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Spectral performance of DEPFET and gateable DEPFET macropixel devices

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ABSTRACT: Future x-ray observatories, such as the proposed ATHENA+ mission, will investigate bright and rapidly evolving radiation sources. To reach the scientific goals, high speed, spatial resolving sensors with excellent spectroscopic performance are mandatory. Well suited for this task are matrices of Depleted P-channel Field Effect Transistors (DEPFETs). DEPFETs provide intrinsic signal amplification, 100 percent fill factor, charge storage capability and a low read noise. Previous studies of DEPFET matrices of 256×256 pixels demonstrated an excellent energy resolution of 126 eV FWHM at 5.9 keV (compared to the theoretical Fano limit 120 eV).

Usually these matrices are read out on demand, using e.g. the ASTEROID ASIC. Because the DEPFET is always sensitive, charge collected during the readout, causes so called misfits, which increase the background. For low frame rates this can be neglected. However, for fast timings, as suggested for ATHENA+, this effect reduces the spectral performance.

We will present measurements on DEPFET macropixel structures, read out using a semi-Gaussian shaper, which demonstrate the excellent spectroscopic performance of these devices. Furthermore we will investigate the effect of misfits on the spectral background of DEPFET devices read out on demand. These measurements show the necessity to suppress misfits when the devices are operated for fast timing modes. As will be shown this can be done using so called gateable DEPFETs. The general advantage of gateable DEPFETs at fast timings, in terms of peak-to-background ratio will be demonstrated.

KEYWORDS: X-ray detectors and telescopes; Imaging spectroscopy

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1 Introduction

The Wide Field Imager (WFI) of the proposed Advanced Telescope for High Energy Astrophysics plus (ATHENA+) is supposed to simultaneously provide a large field of view and the timing capability to investigate the evolution of bright radiation sources such as supermassive black holes and neutron stars [1].

To meet these requirements the WFI will utilize DEPFET Active Pixel Sensors (APS). Key features of the DEPFET are 100 percent fill factor, intrinsic charge amplification, high quantum efficiency and readout on demand due to the analog storage of signal charge [2, 3]. Using the last feature, DEPFET matrices can be operated in a so called window mode, enhancing the time resolution of part of the sensor, while the rest is read out with a lower frame rate [4]. The time resolution of ATHENA+ will be in the 10 μs range, which is in the same order of magnitude as the signal processing time.

On these timescales the random distribution of signal photons in time will result in a non-negligible probability to collect photons during signal processing. Such events lead to an incorrect evaluation of the signal amplitude, called "misfit" [5]. Especially in fast operation, misfits increase the background of DEPFET sensors and thus degrade the spectral performance.

We will present a set of measurements on DEPFET macropixel devices that demonstrate the excellent spectral properties of DEPFETs. Furthermore we will evaluate the effects of misfits on the background during readout on demand. In the final section we will demonstrate that, using the built-in shutter of gateable DEPFETs, the limitations caused by misfits can be overcome.

2 The DEPFET principle

The DEPFET principle is illustrated in figure 1 by a cross section of a circular DEPFET (left) and the corresponding equivalent circuit (right). As shown a DEPFET pixel consists of a MOS-transistor, which is built on a high resistive n-doped silicon bulk substrate. A deep-n implantation

