Current and future developments for soft X-ray detectors at MPG HLL

Jelena Ninković for the HLL team

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

MAX PLANCK SEMICONDUCTOR LABORATORY

Central facility of the Max Planck Society (since 2013)
with 40 employees: scientists, engineers and technicians + guest scientists, engineers and students

At present @ Siemens Campus Neuperlach Munich

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

From end 2023 @ IPP Campus Garching

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

Goal: development of fully depleted silicon radiation sensors
with integrated electronics optimized for different scientific projects

From 2023 MPG HLL is part of MQV
Expanding activities to Integrated photonics and Superconducting Qbits

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

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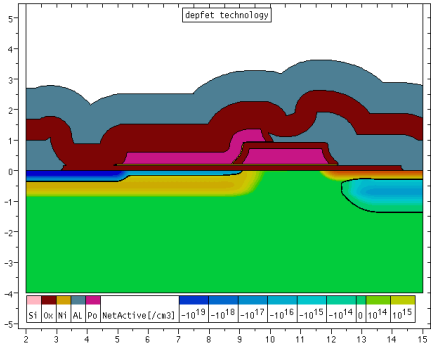
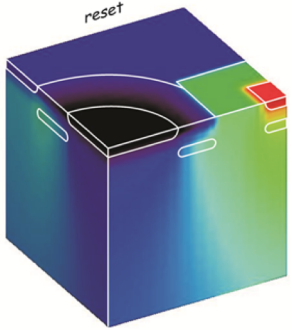
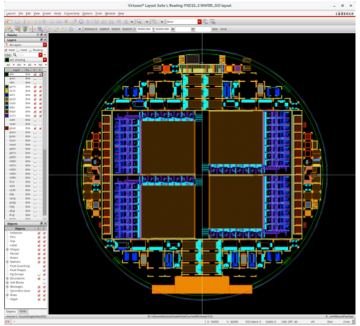
Process simulation



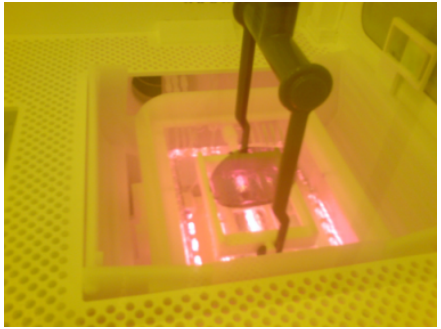
Device simulation, 2D and 3D



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

Sensor technology, interconnection and testing all available in-house

Devices @ HLL

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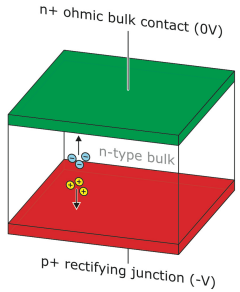
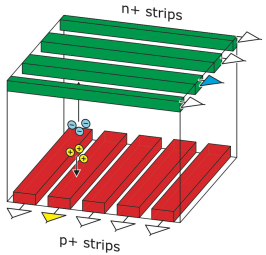
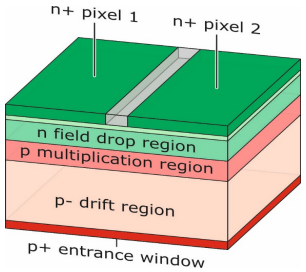
PADs



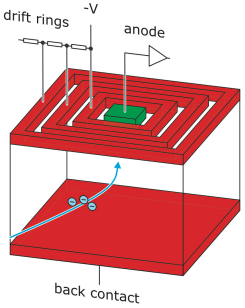
Strip detectors



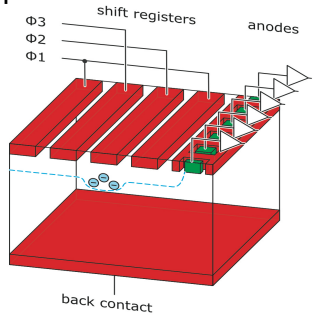
Avalanche devices



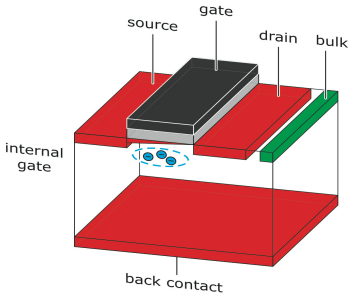
Silicon drift detectors (SDD)



pnCCDs



DEPFETs



Soft X-ray detectors - Highlights from the past

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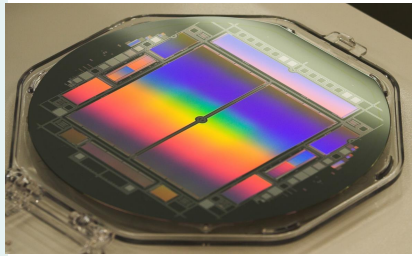
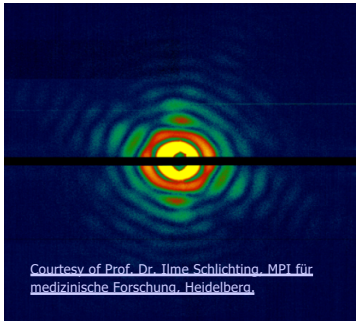
CAMP / LAMP
(pnCCD sensor)

