Advanced silicon detectors developed at MPS Semiconductor Laboratory

– status and future perspectives –

Jelena Ninković

- MPS Semiconductor Lab
- Devices & Selected Applications
- Perspectives

MPS Semiconductor Laboratory (in German: MPG Halbleiterlabor - HLL)

At present @ Siemens Campus Neuperlach Munich

- 1000m^2 of clean room area
- 330m^2 of ISO3 area
- Full 6 inch silicon process line

From mid 2023 @ IPP Campus Garching

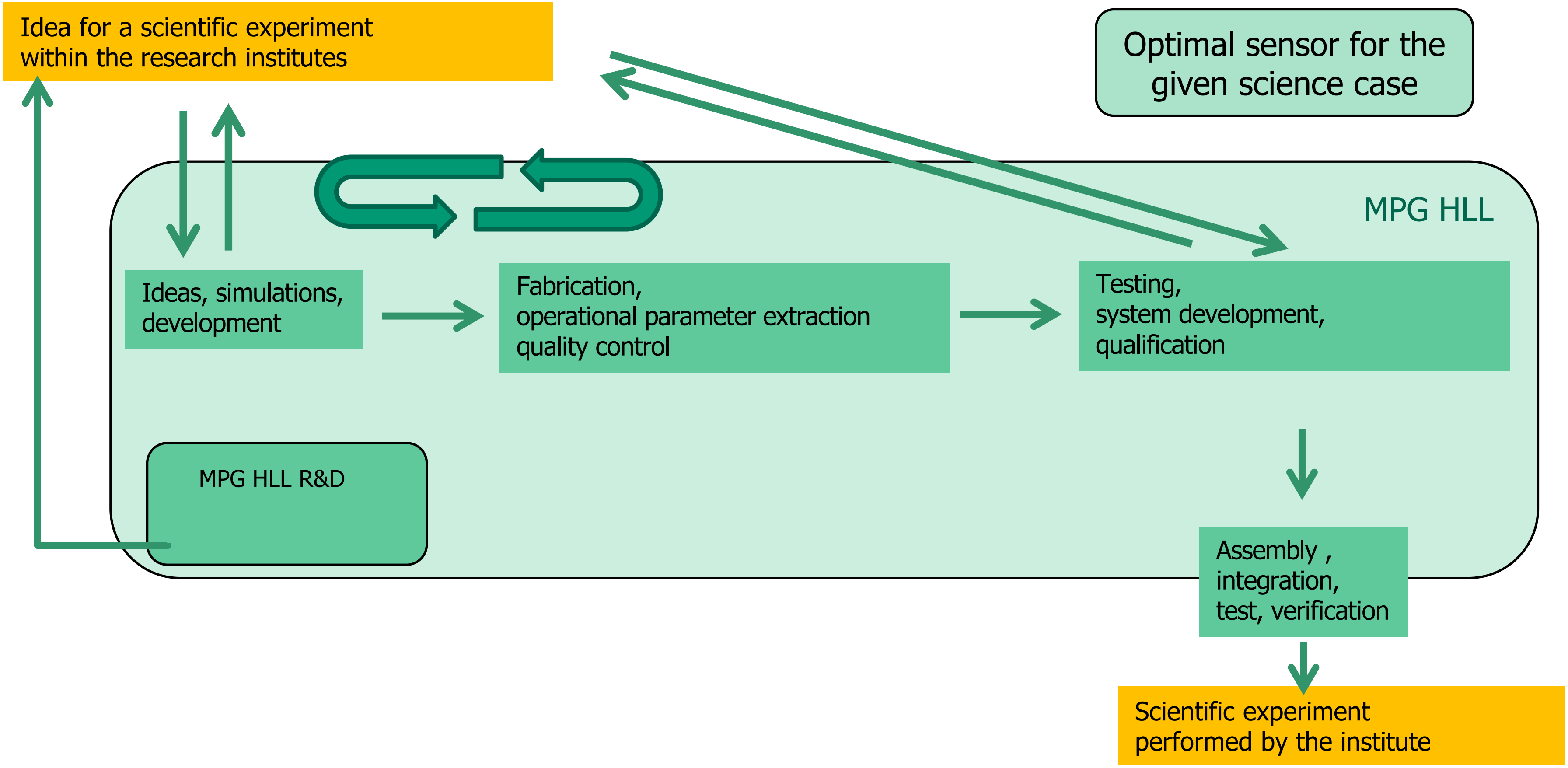
- 1500m^2 of clean room area
- 600m^2 of ISO3 & ISO4 area
- 8 inch silicon process line

From 2023 HLL will be part of Munich Quantum Valley

Central facility of the Max Planck Society
with 40 employees: scientists, engineers and technicians + guest scientists, engineers and students

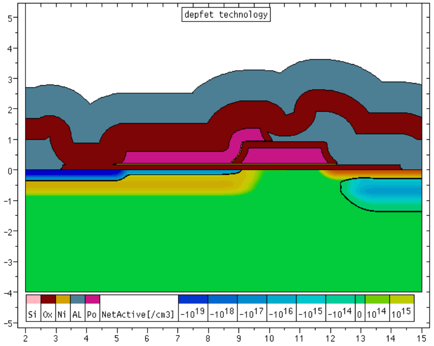
MPG HLL is the only lab worldwide doing fully depleted silicon radiation sensors with integrated electronics optimized for different scientific projects

MPG HLL in a nutshell



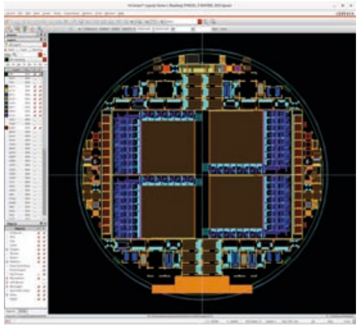
Inside HLL – Sensors and Systems : Design, fabrication & Test

Process simulation

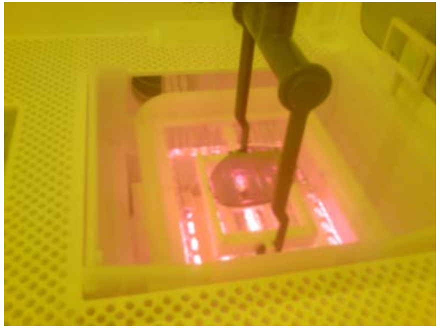


Device simulation, 2D and 3D

State-of-the-art layout tools



In house fabrication



Wire bonding, hybrid assembly

@ HLL:

- sensor design and fabrication
- interconnection
- system/camera design and test

System test facilities

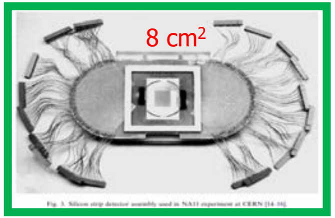
Highlights from the past

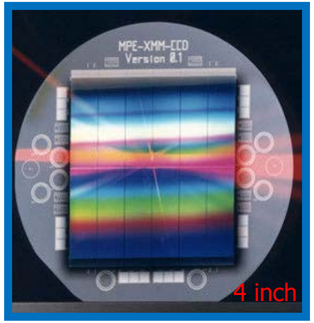
- **NA11 - NA32 experiments at CERN (1982 -1988)   [MPP]**
  First usage of silicon strip detectors in the high energy physics

