A novel way of single optical photon detection: beating the 1/f noise limit with ultra high resolution DEPFET-RNDR devices

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Abstract—In this work we demonstrate theoretically and experimentally the capability to reduce the readout noise of an optical and X-ray photon detector based on the semiconductor DEPFET device below a level of only $0.3e^{-}$ ENC (equivalent noise charge). The readout method used is called "Repetitive Non Destructive Readout" (RNDR) and was realised by placing two single DEPFET-devices next to each other and by coupling their charge storing region by an additional gate. By transferring the stored charge from one DEPFET to the other and vice versa the same charge can be measured non-destructively and arbitrarily often. Taking the average value of a large number $n$ of these measurements, the noise is reduced by $1/\sqrt{n}$. The main advantage of such a detector is to greatly reduce the contribution of the $1/f$ noise to the readout noise. The theoretically and experimentally achievable resolution for different operating parameters (leakage current, readout noise, number and duration of readouts) was investigated by Monte-Carlo simulations and verified on a real RNDR minimatrix (pixelarray). Single optical photon detection with high quantum efficiency and, even more fascinating, the possibility to distinguish between different numbers of photons e.g. 100 from 101 are demonstrated in measurements.

Index Terms—single optical photon detection, RNDR, sub-electron noise, DEPFET, Active Pixel Sensor, low noise readout.

I. INTRODUCTION

One of the most important questions of operating a semiconductor radiation device is how precisely the amount of produced charge (electrons or holes) can be measured in a certain readout time given by the experimental constraints. Usually 1/f noise components limit the minimum achievable readout noise to a value not much smaller than $2e^{-}$ ENC [1], even for very long measurement times in the order of a few ten µs. By having the possibility to measure the amount of collected charge multiple times without loosing the charge during one readout, the uncertainty of many ($n$) of these measurements is reduced by $1/\sqrt{n}$ as explained more in details later. In this work we demonstrate that a combination of two coupled DEPFET devices [2] fulfills the requirements for a repetitive non destructive readout. Also the concept can be used to build large radiation detector matrices with reasonable readout speed of a kHz frame rate and a thin homogenous entrance window with a fill factor of 100% for high quantum efficiency. Theoretical investigations on RNDR detectors have been carried out by Gatti et al. [3]. First measurements were shown by J. Janesick et al. with the floating gate based Skipper CCD, where noise values of $0.5e^{-}$ ENC have been published ([4] and [5]). The main difference in our approach is a reduction of the readout noise below the $0.3e^{-}$ ENC level, which is needed to separate single optical photons from the noise floor and also to distinguish between different numbers of (photo-) electrons.

Fig. 1. Simplified layout of the investigated RNDR device. The collected charge is stored in the internal gates, located under the two external gates (gate 1 and gate 2). The charge can drift from one DEPFET to the other by applying a positive voltage to the transfergate. The difference of the measured source-drain current of each transistor before and after a transfer is proportional to the transferred charge. Because the charge is not lost, but stored in the neighbouring DEPFET, its amount can be measured multiple times that way. The last transfer moves the charge under gate 1, from which it can be (now destructively) completely removed by opening the clear gate and applying a positive voltage to the clear. The size of the investigated structure is $75 \times 75\mu m^2$, smaller variants are under production.
II. DEVICE DESCRIPTION

The essential attribute of a RNDR device [6] must be a complete signal charge storage during all readouts. The capability of a DEPFET-device [7] to store the collected signal electrons in a depleted region and to keep them isolated from other charge within the silicon bulk defines a feasible basic cell to realize a RNDR-device.

Our RNDR devices, which were designed and fabricated at the semiconductor laboratory (HLL) of the Max-Planck-Institutes for physics and for extraterrestrial physics in Munich, were realised by a combination of two DEPFET-devices and a transergate between them which allows a controlled drift of signal charge from one DEPFET to the other (figure 1).

