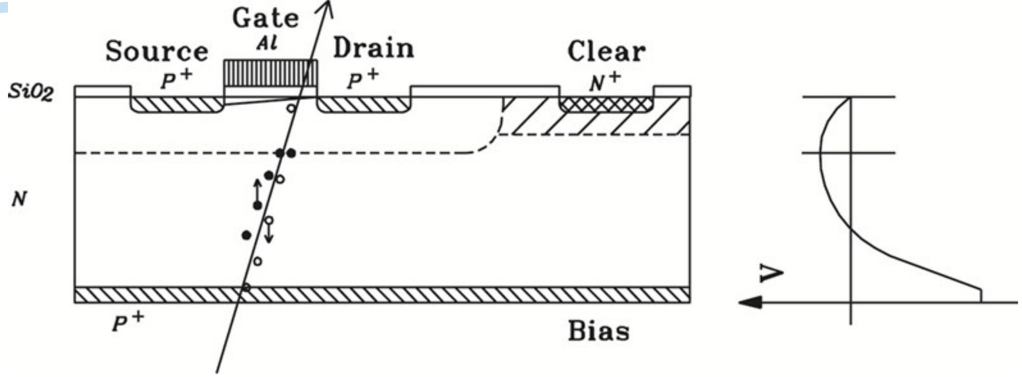
The DEPFET Detector-Amplifier Structure for Spectroscopic Imaging in Astronomy and for Experiments at Free Electron Lasers

G. Lutz , S. Aschauer, P. Majewski, P. Holl and L. Strüder

Introduction



DEPFET by J.Kemmer and G.Lutz invented and patented 1985, published 1987.

Initiated by E.Gatti and P. Rehaks Semiconductor Drift Detector (1983).

Basic concept Field Effect Transistor on top of a fully depleted bulk

Potential minimum for electrons below the transistor channel.

Signal electrons assemble in this „Internal Gate“ and steer the current.

Function principle veryfied soon after invention.

Meanwhile many applications and modifications of DEPFETs have been developed:

DEPFET Pixel detectors, Macropixel detectors, gateable DEPFETs, RNDR DEPFETs with subelectron precisions, Intermediate charge storage DEPFETs, DEPFETs with nonlinear characteristics and high dynamic range (DSSC)

Content

DEPFET principle and properties

DEPFET pixel sensors

Macro Pixel Sensors

BepiColombo Mercury Mission

DEPFETs for Experiments at Free Electron Lasers

with nonlinear characteristics and high dynamic range

RNDR DEPFET sensors (subelectron noise)

Gateable DEPFETs

[Gatable RNDR DEPFET sensors]

Deadtime-Less DEPFET sensors

Summary and Outlook

DEPFET principle

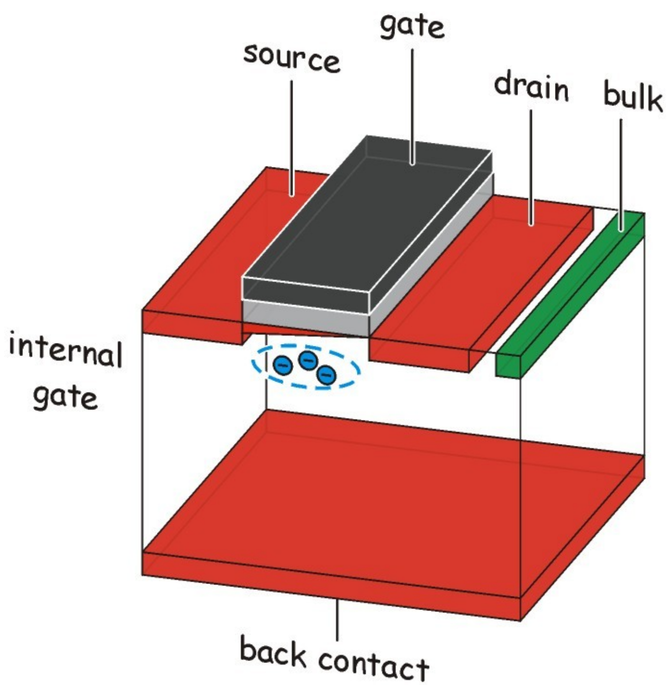
DEPFET (**DE**pleted **F**ield **E**ffect **T**ransistor)

All charge generated in fully (sidewise) depleted bulk drifts into potential minimum underneath the transistor channel (internal gate) steers the transistor current

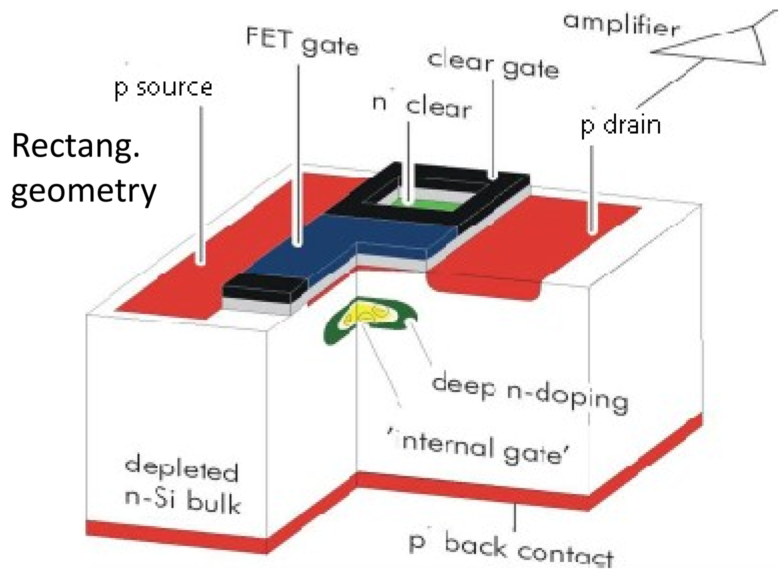
Clearing by positive pulse on clear electrode

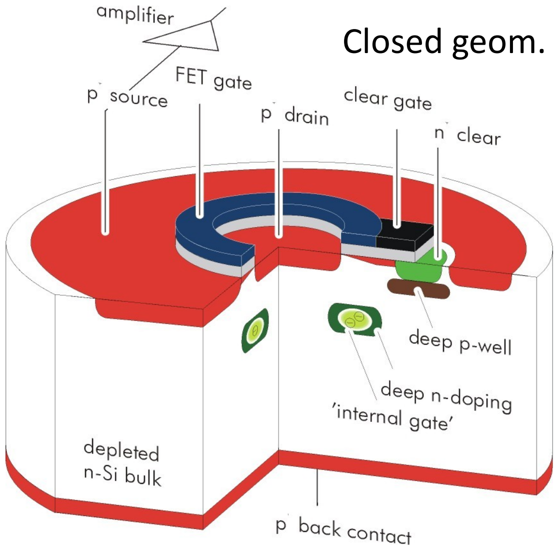
Charge measured by difference of current with/without charge in the internal gate

Combined function of sensor, amplifier and memory cell



DEPFET properties





Charge collection by drift mechanism over full wafer thickness

low capacitance ► low noise

Signal charge remains undisturbed by readout ► repeated readout possible

Complete clearing of signal charge ► no reset noise

Full sensitivity over whole bulk ► large signal for m.i.p.; X-ray sens.

Thin radiation entrance window on backside ► X-ray sensitivity

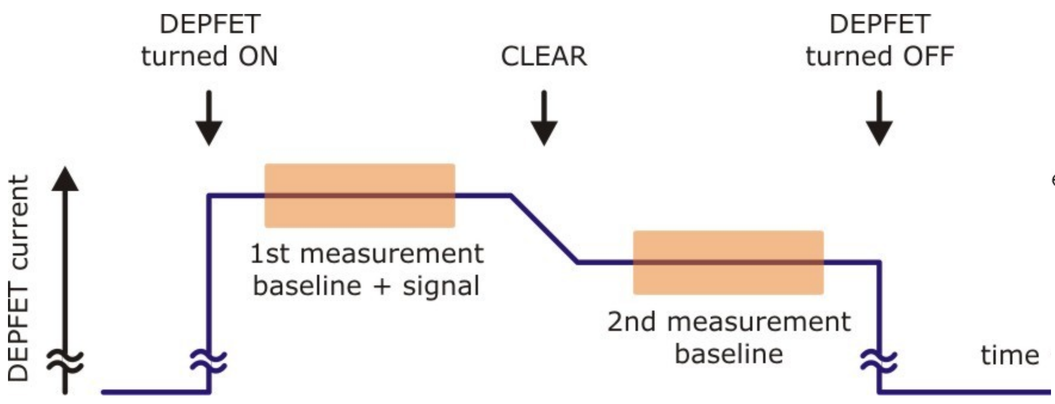
Charge collection also in turned off mode ► low power consumption

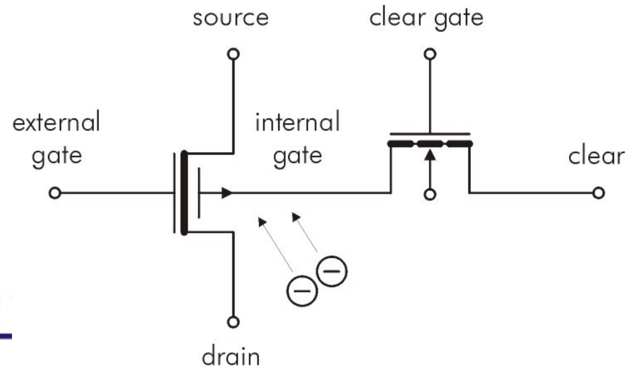
Measurement at place of generation ► no charge transfer (loss) ►

