Sub-electron noise measurements on repetitive non-destructive readout devices

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Abstract

We demonstrate the use of a silicon detector based on a DEPFET device, with sub-electron readout noise (0.6 e^- ENC). The so called RNDR (repetitive non destructive readout) detector was realised by putting two single DEPFETs next to each other, and connecting their charge storing region by an additional gate. By every transfer from gate 1 to gate 2 and vice versa the signal charge can be measured non-destructively. By taking the average value of a large number (n) of these measurements the serial noise is reduced by $1/\sqrt{n}$. This way of readout doesn't only reduce the white noise, but also averages out the 1/f noise. Because the whole readout-time is n times longer than the time for one readout, the device is interesting for low flux applications.

The main advantage of such a detector is the ability to reduce the influence of 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) were investigated by Monte-Carlo simulations and measured on Single-Pixel-RNDR-devices.

Key words: RNDR, sub-electron noise, DEPFET, Active Pixel Sensor, spectroscopy.

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1 Introduction

It was experimentally shown by (1) that it is possible to achieve a readout noise better than detector and system noise of a single amplifying stage by using the method of multiple readout (e.g. floating gate amplifier). Due to the fact, that in such a detector the same charge is moved from one readout node to another and back arbitrarily often, it is called "repetitive non-destructive readout" - device. Our RNDR detector was realised by a combination of two DEPFETs (2) which store and amplify the collected charge, (confined in an electric field inside the depleted silicon) and a transfergate in between them which allows a controlled drift of the charge from one DEPFET to the other.

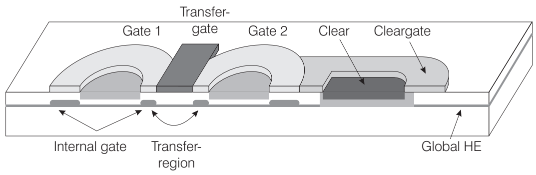

Fig. 1. Cutaway of a simplified layout of the RNDR device. The collected charge is stored in the internal gates, located under the two external gates (**gate 1** and **gate 2**). The charge can be moved from one DEPFET to the other via the **transfergate**. The difference of the measured source-drain current of each transistor before and after a transfer is proportional to the moved charge. Because the charge is not lost but stored in the neighbouring DEPFET, its amount can be measured multiple times. The last transfer moves the charge under gate 2, from which it can be completely removed by opening the **cleargate** and applying a positive voltage to the **clear**.

The DEPFET itself consists of a p-channel-MOSFET processed on a high ohmic silicon substrate, which can be completely sideward depleted and thus provide on the one hand sensitivity over the whole wafer thickness, and on the other hand a lateral potential minimum beneath the wafer surface. An additional n-implantation beneath the two circular external gates (gate 1 and gate 2, figure 1) forces the generated electrons to drift underneath the gates, these locations are called "internal gates" (3). The external gate has two functions:

- As in a normal MOSFET the current from source to drain is steered by the applied gate-source voltage, so the DEPFET can be turned on and off by applying appropriate voltages to the external gate.
- If the DEPFET is turned off, the internal gate becomes capacitively coupled to the external gate. A more positive external gate-off voltage makes the internal gate more attractive to electrons.

The collected electrons in the internal gate modulate the channel conductivity, and have therefore impact on the source-drain current. The influence is given by $g_q = \frac{\delta I}{\delta Q}$ (Q: charge in the internal gate), according to $g_m = \frac{\delta I}{\delta V}$, the external gate transconductance. For a typical device the value is $\approx 300 \frac{pA}{e^-}$.

This first integrated amplifying stage leads to a high resolution detector due to the small input capacitance of only a few tens of fF. In the investigated RNDR device the charge can be moved from the DEPFET which is turned on to the DEPFET which is turned off by applying a positive voltage to the transfergate (figure 1). Measuring the difference of current before and after transfer (henceforth called one "readout"), the amount of moved charge can be derived from the known g_q. By interchanging the on/off states of the two DEPFETs, the charge can be transferred back and measured again the same way. After repeating the measurement n times the serial noise has decreased by eq. 1:

$$\sigma_{end} = \frac{\sqrt{n \cdot \sigma^2}}{n} = \frac{\sigma}{\sqrt{n}} \tag{1}$$

n : number of readouts (e.g. number of transfers)

σ_{end} : readout noise after n readouts

σ : mean noise of one readout

The main advantage of this readout principle is, that even if all single measurements (before and after transfer) are affected by 1/f noise, this normally shaping-time independent noise is also reduced through eq. 1. Because of this, the minimum achievable noise is only limited by the number (n) of readouts, duration (t_{loop}) and readout noise (σ) of one readout, and the leakage current (i_l) (4). After all readouts, an additional n-channel-MOSFET (Cleargate, figure 1) is opened and a positive voltage at the clear contact removes the charge. The DEPFET is now empty and ready for further charge collection.