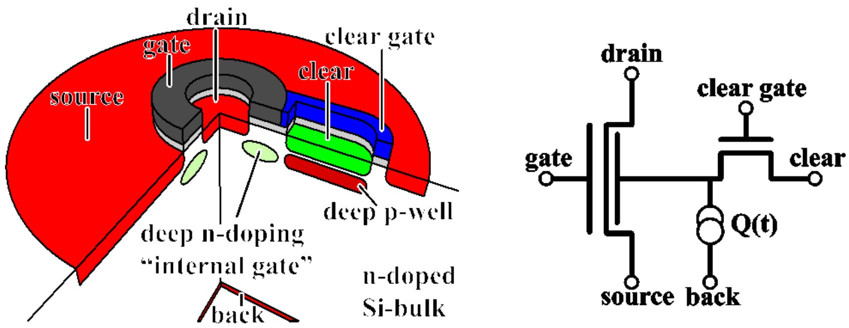

Figure 1. The left picture shows a cross section of a circular DEPFET device. A deep n implantation below the transistor gate forms a potential minimum for electrons. Charge generated in the bulk will be collected in this internal gate, modulate the transistor current and can thus be detected. Applying sufficient positive voltages to the clear and clear gate the collected charge carriers can be removed completely. The equivalent circuit depicted on the right consists of two MOS-transistors, representing the DEPFET and the clear-structure, a collection node to represent the internal gate and a current source to model charge generation in the bulk.

below the gate forms a potential minimum for electrons. Negative charge, generated in the bulk by incident radiation or thermal generation will be collected in this "internal gate" and modulate the channel conductivity. The resulting current change is proportional to the number of collected electrons and thus allows one to measure the energy absorbed in the detector volume. A reset of the DEPFET is possible using the clear structure, consisting of clear electrode and clear gate. Applying a sufficiently positive voltage to these contacts will cause charge collected in the internal gate to drift towards the clear where they will be removed from the device.

DEPFETs can be used as readout node of macroscopic single pixel detectors or as the base cell of an Active Pixel Sensor (APS). They provide low readout noise, 100 per cent fill factor, intrinsic charge amplification and readout on demand. Furthermore it is possible to implement additional properties such as nonlinear signal response [6], the repeated readout of collected charge [7] or a fast built in shutter [8].

Since the first proposal of DEPFETs as radiation detectors by Lutz and Kemmer [3] these devices have been developed for use in many applications including planetology [9], particle physics [10], photon science [11] and astrophysics [1].

3 DEPFET macropixel

All measurements presented in this paper were done on DEPFET macropixel devices. They consist of a DEPFET embedded in a circular driftring structure. The detectors evaluated in this paper have a collection area of $10\,\mathrm{mm}^2$, allowing one to study the properties of DEPFETs with a minimum of disturbances. To suppress split events on the device edge, each detector was equipped with a zirconium on chip collimator.

The following measurements represent a benchmark for the Single Pixel Measurement Setup II (SPIX_II) [8] and DEPFET macropixel devices. In this section, the detector drain current was read out by an impedance converter and a voltage amplifier. This circuit translates a current step,

