A DEPFET pixel Bioscope for the use in autoradiography

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Abstract

The DEPFET structure consists of a field effect transistor integrated on high-resistivity silicon, which can be used as a radiation detector. Due to several features (e.g. very low noise at room temperature, information storage capability and a thin, homogeneous entrance window), the DEPFET concept is useful for various applications. In order to apply a DEPFET pixel detector in autoradiography, 64×64 matrices with a pixel size of $50\ \mu m \times 50\ \mu m$ were built. Using several ASIC chips for the readout control and signal processing, a complete sensor system allows a row-by-row detector readout with almost continuous sensitivity. First results on the device homogenity, the quantum efficiency and the very promising noise performance are presented.

1. Introduction

Autoradiography is one of the main methods used in the fields of cell biology and physiology, giving insight in the structure and dynamics of cells. Extensive descriptions of the method can be found elsewhere [1]; here we will only recall the main issues.

In autoradiography the distribution of radioactive markers inside one cell or a whole agglomeration of cells is examined. Depending on the specific goal of the examination, there are various requirements on the implementation of the experiment.

- A homogeneous response and a small number of erratic hits are of course basic requests for a good detector.
- In order to get a good spatial resolution, it is necessary to detect the outgoing radiation as close to the radioactive emitter as possible. This

requires a small range of the outcoming radiation. Due to the high stopping power which most detector materials show for low-energy electrons, often beta ray emitters are chosen as markers. An especially good choice is ^{3}H with an end point energy of 18.6 keV (mean energy 5.7 keV). In silicon, the emitted electrons have a mean range of about 1 μm. Hydrogen atoms also offer a second advantage: They are abound in organic material and can therefore be easily introduced without changing the properties of the biological tissue. A small range of the incoming radiation puts a remarkable challenge on the construction of detectors. They must have very thin entrance windows and they must show an excellent noise behaviour in order to be sensitive to the small signals generated by low-energetic radiation.

- If a detector also offers energy resolution, interesting studies can be done using different markers at the same time, each of them characterizing different structural or metabolic attributes.
- Although the dynamic behaviour of a sample can be studied with films using several similar tissues, it is much better to use a real-time detector and one identical tissue. This is especially true for in vivo studies. Working with living material on the other hand sets very narrow limits to the environment variables (e.g. temperature, atmosphere, etc.).
- Last but not least, the experimental setup should be small and easy to handle.

Silicon detectors offer several advantages compared to other devices used in autoradiography [1]. Most important of all is the possibility to take fast images allowing to examine dynamic processes. In the following we will show, how a silicon pixel detector based on the DEPFET structure can be used as a device for in vivo β-autoradiography with ^{3}H.

2. DEPFET pixel detectors

The Depleted Field Effect Transistor (DEPFET) structure consists of a field effect transistor inte-

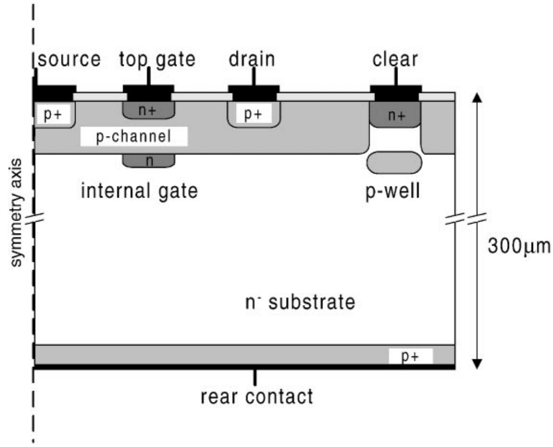

Fig. 1. DEPFET detector principle.

grated on high-resistivity silicon, which can be used as a radiation detector (Fig. 1). Using the sidewards-depletion method [2], a potential minimum for electrons is created in the fully depleted substrate underneath a field effect transistor. Signal charges are produced by a particle or photon impinging on the unstructured, thin rear-side diode. Whereas the holes will disappear in the rear contact, the electrons can be stored in the potential minimum, from where they steer the transistor current. By sensing the current, the information about the incoming radiation can be extracted in a non-destructive way. To prevent the potential minimum from being completely filled up with signal electrons and thermally generated charges, a short reset ("clear") pulse (of approx. 1 μs duration) has to be applied periodically.