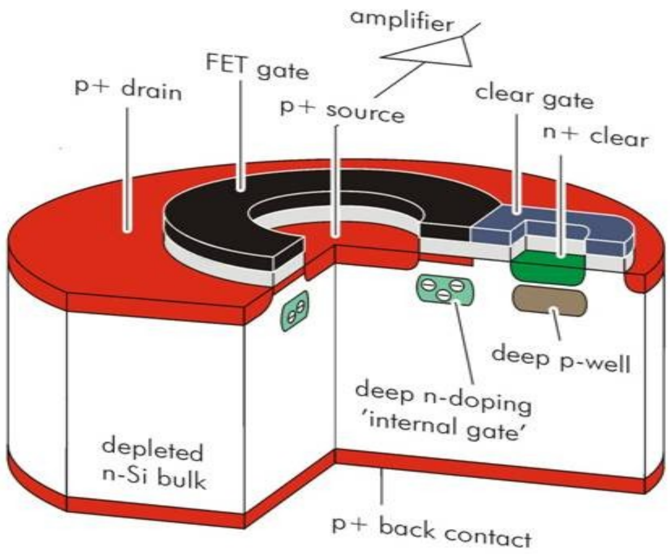
Operation over very large temperature range ► no cooling needed

Combined function of sensor, amplifier and memory cell

DEPFET Readout







- ***Measurement of signal***
  - **Measure signal levels**
    - **source potential / drain current**
  - **Measure both before and after clear**
  - **Calculate the difference**
    - **correlated double sampling (CDS)**

DEPFETs as pixel detector

Fill large area with DEPFETs

Connect electrodes (source, gate, drain, clear) so as to allow individual DEPFETS to be powered (read out)

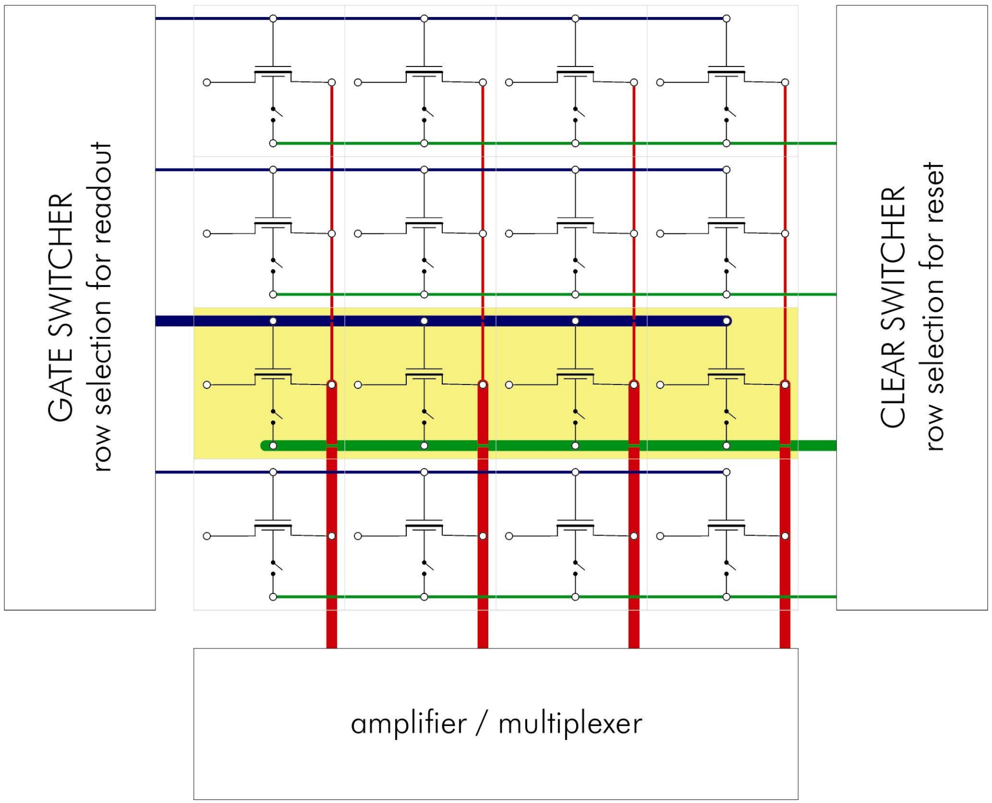
Individual transistors
or rows of transistors
can be selected for readout

All other transistors
are turned off

Those are still able
to collect signal charge

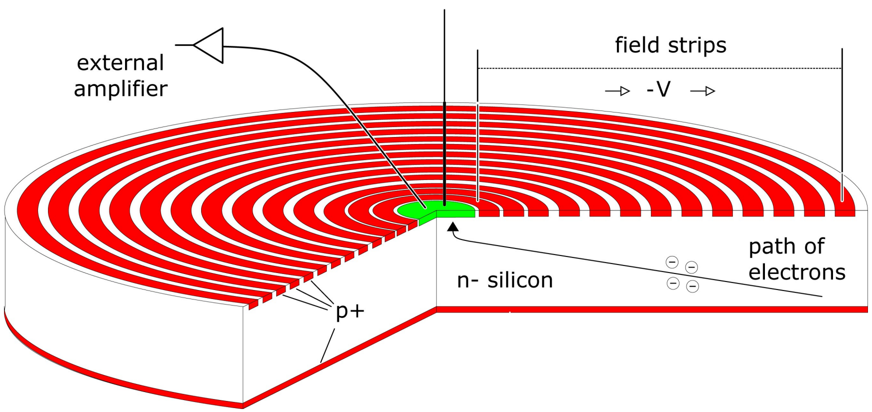
Very low power
consumption

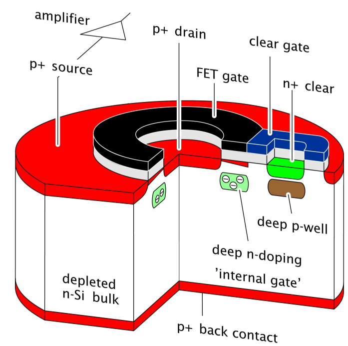
Charge measurement:
difference of drain current
with full and empty internal gate
(before and after clear or
before and after signal)



Macro-pixel detector

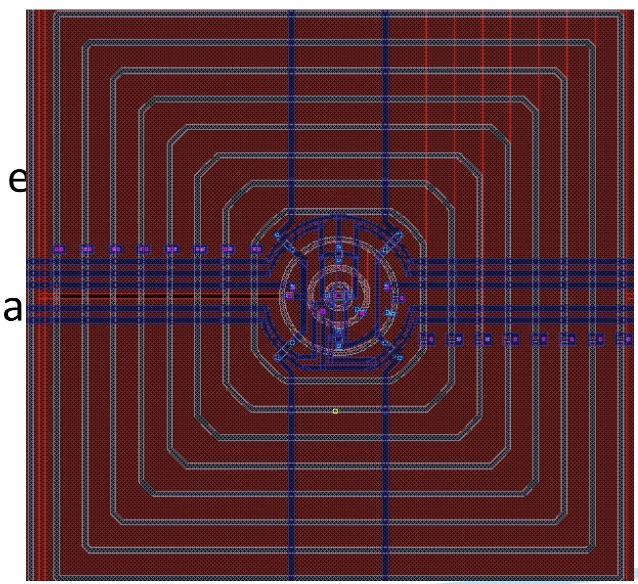
Combination of SDD (Silicon Drift Diode) with DEPFET





Each cell consist of drift diode
with DEPFET as readout e

Cell size can be chosen (adapted
to the application) over a
very wide range



Application: BepiColombo Mercury Mission

BepiColombo Mercury Mission

Physics goal: Investigation of Mercury (least well explored planet in our solar system due to harsh environment: high temperature, radiation, difficulty in decelleration)

Magnetic field, Geological composition and history of Mercury

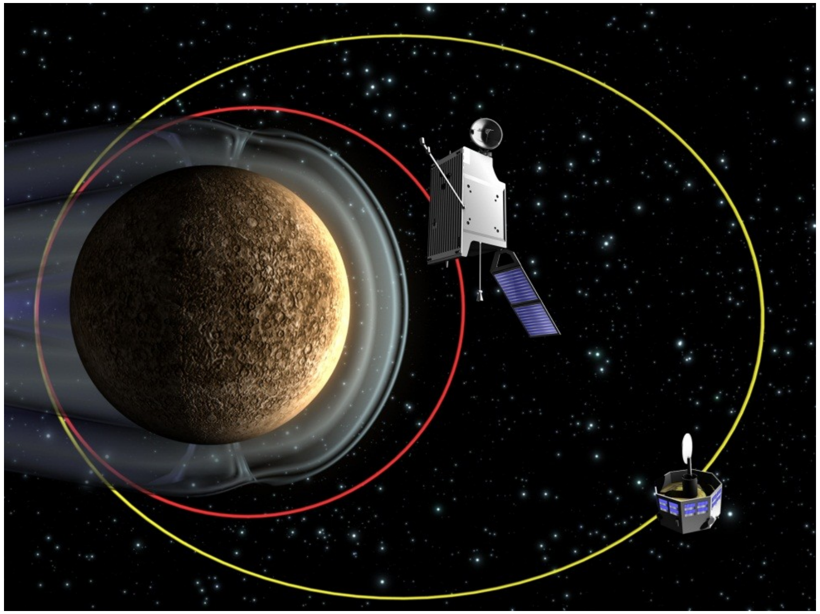
Two satellites on same spacecraft:

MMO (Mercury Magnetospheric Orbiter) and

MPO (Mercury Planetary Orbiter) on common Transfer Module to be separated after decelleration with the help of other planets.