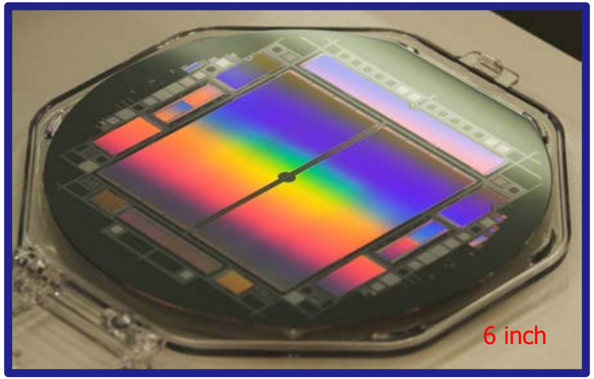
- **XMM Newton (launch 1999) [MPE]**
  Large area device with 100% fill factor, and very sensitive entrance window

- **ATLAS (2004) [MPP]**
  development at HLL, fabrication at industry, 3.000 wafers produced

- **LAMP (2011 – 2014) [CFEL]**
  Photon sicence: Large area device with ultra sensitive entrance windows



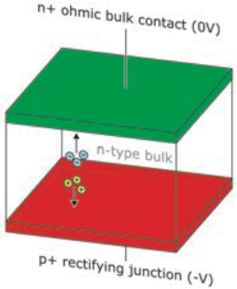




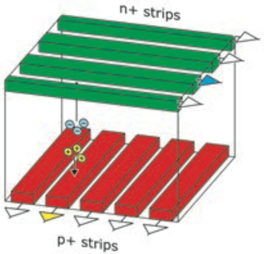
Devices @ HLL

- **Building blocks**

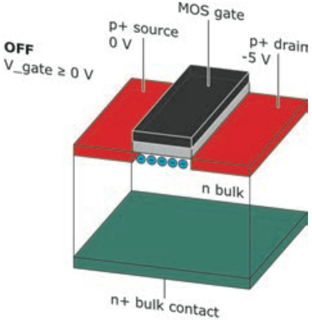
Diodes



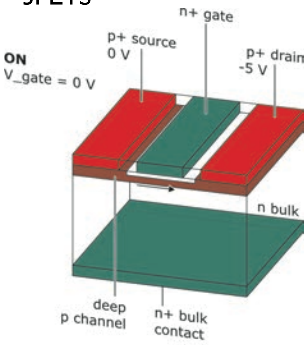
Strip detectors



MOSFETs

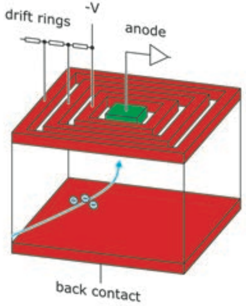


JFETs

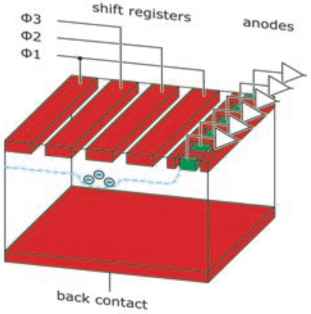


- **Devices**

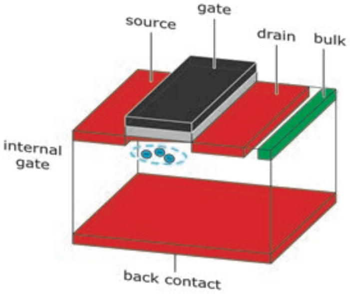
Silicon drift detectors (SDD)



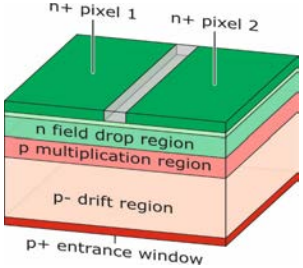
pnCCDs



DEPFETs



Avalanche devices

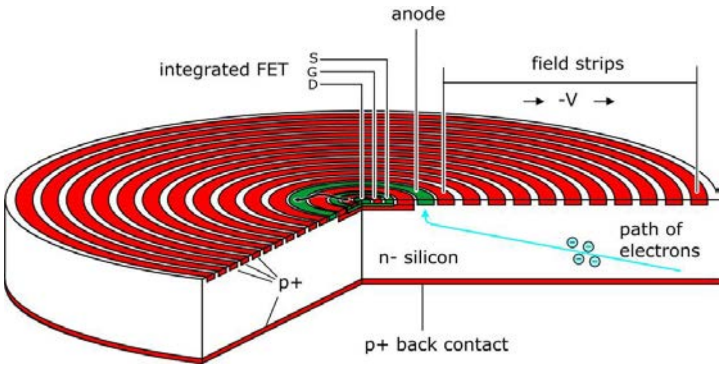


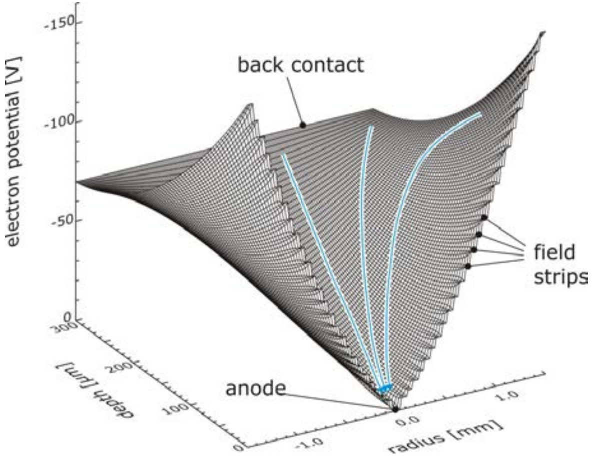
SDD with on-chip FET

Peter Lechner et al., 1994

- ▷ one-sided field strip system
- ▷ backside illuminated
- ▷ integration of 1st amplifying FET
  dedicated n-JFET
  - ↳ minimization of total capacitance
  - ↳ **good energy resolution**
  - ↳ **high count rate capability**
  - ↳ **robust** against pickup, microphony

- ▷ comparison
  - pin diode 10 mm² x 300 µm
    C_{tot} = 3.5 pF
  - SDD with FET 10 mm²
    C_{tot} = 150 fF





SDD highlights

Mini SDD - DSSC @ EuXFEL
(imaging of X-ray diffraction patterns)

M. Porro et al., *The MiniSDD-based 1-Megapixel Camera of the DSSC Project for the European XFEL*, IEEE TNS 68(6), pp. 1334 - 1350, June 2021

camera	**1024 x 1024 pixels** 21 x 21 cm² 32 sensor chips 4 quadrants central hole for direct beam
sensor	mini-SDD cells 128 x 256 pixels 3.0 x 6.2 cm² (chip)
hex. pixel pitch	204 μm × 236 μm
energy range	**0.25 keV – 6 keV**
noise	60 el. r.m.s.
peak frame rate	**4.5 MHz**
frame storage	800 frames

eXTP (enhanced X-ray Timing and Polarimetry) SFA (spectroscopic focusing array)
(fast time-resolved X-ray spectroscopy)

SDD layout plot

SFA instrument	11 telescopes & sensors sensors out of focus
sensor	**19-cells SDD**
SDD cell	hexagonal 3.2 mm side length **30 mm² area**
energy resolution	< 180 eV (FWHM @ 6 keV)
time resolution	< 10 μsec

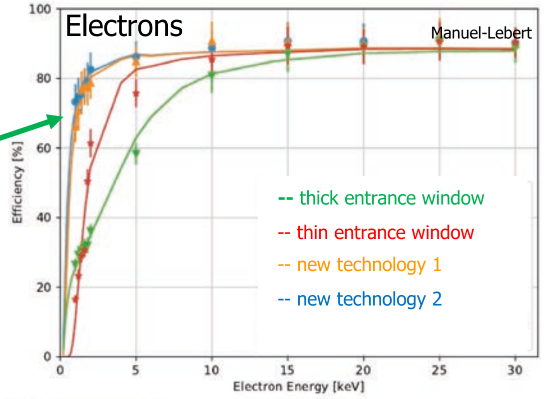
TRISTAN (tritium sterile anti-neutrino) @ KIT
sterile neutrino search by electron spectroscopy

TRISTAN focal plane, 21 modules.

