ePixM: a fully-depleted active pixel sensor for soft X-ray experiments at high-repetition rates FELs

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International Workshop 21st iWoRiD on Radiation Imaging Detectors

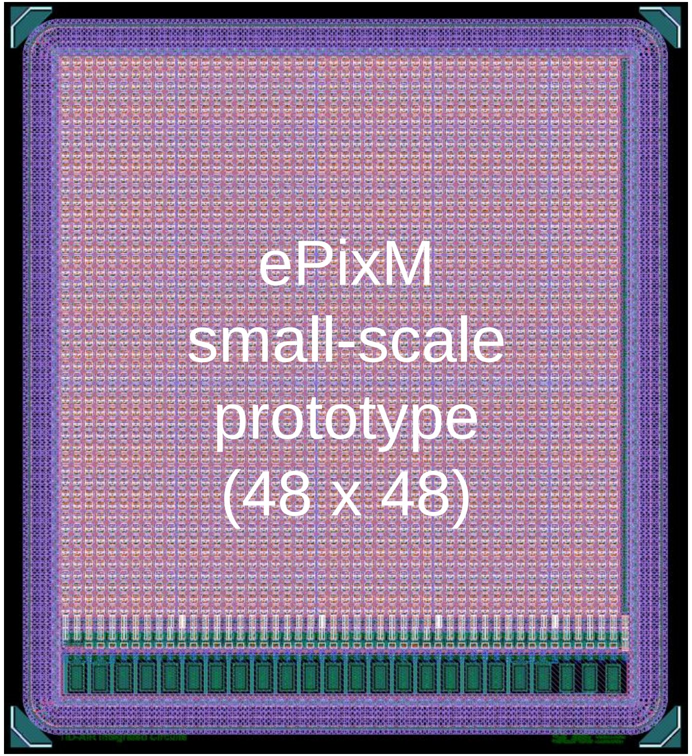
U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

ePixM: overview

Main design features:

- 150 nm CMOS technology
- High-resistivity substrate
- 15 kHz frame-rate (7 kHz first prototype)
- 50 µm pixel size
- 384 x 192 pixels (butteable)
- Single-photon detection @ 250 eV
- Noise < 15 e^-
- Dynamic range > 10^3 photons
- Automatic gain-switching



Motivation: from LCLS to LCLS-II…

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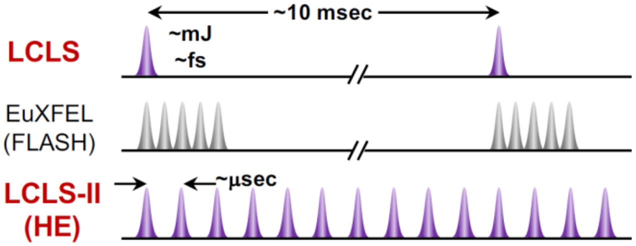
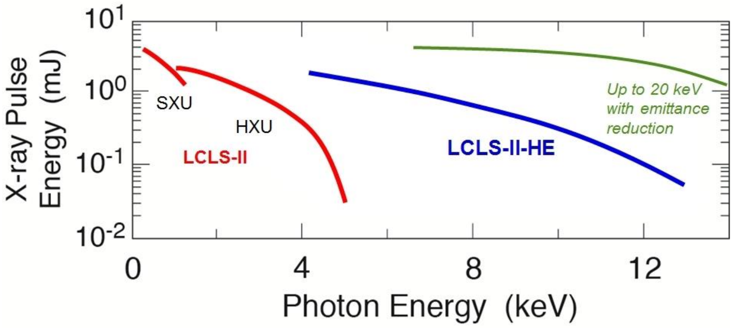
Linear Coherent Light Source II:

- X-ray Free Electron Laser @ SLAC
- First light: 2020/21
- Rep-rate: 1 MHz, evenly spaced
- Soft X-ray detectors needed, with ≥ 5 kfps and ≥ 0.5 MPixels





SLAC – TID-AIR Detector Group

TID-AIR

Largest Detector team in US focused on the development Photon Science X-Ray cameras for FELs and Synchrotron Sources

