DEPFET – Detectors: New Developments

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Abstract

The DEPFET (Depleted Field Effect Transistor) detector-amplifier structure forms the basis of a variety of detectors being developed at the MPI Semiconductor Laboratory. These Detectors are foreseen to be used in astronomy and particle physics as well as other fields of science. The detector developments are described together with some intended applications. They comprise the X-ray astronomy missions XEUS and SIMBOL-X as well as the vertex detector of the planned Linear Collider ILC. All detectors are produced in the MPI Semiconductor Laboratory that has a complete silicon technology available.

Keywords: Silicon detector, pixel detector, DEPFET, XEUS, SIMBOL-X

I. Introduction

Based on the sideward depletion principle (E. Gatti and P. Rehak) [1] the DEPFET (Depleted Field Effect Transistor) detector-amplifier structure has been invented 1985 by J.Kemmer and G.Lutz [2]. A p-channel field transistor is placed on the fully depleted bulk (Fig.1). By suitable doping a potential maximum (internal gate IG) is created below the transistor channel. Electrons created anywhere in the depleted bulk are collected in the IG, inducing a mirror charge within the channel, thus increasing its conductivity. The unique properties of this device as for example combined detector

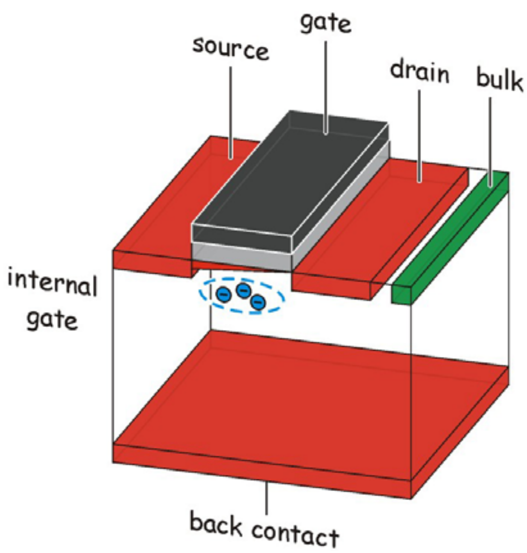

Figure 1. *The Concept of a DEPFET*

and amplification properties, signal charge storage and non destructive readout make it useful for many applications. Of particular interest is its use as building block of a pixel detector with very low noise and power consumption.

II. PIXEL DETECTORS FOR ILC AND XEUS

Although the intended applications and therefore the requirements are rather different, the two developments in their initial stages are done jointly.

XEUS (Fig. 2) [3] is the future European X-ray observatory with the main scientific aim of investigating the Early Evolution Stages of the Universe, observing early black holes, evolution and clustering of galaxies and element synthesis. The observation of these faint objects requires large mirror collection area (more than one order of magnitude increase compared to XMM/Newton [4]) and therefore large focal length (50m compared to 7.5m) since X-ray total reflection occurs at shallow angle only. Mirror and focal plane instrumentation are therefore on two separate satellites following each other at constant distance (within 1 mm^3). A 450 μm thick DEPFET pixel detector of 8x8 cm^2 area and 75x75 μm^2 pixel size is the centre piece of the focal instrumentation.

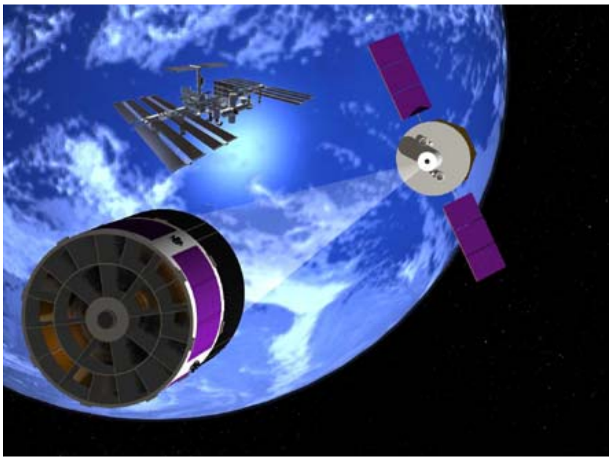

Figure 2. *An artist's view of XEUS. A DEPFET pixel detector located on the focal plane satellite provides a spectroscopicX-ray image.*