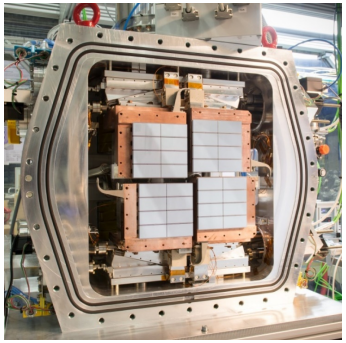


Sensor: 3.7 x 7.8 cm²
1024 × 512 pixels.

Pixel size: 75 x 75 µm²
Frame time: 8 msec (up to 120Hz)



Mini SDD @ EuXFEL
(SDD sensor)



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

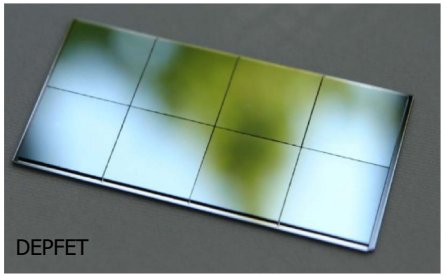
camera **1024 x 1024 pixels**
21 x 21 cm²
32 sensor chips
4 quadrants
central hole for direct beam

sensor mini-SDD cells
128 x 256 pixels
3.0 x 6.2 cm² (chip)

hex. pixel pitch 204 µm × 236 µm

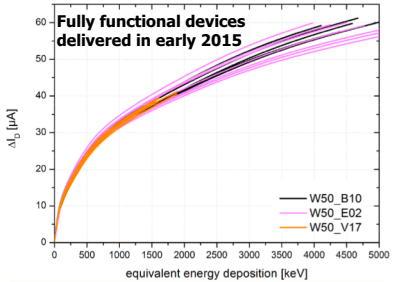
energy range **0.25 keV – 6 keV**
noise 60 el. r.m.s.
peak frame rate **4.5 MHz**
frame storage 800 frames

DSSC @ EuXFEL
DEPFET **S**ensor with **S**ignal **C**ompression



Sensor **2.56 x 10.24 cm²**
512 × 128 pixels

Hybrid detector
with 8 readout ASICs (64x64)
Pixel size: 204 x 236 µm²
Frame time: **220ns (4.5MHz)**



Soft X-ray detectors – ongoing developments

MAX PLANCK SEMICONDUCTOR LABORATORY

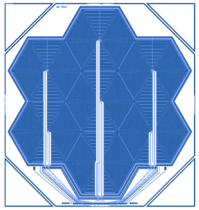
Various SDD projects

IAXO (INTERNATIONAL AXION OBSERVATORY)

requirements
- detection threshold 1 keV
- efficiency interval 1 … 10 keV

single cell & seven cells SDDs

cell diameter 8 mm & 10 mm



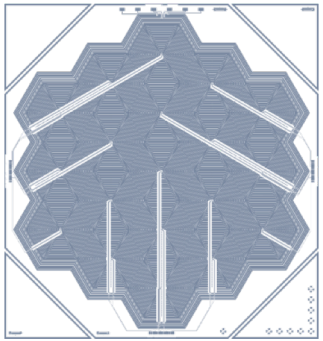
eXTP (ENHANCED X-RAY TIMING & POLARIMETRY)

spectroscopic focusing array SFA (11 x)
circular SDD
effective area 0.6 / 0.9 m² @ 6 / 1 keV
energy resolution < 180 eV (FWHM @ 6 keV)
time resolution < 10 µsec

TRISTAN

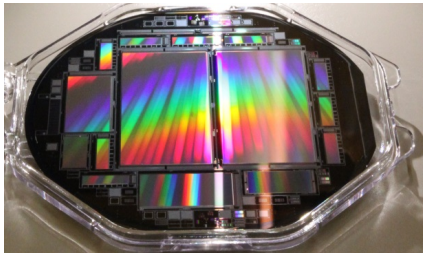
(TRITIUM STERILE ANTI-NEUTRINO)
166-cells SDD (~ 14 x 12 array)
- SDD with integrated FET
- cell format: diameter 3 mm, area 7 mm²
- chip size: 38 x 40 mm²