2 Monte Carlo Simulations

The four most important parameters of a RNDR device are:

i_l leakage current in $e^-/(\mu s \cdot \ pixel)$

σ readout noise for one readout in e^- ENC

t_{loop} readout time for one readout in μs

n number of readouts

The influence of these values to the minimum achievable resolution was investigated by Monte Carlo simulations. The mean value x_k of all n readouts is calculated from eq. 2:

$$x_k = \frac{\sum_{i=1}^{n} (p_i \pm \sigma)}{n} \tag{2}$$

x_k mean value of all readouts

p_i number of collected electrons till loop number i, $p_i = p_{i-1} + m_i$ with m_i = number of leakage current electrons arriving within $t_{i-1} = t_{int} + (i-1) \cdot t_{loop}$ and $t_i = t_{int} + i \cdot t_{loop}$. The distribution of $j_k = \sum_{i=1}^{n} m_i$ for many Monte Carlo runs corresponds to the Poisson distribution for the given leakage current i_l and the sequence time $t_{seq} = t_{int} + n \cdot t_{loop}$. ($t_{int}$: integration time, time from last clear to the beginning of the readout)

n number of readouts

k number of Monte Carlo run $k = 1...q$

If one leakage current electron reaches the detector during the readout time ($t_{aquisition} = n \cdot t_{loop}$), the number of collected electrons is increased by one and is measured 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 readout period is weighted less than an electron arriving close to the beginning. Running the simulation q times for a given leakage current, but different number of loops with adding serial noise of $\sigma =$ 3.3 e^- ENC to every loop's readout value produces noise peaks whose width become smaller with increasing number of loops for n up to 64, because the dominant serial noise is reduced (eq. 1). For longer readout times ($n > 64$) the noisepeaks become asymetric with tails to higher values, because the positions and shapes are now determined by the leakage current mainly (figure 2).

The isolines of fig. 3 show the standard deviation of the noise peak for variable values of the leakage current i_l and number of loops n, with fixed readout noise $\sigma = 2.0\ e^-$ ENC and readout time $t_{loop} = 34\mu$s.

3 Experimental results

3.1 Setup

Figure 4 shows a simplified scheme of the readout setup. The two DEPFETs have one common drain (outer region in figure 1) and two individual sources which are connected together to one readout node, the virtual source potential $V_{virtual\ source}$ is provided by the amplifier. The current change due to electrons

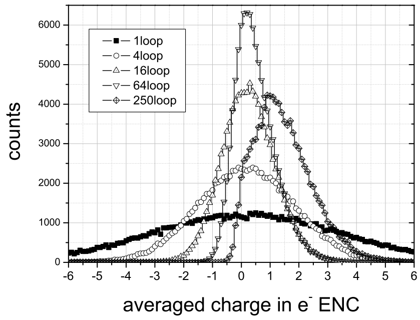

Fig. 2. Simulated noisepeaks of a RNDR detector with $\sigma = 3.3$ e- ENC for different numbers of readouts (1, 4, 16, 64 and 250), for a given leakage current of i_l =0.0003 $e^{-}/(\mu s \cdot Pixel)$ and a readout time of $t_{loop} = 34$ μs and an integration time of $t_{int} =$ 414 μs. For the given parameters, the lowest readout noise can be achieved with 64 loops.

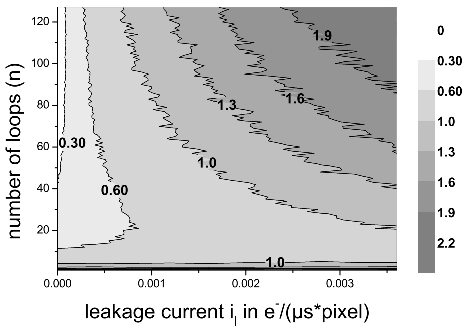

Fig. 3. Monte Carlo map showing the noise in e- ENC as a function of the leakage current vs number of loops. The isolines show the minimum achievable noise in e- ENC, Parameters: $\sigma = 2.0e^{-}ENC$, $t_{loop} = 34\mu$s. To see the pure impact of the leakage current to the resolution an integration time of only t_{int} =1μs was used.

in the internal gate is small compared to the baseline current flowing through the DEPFET in the on-state. This baseline current can be subtracted by choosing a proper value of $V_{subtr.}$. The amplification is done via an I/V converter as a first stage and a voltage amplifier as a second stage (not shown in figure 4). A main sequencer controls the voltages for the external gates, transfergate, cleargate and clear, and triggers the following ADC to sample before and after each transfer.