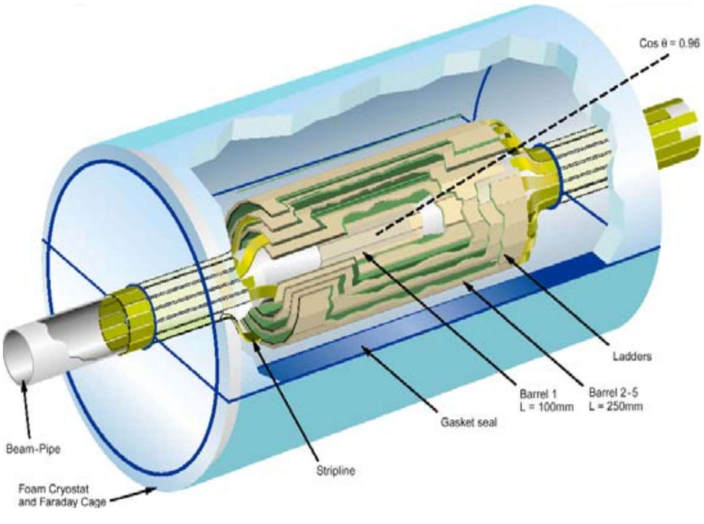

Figure 3. *Schematic view of the ILC vertex detector.*

The purpose and conditions at the International Linear Collider (ILC) [5] are rather different from that at XEUS. Here, the excellent spectroscopic capabilities of the DEPFET pixel detector are not used. Instead, the sole purpose is the high precision position measurement of traversing particles close to the collision point of electrons and positrons. Challenges are the required readout speed, granularity and the minimization of material in order to reduce multiple scattering. In particular for the latter requirement the very good noise properties of DEPFETs are advantageous as the detectors can be made very thin. A detector thickness of 50 µm and a pixel size of 25x25 µm^2 are foreseen.

Covering an extended area with properly connected DEPFETs one arrives at a pixel detector (Fig. 4). An individual row of transistors can be selected for readout while all other DEPFETs are turned off able to collect signals without consuming power. The collected charge is measured by subtracting the drain current before and after clearing the internal gate.

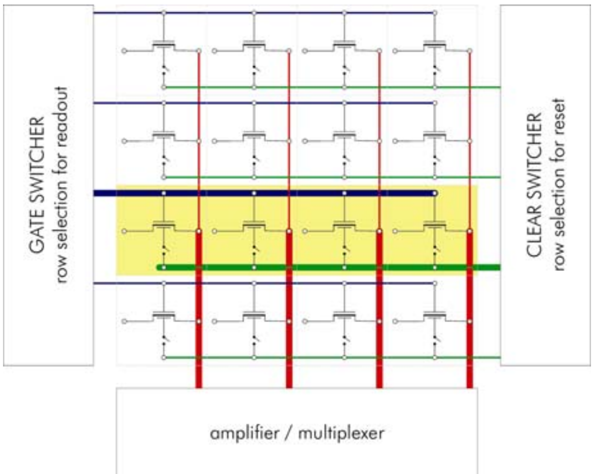

Figure 4. *Schematics of a DEPFET pixel detector.*

Following the difference in requirements we have chosen MOS-type p-channel DEPFETs with cylindrical geometry for XEUS and linear geometry for ILC (Fig. 5). Both types of prototype DEPFET matrices have been produced. Fig. 6 shows the noise performance of a single XEUS-type DEPFET resulting in a noise figure of 2.2 electrons r.m.s.

