Expected performance of the DEPFET sensor with signal compression: A large format X-ray imager with mega-frame readout capability for the European XFEL

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Abstract

The new DSSC (DEPFET sensor with signal compression) detector system is being developed in order to fulfill the requirements of the future XFEL in Hamburg. The instrument will be able to record X-ray images with a maximum frame rate of 5 MHz and to achieve a high dynamic range. The system is based on a silicon pixel sensor with a new designed non-linear-DEPFET as a central amplifier structure. The detector chip is bump-bonded to mixed signal readout ASICs that provide full parallel readout and temporary data storage. The signals coming from the detector are processed by an analog filter, immediately digitized by 8-ENOB ADCs and locally stored in a custom designed memory. The ASICs are designed in 130 nm CMOS technology. During the time gap of 99 ms of the XFEL machine, the digital data are sent off the focal plane to a DAQ electronics that acts as an interface to the back-end of the whole instrument. The pixel sensor has been designed so as to combine high energy resolution at low signal charge with high dynamic range. This has been motivated by the desire to be able to be sensitive to single low energy photons and, at the same time, to measure at other positions of the detector signals corresponding to up to $10^4$ photons of 1 keV. In order to fit this dynamic range into a reasonable output signal swing, achieving at the same time single photon resolution, a strongly non-linear characteristic is required. The new proposed DEPFET provides the required dynamic range compression at the sensor level, considerably facilitating the task of the electronics. At the same time the DEPFET charge handling capacitance is enormously increased with respect to standard DEPFETs. The sensor matrix will comprise $1024 \times 1024$ pixels of hexagonal shape with a side-length of 136 µm. The simultaneous implementation of the 5 MHz frame rate, of the single low-energy photon resolution and of the high dynamic range goes beyond all the existing instruments and requires the development of new concepts and technologies.

1. Introduction

We present the concept for the development of the DSSC (DEPFET sensor with signal compression): a high speed focal plane detector system for the new XFEL (X-ray free electron laser) in Hamburg. The instrument will be able to record X-ray images with a maximum frame rate of 5 MHz and to achieve a high dynamic range. This will allow coping with the very demanding pulse time structure of XFEL. The machine will provide macro-bunches with a repetition rate of 10 Hz. Every macro-bunch is composed of 3000 X-ray pulses with a temporal distance of 200 ns (Fig. 1). Our detector will be able to acquire images every 200 ns obtaining a frame rate of 5 MHz and high dynamic range at the same time. The number of stored frames per macro-bunch will be at least 512 with the possibility to discard bad frames thanks to an external trigger. The key properties of the system are summarized in Table 1.

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The system is based on a pixel-silicon sensor with a DEPFET [1] as a central amplifier structure. The sensor will have the following key properties: the total size will be approximately 21\(\times\)21 cm\(^2\) composed of 1024\(\times\)1024 pixels of hexagonal shape. The pixel array will be subdivided in 16 ladders. Every ladder comprises two monolithic sensors with 128\(\times\)256 pixels each. The ladders will be geometrically arranged such that a central hole is left to let the unscattered photons go through (Fig. 2).

The insensitive space in the focal plane is about 15% with the present mechanical design. A simplified block diagram of the system is reported in Fig. 3.

Every detector ladder is bump-bonded to mixed signal readout ASICs. The ASICs are designed in 130 nm CMOS technology and provide full parallel readout of the DEPFET pixels. The signals coming from the detector, after having been processed by an analog filter, are immediately digitized by a series of 8 bit (or 9 bit in a more advanced solution under study) single-slope ADCs and locally stored in a custom designed memory also integrated in the ASICs. During the 99 ms time gap of cooling phase of the accelerator, the digital data are sent off the focal plane to a DAQ electronics that acts as an interface to the back-end of the whole instrument.

It is the aim of the DSSC to provide a high speed focal plane camera with high spatial resolution for X-rays from 1 keV up to 10 keV with close to 100% detection efficiency.

The most exciting and challenging property is the 200 ns frame rate of the system combined with low-energy single photon resolution. This goes beyond all existing instruments and requires the development of new concepts and technologies.

The pixel sensor has been designed so as to combine high energy resolution at low signal charge with high dynamic range: special care has been taken in order to achieve single photon resolution also in the energy range 0.5–4 keV. This has been motivated by the desire to be able to be sensitive to single low energy photons and at the same time to measure at other positions of the detector signals corresponding to up to \(10^4\) photons of 1 keV per pixel. In order to fit this dynamic range into a reasonable output signal range, achieving at the same time single photon resolution, a strongly non-linear characteristic is required. The new proposed DEPFET provides the required dynamic range compression at the sensor level, considerably facilitating the task of the electronics.