Launch: February 2017

Arrival: January 2024



DEPFET Macro-pixel detector in MIXS (Mercury image X-ray Spectrometer) on MPO

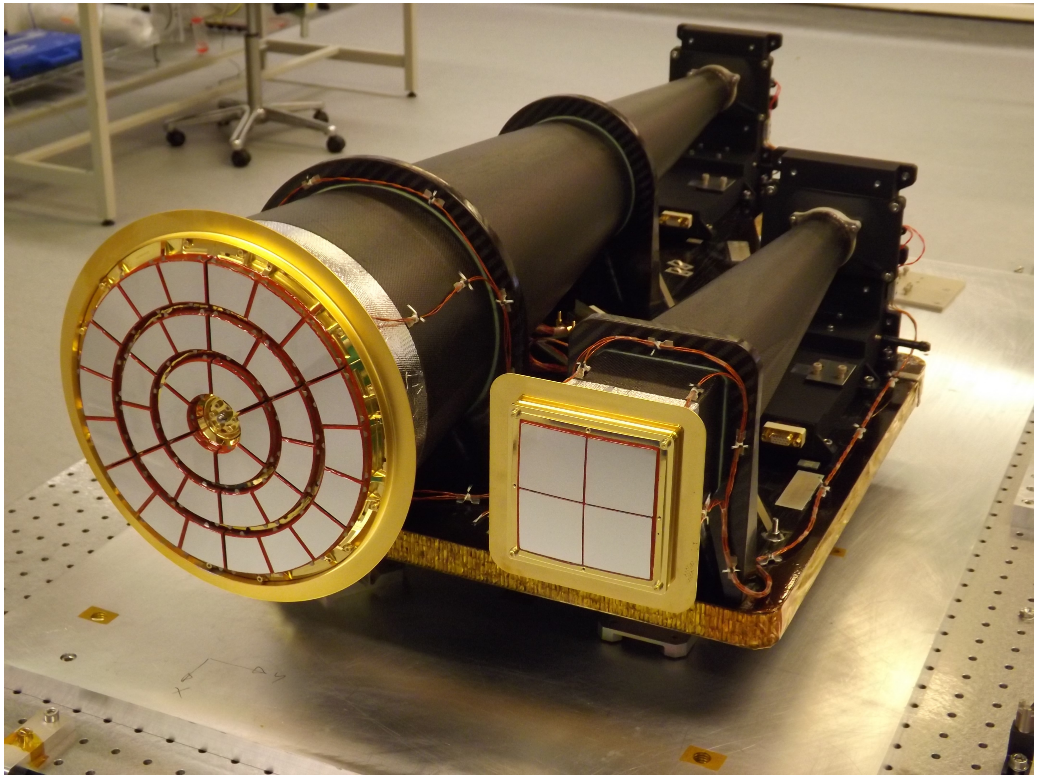
Purpose: investigate experimental composition of Mercury surface from X-ray fluorescence induced by the solar wind.

Two Instruments:

1) MIXS-T Mirror Imaging

2) MIXS-C Collimating

Identical focal plane sensor



Macro-pixel detector for MIXS

MIXS will be the first space instrument flying DEPFET detectors

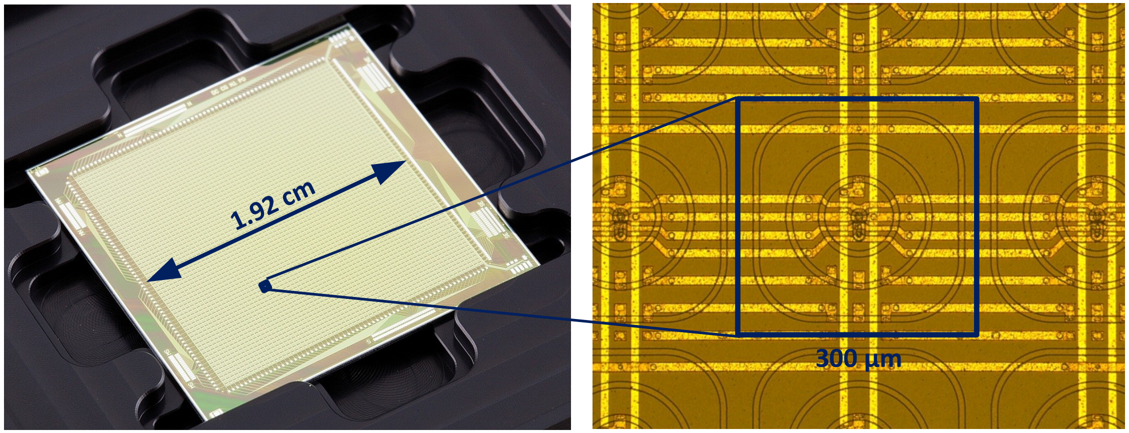
Fully assembled and tested, waiting for launch

Main Detector requirements:

- active area: 1.92 x 1.92 cm^2
- pixel size: 300 x 300 μm^2

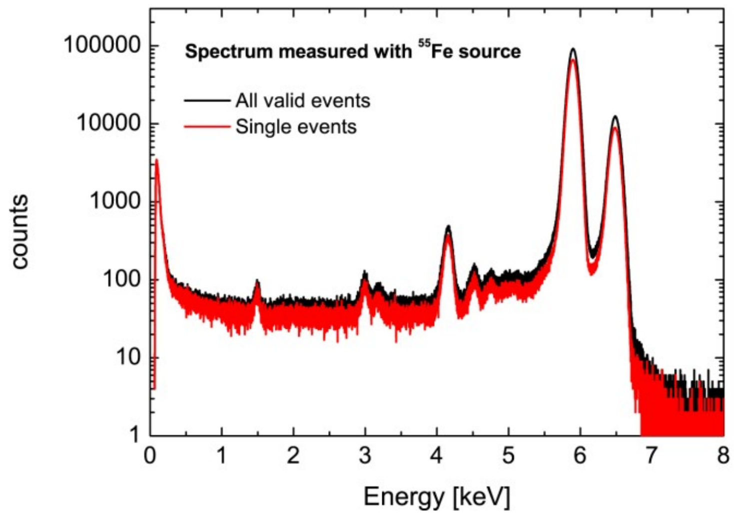
  64 x 64 pixels
- energy range: 0.5keV ≤ E ≤ 7keV
- energy resolution ≤ 200eV @ 1keV

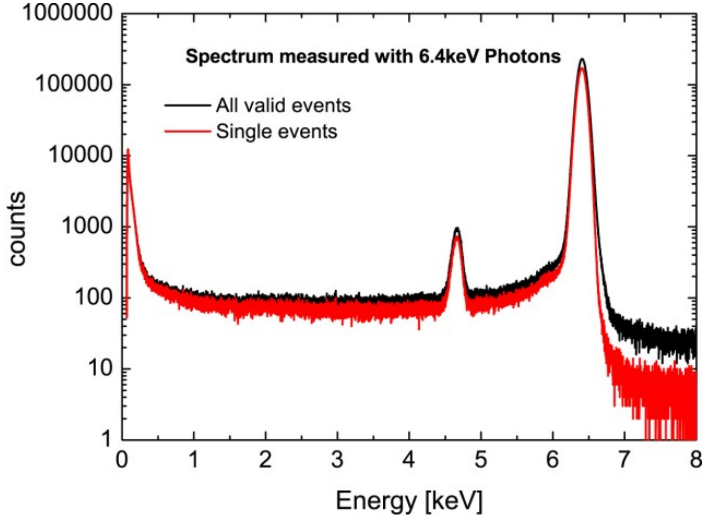
  at mission end
- radiation hardness



MIXS Focal Plane Detector Properties

MIXS focal plane detectors have been tested. All requirements have been reached or surpassed including spectroscopic properties and radiation hardness





X-ray spectra with Fe55 source and with monochromatic 6.5 keV photons

165 µs/frame, Energy resolution at 5.9 keV is ΔE = 129.5 eV (FWHM)

DEPFETs for Experiments at Free Electron Lasers

DEPFET **S**ensor with **S**ignal **C**ompression (DSSC) Pixel Detector

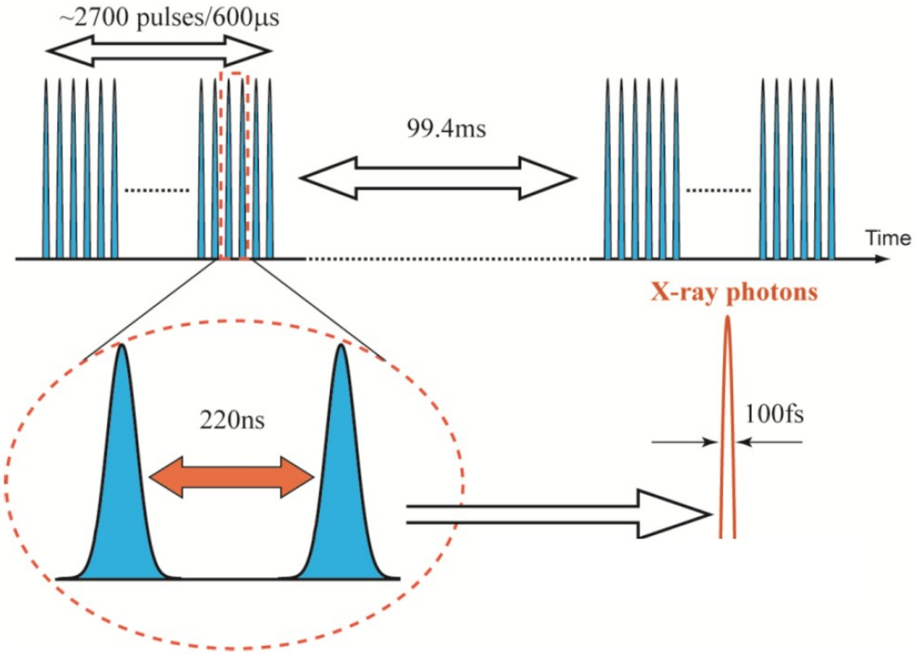
Developed for experiments at the European X-ray Free Electron Laser requiring simultaneousely detection of single X-ray Photon in one pixel and up to 10000 photons in other close by pixels.