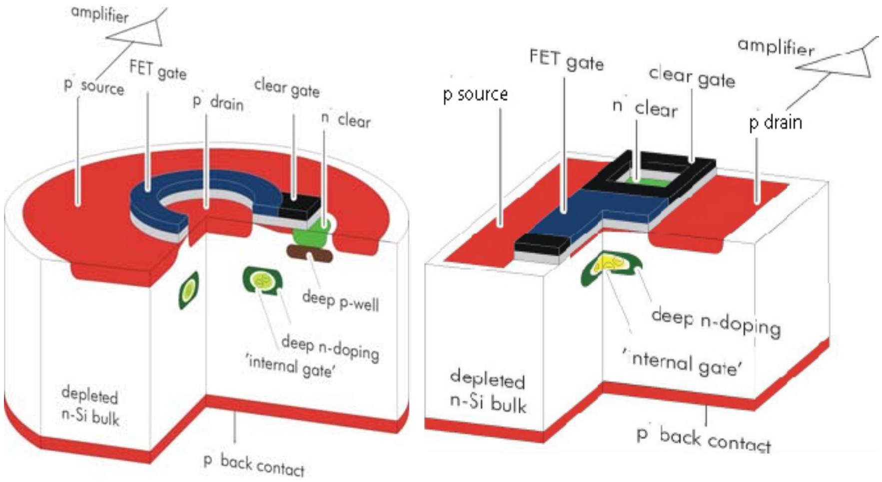

Figure 5. *Cylindrical (XEUS) and linear(ILC) DEPFET geometries.*

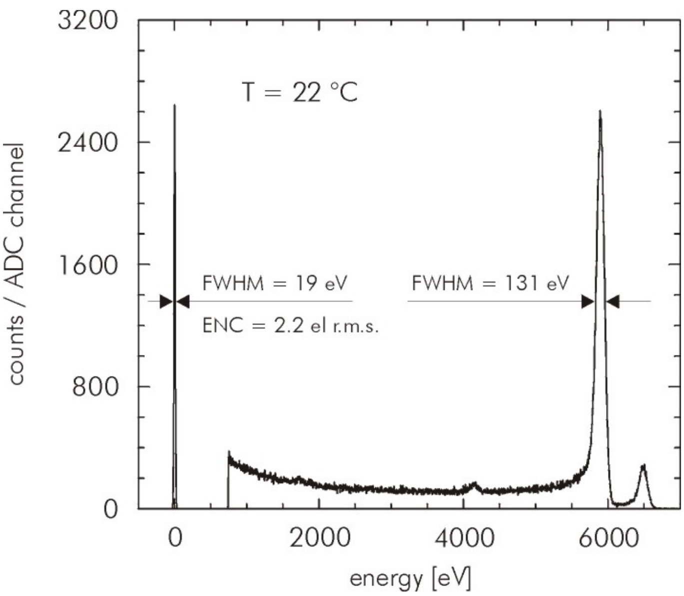

Figure 6. *^{55}Fe spectrum measured at room temperature with a cylindrical DEPFET at 6 µs Gaussian shaping.*

A 64x64 pixel detector prototype has been operated successfully, all of the pixels responding uniformly

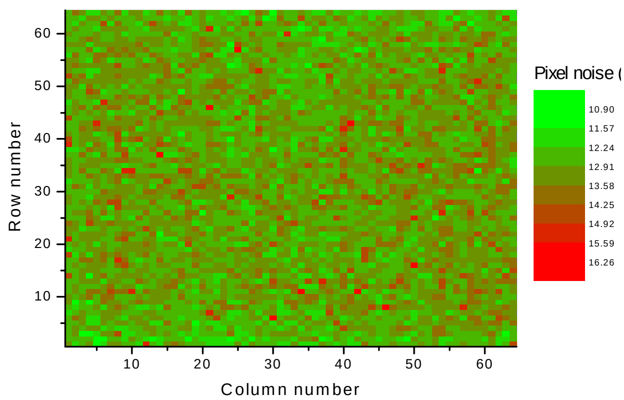

Figure 7. *Noise map of a 64x64 DEPFET prototype detector measured at -40 C. An average noise of 3.8 electrons ENC and a noise dispersion of 10% was found.*

as demonstrated in Figs. 7 (noise map) and 8 (^{55}Fe spectrum).

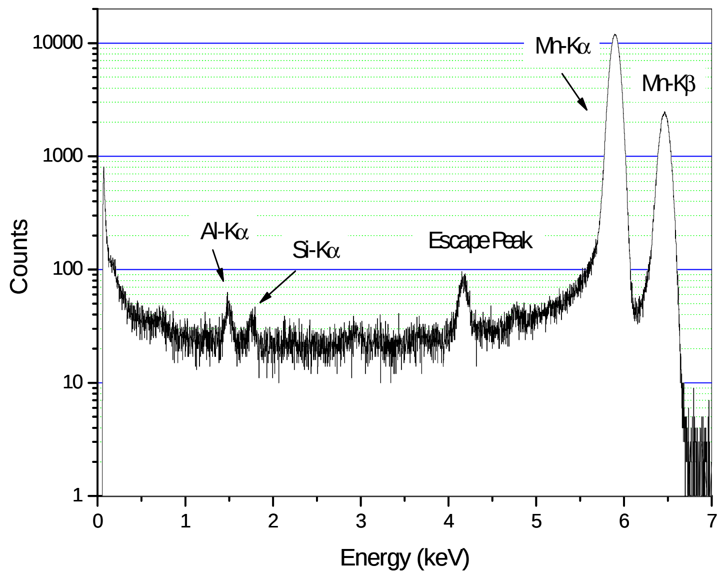

Figure 8. *^{55}Fe spectrum measured at -50C with a 64x64 prototype DEPFET pixel detector. The pixel current was 30µA, the line processing time 25µs. The energy resolution of 126 eV FWHM of the Mn-Ka line corresponds to 4.9 electrons ENC.*