The DEPFET is a combined detector and amplifier structure, which consists of a p-channel-MOSFET processed on a high resistivity silicon substrate. The completely sideward depleted bulk [7] provides both, sensitivity over the whole wafer thickness as well as a lateral potential minimum for electrons beneath the wafer surface. Additional n-implanted regions beneath the two external gates of the MOSFETs (gate 1 and gate 2, figure 1) force the generated (photo-) electrons to drift underneath the gates and confine them in an electric field. These locations are called “internal gates” [7]. The external gate of a DEPFET has two functions:

- As in a normal p-MOSFET the (hole-) current from source to drain is controlled by the applied gate-source voltage, so the DEPFET can be turned on and off by applying appropriate voltages to the external gate. A more negative gate-voltage increases the amount of mirror-holes in the transistor channel, and increases the source-drain current.
- If the external gate is turned off by applying a positive voltage to the gate, (henceforth called gate-off voltage) the layer of holes creating the channel is removed and the internal gate becomes capacitively coupled to the external gate. A more positive external gate-off voltage makes the internal gate also more positive, which increases the attractive force for electrons.

In the same way the external gate voltage controls the source-drain current by $g_m = \frac{\partial I}{\partial V}$ (transconductance), the collected electrons in the internal gate also modulate the channel conductivity by creating mirror charges (holes) in the channel. They have therefore also an additional impact on the source-drain current ($\delta I$). The influence is quantitatively described by $g_q = \frac{\partial q}{\partial V}$ ($\delta q$: charge in the internal gate). For our devices $g_q$ is typically $\approx 300 \, \text{pA/V}$. Because the DEPFET provides both, a charge collection point (internal gate) and the first integrated amplifying stage (MOS transistor), a small input capacitance of only a few tens of $\mu F$ is achieved. Considering that the white series noise, which is dominant at short readout times is proportional to the input capacitance, it is evident that this structure provides low readout noise event at short readout times.

As seen in figure 1, the charge can be moved from the internal gate of the on-DEPFET to the internal gate of the off-DEPFET by applying a positive voltage to the transfer gate, which acts as a n-channel MOSFET coupling the two internal gates. The charge itself drifts in a depth of about $1 \mu m$ with respect to the transfer gate interface. The essential part of the readout is measuring the current before and after transfer (indicated as thick bars in figure 2, named b: measurement before and a: measurement after the transfer). The difference of the two measurements is $\delta I$ (the process measurement - transfer - measurement is henceforth called one "readout"). The method itself is called CDS (correlated double sampling) and will for oncoming devices be integrated into readout hardware, as it is e.g. realised for the CAMEX ASIC ([1] and [7]). The amount of moved charge ($Q$) can be derived from $Q = \frac{\delta I}{g_q}$ (fig. 2) with an uncertainty of $\sigma$, which is in the order of 2 to 5 electrons ENC for a typical DEPFET device.\(^1\) By interchanging the on/off states of the two DEPFETs, the charge can be transferred back and measured again the same way. Because each CDS measurement is self-contained, all readouts are statistically uncorrelated. After repeating the readout $n$ times and taking the average value of all these CDS-readouts the noise has decreased by statistics to

$$\sigma_{\text{end}} = \sqrt{\frac{\sigma_i^2 + \sigma_2^2 + \cdots + \sigma_n^2}{n}} = \sqrt{\frac{n \cdot \sigma^2}{n}} = \frac{\sigma}{\sqrt{n}}.$$  \hspace{1cm} (1)

\(n\) : number of readouts (e.g. number of transfers)
\(\sigma_i\) : readout noise of readout i
\(\sigma_{\text{end}}\) : readout noise after n readouts
\(\sigma\) : mean noise of one readout, $\sigma = \sigma_{i=1,\ldots,n}$

\(^1\)Because of complete charge transfer or clear, the DEPFET is a $kT/C$ noise free device [1].
It is important to note, that eq. 1 is based on the assumption, that the number of electrons does not change during all readouts, e.g. leakage current, which would increase the number of electrons during \( t_{\text{seq}} \), is not considered in eq. 1. The influence will be discussed in the next section. After all \( n \) readouts of one sequence \( (t_{\text{seq}}) \), an additional \( n \)-channel-MOSFET (clear gate, figure 1) is opened and a positive voltage at the clear contact removes the charge. The internal gates of the two DEPFETs are now empty and ready for further charge collection.

The main advantage of this readout principle is that even if all single measurements are affected by \( 1/f \) noise, this shaping-time independent noise source is also reduced by eq. 1. Imagine a detector where the \( 1/f \) noise becomes dominant for effective measurement times longer than 20\( \mu \text{s} \). In this case it is better to measure the collected charge e.g. 5 times for 20\( \mu \text{s} \) each (and taking the average value) than measuring once for 100\( \mu \text{s} \). For this example, it is not possible to reduce the noise further by measuring much longer than 20\( \mu \text{s} \), due to low frequency \( 1/f \) noise components.