### Table 1

Summary of the key properties of the DSSC.

<table>
<thead>
<tr>
<th>Detector parameters</th>
<th>Expected performance</th>
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</thead>
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<tr>
<td>Energy range</td>
<td>0.5 keV (\leq E \leq 20\text{ keV} ) (optimized for (0.5 \leq E \leq 4\text{ keV}))</td>
</tr>
<tr>
<td>Pixel number</td>
<td>1024 (\times) 1024</td>
</tr>
<tr>
<td>Sensor pixel shape</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Sensor pixel pitch</td>
<td>(~204 \times 236\ \mu\text{m}^2)</td>
</tr>
<tr>
<td>Dynamic range photons/pulse/pixel</td>
<td>(&gt; 6000) photons (\not\equiv 1\text{ keV})</td>
</tr>
<tr>
<td>Single photon resolution (S/N) &gt; 6</td>
<td>yes (\not\equiv 1\text{ keV}(5\text{ MHz}))</td>
</tr>
<tr>
<td>Electronics noise</td>
<td>(&lt; 50) electrons (\text{r.m.s.})</td>
</tr>
<tr>
<td>Frame rate</td>
<td>1–5 MHz</td>
</tr>
<tr>
<td>Stored frames per macro-bunch</td>
<td>(\geq 512)</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>(-30\ ^\circ\text{C} ) optimum, room T possible</td>
</tr>
</tbody>
</table>

The insensitive space in the focal plane is about 15% with the present mechanical design. A simplified block diagram of the system is reported in Fig. 3.

![Fig. 1. X-ray bunch structure at the European XFEL. The XFEL machine generates macro-bunches with a repetition rate of 10 Hz. Every macro-bunch is composed of a train of 3000 X-ray pulses with a temporal distance of 200 ns. The DSSC will be able to acquire an image every 200 ns and to store the acquired data in the focal plane. During the 99.4 ms time gap between two macro-bunches the data are sent off the focal plane.](image1)

![Fig. 2. Full focal plane arrangement (1024 \(\times\) 1024 pixels) being composed of four quadrants. Each quadrant consists of four ladders and eight monolithic sensors of 256 \(\times\) 128 pixels each. The ladders will be geometrically arranged such that a central hole is left to let the unscattered photons go through.](image2)

![Fig. 3. Simplified block diagram of our detector concept. The Sensor is bump-bonded to a set of readout ASICs. The ASICs provide an analog signal filtering, 8-bit digitization and data storage for every individual pixel. For the analog front-end two alternative solutions are under study.](image3)
2. DEPFET with non-linear amplification

The DEPFET [1,2] is a field effect transistor located on one surface of a silicon wafer. A large area diode is on the opposite surface of the wafer. The n-type bulk is fully depleted with the help of a sideward located n+ doped clear contact. Suitable doping and choice of bias voltages creates a potential maximum right below the channel of the transistor: the internal gate (IG). Electrons generated by radiation are collected there. They create mirror charges in the channel, thereby increasing channel conductivity. For fixed source and external gate voltages the transistor current is increased. Alternatively for fixed transistor current (source follower) the source voltage will change. Applying a sufficiently strong positive voltage pulse to the clear (bulk) contact removes all charge from the internal gate. Therefore there is no statistical variation in the amount of leftover charge and the reset noise is zero. The charge can be measured by the current increase after charge collection or by the current difference before and after clearing of the IG. The DEPFET is a natural building block for a pixel detector as it combines the properties of detector, amplifier and storage cell in a simple structure. The high repetition rate foreseen for XFEL requires parallel readout of all pixels. Therefore a separate readout channel is required for each pixel and all pixels have to be powered during the pulse train. Nevertheless a new type of DEPFET solves the challenge of providing excellent charge resolution for low signals as required for single photon detection with very large charge handling capacity for pixels containing the overlap of very many photons. This is accomplished by providing a strongly non-linear current - charge characteristic. The basic concept is shown in Fig. 4.