In addition extremely fast readout was required due to the bunch structure of the accellerator.

Concept:

DEPFET with nonlinear characteristics

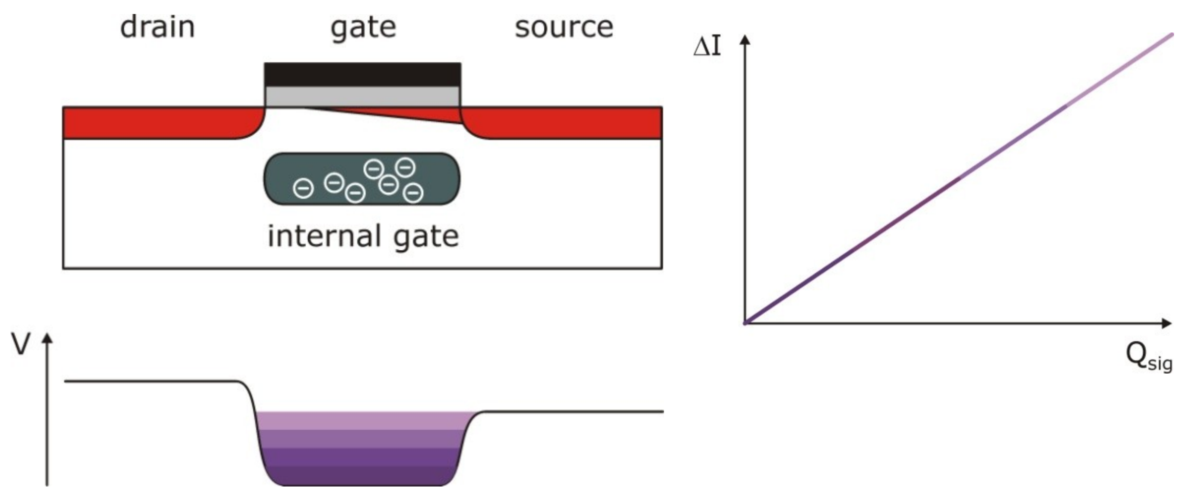
Parallell readout of every pixel



DEPFET with Non-Linear Characteristic

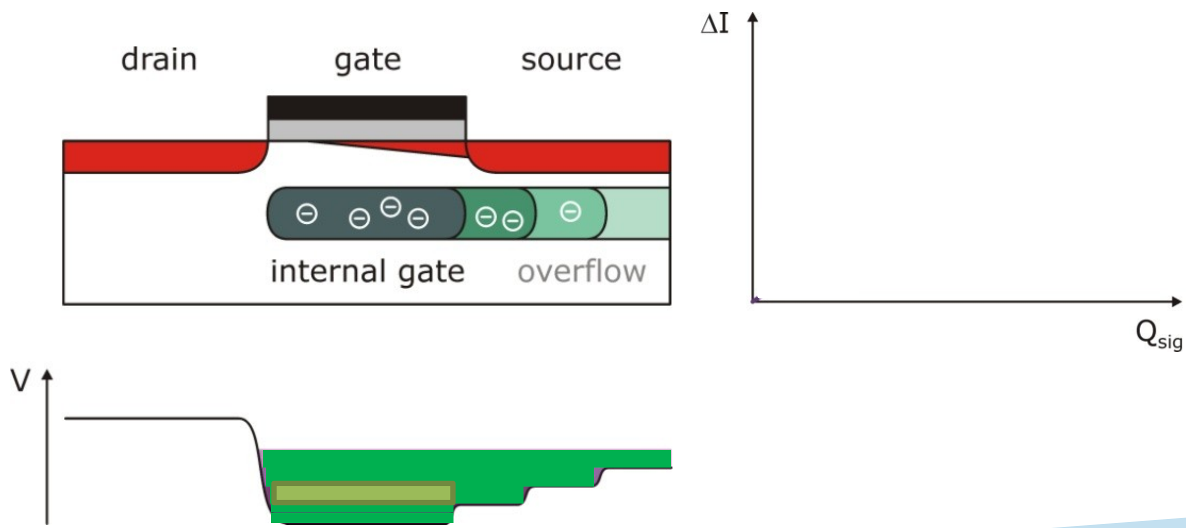
Standard DEPFET principle

- p-FET on depleted n-bulk
  - ↳ All signal charge collected in potential minimum below FET channel
  - **"internal gate"**
  - all signal charges cause an equal effect on the FET current
  - **linear $\Delta I / Q_{sig}$ characteristics**
- reset via ClearFET
- low capacitance & noise



DSSC adaptation

- signal charges at high levels also stored under source
- less/no effect on FET current
- **non-linear $\Delta I / Q_{sig}$ characteristics**
- gain curve engineering by dose & geometry of implantations



PNSensor

DSSC – Design Parameters

Parameter	
Energy range	optimized for 0.5 … 6 keV
Number of pixels	1024 x 1024
Sensor Pixel Shape	Hexagonal
Sensor Pixel pitch	~ 204 x 236 μm^2
Dynamic range / pixel / pulse	~5000 ph @ 0.5 keV > 10000 ph @ E≥1 keV
Resolution	Single photon detection also @ 0.5 keV
Frame rate	0.9-4.5 MHz
Stored frames per Macro bunch	≥ 640
Operating temperature	-20˚C optimum, RT possible

1 Mpixel camera with:

- Single photon sensitivity event at 0.5 keV
- high-dynamic range (>10000 ph/pixel)
- Frame rate up to 4.5 MHz (1 image every 220 ns)

All the properties have to be achieved simultaneously

DSSC will be the first instrument to fulfill this requirement

DSSC: focal plane architecture

- 1024 x 1024 pixel

  Every DEPFET pixel provides detection and amplification with signal compression at the sensor level (nonlinear DEPFET)

- focal plane composed of 32 monolithic sensor chips (128 x 256 pixel)

- Each sensor is bump bonded to 8 readout ASIC chips: fully parallel readout at 0.9-4.5 MHz