Extremely thin entrance window



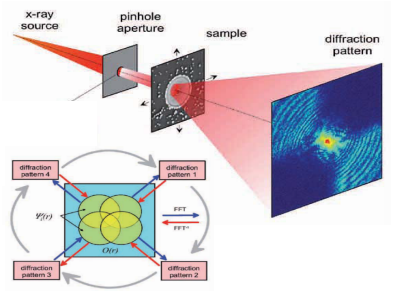
FSP – TNG for MAXIMUS

Fast Small Pixel – The Next Generation



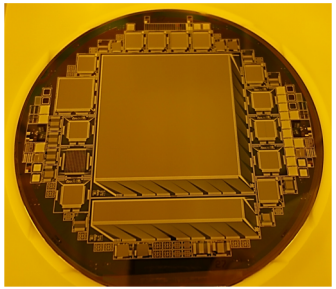
Sensor: 3.7 x 7.4 cm²
1024×1024 +(2x512) pixels

Pixel size: **36 x 36 µm²**
Frame time: 2.5 msec (**400Hz**)

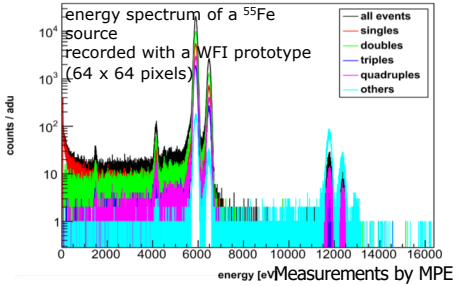


ATHENA Wide Field Imager

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

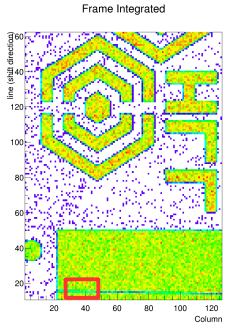


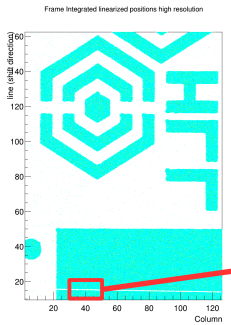
Sensor: 512 x 512 pixels
78.00 x 76.15 mm²
rolling shutter mode
Pixel size**:** **130x 130 µm²**
Frame time**:** **1.28 msec, i.e. 2.5 µsec / row**
with 128 eV (singles) & 136 eV (all)

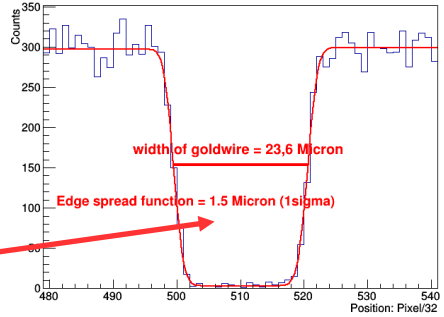


pnCCD state of the art – FSP TNG pnCCDs

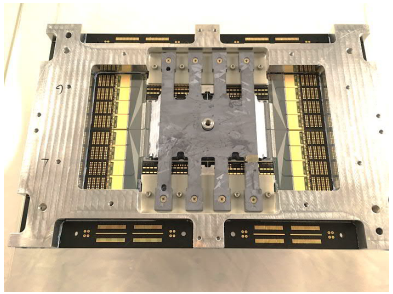
Improved pnCCD technology in use since 2020 – faster devices, smaller pixels (36μm)
New compact and intelligent system almost finalized







Prototype devices with next generation pnCCD technology finalized 3 weeks ago.

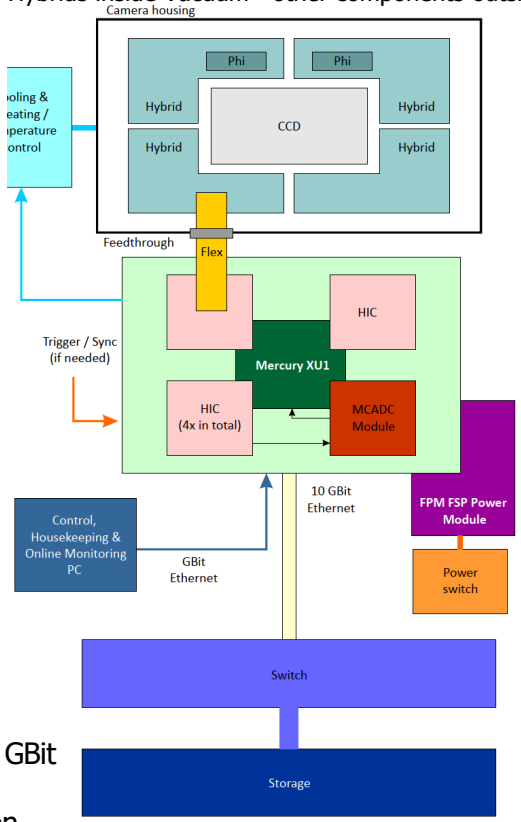


system with integrated power supplies - single 12 V supply
an integrated controller based on a state-of-the-art Xilinx SoC

- allow for comprehensive housekeeping,
- intelligent sequencing and
- user-defined data pre-processing functionality

Output data to mass storage as UDP data stream using dual 10 GBit Ethernet optical link
controlled by a single PC via a standard GBit Ethernet connection.