The internal gate extends into the region below the large area source. Small signal charges cumulate below the channel only, being fully effective in steering the transistor current. Large signal charges will spill over into the region below the source and correspondingly be less effective in steering the transistor current. Hexagonal pixel cells have been designed. As shown in Fig. 5 the hexagon has an side length of 136 μm and the sensor pitch is 204 × 236 μm. This size is mainly dictated by the minimum pitch of 200 μm allowed by the IBM C4 process that is adopted to bump bond the readout ASIC. In addition a much smaller area would not allow to implement the required readout electronics. The hexagonal shape is beneficial in order to minimize the charge collection time. The DEPFET is located in the middle of the pixel structure and is surrounded by a small drift chamber. The hexagonal shape of the drift rings provides a more homogeneous drift field with respect to a conventional squared pixel and it is more effective in focusing the collected charge into the internal gate of the DEPFET located in the center of the cell. The hexagonal geometry also decreases the probability of split events (charge sharing). The designed pixel has been simulated: 37 consecutive depositions of 10 fC signal charge have been generated. In the top part of Fig. 6 the resulting drain output current has been plotted. One notices the non-linear response with three quasi linear regions of decreasing slope.

If the current is imposed into the DEPFET by a current source, the charge deposited into the internal gate produces a change in the voltage level of the source node: the device is operated in source follower mode. In the simulation presented in Fig. 7 the DEPFET has been used in source follower configuration with a 500 fF capacitive load in parallel to a 100 kΩ resistor placed on the source node. As expected, also the DEPFET characteristic in source follower mode presents a strong non-linear behavior. The curve looks smoother with respect to that of Fig. 6 just because it has been simulated injecting the charge into the internal gate by a constant current and not by delta-like current pulses. At low dynamic range (Fig. 7(b)) the DEPFET output response is almost linear up to 10–15 photons at 1 keV and the gain is about 2.8 μV/electron. At the end of the plotted input range (8000

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Fig. 4. XFEL DEPFET concept. The first signal electrons are collected in the potential well exactly below the gate (IG) due to its most positive potential. If that area is filled up with electron the next disk—extending below the source and the gate—collects electrons and so forth. Only the fraction of the additional charge that arrives below the internal gate (IG) is effective in modulating the transistor current. This leads to the non-linear amplification behavior of the DEPFET APS.

Fig. 5. Geometry and simplified layout of a pixel for source follower configuration. The DEFFET is located in the middle of the pixel cell and it is surrounded by two drift rings. A 100 kΩ resistor needed to bias the pixel in source follower mode is integrated in the pixel cell. The pixel comprises also a 0.5 pF coupling capacitor that is not visible in the figure.
photons at 1 keV, Fig. 7(a)) the sensitivity is reduced to 0.05 mV/electron. The corresponding output swing for 8000 photons at 1 keV is about 220 mV. If the highest sensitivity were extrapolated to 8000 photons, the output dynamic range would be 6.2 V and no low-power integrated electronics would be able to handle it. On the other side it is not convenient to reduce the gain of the low dynamic range region, i.e. the amplification for small signals. As it will be explained later, this would turn out into an increase of the input capacitance of the system and, as a consequence, into an increase of electronics noise. So the non-linear characteristic is necessary in order to achieve high dynamic range and single 1 keV photon resolution simultaneously. The slope and the maximum voltage swing can easily be tailored through geometry, doping and dielectric variations.

The same conclusions on the dynamic range can be achieved in the case of drain current readout strategy. In this case all the DEPFET terminals are kept to a fixed potential and the drain current, which is proportional to the collected signal charge, is read-out. The readout ASIC filters this current signal and transforms it into a voltage that is fed to the input of the ADC, exactly as in the case of the source follower readout. In case of the source follower readout the DEPFET is biased by a 100 kΩ resistor and the source is AC coupled to the input of the readout ASIC. The biasing resistor and the 0.5 pF coupling capacitor are integrated on the sensor pixel. In the case of drain current readout no passive components are required in the pixel cell, but on the other side a more complex input stage of the readout ASIC is needed. The source follower readout presents the advantage of an easy compensation of eventual DEPFET threshold voltage shifts, while the drain current readout has better noise performance at high speed, as it will be explained in Section 5.1. In the first phase of the DSSC development we will investigate both readout options. A final decision will be taken after the first experimental results on prototype structures.

3. DEPFET readout mechanism and speed

Since all the pixels are read-out in parallel the frame-rate corresponds to the single-pixel processing time. In other words, if
we want to readout every incoming X-ray pulse (5 MHz operation), 200 ns are available to read-out one DEPFET. The operating speed of our system can be tuned in order to readout every second pulse (2.5 MHz operation) and every fifth pulse (1 MHz operation). This reduced speed allows to achieve better noise performance as explained in Section 5.1. Nevertheless we aim at operating the system at 5 MHz with a resolution sufficient to detect single 1 keV photons. In order to determine the signal charge that is deposited into the internal gate of the DEPFET, it is necessary to perform two measurements. We can assume that before the signal charge arrival the internal gate is completely empty, since the whole charge (both the signal charge of the previous measurement and the leakage current charge) has been removed by a clear pulse. The output of the DEPFET, i.e. the drain current or the source voltage, is measured. This corresponds to evaluate the baseline of the system: the output corresponding to the empty internal gate. Then the signal charge is deposited into the internal gate of the DEPFET, as a consequence of the interaction of a X-ray pulse with the target, and a second measurement of the device output is performed. This time the baseline + the signal are evaluated. The difference of the two measurements (baseline only and baseline + signal) gives the information about the amount of the signal charge.