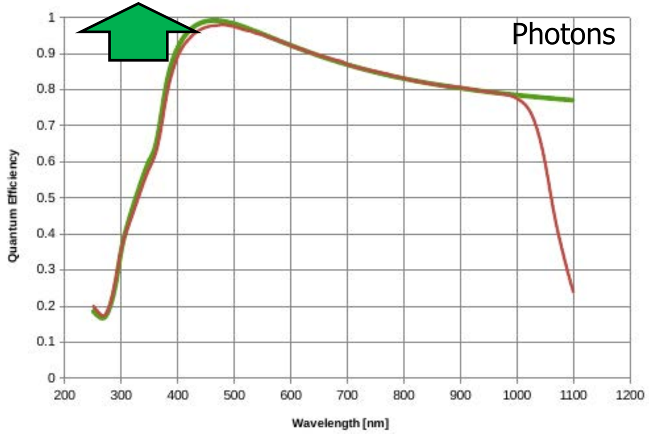
system	21 sensors **20 cm diameter**
sensor	SDD with integrated FET **166 cells (~ 14 x 12 array)** **3.8 x 4.0 cm² (chip)**
SDD cell	hexagonal, 3 mm side length 7 mm² area
energy resolution	< 300 eV FWHM @ 20 keV
count rate	≤ 10^8/sec on focal plane ≤ 10^5/sec on sensor cell
dead layer	**as thin as possible**

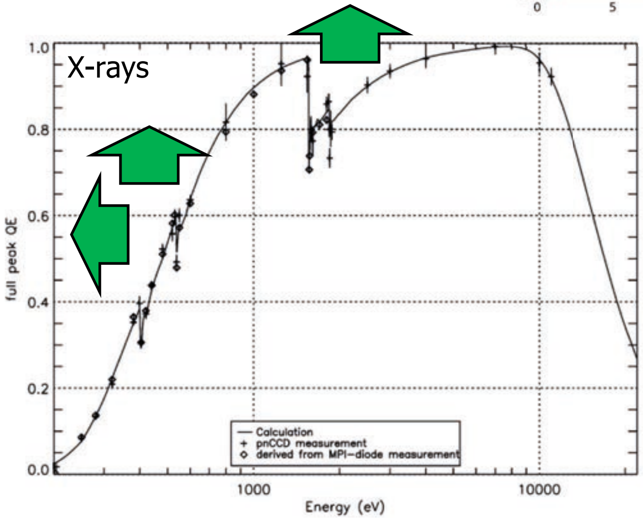
Entrance window engineering – application optimization

- anti-reflective coating (ARC)
  - sequence of dielectric layers deposited on the entrance window
  - variation of material and thickness
  - transmittance tuning to application needs
  - blocking filters
  - mechanical protection
  - optical coupling



Ongoing developments
Reduction of dead layer to < 20nm

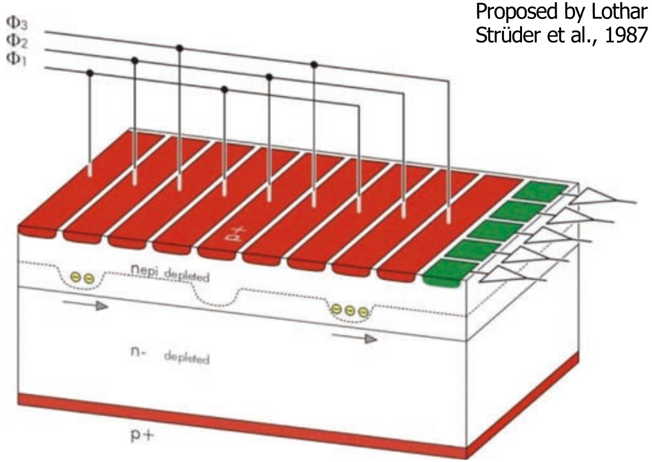




pnCCDs

- ▷ definition of potential pockets by differently reverse-biased diodes
- ▷ charge transport by periodic clocking of shift registers
- ▷ **column-parallel readout** → high frame rate (5 msec @ 200 pixel)
- ▷ integrated 1st FET (1 / column) → **low noise** (**2el. ENC**)
- ▷ backside illuminated, **fully depleted** → **high quantum efficiency**

Proposed by Lothar Strüder et al., 1987



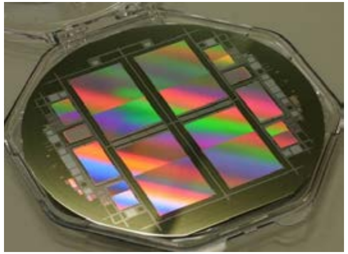
- format ~ cm² … **wafer scale**
- thickness 450 µm
- **pixel size 36 … 150 µm**

Applications

- X-ray imaging & spectroscopy
- optical light imaging

World leading soft X-ray large area pnCCD devices @ MPG HLL

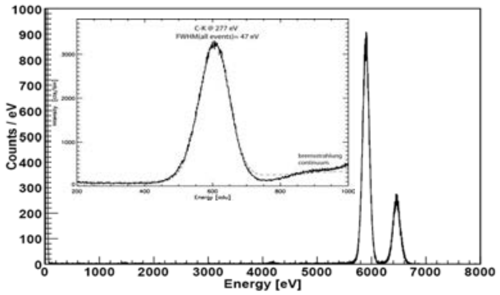
eROSITA
X-ray imaging & spectroscopy



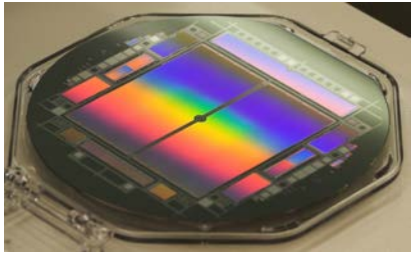
Sensor: 3 x 3 cm^2, 384 × 384

Pixel size: 75 x 75 µm^2

Frame time: 50msec (20Hz)



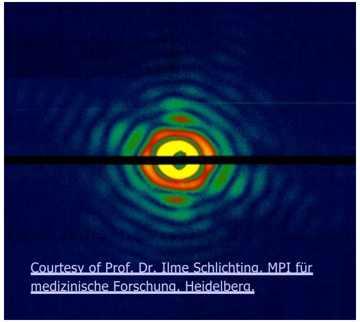
CAMP / LAMP
Soft Xray camera for Photon science



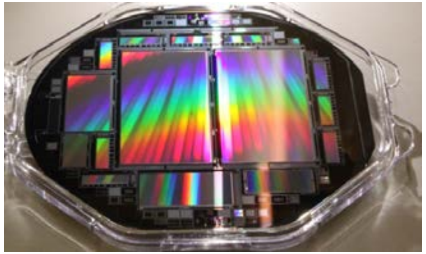
Sensor: 3.7 x 7.8 cm^2, 1024 × 512 pixels.

