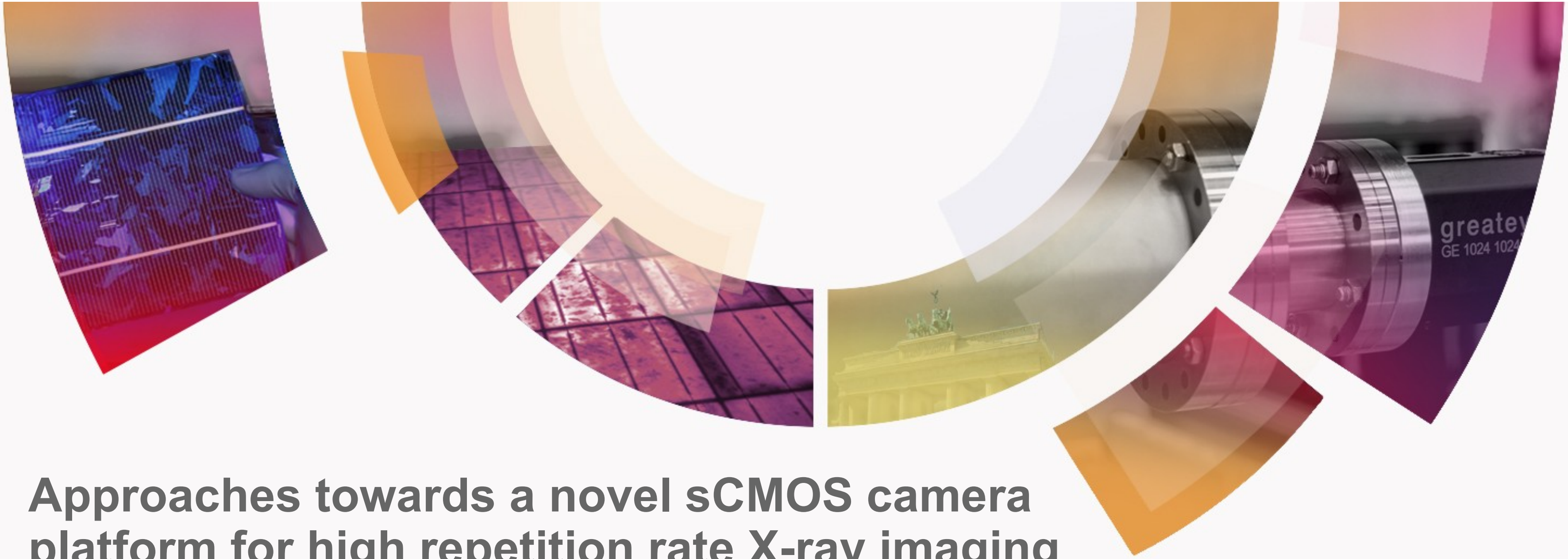
DISCOVER WHAT
THE EYE CAN'T SEE

greateyes



Approaches towards a novel sCMOS camera platform for high repetition rate X-ray imaging and single photon detection

SMART-X Stockholm Network Symposium

Conrad Friedrich

Overview

„greateyes develops, manufactures and markets high performance (scientific) digital cameras as well as optical inspection systems for research & industry.“

- Founded in 2008, headquarters in Berlin
- Quickly developed into an internationally acting company
- Two main business units: scientific cameras & inspection systems

  Strong focus on new technologies & innovations, currently two funded research projects

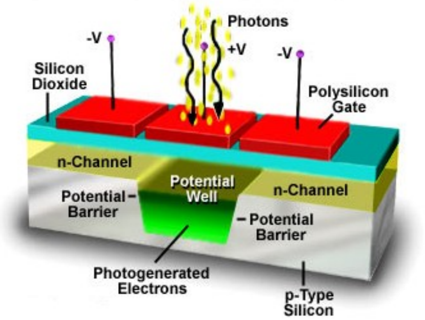
- One of greateyes’ core competencies has been in designing EUV and X-ray detectors

