New Developments in Silicon Detectors

(at Max Planck Society Semiconductor Lab)

Jelena Ninkovic

- MPS Semiconductor Lab
- Devices & Selected Applications

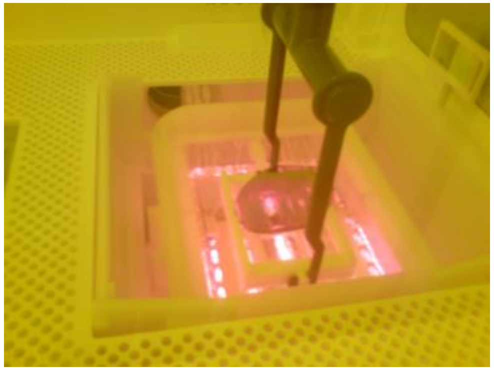
MPS Semiconductor Laboratory (in German: MPG Halbleiterlabor - HLL)

Located in the south-east of Munich on the Siemens Campus in Neuperlach
30 employees: scientists, engineers and technicians
+ guest scientists, engineers and students

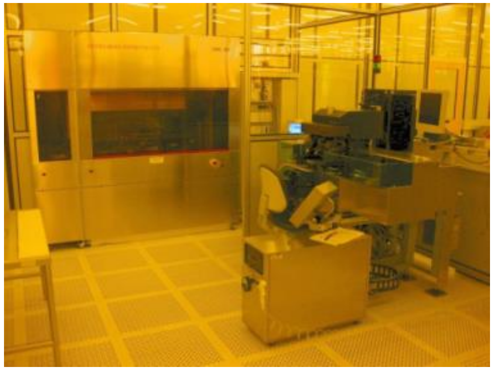
MPG HLL is the only lab worldwide doing fully depleted silicon radiation sensors with integrated electronics optimized for different scientific projects

Inside HLL – Sensor Fabrication

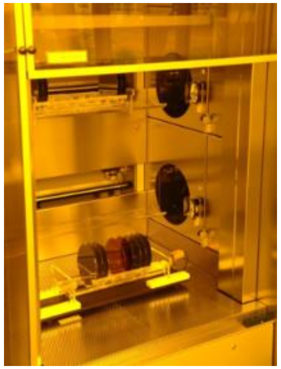
cleaning



lithography

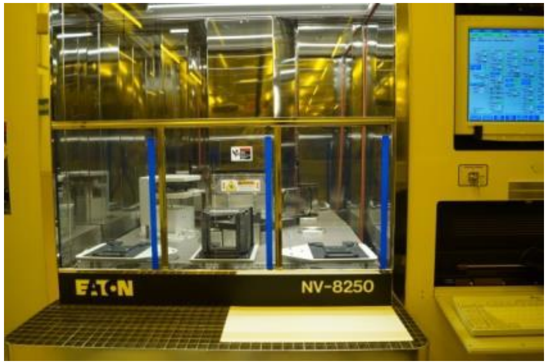


thermal



inspection

implantation



6″ Si full processing line
class 1000 to class 1 in certain areas

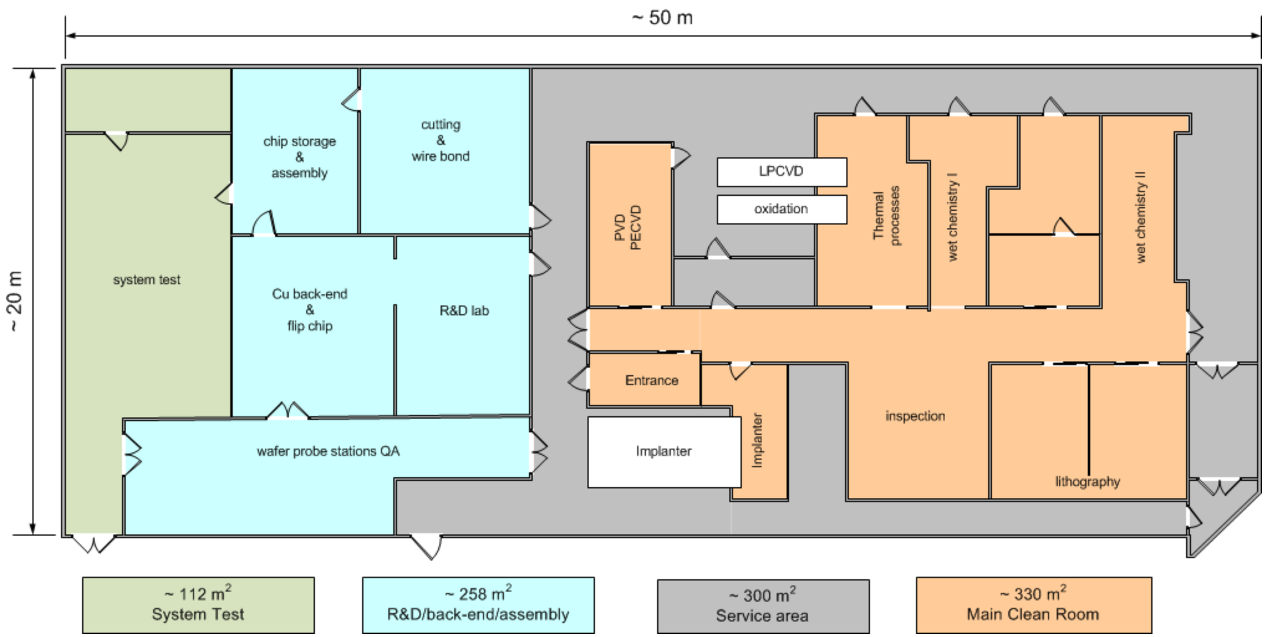
Inside HLL – Sensor Fabrication

plasma and sputter

Cu line

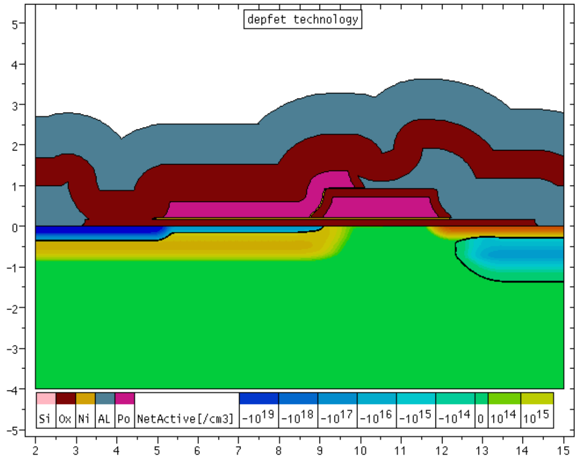
flip chip

assembly and test

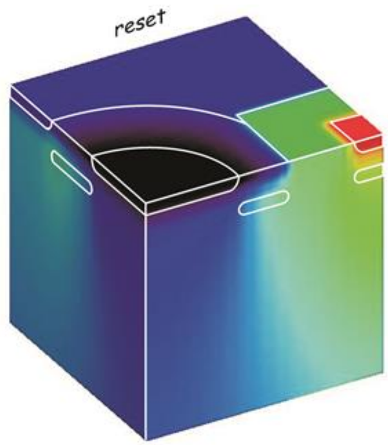


Inside HLL – Sensors and Systems: Design & Test

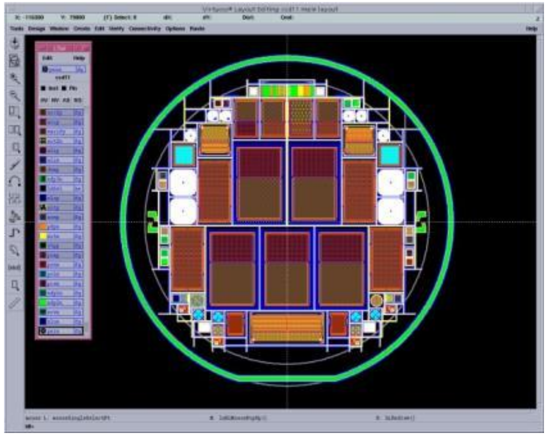
Process simulation



Device simulation, 2D and 3D



State-of-the-art layout tools



Wire bonding, hybrid assembly

@ HLL:

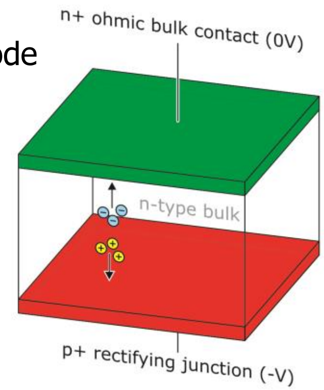
- sensor design and fabrication
- interconnection
- system/camera design and test

System test facilities

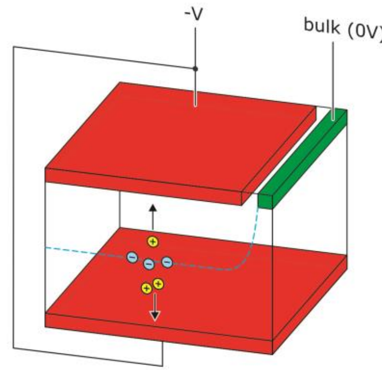
Goal : High SNR

- **Decrease noise**

Diode



Sideward depletion structure

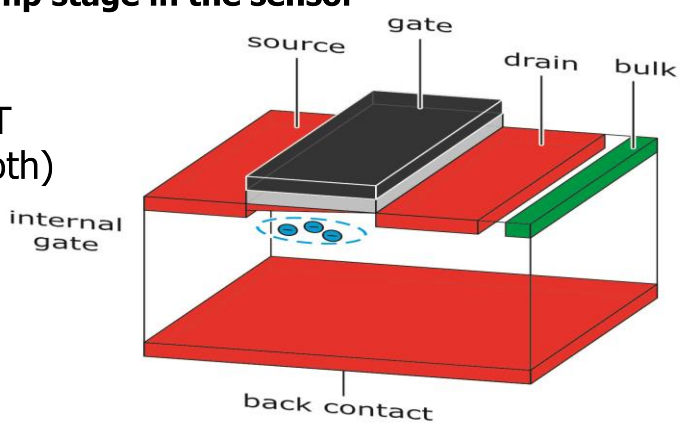


$$ENC = \sqrt{\alpha \frac{2kT}{g_m} C_{tot}^2 A_1 \frac{1}{\tau} + 2\pi a_f C_{tot}^2 A_2 + q I_L A_3 \tau}$$

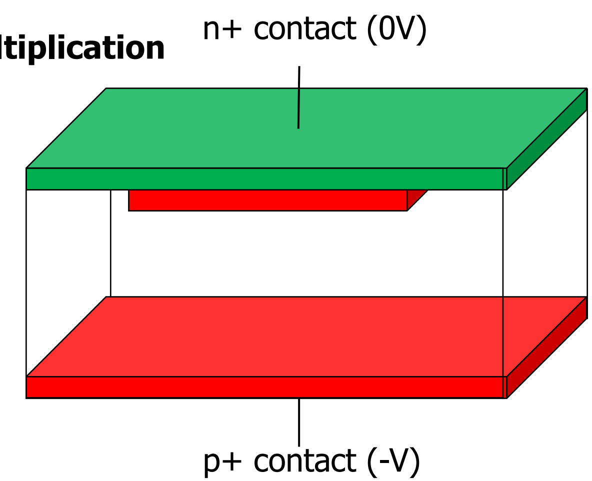
- **Amplify signal**

First Amp stage in the sensor

DEPFET
(has both)



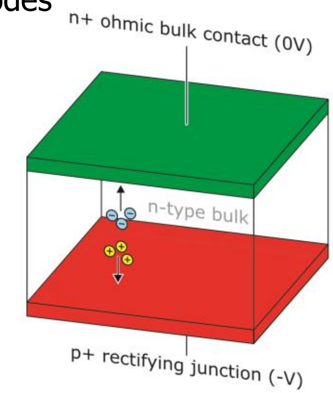
Avalanche multiplication



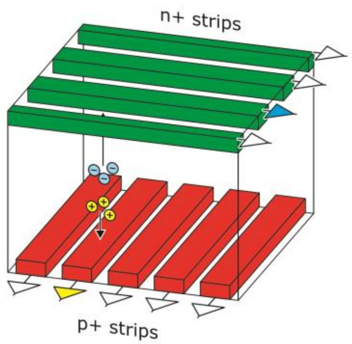
Devices @ HLL

- **Building blocks**

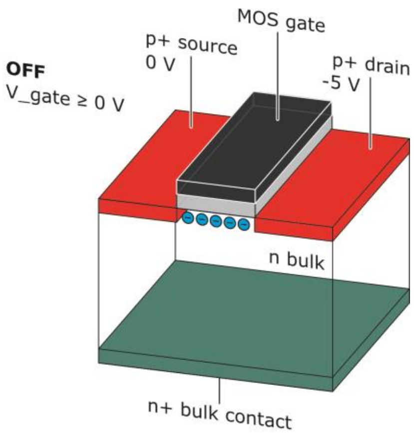
Diodes



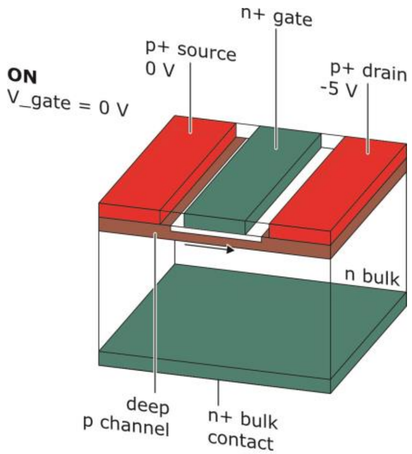
Strip detectors



MOSFETs

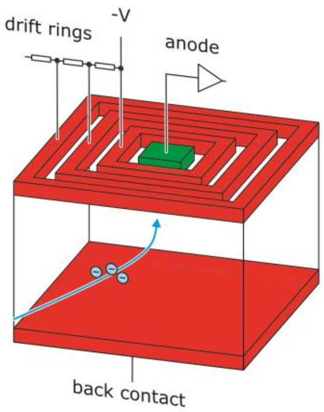


JFETs

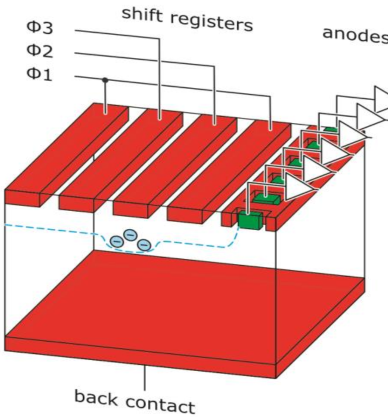


- **Devices**

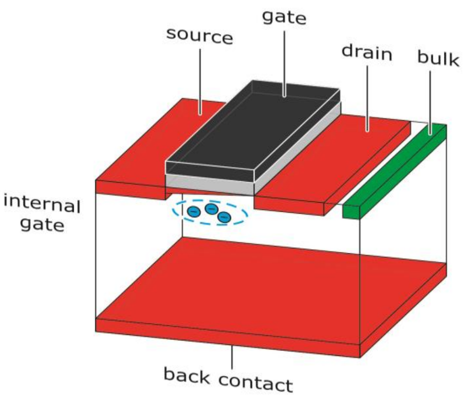
Silicon drift detectors (SDD)



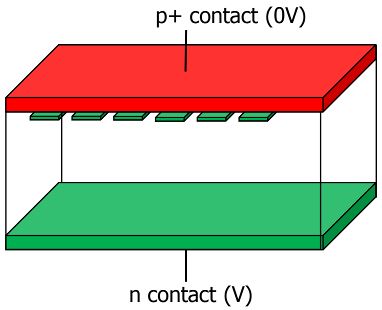
pnCCDs



DEPFETs

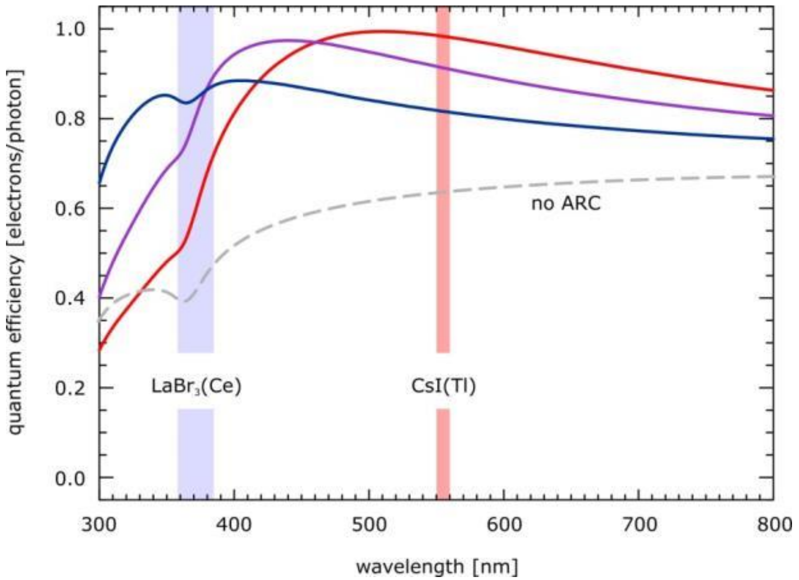


SiMPl

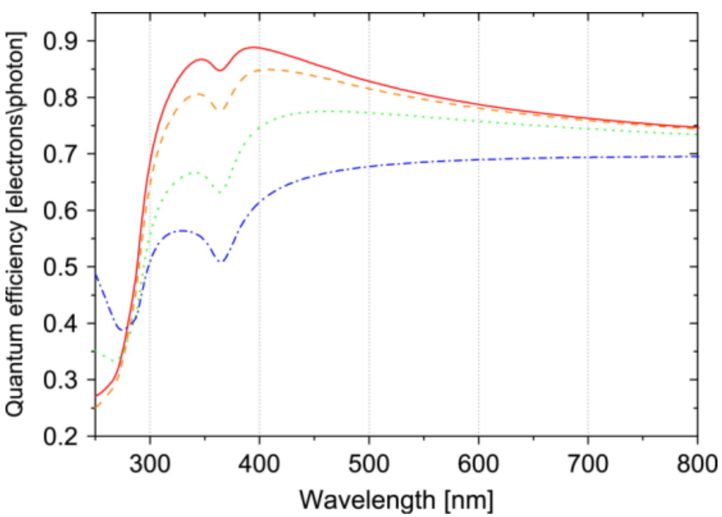


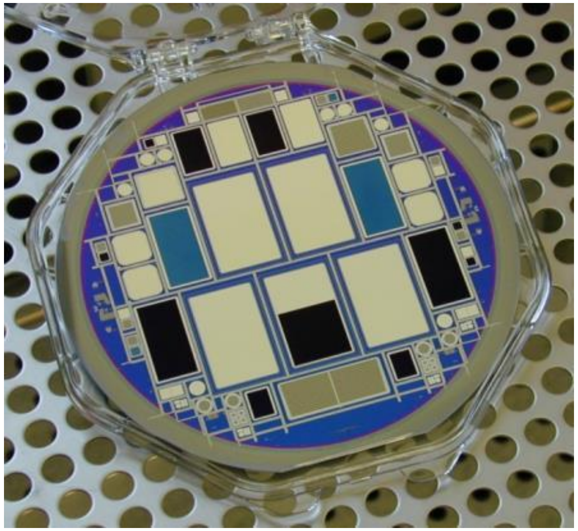
Entrance window engineering – application optimization