Pixel size: 75 x 75 µm^2

Frame time: 8 msec (up to 120Hz)



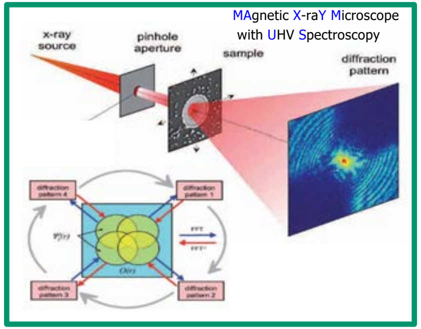
FSP – TNG for MAXIMUS
Fast Small Pixel – The Next Generation



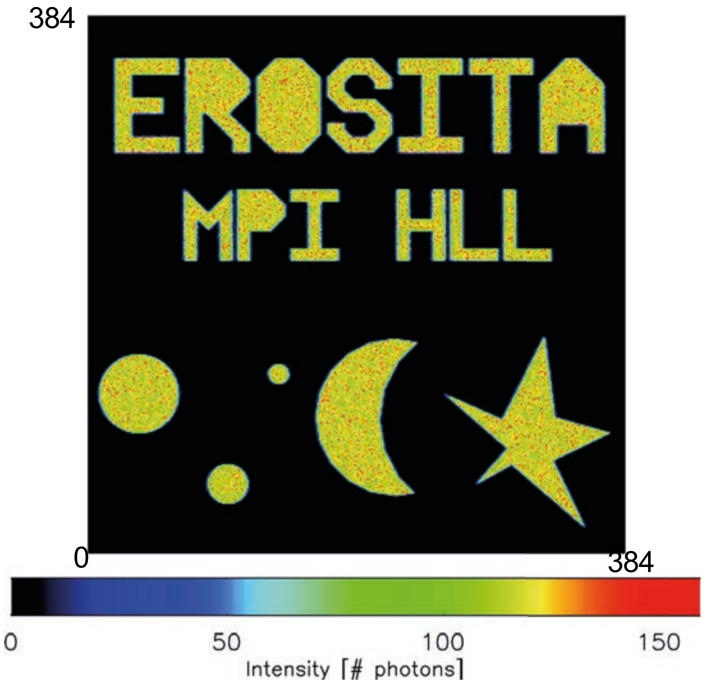
Sensor: 3.7 x 7.4 cm^2, 1024×1024 +(2x512) pixels

Pixel size: 36 x 36 µm^2

Frame time: 2.5 msec (400Hz)

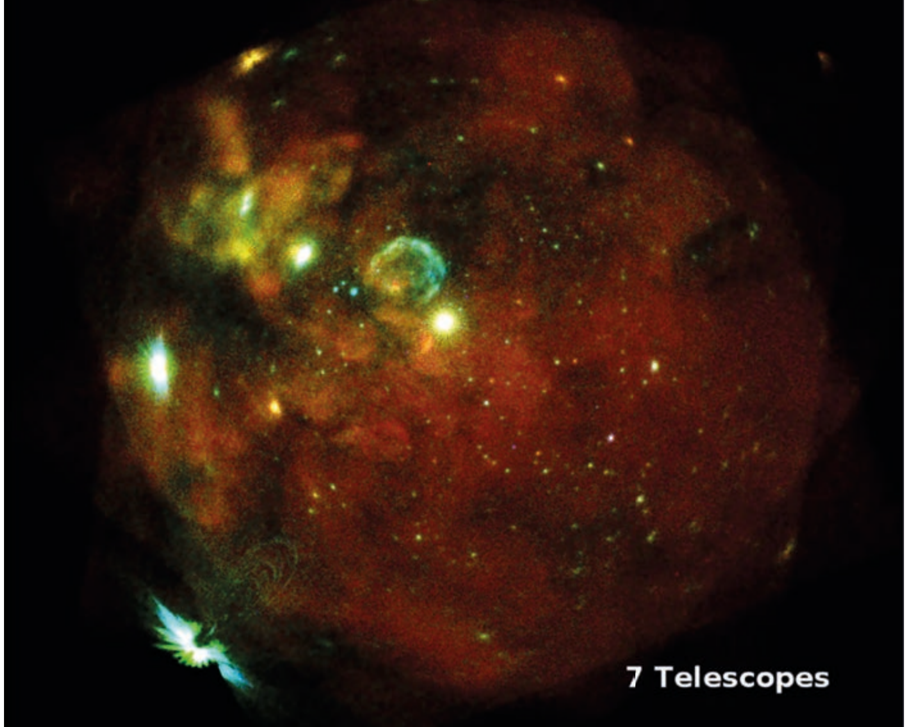


Erosita's performance



Shadow image of a 450 μm thick silicon baffle with an ^{55}Fe source mounted directly in front of the sensor

Large Magellanic Cloud, observed in series of exposures with all seven eROSITA telescope modules taken from 18 to 19 October 2019



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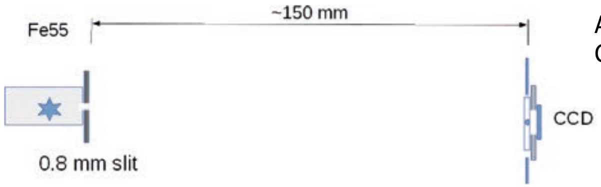
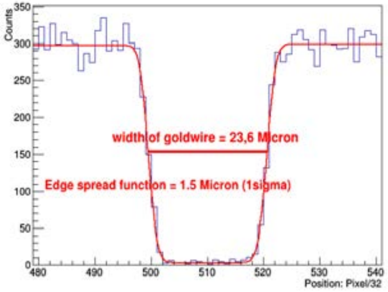
Subpixel resolution with 36μm pnCCDs



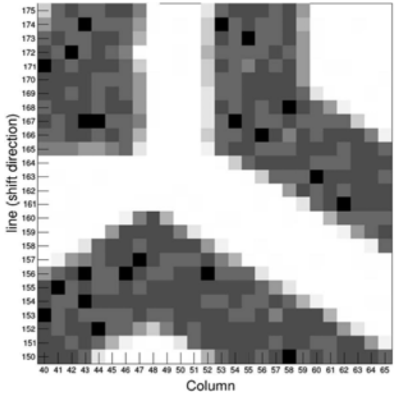
A 50µm thick W-wire is placed in ~0.5 mm distance from the CCD backside and illuminated.