Activities & Contributions in SMART-X project

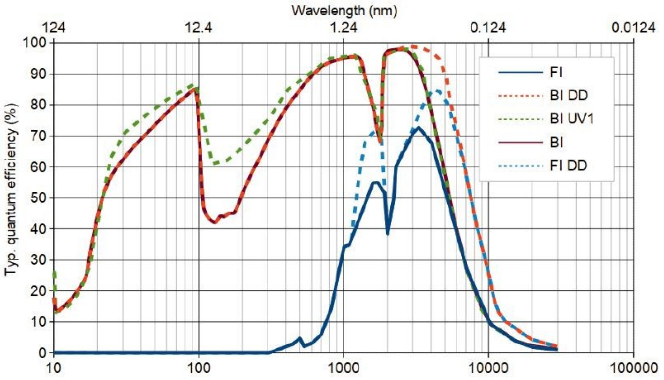
- **development of high repetition rate XUV/X-ray imaging and single photon detection system**
  ESR15 (GREATEYES) in collaboration with ESR3 (Max Born Inst.)
  - comparison of present detector technologies (i.e. CCD vs. CMOS)
    - quantum efficiency, spatial resolution, detector sizes, frame rate, read-out noise
  - evaluation of novel technologies (e.g. TimePix/MediPix, SPAD sensor arrays,...)
- **extend present CCD/CMOS camera hardware platform**
- **proof of principle & characterization of the camera at FVB-MBI**
- **application in ultrafast X-ray spectroscopy of molecules in solution and molecular powders**
  - investigation of the transient electronic structure of push-pull chromophores undergoing ultrafast charge transfer process by means of time-resolved soft x-ray absorption spectroscopy

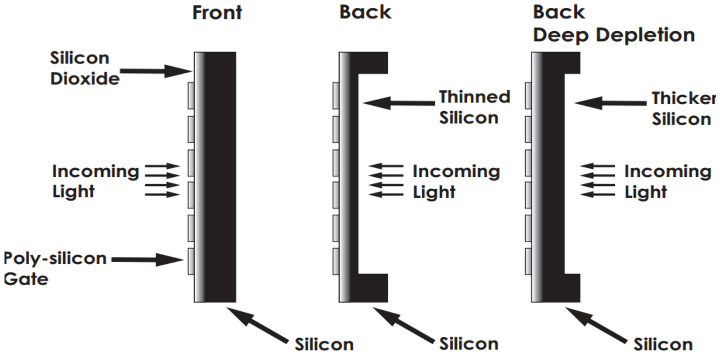
    (also see talk on Wednesday by Erik Nibbering)

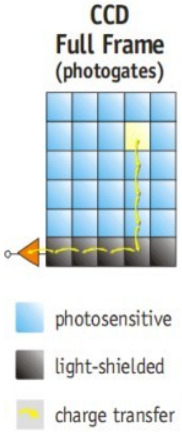
Sensor technologies for scientific X-ray/XUV cameras



- **CCD detectors** still dominant in XUV/X-ray experiments
  - photo-generated electrons are trapped in a potential well
  - accumulated charge is readout sequentially for each pixel individually
- Back-illuminated (BI) CCDs required for (direct) soft X-ray, EUV, VUV detection







Sensor technologies for scientific X-ray/XUV cameras

- CCD read-out speed is most limiting factor
  - Pixel rates ~5MHz → ~1 Hz/fps for CCD arrays (2kx2k)
  - Pros: high QE, dynamic range & SNR

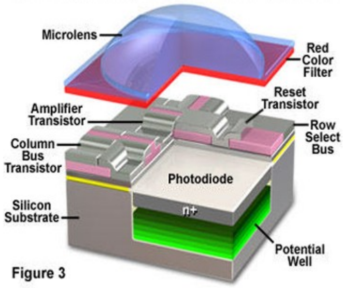
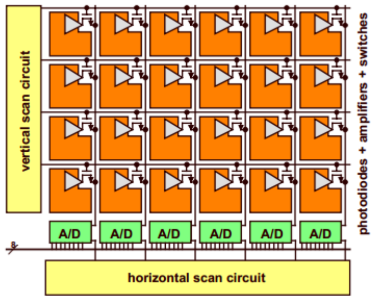
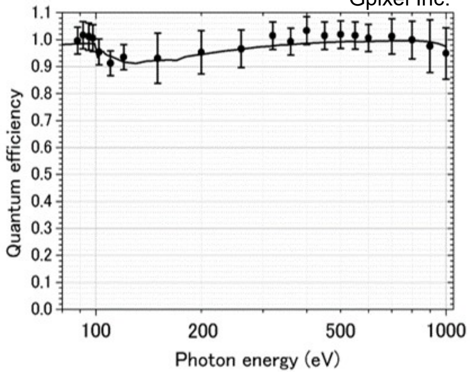


