First operation of a pixel imaging matrix based on DEPFET pixels

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Abstract

In the DEPFET pixel concept the detected incident radiation is directly sensed and amplified by a JFET integrated in every pixel cell. While the DEPFET detector principle has already been demonstrated previously on single pixel structures, we present here the first successful operation of a large 32×32 DEPFET pixel matrix as an imaging device. The matrix has been exposed to 60 keV gamma rays of a ^{241}Am source and has been scanned using an IR laser. The principle of operation as well as the charge collection in the structure and possible improvements are discussed.

In this paper we present first dynamical measurements on a large 32×32 pulsed clear DEPFET matrix using a radioactive γ-source and an IR laser. The DEPFET pixel structure consists of an n-type detector substrate with a p-channel JFET transistor integrated on the top [1] (Fig. 1). The detector substrate is depleted using the sidewards depletion technique [2] which forms a potential minimum for electrons inside the silicon bulk in a plane parallel and about 1 μm below the detector top surface. In this plane a local minimum is created exactly under the channel of the JFET transistor by a local deep n-implant region (internal gate). Upon the energy deposit due to the incident radiation electron–hole pairs are created. While the holes drift to the rear side p-electrode the electrons are collected in the internal gate with the effect that they induce an increase of the channel current density resulting in a change of the transistor current which is sensed at the drain electrode. The pixel thus returns a current signal which is proportional to the number of collected electrons in the internal gate. To achieve a uniform thin entrance window the backside of the detector is left unstructured to minimize reflection

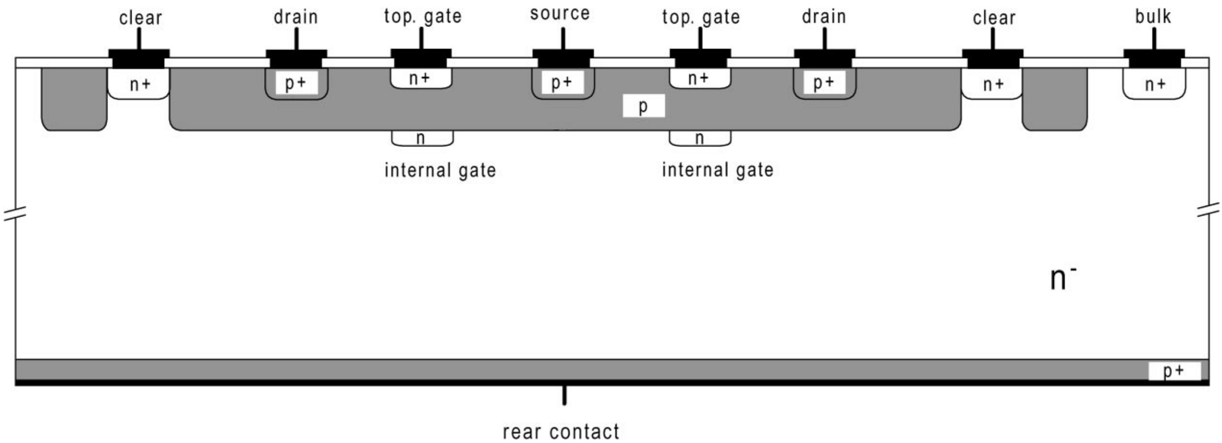

Fig. 1. Schematic cross section of a pulsed clear DEPFET.

and absorption. Due to the small input capacitance of the JFET a high signal-to-noise ratio has been achieved [3].

Fig. 1 shows a simplified cross section of the annular DEPFET device. The JFET has an external gate to which an external voltage can be applied. This allows to externally switch off the current of each detector pixel while the signal charge is still stored in the internal gate of the JFET or to switch on the current of this pixel for read out. Signal electrons as well as electrons accumulated from bulk leakage current must be removed from the internal gate after read out. Clearing is obtained by periodically applying a positive voltage pulse to a clear contact (n^+-implantation enclosed by the p-channel and drain area). This mechanism is called "pulsed clear" and is used in the matrix described in this paper. Another possibility to remove electrons from the internal gate is the so-called "continuous clear" mode where a positive voltage applied to an n^+pn punch-through structure continuously empties the internal gate. A 2×2 matrix of continuous clear DEPFET detectors has been characterized in Ref. [4].