R&D on X-Ray cameras from concept to production and characterization

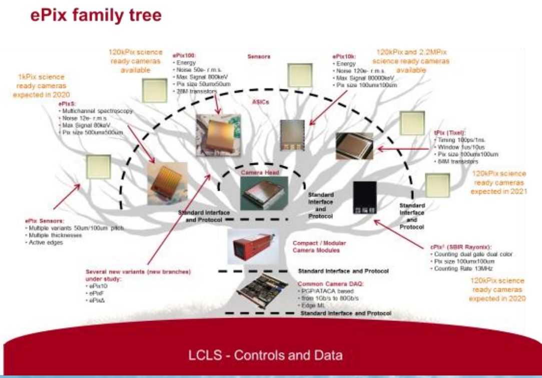
- Camera System design
- Sensors Design and Fabrication
- ASIC Design
- Camera DAQ
- Camera Mechanics
- Characterization and Calibration

Highlights:

ePix - Pixel Array Detectors for FELs

120Hz family of cameras 6 variants

(3 available now)



Ongoing Projects:

- 3rd Generation FEL cameras for LCLS-II:
  - ePixHR family 5   25kHz
  - ePixM (this talk)
  - Tixel – 100ps ToF sparse
- 4th Generation FEL cameras for LCLS-II / HE:
  - ePixUHR family 100kHz
  - SparkPix family – Intelligent 1MHz Experiment Specific X-Ray Cameras (ESXC)
- Camera variants for SR and DLSR:
  - cPix^2 – Gated photon counter

260 kPix science ready prototype camera

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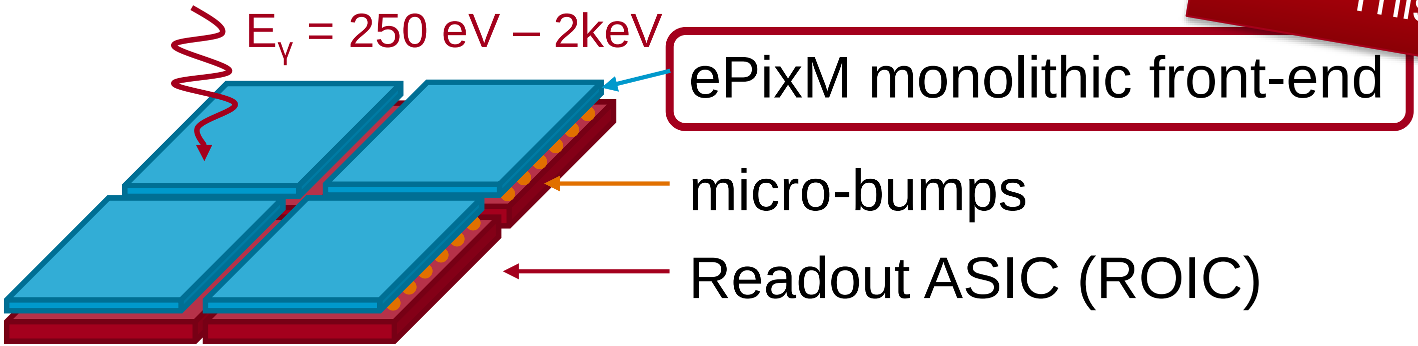
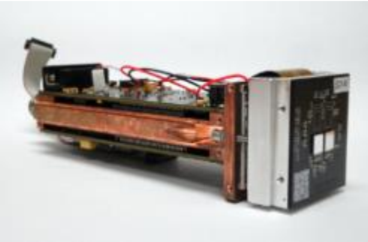
This talk

