STATE-OF-THE-ART SILICON DETECTORS FOR X-RAY SPECTROSCOPY

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ABSTRACT

The semiconductor laboratory of the Max-Planck-Institutes for physics and for extraterrestrial physics develops and fabricates silicon sensors for scientific experiments in astronomy and high-energy physics, as well as for industrial applications. Among them are state-of-the-art detectors for X-ray imaging and spectroscopy. Their common features are the integration of the readout electronics on the detector chip and a fully depleted bulk with a non-structured thin entrance window, guaranteeing excellent energy resolution and high quantum efficiency over a wide energy range. Fully depleted and backside illuminated Charge Coupled Devices (pn-CCDs) have been developed and are operated successfully as focal plane detector of the XMM-Newton satellite. They have a sensitive area of 6 x 6 cm² with a pixel size of 150 x 150 µm², an equivalent noise charge of 4 el. rms. operating at 150 K, and an ultra-fast full frame readout time of 4.5 msec. The integrated detector-preamplifier structure DEPFET (DEpleted P-channel Field Effect Transistor) is the basic element of an Active Pixel Sensor (APS) with random accessible pixels, flexible readout modes, and the potential for repetitive non-destructive readout with sub-electron resolution. Spectroscopy measurements of single DEPFET structures demonstrate an unequalled electronic noise of 2.2 el. rms at room temperature.

INTRODUCTION

In 1984 E. Gatti and P. Rehak proposed a new detector scheme based on the principle of sideward depletion [1]. The idea is that a large area semiconductor wafer, e.g. of high-resistivity n-type silicon, is covered by large area p⁺ junctions on both surfaces. In reverse bias of the p⁺ junctions with respect to a small sized n⁺ ohmic contact depletion layers expand from the p⁺ layers into the n-type bulk with the square root of the applied voltage. Both depletion zones propagate until, at a given voltage, they touch each other and the entire device is depleted at a voltage four times lower than that needed to deplete a conventional p⁺nn⁺ diode of the same thickness. In that condition the electron potential energy along a cross section perpendicular to the surface of the device has a parabolic shape with a minimum in the center plane.

The sideward depletion structure is the point of origin for the development of high-performance semiconductor detectors. It combines a large depleted volume for the absorption of ionizing radiation with a small value of the n⁺ bulk contact’s capacitance, the precondition for collection
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and readout of the signal electrons with minimum serial noise contribution. However, except for
the slow process of diffusion it does not imply a charge transport mechanism to the n+ charge
collecting anode. Three different solutions to this question lead to three types of X-ray
spectroscopy detectors designed, fabricated, and qualified at the MPI semiconductor laboratory:

• In a **Silicon Drift Detector (SDD)** an electric field that forces signal electrons to drift to the
  n+ anode is superposed to the sideward depletion structure [1, 2]. As SDDs are subject of another
  publication of these proceedings [3] they will not be treated in further detail here.

• A special type of Charge Coupled Device the so called **pn-CCD** is the adaptation of clocked
  charge transfer parallel to the detector surface to the principle of sideward depletion.

• The **Active Pixel Sensor** based on the integrated amplifier **DEPFET** bypasses the problem of
  charge transport to the anode over long distances by placing a number of readout structures at a
  lateral distance smaller than the wafer thickness in a regular two-dimensional array.

**FULLY DEPLETED PN-CCD**

For the European Space Agency’s 1999 XMM-Newton (X-ray Multi Mirror) satellite mission [4]
a non-standard X-ray Charge Coupled Device, the pn-CCD, has been developed as focal plane
instrumentation of a mirror telescope. The system requirements are high-resolution imaging and
spectroscopy of X-ray emitting objects in space with high detection probability in a single-photon
counting mode with a readout rate high enough to avoid event pile-up.

Conceptually the pn-CCD is the combination of clocked charge transfer parallel to the detector
surface with a sideward depletion structure. To obtain a pronounced potential minimum in a
defined depth of about 10 µm an additional higher n-doped \((10^{14} \text{ cm}^{-3})\) 12 µm thick epitaxial
layer is deposited on the upper side of the 280 µm thick high-resistivity \((10^{12} \text{ cm}^{-3})\) n-type bulk
and asymmetric voltages are applied: -15 V … -20 V on the upper side, -160 V on the non-
structured backside. To realise a CCD-type detector, the upper p+ implant is divided in p+ strips
or shift registers as shown in figure 1 with three strips comprising one pixel. A periodic
modulation of the register voltages \(\Phi_1, \Phi_2, \Phi_3\) generates potential wells in the direction
perpendicular to the strips. In the lateral direction the pixel is confined by deep channel stop and
channel guide implants. Electrons released by the absorption of ionising radiation within the

![Figure 1](image)

Schematic cross section through the pn-CCD along a transfer channel. The device is back illuminated and fully depleted over 300 µm. The pixel size is 150 x 150 µm².
depleted volume drift to the local potential minima of the pixels and are stored at the projected position of their generation, while the holes move to the negative biased p\(^+\) contacts. Clocking the voltages $\Phi_1$, $\Phi_2$, $\Phi_3$ in a defined way the stored signal electrons are transferred to the readout node.