The readout sequence is sketched in Fig. 8. In the real case it is not possible to exploit the whole interval of 200 ns in order to process the signal. In fact a signal settling time and a signal clearing time are needed.

The settling time of the device has been simulated both for the source follower and the drain current readout [3]. In the drain current readout the settling time corresponds, in first approximation, to the charge collection time. In case of the source follower readout the settling time is longer, as not only the charge collection time, but also the time constant due to the capacitive load of the source node must be taken into account. The pixel has been simulated with a 500 fF capacitive load in parallel to a 100 kΩ resistor. For charge generated in the center of the pixel it takes 20 ns for complete collection in the internal gate. For charge deposition at the rim the maximum drift time increases to 65 ns. The output current follows the charge collection with insignificant delay in case of drain readout. For the source follower configuration the settling time is up to 80 ns for the worst case.

Considering that the charge clearing time is comparable to the charge settling time, it is realistic to conclude that about 70 (200—65 × 2) and 40 (200—80 × 2) ns out of 200 are used to process the signal in case of current readout and source follower, respectively. It is worth pointing out that the settling time and the clearing time are independent from the operating speed of the system. So, for example, if we operate the system at 1 MHz, 870 ns (1000—65 × 2) ns are available for the current readout and 840 ns for the source follower.

Since the signal arrival time is known, a time variant filter is used for the system readout. Every channel of the readout ASIC implements a trapezoidal weighting function. This is the time-limited optimum filter for white series noise, which is dominant at the foreseen readout speed [4–7]. A trapezoidal weighting function associated to the operating time structure of the instrument is shown in Fig. 9.

![Fig. 8. Timing diagram of the DEPFET readout. The arrival time of the signal is known. One measurement is composed of the evaluation both of the baseline and the signal+baseline. In the real case it is not possible to exploit the whole time interval of 200 ns between two pulses. In fact setting times for the signal build-up and for the DEPFET clear are needed. They are independent from the operating frequency of the system.](image1)

![Fig. 9. Trapezoidal weighting function implemented by the readout ASIC. In the figure (not in scale) the weighting function is associated to the timing structure of the current readout at 5 MHz. Lower speed allows a longer processing time (τ) and therefore a lower series noise. The settling times are independent from the operating frequency.](image2)

### 4. Achievable dynamic range

In this and in the next section we show how it is possible to reach simultaneously single photon resolution and high dynamic range. Our analysis, which is based on device and circuit simulations, takes into account the complete processing chain (DEPFET, analog preamplifier-shaper and ADC) and demonstrates the Poisson limited performance over the entire dynamic range. An 8-bit ADC can be sufficient to keep the digitization noise below the Poisson limit throughout the entire dynamic range thanks to a proper tuning of the characteristic of the DEPFET. The achievable dynamic range depends on the shape of the DEPFET characteristic, i.e. on the gain distribution as a function of the incoming signal, and on the number of ADC bits. We have already seen that for the first 10–15 photons the gain of the DEPFET in source follower mode is about 2.8 μV/electron. This means that the first 1 keV photon (producing a charge of 277 electrons) collected by the pixel produces a voltage step at the source (the output) of the DEPFET of about 0.8 mV (Fig. 10).

Since we want to be able to detect a single 1 keV photon, the output voltage swing produced by the charge generated by the first 1 keV photon collected by the sensor defines the bin size of the ADC. The bin size multiplied by the number \( n \) of the
ADC bins ($n=2^n$ for a $N$-bit ADC) gives the voltage swing that can be covered by the ADC. For example, with a 7-bit ADC we would be able to accept an output swing of the DEPFET of 0.8 mV $\times 2^7 \approx 100$ mV, which corresponds to approximately 1250 photons at 1 keV, as it is possible to see from Fig. 11.

Our baseline 8-bit ADC will allow to cover a range of 0.8 mV $\times 2^8 \approx 200$ mV, i.e. to achieve a dynamic range of about 6000 1 keV photons per pixel. This corresponds to a dynamic range of 600 photons at 10 keV without changing the gain of the preamplifier. With the introduction of photon energy dependent selectable gains, it will be possible to extend the dynamic range to few thousands of photons also for the high energy operation. Moreover we are convinced that further optimizations of the DEPFET characteristic are possible.