Figure 3

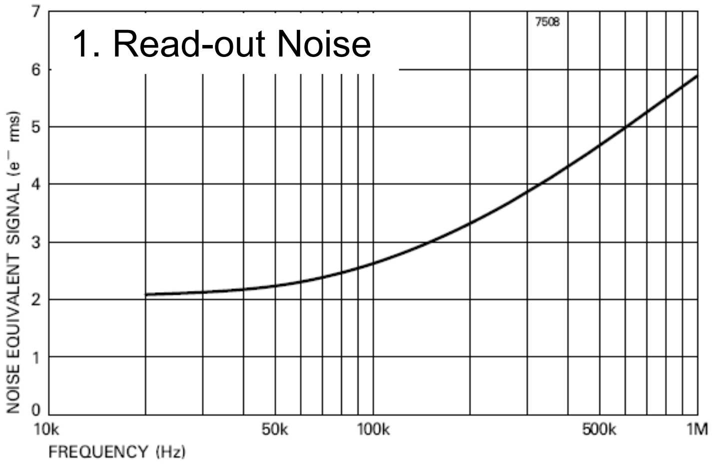


- XUV/X-ray sensitive **CMOS sensors** have been emerging
  - accumulated charge is readout in parallel for entire pixel columns
  - A/D conversion performed on-chip (amplifier & ADC array at periphery)
  - much higher read-out speeds up to several 10-100 fps (2kx2k)
- Scientific CMOS sensors are catching up fast in terms of QE and SNR
  - back-illuminated, back-thinned, uncoated sensors with thin passivation layers

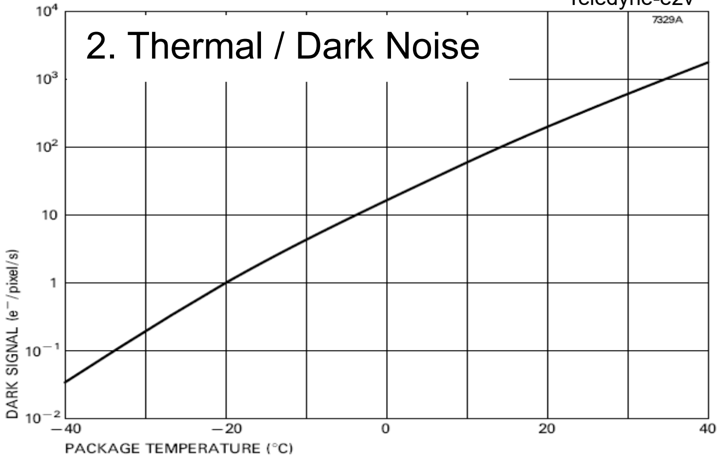
Gpixel Inc.



Dominant Noise Sources in CCD / CMOS Imaging Detectors

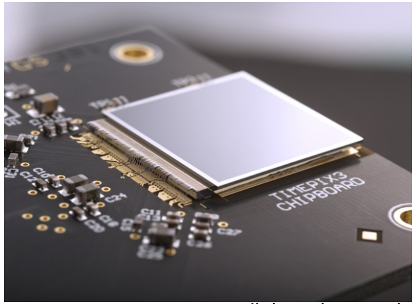


Teledyne-e2v



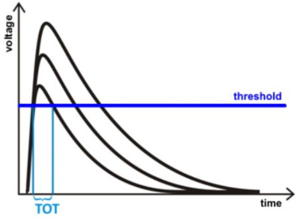
3. Reset Noise → usually eliminated by Correlated Double Sampling (CDS)
4. Fixed Pattern Noise → more important for CMOS sensors
5. Multiplication Noise → only relevant for EM-CCDs (SiPM/SPAD sensors)