Shifting the charge-collecting transistor gate from the surface into the bulk allows to minimize the input capacitance without largely influencing the transistor parameters, which are dominated by the independent top gate at the surface. The splitting up into two gates with differing tasks allows a reduction of the thermal noise of the device as the relevant "internal gate" has a very small capacitance. Compared to other charge amplifiers a higher leakage current of the top gate can be tolerated, as this gate has a low-ohmic connection to the source.

A pixel detector can be realized by building an array of DEPFET transistors. In contrast to other

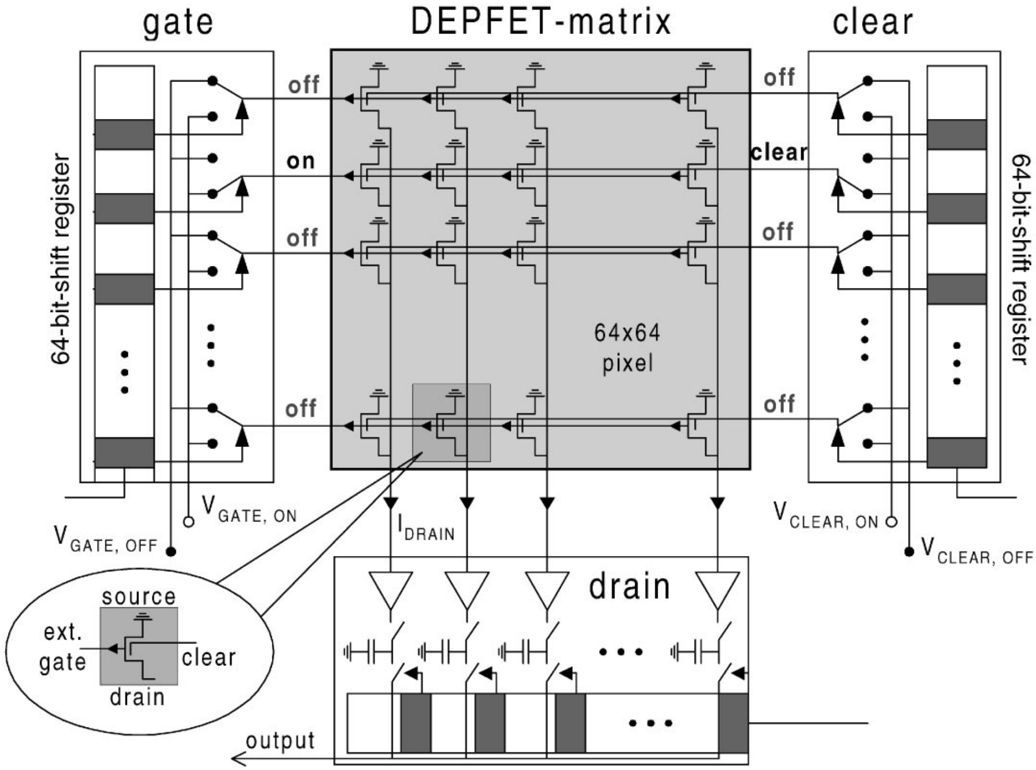

Fig. 2. Readout concept for the DEPFET pixel matrices.

silicon pixel detectors an expensive bump-bond procedure can be avoided. As one pixel is equivalent to one DEPFET transistor, all transistor gates within one row can be connected to each other as well as all transistor drains within one column. This is shown in Fig. 2, where two shift registers are used to apply the appropriate gate and clear voltages to the individual rows.

The concept significantly reduces the number of readout channels. The readout scheme is as follows: Only the transistors within one row are switched on at the same time and the drain current of each of these transistors is amplified and multiplexed by a current-sensing amplifier chip at the end of the columns. Afterwards a clear pulse is applied just to this particular row. Following the output of the continuously working shift register, the transistors in this row are switched off and the next row is switched on, etc.