In parallel to the implementation of our baseline 8 bit ADC, we are studying the option of a 9 bit architecture. The 9th bit could be used in two ways.

In a first way one can think to attribute the first collected photon to the first bin of the ADC, as it is done for the 8 bit ADC. In this case the additional bit would bring a considerable increase of the dynamic range (more than a factor 2, since the DEPFET response is non-linear). In a second and—most probably—more beneficial way, it is possible to use the 9th bit in order to attribute to the first photon (actually to all the photons in the linear region) two ADC bins. This would be a big advantage since it would make much easier to cope with possible gain dispersions among the pixel matrix and it would simplify the pixel-wise gain and pedestal calibration. In addition it would be possible to detect half-photon signals. This would increase the probability to correctly identify split events, i.e. events for which the charge generated by a photon is distributed among two or more pixels. Lastly this second use of the 9th bit would further decrease the quantization noise, even if this is not strictly necessary as it will be shown in Section 5.2.

5. System noise and energy resolution

The noise sources of the system are the following:

- the noise of the Poisson-distributed photon generation process of the XFEL source;
- the electronics noise, mainly given by the DEPFET and the analog front-end;
- the quantization noise introduced by the ADC.

The peculiarity of our concept is that the electronics noise and the quantization noise are signal-dependent because of the nonlinear characteristic of the DEPFET. The system must be designed in such a way that the quadratic sum of the electronics noise and the quantization noise is negligible with respect to Poisson generation noise over the entire input dynamic range.

5.1. Electronics noise

In order to calculate the electronics noise associated to our detector, we can extend the definition of equivalent noise charge (ENC) usually adopted for linear systems \[8,9\]. In our case the system amplification depends on the input signal and the ENC can be defined as the charge that must be added to a defined input signal charge $Q_{IN}$ in order to compensate the r.m.s. fluctuation of the output due to the noise. It is evident that with this definition the ENC is signal dependent. We can write:

$$ENC^2(Q_{IN}) = \frac{1}{Q_{IN}} C_{EQ}(Q_{IN}) A_1 + 2\pi a_1 C_{EQ}^2(Q_{IN}) A_2 + b/r A_3$$

The three terms of the ENC formula represent the main three noise contributions, i.e. the series white, the series 1/f and the parallel white noise contribution, respectively.

- $C_{EQ}(Q_{IN})$ is the equivalent input capacitance \[2\] of the system, which, in this case, depends on the input charge $Q_{IN}$;
- $a$, $a_1$ and $b$ are the series white, the series 1/f and the parallel white physical noise sources referred to the input;
• $A_1, A_2$ and $A_3$ are the filter parameters, and depend on the shape of the weighting function performed by the readout electronics. $A_1$, which is the filter coefficient for the white series noise, i.e. the dominant noise source at the foreseen operating speed, is minimized for the trapezoidal weighting function;

- $\tau$ is the shaping time of the readout filter and it is an expression of the time used to perform one measurement.

In case of source follower readout, in order to define the $C_{EQ}(Q_{IN})$ we can refer the physical noise sources to the source node of the DEPFET, which is the pixel output node in source follower configuration. In such a way the $C_{EQ}(Q_{IN})$ is the inverse of the derivative of the output current with respect to the input:

$$C_{EQ}(Q_{IN}) = \frac{dQ_{IN}}{dI_{source}}.$$  \hfill (2)

The fact that the ENC, i.e. the noise charge referred to the input, increases with the input signal is intuitive if one considers that the DEPFET and the analog front-end physical noise sources are in first approximation constant, while the DEPFET amplification decreases (the $C_{EQ}$ increases) as the input charge gets bigger.

When the internal gate is empty the simulated value of $C_{EQ}$ is 57 fF, as it is possible to extrapolate from Fig. 7(b). In this region in fact the small signal gain is $2^{57}$ fF, as it is possible to extrapolate from Fig. 7(b). In this region in fact the small signal gain is $2^{57}$ fF, as it is possible to extrapolate from Fig. 7(b). In this region in fact the small signal gain is $2^{57}$ fF, as it is possible to extrapolate from Fig. 7(b). In this region in fact the small signal gain is $2^{57}$ fF, as it is possible to extrapolate from Fig. 7(b). In this region in fact the small signal gain is $2^{57}$ fF, as it is possible to extrapolate from Fig. 7(b). In this region in fact the small signal gain is $2^{57}$ fF, as it is possible to extrapolate from Fig. 7(b). In this region in fact the small signal gain is $2^{57}$ fF, as it is possible to extrapolate from Fig. 7(b).