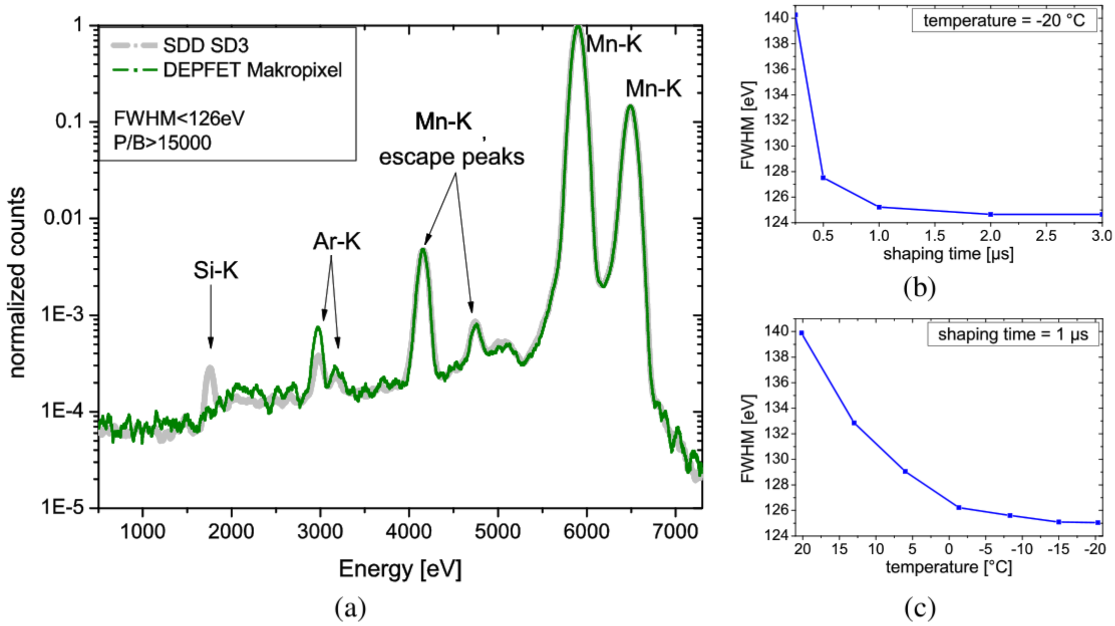

Figure 2. (a) Spectrum of a ^{55}Fe source recorded with a DEPFET macropixel at -20°C. The device was read out using a semi-Gaussian shaper. At a count rate of 3000 cps, with a shaping time of 1 μs an energy resolution of 125 eV at 5.9 keV and a P/B ratio of 15000:1 were measured. These values are similar those of a SDD of equal size. The Si-K peak in the SDD spectrum was caused by the chip housing. The sensors were operated in a dry air atmosphere, which causes the observation of the Ar-K lines. As shown in (b) and (c), the FWHM scales with shaping time and temperature. The high degradation of the energy resolution at 0.25 μs shaping times is related to the rise time of 200 ns of the pre amplifying circuit.

caused by charge entering the internal gate, to a voltage signal. The signal was processed by a semi-Gaussian shaper consisting of one differentiator and two integration stages. Its near Gaussian step response provides a high and low frequency cutoff. The peak values were digitized by a pulse sensitive ADC.

A spectrum of a ^{55}Fe X-ray source, taken at -20°C, is shown in figure 2(a). ^{55}Fe decays to ^{55}Mn, which emits two dominant lines at 5.9 keV and 6.5 keV.[1] At a count rate of $\sim$ 3000 cps with a shaping time of 1 μs, an energy resolution of 125 eV FWHM for the Mn K_α line at 5.9 keV was measured. Evaluating the background in the range from 800 eV to 1200 eV shows an excellent peak-to-background (P/B) ratio of 15000:1. Energy resolution and P/B ratio are comparable to those of Silicon Drift Detectors (SDD) of the same size [12].

Varying the shaping time from 0.25 μs to 3 μs at -20°C changes the energy resolution from 142 eV to 124.6 eV as depicted in figure 2(b). The behaviour at 0.25 μs is caused by the pre amplifier rise time of 200 ns, which limits the signal bandwidth. Main noise source is the used I to V converter. The noise gain of this circuit is defined by input and feedback impedance, while the bandwidth limitation depends on the used operational amplifier. At high frequencies the signal bandwidth is limited by the rise time of the amplifier, while the noise bandwidth is not affected. The dif-

[1]In fact the K_α line consists of two lines with energies of 5.898 keV and 5.888 keV. The relative ratio is 66% and 33%. However, since the energy resolution is limited by the fano noise these lines can be treated as monochromatic with an energy of 5.895 eV.

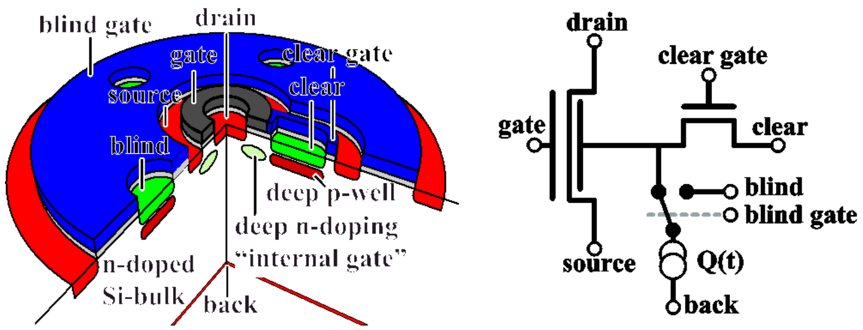

Figure 3. Expanding a circular DEPFET with a blind gate and blind implements an electronic shutter (see left). In the sensitive state these contacts are biased such that charge is collected as for conventional DEPFETs. For the insensitive state sufficiently positive voltages are applied to both contacts. Charge generated in the bulk will move to the blind and be removed. Charge already collected in the internal gate will be preserved. The behavior is illustrated by the equivalent circuit shown on the right. As depicted the state is mostly controlled by the voltage applied to the blind gate.