- anti-reflective coating (ARC)
  - ▷ sequence of dielectric layers deposited on the entrance window
  - ▷ variation of material and thickness
  - ▷ transmittance tuning to application needs



- polymer passivation
  - ▷ mechanical protection
  - ▷ optical coupling

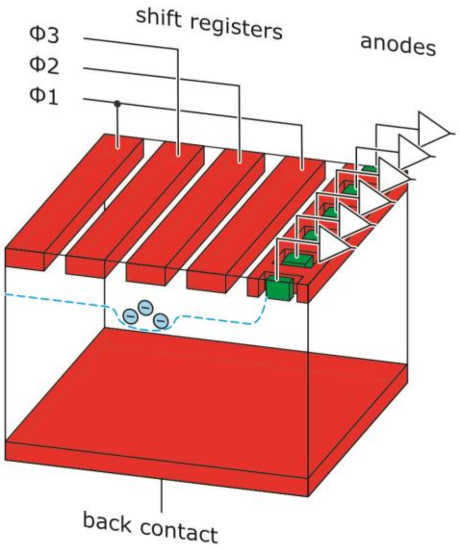




pnCCDs

Proposed by Lothar Strüder et al., 1987

- ▷ 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** (**3el. ENC**)
- ▷ backside illuminated, **fully depleted** → **high quantum efficiency**



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

Applications

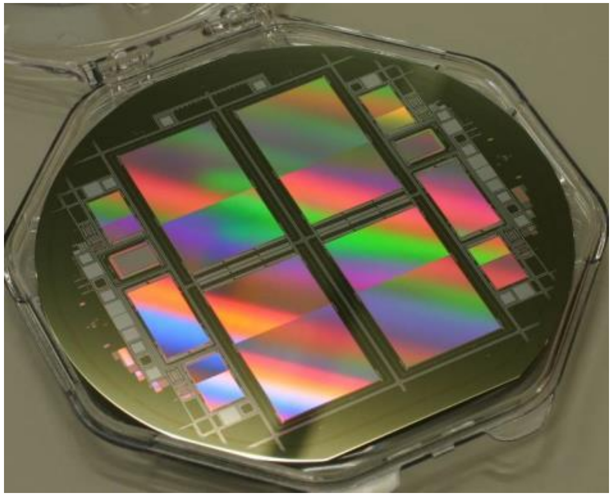
- X-ray imaging & spectroscopy
- optical light imaging

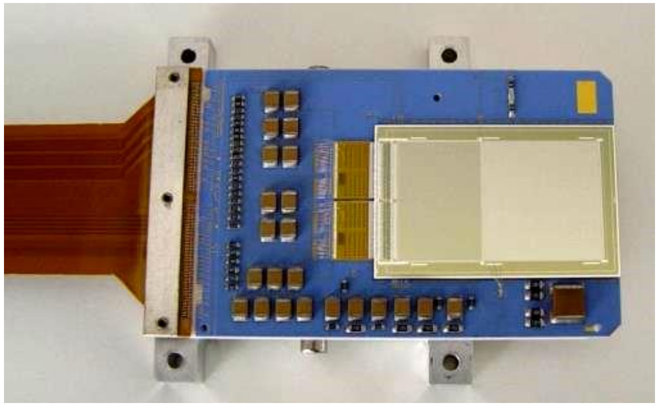
pnCCDs for eROSITA

„ extended ROentgen Survey with an Imaging Telescope Array “

The main scientific goals are:

- map out the large scale structure in the Universe for the study of cosmic structure evolution
- Black Holes in nearby galaxies and many (up to 3 Million) new, distant active galactic nuclei and
- physics of galactic X-ray source populations, like pre-main sequence stars, supernova remnants and X-ray binaries.



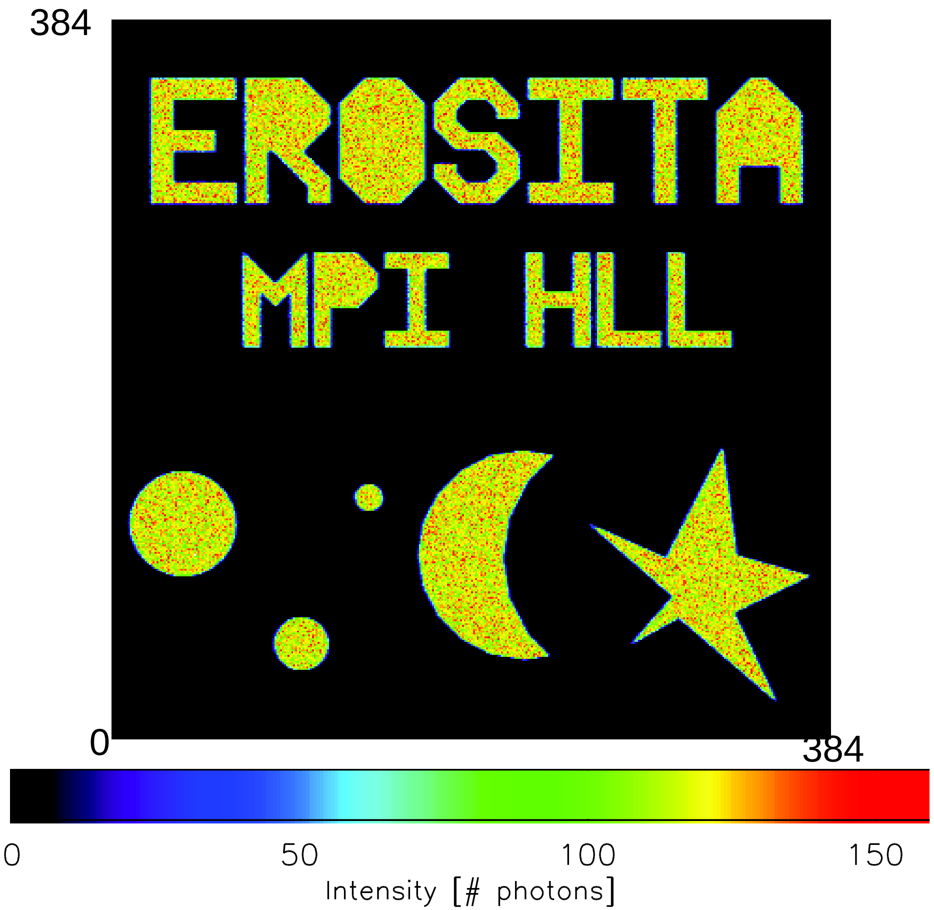


3cm x 3cm pnCCDs still on Si-Wafer.
The pn CCDs have 384 × 384 pixels in both image and frame store area.

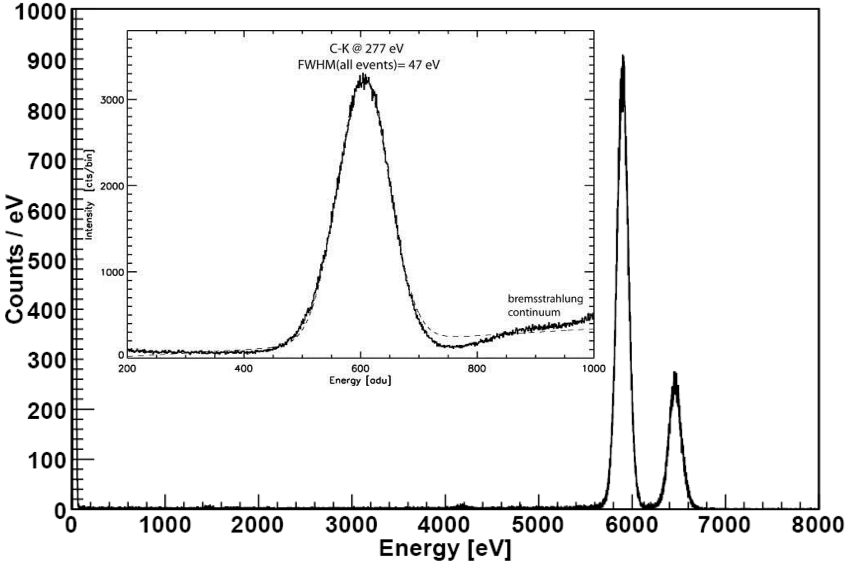
Pixel size: 75 x 75 µm^2.
Frame time: 50 msec (20Hz)

(collaboration partner MP Extraterrestrial Physics)

eROSITA pnCCD-Module



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



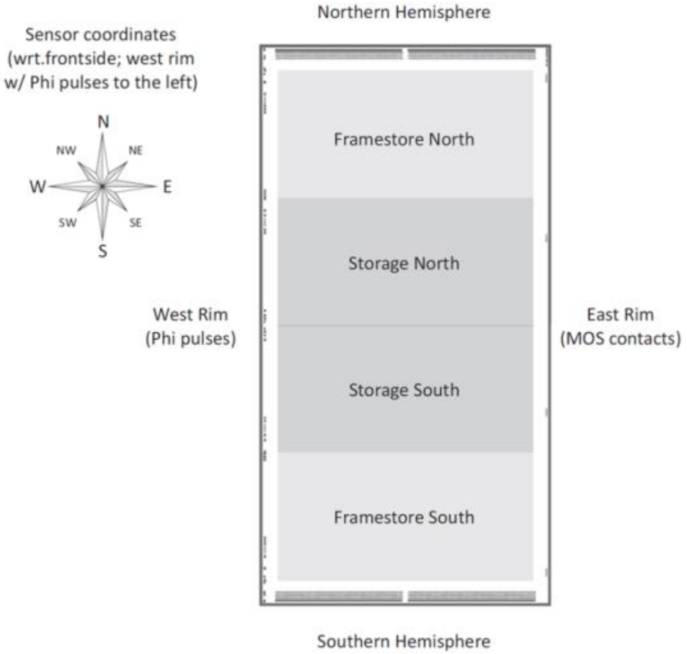
Measurements at C Ka (277eV) and Mn Ka (5,9 keV) on flight- CCDs (2cm × 2cm) show the expected energy resolution and low energy response.

Small pixel pnCCD @ HLL

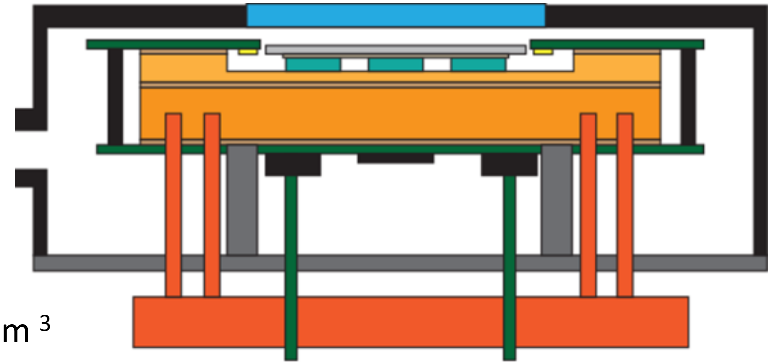
Motivation: development of a sensor for Fast Solar polarimetry (collaboration partner MP Solar System Research)

Device characteristics:

- pnCCD concept:
  - Backside illuminated,
  - frame store,
  - split frame,
  - column-parallel readout
- Format: **1k x 1k** storage, 2 x 1 k x 0.5 k framestore
- Pixel size: **36 x 36** μm^2
- Total sensitive area: 36.8 x 73.3 mm^2
- Total chip size: 4.2 x 8.1 cm^2
- Optimized for **optical wavelength** using ARC
- Operating temperature: -35°C (target)
- Target operating frame rate: **400 Hz** (~4 μs /row)
- Data rate: 840 Mbyte / s (16 bit)



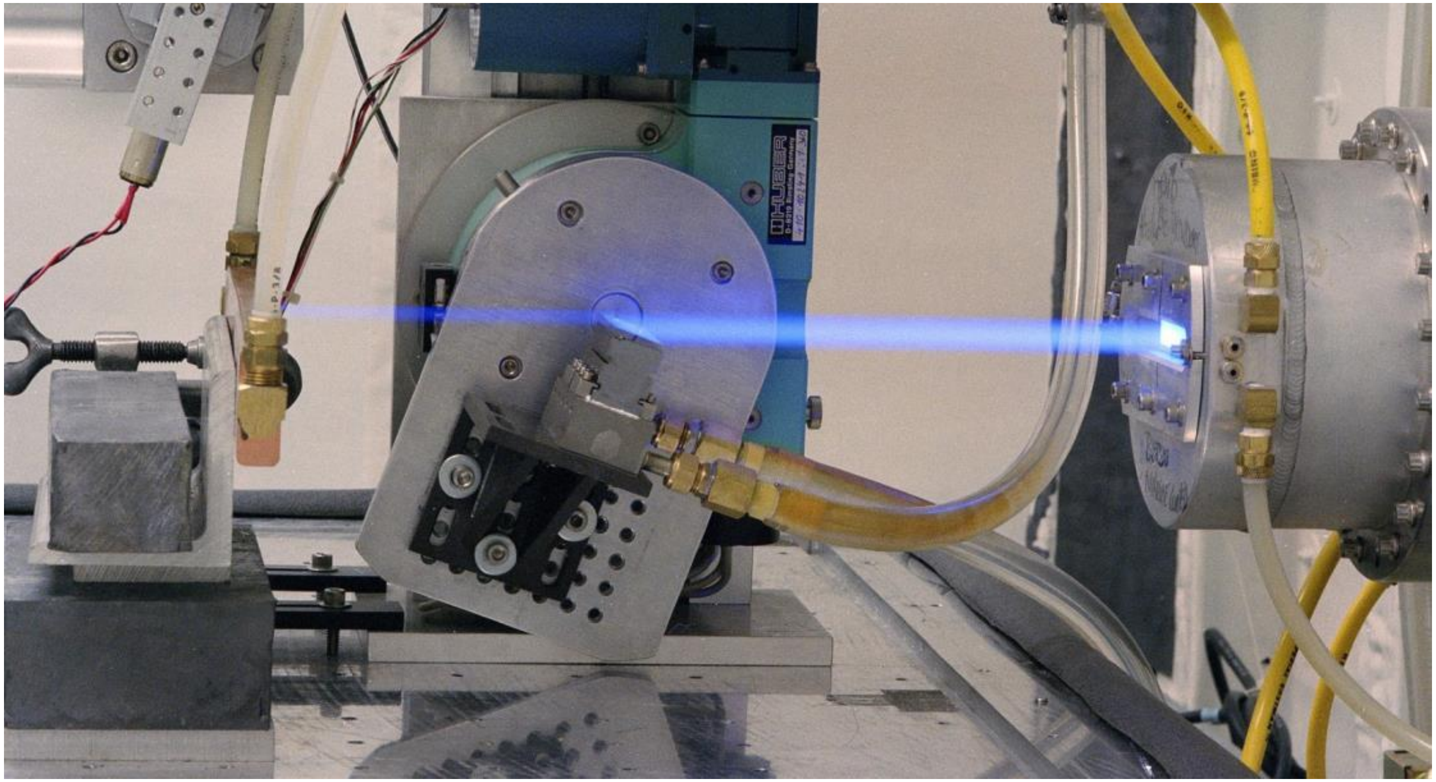
Frame store, split frame, column parallel readout pnCCD



Compact vacuum-tight camera housing ~ 18 x 25 x 10cm ^{3}

FEL radiation detection

- Sensors for LCLS (collaboration partner MP Extraterrestrial Physics)