With a similar procedure the same value can be obtained for the current readout.

We have calculated the equivalent noise charge associated to the linear region of the DEPFET for the two readout strategies at different operating speeds. The results are reported in Table 2. For the sake of completeness we show also the simulated noise contribution of the readout ASIC, even if it is not discussed in details in this paper.

In the calculations the following parameters have been used:

- $C_{EQ} = 60 \text{ fF}$;
- $a = 1.53 \times 10^{-16} \text{ V}^2/\text{Hz}$, $a_t = 4.5 \times 10^{-12} \text{ V}^2$. These values refer to the noise source of the DEPFET and have been extracted from noise power spectral density measurements on DEPFET prototypes [2]. The leakage current noise is negligible.
- $A_1 = 2$, $A_2 = 1.38$ are the filter parameters for the trapezoidal weighting function.
- $\tau$ has been defined as half of the time available to process the signal (see Fig. 9). So the used values for the 5 MHz, the 2.5 MHz and the 1 MHz operation are 35, 135 and 435 ns for the current readout. For the source follower readout: 20, 120 and 420 ns.

Table 2

<table>
<thead>
<tr>
<th>Speed (MHz)</th>
<th>Source follower</th>
<th>Current readout</th>
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<tbody>
<tr>
<td></td>
<td>DEPFET (el.)</td>
<td>ASIC (el.)</td>
</tr>
<tr>
<td>5</td>
<td>46</td>
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<td>2.5</td>
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<td>10.3</td>
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</table>

The ENC expressed in electrons r.m.s. for different readout speed and readout strategies.

The drain current readout shows much better performance at 5 MHz. This is due to the fact that the time available to process the signal is longer thanks to the faster settling time. Since, as explained in Section 3, the settling time is independent from

The noise values of Table 2 are valid only for a few photons collected by the detector, i.e. in the linear region of the DEPFET response. The sum of the electronics noise and of the Fano noise as a function of the input photons is plotted in Fig. 12.

The drain current readout shows much better performance at 5 MHz. This is due to the fact that the time available to process the signal is longer thanks to the faster settling time. Since, as explained in Section 3, the settling time is independent from

Fig. 12. (a) Noise curves of the system: Poisson-distributed photon generation noise of the XFEL source; 8-bit quantization noise and electronics noise summed to the Fano noise. For high number of photons, the quantization noise can be obtained dividing by $\sqrt{2}$ the curve which represents the number of photons encoded with the same ADC bin. (b) In the low dynamic range there is a correspondence one to one between the collected photons and the ADC bins: there is no uncertainty introduced by the ADC. What counts is the electronics noise due to the DEPFET and the analog front-end. This noise is about 70 electrons r.m.s. This must be considered that this is the worst case estimation for the source follower readout at 5 MHz. All the other readout options guarantee a signal to noise ratio higher than 6:1 (see Table 2).
the readout speed, at lower operating frequency the difference between drain current readout and source follower is reduced. The ASIC noise component is higher for the source follower because in this readout scheme a low-gain voltage to current converter must be added at the input of the trapezoidal filter and its noise generators are not negligible.

5.2. Quantization noise

We have to define the quantization error of the ADC. It is possible to give different definitions of quantization noise: generally they depend on the shape of the input signal. We try to define the maximum uncertainty associated to the measurement of the number of photons collected by one pixel, due to our encoding scheme. We have set the gain of the system in such a way that the first 1 keV photon collected by the detector produces an output signal of one ADC bin. This conversion factor is valid in the whole linear region of the output characteristic of the DEPFET, i.e. for the few first photons (Fig. 7(b)). This means that there is a one to one correspondence between the number of collected photons and the number of ADC bins, as shown in Fig. 13(a). In this region what counts is the electronics noise of the DEPFET and of the analog front-end. In other words the ambiguity on the number of measured photons depends only on the fluctuation of the output signal of the DEPFET+analog front-end (the input signal of the ADC) due to the electronics noise. For example, this fluctuation, added to the ideal output of the DEPFET, can make the output of an empty pixel to be wrongly assigned to the first bin of the ADC (one photon erroneously detected instead of zero), but this is not due to the 8-bit quantization of the ADC.