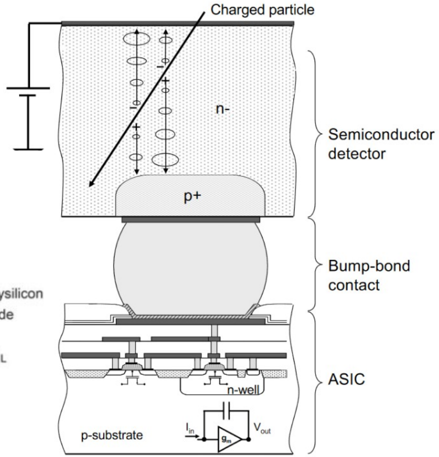
Alternative sensor technologies for direct X-ray/XUV detection



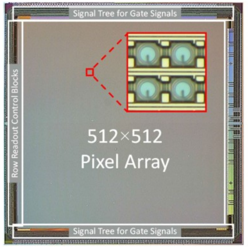
medipix.web.cern.ch

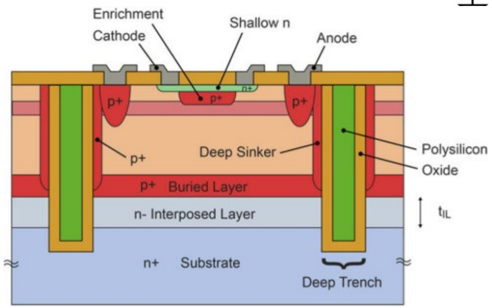
- "real" pixel sensors (e.g. via TimePix, MediPix readout-chip)
  - arbitrary sensor material (semiconductor, gas gain grid, MCP)
  - programmable measurement of counts/hits, deposited energy (per Time over Threshold - ToT), arrival time O(ns)
  - very high repetition rates
  - limited array size (but buttable layout possible)





- SiPM / SPAD array detectors
  - picosecond photoresponse
  - still limited in area / array size
  - limited fill factor (→ QE)





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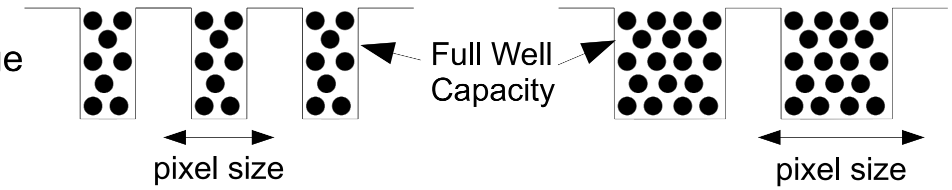
Comparison of CCD/CMOS imaging sensor technologies

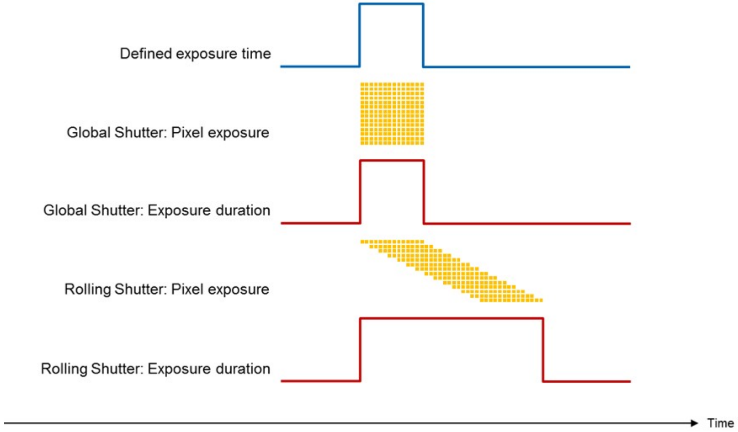
- common trade-off: pixel size
  → spatial resolution vs. dynamic range



