The DEPFET pixel BIOSCOPE[1]

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Abstract

The DEPFET pixel Bioscope system based on a DEPFET pixel matrix provides good spatial and energy resolution in real-time digital autoradiography. Due to its very low noise and an optimized entrance window the online detection of tritium without vacuum or cooling is demonstrated for the first time. To achieve this milestone a p-channel junction field effect transistor on a fully depleted high ohmic silicon substrate (DEPFET) is used as unit cell for pixel detectors providing an excellent noise performance of $158\,\mathrm{eV}$ FWHM at $6\,\mathrm{keV}$ (12 e ENC) at room temperature (300 K). 64 × 64 DEPFET pixel matrices with square ($50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$) or hexagonal ($50\,\mu\mathrm{m} \times 42\,\mu\mathrm{m}$) pixels have been developed and operated successfully. First measurements result in a homogeneous charge collection efficiency on the whole matrix area and a good linearity in the X-ray range from $5\,\mathrm{keV}$ to $60\,\mathrm{keV}$. First images taken with the square and the hexagonal pixel matrices using an ^{55}Fe-source as well as a 'proof of principle' experiment for online ^{3}H-detection are presented and discussed.

I. Introduction

The principle of the DEPFET pixel detector is the integration of the first amplifying transistor into a high resistivity silicon detector [1] resulting in a good noise performance as measured with first prototype single pixels [2], [3], [4]. A cross section of a DEPFET pixel structure is shown in fig. 1. A p-channel JFET combined with sidewards depletion [5] creates a sensor-amplifier structure that collects signal electrons generated in the bulk in its so called 'internal gate' to directly modulate the current of the amplifying JFET. In order to have a high and homogeneous sensitivity throughout the whole detector area the radiation enters the $300\,\mu\mathrm{m}$ thick bulk from the completely unstructured backside with an entrance window of only $200\,\mathrm{nm}$ effective thickness. This allows the detection of tritium ($^3H-\beta$-decay with $5.7\,\mathrm{keV}$ mean energy) as well as X-rays below $30\,\mathrm{keV}$ with high efficiency [7]. Since the internal gate fills up with electrons from signals as well as from leakage currents it has to be emptied by periodically applying a short positive voltage pulse to the n-type clear contact ('pulsed clear' DEPFET). Due to the pixel size of $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ and small leakage currents even at room temperature a clear pulse repetition rate of several Hertz can be realized resulting in a dead time of less than 1%. With single DEPFET pixels an electronic equivalent noise charge of $ENC = (12 \pm 1)$ e has been achieved [6].

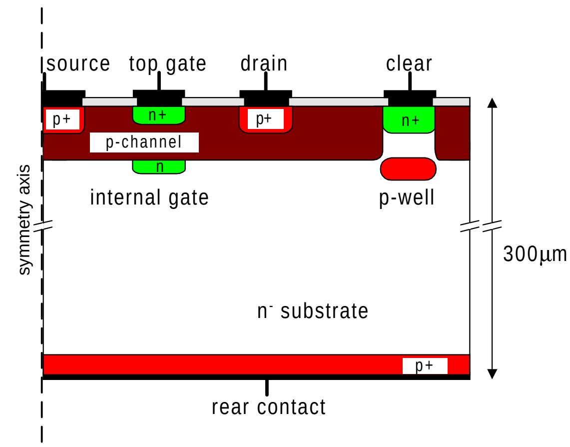

Figure 1: Cross section of an annular DEPFET pixel. The structure is is symmetric along the symmetry axis shown.

II. The DEPFET pixel Bioscope

A DEPFET pixel Bioscope has been developed using a 64 × 64 DEPFET pixel matrix as sensor. The system is mainly designed for use in digital autoradiography [8] and is described in more detail in [6]. Different pixel geometries and sizes were produced to evaluate the best spatial and energy resolution.