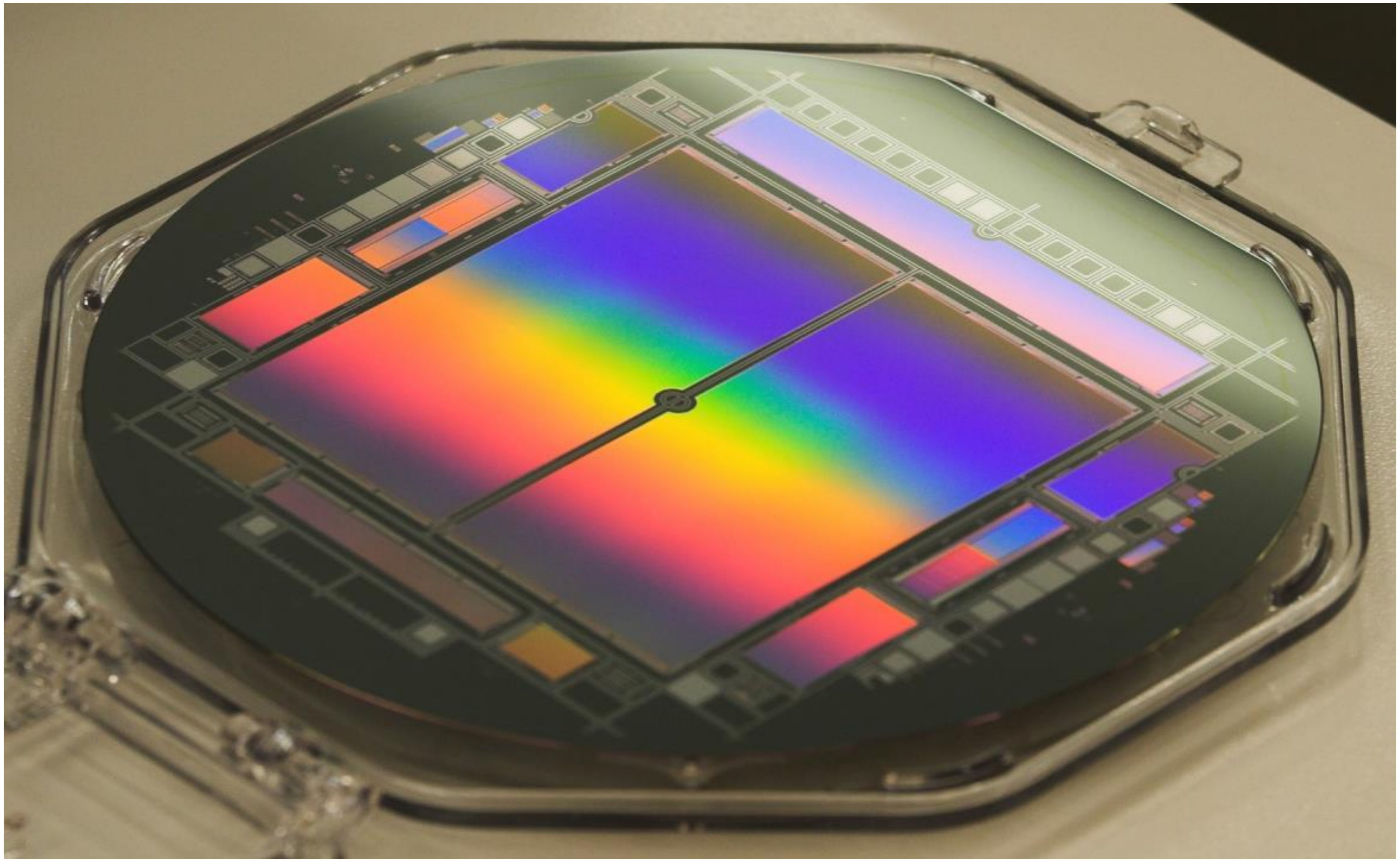
Synchrotron light from the National Synchrotron Light Source (NSLS), Brookhaven

Requirements in FEL radiation applications

Requirements of the LCLS

	LCLS	pnCCD
single photon resolution	yes	yes
energy range	0.05 < E < 24 (keV)	**0.05 < E < 25 [keV]**
pixel size (µm)	100	75 (150)
sig.rate/pixel/bunch	10^3 (10^5)	10^4
quantum efficiency	> 0.8	**> 0.8 from 0.3 to 12 keV**
number of pixels	512 x 512 (min.)	**1024 x 1024**
frame rate/repetition rate	10 Hz - 120 Hz	**up to 250 Hz**
Readout noise	< 150 e^- (rms)	**< 30 e^- (rms) (2 e^- possible)**
cooling	possible	- 20° C optimum room temperature possible
vacuum compatibility	yes	yes
preprocessing	no (yes) ?	possible upon request

Large area pnCCDs



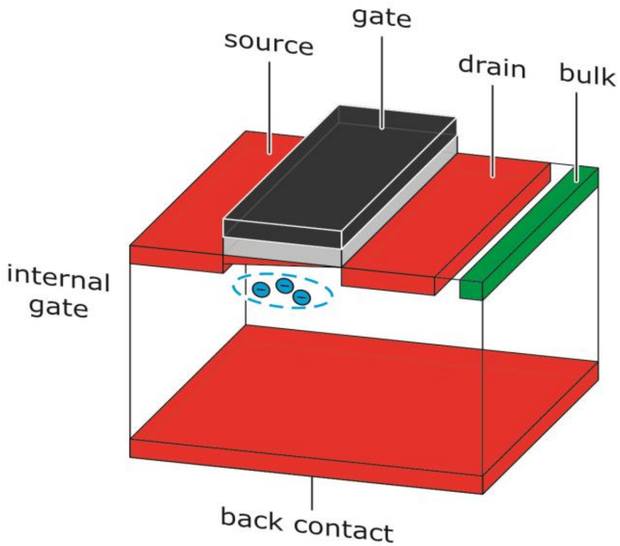
- ▷ Large area pnCCDs: 30 cm^2
- ▷ 1024 x 512 pixel of 75 x 75 μm^2
- ▷ 3.7 x 7.8 cm^2

DEPFETs

Proposed by
Josef Kemmer &
Gerhard Lutz, 1987

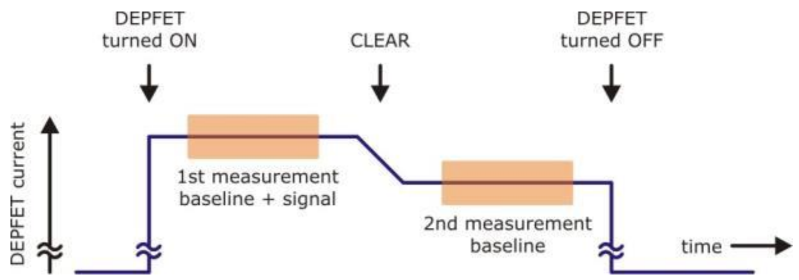
p-MOSFET on fully depleted n-substrate

- **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 (300 pA/el.)
  - large signal, even for thin devices
  - r/o cap. independent of sensor thickness (20 fF)

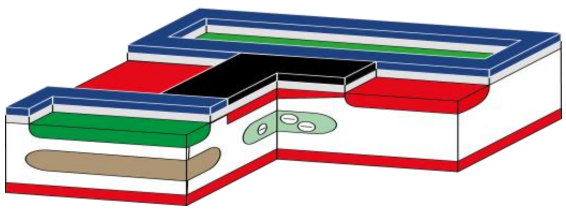


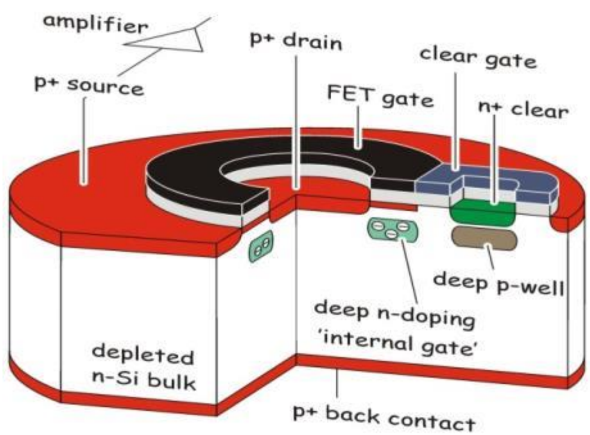
Applications:

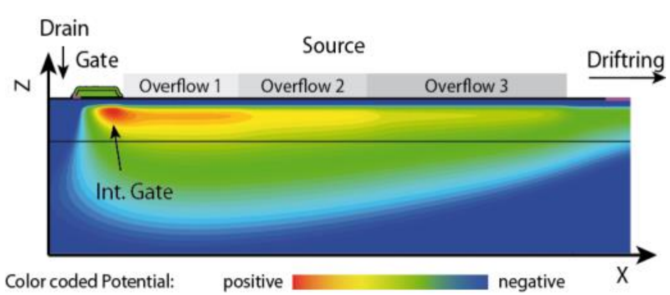
- unit cell of active pixel sensor
- integrated readout device of SDD, pnCCD, …



DEPFET classes







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: 50µm…75µm → still large signal: 40nA/µm for MIP

Low noise: Spectroscopic X-Ray imaging

pixel size: 100µm, with drift rings several 100s of µm
read out time per row: few µs
Noise: ≈4 el ENC
fully depleted, the thicker the better → large QE for higher E

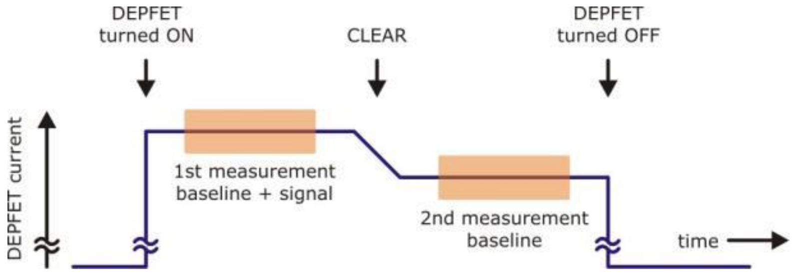
High Dynamic range

DEPFET **S**ensor with **S**ignal **C**ompression
Sensitivity to single photons and high dynamic range
pixel size: ~200 µm
hybrid sensor : 1-to-1 bonded to readout chip

DEPFET detectors

DEPFET readout

▷ readout sequence



➢ Double sampling

- 1st measurement: signal + baseline
- clear: removal of signal charges
- 2nd measurement: baseline
- difference = signal

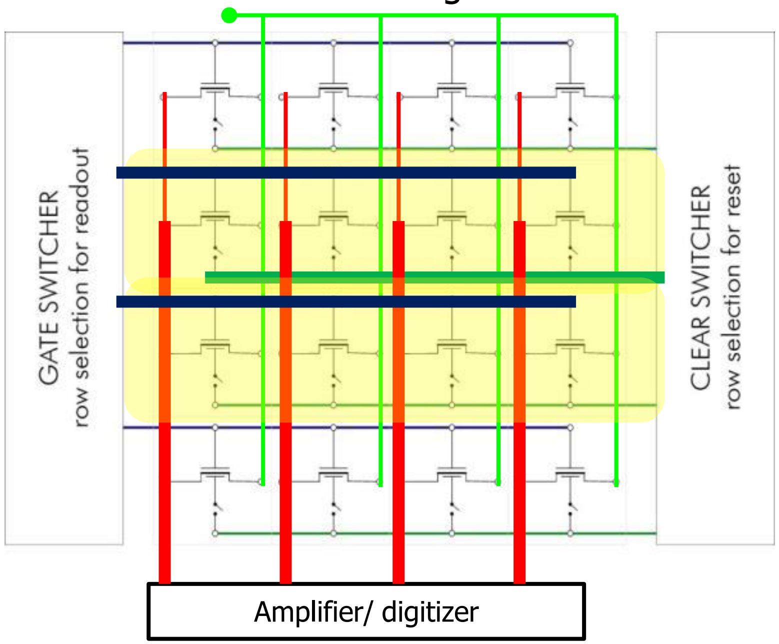
➢ Single sampling

- Measure pedestals and store
- Read once and clear

▷ active pixel sensor operation

- horizontal supply lines, row selection
- vertical signal lines
- 1 active row, other pixels integrating

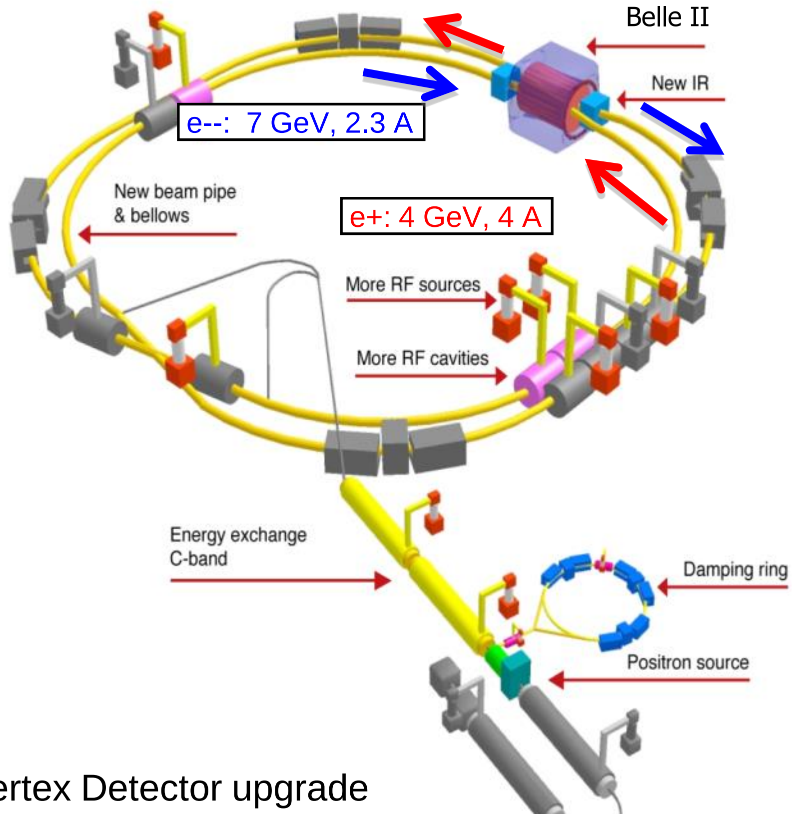
Rolling shutter read out



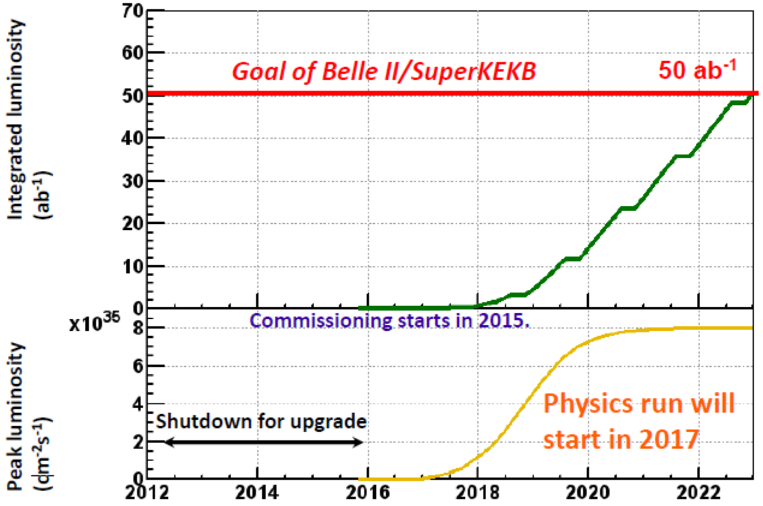
Projects using DEPFETs developed and fabricated @ MPG HLL

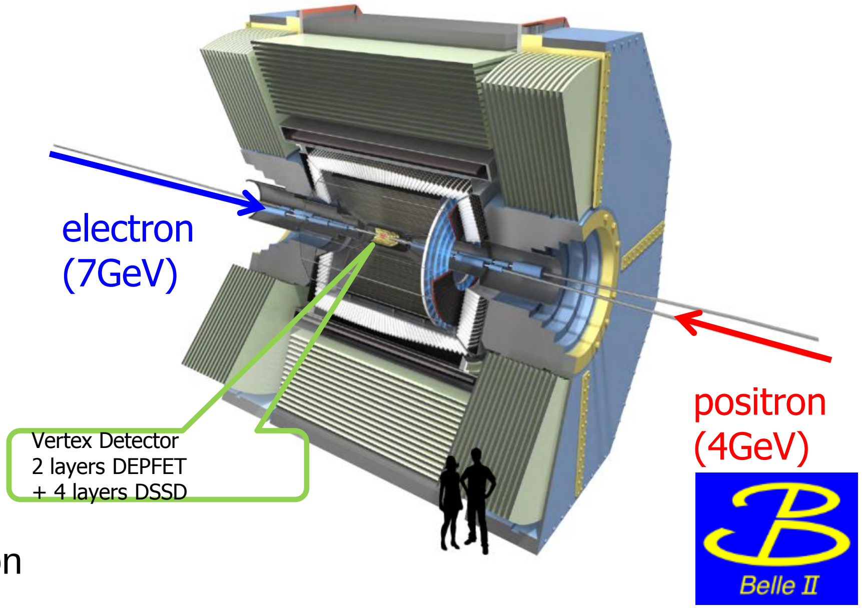
- Vertex detectors for high energy physics experiments
- X-ray fluorescence spectrometer for MIXS on BepiColombo
- X-ray imaging spectroscopy - ATHENA mission – Wide Field Imager (WFI)
- FEL radiation detection – sensors for European XFEL
- Electron Detectors - 80k low E electron detectors