	Scientific CCDs	sCMOS
Quantum Efficiency	High (20-90%)	Moderate (but close to CCDs)
Dynamic Range	100.000:1	20.000:1 (50:000:1 via HDR modes)
Read-out Noise	down to 2-3 e^-	1-2 e^-
Read-out Speed	up to 10-20 Mpx/s	~ several 100-1000 Mpx/s
Spatial resolution / pixel size	typ. 5-25µm	typ. 2-15µm
array size / (active area)	up to 9kpx × 9 kpx / (92mm × 92mm)	up to 6kpx × 6kpx / (62mm × 62mm)
Other (dis-)advantages	requires complex electronics light sensitive during read-out, CTE	easier hardware integration (no ADCs) more complex wrt. SW/FW design

Hardware platform for CMOS-based scientific cameras

- **present CMOS camera platform at greateyes needs to be extended / redesigned**
  - easier & faster electrical integration of different new CMOS sensor types and formats
  - increased external interface speeds
  - implementation of flexible sensor read-out firmware
    - use of different gain channels of many sensors
    - on-board image post-processing / calibration
    - use of rolling / global shutter modes (noise penalty)
    - region of interest (RoI) functions

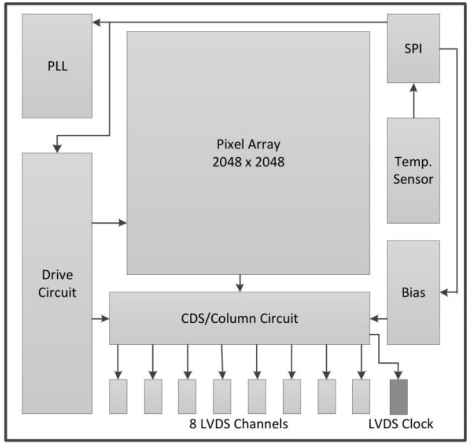


→ highest possible repetition rates (low dead times, low pile-up)

→ lowest possible read noise (high SNR)

Sensor interface & control

- SPI configuration interface
- CMOS-level I/O's for readout control (pixel reset, row selection)
- data transfer typically via multiple parallel high-speed LVDS lanes:
  - GSense400 2048(H) x 2048(V): 2.4 Gbps
  - Gsense4040 4096 (H) × 4096 (V): 9.6 Gbps
  - GSense6060 6144 (H) x 6144 (V): 21Gbps
  - HFR Sensors (e.g. GSPRINT4521): 192Gbps
- bandwidth of external interface / storage becomes limiting factor
- also puts high demands on on-board memory & FPGA resources
- for mid-sized sensors: integration of 10GbE / USB3.2 interfaces via PCIe



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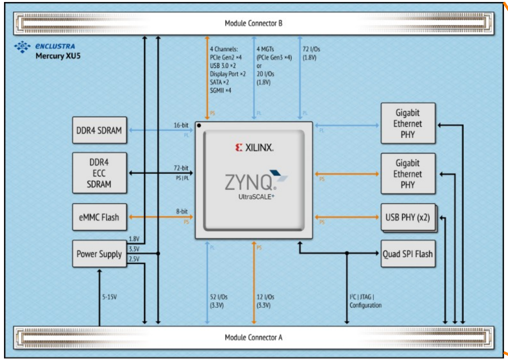
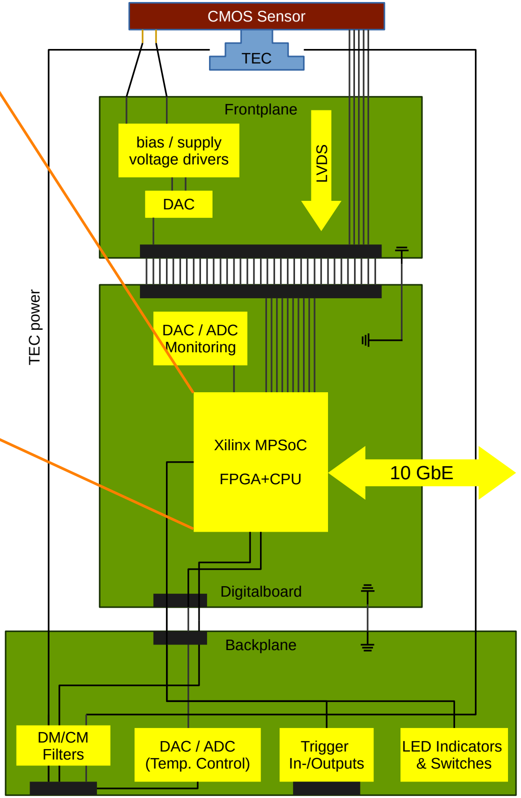
Camera Electronics Design