Fig. 2 shows a section of a 64 × 64 DEPFET matrix layout with hexagonal pixels of $50\,\mu\mathrm{m} \times 42\,\mu\mathrm{m}$ and fig. 3 shows a photo of a DEPFET matrix using square pixel geometry of $50 \times 50\,\mu\mathrm{m}^2$. Both matrix types have been examined and are described briefly. Source, gate and clear contacts of one pixel row are connected with each other via aluminum traces and are contacted on the sides of the matrix using wire bonding. The source in the pixel center is surrounded by an annular gate n-implantation and a drain p-implantation. The clear contacts

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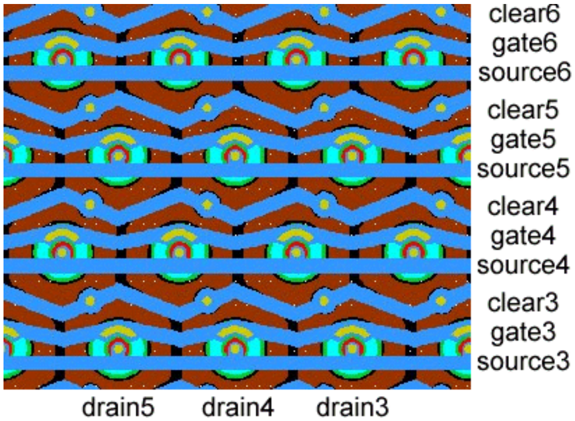

Figure 2: Section of a DEPFET matrix layout with hexagonal pixels.

are embedded in the drain areas and contacted on the right side of the matrix whereas the gate row contacts are located on the left side (see fig. 3). The drain p-implantations are connected column-wise via their p-implantation and can be accessed through an aluminum contact at the bottom of the matrix. In the hexagonal pixel matrix (see fig. 2) the drains are connected in a zigzag column not visible here as the connecting p-implant is covered by the clear aluminum traces.

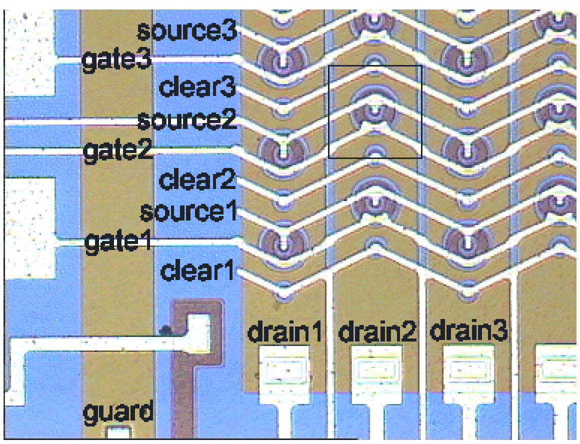

Figure 3: Photograph of a corner of a DEPFET matrix with square pixels. The size of one pixel is indicated with a black frame.

The data acquisition (Fig. 4) of the DEPFET pixel Bioscope can be split up into two parts, the integration phase and the readout-reset phase. According to the event rate in a given application the integration phase can be reduced to a minimum by permanent repetition of the readout-reset phase which takes about 1 ms for all pixels of the 64×64 DEPFET pixel Bioscope in the actual setup.

During the integration phase all JFET pixel currents are switched off by applying the pinch-off voltage to all gate rows. Even though all transistors are switched off the sensor is still active and electrons generated in the bulk are collected in the internal gates of the pixels where they are stored. To analyze the amount of collected charges in a pixel in the readout phase the change in the JFET pixel current has to be measured

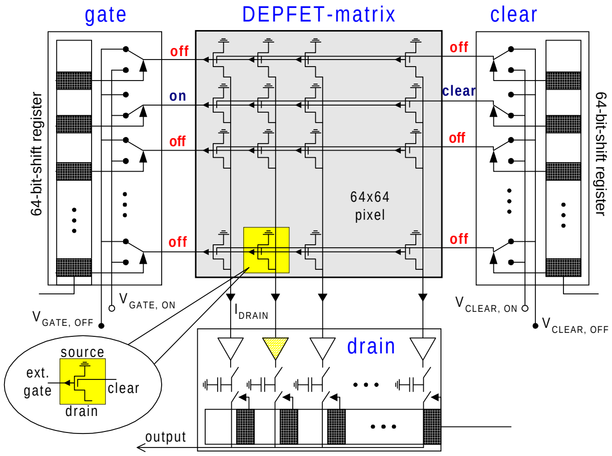

Figure 4: Block diagram of data acquisition of a DEPFET pixel matrix using 3 ASICs for controlling and amplification (refer text).

precisely as an additional charge of 100 electrons will cause a current change of only 10 nA of the standing transistor current of 100 μA.

