Study of a DEPFET pixel matrix with continuous clear mechanism *

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Abstract 

A new kind of silicon pixel detector with integrated amplification has been built and tested. Each pixel consists of a p-channel JFET located on a fully depleted substrate. The pixel size can be customized by using a drift-chamber like transport mechanism in each pixel. The homogeneity of the signal response of a small matrix was investigated with a laser diode. The measured rise time and gain of the device are analyzed with a simple small signal model.

1 Introduction

The noise performance of silicon detectors can be considerably improved by integrating an amplifying element directly into the detector silicon. In the case of DEPFET devices [1], a p-channel junction field effect transistor is located on top of a n− detector substrate which is fully sidewards - depleted [2]. Electron - hole pairs which are generated in the bulk material by ionizing particles, X-rays or visible photons are separated by the electric field in the depletion region. The electrons drift to a region underneath the transistor channel (the 'internal gate') where the resulting change of the electric potential modulates the drain-source current in the DEPFET. Because the radiation

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is impinging from the unstructured backside of the detector, no inefficiencies due to the absorption of radiation at the detector surface occur.

Fig. 1 shows a simplified layout and a cross section of a circular DEPJFET device. The circular drain in the center is surrounded by a ring shaped gate and a ring shaped source, the latter being open on the left side freeing space for the clear contact. Additional annular electrode rings (‘drift rings’) are used to shape the electric field in the bulk such that all electrons in a 200 μm × 200 μm area are collected at the internal gate while keeping its capacitance as low as possible [3]. This internal gate represents a local potential minimum for electrons. It slowly fills up due to signal charges and detector leakage current so that the device would get out of its proper operation region without any kind of reset mechanism. In order to empty the internal gate from electrons, regular positive clear pulses can be applied to a n⁺ clear contact (pulsed-clear device [5]) or a npn⁺ punch-through structure [6] can be used to provide a dc path with very high resistance (continuous-clear DEPJFET [4]). In the latter case, the potential of the internal gate is controlled by the clear voltage. The external gate is connected to the internal gate by a vertical opening in the channel implantation next to the clear contact (see fig. 1). This allows to shrink the gate dimensions as no separate external gate connection is needed. DEPJFET devices with this continuous clear mechanism have been operated successfully with a noise of only ENC ≈ 20e at room temperature [4].

In this paper, we present first measurements of a small 2-d-matrix of continuously cleared DEPJFET devices. Using photon illumination on the backside, the homogeneity of the detector response as a function of the light spot position is studied and compared to the results from a single pixel device. Furthermore, gain and rise times of the detector signals are compared with theoretical expectations. Finally, conclusions for new detector designs are discussed.

2 Test setup

For a fast readout, the DEPJFET transistor is connected in a source follower configuration with a bias current of 1 μA. In order to reduce the capacitive load of the output node, a custom made integrated buffer chip is directly wire-bonded to the source of the DEPJFET. This chip contains the bias current source and a two stage buffer with a total gain of v_{buf} = 0.79 and a measured bandwidth of 30 MHz. For the pixel matrix, one buffer channel per pixel is used.

The devices are mounted on a computer controlled xy-table in a light-tight shielding box. A 200 μm pinhole is illuminated with LEDs of different wavelengths (522 nm or 633 nm) or a fast IR-laser diode (810 nm) and focussed
Fig. 1. *Simplified layout and cross section of single pixel DEPJFET device*

through a microscope (×10) onto the backside of the detector.
3 Measurements on single pixels

For a study of the gain and the speed of the devices, a single pixel has been operated in saturation \((V_{ds} \approx -4V)\) at a constant current of 1 \(\mu\)A. The transconductance and the output resistance of the annular transistor \((W = 42 \, \mu m, L = 4 \, \mu m)\) is determined by static measurements to \(g_m = 10 \, \mu S\) and \(r_{ds} = 1 \, M\Omega\) at this current.

<table>
<thead>
<tr>
<th>source</th>
<th>radiation</th>
<th>energy [keV]</th>
<th>deposited charge [e-h-pairs]</th>
<th>average signal [mV]</th>
<th>signal/charge [mV/fC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{90}\text{Sr})</td>
<td>(\beta)</td>
<td>2300</td>
<td>23300</td>
<td>105 ± 5</td>
<td>28 ± 1</td>
</tr>
<tr>
<td>(^{241}\text{Am})</td>
<td>(\gamma)</td>
<td>59.5</td>
<td>16500</td>
<td>75 ± 5</td>
<td>28 ± 2</td>
</tr>
<tr>
<td>(^{55}\text{Fe})</td>
<td>(\gamma)</td>
<td>5.9</td>
<td>1600</td>
<td>8 ± 2</td>
<td>31 ± 7</td>
</tr>
</tbody>
</table>

Table 1

Measured output signal amplitudes for different signal sources

Table 1 summarizes the measured average signal amplitudes for different radioactive sources. A very good linearity of the signal response for various numbers of e-h-pairs could be observed. The average gain of the pixel in this mode of operation is \(v_{gs} \approx 28mV/fC\). The rise time of the output signal is measured with radioactive sources or with fast IR light-pulses to \(t_r \approx 360\) ns. The influence of the buffer chip is negligible for this rise time.

