IMAGING SPECTROMETERS FOR FUTURE X–RAY MISSIONS

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Abstract

Based on the operational experience with the EPIC pn-CCD system on board of XMM-Newton [1], new imaging X-ray spectroscopic detector systems for future X-ray missions will be introduced in terms of energy, position and time resolving detectors.

As the readout speed requirement in the case of single photon counting detectors increases drastically with the collecting area and improved angular resolution, but noise figures have to be on the lowest possible level, new detector schemes must be developed: Active pixel sensors (APS) for X-ray detection have the capability to randomly select areas of interest and to operate at noise levels below 1 electron (rms). About 1000 frames per second can be read out with a relatively low level of electric power with the proposed DEPFET arrays.

One prominent candidate for the use of an APS is ESA's XEUS – the X-ray Evolving Universe Spectroscopy mission. It represents a potential follow-on mission to the cornerstone XMM-Newton, currently in orbit. The XEUS mission is considered as part of ESA's Horizon 2000^+ program within the context of the International Space Station (ISS).

1 Introduction

Future X-ray missions will require focal plane instruments with pixel sizes in the order of 75μm and with a position resolution in the 50 μm range, faster readout because of the highly increased effective telescope area, and improved quantum efficiency at the high and low energy end. In addition operation should be possible at higher temperatures and the optical light should be blocked at the camera level to avoid large area fragile structures in front of the radiation entrance window.

To face this situation we pursue two options: (1) The continuous improvement of the pn-CCD technology and operation, and (2) the development of a new detector-amplifier structure (DEPFET) operating as an active pixel sensor [2]. Recent results will be presented.

The frame store pn-CCD development is described in detail in the paper [3]. Both detector systems, the CCD as well as the APS may cover the radiation entrance side with a thin aluminum layer acting as a light blocking filter in the visible. A 100Å thick monolythically grown Al layer reduces the optical throughput by a factor of 5×10^6, but also lowers the quantum efficiency at e.g. C_K from 90% without filter to 40% with the Al filter. But large area fragile thin filters can be avoided (see ref. [3]).

In addition both detector systems can be operated with a spectroscopic high speed channel, being able to process 10^7 X-rays per second within an active area of 10 to 20 mm^2 based on an silicon drift detector.

2 Active Pixel Sensors

Several limitations of CCD type detectors operated as a single photon counter, can be overcome by pixel detectors, where every pixel has its own amplifier. A long charge transfer through the device is not needed any more and every pixel could be x-y-addressable offering an observation adapted readout mode. In addition, the signal charge can be read out several times, reducing the electronic noise with the square root of the number of readings.

2.1 The DEPFET Principle

The DEPFET is a p-channel field effect transistor on high resistivity n-type bulk [5]. The transistor may be either a JFET, or a MOSFET of enhancement and depletion type. The bulk is completely depleted by the reverse biased backside diode, thus creating a potential minimum for electrons close to the surface. An additional buried n-doped channel underneath the transistor gate enhances the potential minumum for electrons and thus confines them to the region below the FET channel (see Fig.1). Each electron released in the depleted volume below the transistor by absorption of ionizing radiation or by thermal generation will drift to the potential minimum, called 'internal gate', and enhance the transistor current by inducing an additional positive charge inside the FET channel. Thus, the DEPFETs current is a function of the amount of charge in the potential minimum, and its measurement yields information about the energy absorbed in the depleted volume. One electron in the 'internal gate' typically increases the transistor current by 0.5 nA. Depending on leakage current