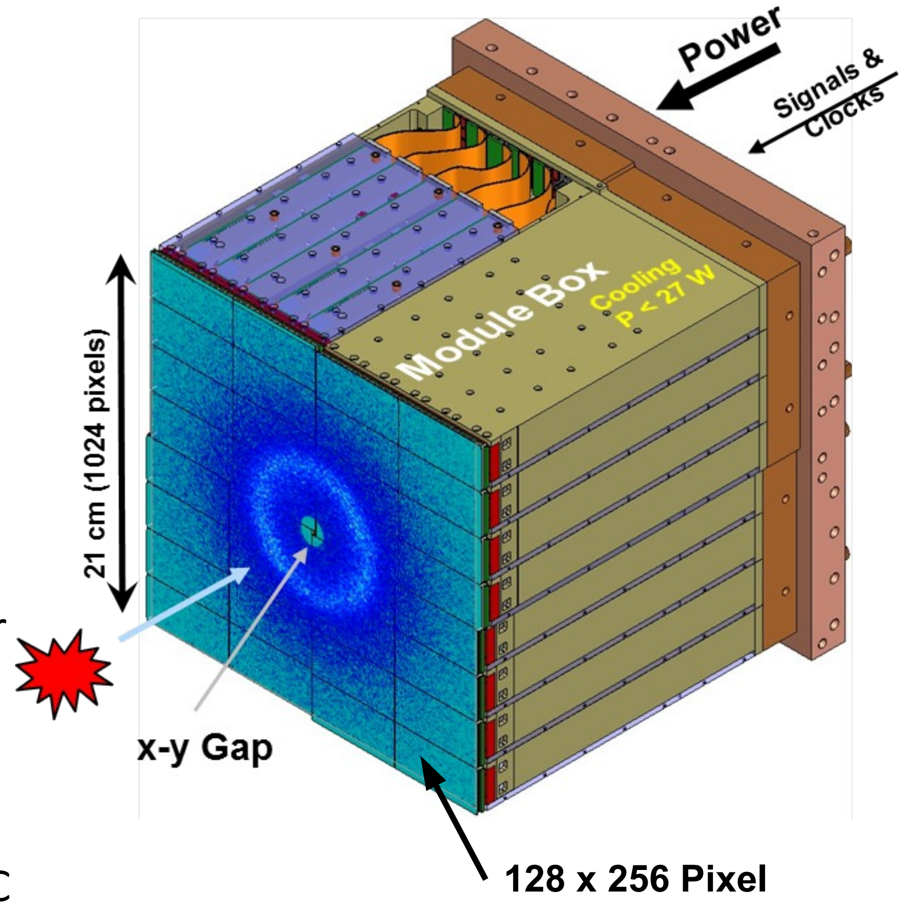
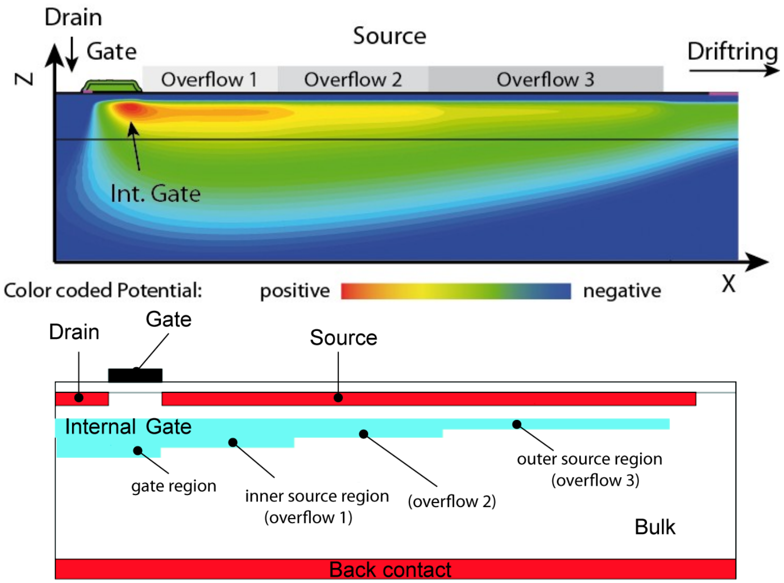
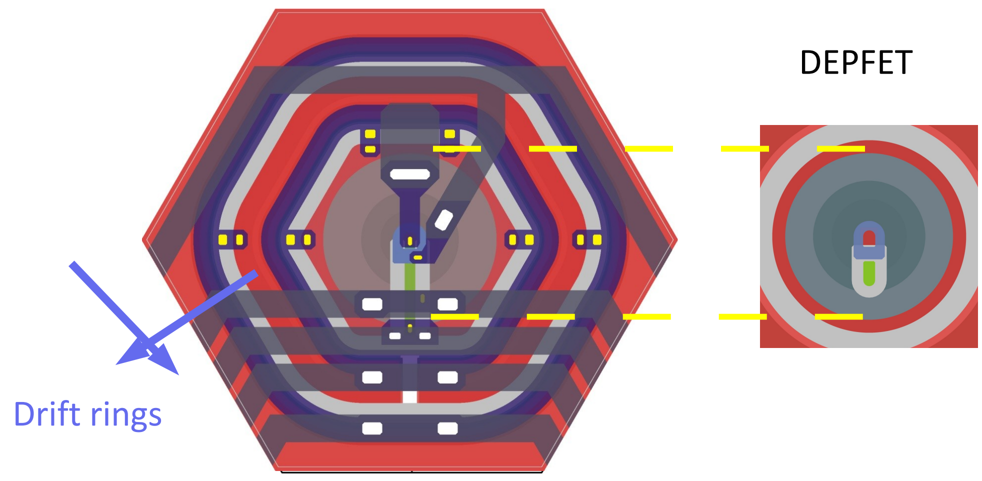
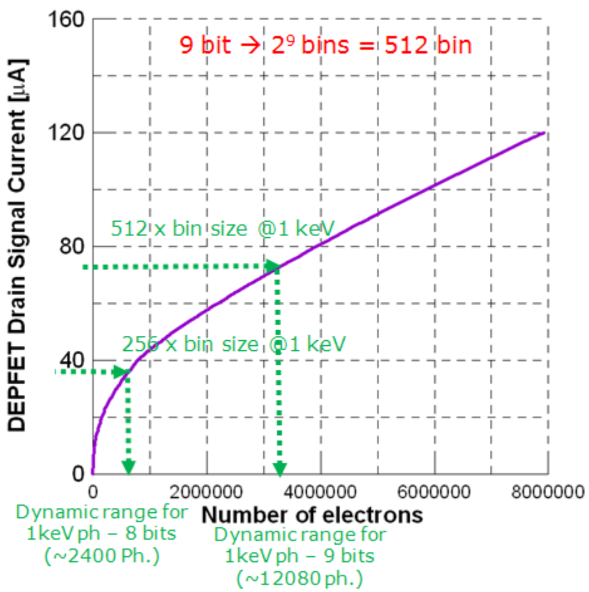


Image: K. Hansen, DESY

DSSC DEPFET – Simulation and Layout







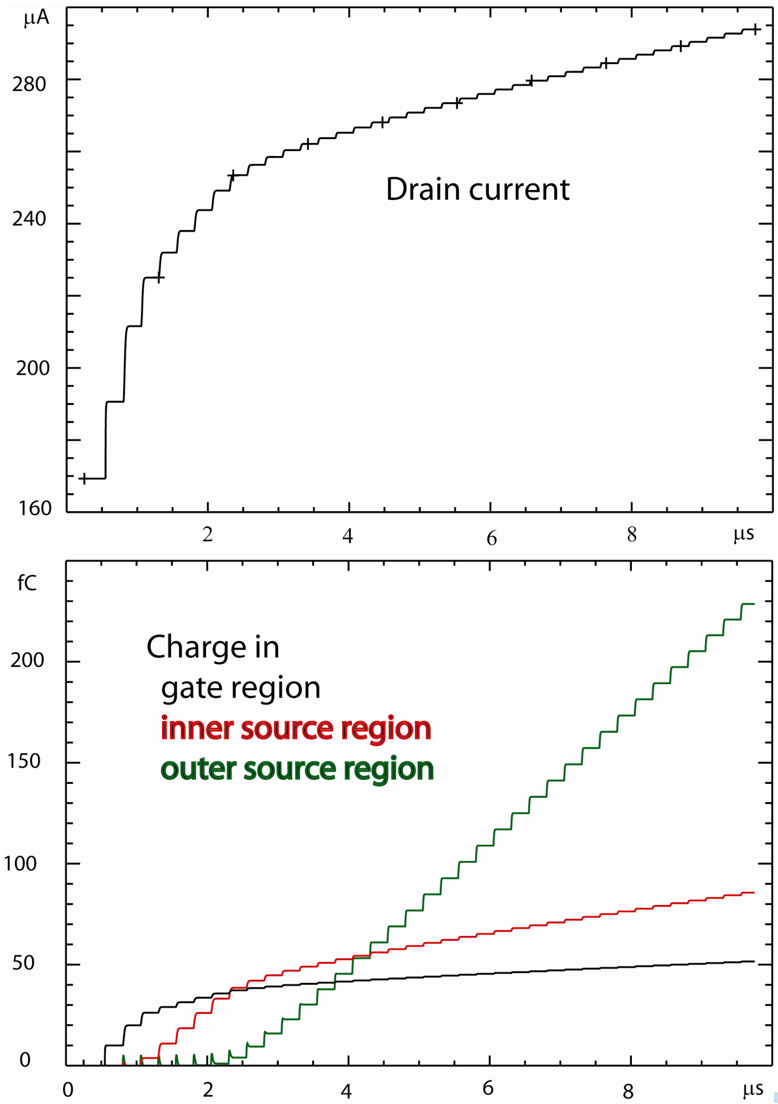
- hexagonal shape
  - side length 136 µm (A=48144 µm^2)
- technology
  - 2 polySi layers
  - 2 metal layers
  - 12 implantations

Non-linear DEPFET: Simulation

Charge distribution in internal gate and

Resulting drain current

37 consecutive steps of 1e-14 C charge deposition were simulated



Experimental tests on DSSC prototypes

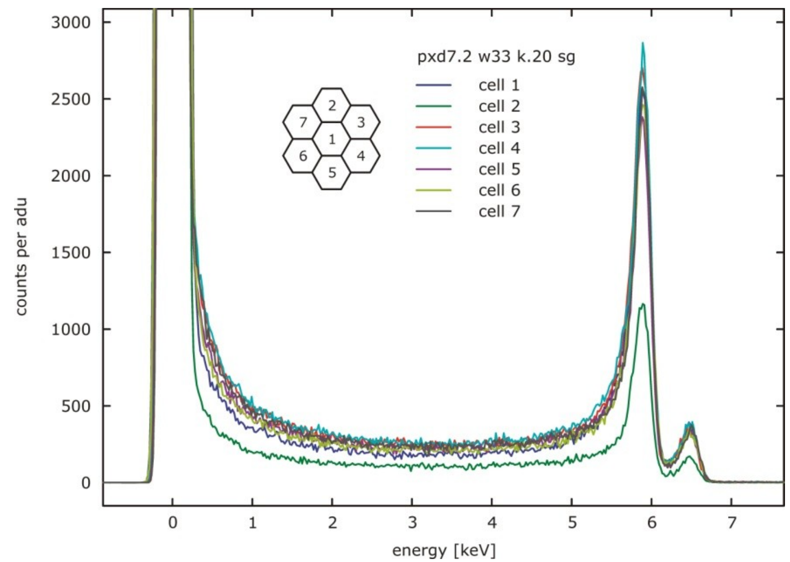
spectroscopy

- Fe55 source

  linear region of the gain curve

  noise peak ~ 10 el. ENC

  Mn-K_{α} line ~ 150 eV FWHM @ 5.9 keV



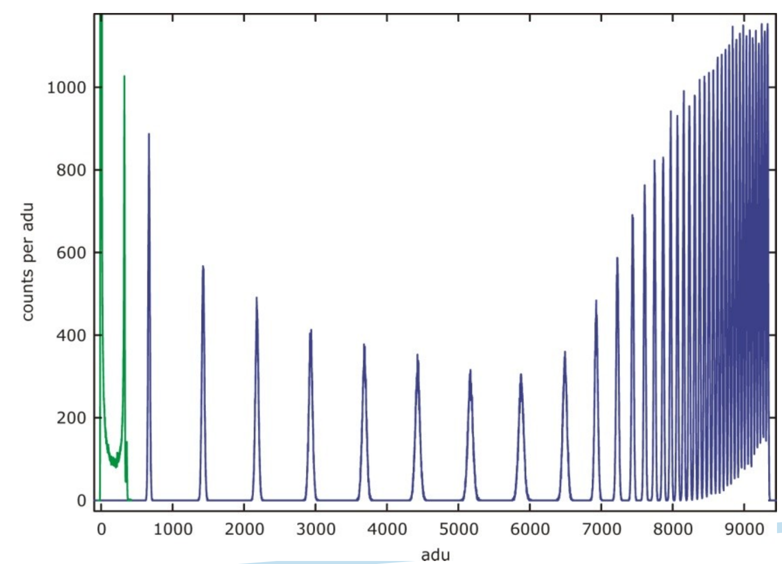
Response to a pulsed laser

increasing number of identical pulses

peaks are equidistant in terms of signal charge

signal compression @ large charge amount

"energy" calibration using Fe55 spectrum



Status of DSSC DEPFET Sensors

Prototypes produced in Scientific Laboratory proved correct functioning fulfilling all requirements.