Due to the non-linear response of the DEPFET, the number of photons attributed to one ADC bin increases as a function of the collected signal. So it is not possible to determine the exact number of photons for a high input signal. One of the curves in Fig. 12 represents the number of photons attributed to the same ADC bin. In the dynamic range corresponding to the linear region of the DEPFET the value of this curve is 1: for every single photon there is a single ADC bin (see also Fig. 13(a)). This means that there is no uncertainty in the number of collected photons given by the ADC (as already mentioned in this region the uncertainty is given by the electronic noise that can lead to a wrong bin attribution). For high dynamic range the uncertainty of the ADC becomes higher. As it can be seen from Fig. 12(a), e.g., at 2000 photons, the number of photons attributed to the same ADC bin is 30. This is also shown in Fig. 13(b). It follows that in this region of the dynamic range it is possible to know the number of collected photons only with an intrinsic uncertainty. This would be true even if the system were completely free of electronic noise. The noise associated with this uncertainty can be expressed by the root mean square error made encoding all the photons contained in a bin with the central value. For a high number of photons the r.m.s. error can be approximated by the number of photons contained in one bin divided by \( \sqrt{2} \), i.e. the distribution of the number of photons in one bin can be considered, in first approximation, uniform. The quantization noise is plotted in Fig. 12(a).

From Fig. 14 it is possible to see that our system well achieves Poisson limited performance, since both the electronics noise and the quantization noise curves are well below the Poisson fluctuation of the Poisson photon generation process. In addition it must be considered that the figure refers to the worst case in which the system is operated in source follower mode at 5 MHz with an 8 bit ADC.

![Fig. 13.](image)

5.3. Single photon resolution

We can also conclude that single 1 keV photon resolution is achievable. We have calculated the electronics noise for few input photons for the different operating speeds and for the two different readout strategies (Table 3). The mean charge generated by a single 1 keV photon is 277 electrons. This gives a signal to noise ratio bigger than 6:1 except for the case of 5 MHz with source follower readout. Now we can consider a Gaussian distribution for the electronics noise and place the ADC threshold which discriminates e.g. between zero and one photon in the middle of the bin. Taking into account the different noise values of Table 2, that are the sigma of the Gaussian noise distributions, we have calculated the probability \( P_{1,0} \) that a zero signal is misinterpreted as a one photon signal, as shown in Fig. 15. So we have calculated the probability that one pixel erroneously detects one photon even if no photon has been collected, as the area of the tail of the Gaussian curve in Fig. 15. In other words \( P_{1,0} \) is the probability that the output of an empty pixel is above the...
threshold (139 electrons and 70 electrons in case of 1 keV photons and 0.5 keV photons, respectively,) due to noise fluctuations.

For 1 keV photons in the current readout mode at 5 MHz, it is $P_{10} = 0.1\%$. This value is sufficient for the requirements of the target application. The related probability that a signal attributed to the first bin of the ADC actually corresponds to a real single 1 keV photon collected by the pixel is over 99.7%.

For the source follower at 5 MHz it is: $P_{10} = 2.3\%$. This is due to the higher noise. Even if this probability can be critical for some specific applications, it should be noticed that better values can be achieved moving the threshold to a higher value with respect to the middle of the first ADC bin. In this way the number of fake events will be reduced, but the detection efficiency will be reduced as well. An optimum value of the threshold can be found according to the experimental requirements. At lower operating speeds both source follower and current readout show negligible values of $P_{10} (< 10^{-4})$, as reported in Table 3.

Considering now the lowest foreseen energy of about 0.5 keV, a signal to noise 6:1 together with the associated small values of $P_{10}$ are achievable operating the system at 2.5 MHz.

It should be noted that these results require a precise setting of the ADC bin width and offset so as to set the transitions in between the 0, 1, 2,.... photon signals. Adequate trimming on a pixel-by-pixel basis will be provided by the ASIC.

Table 3

<table>
<thead>
<tr>
<th>Speed (MHz)</th>
<th>Source follower</th>
<th>Current readout</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ENC (el.) 1 keV</td>
<td>ENC (el.) 1 keV</td>
</tr>
<tr>
<td>5</td>
<td>69.7 2.3% 16%</td>
<td>44.6 0.1% 6%</td>
</tr>
<tr>
<td>2.5</td>
<td>27.9 ~0 0.8%</td>
<td>20 ~0 0.03%</td>
</tr>
<tr>
<td>1</td>
<td>15.3 ~0 ~0</td>
<td>11 ~0 ~0</td>
</tr>
</tbody>
</table>

This may happen because the electronics can make the output of the pixel fluctuate above the threshold that is placed in the middle of the ADC bin. One ADC bin has the size of the output signal generated by one single photon.