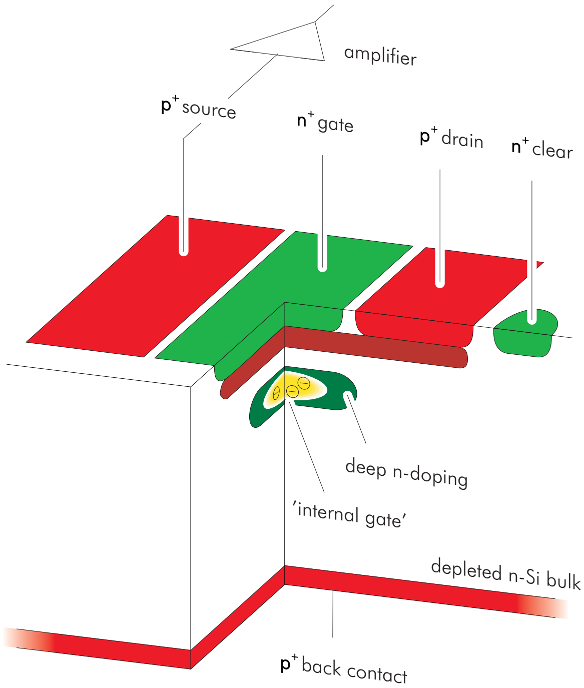

Figure 1: Cross section of a DEPFET. Signal electrons stored in the internal gate steer the current of the p-channel JFET. The n^+clear removes the charges under the p-channel after the first amplification is completed.

and signal rate the internal gate has to be reset periodically by applying a positive voltage to an adjacent n^+-doped 'clear' contact to remove the stored electrons.

Charge collection in the internal gate functions equally well, when the transistor current is turned off. Therefore it is also possible to collect the signal charge in "off" state condition, measure the current after turning the transistor on with the external gate and compare this current with that obtained after emptying the internal gate with the help of the n^+clear contact. As only the DEPFET pixels are powered which are read out, the total power dissipation can be reduced by a factor of 1,000 for the whole focal plane. This leads to a total power requirement for the focal plane of approximately 15 W including signal processing and analog-to-digital conversion.

Unlike a conventional detector-preamplifier system the DEPFET is free of interconnection strays capacitances. The noise characteristics of single DEPFET devices have been evaluated by spectroscopic measurements. From the width of the noise peak an equivalent noise charge (ENC) of 4.6 electrons (rms) at room temperature and 3.6 electrons (rms) at – 60 ° C has been deduced (see Figs. 2 and 3). The measurement of 4.6 electrons (rms) is to our knowledge the best spectroscopic measurement at room temperature ever made with silicon.

The remomal of charges (from signal and leakage current) can be done in an elegant way: A small ohmic n^+contact, the clear contact, to be seen on the left side of Fig. 1, can be electronically hidden

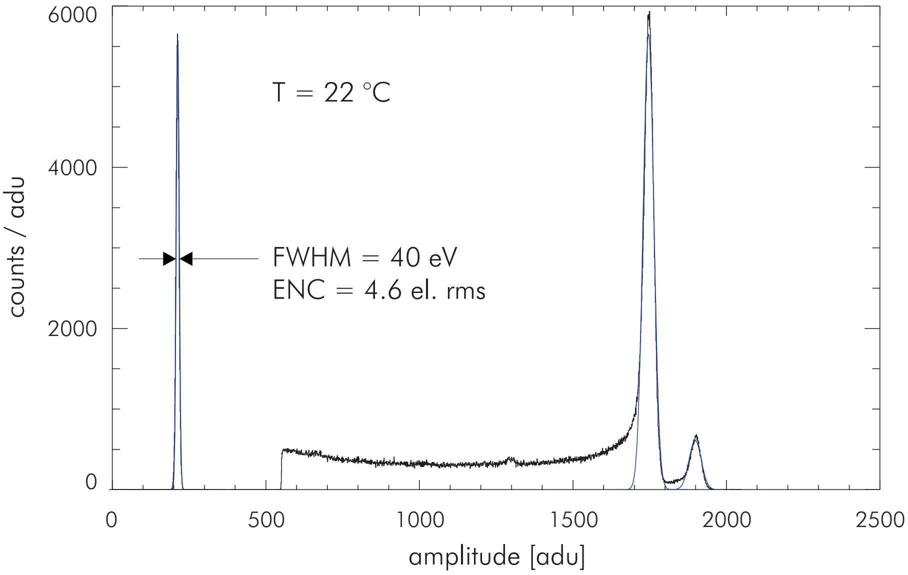

Figure 2: Measurment of the Mn K_α and Mn K_β spectrum of an ^{55}Fe source at room temperature with a single DEPFET structure. The position of noise peak indicates zero of the energy scale, Mn K_α is at 5.898 keV, Mn K_β at 6.49 keV. The continuous hits from ADC count 550 (trigger threshold) to 1,700 is due to split events at the border of the pixel.