Fig. 2 shows the schematic of a simple small signal model of the source follower setup which can be used to analyze the JFET.

The gate-drain and gate-source capacitances, \(C_{gd}\) and \(C_{gs}\), can be determined with the help of eq. (1) and (2) which express the dc-gain \(v_{gs}\) and the rise time \(t_r\) for the simple small signal model of the device.

\[
v_{gs}(Q_{in}) = \frac{Q_{in}}{C_{gd}} \left( 1 + \frac{1 + C_{gs}/C_{gd}}{g_m r_L} \right)^{-1}
\]
\[
t_r = 2.2 \cdot \frac{C_L \left( 1 + \frac{C_{gs}}{C_{gd}} \right) + C_{gs}}{g_m}
\]

The calculated values of \(C_{gd} = 15fF\) and \(C_{gs} = 200fF\) depend strongly on the estimated capacitative load of the source-follower output of \(C_L \approx 100fF\). As apparent in eq. (2), the signal rise time is a function of the transconductance \(g_m\) and can therefore be decreased through a higher channel current at the cost of higher power consumption.
Fig. 2. *Small signal model of the source follower readout*

The position-dependent response of the device for illumination with a 20 μm light spot has been measured on the xy table for different field configurations in the drift structure. The measurement for the normal operation of the drift structure is shown in fig. 3 (bottom).

The quadratic acceptance corresponds well to the quadratic layout of the outermost drift ring (the tilt angle of the square is due to the arbitrary positioning of the device onto the xy-table). If the outermost drift ring is biased at a potential which is more positive than the next innermost ring, electrons in the outer part of the device are no longer directed to the internal gate and are lost. This can be seen in the upper figure. The acceptance is reduced to the size of the annular second drift electrode. These measurements confirm the expected operation of the build-in drift chamber.
Fig. 3. Spatial efficiency of a single DEPJFET device for different biasing of the drift structure: nominal field (bottom), outermost ring more positive (top). Grey levels indicate signal amplitudes.

4 Measurements on a $2 \times 2$ matrix

A $2 \times 2$ matrix of continuously cleared DEPJFET pixels has been operated for the first time to investigate the homogeneity of the signal response across the
sensitive area. Using the same setup as for the single pixel, the $2 \times 2$ DEPJFET matrix shown in fig. 4 with 4 parallel channels was illuminated with a small light spot of visible or infrared light from the backside.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Fig. 4. \textit{Layout of small $2 \times 2$ DEPJFET matrix. The 4 buffer channels are wire-bonded to the 'butterfly' aluminium structures on top of each pixel (= source).}}
\end{figure}

The results of these measurements are identical for green and infrared light. The signal amplitudes of the 4 channels are superimposed in the 2d plot in fig. 5. The total sensitive area is bigger than the expected $400 \mu m \times 400 \mu m$ area because the guard ring acts as an additional drift ring as it is much closer to the active pixel area than in the single pixel layout.

Due to the extended width of the outermost drift ring at the corners of the matrix, the drift field is insufficient to focus the signal electrons towards the internal gate, as can be seen in fig. 5. These electrons are therefore lost.

The reduced sensitive area of the lower right pixel in fig. 5 is due to one missing wire bond to the outermost drift ring of this pixel. The visible influence of this missing field shaping electrode can be understood in analogy to the measurements on a single pixel shown in fig. 3. The insensitive spacing between the pixels is due to a gap between the outermost drift rings biased at the same
Fig. 5. *Measured spatial efficiency of 2 × 2 DEPJFET matrix. Grey levels indicate signal amplitudes.*

Voltage $V_{\text{Ring3}} = -22V$ which leads to an unwanted potential minimum for electrons.

5 Summary

Countinuously cleared DEPJFET pixels have been operated successfully in a small $2 \times 2$ matrix. The observed inefficiencies are understood and will be avoided in the next layout by proper field rings. The speed and the gain of the JFETs are within the expectations and will be simulated with ToSCA [7] for a better understanding of the device. The speed can be increased by using a transistor with reduced gate length and higher supply currents.

6 Acknowledgements

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References