The layout of a pixel cell is shown in Fig. 2. The cell has a square geometry with dimensions $200 \times 200\ \mu m^2$ with the source of the JFET in the center of the pixel surrounded by a circular gate of 9 μm length. Four contacts for clearing are placed symmetrically to the pixel center in the drain implantation of the JFET.

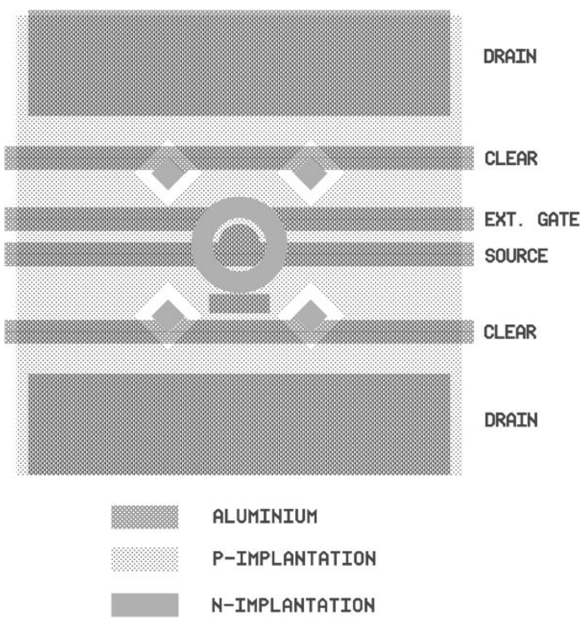

Fig. 2. Layout of one cell of the pixel matrix. Note that the drain terminal of the JFET transistor is entire area outside the gate ring, contacted at the top and the bottom.

1. System description

The drains of 32 DEPFET transistors in one column are connected together via their drain p-implants. Each of the 32 columns is connected to a wire bondpad so that a parallel readout of 32 pixels at a time via 32 channels is realized. The external gates of the DEPFET transistors of one row are connected by a metal line such that all transistors of that row can be simultaneously switched on or off. Hence in order to read out one pixel cell the corresponding column must be selected and the corresponding gate of a row must be switched on while all other rows are switched off (Fig. 3). The current signal measured by the amplifying electronics of the selected column is modulated by the signal charge stored in the internal gate under the corresponding JFET transistor channel. To calculate the deposited signal charge in a single pixel an individual pedestal has to be substracted. The pedestal can be measured and stored before the detector is exposed to a signal source.

A readout cycle of the whole 32×32 matrix has the following sequence. First a global clear pulse is applied to the matrix which resets all 1024 pixel cells. Then 32 pixel cells of one row are successively switched on by applying the gate-on voltage to the external gates of this row, while the cells of all other rows remain switched off. After having digitized the current signals of the pixels in the selected row the next row is turned on while all other rows are again switched off. This is continued until the data of all rows are recorded. Finally, the global clear pulse is applied again and a new readout cycle begins. As the clear is issued globally to all internal gates and the readout sequence is started 25 ms later and proceeds row by row for 15 ms, the earlier rows have a shorter integration time than the later rows. The first row is exposed for 25 ms, the last row 40 ms, limited by the speed of the data acquisition. A row-wise clear pulse would cure this limitation but the current layout does not allow this mode of operation.