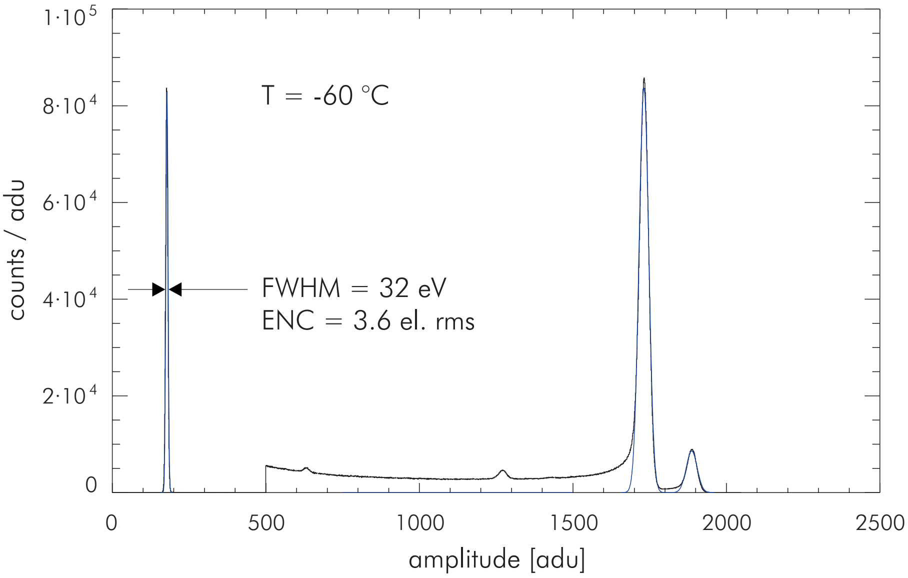

Figure 3: Measurment of the Mn K_α and Mn K_β spectrum of an ^{55}Fe source at – 60 ° C. The Si K_α line at 1.74 keV and the escape peak at 4.15 keV is clearly to be seen. The ENC of this measurement is 3.6 electrons (rms)