36μm pnCCDs due to the high speed and high S/N allow subpixel resolution

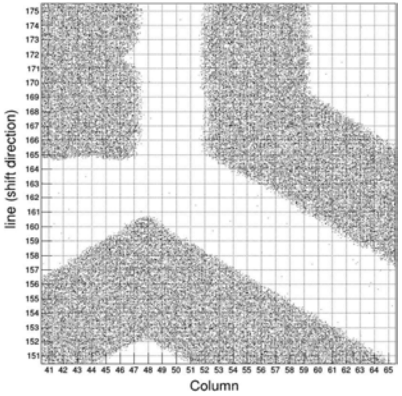
36 μm pixel size
→ resolution <2 μm
→ still nice Fe^{55} spectrum (s=80eV)

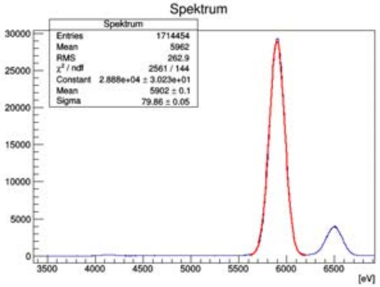


integration of photons per pixel



cluster reconstruction and integration per subpixel (32x32 subgrid)





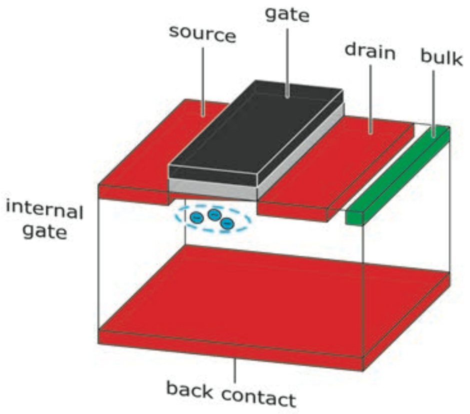
Schopper, F. et al. (2017)
High resolution X-ray imaging with pnCCDs
NIM A 912

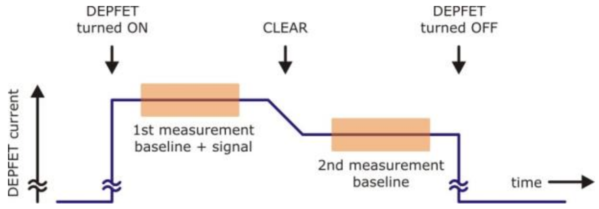
DEPFETs

p-MOSFET on fully depleted n-substrate

- **fully depleted** sensitive volume
  - fast signal rise time (~ns), small cluster size
  - no stitching, 100% fill factor
- **Charge collection in "off" state**, read out on demand
  - potentially low power device
  - non destructive readout
- **internal amplification**
  - charge-to-current conversion (500 pA/el.)
  - large signal, even for thin devices
  - r/o cap. independent of sensor thickness (20 fF)

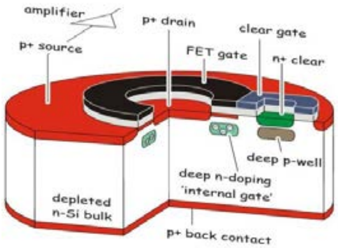
Proposed by
Josef Kemmer &
Gerhard Lutz, 1987





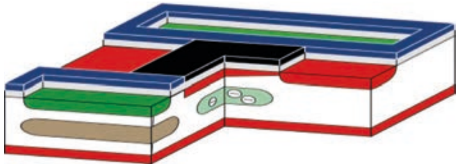
Applications:
- unit cell of active pixel sensor
- integrated readout device of SDD, pnCCD, …

DEPFET flavors



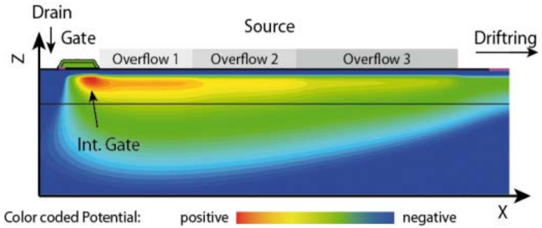
Low noise: Spectroscopic X-Ray imaging

pixel size: 100µm, with drift rings several 100s of µm
read out time per row: few µs
Noise: ≈2 el ENC
fully depleted, the thicker the better → large QE for higher E



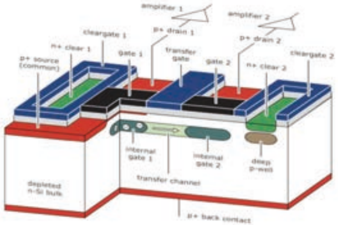
Thin & small pixel: vertex, low E electron detectors (TEM)

pixel size: 20µm…75µm
read out time per row: 25ns-100ns
Noise: ≈100 el ENC
thin detectors: 30µm…75µm → still large signal: 40nA/µm for MIP



High Dynamic range, ultra-fast read-out – NON linear DEPFETs

DEPFET **S**ensor with **S**ignal **C**ompression
Sensitivity to single photons and high dynamic range
pixel size: ~ 60 µm - 200 µm
hybrid sensor : 1-to-1 bonded to readout chip, or rolling shutter 25ns/row

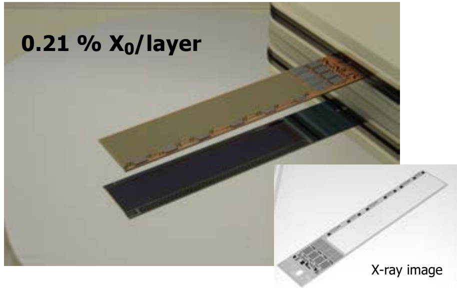


Advanced DEPFET concepts

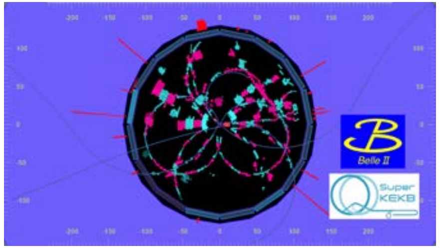
DEPFET **with multiple internal gates**
Sensitivity to single photons
pixel size: ~60- 200 µm or more

Highlights from DEPFET projects

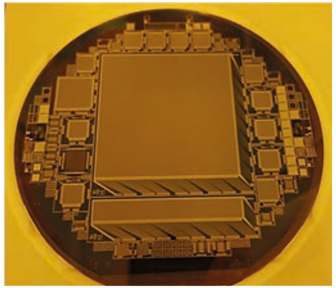
BELLE II pixel detector
High energy particle vertexing



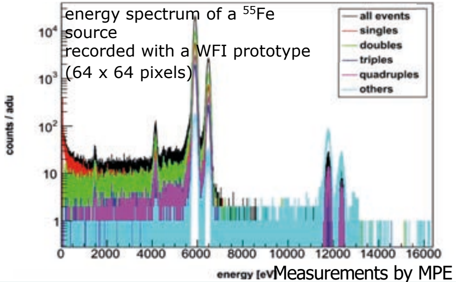
Active area 12.5 x 44.8(61.44)mm^2
250 x 800 pixels
Thickness: **75 μm**
rolling shutter mode
Pixel size: 50 x 55(85) μm^2
Frame time: 20ms (50kHz) (10MHz -row)



ATHENA Wide Field Imager
the **A**dvanced **T**elescope for **H**igh-**En**ergy **A**strophysics
as ESA's next-generation X-ray astronomy observatory

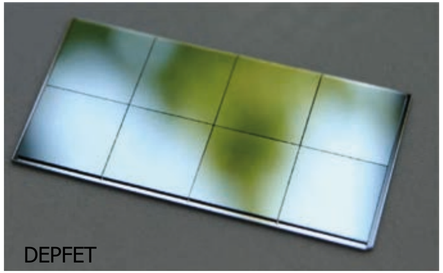


Sensor: 512 x 512 pixels
78.00 x 76.15 mm²
rolling shutter mode
Pixel size: 130x 130 μm^2
Frame time: **1.28 msec, i.e. 2.5 μsec / row**
with 128 eV (singles) & 136 eV (all)