The readout electronics of the prototype matrix presented here is still realized using discrete electronic components. Fig. 3 shows a block diagram of the whole system. Analog switches are used to apply the gate-off voltage or the gate-on voltage to the pixel rows to toggle the external gates on or off. The switching sequence of a readout cycle is transmitted to these analog switches by a shift register. Every matrix row has its own current–voltage converter which is realized by a low-noise OpAmp

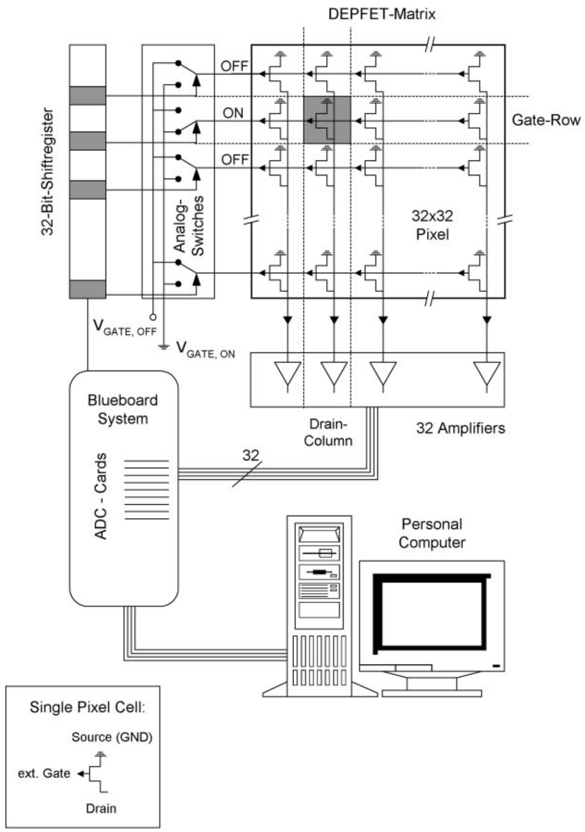

Fig. 3. Block diagram of the system.

(Analog Devices AD844) with a feedback resistor $R_{\mathrm{fb}} = 550\ \mathrm{k}\Omega$. The outputs of the 32 current–voltage converters are connected to 32 ADC-cards of the Blue Board System (Silicon Solutions [5]). The entire readout electronics is controlled through the Blue Board System by a PC.

2. First measurements

2.1. Image of a nut

A shadow image of a brass nut (hole diameter $= 2$ mm) has been taken with the system and is shown in Fig. 4. The nut has been placed on the non-structered backside of the detector. The result of a 7 min long irradiation with a ^{241}Am source (59.5 keV γ, 74 MBq) was recorded showing a reduced counting rate in the cells covered by the nut.

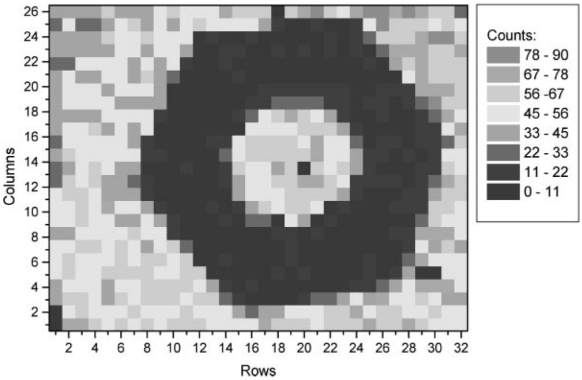

Fig. 4. Shadow image of an M2 nut.

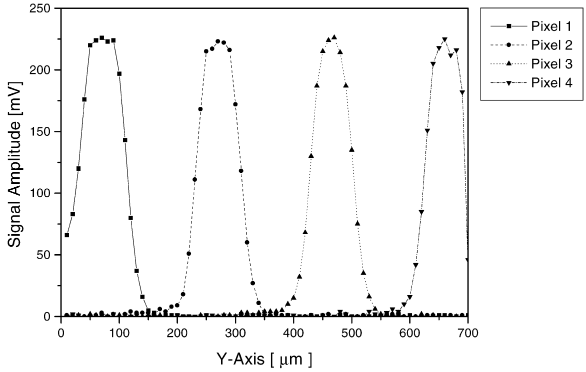

Fig. 5. Position-dependent sensitivity of four adjacent DEPFET pixels.