ferent frequency response of signal and noise leads to an increased Equivalent Noise Charge (ENC) at short shaping times, and thus a reduced energy resolution. The energy resolution depends on temperature as shown in figure 2(c). The shaping time for these measurements was $1\,\mu$s. Due to the reduction of leakage current the energy resolution improved from 140 eV at 20°C to 125 eV at -20°C.

The measurements show that DEPFETs can be used to form macroscopic detector devices with built in amplification, which provide low noise readout, good energy resolution and excellent P/B ratios. Further this macropixels can be used to study the properties of DEPFET devices in an isolated environment without disturbances caused by border effects (as is the case for smaller single pixel structures) or neighbouring pixels (as in matrices).

4 Gateable DEPFET macropixel

The DEPFET concept is highly flexible and can be optimized to provide a multitude of diverse properties. The gateable DEPFET structures investigated in the following sections combine a circular DEPFET with a fast, built-in shutter [8, 13]. As the cross section on the left of figure 3 shows, this feature is implemented by adding the "blind" and "blind gate" to the circular DEPFET design depicted in figure 1. The equivalent circuit is shown in figure 3 on the right.

Due to the shutter the device can be set sensitive or insensitive. When sensitive all contacts are biased such that the device behaves like a standard DEPFET. Applying sufficiently positive voltages to blind and blind gate sets the device insensitive. Charge generated in the bulk will move toward the blind contact and be removed from the device. However electrons already collected in the internal gate will be preserved. One use of this feature is the suppression of charge collection during readout, hence suppressing misfits.

To demonstrate the benefit of the built-in shutter a gateable DEPFET was read out on demand, with and without use of the built-in shutter. The applied timing is divided into signal integration and signal processing time as depicted in figure 4 on the left. Readout was performed using an ASTEROID ASIC [14]. The ASTEROID is a 64 channel ASIC designed for DEPFET readout.

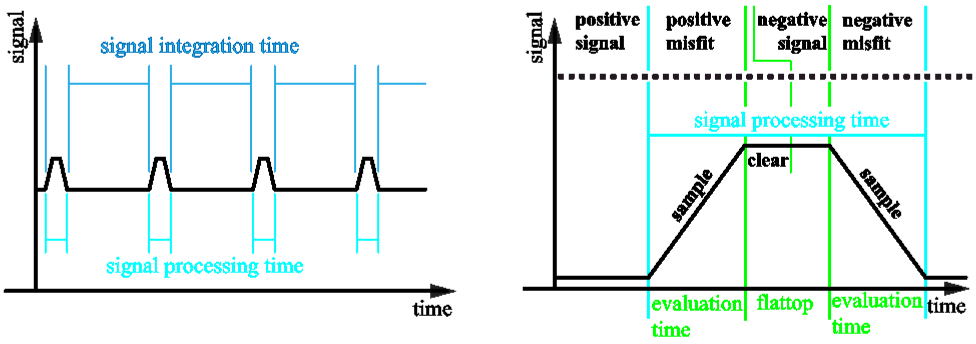

Figure 4. To reduce power consumption of DEPFET matrices readout is usually done row wise in parallel. While one row is read out, the rest of the matrix accumulates signal charges. The timing of a single pixel can thus be divided into signal integration and signal processing time (left). As shown in the right picture the signal processing consists of sampling the signal, applying a clear pulse and sampling the baseline. The corresponding times will be referred to as signal evaluation time and flattop. Because DEPFETs are always sensitive, charge arriving during signal processing will cause so called misfits. Depending on the arrival time they have different effects on the spectrum.