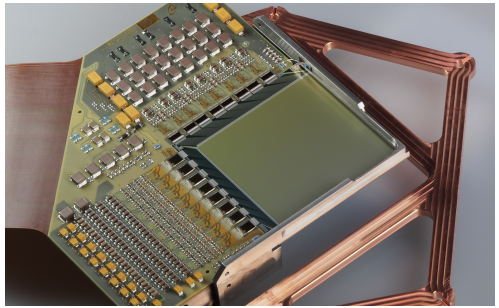
Sensor + Hybrids inside Vacuum - other components outside



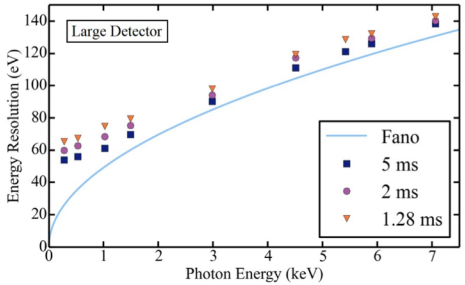
DEPFETs – state of the art technology and ongoing developments

MAX PLANCK SEMICONDUCTOR LABORATORY

ATHENA WFI – spectroscopic device



https://arxiv.org/pdf/2208.04178.pdf



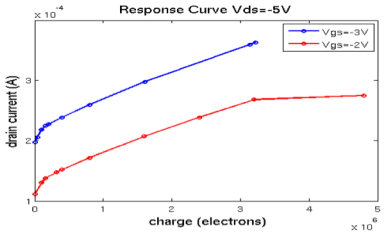
Sensor: **78.00 x 76.15 mm²**
rolling shutter mode
Pixel size**:** **130x 130 µm²**

First flight devices produced – 6/36 wafers

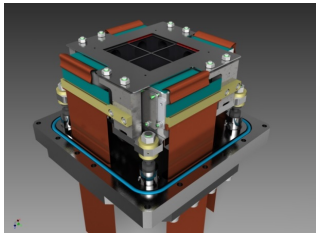
Yield 6 out of 6 wafers past all quality checks

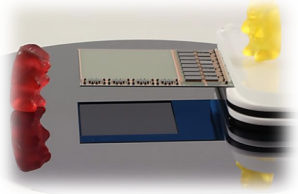
EDET 80k – fast direct electron detector

- 1Mpix, **60µm** DEPFET pixel, 4 quadrants, **6x6 cm²** sensitive
- **1-3 M electrons to store into internal gate**
- **30-50µm** thin sensitive area
- 4-fold read out, frame rate**: 80kHz**
- memory to store ~60 frames

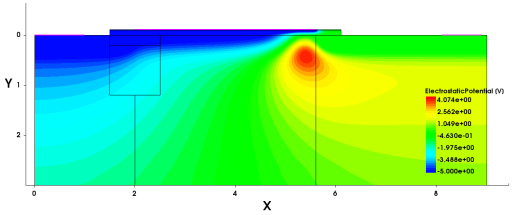


Simplified production of non linear devices



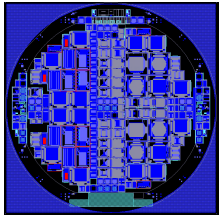


Yield of production > 80%



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

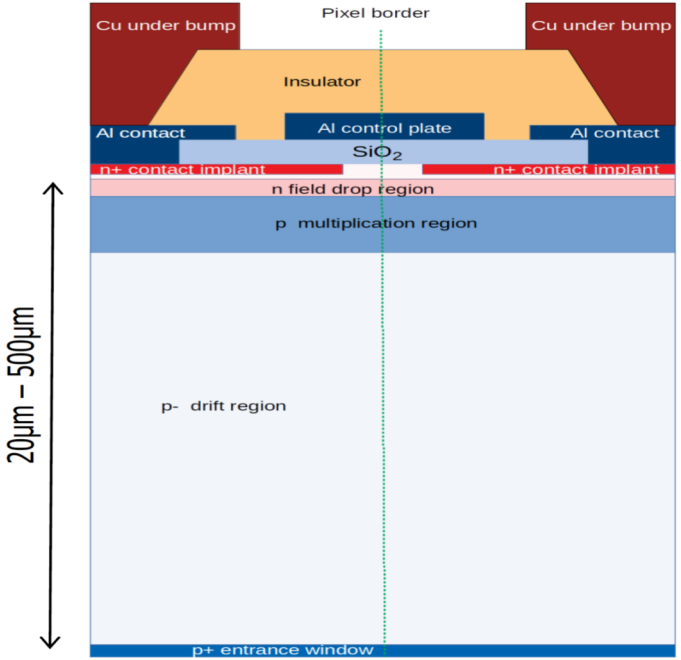


Test production finished 4 weeks ago
Fast production mode tested –
10 months production time