The yield was lower than expected.

At present the process and design is adapted to produce the sensors in an industrial type production line. This allows for additional improvements due to smaller feature sizes as well as faster turn-around time

DEPFETs so far described

Basic DEPFET

Signal charge stored in potential minimum below the transistor channel

Combined detector and amplifier properties

Low readout noise and absence of reset noise: excellent spectroscopic performance

Fully depleted, backside illumination: 100% fill factor, high quantum efficiency

Nondestructive readout of signal charge

Room temperature operation possible

Arranged into a pixel matrix a DEPFET detector has the advantage of

* Low power consumption, as transistors are turned off during charge collection
* Charge readout at place of generation, no charge shifting needed
* Readout on demand and window-mode capability
* High speed operation possible
* Significantly improved radiation hardness compared to CCDs

DEPFET combined with Silicon Drift Detector (Macropixel detector)

Pixel cell size can be varied from tens of µm to centimeters

The detector can be easily tailored to the telescope's point spread function

DSSC DEPFET (DEPFET Sensor with Signal Compression)

Intrinsic non-linear amplification, tunable by doping and operation voltages

Combines high dynamic range with excellent resolution for small signals

DEPFETs not yet described

Repetitive Non-Destructive Readout (RNDR) DEPFET detectors

Repetitive readout of the signal allows sub-electron measurement precision

useful for low energy x-ray spectroscopy and photon counting in the optical

Gateable DEPFET detectors

Intrinsic electronic shutter: collection of signal charge only in selected time intervals

Suppression of "misfits" (due to arrival of signals during readout phase): improved signal-to-noise ratio for high speed applications

Gateable DEPFETs with intermediate charge storage

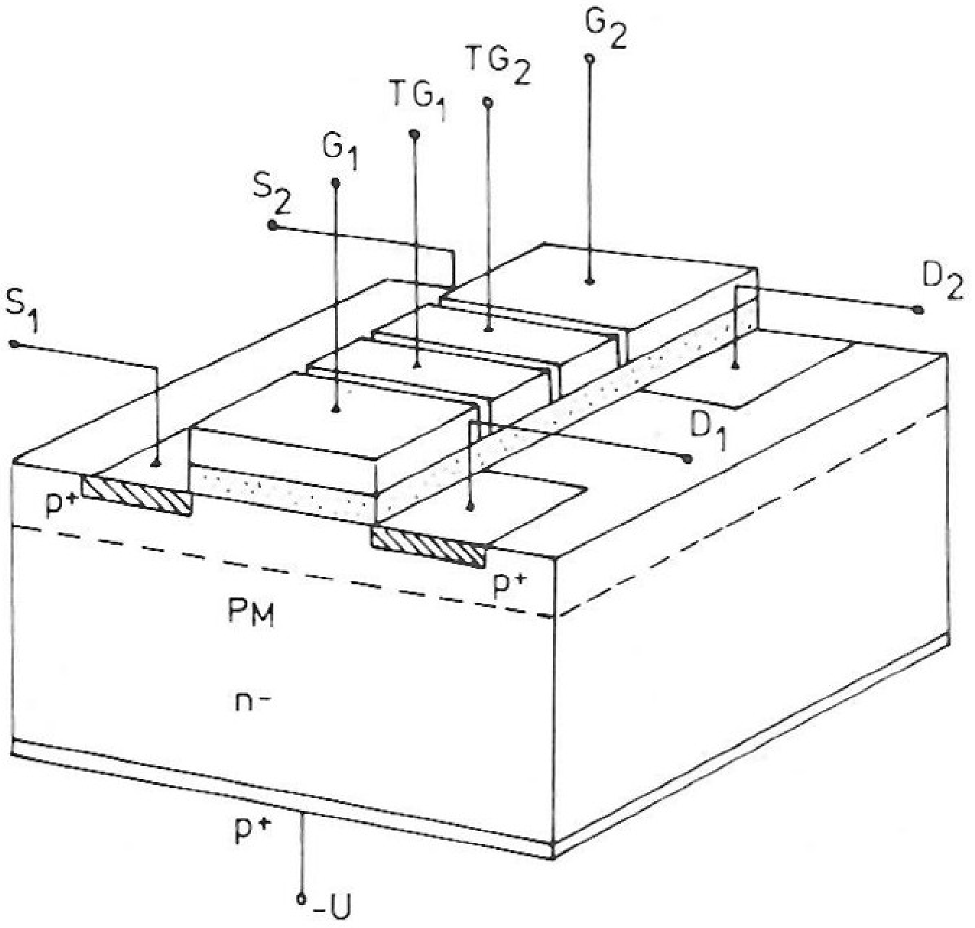
Allows nearly dead-time-free operation and/or gateability

Optimized for spectroscopy at high frame rates

RNDR DEPFET Detector

The proposal of using the non-destructable reading in DEPFETs for reducing the noise was already contained in the original DEPFET publication.

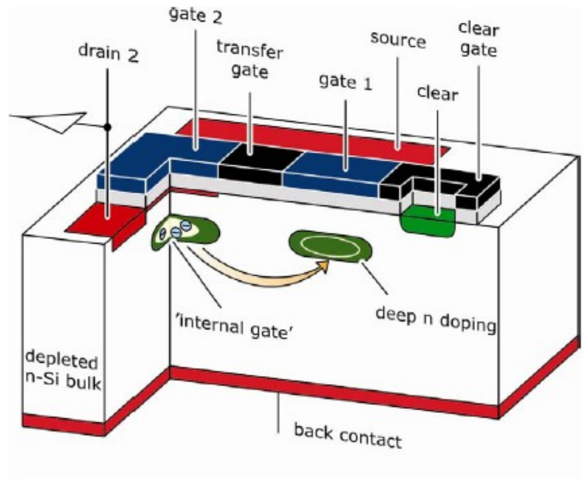
Two DEPFETs placed close to each other were connected with a CCD like structure allowing the shifting of signal charge from one IG to the other and reverse. Such it was possible to read the same charge multiple times and reduce the noise by the square root of the number of readings.

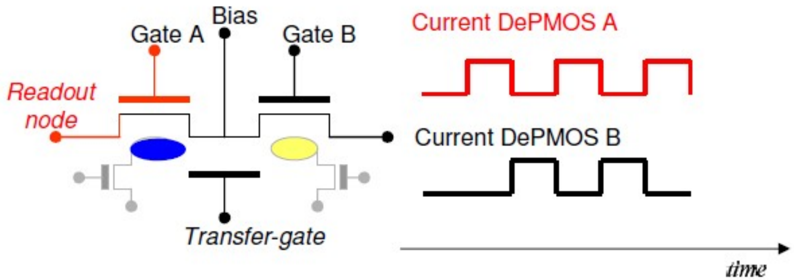


RNDR DEPFET Detector

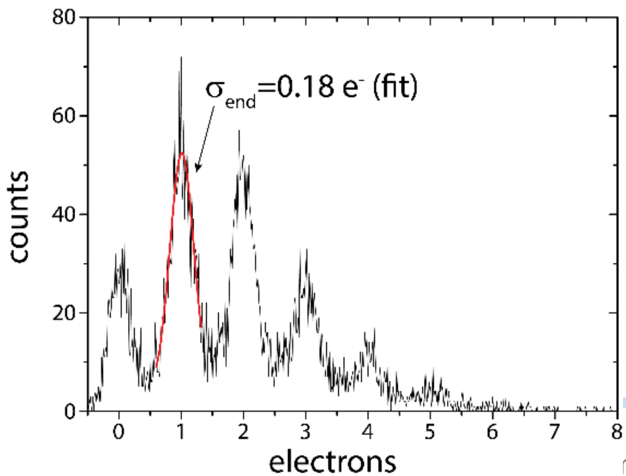
Developed in the framework of a PhD thesis(Stefan Wölfel)

Aim: demonstrate sub-electron charge measurement precision, suppression of 1/f noise