Each channel provides a current source for source follower readout and performs a trapezoidal weighting of the input signal as depicted in figure 4 on the right. This time variant filtering is composed of a first signal evaluation, a flat top and a second signal evaluation. Collected charge is removed by the clear, which is applied in the course of the flat top. The voltage difference between first and second signal evaluation is proportional to the signal change during the flattop and is evaluated on the subtraction stage of the ASIC. It is then stored on the sample and hold stage and serialized by a 64:1 multiplexer.

For the measurements presented in the following sections the source of a gateable DEPFET macropixel was connected to a single channel of the ASTEROID. Digitalization of the analog values was done using a 14 bit ADC.

4.1 Readout on demand in standard operation

Gateable DEPFETs can be operated like standard DEPFET devices. In this mode the sensor is always sensitive to incident radiation. The energy of arriving photons will be interpreted depending on their exact arrival time as indicated in figure 4.

Signal charge collected during the signal integration time will cause a signal proportional to the photon energy and contribute to the signal peak. However, charges arriving during the signal processing will cause incorrect entries in the spectrum. Due to the trapezoidal weighting signal collected directly after the clear will cause entries with negative amplitude causing a peak at apparently negative photon energy. If the signal is collected during the positive or negative signal integration the corresponding entry will be between zero and the actual photon energy respectively the negative photon energy. These entries are equally distributed over the spectrum and decrease the P/B. The following will show that the background component generated by these misfits is proportional to the ratio of signal integration time to signal evaluation time.

For the measurements depicted in figure 5(a) and (b) the signal evaluation times of the weighting function were 1.5 μs, with a flat top of 1.25 μs leading to an overall signal processing time