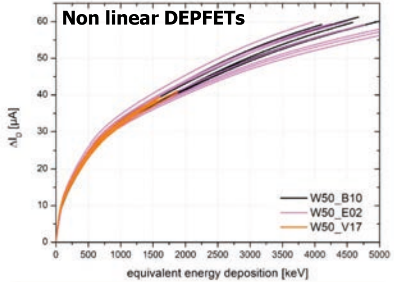


Measurements by MPE

DSSC @ EuXFEL
DEPFET **S**ensor with **S**ignal **C**ompression
(imaging of X-ray diffraction patterns)

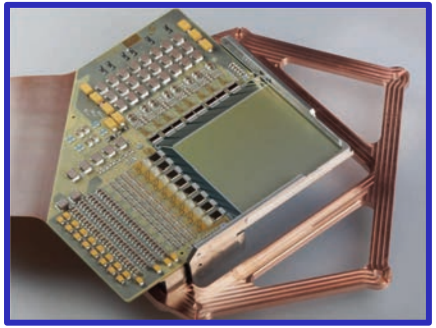


Sensor **2.56 x 10.24 cm²**
512 × 128 pixels
Hybrid detector
with 8 readout ASICs (64x64)
Pixel size: 204 x 236 μm^2
Frame time: **220ns (4.5MHz)**

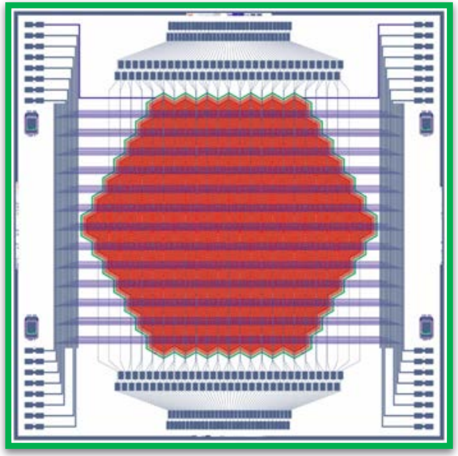


Interconnection technologies

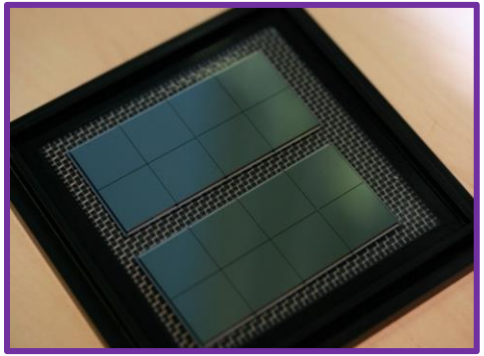
Standard wire bonding (Al and Au)
Frame time: 1.28 msec,
i.e. 2.5 µsec / row



Athena WFI module
Courtesy MPE



Full parallel readout
- dedicated wire routing
- flip chip technology – hybrid detectors



DSSC module
With 8 CMOS chips
Frame rate: 4.5MHz

Full frame read-out DEPFET detector

application **ultra-fast X-ray timing & imaging**
frame rate **> 100 kHz**

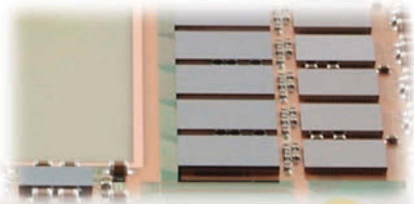
sensor 127 hexagonal hexagonal pixels
cell diameter 800 µm

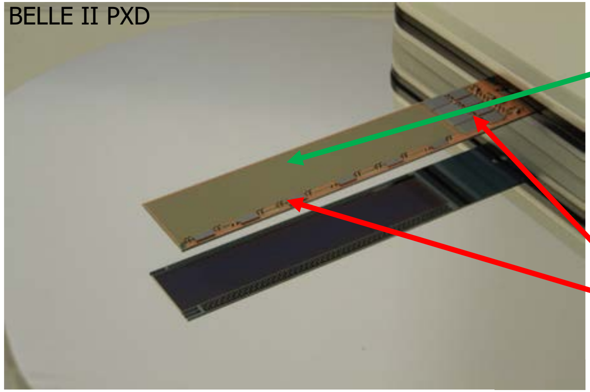
DePFET with internal storage

Interconnection technologies – All Silicon Module (ASM)

Sensor and Hybrid in one silicon piece

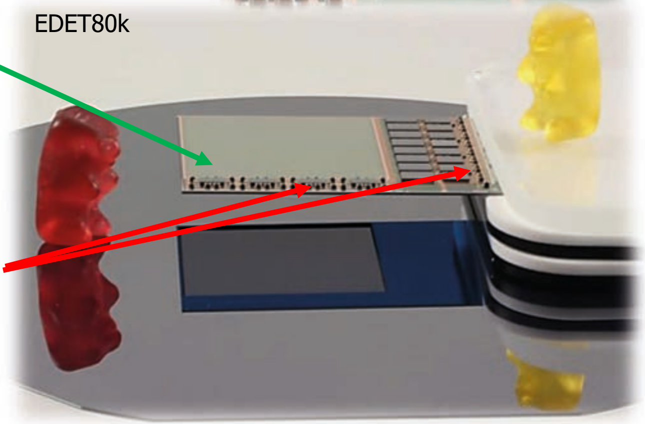
- Belle II Pixel detector – tracking of high energy particles
- EDET80k project – development of ultra fast direct electron detectors for TEM





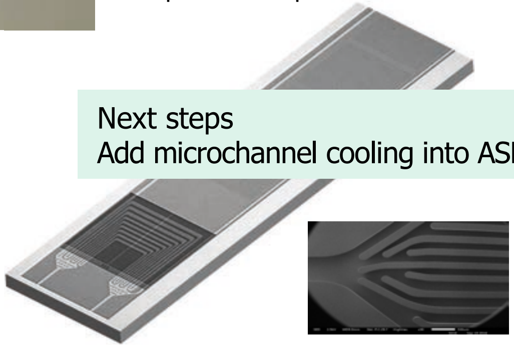
Thin sensitive area with nonlinear DEPFETs

Thick silicon area for cooling and landing pads and interconnection for the read out and steering electronics and all passive components.

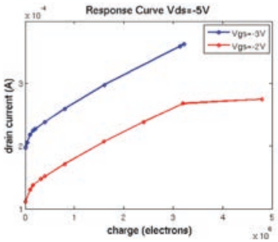


~50μm pixel size
8M pixel detector
50kHz frame time
75 μm thin detectors
Linear DEPFETs

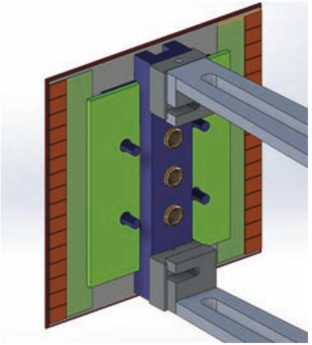
Next steps
Add microchannel cooling into ASM

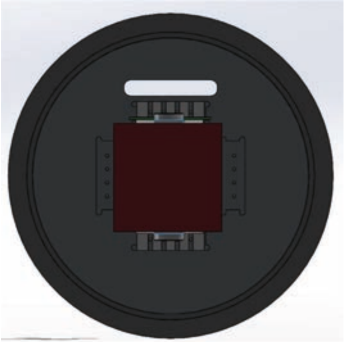


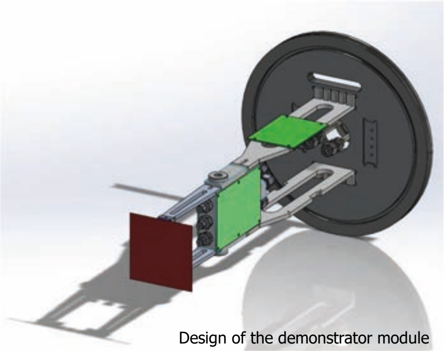
60μm pixel size
1M pixel camera
80kHz frame time
30 and 50 μm thin detectors
Nonlinear DEPFETs



