurement Results

A. Quantum efficiency

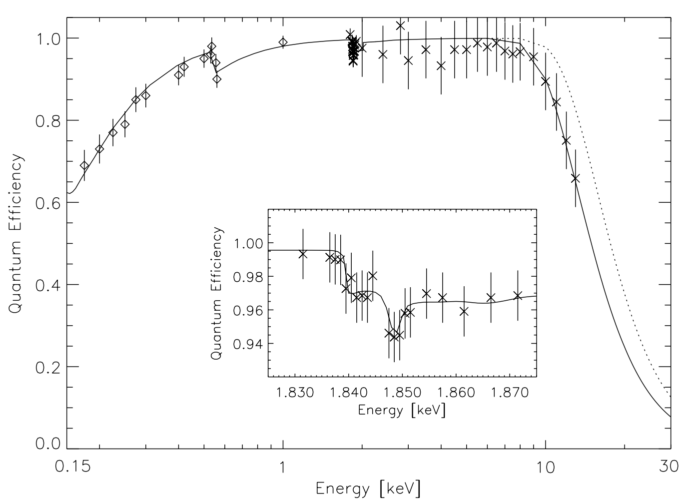

Figure 5: Quantum efficiency measured with the pn-CCD. The drops at 538 eV and 1,840 eV are due to absorption loss at the oxygen and silicon K-edges respectively in a 30 nm SiO_2 surface layer. Crosses indicate measurements with the XMM flight camera and diamonds with a test CCD. Solid (for a 280 µm thick silicon) and dashed (500 µm) lines are based on a model [8] and in excellent agreement with the measurement.

The quantum efficiency of a DEPFET pixel detector can be precisely predicted. Figure 5 shows the response to X-ray photons in the range from 150 eV to 30 keV. Although the measurement has been carried out with pn-CCDs the results are equally valid for the DEPFET pixel matrix, since the relevant production steps are 100 % compatible.

B. Isolated Pixel Spectrum

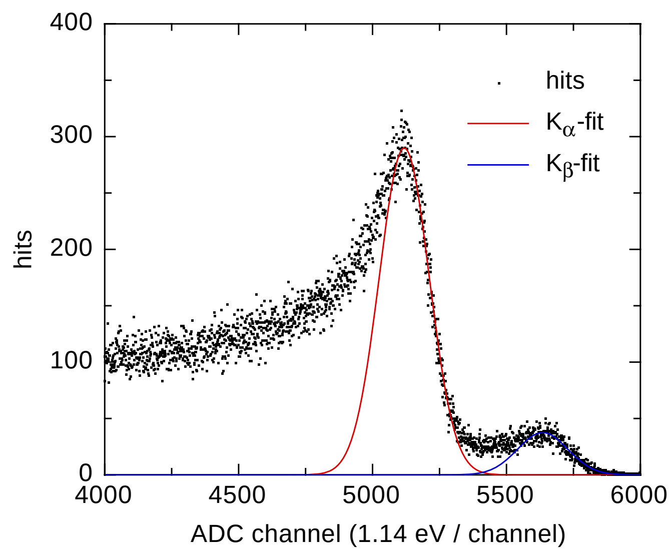

Figure 6: ^{55}Fe Spectrum from an isolated pixel test structure. An electronic noise contribution of 158 eV (12 e$^-$ ENC) at room temperature can be derived.

To test the performance of the DEPFET pixel without the complications of the complete setup to operate a pixel matrix, dedicated test structures were produced. They correspond in design and layout to a single pixel from the matrix, but can be operated with a minimum amount of bond connections. The spectrum in Figure 6 was recorded with such a test structure using the X-ray photons from the Manganese K_{α} and K_{β} decays of an ^{55}Fe isotope.

Due to the small area of the single pixel (50 µm × 50 µm) a large number of partial events (i.e. signal charges are only partially collected in the pixel) are present in the spectrum. In a matrix arrangement these charges are not lost, but are recorded in the neighboring pixels, while for the test structure measurement the peaks become distorted asymmetrically. A careful analysis about this problem can be found in [12], where a noise contribution of 12 e^- ENC is derived.

Measurements on pixel matrix prototype systems have been carried out at the University in Bonn [12, 13]. In the near future temperature scans shall verify that further improvement of the noise performance is possible when the devices are cooled.

V. SUMMARY OF PROPERTIES

The design of the DEPFET pixel results in the following performance properties:

- Geometrically homogeneous energy response
- Sensitivity at higher X-ray energies (up to 30 keV)
- Low energy threshold (~ 200 eV)
- Low noise, spectroscopic energy response
- Non-destructive, fast and flexible read-out
- Radiation hardness (also shielding effect for the pixel side)
- High MIP rejection ratio
- No charge transfer, no geometrical confusion of out-of-time events

VI. CONCLUSIONS

With these properties an active pixel matrix seems a promising focal plane instrument for wide field imaging, wide energy range spectroscopy and high time resolving observations on X-ray satellite missions.

VII. ACKNOWLEDGEMENTS

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