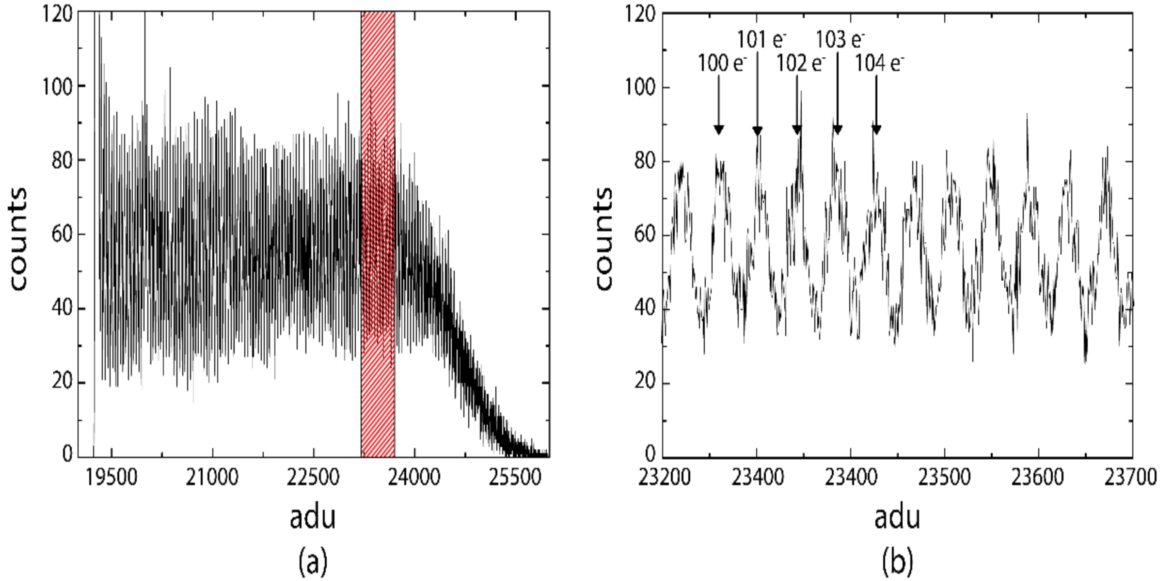


Exposure with faint light source
(1 photon per exposure on average)
Resolution 0,18 el. r.m.s.



RNDR DEPFET Detector

Extending exposure time
Continuously all channels are populated



Number of electrons can be measured with same precision up to very high numbers.

Applications in low energy X-ray spectroscopy,

Optical photon counting

Gateable DEPFET Sensors

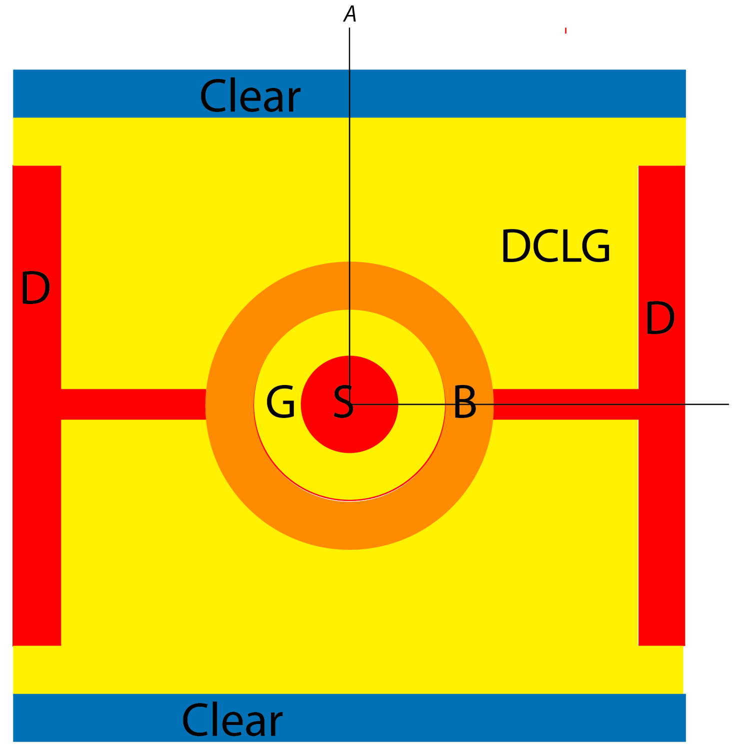
DEPFETs described so far were continuosly sensitive. Charge was collected in the Internal Gate, even during readout.

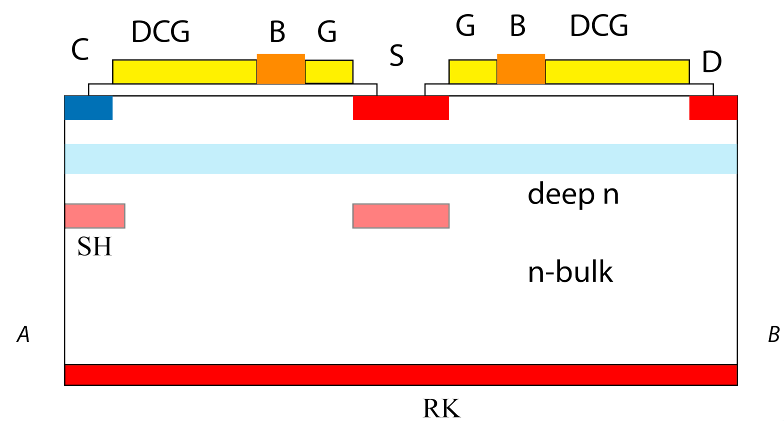
To restrict charge collection to desired time interval an externaly controllable shutter can be integrated into the DEPFET.

Source (S) surrounded by Gate (G) and Barrier Gate (B).

Outer region covered by Drain-Clear-Gate (DCG) creating underneath either (for negative voltage) an inversion layer (connected to the drain) or for positive voltage an accumulation-layer connected to Clear.

Barrier gate B controls flow of signal charge out of Internal gate.

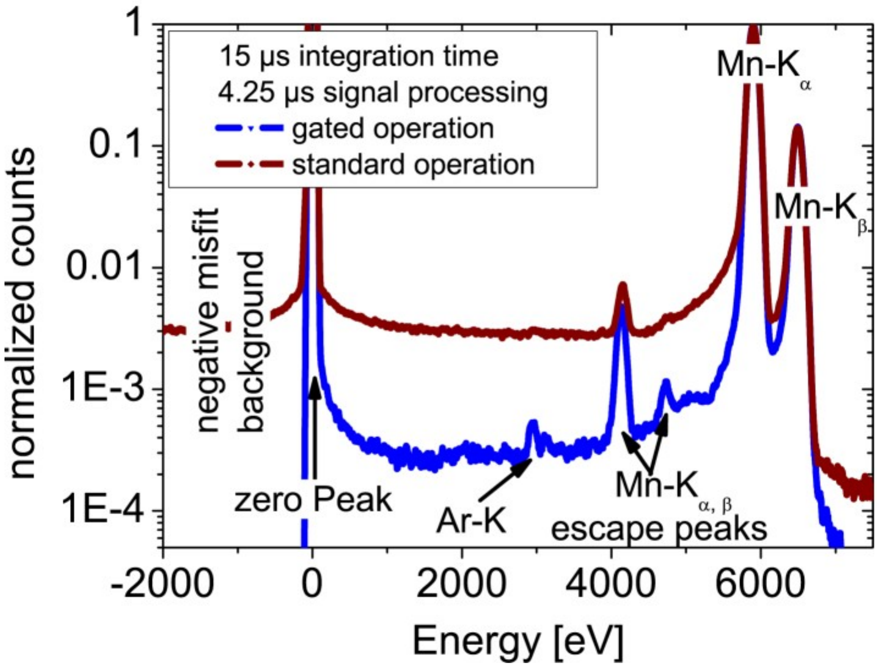




Gateable DEPFET Sensors

Gateable pixel sensors can be used for observation of periodically varying objects and for suppressing events occurring during the readout phase of the device

(misfit events)



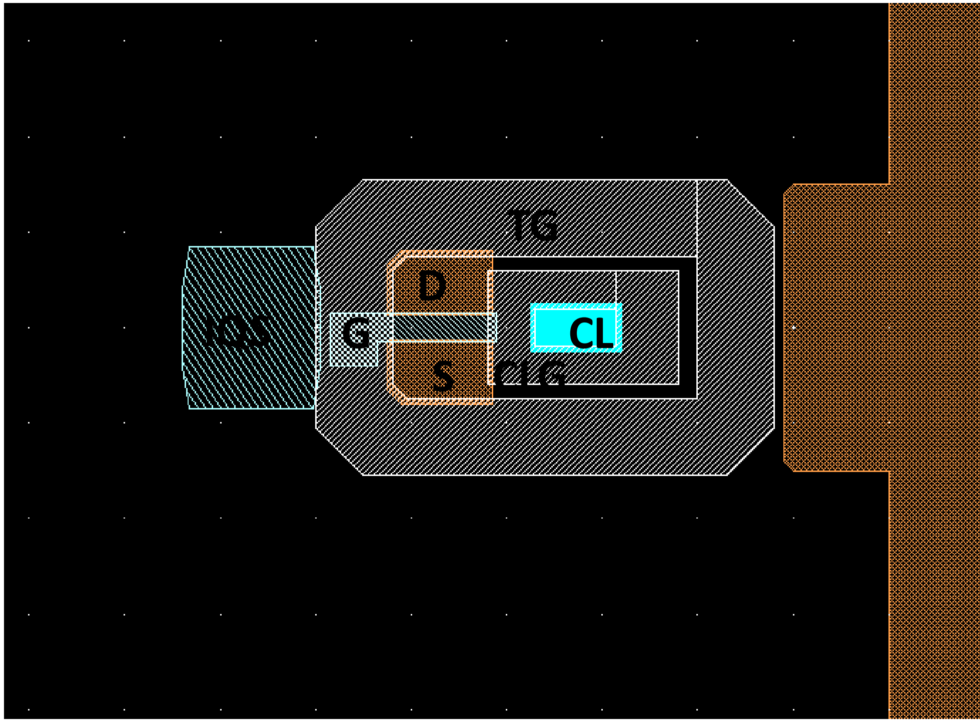
IQS (Intermediate Charge Store) DEPFETs

Gateable DEPFETs with intermediate charge storage

For applications in X-ray astronomy a fast gateble pixel detector with continous deadtime-less sensitivity was desired.