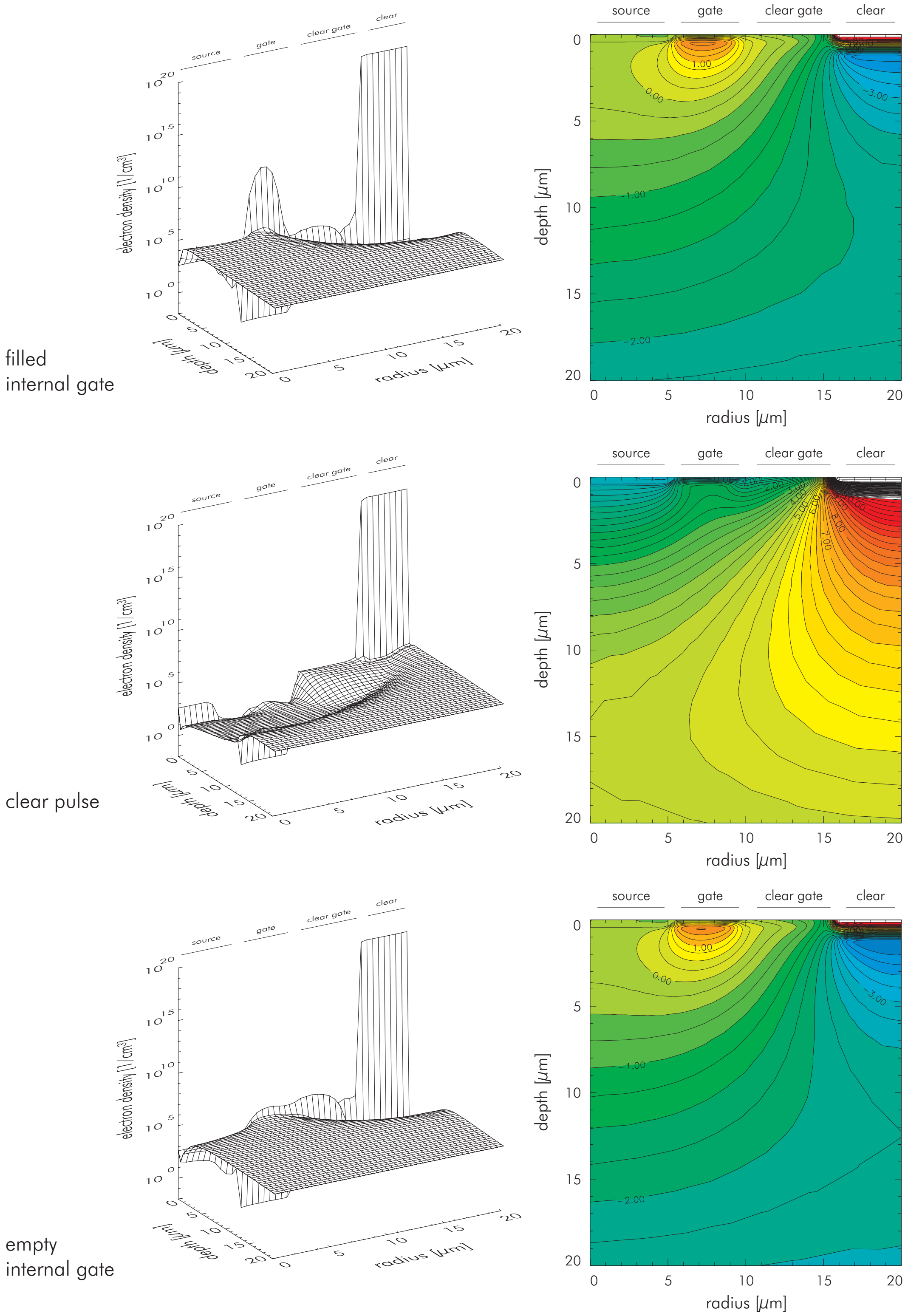

Figure 4: Simulation of the charge integration and clear process in DEPFET type detector-amplifier structures. Upper plots: electron density and electric potential during the signal integration, center plot: during the clear process and lower plot: after clearing of the pixel.

in the substrate: It remains attractive for electrons during the clear process, but during the signal integration time, when the transistor is in “off” state, its capability to attract electrons can be completely suppressed; no signal electron can reach the clear contact The intergation and clear process is shown in the device simulation of Fig. 4. In the upper plot the electron density distribution is schown as well as the electric potential during the signal integration phase. Upon request, a positive pulse is applied to the n^+clear contact, removing all electrons from the internal gate (center plots). Immediately alter the clear process no electron (less than 10^{-3} electrons per pixel) are left under the transistor channel (lower plot).

2.2 DEPFET arrays as Active Pixel Sensors

The matrix-like arrangement of DEPFETs with a single common back contact results in a back illuminated APS system with 100% fill factor, i.e. no signal charge is lost between the pixel boundaries or in the electronics implemented in the pixel area. Therefore this concept is actually the only APS suited for spectroscopic X-ray measurements. The depletion depth at present is 300μm . In the upcoming fabrications on 6 inch wafers with 500μm sensitive volume the quantum efficiencies will be above 95% at 10 keV and still 40% at 20 keV. In the low energy part of the spectrum the thin entrance window technology guarantees a quantum efficiency above 90% for energies around 300 eV, however, without the Al light filter.

All DEPFETs in the pixel sensor have a common drain contact, while the gates and clear contacts are connected row-wise and the source contacts, i.e. the signal lines are connected within each column as can be seen in Fig.5. In normal operation the transistors of one row after the other are turned on, read and cleared by CMOS control chips. While the DEPFETs of the active row are read in parallel by a multi-channel CMOS preamplifier/multiplexer of the CAMEX type [6], the rest of the pixels is turned off, but still capable to collect signal charge, thus keeping dead time short and power consumption low. The read time for one row is of the order of a few μsec. That keeps the so called out-of-time events, i.e. events hitting the DEPFET during readout well below 0.5%. Besides the usual full frame readout mode the random accessibility of the pixels allows for any kind of windowing or mixed mode, in which only a selected region of interest is read with higher speed, while the remaining area is read at a lower rate.