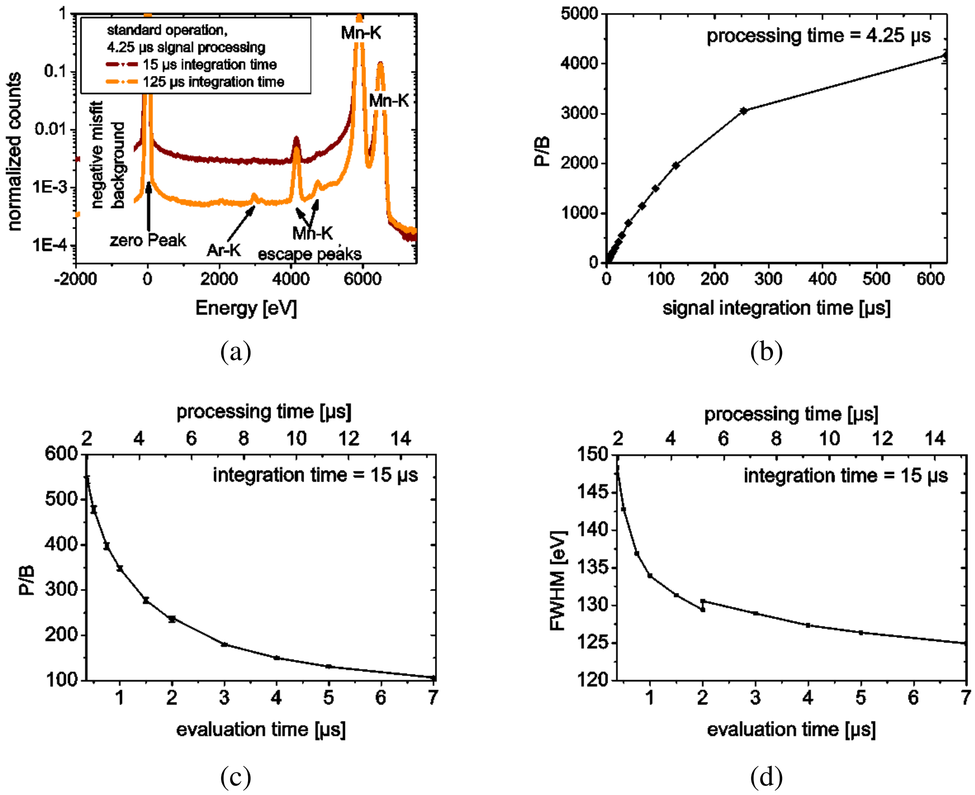

Figure 5. (a) If a DEPFET is read out on demand, spectral background may be dominated by events entering the device during signal processing. As shown, changing the signal integration time from 15 μs to 125 μs while keeping signal processing constant at 4.25 μs improves the P/B ratio significantly. A variation of the signal integration time from 2.2 μs up to 625 μs is depicted in (b). The best P/B ratio is in the range of 4000:1 for a signal integration of 625 μs. Reducing the signal evaluation and hence the signal processing improves the P/B ratio (c). However, this also affects the energy resolution as shown in figure (d). The two values at 2 μs evaluation time are caused by a different gain setting in the pre amplifier stage of the ASTEROID.

of 4.25 μs. Figure 5(a) shows two example spectra taken with 15 μs and 125 μs signal integration time. Obviously, the P/B ratio scales with the signal integration time. Figure 5(b) depicts a variation of the signal integration time from 2 μs up to 625 μs, measured with a constant signal processing time of 4.25 μs. For signal integration times longer than 50 μs the P/B ratio is above 1000:1. For shorter signal integration times the P/B degrades to ratios of 100:1 and less. In this operation, feint sources can completely be covered by the background caused by the presence of a bright higher energetic source, making an exact identification of material compositions impossible.

Figure 5(c) and (d) show the influence of signal evaluation time on P/B ratio and energy resolution. For these measurements the timings of flat top and clear were kept constant. As expected the P/B ratio improves with shorter signal processing time while the energy resolution decreases.

As demonstrated by the measurements, for standard DEPFETs a trade-off between optimal spectroscopic performance and high time resolution has to be done, to select the best operation mode for the application. Due to the dependency of the P/B ratio on the ratio of signal integration and signal processing time it can be concluded that the limitations demonstrated in this section are

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related to misfit events. Suppressing charge collection during signal processing should improve the P/B ratios significantly.

4.2 Readout on demand using the built in shutter

The measurements presented in subsection 4.1 have been repeated using the built-in shutter during readout. Figure 6(a) demonstrates the benefit of misfit suppression during device readout. The improvement of the P/B ratio by one order of magnitude is especially illustrated by the two Ar-K lines which can now be clearly identified.

By varying the signal integration time as shown in figure 6(b), P/B ratios up to 12000:1 are measured. Although the improvement is significant, the background is still higher than for the time continuous readout (see section 3). The difference between the two readout methods is caused by the finite switching speed of the shutter and the charge collection time. If electrons arrive at the DEPFET during the switching time of the shutter, a part of the charge will be collected in the internal gate; the other electrons will move towards the blind and be removed from the device. Depending on the number of collected signal electrons, this causes an entry in the spectrum between 0 eV and the energy of the incident photon. Supposing a monochromatic radiation source and a linear switching behavior of the shutter the entries caused by this effect will be uniformly distributed between 0 eV and the photon energy. However the switching time in the range of 100 ns guaranties a significant improvement of the P/B ratios compared to the measurements without use of the shutter.

At a fixed signal integration time of 15 μs the P/B ratio shows only a minor dependency on the signal processing as shown in figure 6(c). The observable dependency is caused by the improvement of energy resolution depicted in figure 6(d).

As was demonstrated in this section, the spectral resolution of gateable DEPFETs, read out on demand and operated at fast timings is superior to that of DEPFETs without the gateable feature. At short integration times the P/B ratio is enhanced by up to one order of magnitude.

5 Summary

The measurements presented in this paper demonstrate that DEPFETs provide excellent spectral performance. Already at room temperature DEPFET macropixels show an energy resolution of 140 eV when readout using a semi-gaussian shaper. By cooling down to -20°C, this value was improves to 125 eV. Furthermore an excellent P/B ratio of 15000:1 was measured. Improving the used preamplifier circuit, an enhancement of the energy resolution at short shaping times is possible. Overall DEPFET macropixels have excellent spectroscopic qualities and provide a disturbance free environment to study the properties of DEPFET devices.