The readout rate of the entire matrix was 25 Hz. Pixel signals having a signal above a threshold of 4000e have been counted. Note that the integration time varies by a factor 1.6 between rows 1 and 32. Few pixel cells (e.g. the one in the center of the nut hole) show no hits although not covered by the nut. These pixel cells function correctly but their current signals exceed the operating range of the ADCs. This is the first successful demonstration of the imaging capabilities of a DEPFET pixel matrix.

2.2. Sensitivity of the matrix pixels

To further investigate the characteristics of the DEPFET pixel matrix it is important to study the sensitivity to radiation of a single pixel cell as a function of the precise location of the γ-ray absorption. A laser scan of a matrix region using a pulsed laser with a spot size of about 16 μm was performed and the position-dependent response was studied. For this measurement the matrix detector is mounted on a computer-controlled XY-table and is moved in two dimensions in steps of 10 μm. Laser light of 810 nm wavelength is focussed onto the detector's unstructured backside using a microscope. A single laser pulse generates about $20\,000e^-$ in the DEPFET detector to be compared to the $23\,300e^-$ generated by a high energetic particle in 300 μm Si by ionization.

Fig. 5 shows a sensitivity profile of four adjacent pixels. It is evident that there is a region of maximum sensitivity in the center of a pixel. The sensitivity drops to zero in the regions between pixels. To understand this behavior a two-dimensional sensitivity map of one pixel is compared with the pixel layout in Fig. 6. The simplified layout shows the gate ring of the DEPFET detector surrounding

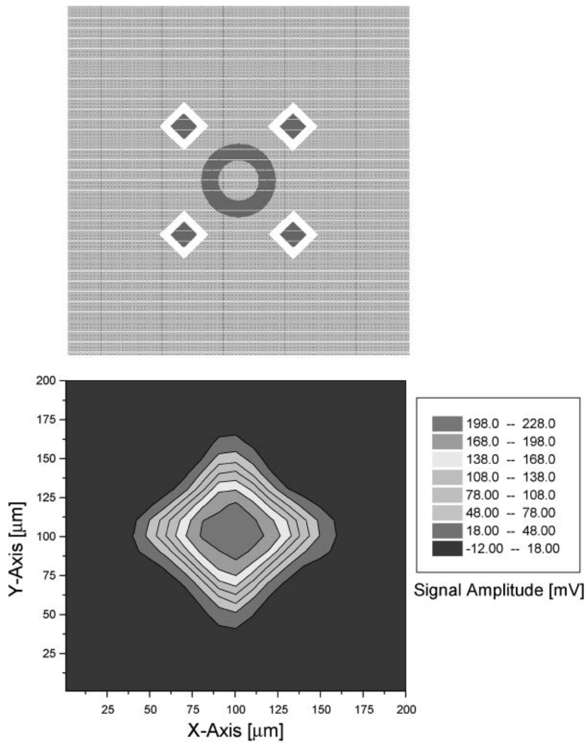

Fig. 6. Layout and sensitivity of one matrix pixel.

the source in the center and the four square clear contacts embedded in the drain area. The sensitivity drastically decreases in the region of the clear contacts. This indicates that charge is lost into the clear contacts and hence escapes detection in the internal gate of the amplifying transistor. This occurs because the clear contacts are held at source potential when no clear pulses are applied and electrons which are generated in the outer region of the pixel cell will tend to drift towards the clear contacts. Due to these charge losses the sensitive area of a 200 μm × 200 μm pixel is reduced to a region of about 50 μm × 50 μm. This problem of charge loss in the clear contacts could be dealt with in a forthcoming generation of DEPFET detectors by implanting an additional p-layer underneath the clear contacts.