4 side buttable module development @ HLL







Design of the demonstrator module

TrueTile:

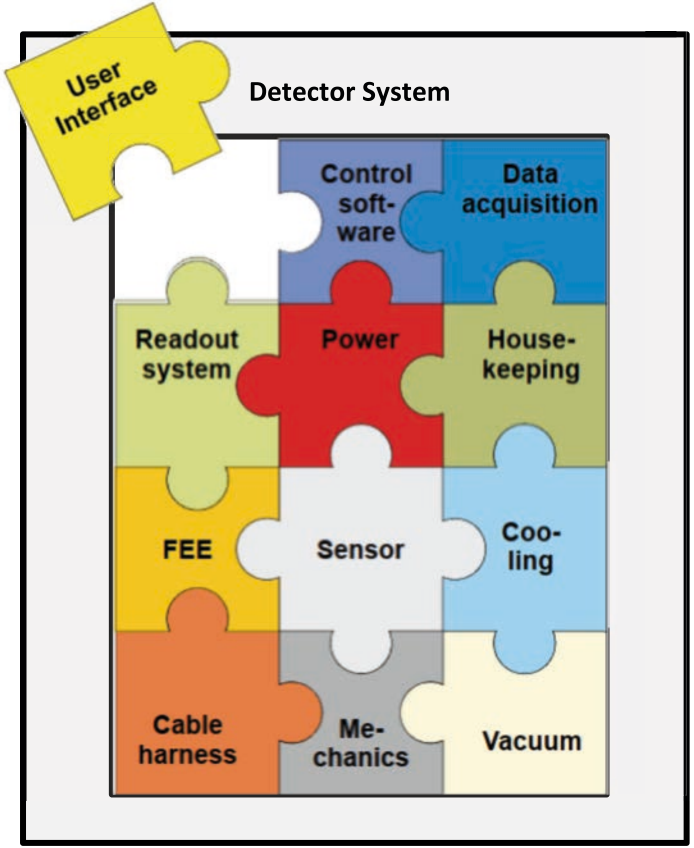
- **Novel concept** for sensor integration
- **Compact and modular** for high-density sensor integration
- **4-side buttable** devices - large sensor areas with extremely low sensitivity gaps
- Core element: **Active interposer** (AI) for
  frontend supply integration and cooling
- Multi-level development project

- Large area pnCCD as demonstrator device
  - 1 MPixel with 75 x 75 mm^2 pixels, 76.8 x 76.8 mm^2
- Active interposer with microchannel cooling structures
- Compact camera interior for standalone operation

System development

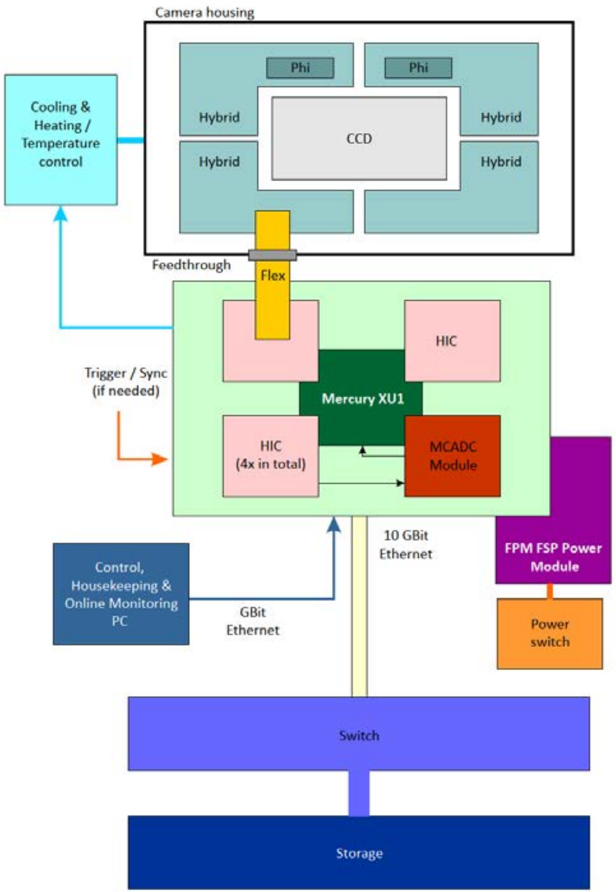
Complex puzzle:

- Combining know-how from a variety of engineering disciplines
- Driven by both sensor and user requirements
- Keeping pace with technological advancements



System development: Example FSP TNG

- **Compact camera head** featuring efficient heat removal
- Hybrids for optimized accommodation of front end electronics
- **Compact integrated power supply** including housekeeping solution
- Integrated **high-speed state-of-the-art multichannel ADCs**
- **FPGA System on Chip (SoC) based „brain“ including**
    - sequencing for camera
    - 10 GBit Ethernet for data acquisition backend
    - automated housekeeping
    - maximum flexibility to adopt user requirements, e.g.
        - special timing requirements
        - data preprocessing
- User friendly control software is work in progress
- **Modular and reusable**



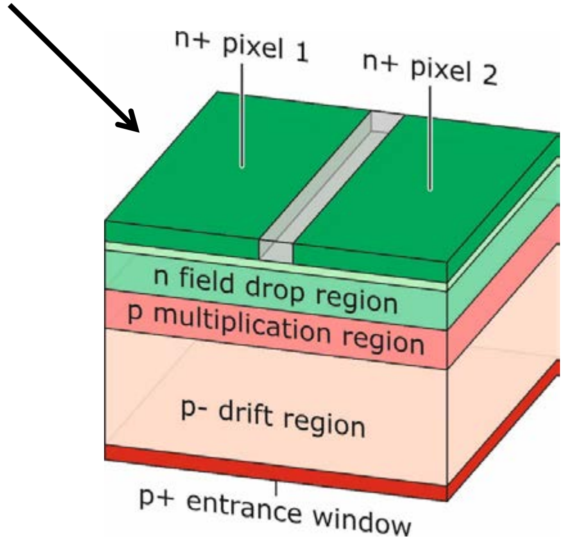
Ongoing and planned improvements

Sensor technology:

- **smaller feature size**
- **higher signal** and **lower noise**
- **higher number of metal layers**
- even **thinner entrance window**
- even **higher radiation hardness**
- **new avalanche large area (low gain) devices**
  - MARTHA (Monolithic Arrays of Reach-Through Avalanche photo diodes) devices
    - a new approach for the monolithic integration of APDs which has a fill factor of 100%, in contrast to conventional APDs requiring large gaps or comparable approaches like e.g. LGAD structures.
- **Adding some CMOS structures** to simplify operation of devices

MARTHA

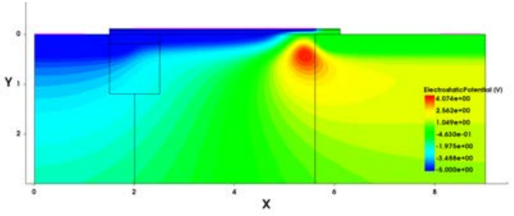
global multiplication layer
major fraction of E-field drops
across a lower doped n-region