BELLE II @ SuperKEKB

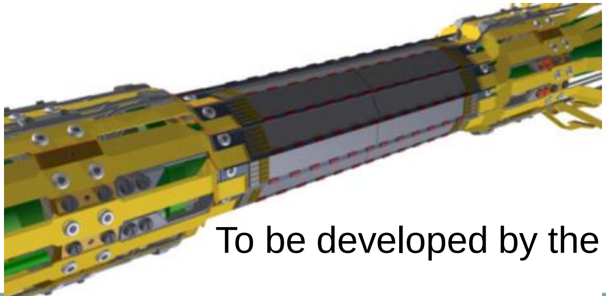


SuperKEKB luminosity projection





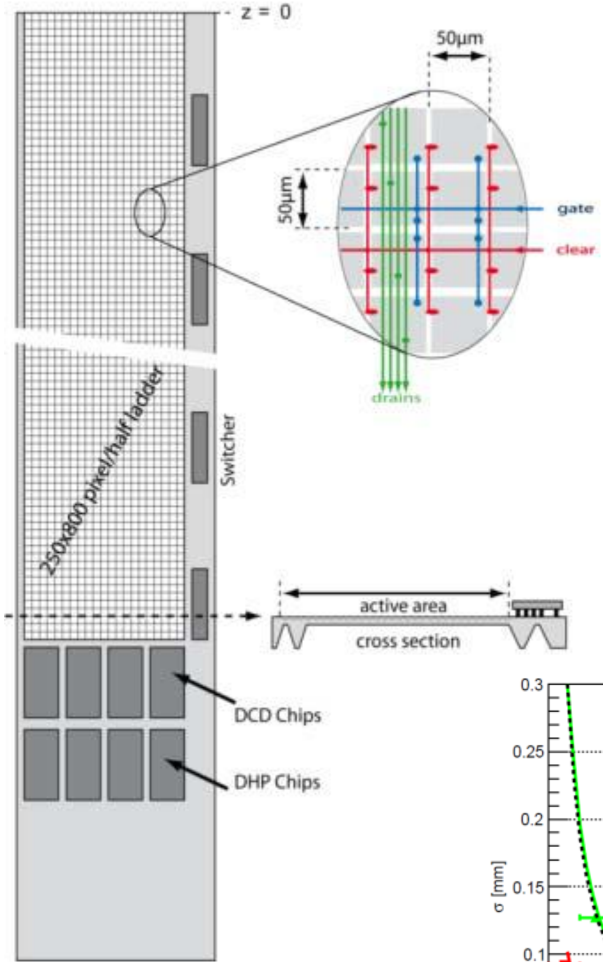
Vertex Detector upgrade
DEPFETs are chosen for the inner layers



To be developed by the DEPFET collaboration

DEPFETs for BELLE II vertexing - Module

All silicon module

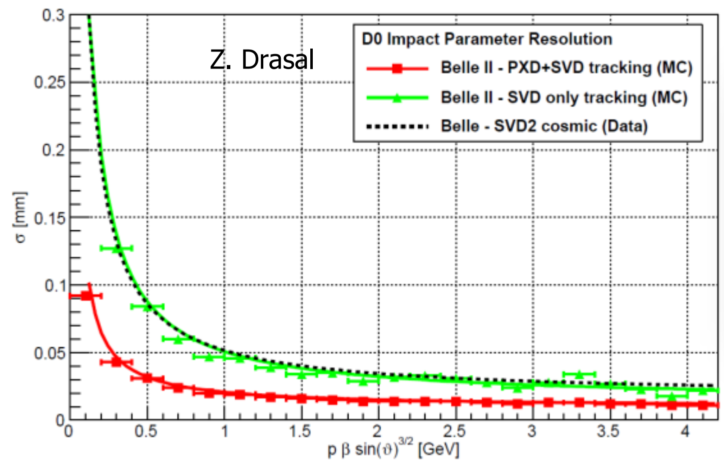


DCDB & SWB developed by UNI Heide
DHP developed by UNI Bonn

Requirements:

- Single point resolution **~10 µm**
- Radiation **~20 Mrad (10 years)**
- Material budget **0.2 % X_0/layer**
- Frame time **20 µs**

	Inner layer	**Outer layer**
# ladders	8	12
Sens. length	90mm	123mm
Radius	1.4cm	2.2cm
Pixel size	50x50 µm2	50x75 µm2
# pixels	1600(z)x250(R-ϕ)	
Thickness	**75 µm**	
Frame/row rate	50 kHz/10 MHz	

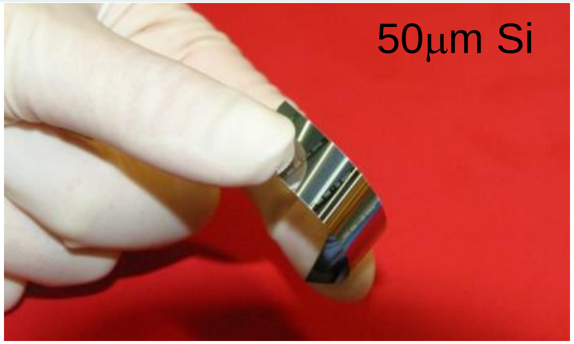


Low mass vertex detectors

MCMs with highest possible **integration!**

↳ Thin sensor area
↳ EOS for r/o ASICs
↳ Thin (perforated) frame with steering ASICs

Thin DEPFETs for BELLE II PXD



Thin (50µm-75µm) self-supporting all silicon module

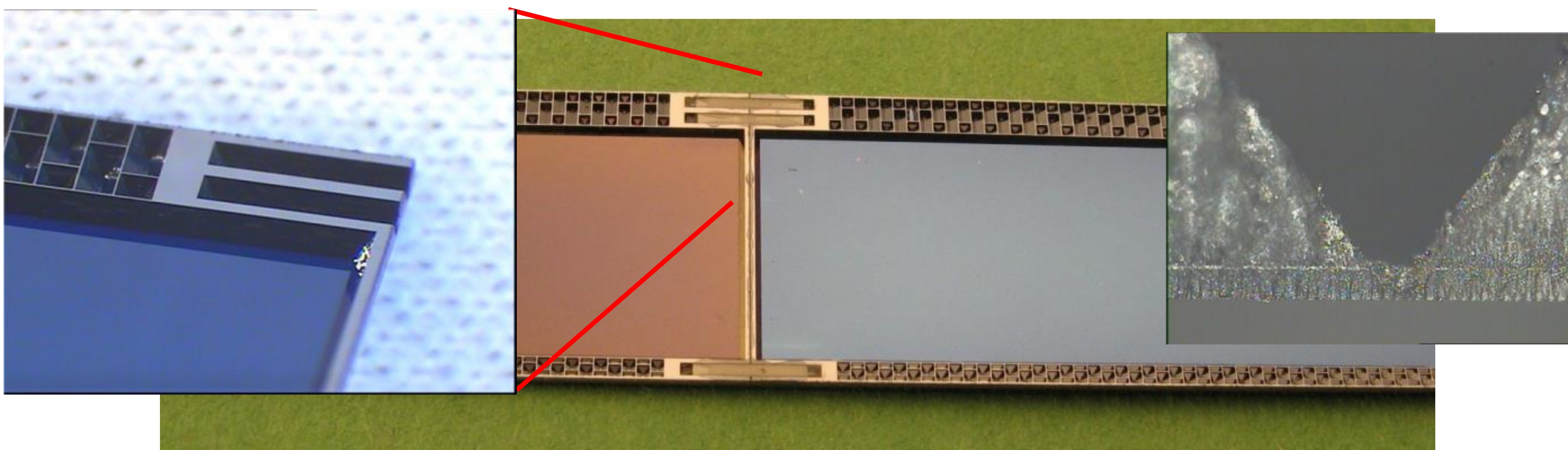
Process backside e.g. structured implant

Wafer bonding SOI process

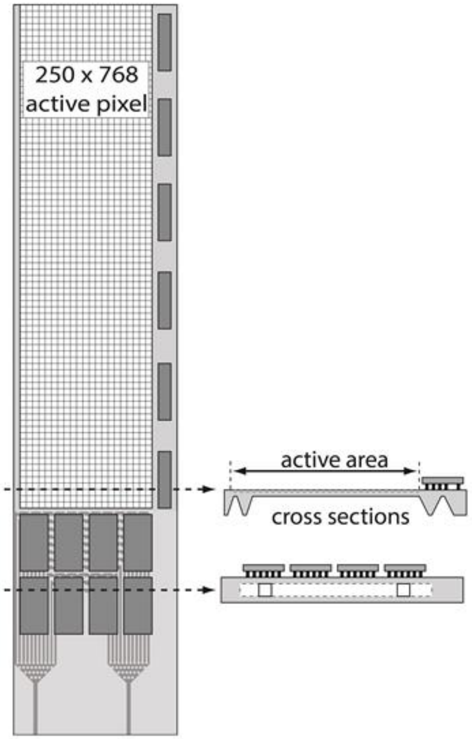
Thinning of top wafer (CMP)

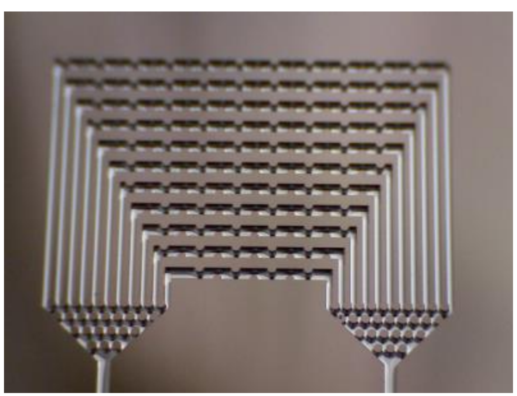
Processing

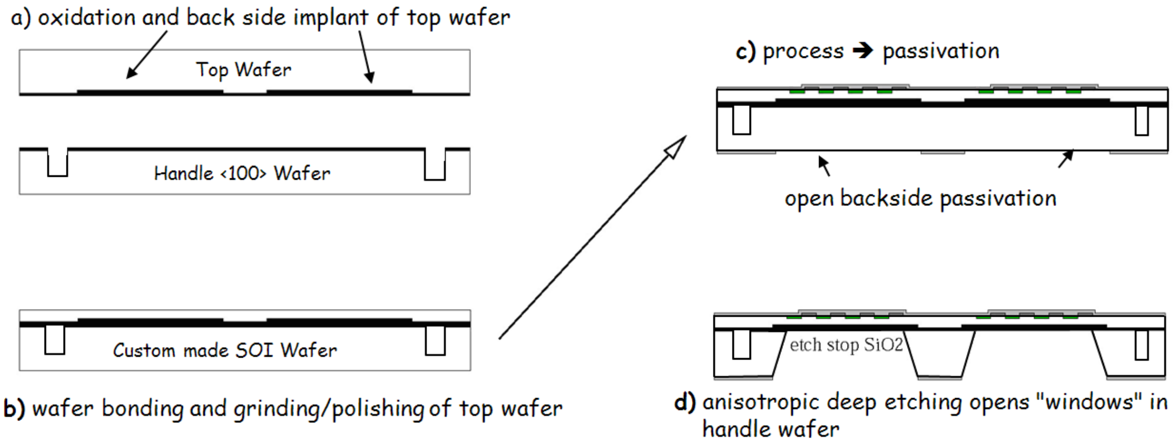
etching of handle wafer (structured)



Future all silicon modules - Integrated micro-channels







The SOI approach: thinned all-silicon module with integ. cooling

- most heat generated by read-out ASICs
- idea: integrate channels into handle wafer beneath the ASICs
- make use of the thick handle wafer at the end-of-module
- channels etched before wafer bonding → cavity SOI (C-SOI)
- full processing on C-SOI, thinning of sensitive area
- micro-channels accessible only after cutting (laser)

X-ray fluorescence spectroscopy: MIXS on BepiColombo

MIXS - First Imaging X-ray spectrometer for planetary X-ray fluorescence

- is the first planetary XRF instrument using a high performance imaging optics, not just a collimator.

Much better spatial resolution!
Look inside craters, identify more features!

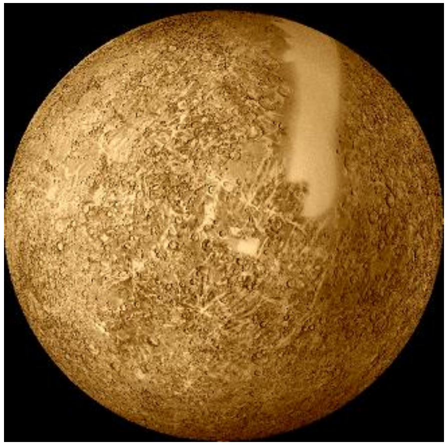
- is the first planetary XRF instrument using an energy dispersive solid-state detector

with excellent energy resolution and low energy threshold.
Allows to observe the important lines of Iron, Silicon, Magnesium etc. directly!

(collaboration partner MP Solar System Research)

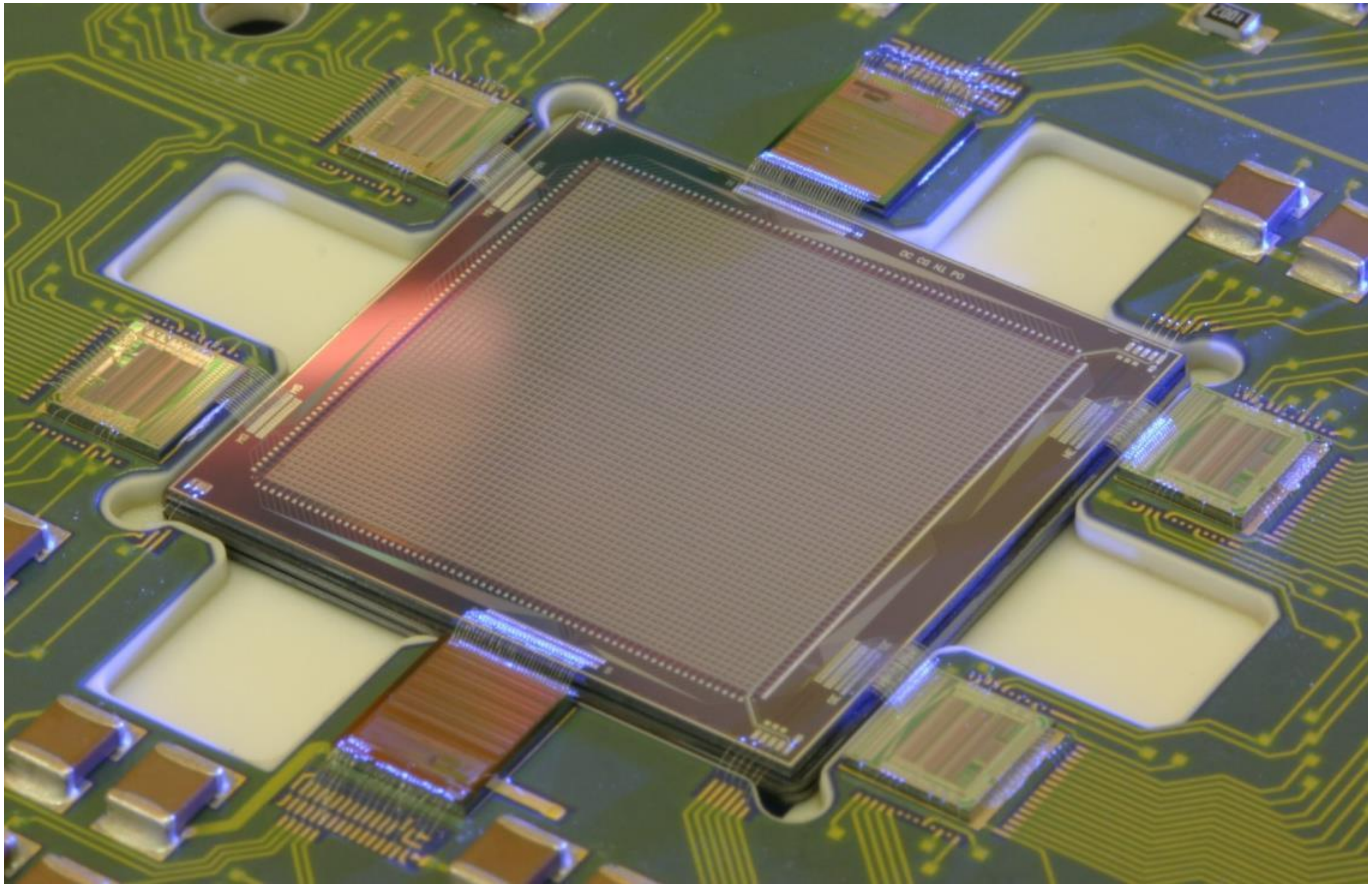
DEPFET Macropixel Matrix

- Format
  - **1.92 x 1.92** cm^2
  - **64 x 64** pixels
  - **300 x 300 μm^2** pixel size
- Energy resolution
  - **200 eV FWHM @ 1 keV**
  - QE > of 80 % @ 500 eV
- Time resolution
  - **< 1 ms** due to dynamics
- Radiation hardness
  - ~ 20 krad ionizing
  - 3×10^{10} 10 MeV p/cm^2
  - **equivalent to** 1.11×10^{11} 1 MeV n/cm^2