At the beginning of the readout phase the first gate row is switched on and the currents of these 64 pixels are sensed with a 64 channel amplifying chip CARLOS 1.0 [9]. They are sampled, amplified, digitized and stored as 'signal currents' I_{sig}. After a reset pulse has been applied to the clear contact of the same row to empty the internal gates of these pixels the currents are sampled again yielding the 'pedestal currents' I_{ped}. Then this row is switched off and the next row is switched on, sampled, cleared, sampled again, switched off and so on for all 64 rows. The total amount of charges Q_{total} collected in a pixel is the sum of signal electrons generated by a hit Q_{hit} and electrons due to leakage current I_{leak} and can be calculated using formula 1 with g_q as the DEPFET amplification:

$$Q_{total} = Q_{hit} + I_{leak} \cdot \tau_{frame} = \frac{I_{sig} - I_{ped}}{g_q}; \qquad (1)$$

As long as the total readout time τ_{frame} is short and constant and the leakage current is small, the leakage current contribution is constant and its fluctuation is small (e.g. 14 electrons for $\tau_{frame} = 1\,\mathrm{ms}$ and $1nA/cm^2$ leakage current at room temperature) and any change in Q_{total} is due to a hit in this pixel. Fast low-noise data acquisition and very small leakage currents have to be realized in order to obtain a good energy resolution. Small leakage currents have been achieved by careful matrix layout using multi guardring structures and an optimized process technology. A fast low-noise readout is arranged with the PC based Bioscope system using the dedicated custom chips SWITCHER [10] and CARLOS [9], a 40 MHz 12 bit ADC and several FPGAs as described in [6].

III. Measurements with the DEPFET pixel Bioscope

Two hybrids with square and hexagonal DEPFET pixel matrices wire-bonded to the controlling or amplifying ASICs have been assembled. A picture of a hybrid and a description of the complete system can be found in [6]. Initially a slightly simplified readout sequence has been used in order to study the system. No row-wise clear but a global clear mechanism has been used not affecting the described characteristics. As the programming of a cluster finding and interpolating routine has not yet been finished all images are displayed in a binary mode although the signal amplitude information was recorded.

A. *Sensitivity of matrix pixels*

To examine the sensitivity of the whole matrix area the DEPFET pixel Bioscope was mounted on an xy-table and placed under a microscope used to focus a laser ($635\,\mathrm{nm}$) onto the backside of the detector. Although the laser beam spot is only a few μm wide the charge cloud spreads during the drift through the $300\ \mu$m bulk.

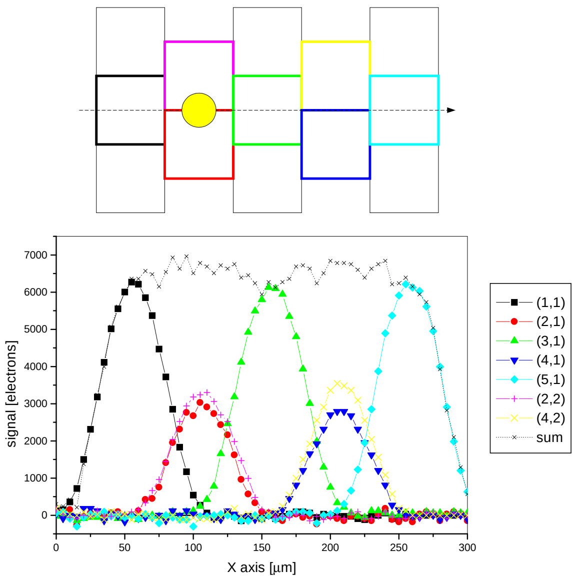

Figure 5: Scan with laser across 5 drain columns of the square pixel matrix. a) Schematic drawing of the laser scan (top) b) measured sensitivity of the 7 adjacent pixels (bottom).