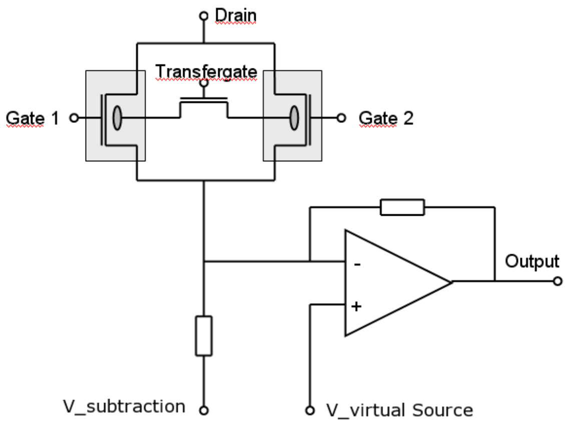

Fig. 4. Simplified scheme of the RNDR device and the readout setup. The I/V converter defines a common Source potential for both DEPFETs ($V_{virtual\ source}$). By turning one DEPFET off during the other one is on and vice versa enables the readout of both DEPFETs with only one readout node.

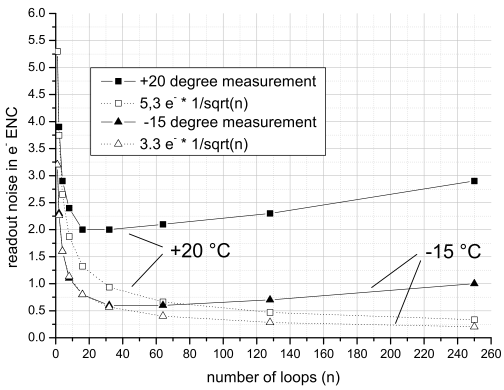

Fig. 5. Theoretical expectation and measured noise in e^- ENC vs number of transfer loops. For two different temperatures of +20 degree and -15 degree measurements are shown, the monotonously falling curves show the respective theoretical noise limits given by eq. 1.

3.2 Measurements

In figure 5 the measured noise is shown vs the number of readouts. The measurements and calibration (^{55}Fe, 5.9 keV K_α) were done at an environment temperature of -15 degree. As can be seen in the plot the noise decreases by $1/\sqrt{n}$ for up to 32 readouts. The best resolution was achieved at 32 and 64 readouts (0.6 ±0.1 e^- ENC). The monotonous falling lines show the theoretical limit defined by $\sigma_{limit} = \sigma \cdot \frac{1}{\sqrt{n}}$. The increase of noise for a higher number of readouts is believed to be caused by the leakage current in agreement with the Monte Carlo simulation.

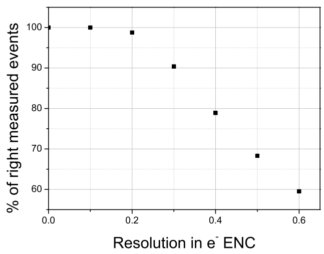

Fig. 6. Probability to measure the right number of electrons for different resolutions. With a resolution of $\sigma_{end} = 0.3\ e^{-}$ ENC it it possible to determine the right number of collected electrons with a probability of 90 percent.

4 Outlook

With a further decrease of noise down to 0.3 e^{-} ENC and less, a readout element for a detector could be realised which is able to detect single optical photons with an 90 % accuracy (figure 6). If one optical photon produces one electron hole pair in silicon, and this one electron can be separated from the noise, the single photon can be measured. That way, a single photon detector can be realised in terms of a real linear amplifier. Figure 6 shows the probability to measure the right number of electrons for different noise values. Because of the ability to measure the discrete nature of single photons/electrons, tests of statistical fluctuations of photon sources can be made. In the astronomical field the detector can help to measure the complete photon flux rate of a star entering the detector without loosing events in the noise of the detector, which is typically 2-3 e- ENC for nowadays often used CCDs.

5 Conclusion

The DEPFET is very appropriate to fulfill the requirements to realise a repetitive non-destructive readout (RNDR) element. Single pixel prototypes were produced and first tests show promising results. With our detector we achieved noise values down to of 0.6 e^{-} ENC at -15 degree. To our knowledge, this is the best read noise value ever measured with linear amplifying detectors. Because matrix operation is also possible with DEPFETs, a large area sensor could be realised, for instance to obtain position-sensitive single photon detection for the optical spectrum.

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