3. Setup of the DEPFET pixel Bioscope

In order to build up a first system applicable in the field of autoradiography, 64×64 matrices with a pixel size of $50\ \mu m \times 50\ \mu m$ were produced. The rear side of the detector chip, on which the samples are placed, is composed of a shallow p^+ implantation (quite similar to that used in [3]), 30 nm of SiO_2 and a thin protective nitride layer (100 nm) on the surface. This results in an insensitive region of $\sim 0.15\ \mu m$ thickness forming the uniform entrance window. Using the relation given by Fitting [4] for electron energies below 10 keV

$$R = 900\rho^{-0.8}E_0^{1.3}$$

it can be estimated which part of the tritium beta spectrum is accessible by the detector. Here, R is the range within which 99% of the incoming radiation has been absorbed (in Å), ρ is the material

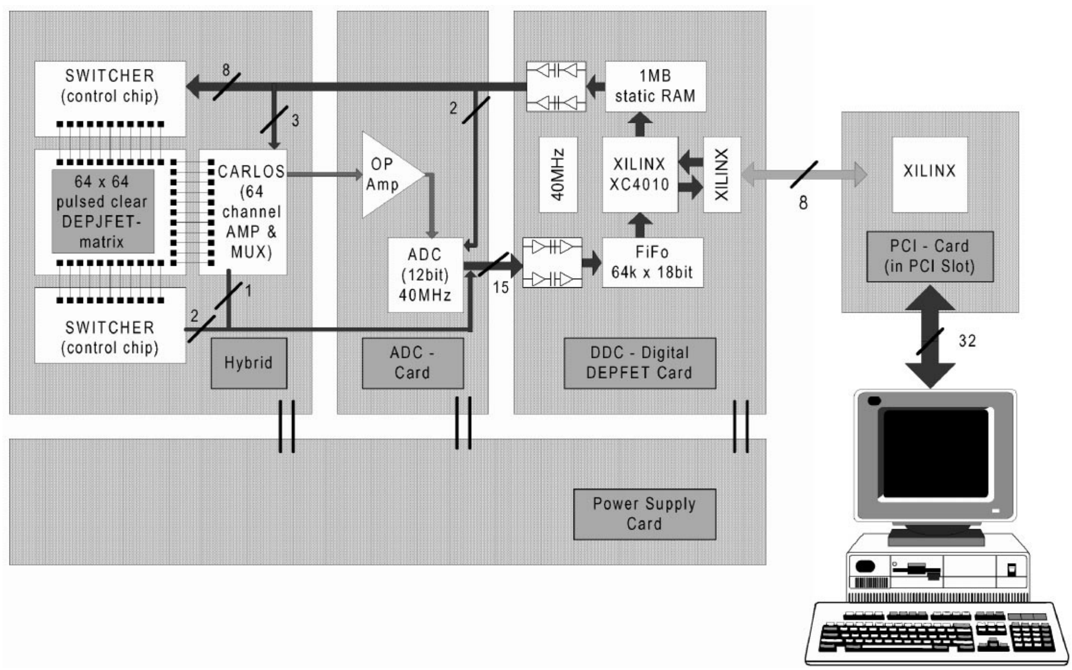

Fig. 3. DEPFET Bioscope system.

density (in g/cm^3) and E_0 is the initial energy of the electrons (given in keV). The estimation shows, that the detector should be able to detect tritium electrons whose energy exceeds 3 keV. Therefore, neglecting the self-absorption in the radiating sample, more than half of the emitted tritium beta electrons could be detected.

Using a row-by-row detector readout as described above, where also the clear pulse is applied to only one row at a time, the detector is sensitive more than 99% of the operating cycle time.

The detector chip is mounted on a ceramics hybrid together with a specifically designed readout chip (CARLOS) and two steering ASICs (SWITCHER) implementing the gate and clear control of the individual rows (see Fig. 3). The CARLOS chip [5] contains 64 current amplifiers and a multiplexer and is connected to a fast ADC (40 MHz, 12 bit).

The data acquisition is controlled with the help of a dedicated FPGA board (Digital DEPFET Card (DDC)), that can be programmed by a PC. Further information on the DEPFET pixel Bioscope can be found in Ref. [6].