One pn-CCD unit with a sensitive area of $3 \times 1 \text{ cm}^2$ consists of 200 rows in readout direction and 64 individual transfer channels. The $150 \times 150 \mu\text{m}^2$ pixel size was chosen on one side to match to the telescope’s resolution and on the other side as large as possible to avoid unnecessary oversampling and to keep the readout time short. Each transfer channel is terminated by an on-chip preamplifier of the single-sided n-JFET type [5, 6]. The on-chip preamplifiers are connected to CAMEX amplifier/multiplexer chips in VLSI JFET-CMOS technology [7, 8]. For the XMM-Newton focal plane detector, 12 pn-CCD units with a total of 400 x 384 pixels and a sensitive area of $6 \times 6 \text{ cm}^2$ are integrated monolithically on a 4-inch wafer (figure 2).

Compared to standard CCDs the pn-concept has a number of intrinsic advantages [9, 10]:

- The pn-CCD concept allows for optimum adaptation of the pixel size to the resolution of the X-ray optics, varying from 30 $\mu\text{m}$ to 300 $\mu\text{m}$ pixel dimensions.
- The transfer of signal charges in a depth of 10 $\mu\text{m}$ guarantees small transfer inefficiency in the order of a few percent signal loss over the entire 200 pixels or a distance of 3 cm.
- Because of the full depletion of the 300 $\mu\text{m}$ thick detector bulk the quantum efficiency is high for X-rays from the hard end of the XMM-Newton energy range, e.g. above 90 $\%$ at 10 keV.
- The low-energy response is given by the shallow p-implanted entrance window with an effective thickness smaller than 15 nm and an efficiency of 81 $\%$ at the C-K line (277 eV).
- Due to the large pixel size and the parallel processing of the channels the full frame of a $3 \times 1 \text{ cm}^2$ pn-CCD unit is read out in 4.5 msec. Compared to a conventional CCD with serial readout this is faster by two orders of magnitude.

Figure 2

The focal plane of the pn-CCD camera on XMM-Newton consists of 12 independent, monolithically integrated pn-CCDs with a total area of $6 \times 6 \text{ cm}^2$. In total 768 on-chip amplifiers process the signals and transfer them to a JFET-CMOS amplifier array. 12 output nodes of the CAMEX arrays are fed into 4 ADCs, i.e. one ADC per quadrant.

Figure 3

Spectrum of a $^{55}\text{Fe}$ source with the Mn-K\(_\alpha\) and Mn-K\(_\beta\) lines at 5.9 keV and 6.5 keV recorded with a $1 \times 3 \text{ cm}^2$ pn-CCD in a flat field measurement. The energy resolution is 130 eV (FWHM at 5.9 keV) at an operating temperature of -120°C.
The pn-CCD has a built-in high radiation tolerance by avoiding active MOS structures. Irradiated with a fluence of $4 \cdot 10^8$ protons per cm$^2$ (10 MeV), which is the equivalent dose over the expected 10 years mission time of XMM-Newton, the energy resolution (FWHM at 5.9 keV) showed a tolerable decrease from 145 eV to 158 eV at an operating temperature of -100°C. The system noise expressed in terms of equivalent noise charge (ENC) is typically 4 … 5 el. rms. Figure 3 shows the flat field spectrum of a $^{55}$Fe source recorded with a 3 x 1 cm$^2$ pn-CCD at -120 °C. The FWHM of the Mn-K$\alpha$ line is 130 eV.

The satellite XMM-Newton was launched in December 1999. The performance of the pn-CCD camera known from calibration on ground could be reproduced in space. In more than three years of operation in space all system parameters stayed stable and many scientific observations profited from the high-performance pn-CCD camera [11].

DEPFET-BASED ACTIVE PIXEL SENSOR

The satellite XEUS (X-ray Evolving Universe Spectroscopy) [12] is currently under study by the European Space Agency as follow-on mission to XMM-Newton. Compared to XMM-Newton the XEUS telescope will bring an enormous increase in sampling area. Consequently the photon throughput will be one or two orders of magnitude higher and, next to energy and position resolution, count rate capability is the major challenge for the XEUS focal plane instrumentation. In that respect CCDs have an intrinsic limitation imposed by the need of a close-to-perfect charge transfer over macroscopic distances within the detector bulk. Therefore, the development of an Active Pixel Sensor (APS) based on the principle of sideward depletion has been initiated for the XEUS Wide Field Imager (WFI) instrument.