DEPFETs – advanced concepts

Super g_q DEPFETs – Super high S/N

- New DEPFET technology allows **improved S/N** of a factor of 3
- better S/N -> better spectroscopic applications (**ENC>1e-**)
- **High speed** readout devices
- **High precision** devices
- **High dynamic range** DEPFETs
- thinner detectors
- Smaller bias current - **less power** in pixel area
- Thinner gate isolator - **higher radiation** tolerance

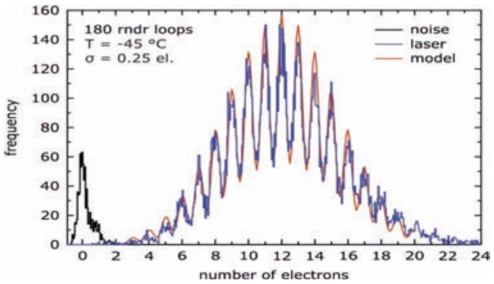


Combine different conceptual features

Create devices with multiple capabilities

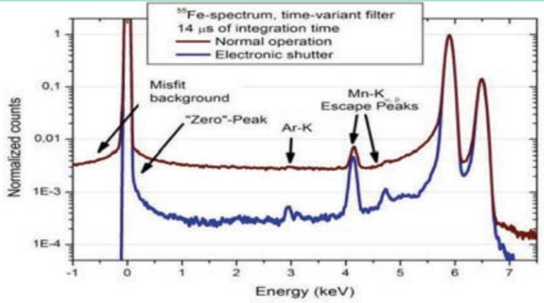
Repetitive readout – sub e$^-$ resolution RNDR DEPFETs

- an equivalent noise of 0.2 e- is achieved in ~6ms with 180 transfers
- **Extremely low noise** and background suppression
- Experiments w/ single electron sensitivity (e.g. low light level astronomy)
- Extremely low background applications (e.g. dark matter detection)



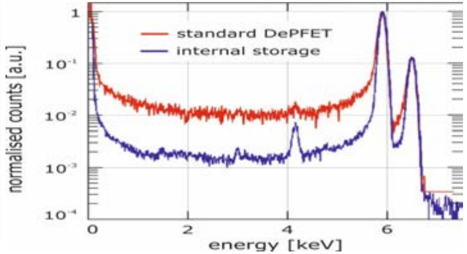
Gated DEPFETs - precise timing

- allows replacement of external shutters → better timing properties
- Sensors for experiments requiring **selective sensitivity**, e.g. light curve measurements, LIDAR, AO etc.



Multiple DEPFET structure – NO deadtime

- superpixel is composed of two or more standard or advanced DEPFET subpixels, which are alternately used for the detection of charge.
- one subpixel is read out, while the other one is collecting new charge



DEPFETs – advanced concepts

MAX PLANCK SEMICONDUCTOR LABORATORY

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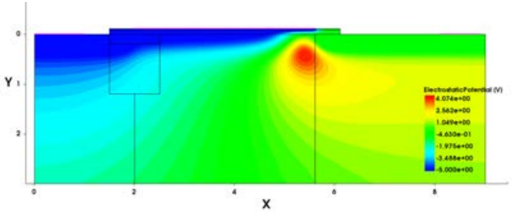

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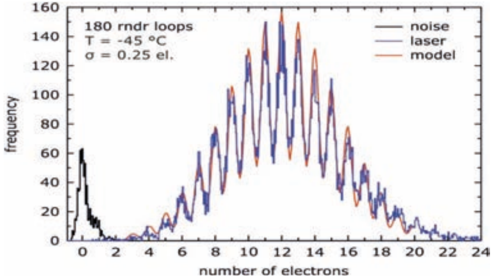

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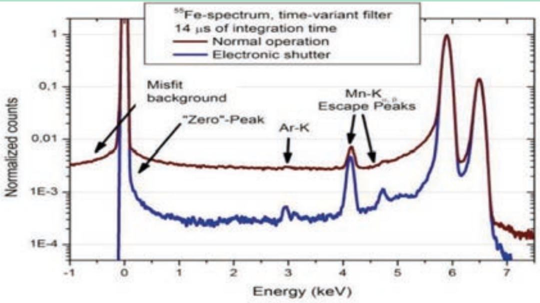

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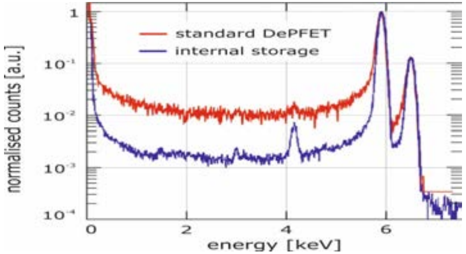
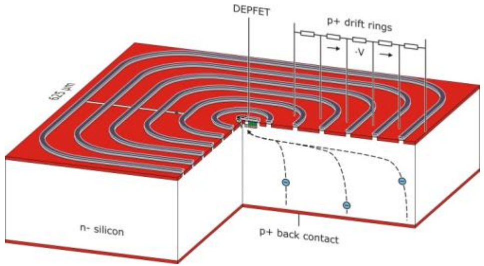


Ongoing and planned improvements

SDD device developments:

- SDDs with DEPFET read out
  - Precision SDD e.g. for **extremely high rate spectroscopy**
  - Ultralow noise device for e.g. for **ultrasoft X-ray spectroscopy**



DEPFET macropixels

- New DEPFET flavors as a first stage amplifier of a SDD device
- an equivalent noise of down to 2 e-
- FWHM @ 5.9 keV 127 eV (singles)
- peak/background ratio 3.000:1
- thin entrance window and thickness 450 µm (0.5-20keV)

pnCCD device developments:

- increase of **charge handling capacity**,
- **high dynamic range**
- **room temperature operation**
- flexibility in the read out – **smart binning**
- addition of **DEFPET readout**
  - Precision CCD with extremely fast readout (Super g_q)
  - Ultra-high dynamic range CCD for e.g. Xray diffraction imaging (non linear DEPFETs)
  - Ultralow noise device with single electron sensitivity with fast readout for e.g. low light level Astronomy (RNDR DEPFET)

What to do in future … tailor sensors to the applications

- Combine building blocks into new device
- Optimizations for specific applications are necessary
- There is no ideal detector for all applications

- Some very attractive devices developed and produced at MPS Semiconductor Laboratory
  SDDs, pnCCDs, DEPFETs …
- Some of the potentials of those devices are used in current projects
- Still space to explore much more …

X-ray and particle spectroscopy
High S/N, high QE, high speed
SDD, pnCCD, DEPFET

Free electron Laser science detectors
huge variety of requirements depending on specific application
SDD, pnCCD, DEPFET, MARTHA

Quantum applications
New devices in HLL portfolio

UV light sources
require fast readout, large-area systems with high QE
pnCCD, DEPFETs, MARTHA devices

Future collider experiments
vertex: fast, precise timing, low material - DEPFET, MARTHA
calorimeter: compact, high dynamic range photo-sensors
MARTHA

Dark matter search
low noise, high radiopurity
SDD, DEPFET, MARTHA

Biomedical imaging
precise imaging, fast, large area
SDD, DEPFET, MARTHA

Optical high-time-resolution astronomy
readout noise reductions
Increased QE
DEPFET, MARTHA

New ideas …