MARTHA - **M**onolytic **A**rray of **R**each **T**hrough **A**PDs

MAX PLANCK SEMICONDUCTOR LABORATORY

Initial motivation – develop low gain avalanche device with high fill factor for photon science applications



Expected features:

Gain up to 20

Collection efficiencies: **> 99%**

Pixel pitch: given by bump bond technology

and read out electronics space consumption (ATLAS 50µm)

Position resolution: << $\frac{pitch}{\sqrt{12}}$ (<< 10µm)

Time resolution:

Application dependent

Leading edge trigger: <50ps

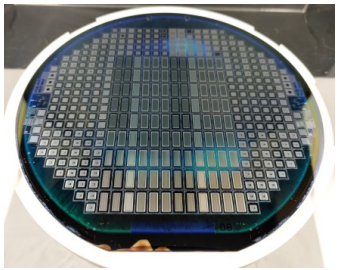
Full signal formation 50ns (for thickness 500µm)

Proof of principle production ongoing on standard thick material

Finalization end of September

Designed structures:

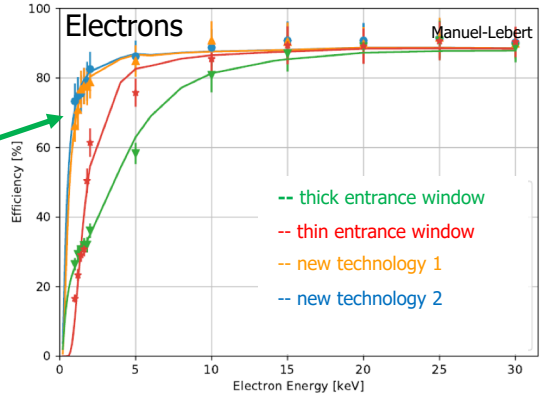
- Pixel arrays
- Strip sensors
- Diodes
- Multi Guard Ring Test diodes

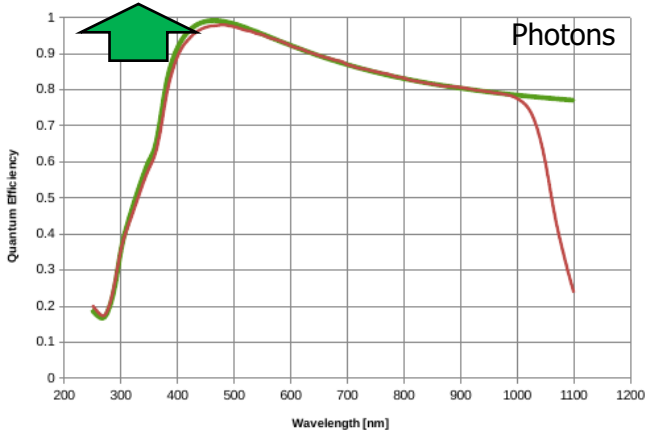


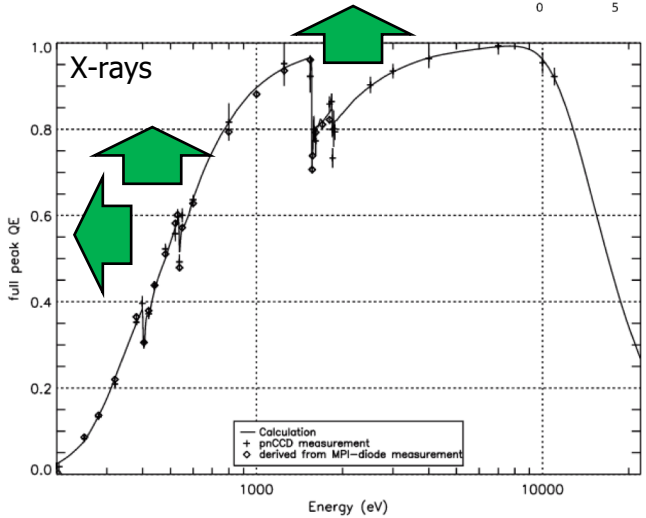
Entrance window engineering – application optimization