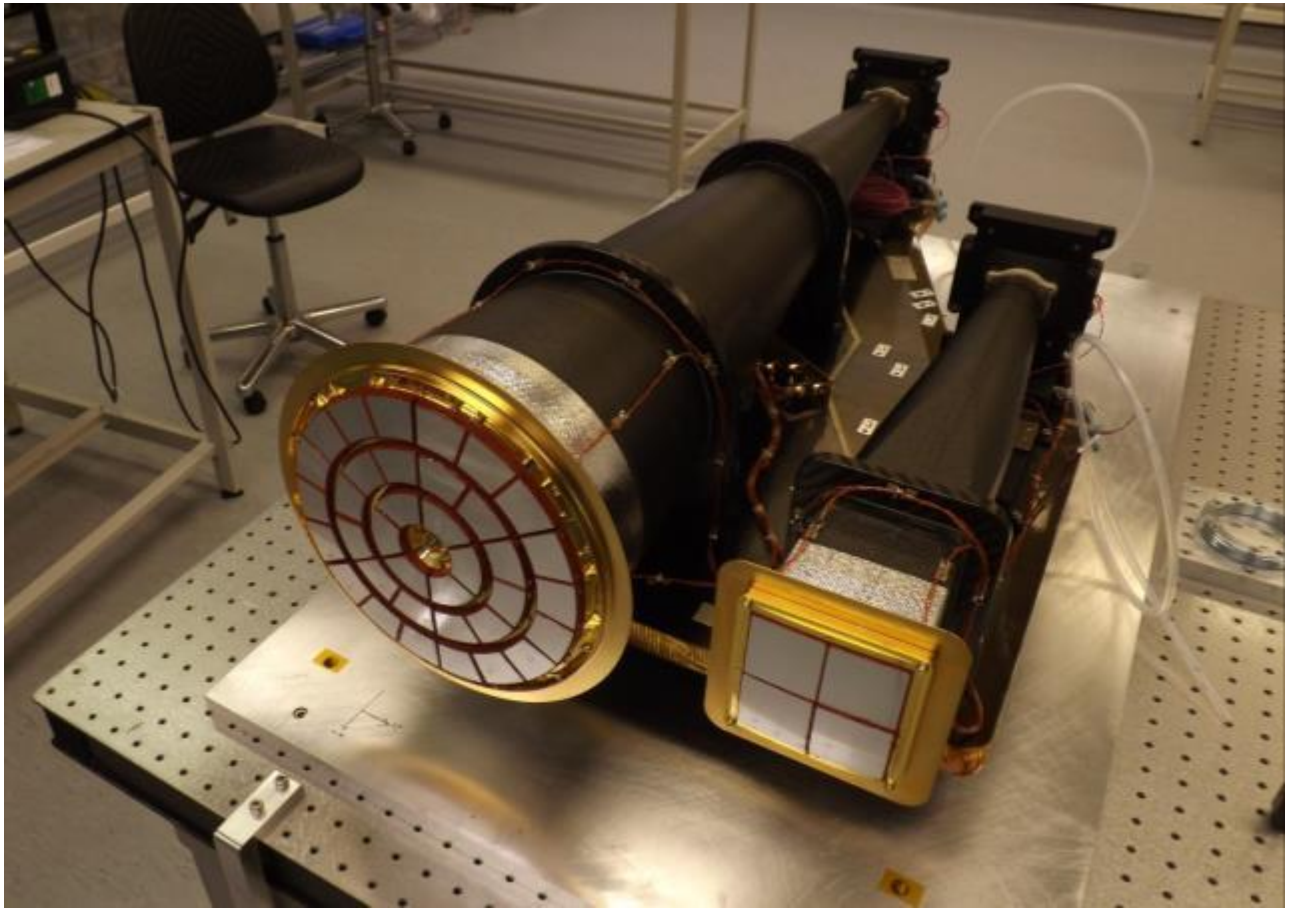


Mercury surface as seem by Mariner 10

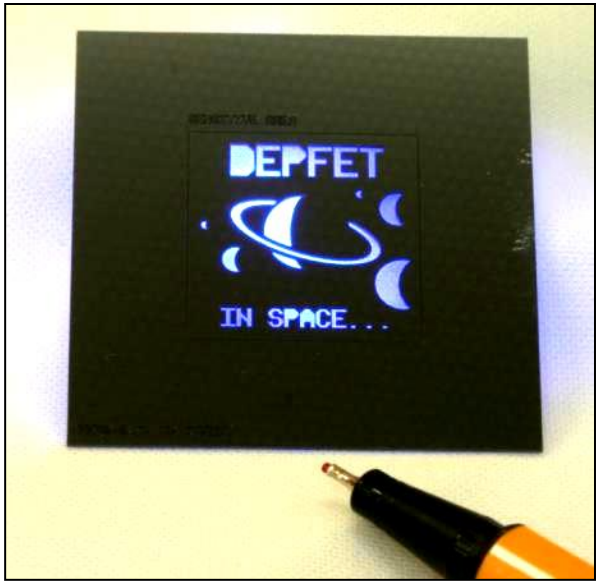
MIXS hybrid

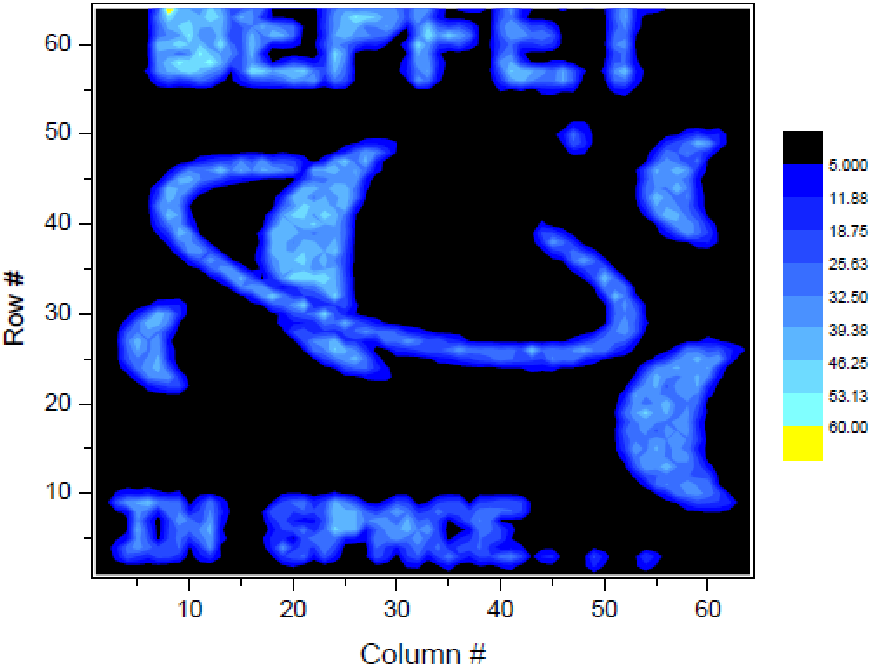


Fully assembled Qualification Model



Measurements

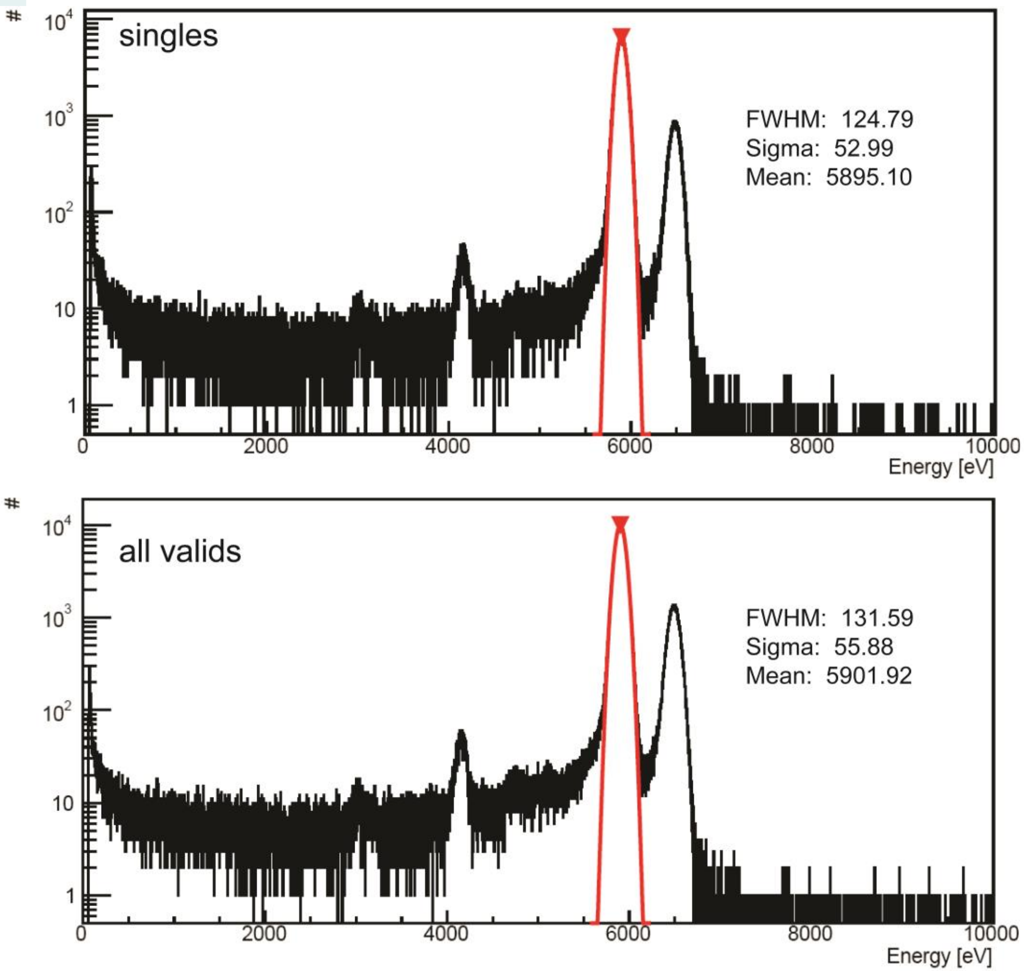


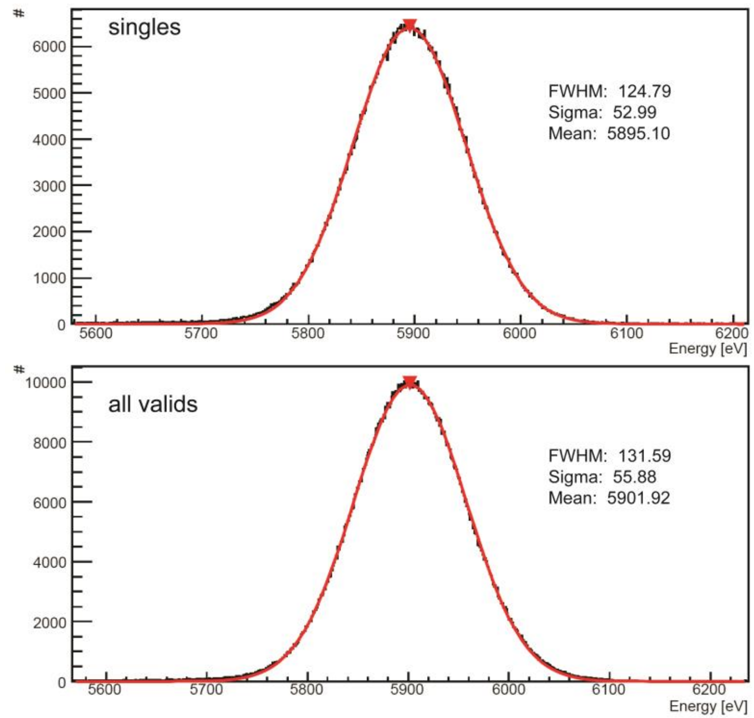


- **Operating conditions**
  - -40 °C
  - T_{row} = 5.2 µs
  - T_{frame} = 167 µs / frame
  - Framerate ~ 6 kfps
  - I_{pixel} = 125 µA

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

Spectral performance



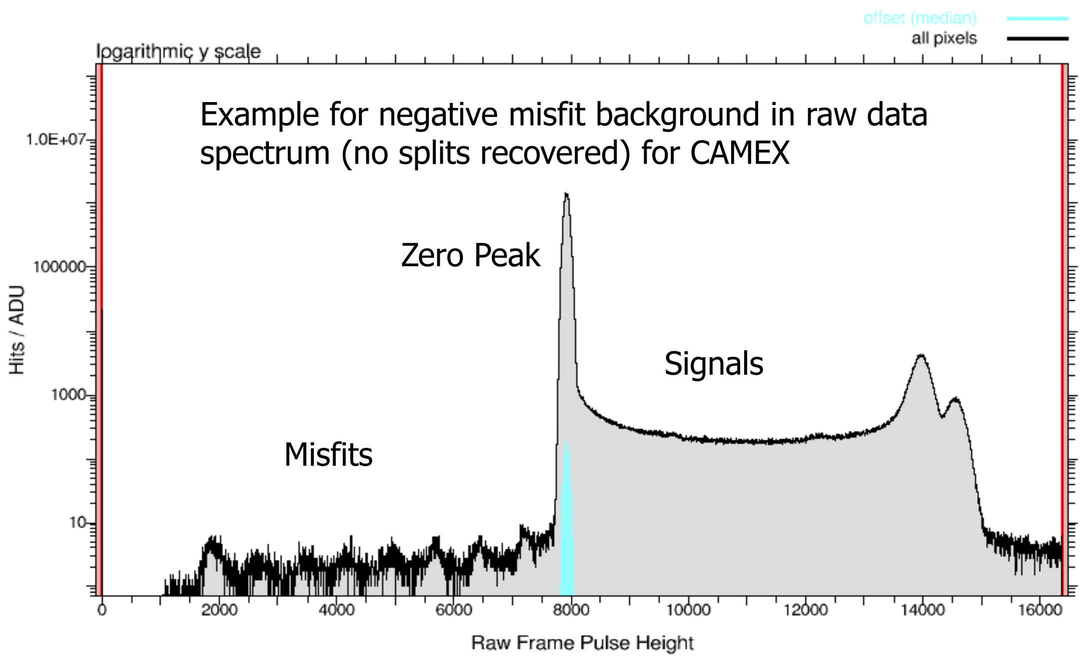


- ^{55}Fe source
- singles: FWHM = 124.8 eV @ 5.9keV
- T ~ -85°C
- 415 µs/frame

Misfits

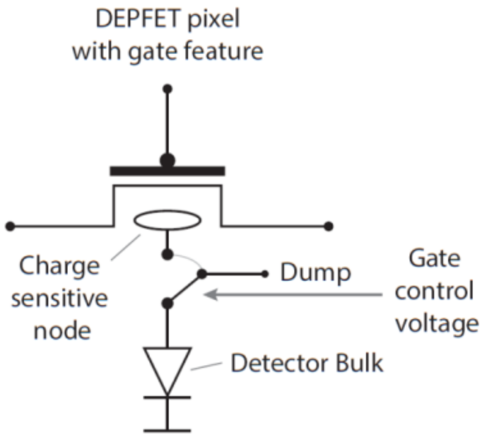
- Events arriving during signal processing time cause “negative” and “positive” background in signal (Misfits)
- Negative signals are easy to be tagged
- Positive signals cause irreducible background
- Spectral shape corresponds to the negative misfit background mirrored at the zero peak

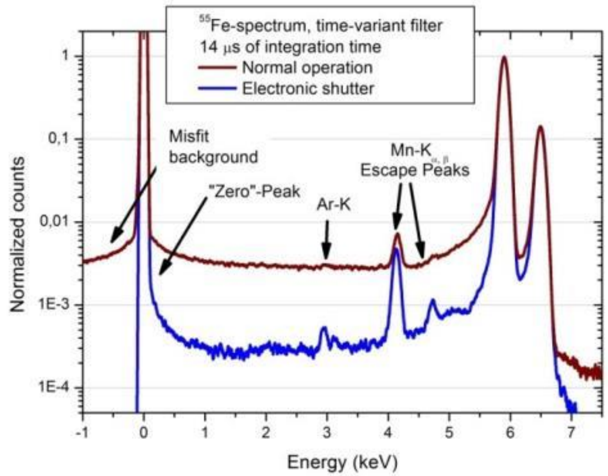
- Fraction of misfits only depends on ratio between readout time and integration time
- Worse for higher degree of parallelization
- Worst case is fully parallel readout (hybrid pixel sensor)
- How to avoid?