4. First measurement results

First results showing the capability to detect tritium were already presented in a previous paper [7]. Here we will show some recent results on the noise performance and the detector homogeneity.

The noise performance of a DEPFET pixel was measured by doing an energy calibration with the help of the Mn-K_α line and the Mn-K_β line of an ^{55}Fe source (see Fig. 4). Determining the width of the noise peak leads to an ENC of $9.5 \pm 0.1e^-$ at $T = 300$ K and a shaping time of 10 μs. Taking into account the unavoidable Fano noise contribution, this means that the signal/noise value for this photon energy is 96 ± 1. To our knowledge the value of 146 eV FWHM for the Mn-K_α line is the best result obtained so far with silicon detectors at room temperature ($T = 300$ K).

This good noise behaviour does not only lead to an increased detection efficiency for electrons with low energies, but is also important for a good spatial resolution when charge splitting is used to determine the exact hit position.

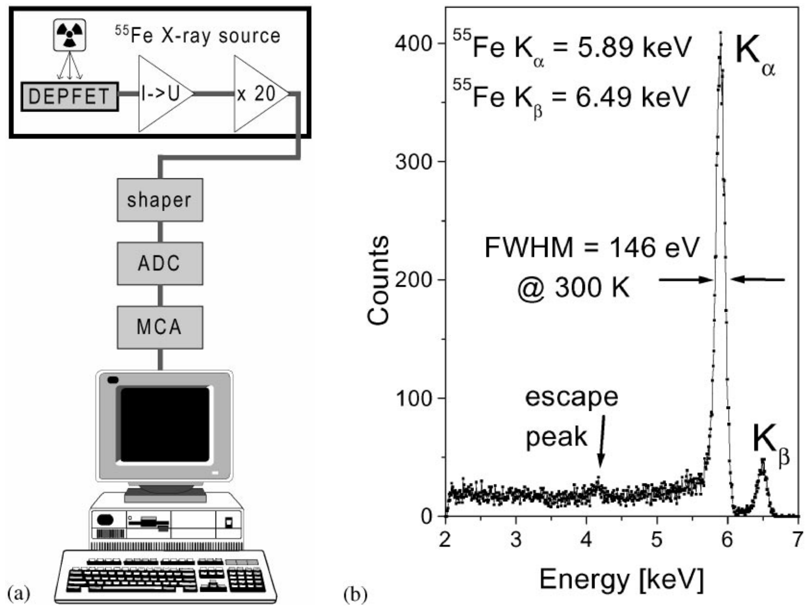

Fig. 4. ^{55}Fe spectrum recorded with one DEPFET pixel; doing an energy calibration with the K_α line and the K_β line and taking into consideration the Fano noise contribution, a noise value of $9.5 \pm 0.1e^-$ at $T = 30$ K and a shaping time of 10 μs was determined.

To examine the homogeneity of the electrical parameters of the pixels, the transistor parameters were measured using a 16×16 matrix, which was designed to have the same resistance of the voltage supply lines as the larger matrix. Reducing the number of pixels for these tests makes the test setup much simpler. Fig. 5 shows the variation of the DEPFET currents. Calculating a σ value of ~ 5 μA corresponding to $\sim 1.3\%$ for the current variation, leads to a variation of approx. 0.7% in the transconductance of the pixels. This means, it is not necessary to calibrate each pixel, even when using charge splitting.

A further investigation of the small inhomogenity showed that to a large extent it is caused by the resistance of the drain and source supply lines. As the sum of the currents of all transistors in this row is flowing through the source supply line of one matrix row, even the low sheet resistance of the on-chip aluminium leads to a drop in the gate-source voltage and therefore a current reduction. By some changes to the aluminium mask, in a second iteration we therefore lowered the resistance of the source supply lines by a factor of 4. The drain supply line is implemented by a high-dose implantation which leads to a drain resistance of $298 \pm 1\ \Omega$ per pixel. This leads to a drain voltage drop when moving through a column. As the transistors have an output resistance of 233 ± 6 kΩ, this voltage drop leads also to a current drop in the matrix. The drain resistance can be lowered to less than 0.1% of the actual value by introducing a second metal layer, which was not available in our technology, when the detectors were produced.