- 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

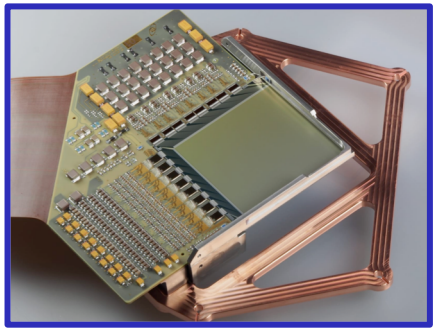




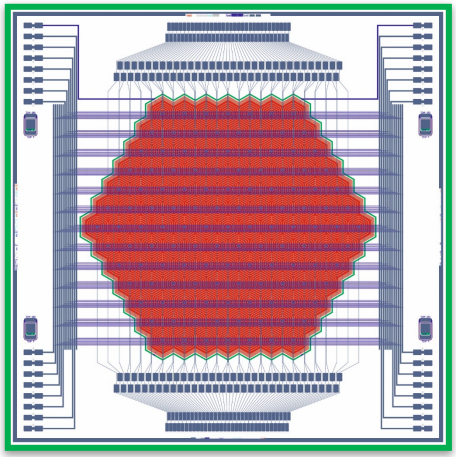


Interconnection technologies

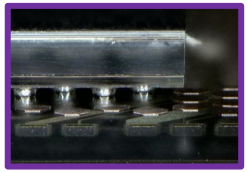
Standard wire bonding (Al and Au)
Frame time: 1.28 msec,
i.e. 2.5 µsec / row



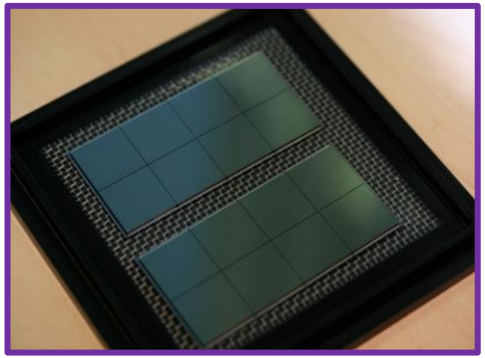
Athena WFI module
Courtesy MPE



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

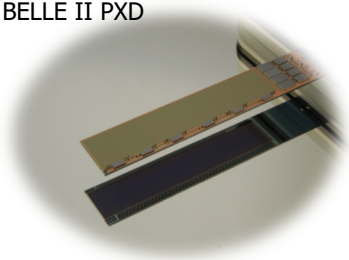
DePFET with internal storage

Interconnection technologies

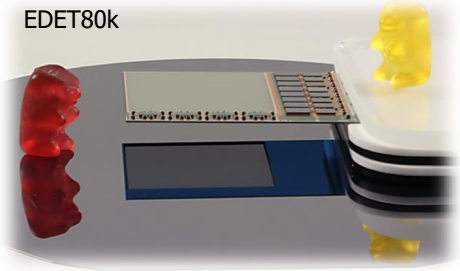
All silicon module (ASM) : Sensor and Hybrid in one silicon piece

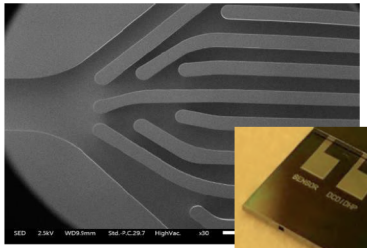
- Belle II Pixel detector – tracking of high energy particles
- EDET80k project – development of ultra fast direct electron detectors for TEM

BELLE II PXD

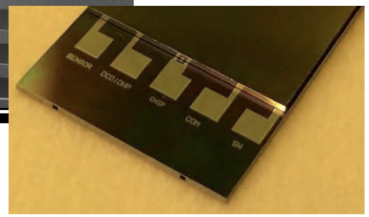


EDET80k



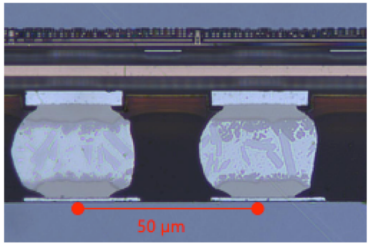


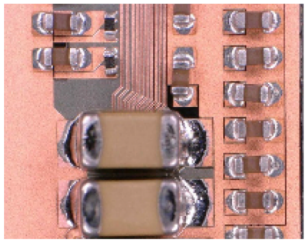
Micro-channel-cooling



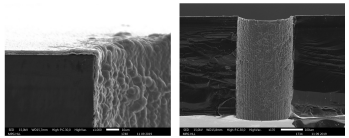
~50μm pixel size
8M pixel detector
50kHz frame time
75 μm thin detectors
Linear DEPFETs

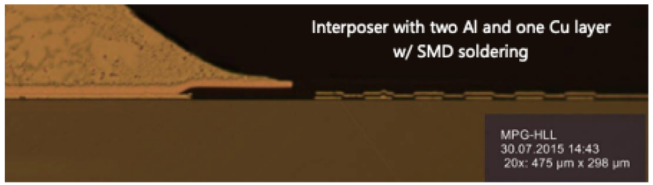
60μm pixel size
1M pixel camera
80kHz frame time
30 and 50 μm thin detectors
Nonlinear DEPFETs