Concept: collect data in intermediate storage regions outside of the DEPFETs while data from previos event are read out.

Transfer complete event rapidly into DEPFET regions of the pixels.



Summary and Outlook

DEPFET is a very old concept (1985) that only recently has found its way into large projects (MIXS, DSSC, BELLE II)

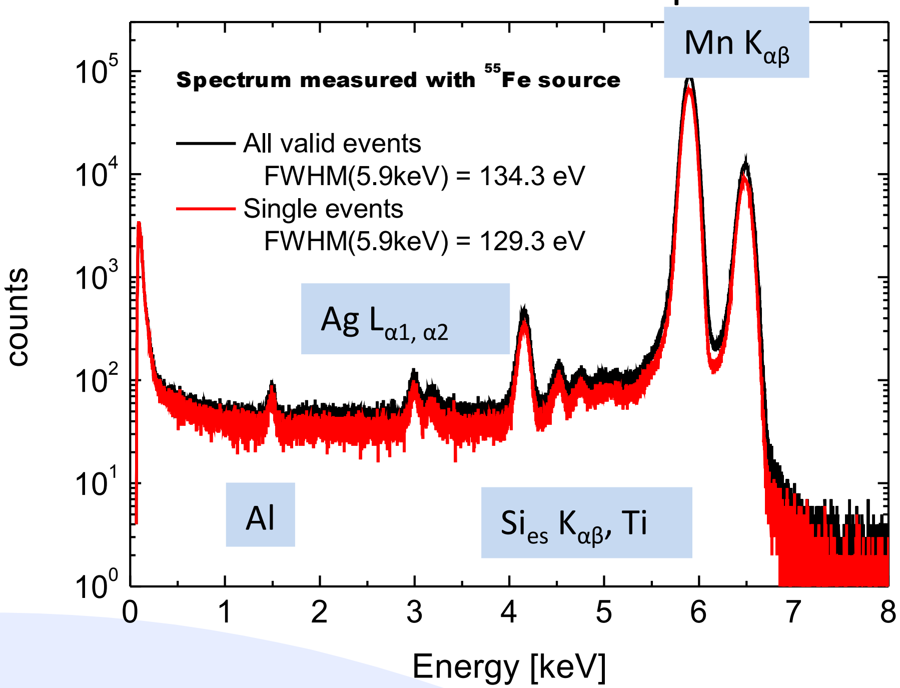
It combines detector and amplifier and signal storage properties and can be adapted to many requirements.

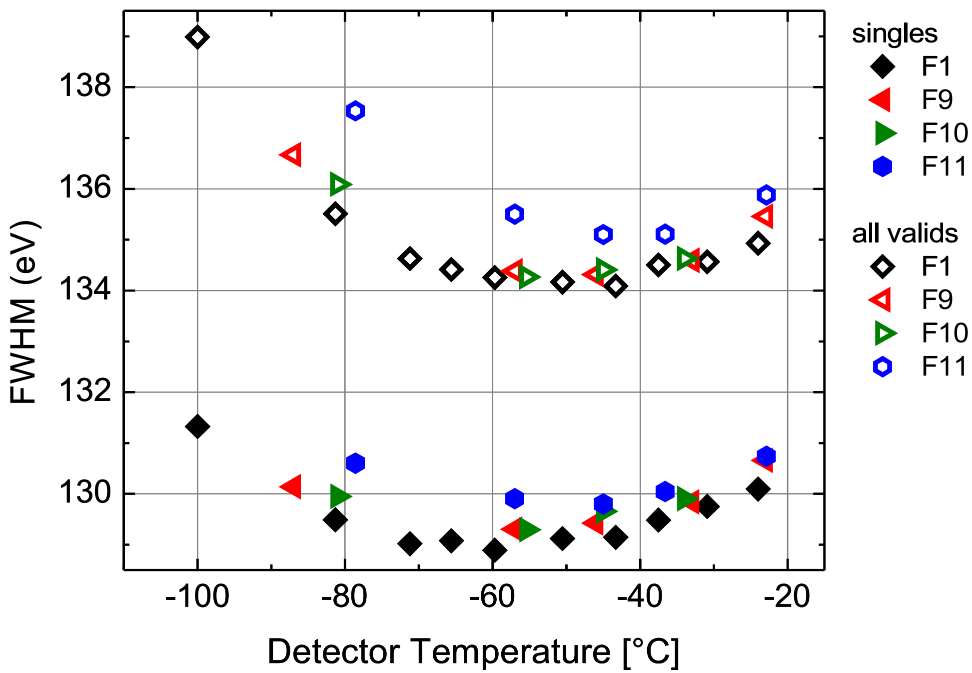
Detector performance

2. spectroscopic performance measurements: ^{55}Fe source 5.9 keV (Mn K$\tilde{\alpha}$)

readout speed: 165 µs/frame

measurements over a wide temperature range





Majewski et al., TNS 59 pp. 2479-2486 (2012)

Detector performance

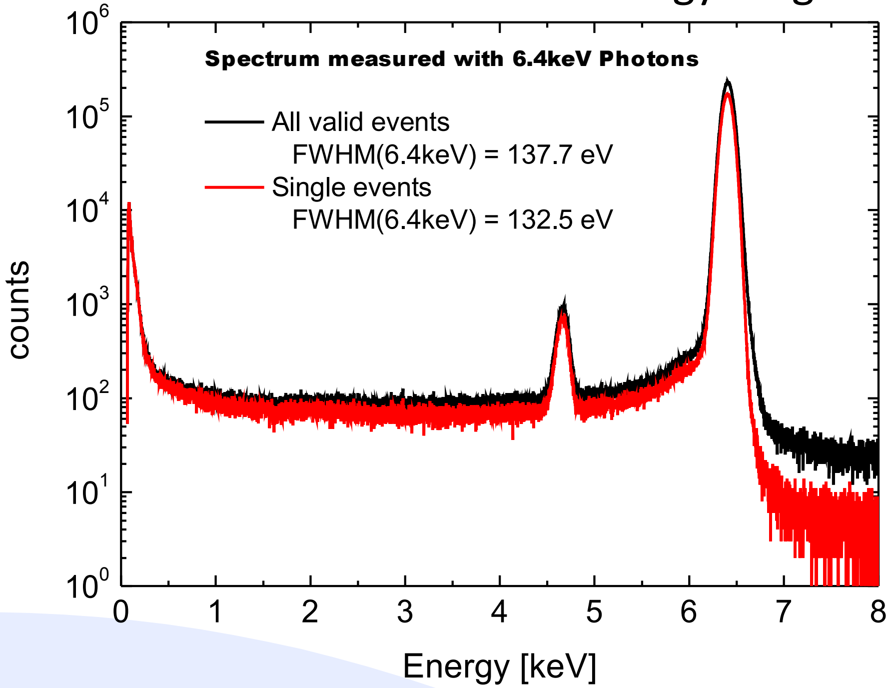
3. calibration measurements @ BESSY-II

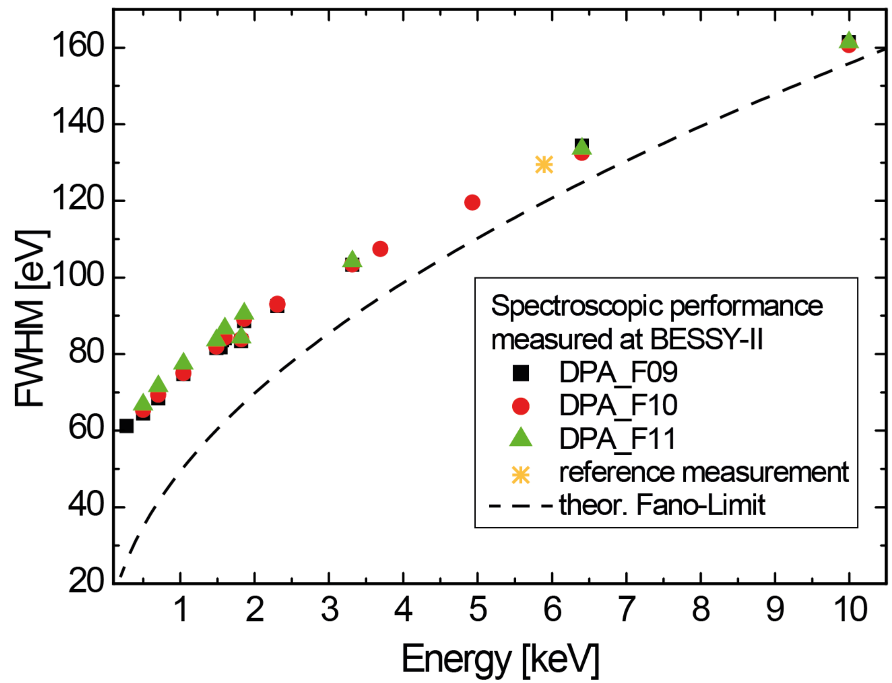
Additional measurement (1 device):

FWHM (277eV) = 61 eV

readout speed: 165 µs/frame;

measurements over a wide energy range from 500 eV to 10 keV





Majewski et al., Exp. Astronomy (2014),
DOI:10.1007/s10686-014-9374-5