2.3. *Spectrum of a* ^{241}Am *γ-source*

The energy spectrum of the γ's from a ^{241}Am source measured with the DEPFET prototype system shows a particular shape due to partial charge collection (Fig. 7a). The spread of the charge cloud in the bulk of the DEPFET sensor is of the order of $\sigma = 8$ μm depending on drift time and the start distribution of the charges. Only clouds of signal electrons created in the center of a pixel are completely collected while signal electrons created in the outer region of the pixel cell suffer from partial charge loss into the clear contacts. The partial charge loss gives rise to signals at a smaller amplitude in the spectrum and so the monoenergetic 59.5 keV peak of ^{241}Am shows a "background" of these events of lower energy (see Fig. 7a). The threshold was set to 16 keV at about 5σ of the measured noise (see Fig. 7b). A simple Gaussian fit of the peak yields an energy resolution of $\sigma = (898 \pm 33)e^-$. To understand the noise behavior of the device a Monte-Carlo simulation was used which is discussed below.

3. Noise of the system

The noise of the entire imaging system including the contribution from the DEPFET sensor and from the readout electronics is determined by a measurement where the detector response is recorded in the absence of any signal source (Fig. 7b). A value of ENC $= (602 \pm 4)e^-$ has been measured for this prototype system being mostly due to the shot noise caused by the detector leakage current. This noise contribution grows proportional to the square root of the measurement (integration) time T. With the present (preliminary) readout electronics the time needed for one readout cycle is rather long, $T = 16$ ms. During this time electrons from the leakage current fill up the internal gate and their fluctuations from one readout cycle to the next result in a noise contribution $\mathrm{ENC_{leak}}$. In a simplified model (Gaussian distribution of the leakage current variation) the fluctuation of the integrated electrons corresponds to the square root of the total number of collected electrons in the internal gate:

$$\mathrm{ENC_{leak}} = \sqrt{\frac{\langle i_{\mathrm{leck,pix}} \rangle T}{e}} \tag{1}$$

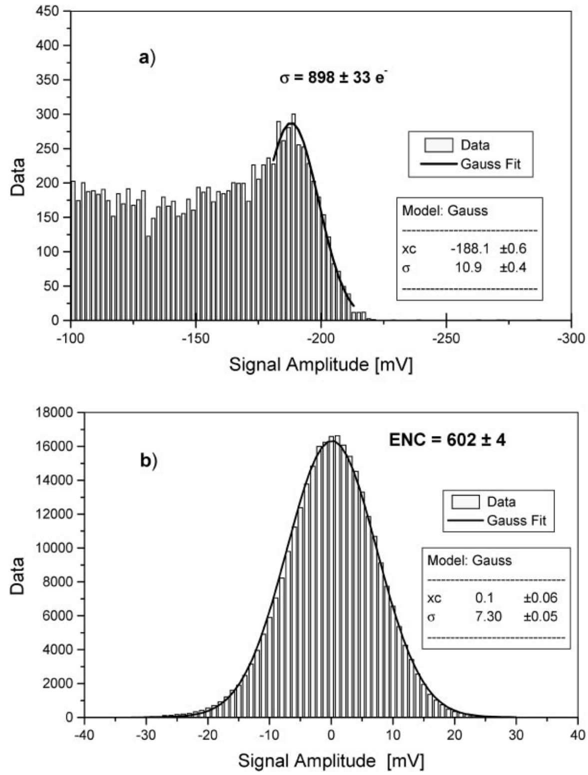

Fig. 7. (a) ^{241}Am spectrum measured with DEPFET matrix and (b) Gaussian noise spectrum of DEPFET matrix.