Fig. 5 shows the recorded response of 7 adjacent square pixels and the sum of all signals. As shown in fig. 3 adjacent pixels are staggered by half the pixel size. The laser beam is stepped on a line connecting the source contacts of the first, the third and the fifth pixel and the clear contacts of the second and the fourth column. The total charge of 6500 electrons is generated with each single laser shot and the whole matrix is read out there after. Pixels in the first, third and fifth column record the same signal amplitude. In the second and in the fourth column the charge is split between two pixels but the sum remains constant. Thus no charge is lost into the drain column gaps or into the clear contacts as observed on the earlier prototype DEPFET structures [4]. This is due to an additional deep p-implantation 'p-well' underneath the clear contacts (see fig. 1) and to the reduced width of the drain column gaps.

B. *Linearity of the DEPFET pixel Bioscope*

The detector has been illuminated homogeneously by different radioactive X-ray- and γ-sources to test the linearity of the recorded signal amplitudes.

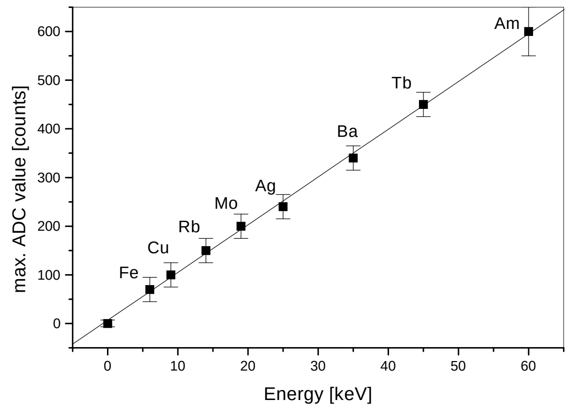

Figure 6: Signal amplitudes of various sources recorded with the DEPFET pixel Bioscope.

Fig. 6 shows a plot of all measured sources covering the range from ^{55}Fe at $6\,\mathrm{keV}$ to ^{241}Am at $60\,\mathrm{keV}$. A good linearity can be observed.

C. *2D images using an ^{55}Fe-source*

To evaluate the performance of the DEPFET pixel Bioscope a shadow image of a brass nut (hole diameter $\approx\ 1\,\mathrm{mm}$) was taken using an ^{55}Fe-source with $6\,\mathrm{keV}$-X-rays. The nut was placed directly on the $3.2 \times 3.2\ \mathrm{mm}^2$ backside of the square pixel matrix and illuminated for one hour.

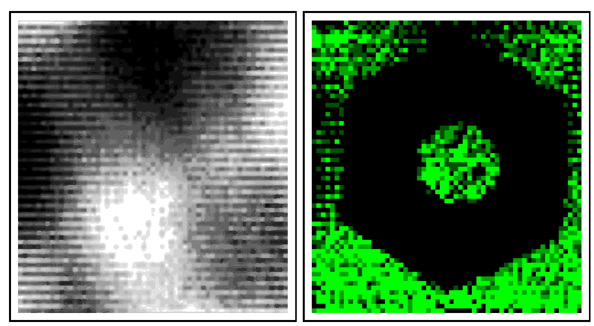

Figure 7: a) Pedestal current distribution (left) b) shadow image of a M1 nut illuminated with an ^{55}Fe X-ray source (right).

Fig. 7 a) shows the pedestal current distribution where black indicates the lower edge and white the upper edge of the dynamic range of the used amplifying chip CARLOS 1.0. About 200 of the 4096 pixels cannot be read out because their pedestal currents lie out of the operation range of the amplifier. In the next version of CARLOS the gain will be decreased in order to increase the dynamic range. Fig. 7 b) shows the recorded image with some inactive (black) pixel areas at the left and the right of the nut due to the saturation of the readout. The threshold for this measurement was set to 700 electrons resulting in no noise hits at all in the shadow area of the nut.

The hexagonal pixel matrix was also tested using an ^{55}Fe-source. A small $75\,\mu$m thick tungsten Modulation Transfer Function (MTF) test chart was placed on the backside of the 3.2×2.7 mm^2 detector.