The only noise limiting factor remaining is the leakage current value \( (i_l) \). Every leakage current electron entering the internal gate during \( t_{\text{seq}} \) increases the number of collected electrons by one. The influence of this effect to the achievable noise value is discussed in the following section.

III. SIMULATIONS

To understand the influence of the leakage current, which is not included in eq. 1, to the overall detector performance Monte-Carlo simulations have been carried out. Also a short evaluation of single optical-photon imaging is given.

A. Monte-Carlo

To investigate a RNDR device from the theoretical point of view the four most important parameters to be looked at are:

\[
i_l \quad \text{pixel leakage current rate in } e^-/ (\mu \text{s} \cdot \text{pixel})
\]

\[
t_{\text{readout}} \quad \text{readout time for one readout in } \mu \text{s}
\]

\[
\sigma \quad \text{readout noise for one readout in } e^- \text{ ENC}
\]

\[
n \quad \text{number of readouts}
\]

The influence of these values to the achievable resolution was investigated by Monte Carlo simulations. The mean value \( x_{k(=1...p)} \) of all \( n \) readouts is calculated from eq. 2:

\[
x_{k(=1...p)} = \frac{1}{n} \cdot \sum_{i=1}^{n} (q_i \pm \sigma)
\]

whereat

\[
n \quad \text{number of readouts}
\]

\[
p \quad \text{overall Monte-Carlo runs}
\]

\[
k \quad \text{index of Monte-Carlo run, } k = 1...p
\]

\[
x_k \quad \text{mean value of all readouts of one Monte Carlo run}
\]

\[
q_i \quad \text{number of collected electrons till readout number } i
\]

\[
\pm \sigma \quad \text{indicates, that } q_i \text{ is affected by Gaussian distributed noise with a variance of } \sigma
\]

Also important for the discussion is the integration time \( t_{\text{int}} \), which is the time from last clear up to the beginning of the readout (fig. 2). The distribution of the number of leakage current electrons for an infinite \((p \to \infty)\) number of Monte Carlo runs corresponds to the Poisson distribution for the given leakage current rate \( i_l \) and the acquisition time \( t_{\text{seq}} = n \cdot t_{\text{readout}} \).

B. Influence of the leakage current

![fig.3](image-url)

Fig. 3. This plot shows the probability to get within the acquisition time \( (t_{\text{seq}}) \) a certain number of leakage current electrons as a function of a mean leakage current value. For example leads a mean leakage current of 0.5 electrons within \( t_{\text{seq}} \) to a probability of \( \approx 61\% \) that no electron enters during the acquisition time, \( \approx 30\% \) that exactly one electron enters, and \( \approx 9\% \) that two or more electrons are collected.

The random variable in the Monte-Carlo Simulations was the arrival time of the leakage current electrons according to the leakage current rate \( i_l \). Fig. 3 presents an overview of the probabilities \( W(m,y) = m^y \cdot e^{-m}/y! \) (Poisson distribution [8]) to get a certain number of leakage current electrons \((y)\) for a given mean amount of collected electrons \( m \) \((m = i_l \cdot t_{\text{seq}})\) during \( t_{\text{seq}} \). If a leakage current electron reaches the detector during the acquisition time while readout number \( i \) is performed, the number of collected electrons \( q_i \) is increased by one for all following readouts. The amount of increase of \( x_k \) produced by this depends on the arrival time of the charge. An electron entering the detector at the end of the acquisition time \( (i \text{ high compared to } n) \) is weighted less than an electron arriving close to the beginning \( (i \text{ low compared to } n) \). Running the simulation \( p \) times for a given leakage current of \( 2 \cdot 10^{-6} e^-/(\mu \text{s} \cdot \text{pixel}) \), but different number of readouts with adding serial noise of \( \sigma = 3.3 e^- \) to every readout’s value produces noise peaks whose widths become smaller with increasing number of readouts for \( n \) up to \( \approx 360 \) (fig. 4), because the noise is reduced by eq. 1. For longer acquisition times \((n > 3600)\) the noisepeaks become asymmetric with tails to higher values, because the positions and shapes are now determined by the leakage current mainly (fig. 5).
shows that, for a given leakage current, an optimum number of readouts \( n_{\text{opt}} \) exists for which the lowest noise value can be achieved.