On our way to the proposed focal plane detector for XEUS smaller devices have been produced and tested together with the CMOS control electronics. First X-ray images have been recorded with reasonable quality proving the functional principles of the whole sensor concept [7]. In this first system several technological problems have limited the resolution: (a) inhomogeneous implants leading to a spatial variation of DEPFET currents; (b) large resistance of inter-chip connections due to the availability of only one interconnection metal layer at that time and (c) a complete clear of the signal charges was not possible due to limitations in the CMOS circuits. The clear contact was too attractive for signal charges during readout. A new version of DEPFETs and CMOS electronics which avoids the above limitations is in production.

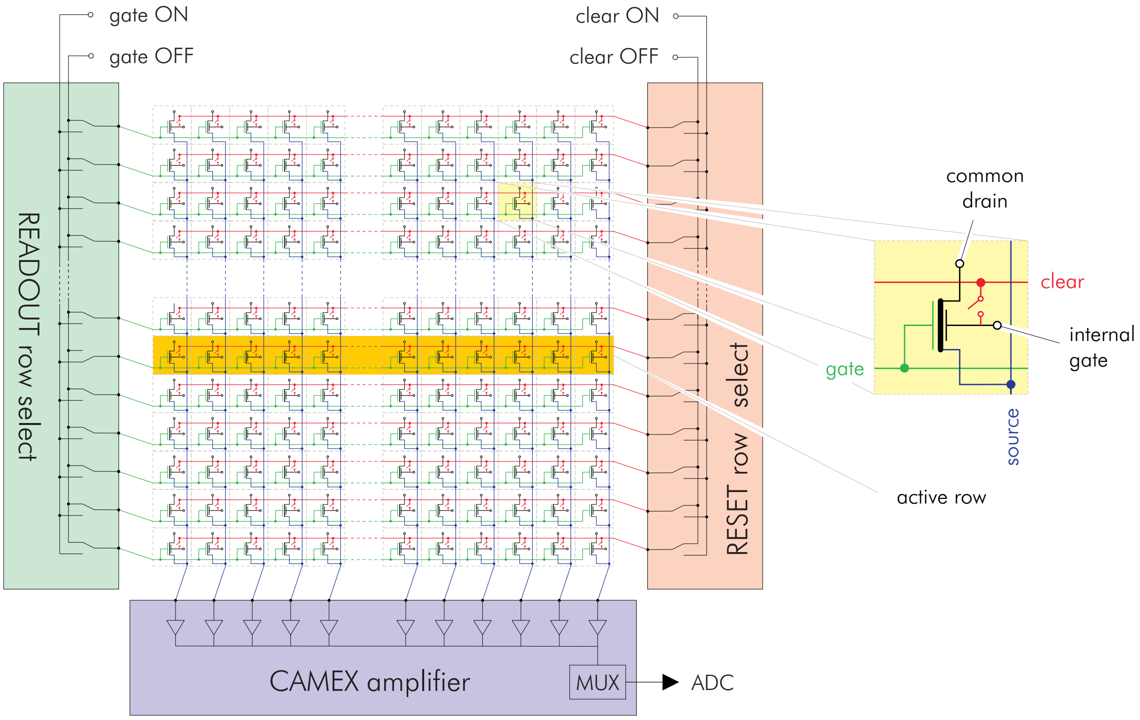

Figure 5: Concept of a DEPFET active Pixel sensor readout, including the control CMOS electronics 'readout row select' and the 'reset row select'.

2.3 The non-destructive readout of DEPFETs

In a DEPFET the signal charges are stricly confined in a potential well below a single transistor. The information, i.e. the number of charges in the internal gate, is conserved during the readout so that multiple reading of the same signal charges with subsequent averaging is possible. Repetitive readout results in a serial noise reduction by $\sqrt{n}$, with n the number of read cycles, allowing spectroscopy measurements with a noise contribution (ENC) of a single electron. The technique of repetitive non-destructive readout is best realized by the combination of two neighbouring DEPFETs within one pixel (see Fig. 6). The signal charge can be shifted repeatedly between two neighbouring gates. That way one of the DEPFETs reads the signal while the other one reads the reference value (baseline) of the empty internal gate. Devices of that type are currently under test. In dedicated areas the repetitive reading may be applied, while the rest of the sensor can be read out conventionally (see chapter 2.2). This offers a large variety of observation adapted operating modes. Therefore, compared to CCD type operation, windowing modes do no longer lead to a loss of sensitive area in order to gain readout speed.