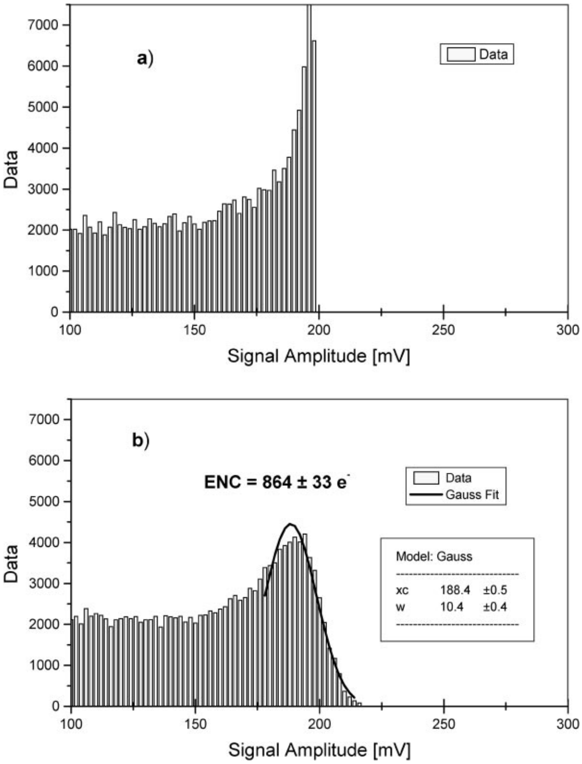

Fig. 8. Monte-Carlo simulation of a monoenergetic spectrum (^{241}Am) for a pixel cell with an sensitive area of 50 μm × 50 μm and for charge clouds of $\sigma_{\text{charge}} = 8$ μm: (a) no noise; and (b) $600e^-$ noise added.

where T is the integration time, $\langle i_{\text{leck,pix}} \rangle = 1.6$ pA is the mean value of the leakage current and e is the elementary charge. Calculating the noise contribution from each row using its corresponding integration time and adding them in quadrature weighted by the number of collected hits yields

$$\text{ENC}_{\text{leak}} = 568e. \quad (2)$$

We conclude that with a faster readout electronics noise values below $100e^-$ over the entire matrix can be achieved.

The energy resolution and the noise have been studied with Monte-Carlo simulations. Fig. 8 shows two simulated spectra for a pixel cell with a sensitive area of 50 μm × 50 μm and for Gaussian charge clouds of $\sigma_{\text{charge}} = 8$ μm [6]. In the first spectrum (Fig. 8a) no noise has been considered which leads to a sharp edge of the peak corresponding to 59.5 keV. In the second spectrum a Gaussian distributed noise of $600e^-$ has been added (convolution of the first spectrum with a Gauss function). The peak is broadened and the center of the peak is shifted to lower energies. A Gaussian fit to the shifted peak yields $\sigma = (864 \pm 33)e^-$ which is in good agreement with the measured energy resolution of the DEPFET prototype system (Fig. 7).

4. Conclusions

The principle of DEPFET pixels has been introduced as a promising concept for radiation detection already more than 10 yr ago and has since been demonstrated with single pixel structures. We have now shown for the first time that a large 32 × 32 prototype matrix of pulsed clear DEPFET pixels can be operated in an imaging mode. The shadow image of a nut was recorded using a ^{241}Am γ source. Laser scans show a reduced sensitive area due to charge loss into the clear contacts. The energy resolution and observed system noise are still limited by the readout speed of the prototype system. Improvements for a better charge collection and lower noise have been suggested.

Acknowledgements

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References

[1] J. Kemmer, G. Lutz, Nucl. Instr. and Meth. A 253 (1987) 365.
[2] E. Gatti, P. Rehak, Nucl. Instr. and Meth. A 225 (1984) 608.
[3] G. Cesura et al., Nucl. Instr. and Meth. A 377 (1996) 521.
[4] P. Klein, G. Cesura, P. Fischer, G. Lutz, W. Neeser, R.H. Richter, N. Wermes, Nucl. Instr. and Meth. A 392 (1997) 254.
[5] Silicon Solutions: email:silicons@faust03.physik.uni-bonn.de.
[6] N. Meidinger, Diffusion und Drift von Ladungen in Halbleiterdetektoren, Diplomarbeit an der TU Muenchen, MPE-Report 225, January 1991.