### C. Discussion of the noise level

If later used as a RNDR-based imaging matrix device, it is important to understand, what a certain resolution means in terms of contrast. To get an idea of this a simulated 30 \( \times \) 30 RNDR-pixel matrix was filled with (exactly) one electron in each pixel position marked in plot (a) of figure 7 in white (mask, no noise). Afterwards Gaussian distributed noise with \( \sigma = 1 \text{e}^- \) (b), \( 0.5 \text{e}^- \) (c), \( 0.3 \text{e}^- \) (d), \( 0.2 \text{e}^- \) (e) and \( 0.1 \text{e}^- \) (f) ENC was added to each matrix-pixel. The plots show, that a resolution of better than 0.3e\(^-\) ENC is required to separate a theoretical one electron (photon) structure from the noise. Although the simulations does not include statistical fluctuations of the photon source, it illustrates the relation between noise level and image quality in terms of contrast.

### IV. Experimental Results

To verify the theoretical model, measurements on different devices have been done. To reduce the influence of the leakage current, the measurement setup, consisting of the RNDR device itself, bonded to a ceramic carrier, and the first amplifying readout electronic was operated in a climatic chamber at temperatures down to \(-55^\circ\text{C}\).

#### A. Setup

Figure 8 shows a simplified scheme of the readout setup. The two DEPFETs, our RNDR device are based on, have one
common source and two individual drains (figure 1), which are connected together to one readout node. The amplifier provides the virtual drain potential \( V_{\text{virtual drain}} \) at its inverting input. If the source-drain current increases, the current through \( R_{FB} \) increases the same amount, which leads to a higher voltage drop over it. This way a small change in current \( \delta I \) is amplified and converted to a change in voltage \( \Delta U \) by \( \Delta U = R_{FB} \cdot \delta I \). The current change due to electrons in the internal gate (ca. 300\,\mu A) is small compared to the baseline current flowing through the DEPFET in the on-state (some ten \( \mu A \)). This baseline current can be subtracted by choosing a proper value of \( V_{\text{subr}} \). The amplification is done via an I/V (current-to-voltage) converter as a first stage and a voltage amplifier as a second stage (not shown in figure 8). A main sequencer (FPGA) controls the voltages for the external gates, transfer gate, clear gate and clear, and triggers the ADC (analog to digital converter) to sample the amplified output current of the device.

B. Noise measurements

To verify the simulated data, measurements were done by investigating one pixel of a \( 4 \times 4 \) RNDR minimatrix. In figure 9 the measured noise is shown for a variation of the readout numbers from \( n = 2 \) to \( n = 200 \) for three different temperatures of \(-30^\circ C, -40^\circ C \) and \(-55^\circ C \) (\( \sigma_{n=2} = 4.6 \sigma_{n=200} = 3.3 \sigma_{n=200} \)). Obviously, the decrease in noise follows the \( 1/\sqrt{n} \) law up to a certain number of readouts, which depends on the temperature (e.g. \( n_{\text{best}} \approx 100 \) for the \(-30^\circ C \) measurement). Figure 10 shows the same plot for a higher number of readouts of up to \( n = 2000 \), which corresponds to an acquisition time of \( t_{\text{acq}} = 51 \, \text{ms} \). The degradation of the readout noise shown here can be explained by the higher probability that a leakage current electron enters one of the two internal gates during acquisition time (as theoretically investigated in Section III-B).

The mean leakage current in the case of the \(-55^\circ C \) measurement with \( n = 2000 \) readouts was \( 0.98 \mu A \), resulting in a probability of 37\% that no leakage electrons enter the detector during the 2000 readouts, 36\% that one electron enters the detector, 18\% that two electrons enter the detector and 9\% that three or more electrons enter during the readouts (fig. 3). These leakage current electrons, which are randomly distributed in time, broaden the noise peak and also shift it to higher values.

C. Single photon spectra

To test the detector under optical photon illumination, working parameters of \( T = -45^\circ C, n = 360 \) and \( t_{\text{readout}} = 25.5 \, \mu s \) have been chosen. All readout sequences \( k \) started with a clear, followed by a short photon injection with a weak laser source (672 nm) during \( t_{\text{int}} \).