5.4. Charge sharing effects on single photon resolution

We have so far considered the case in which the whole charge generated by one single 1 keV photon is collected by one individual pixel, i.e. we have neglected the split-events. Now we evaluate the effect of charge sharing on single photon resolution as a function of the electronics noise of the system and therefore the operating speed. It is assumed that a single 1 keV photon is impinging on the back of the sensor in a random position on the detector plane. The sensor thickness is 450 μm. The charge sharing mechanism along the edge among two neighboring pixels has been simulated using TESCA [10]. The charge sharing among three neighboring pixels at the pixel corners has been neglected for simplicity, but it will be introduced in future studies. The charge sharing as a function of the distance of the interaction point from the pixel border is reported in Fig. 16. It can be seen that a pixel collects more that 99.5% of the charge if the incoming photon hits the pixel at a distance > 20 μm from the pixel edge. In the simulation the internal gate stays at 0 V, while the back contact is at −150 V. −30 and −70 V have been applied to the ring1 and ring2, respectively (see Fig. 5).

It is now possible to estimate the combined effects of the charge sharing and of the electronics noise on the single photon detection capability of our system. We assume an 8-bit ADC with a bin size equal to the full signal of a 1 keV photon, i.e. equal to the signal generated by a DEPFET that has collected the whole charge generated by an incoming photon. The threshold is placed in the middle of the bin. This means that, in an ideal system with no electronics noise, one pixel detects one 1 keV photon if it collects more than half of the associated charge (> 139 electrons), see Fig. 15. Now we consider one pixel that has been hit by one single photon together with all its neighboring pixels, as sketched in Fig. 17. In our calculations the photon can interact with uniform
probability at any position of the pixel surface. Table 4 reports the results of our calculations for the electronics noise values associated to the three different operating speeds of the system. The probability $P_0$ is the probability that none of the seven pixels (the hit pixel together with all the neighbors) detects the incoming photon, i.e. it is an expression of the inefficiency of our detector. $P_{H,1}$ is the probability that the 1 keV X-ray photon is detected by the hit pixel (the central pixel in Fig. 17) and no photon is detected in any of the neighboring pixels. $P_{N,1}$ is the probability that one photon in total is detected in the set of the seven pixels, but not in the central pixel where the photon has arrived. It must be noticed that also the detection of only one photon, even if not in the central pixel, can be considered a “good” or “valid” event. In fact we do not measure the amount of charge collected by the single pixels. We are just able to discriminate whether the amount of charge collected by one pixel is above threshold or not, i.e. we can just count the number of the incoming photons with a certain error probability given by the electronics noise. In this sense we cannot reconstruct the position of the interaction point within a pixel calculating the center of mass of the charge shared among different cells. Therefore the spatial resolution is intrinsically limited by the pixel size. If, because of the electronics noise, one photon is not detected by the hit pixel but by one of the neighboring pixels, most probably the interaction position is close to the border of these two pixels. So the neighboring pixel that fires has collected a large fraction of the deposited charge. Since the interaction point is close to the border and the spatial resolution is limited by the pixel size, the error which is made attributing the interaction point to the center of the hit pixel or to the center of the neighboring pixel is basically the same. So the probability that our system correctly detects one photon is $P_1 = P_{H,1} + P_{N,1}$. $P_2$ is the probability that two pixels detect one photon.

### Table 4

<table>
<thead>
<tr>
<th>ENC (el.)</th>
<th>$P_0$</th>
<th>$P_{H,1}$</th>
<th>$P_{N,1}$</th>
<th>$P_1 = P_{H,1} + P_{N,1}$</th>
<th>$P_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>0.02%</td>
<td>92.5%</td>
<td>0.8%</td>
<td>95.5%</td>
<td>2%</td>
</tr>
<tr>
<td>20</td>
<td>0.84%</td>
<td>98.0%</td>
<td>0.2%</td>
<td>98.2%</td>
<td>0.8%</td>
</tr>
<tr>
<td>11</td>
<td>0.48%</td>
<td>98.9%</td>
<td>0.2%</td>
<td>99.1%</td>
<td>0.45%</td>
</tr>
</tbody>
</table>

6. Conclusions

We have shown a new concept of pixel detector system for XFEL, based on innovative non-linear DEPFETs. Preliminary device and circuit simulations have shown that thanks to the intrinsic low noise of the pixel and the signal compression at the sensor level it is possible to achieve a high dynamic range of at least 6000 photons at 1 keV, preserving at the same time single 1 keV photon resolution with a signal to noise ratio $> 6 : 1$. Simulations show that the required frame rate of 5 MHz is also achievable.
Single photon detection is also possible for 0.5 keV photons, operating the system at 2.5 MHz.

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References