Solutions for Misfits

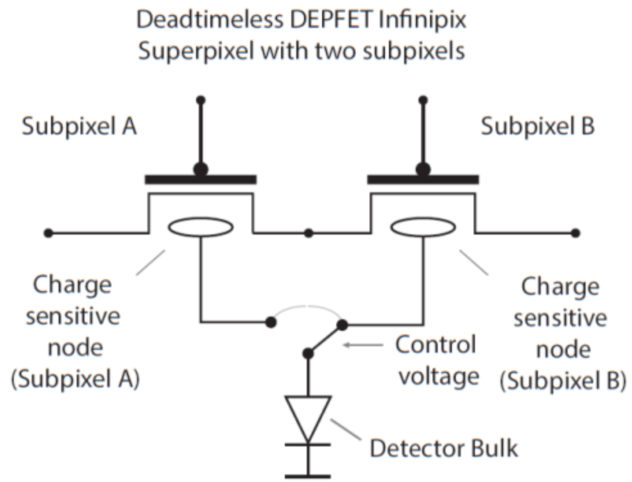
Gated PIX (GPIX)





- Very effective!
- **Drawback: Deadtime!**

InfiniPIX



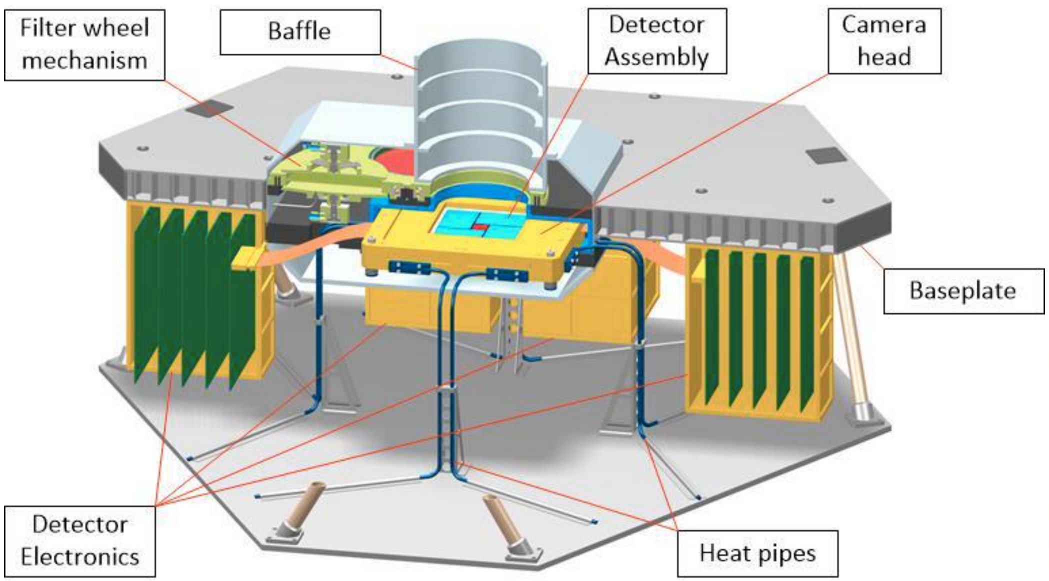
- Superpixel composed of two subpixels
- One subpixel is sensitive. i.e. collects charge from bulk
- The second one is insensitive, i.e. keeps charge already collected, but no new charge will be added, as it is collected by sensitive subpixel
- Only insensitive pixel can be read out
- Shielding is achieved by deviating potentials
- Most simple solution: switching the drain potentials of subpixels

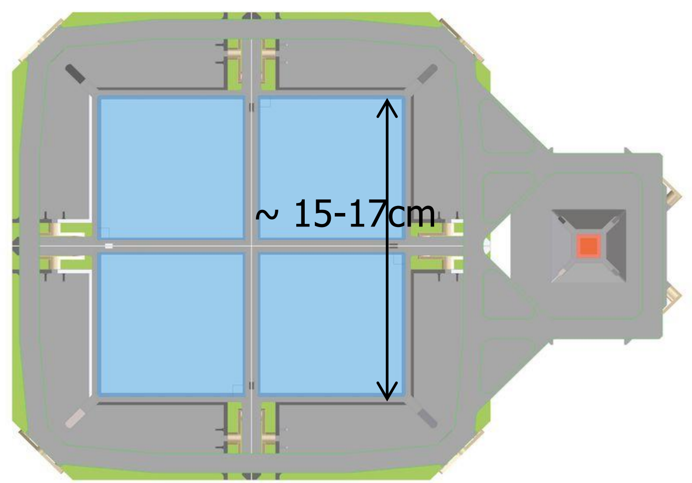
ATHENA mission – Wide Field Imager (WFI)

Athena (the Advanced Telescope for High-Energy Astrophysics), has been proposed as ESA's next-generation X-ray astronomy observatory (Launch slot 2028).
To address two key questions in modern astrophysics:

- How does ordinary matter form the large-scale structures that we see today?
- How do black holes grow and shape the Universe?

(collaboration partner
MP Extraterrestrial Physics)

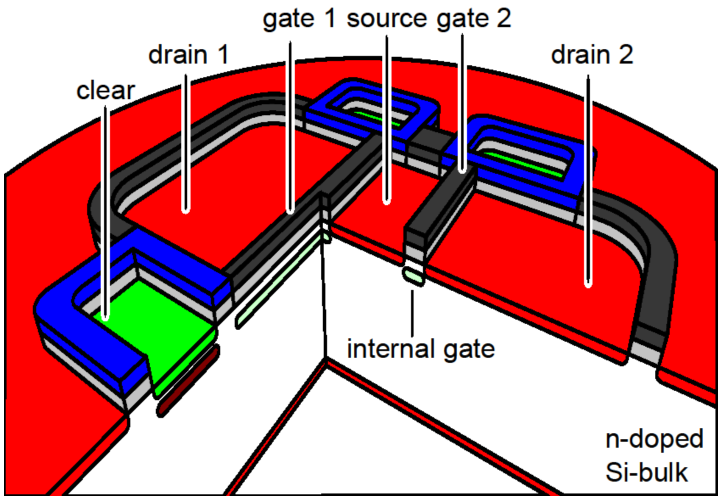




ATHENA mission – Wide Field Imager (WFI)

Central chip: fast timing and high count rate capability

Idea: use infinipix like DEPFET matrix



First prototypes Infinipix DEPFET

->shutter speed < 200ns

->charge suppression < $5*10^{-4}$

->charge handling ≈23500e (≈85keV)

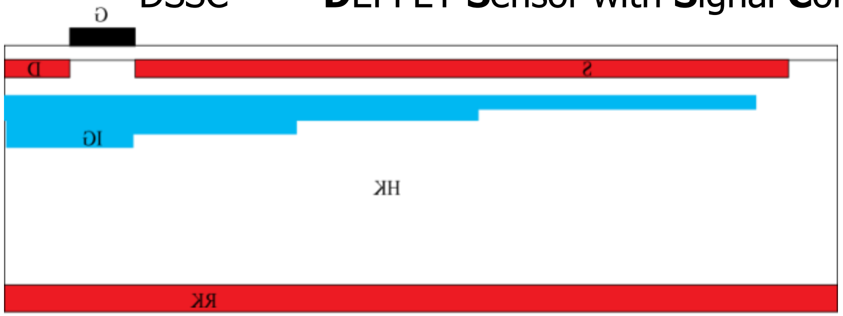
Requirements for the XFEL detectors

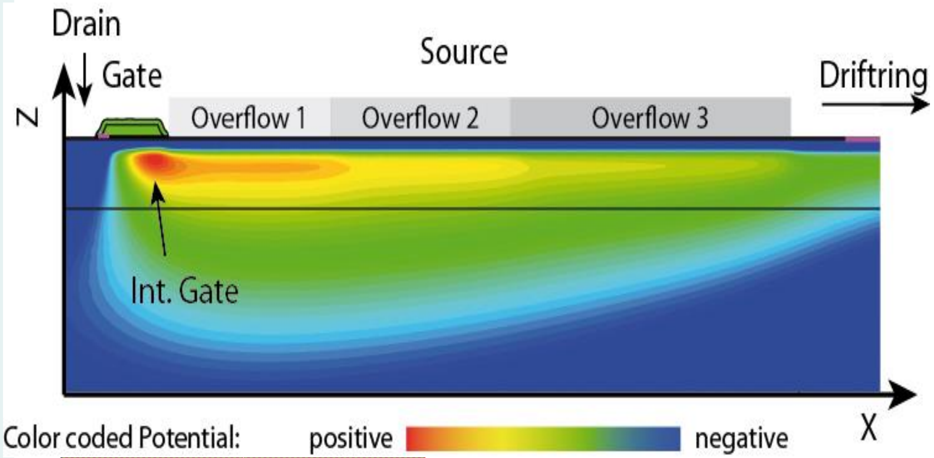
Integrating Area Detector

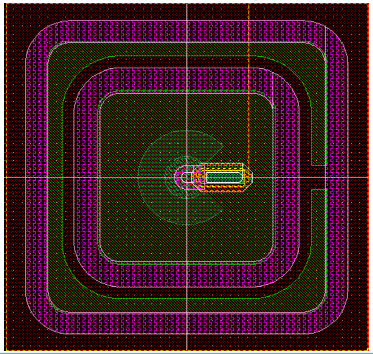
	XFEL (e.g. XPCS)	DEPFET array system
single photon resolution	yes	yes
energy range	0.5< E < 24 (keV)	0.5 < E < 25 [keV]
ang. resolution or pixel size	4 µrad	200 µm
sig.rate/pixel/bunch	10^3	10^3@10KeV
quantum efficiency	> 0.8	> 0.8 from 0.3 to 12 keV
number of pixels	512 x 512 (min.)	1024 x 1024
frame rate/repetition rate	10 Hz	yes, triggerable
XFEL burst mode	5 MHz (3.000 bunches)	4.5 MHz
Readout noise	< 150 e^- (rms)	< 50 e^- (rms)
cooling	possible	- 20° C optimum, room temperature possible
vacuum compatibility	yes	yes
preprocessing	no (yes) ?	possible upon request
4-side buttability	yes	yes

Detector Concept – DEPFET with signal compression

DSSC - **D**EPFET **S**ensor with **S**ignal **C**ompression

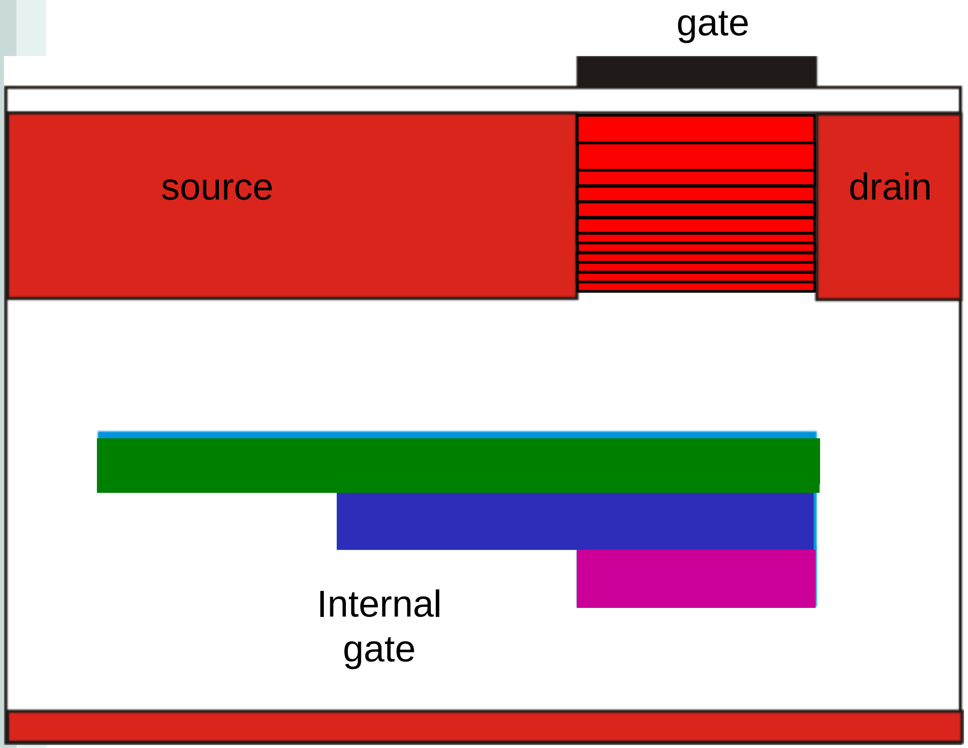


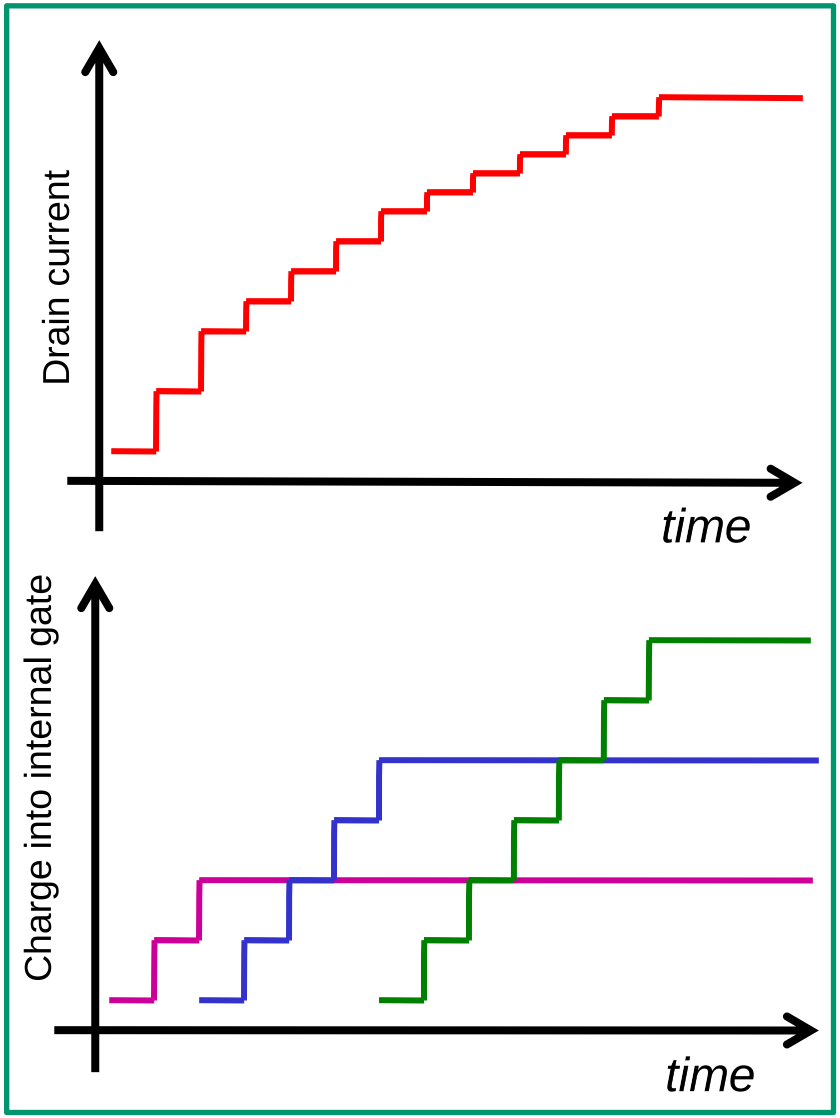




- The internal gate extends into the region below the source
- Small signals assemble below the channel, being fully effective in steering the transistor current
- Large signals spill over into the region below the source. They are less effective in steering the transistor current.
- 200 x 200 μm pixel has been designed and produced

Detector Concept – Working principle

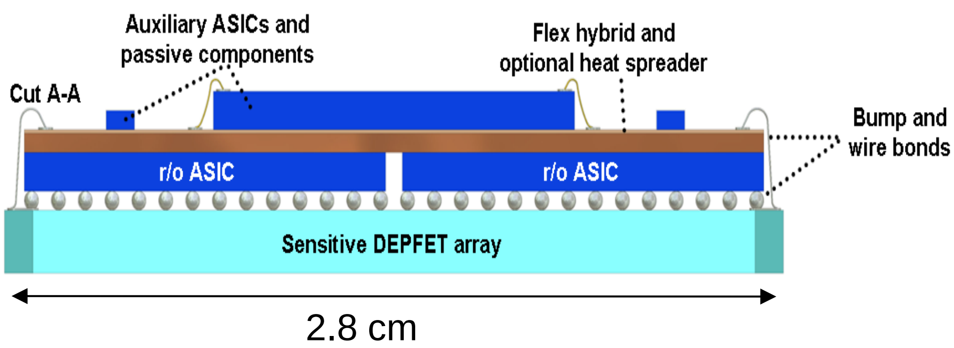


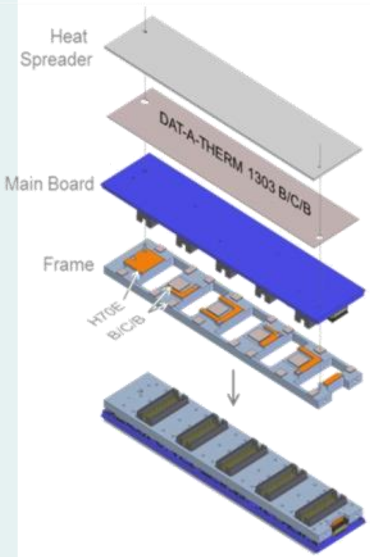


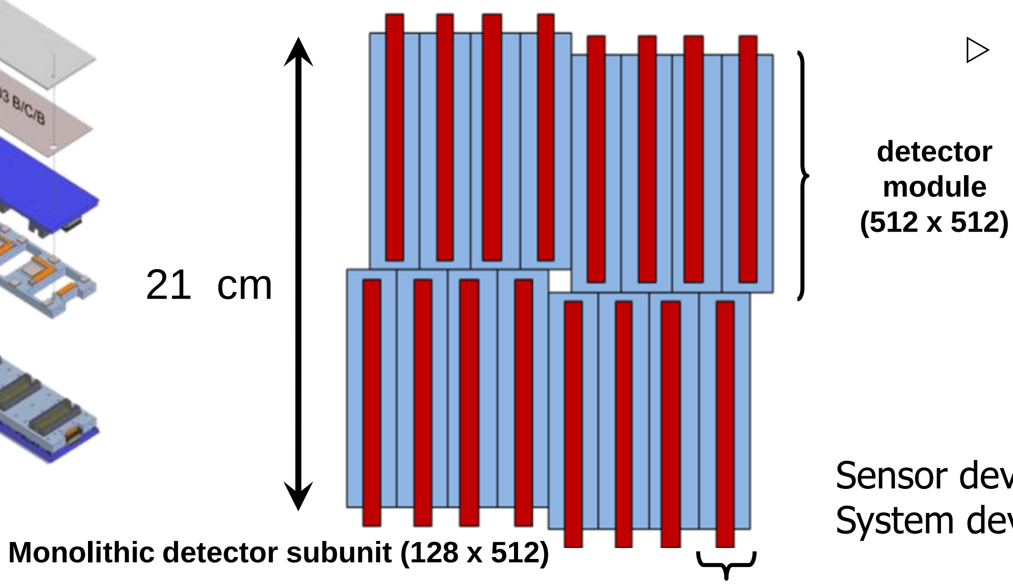
- A constant charge is injected at fixed time intervals and the internal gate regions are progressively filled
- In the experiment the charge is deposited at once but the DEPFET response is the same