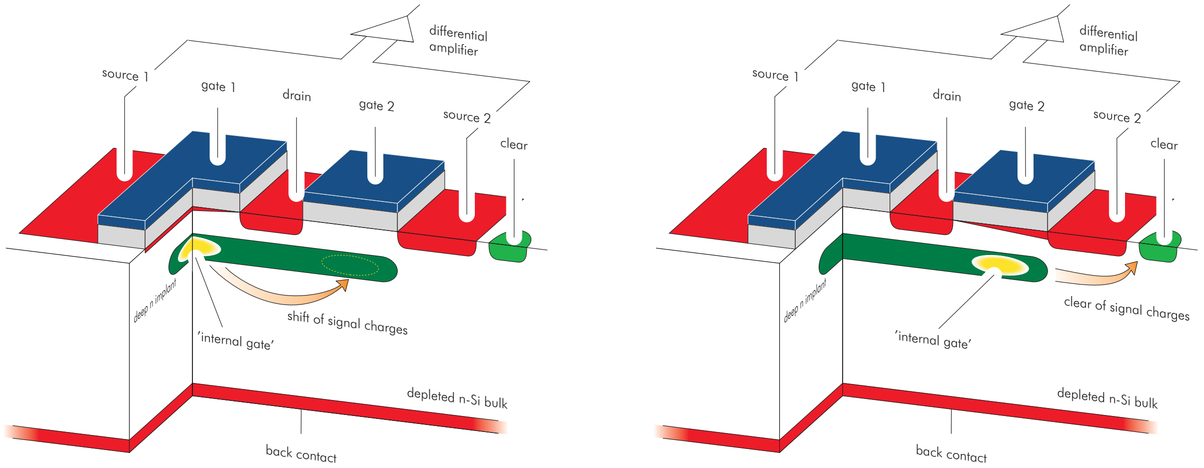

Figure 6: Schematic diagram of a DEPFET (MOS-type) for the repetitive non-destructive readout of signal charges. The common drain of both pixels separates the two internal gates. After finishing the readout all electrons are taken out from the internal gate through the clear contact.

2.4 A high speed spectroscopic channel with SDD's

For the observation of the brightest X-ray point sources it seems to be interesting to be able to detect precisely,in a single photon counting mode, the light curve as a function of the energy. A very fast spectroscopic detector is required for that purpose.

Silicon drift detectors (SDD) with integrated JFET's are used today as high speed spectrometers in many applications in material analysis and basic research [8]. As their fabrication process is similar to the one of DEPFET arrays, they can be monolythically integrated at the edges of the wide field imager. Areas of 10 mm^2 are suffucient to monitor the X-rays from point sources with fluences above to 10^6 counts per second. The singnal shaping time τ has to be of the order 50 ns only in order to keep signal pile-up at a reasonably low level. The signal rise time in the detector (including first FET) can be kept clearly below 5 ns guaranteeing the high speed operation. For $\tau = 50$ ns the pile-up of randomly arriving X-rays at 1 million hits per second is about 18%. At shaping times below 100 ns the electronic noise widens the energy resolution of an e.g. Mn K_α line to 250 eV only at 10^6 counts per second. This kind of high speed measurements can be realized only because of the extremly low total readout capacitance of the SDD in the 100 fF range including the first amplifier.

3 Conclusion

We have described our roadmap towards future imaging X-ray spectrometers. They fullfill the astrophysical requirements like position, energy and time resolution, count rate capability and quantum efficiency. Thechnical boundary conditions like higher operating temperature, avoidance of thin seperate optical blocking filters, low power dissipation and increased radiation hardness are equally matched. As a wide field imager the DEPFET seems to be the ideal focal plane detector. In addition, the high speed spectroscopic channel in terms of a silicon drift detectors will allow for a direct spectroscopic detection of the brightest X-ray sources in the sky.

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