In addition to all its intrinsic features the DEPFET design allows the implementation of new attributes like the built-in shutter for high speed applications. In this paper we demonstrated the benefit of a built-in shutter for DEPFET devices which are readout on demand. Without suppression of misfits the background at high frame rates is proportional to the ratio of signal integration to signal processing time. As demonstrated this limitation was overcome, using the built-in shutter of gateable DEPFETs during the device readout, enhancing the P/B ratio significantly.

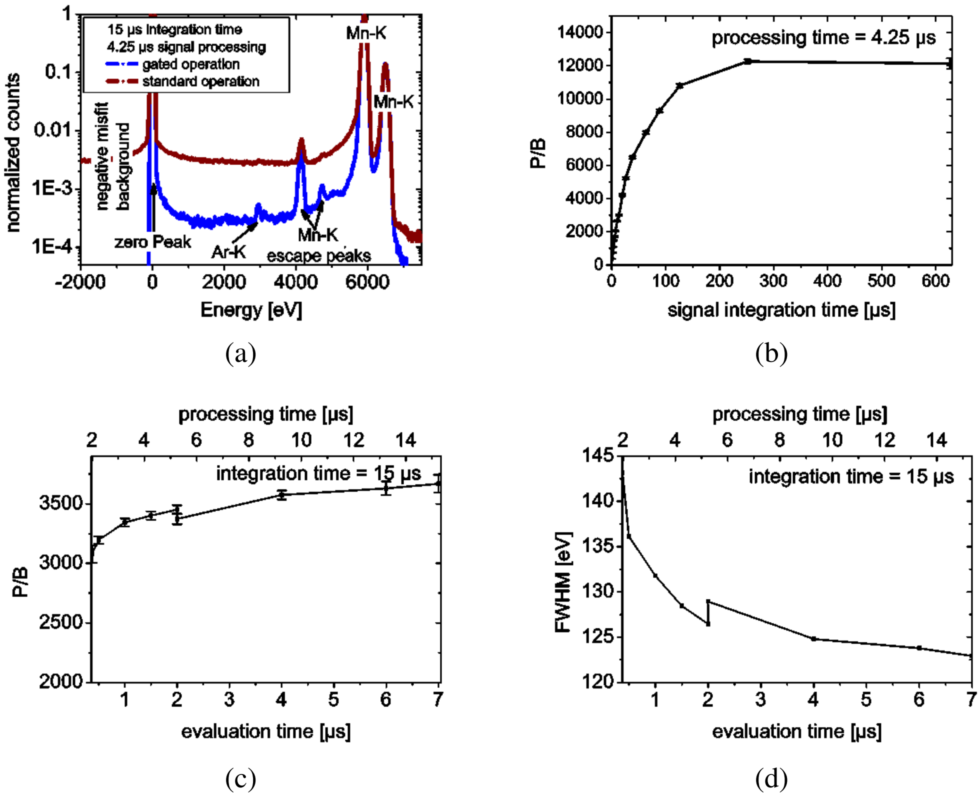

Figure 6. (a) The benefit of the built in shutter is obvious. At a signal integration time of 15 μs with a signal processing of 4.25 using the shutter (blue) improves the P/B ratio by one order of magnitude. b) Increasing the signal integration time further improves time P/B up to 12000:1. As shown in (c) the P/B ratio shows only a minor dependency on the signal evaluation time, while the energy resolution can be improves significantly (d) with longer evaluation times. The two data points at 2 μs signal evaluation time are related to a change in the preamplifier settings of the ASTEROID ASIC.

Especially for short signal integration times an improvement of the P/B ratio by up to one order of magnitude was demonstrated. Due to this property pixelated detector matrices build of gateable DEPFET devices will, even at high speed timings as required for fast window mode operation, provide a better spectral resolution and especially higher P/B ratios than DEPFETs without this feature.

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