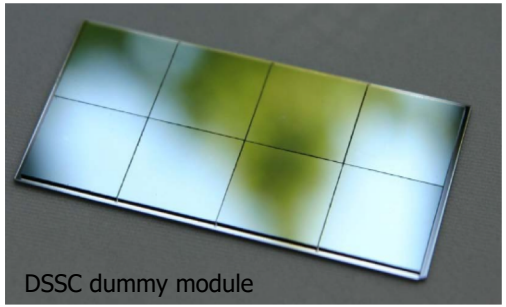


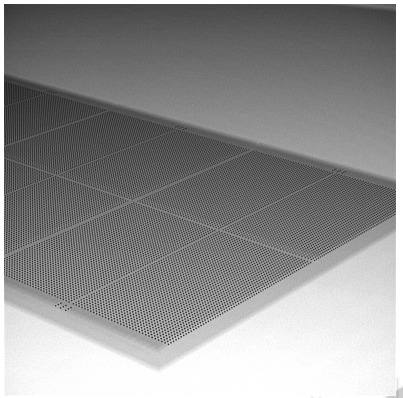
TSV

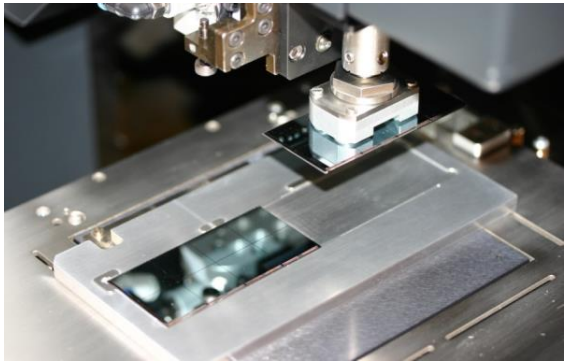


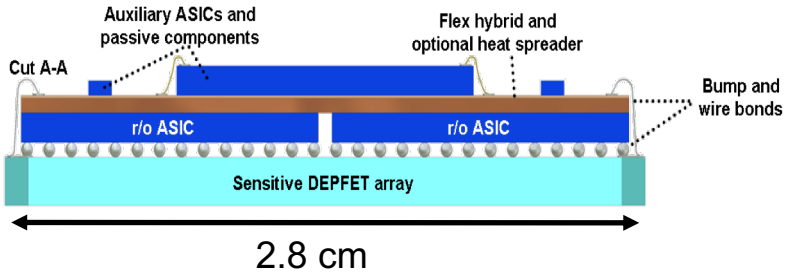


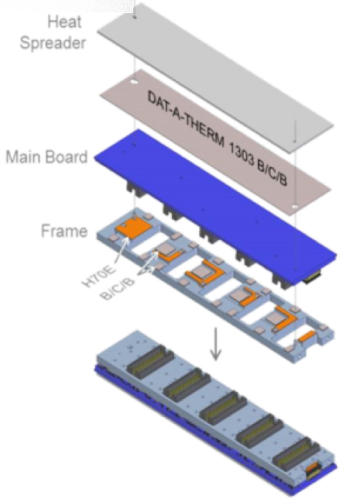
Macro/Micro assemblies

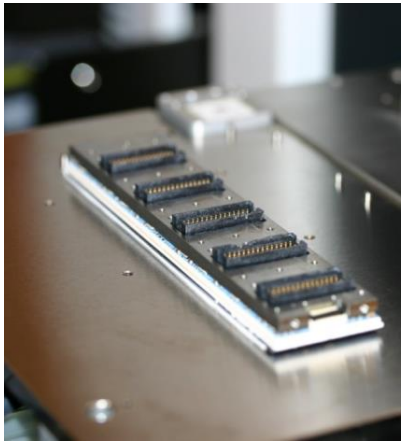






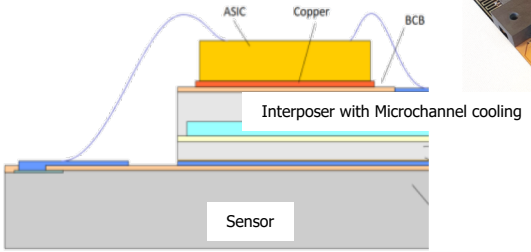


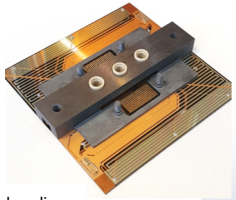


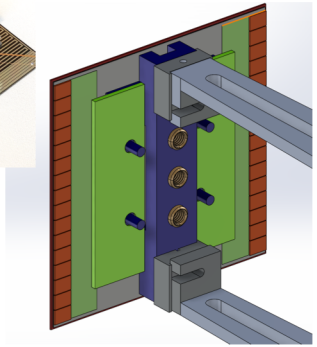


All tools and technology available at HLL

4 side buttable module development @ HLL







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

TRISTAN (TRITIUM STERILE ANTI-NEUTRINO)