- follows strictly modular design
  - adaptable to different sensors via exchangeable Interface board
  - up to 32 high-speed differential links to sensor (e.g. LVDS)
  - modular central CPU/FPGA board



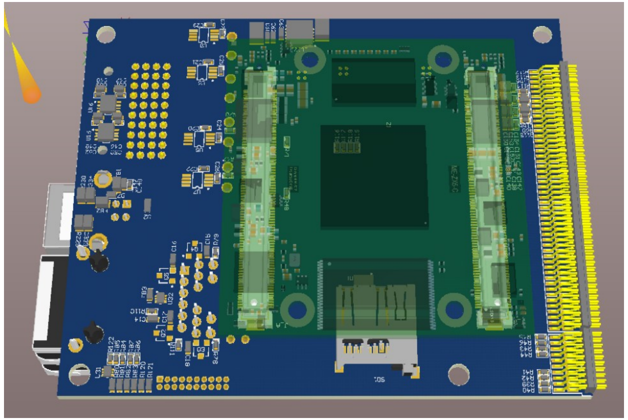


- Xilinx Zynq Ultrascale+ MPSoC Module (CPU+FPGA)
  - 2-4x ARM Cortex-A53 (64bit) + 2x ARM Cortex-R5 (32bit)
  - FPGA options: ZU2CG, ZU3EG/4CG/4EV/5EV
  - up to 8 GB DDR4 (PS) / 2 GB DDR4 (PL)
  - 64 MB QSPI flash, 16 GB eMMC flash + SD-card

Camera Electronics – status & features

- External interfaces:
  - 1Gb/s Ethernet & 5Gb/s USB3.0 interface already implemented & running
  - TODO: integration of PCIe interface & 10GbE MAC/PHY (flexible SFP+ socket for different media types)
  - I2C, SPI, UART, GPIOs (Switches, Status LEDs)
  - 2x/2x trigger input/output (flexible logic functions)

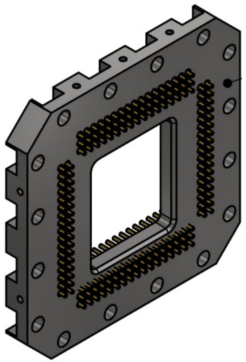
- Monitoring & Cooling:
  - Piranii sensor interface (to avoid condensation)
  - Monitoring of all sensor bias voltages (12bit ADCs)
  - Steering up to 4 thermoelectric coolers (I&V control)
  - max. 8 temperature sensors (e.g. thermistors)



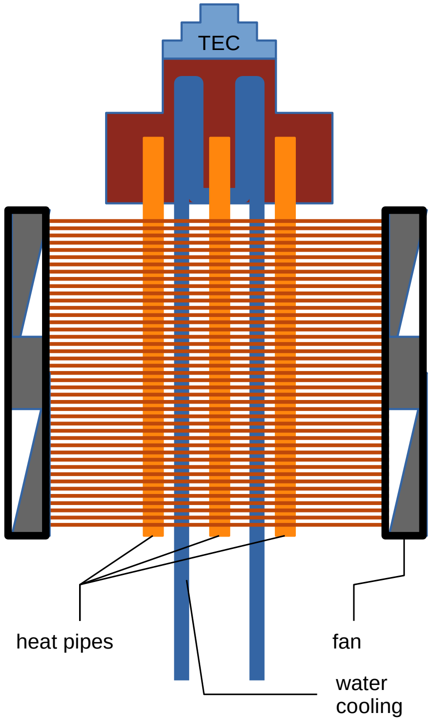
Mechanics & Cooling

- max volume/size of detector often is limited → small footprint
- number of vacuum feedthroughs heavily increased
  - ~20-80 (CCDs) → up to 250 pins (CMOS)
  - larger potential for leaks (thermal cycling)