Focal Plane

Submodule 128x512







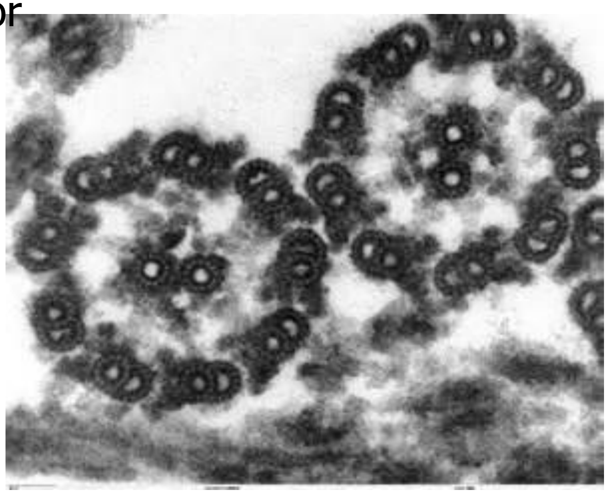
Multi Chip Modules

- DEPFET Sensor bump bonded to Readout ASICs
- Optional Heat spreader
- Flex Hybrid with passive components and auxiliary ASICs (e.g. voltage regulators)
- Sensor (512x128 pixels) $2.56 \times 10.24\ cm^2$
- 16 readout ASICs (64x64)
- Dead area: 10-15%

Sensor development by MPG HLL
System development by DSSC collaboration

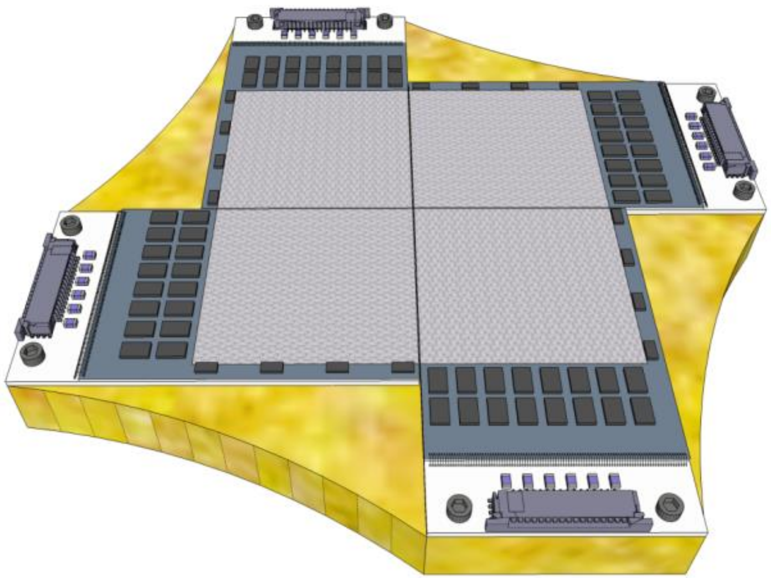
DEPFETs for low E electron detectors

Goal: develop high speed direct hit low energy electron detector
Solution: thin, nonlinear DEPFETs with 80kHz frame rate



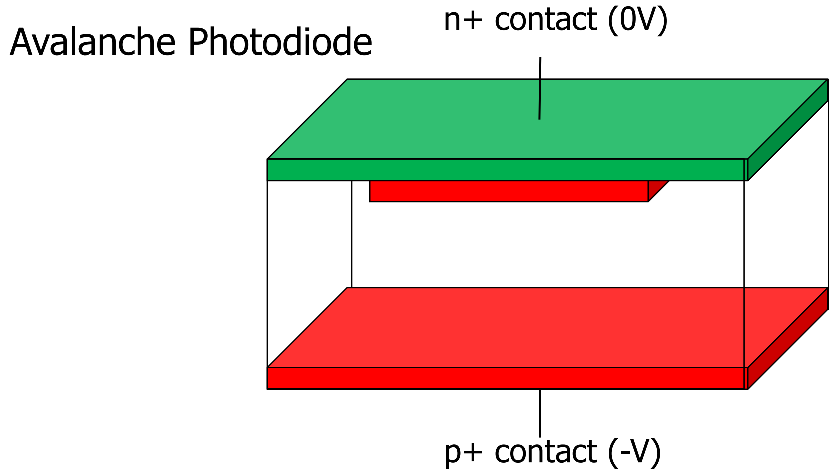
(collaboration partner MP Structural Dynamics)

- 1Mpix, 60µm DEPFET pixel, 4 quadrants, 6x6 cm² sensitive
- 50µm thin sensitive area
- Bidirectional 4-fold read out, frame rate: 80kHz
- memory to store ~100 frames



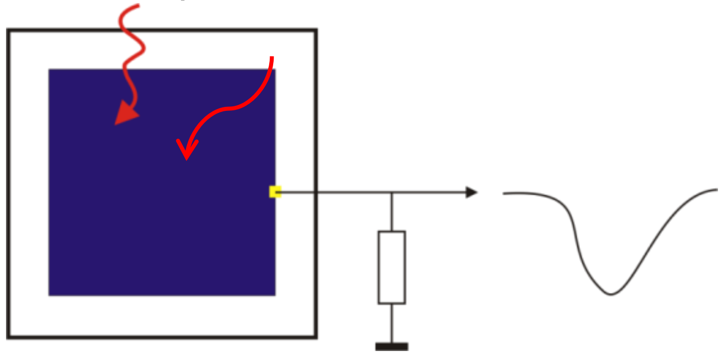
SNR improvements

- **Amplify signal**

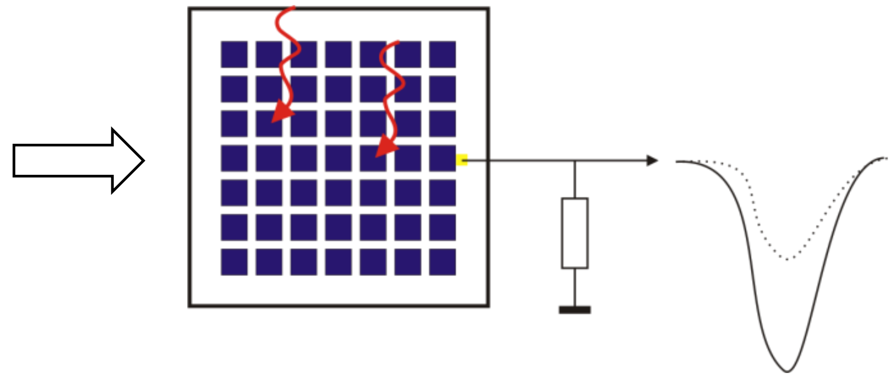


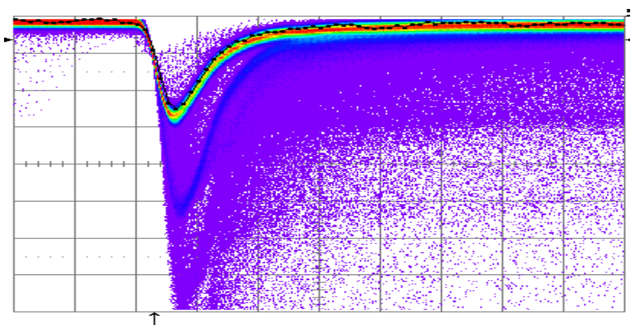
Silicon photomultiplier

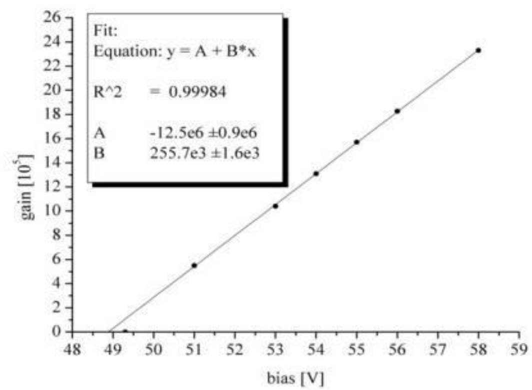
Avalanche photodiode

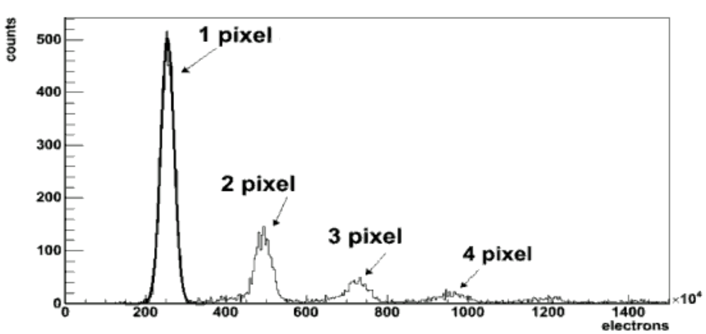


Silicon photomultiplier



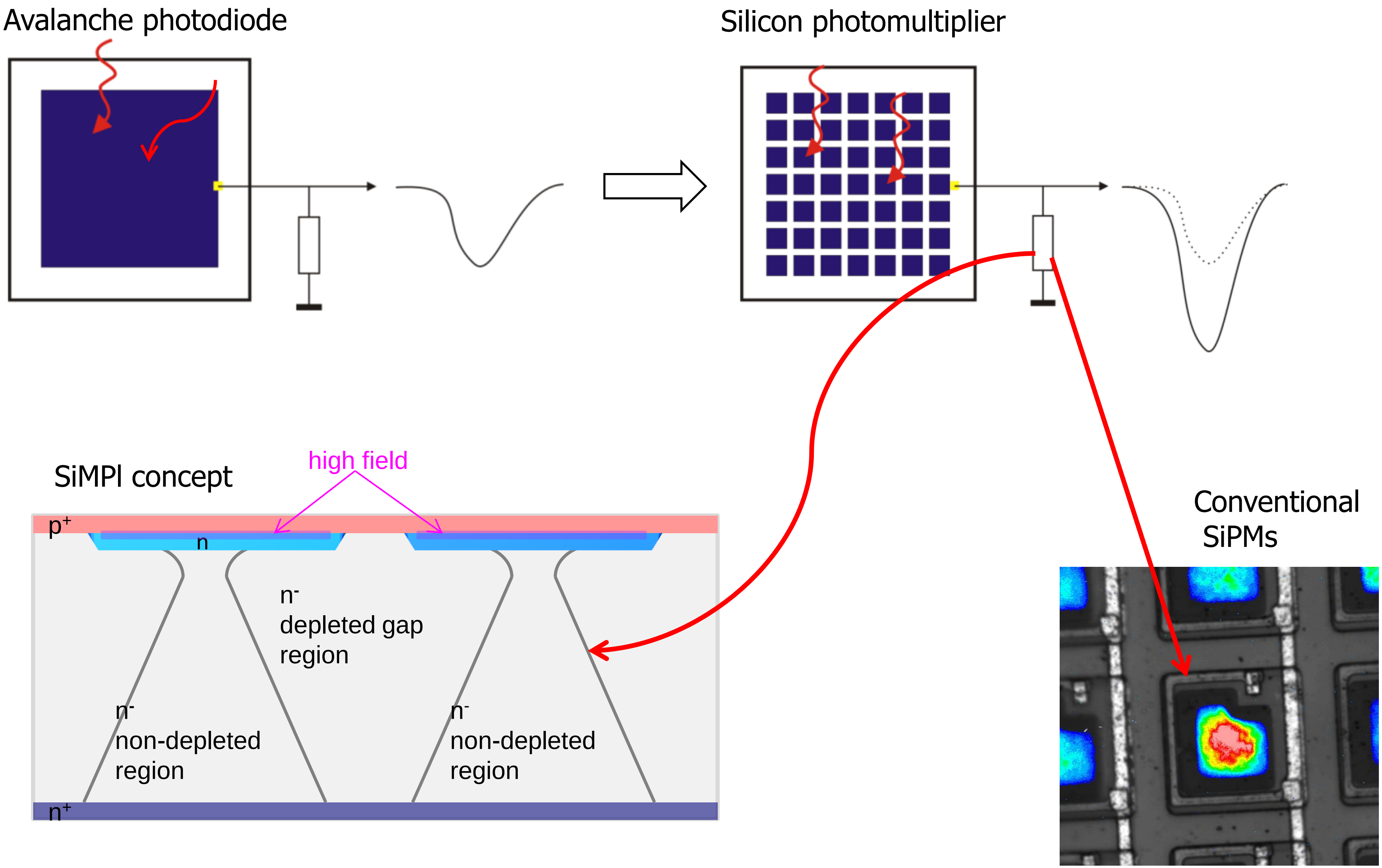




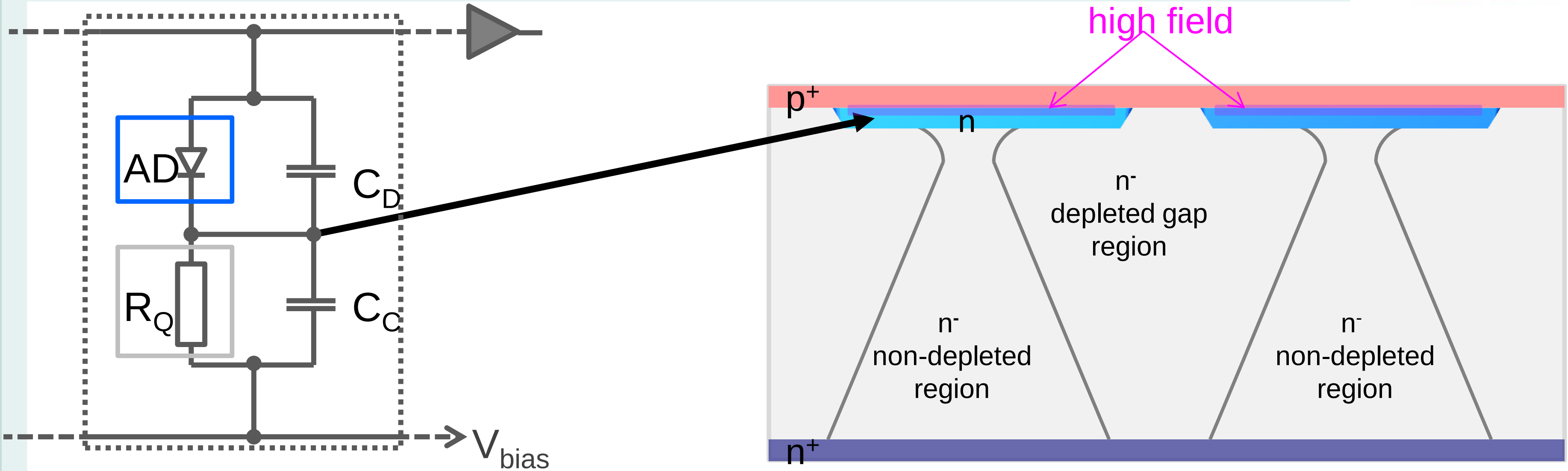


Operating voltage: «100 V
Gain: 10^5 up to 10^7
dependence of Gain on Temp.: 0.5% dG/dT