166-cells SDD (~ 14 x 12 array)

- SDD with integrated FET
- cell format: diameter 3 mm, area 7 mm²
- chip size: 38 x 40 mm²

module

- TRISTAN sensor plane = 3 x 3 array
- 4-side buttable module
- perpendicular mechanical, thermal, electronic connections

Final detector production finalized last week

Assembly to follow in the new lab

Developed by Tristan collaboration

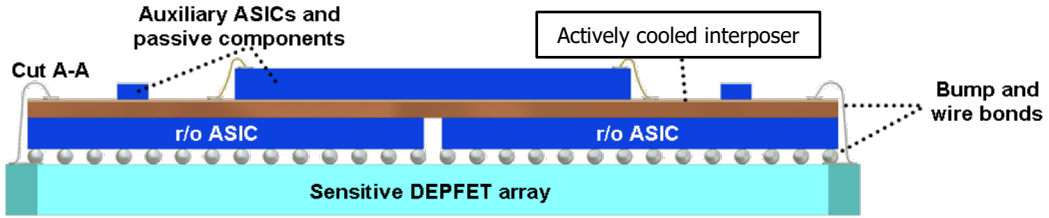
XFEL requirements vs. HLL detectors

MAX PLANCK SEMICONDUCTOR LABORATORY

	Target values (hard X-rays)	Target Values (soft X-rays)	SDD with/without FET DAY0 like system	Non linear (Sg_q) DEPFETs 2. GEN DSSC like system	MARTHA DAY0 like system/ AGIPD like system
Sensitive Energy Range	5 - 13 keV	0.4 - 3 keV	YES 0.3 – 15keV	YES 0.3 – 15keV	YES 0.3 – 15keV
Dynamic range in photons	> 5 x 10^3 12 keV ph./px (16.5 Me^-)	> 5 x 10^3 1 keV ph./px (1.4 Me^-)	soft - YES	soft - YES hard – NO	soft - YES
Dynamic range (one gain)	500-1000 12 keV ph./px (1.6-3.2 Me^-)	500-1000 1 keV ph./px (0.14-0.27 Me^-)	~10^5 e^-	NLA - ~2 x 10^6 e^-	~10^5 e^-
Noise (ENC)	< 300 el. rms. ~1keV photon	< 30 el. rms. ~1keV photon	YES 30- 60 el. rms.	YES 20 el. rms.	YES Not known
Frame rate	Burst mode, 1.1 - 4.5 MHz	Burst mode, 1.1 - 4.5 MHz	YES 1.1 - 4.5 MHz	YES 1.1 - 4.5 MHz	YES 1.1 - 4.5 MHz
Sensor type	2D pixelated	2D pixelated	YES	YES	YES
Pixel size	80 - 100 µm pitch	80 - 100 µm pitch	YES 60-100µm	YES 60-100µm	YES 50-100µm
Pixel count	modular approach, max 4 Mpix	modular approach, max 4 Mpix	YES 4-side buttability	YES 4-side buttability	YES 4-side buttability
Operating pressure range	Both ambient and vacuum (below 10^{-3} mbar) versions needed	< 10^{-6} mbar versions needed	YES -20°C optimum RT possible	YES -20°C optimum RT possible	YES -20°C optimum RT possible

Possible HLL activities for XFEL future detector developments

System development to be organized by collaboration partners – HLL could be coordinator of activities
Keep system close to already developed systems but modify module design
Sensor – pixel size to be defined by available bump bonding technology for a RO chip
New RO chip needs to be developed – task of collaborative partner
Thermomechanical coupling via actively cooled interposer → reduction of dead area
Module design – HLL
System – to be checked what can be reused and what needs new development.



Sensor module 256x512 pixels
RO ASICs 128x128
Ladder 256x1024 pixels
Quadrant 1024x4096 pixels

Ongoing and planned improvements

MAX PLANCK SEMICONDUCTOR LABORATORY

Sensor technology:

- planarization of technology → **smaller feature size → smaller pixels** 15-20μm should be feasible
  → **higher number of metal layers → faster detectors**
  → **faster production time**
- new DEPFET technology developed → **higher signal** and **lower noise → even better sensor performance**
- even **thinner entrance window**
- even **higher radiation hardness**
- Wafer thickness present standard 450μm, at present 1mm possible with minor adjustments → **adjustment of tools possible to 2mm**
- **E-beam lithography @ HLL would allow adding some CMOS structures** to simplify operation of devices
- **3D integration** – Wafer bonding, TSV
- wafer size 6 → 8 inch → **larger area devices**

- Thanks for your attention

Looking forward to new projects in the new lab …