A double DEPFET pixel geometry has been chosen for ILC (Fig. 9) allowing simultaneous readout of two pixel rows at a time. The pair of DEPFETs share source and common gates and clear contact while the drains are read out separately. Such an arrangement allows smaller pixel size and speeds up readout by a factor of two at the expense of doubling the readout channels. These devices have been shown to be radiation hard as demonstrated in Fig. 10 which compares ^{55}Fe spectra before and after 1Mrad ^{60}Co irradiation The devices so far have been processed on 450 µm thick 150 mm wafers. The thinning procedure to obtain 50 µm thin detectors has been developed and tested on diodes already.

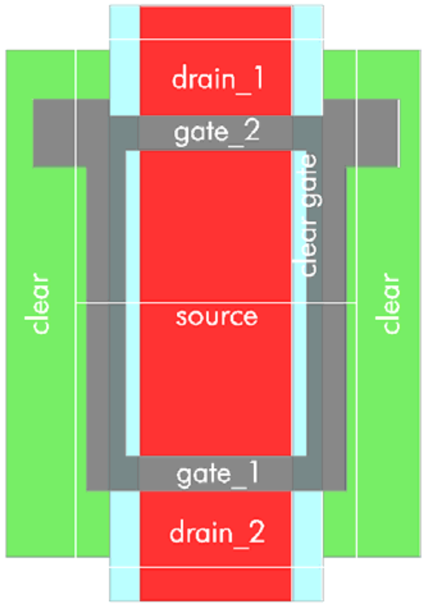

Figure 9. *Linear DEPFETs with double pixel structure as foreseen for ILC. A pixel size of 24x36 µm has been realized,.*

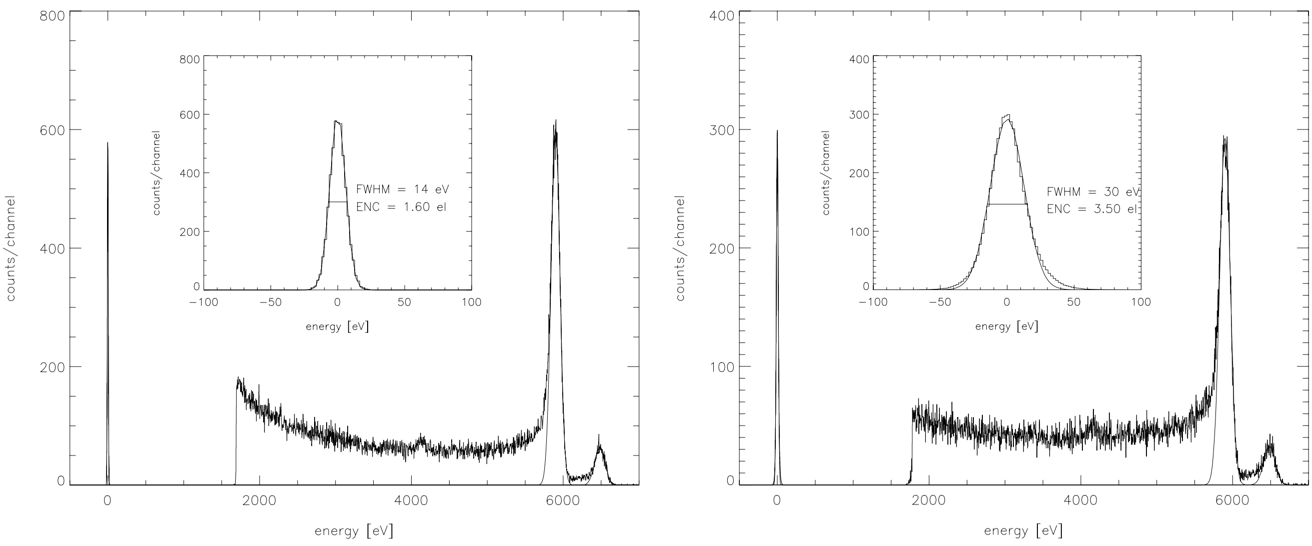

Figure 10. *ILC DEPFET single pixel performance before and after irradiation with 1 Mrad ^{60}Co measured at room temperature with 10 µs shaping and 40 mA drain current. The noise increases from 2 to 3.5 electrons ENC, the gate voltage had to be changed from -2 to -6V to compensate for the threshold voltage shift from -0.2 to 4V. The noise increase is almost independent on the shaping time.*