An APS is defined as a two-dimensional detector array with an amplifying element in each pixel. As integrated amplifier the DEPFET (DEpleted P channel Field Effect Transistor) was introduced in 1987 [13, 14]. It consists of a p-channel field effect transistor on a high resistivity n-type silicon bulk. The transistor may be either a JFET, or a MOSFET of enhancement or depletion type. The bulk is completely depleted by the reverse biased backside diode thus creating a potential minimum for electrons close to the surface. An additional deep n-doped region enhances the depth of the potential minimum and confines it in the lateral direction to the extent of the FET channel (figure 4). Each electron released in the depleted volume by thermal

Figure 4
Section of a DEPFET in circular geometry. Electrons generated by the absorption ionizing radiation drift to the potential minimum of the ‘internal gate’ and enhance the transistor current by inducing positive image charges inside the FET channel. Applying a positive voltage pulse to the clear contact and to the clear gate resets the device.
generation or by the absorption of ionizing radiation will drift to the potential minimum and enhance the transistor current by inducing an additional positive image charge inside the FET channel. Thus the DEPFET’s current is a function of the amount of charges in the potential minimum, and its measurement yields information about the energy absorbed in the depleted volume. To express the current steering function of the stored electrons the potential minimum is called ‘internal gate’. Its measured sensitivity is 200 pA per electron [15].

The internal gate exists, i.e. electrons can be collected and stored in it, regardless of a current flowing in the channel of the DEPFET or not. The transistor current is usually turned off during signal integration and only switched on via the external gate for the signal readout, thus minimizing power consumption. The internal gate’s geometric size and doping concentration are dimensioned to store up to a total of $10^5$ electrons. As the signal charges are confined in a potential well, the information is not destroyed during the readout so that multiple readings with subsequent averaging are possible, thus reducing the 1/f noise contribution by the square root of the number of readings. Unlike a conventional detector-preamplifier system, the DEPFET is free of interconnection stray capacitance and the overall capacitance is minimized. Depending on leakage current and signal rate the device must be reset periodically by emptying the internal gate. This is done by applying a positive voltage pulse to an adjacent n$^+$ doped ‘clear’ contact acting as drain for electrons supported by an additional MOS ‘clear gate’. For the reset both clear contact and clear gate are set to a more positive voltage. The clear contact is separated from the detector bulk by a deep p-implanted well (figure 4).

The noise characteristics of single DEPFET devices have been evaluated by spectroscopic measurements. The DEPFET was configured in a source-follower circuit, and the data have been taken by a commercial spectroscopy system using a time-continuous filter with a shaping time constant of 6 µsec. Figure 5 shows the spectrum of a radioactive $^{55}$Fe source with the Mn-K lines (5.9 keV, 6.5 keV) and the noise peak (0 eV) recorded with an isolated DEPFET pixel at room temperature. The noise in terms of equivalent noise charge is 2.2 el. rms. The low energy background is caused by charge splitting at the pixel borders.
The matrix-like formation of DEPFETs with common back contact results in a backside illuminated Active Pixel Sensor (APS) with a unity fill factor. All DEPFETs in the pixel sensor have a common drain contact, while the gates, clear contacts, and clear gates are connected row-wise. The row selection for readout and reset is controlled by chips of the SWITCHER type fabricated in a high-voltage CMOS technology [16]. The source contacts, i.e. the signal lines, of each column of pixels are connected in perpendicular direction to one channel of a modified preamplifier chip of the CAMEX type [7, 8].

As the individual pixels are random accessible, the APS has a high degree of flexibility in the choice of readout modes depending on the object and the scientific goal of an observation:

- In full frame mode the whole sensor area is read row by row. With the exception of one active row, all pixels are turned off and in integration mode, keeping dead time short and power consumption low. The processing time for one row is of the order of a few µsec.
- In window mode only selected regions of interest (ROIs) that may have arbitrary rectangular shapes and sizes are read at a higher repetition rate, while the other pixels are suppressed.
- Time variations of fast transients will be observed in timing mode, i.e. a selected ROI is read at maximum speed but with reduced energy resolution. A limited area of 32 pixel rows or 2.5 mm in the readout direction could then be processed up to count rates of $10^5$ sec$^{-1}$.
- Any combination of the above specified readout modes or mixed mode applied to dedicated regions of the sensor area is possible.

In its proposed layout the XEUS Wide Field Imager will be composed of 1024 x 1024 DEPFETs with a pixel size of 75 x 75 µm$^2$ resulting in a total area of 7.68 x 7.68 cm$^2$. Currently a first batch of 64 x 64 prototype batch of DEPFET-based APS including SWITCHER control chips and CAMEX readout ASICS is under test.

REFERENCES

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