  → investigating alternative feed-through techniques

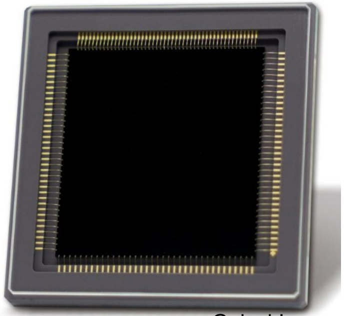


- higher demands on cooling system
  - sensor power dissipation much larger than of CCDs (~ x4)
  - power dissipation of electronics (dep. on FPGA size/load)
  - typ. 50-200W need to be removed → water cooling option mandatory



Integration of first sensor candidate

- **First prototypes using Gpixel GSENSE-400BSI back-illuminated CMOS sensor**
  - prototype samples of X-ray / XUV optimized version now available for evaluation
  - 2048(H) x 2048(V); 11µm x 11µm pixels → active area 22.5mm x 22.5mm
  - 24 fps @HDR mode (2x12bit /pixel) / 48 fps @STD mode (1x12bit /pixel)
  - Full well capacity: 90 ke^-; readout noise: 1.6 e-
  - Electronic Rolling Shutter
  - Data interface: 8xLVDS @300Mbps (2.4Gbps)

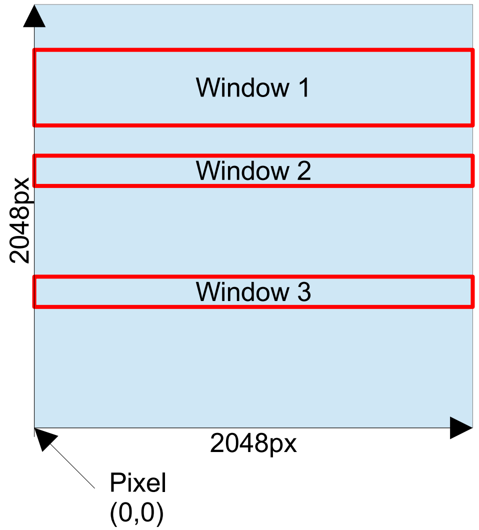


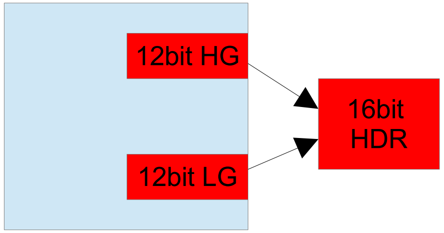
Gpixel Inc.

- **first batch of electronics & sensor interface boards powered up**
  - sensor configuration interface + data link & training is working
  - next steps: get "real image" & implement correction / post-processing algorithms

Firware & Software features

- **Windowing (RoI) operation**
  - on sensor: often only in vertical direction
  - on camera: fully flexible (reduces data rate on ext. interface)
- **HDR image composition**
  - image signals readout from the PGA high gain (HG) and low gain (LG) channel simultaneously row by row after exposure
  - digitized with on-chip 12-bit ADC respectively
    → two images are readout
  - combine HG and LG image to generate "16bit" HDR image on camera
  - all channels configured with same gain setting
    → two different rows readout at the same time (frame rate is doubled)
- GUI & SDK; TANGO/EPICS drivers; interfaces for setup & monitoring





Summary & Outlook

- **present CMOS camera platform at greateyes is extended / redesigned**
  - flexibility to accommodate different new CMOS sensor types and formats
  - implementation of key read-out functions (RoI, HDR, rolling/global shutter)
    - → highest possible repetition rates → O(100fps), low dead times
    - → lowest possible read noise → O(1e^-)
- **finalize design & assembly of 1st prototype**
- **proof of principle & characterization at MBI**
  - quantum efficiency, spatial resolution,repetition rate, pixel charge capacity, response linearity, read-out noise & dark current (→ SNR), ...