III. MACRO PIXEL DETECTORS FOR SIMBOL-X

In some circumstances large pixel sizes are desired. This is the case for two missions in which the X-ray optics provides coarse resolution. SIMBOL-X will investigate the physics of black holes, extending the X-ray energy range up to 80keV and therefore increasing also the focal length to 30m in order to maintain total reflection. As is the case for XEUS optics and mirror are on separate satellites.

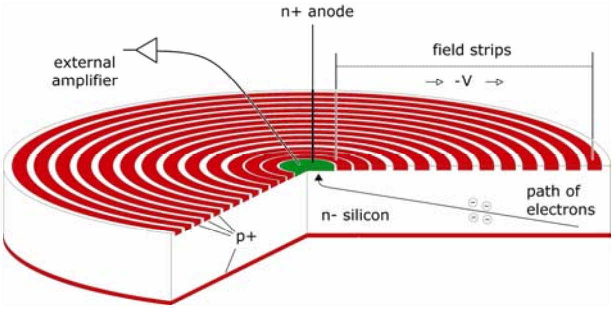

Figure 11. *Silicon Drift Diode with a homogeneous backside radiation entrance window. The signal charge drifts along a inclined path towards the centre electrode.*

Large pixel sizes can be obtained by combining the DEPFET structure (Fig. 5) as signal storage and readout device with the drift diode concept (Fig. 11). Single pixels and 4x4 matrices prototype matrices with 1x1 mm^2 pixel size (Fig. 12) have been produced and tested. 64x64 matrices with 0.5x0.5 mm2 pixel size are in production. The DEPFET geometry in the prototype matrix has been chosen rather conservatively. At -20 C a noise figure ENC=5.4 electrons has been obtained with a pixel current of 100 µA and a shaping time of 6 µs. Single pixels with smaller DEPFET geometry give ENC=2 electrons at 40 µA.

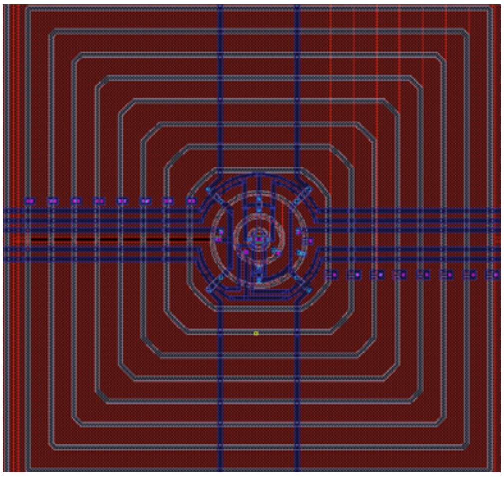

Figure 12. *Macro pixel cell layout: The circular DEPFET lies in the centre of a drift diode that provides a geometrical adaptation to the quadratic pixel boundary.*

IV. SUMMARY

DEPFET pixel detectors are developed for several experiments in X-ray astronomy and in particle physics. The DEPFET potential has only partially been exploited so far and many generic developments are going on. One of them is the use of repeated non destructive readout which has already lead to sub electron noise.

References

[1] E. Gatti and P. Rehak: "Semiconductor drift chamber - an application of a novel charge transport scheme", *NIM A*, 225, p.608 – 621, 1984.
[2] J. Kemmer and G. Lutz: "New semiconductor detector concepts", Nucl. Instr. & Meth. A 253 (1987) 365-377
[3] XEUS Astrophysics working group: "X-ray Evolving - Universe Spectroscopy - The XEUS scientific case", ESA SP-1238 (1999), 30 pages
[4] L. Strüder et al.: pnCCDs on XMM-Newton – 42 months in orbit, NIM A512 (2003) 386-400
[5] T. Behnke,S. Bertolucci, R.D. Heuer, R.Settles: "TESLA Technical design report, Part IV: Adetector for TESLA, Vol. 2b, DESY-010011,2001.