5. Conclusion

Spectroscopic measurements on a DEPFET pixel show an extremely low noise at room temperature. The value of 146 eV FWHM for the Mn-K_α line is to our knowledge the best result obtained so far at room temperature ($T = 300$ K).

Examinations of the detector homogeneity reveal that the current variations within a matrix are very small and to a large extent are due to supply line resistances. Introducing a second metal layer, which was not available, when the detectors were

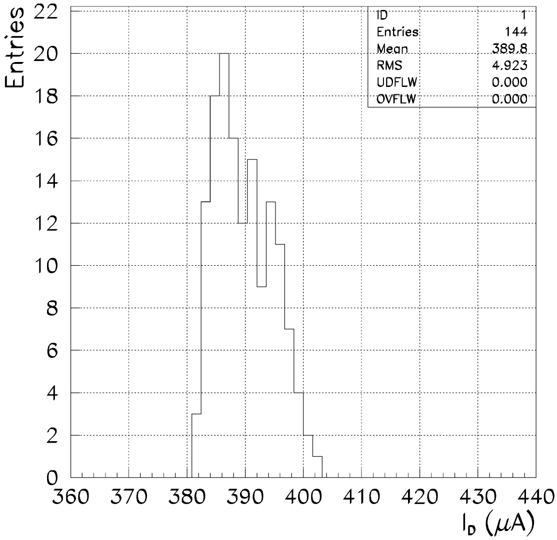

Fig. 5. Current variation within a 16×16 DEPFET pixel matrix.

produced, will effectively reduce these resistances and will be done in a future production.

Summarizing, it can be stated that a DEPFET pixel detector system offers all properties, that are necessary for successful autoradiography with tritium:

- The good noise performance of the DEPFET allows the detection of low-energy electrons.
- The thin, homogeneous entrance window leads to a high and homogeneous quantum efficiency over the whole detector area. Up to now no insensitive regions were found.
- The system setup is simple and small with no bulky vacuum or cooling devices.
- The detector system is ideal for in vivo studies:
  - All measurements can be done at room temperature.
  - The samples are examined in normal atmosphere, no vacuum is needed.
  - Due to the fast readout, real-time studies of dynamic processes are possible.
- The matrix setup allows dynamic changes of the sensitive area, so that e.g. subregions of particular interest can be studied in detail.
- Due to the spectroscopic properties of the detector, different markers can be used at the same time.

At the moment two Bioscope systems are in operation, results on specific biological studies shall be published soon.

References

[1] M. Overdick, Digital Autoradiography Using Silicon Strip Detectors, Wissenschaftsverlag Mainz, Aachen, 1999.

[2] E. Gatti, P. Rehak, Nucl. Instr. and Meth. A 225 (1984) 608.

[3] R. Hartmann, D. Hauff, P. Lechner, R.H. Richter, L. Strüder, J. Kemmer, S. Krisch, F. Scholze, G. Ulm, Nucl. Instr. and Meth. A 377 (1996) 191.

[4] H.-J. Fitting, Phys. Status Solidi. A 26 (1974) 525.

[5] P. Fischer, W. Neeser, A current amplifying readout chip for low noise sensors: CARLOS 1.0, Nucl. Instr. and Meth. A, in preparation.

[6] W. Neeser, M. Böcker, P. Buchholz, P. Fischer, P. Holl, P. Klein, H. Koch, M. Löcker, G. Lutz, H. Matthäy, L. Strü‡der, M. Trimpl, J. Ulrici, N. Wermes, DEPFET–A pixel device with integrated amplification, Nucl. Instr. and Meth. A, submitted for publication.

[7] W. Neeser, M. Böcker, P. Buchholz, P. Fischer, P. Holl, J. Kemmer, P. Klein, H. Koch, M. Löcker, G. Lutz, H. Matthäy, L. Strüder, M. Trimpl, J. Ulrici, N. Wermes, The DEPFET pixel BIOSCOPE, IEEE Trans. Nucl. Sci., submitted for publication.