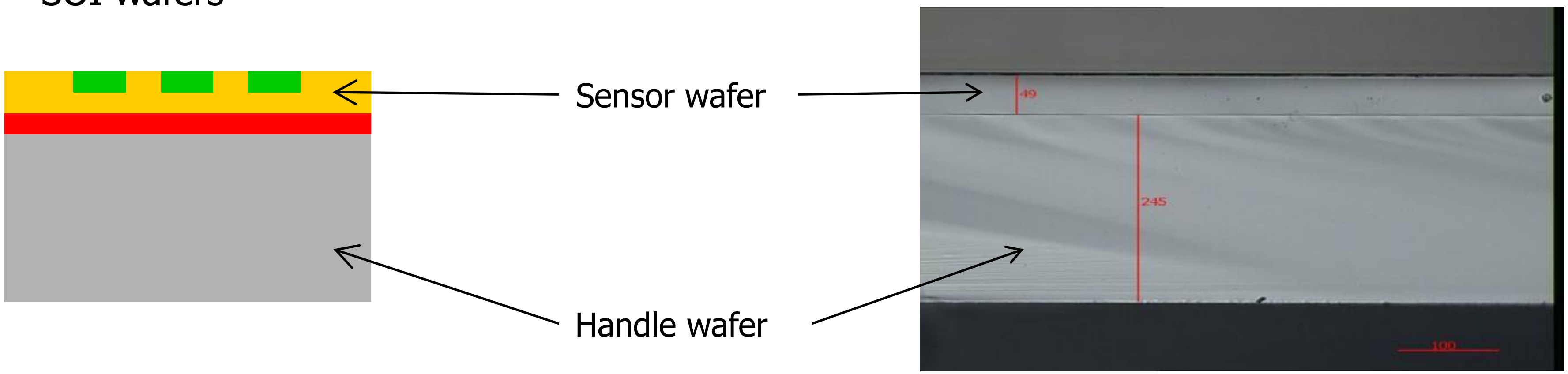
Silicon photomultiplier



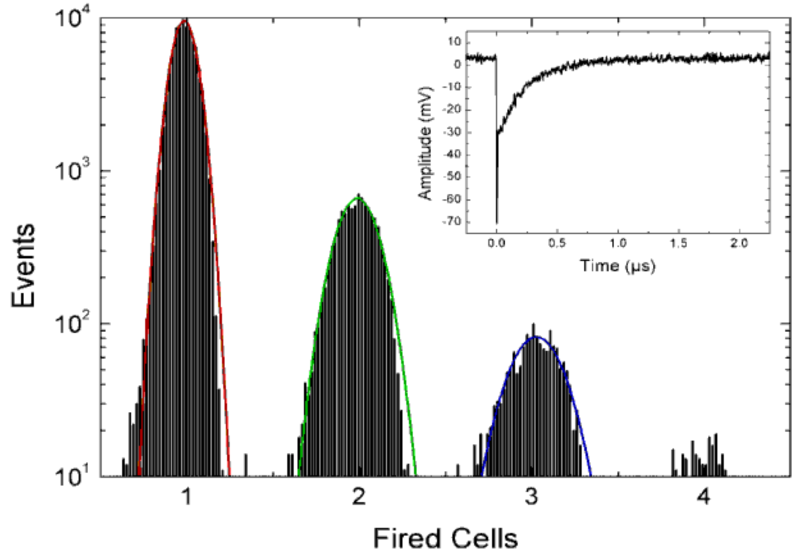
SiPM cell components → SiMPl approach

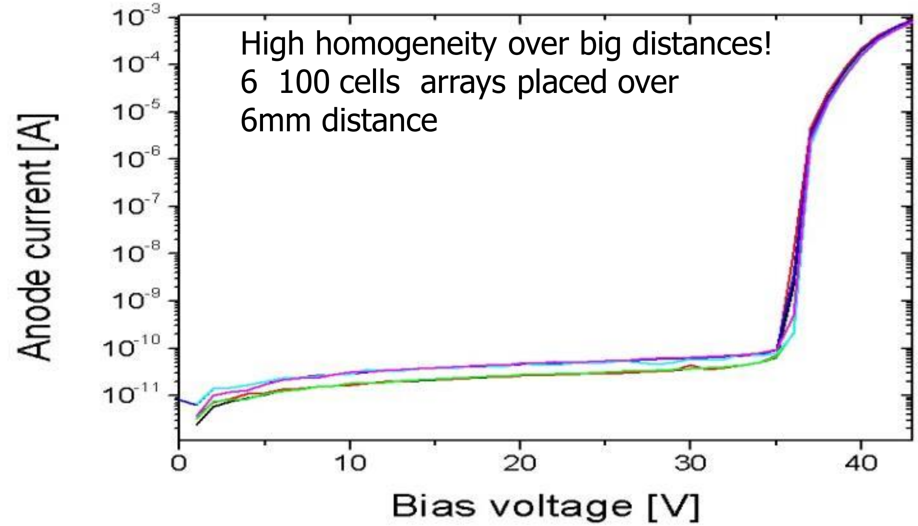


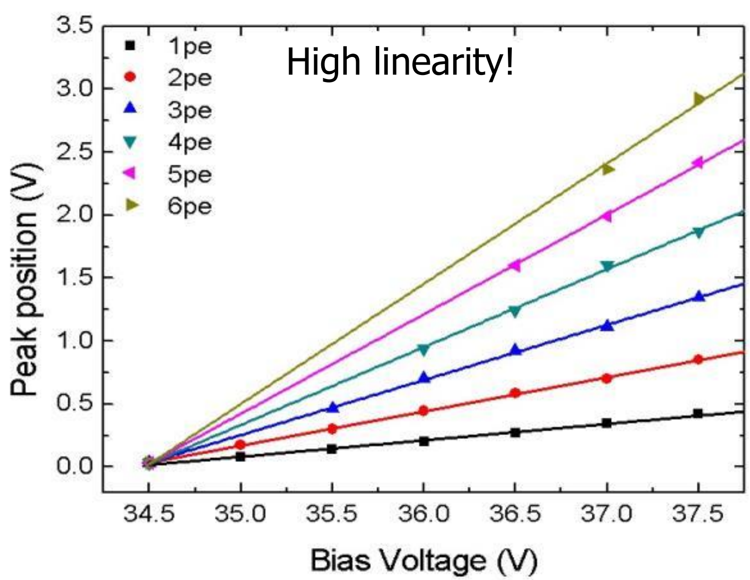
SOI wafers

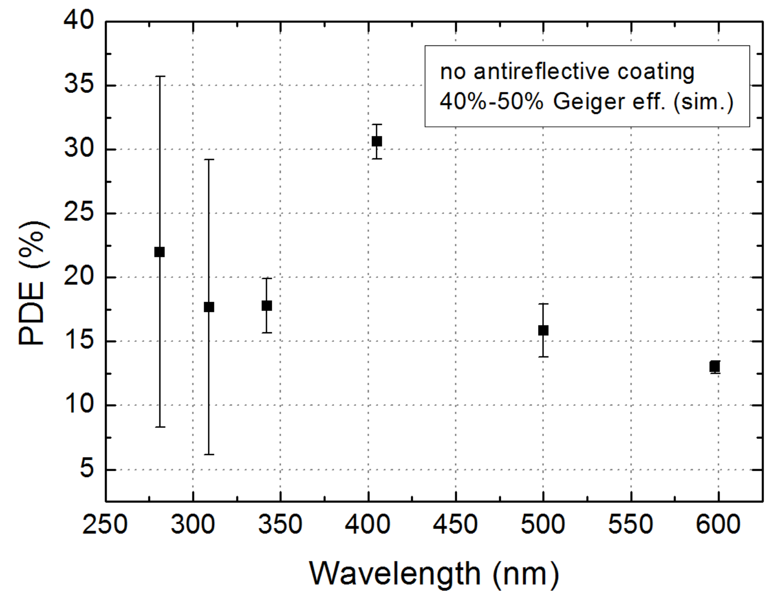


Prototype production





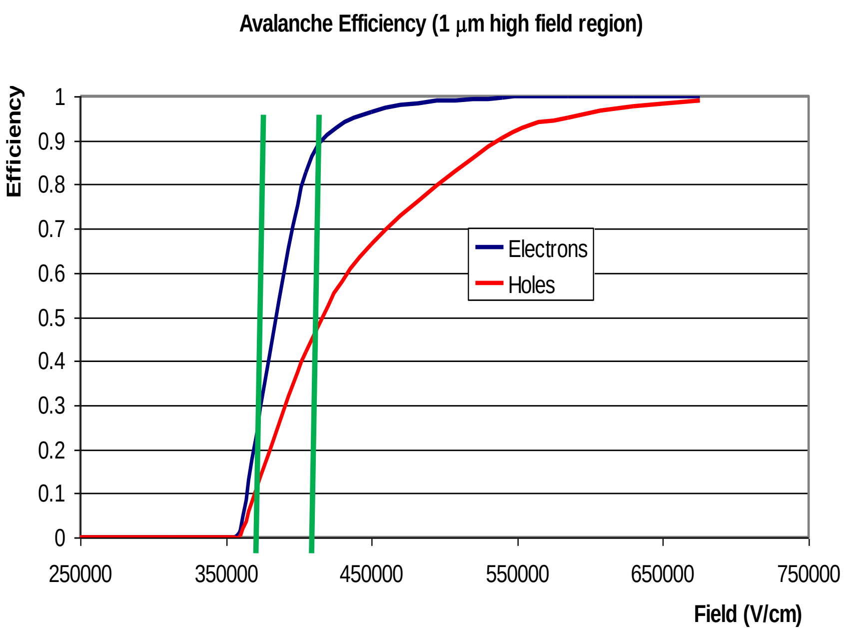


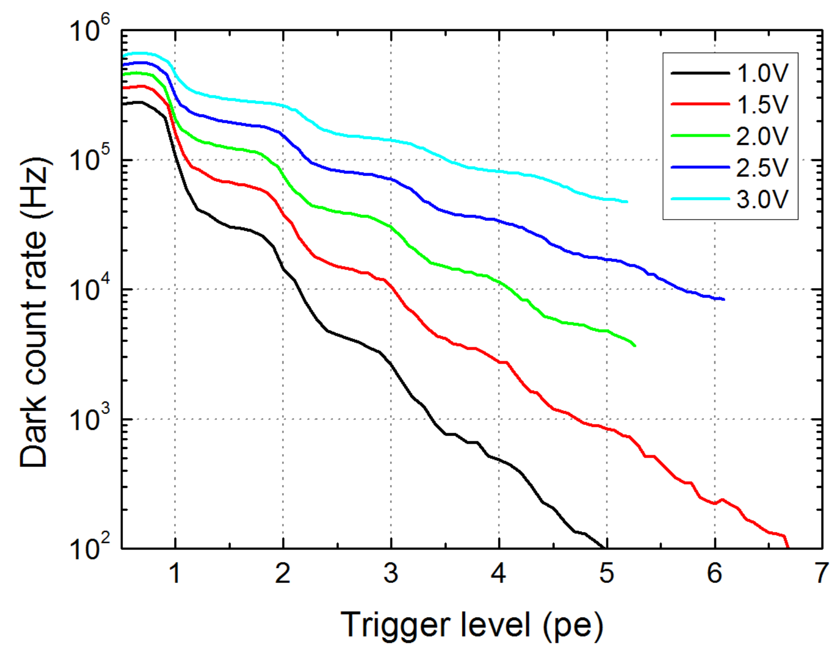


Detection of particles

Detection of particles:

- High gain in the sensor
- Excellent time stamping due to avalanche process (sub-ns)
- Minimum ionizing particles generate about 80 e-h-pairs/µm
- No need for high trigger efficiency

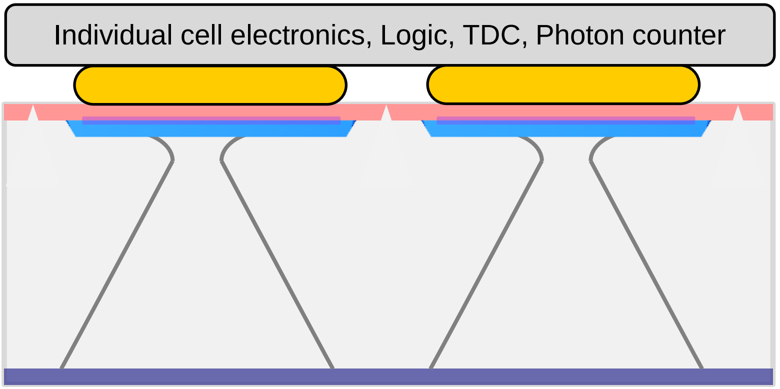




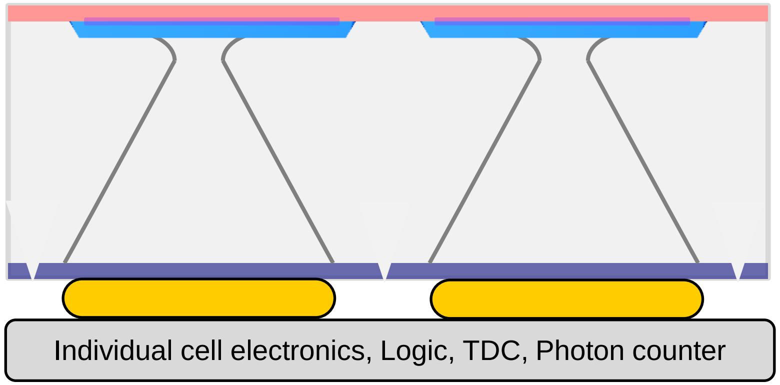
Reduction of dark rate and cross talk by order of magnitude

Next generation SiMPl devices - DSiPMl – collaboration with DESY

Ultra fast particle tracker - ***High energy physics application***



Ultra fast single photon sensitive imager – ***Photon science***



Sensor @ MPG HLL:

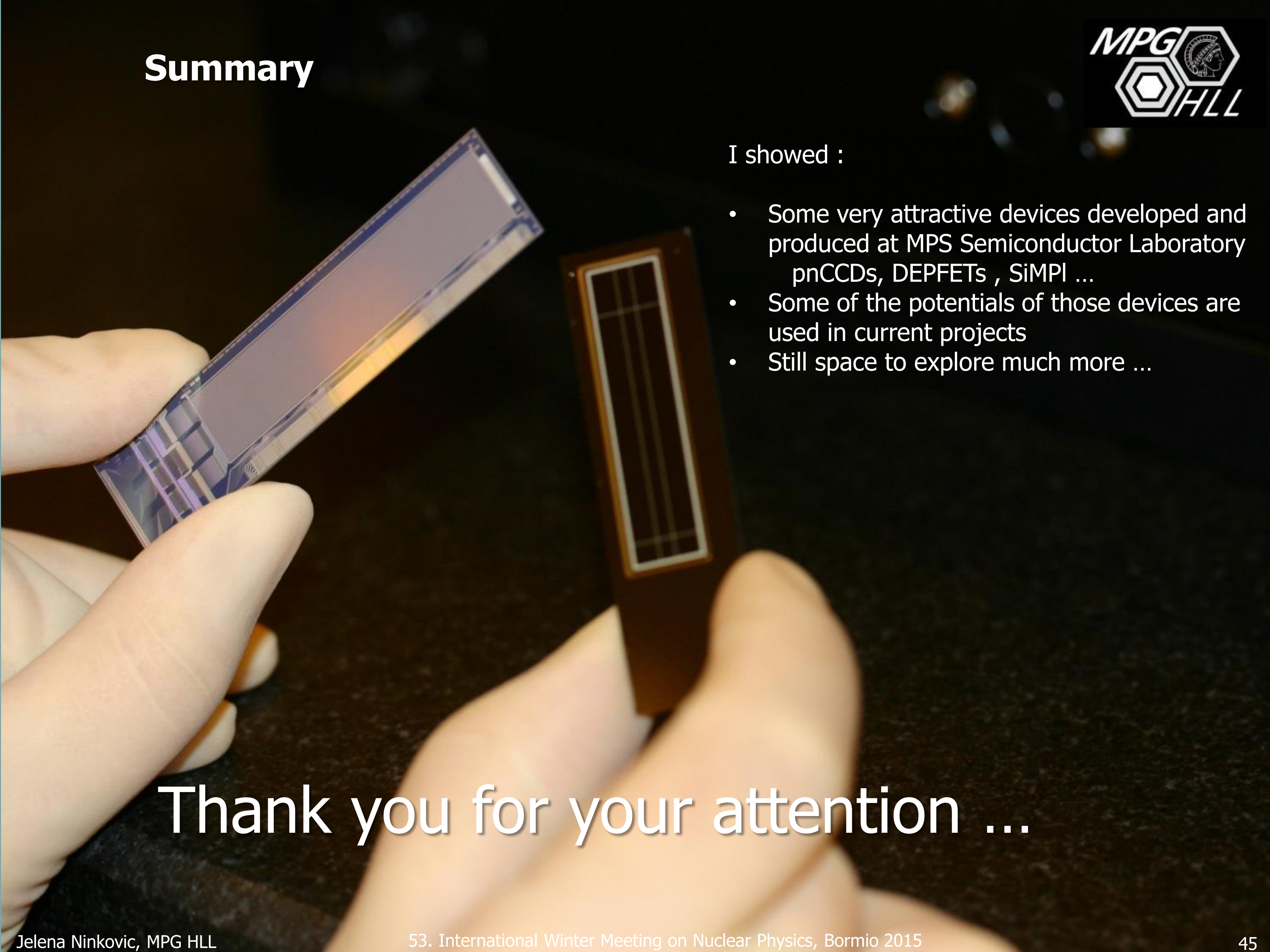
- Topologically flat surface
- High fill factor
- Adjustable resistor value
  Low RC -> very fast
- Single pixel readout
- Position sensitivity

ASIC @ DESY:

- Active recharge
- Ability to turn off noisy pixels
- Fast timing
- Pitch limited by the bump bonding
- Position resolving signal processing

Possible applications:

- Future trackers at colliders
- Detectors for hadron therapies
- X ray detectors
- PET detectors
- Adaptive optic sensors



Summary

I showed :

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

Thank you for your attention …