Figure 8: a) FAUST-MTF test chart as placed on the hexagonal pixel DEPFET matrix (left) b) recorded shadow image in binary readout using 6 keV X-rays (right) .

Fig. 8 a) shows the MTF test chart placed on the backside of the hexagonal pixel DEPFET matrix. The letters are $\approx$ $125\,\mu$m wide, the line pairs are 1 mm long and decrease from 5 lp/mm via 6.66 and 10 to 20 lp/mm. Due to the preliminary binary display mode not all MTF line pairs can be resolved. The resolution will be improved with implementation of interpolation for split events.

D. Detection of ^{3}H-source

^{3}H plays an important role as a radioactive tracer but due to its short mean range of $800\,$nm in silicon a direct online detection of the β-particle has been difficult. Due to its thin entrance window and its good noise performance the DEPFET pixel Bioscope should be able to record tritium with good efficiency. A first 'proof of principle' test was performed using ^{3}H-Microscales [11] as they are standards in autoradiography and easy to handle. The threshold for this measurement was set to 9σ of the system noise to assure that no noise hits were registered.

Fig. 9 shows the setup of the experiment. Only a small part of the ^{3}H-Microscale can be placed on the backside due to the small area of the detector of 3.2×3.2 mm^2. The tritium is located in the white areas of the Microscale. Fig. 9 b) shows the online display of the detected events after several hours which is clearly correlated to the labeled Microscale areas.

IV. Conclusions

Low noise silicon pixel detectors open new possibilities in biomedical applications, but also have a potential in particle physics and astrophysics. New improved DEPFETs with a reduced gate length of $5\,\mu$m and a pixel size of $50\,\mu$m $\times$ $50\,\mu$m have been designed and produced. Tests with single pixels show a noise performance of 12 e ENC at room temperature. A system for digital autoradiography was developed providing good spatial and energy resolution. Radioactive decays within a biological sample can be detected by a 64×64 array of

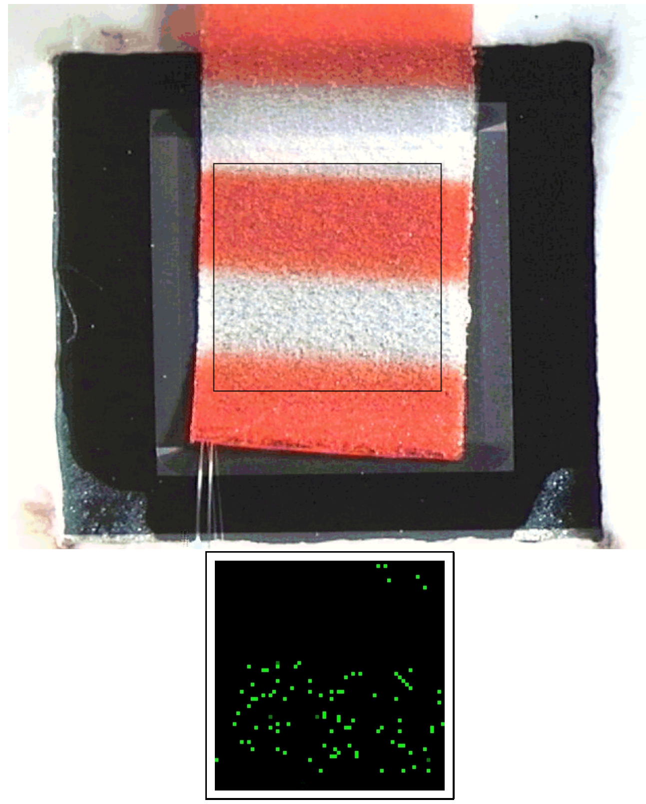

Figure 9: a) Photograph of a ^{3}H-Microscale^{TM} [11] placed on the entrance window of the DEPFET pixel Bioscope (top) b) screen shot of the online event display after several hours (bottom).

DEPFET-pixels in real-time. Laser scans show a homogeneous charge collection over the entire detector. Shadow images obtained using an ^{55}Fe-X-ray-source were presented. The successful detection of Tritium decays has demonstrated the good low-noise characteristics of the detector.

V. Acknowledgments

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