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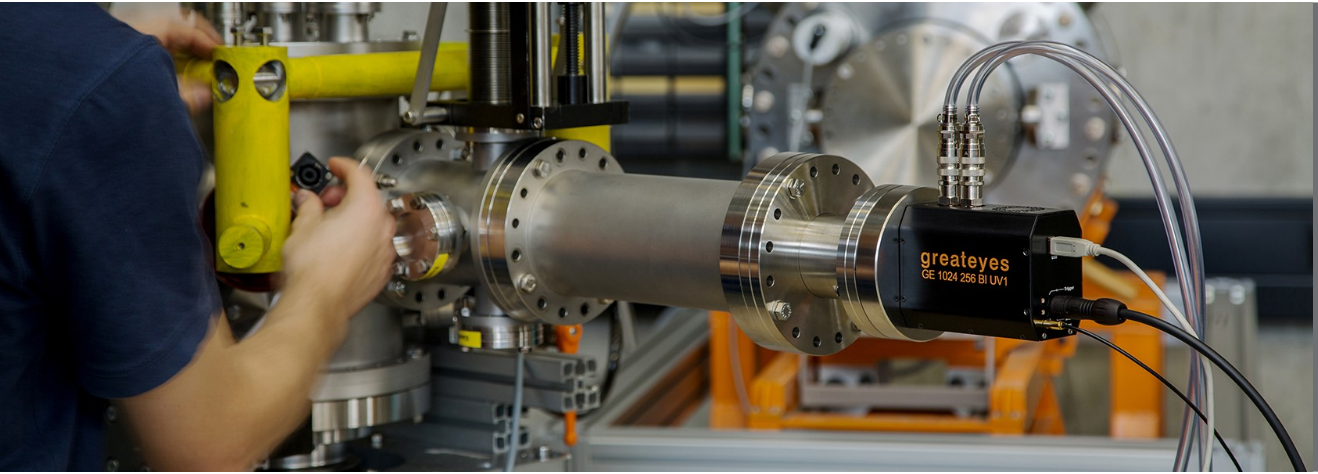
Thank You!



- High quantum efficiency from NIR to X-ray
- Low readout noise
- Deep cooling
- High dynamic range
- Compact design
- Broad portfolio
- Customized solutions

Scientific high-performance CCD cameras

→ More than 50 different cameras for X-Ray, EUV, UV, VIS and NIR applications

→ Pixel arrays: 1024 × 128/256/1024, 2048 × 512/2048, and 4096 × 4096

→ Read noise of 2.4e$^-$, Cooling down to -100°C, 16/18 bit ADC

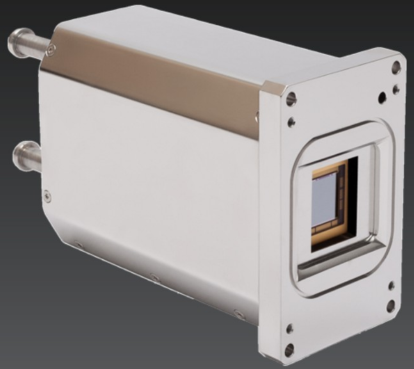
Scientific CCD Camera Portfolio

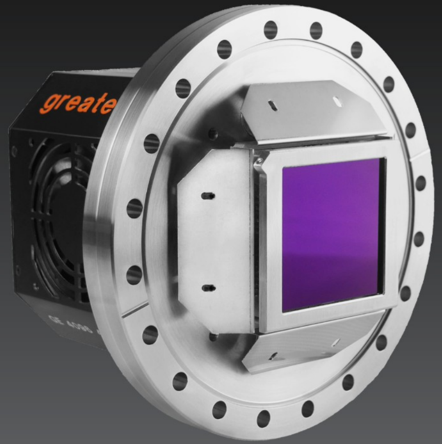
NIR / VIS / UV

- ➔ window flange series
- ➔ vacuum head
- ➔ more than 20 models

- ➔ vacuum flange series
- ➔ more than 15 models

EUV & Soft X-Ray Detectors





- ➔ in-vacuum series
- ➔ more than 10 models

- ➔ wafer-scale camera

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