Afterwards, the amount of collected photoelectrons was measured \( n = 360 \) times and the average value \( \langle x_k \rangle \) was calculated. The distribution of the averaged values obtained for a very weak laser intensity is shown as a histogram in figure 11. Every entry in the histogram belongs to one individual sequence.
consisting of $n = 360$ readouts. In figure 12 the distribution of averages values is shown for a higher laser intensity, where the mean number of collected photoelectrons was twelve. The peaks belonging to different numbers of electrons, generated by the laser pulse, can clearly be distinguished. Also the quantum Poisson nature of the laser source can be nicely seen in the two plots. In the case of fig. 12 the Poisson statistics can be approximated by a Gaussian distribution fitted by the envelope curve with a width of $3.48 \approx \sqrt{12}$. An experimental example of the influence of the leakage current on the noise peak (see section III-B) can be found in figure 11 by the asymmetric noise peak. A description of the noise peak with only one parameter (e.g. $\sigma$) is not sufficient here.

Figure 13 was obtained by a stepwise increase of the laser intensity from 0 to approximately 130 collected photoelectrons. For each intensity level a photoelectron histogram was generated, which were all added to one histogram at the end. For this reason all possible numbers of photoelectrons between 0 and $\approx 130$ occur in the shown spectrum. It shows nicely that the readout mechanism also behaves linearly for a higher amount of collected electrons, and that calibration can be done by simply counting the peaks. Figure 14 shows the highlighted region of fig. 13 magnified (23200 - 23700 ADC units). It displays in more detail that e.g. 100 electrons can be clearly distinguished from 101.

V. OUTLOOK AND APPLICATIONS

Although the results were very promising so far there is still space for future improvements. A further reduction in readout noise is expected by

- using a faster acquisition system with integrated readout ASIC and a faster gate- and transfer gate pulse generator (Switcher), as it is already uses for the classical DEPFET readout, which will shorten $t_{acq}$ and thus reduce the influence of the leakage current.
- a new RNDR-design, which uses three instead of one transfer gate. This allows a simultaneous readout of the full and empty DEPFET by a differential readout system, resulting in a reduction of the readout time by a factor of two.
- cooling down to $-80^\circ C$ and less will further reduce the leakage current.
- reducing the readout noise $\sigma$ of one readout to values down to $2e^-\text{ENC}$ and less, as was shown for DEPFET detectors with smaller gate length, will help to reduce the number of readouts $n$ needed to achieve a certain resolution. Such devices are currently under production.

The most obvious application of such a detector is single optical photon detection in low flux environments, for example in the field of astronomy, where faint galaxies or stars can be characterized even though only a extremely low number of emitted photons reaches the earth.

Another auspicious research field is molecular biology. Here the detection of a few photons emitted by only a small number optical fluorescence tracer molecules, which had been attached to molecules under study, is needed to learn more about the dynamic course of reactions involving these molecules.

But because of the detector’s ability to dynamically adapt a desired resolution by choosing a proper number of readouts, also a low noise X-ray detector can be realised. In this case the fano-noise of the x-rays define the minimum reasonable resolution. By this means a resolution of e.g. $1e^-\text{ENC}$ ($\sigma =$...
$2e^{-\text{ENC}}$ can be achieved with $n = 4$ which leads to a 5\,$\sigma$ X-ray noise cut at 18.2 eV. Of course the entrance window of the detector must be able to handle such photons, but this resolution would allow to see e.g. Iron or Carbon lines from far away extremely red-shifted astronomical X-ray objects.

VI. CONCLUSION

It was theoretically and experimentally shown, that with our DEPFET-based RNDR-detector a noise value down to $0.25e^{-}$ ENC can be achieved by using the method of repetitive non-destructive readout. To our knowledge this is the lowest readout noise value ever measured with linearly amplifying detectors. It has been shown that the DEPFET is very appropriate to fulfill the requirements to realize such a readout element. The produced single pixels and minimatix prototypes show promising results at moderate cooling of only $-55^\circ$C. Because matrix operation is also possible with DEPFETs, larger area sensors are currently under production, to obtain position sensitive single photon detection. Another promising approach is, using a single RNDR-device as a readout node for a CCD column. Such devices are also under production and combine the good CCD properties with an ultra low noise readout.

REFERENCES


Fig. 14. Zoom in fig. 13. Even 100 collected photoelectrons can clearly be distinguished from 101, 102, 103 and so on.