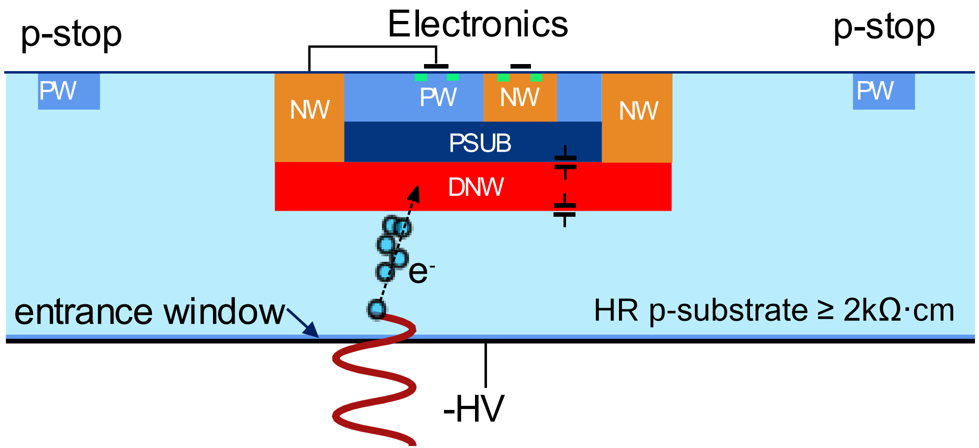




- ePixM front-end bump-bonded to ROIC
- Total of 4 ePixM+ROICs butted together, for a total of 260 kPix
- ROIC: 768 SigmaDelta ADCs @ 780 kS/s, 14b resolution [1]
- Readout rate: 7/15 kHz
- Same DAQ/mechanics/etc of other ePix detectors [2]
  → minimize commissioning effort
- 1 Mpix shingled science camera in 2023

[1] Caragiulo P. *et al.*, Design and Characterization of a high-rate readout backend for ePix detectors at LCLS II, NSS-2018
[2] Dragone A. *et al.*, ePix: a class of architectures for second generation LCLS cameras, doi.org/10.1088/1742-6596/493/1/012012

Fully-depleted monolithic pixel sensor architecture



$$C_d = C_{DNW-SUB} + C_{DNW-PSUB}$$

$$\mathrm{ENC} \propto {g_m}/{C_d} \quad \text{(thermal)}$$

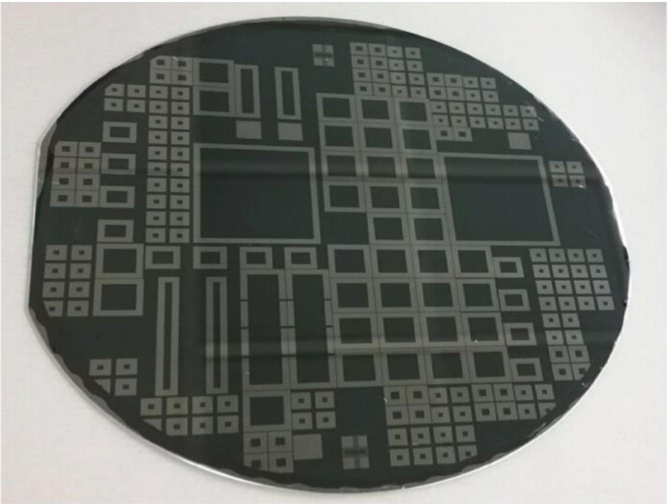
Trade-off:
C_D (noise) - Area (complexity)

- HV applied on backside: full-depletion, charge collected by drift
- Electronics sits in deep n-well (DNW), which also acts as collection node
- Additional deep p implant (PSUB) isolates NW (PMOS transistors) from DNW
- P-stop around pixels, guard rings at chip periphery
- Wafers thinned and back-processed (final thickness will depend on $V_{breakdown}$)
- Similar architecture proposed for ATLAS inner tracker upgrade [1]

[1] Hemperek T., LF-MONOPIX a depleted monolithic CMOS pixel sensor in a 150 nm CMOS technology for the ATLAS Inner Tracker upgrade, FEE2018

Thin entrance window for soft X-rays

- Wafers post-processed by SLAC to form thin entrance windows on the backside
- MicroWave Annealing (MWA) process is robust, inexpensive and fast
- Sensors with thin entrance window bonded to ePix250s and ePix10k-Tender prototypes
- No degradation observed in Si sensor due to window process

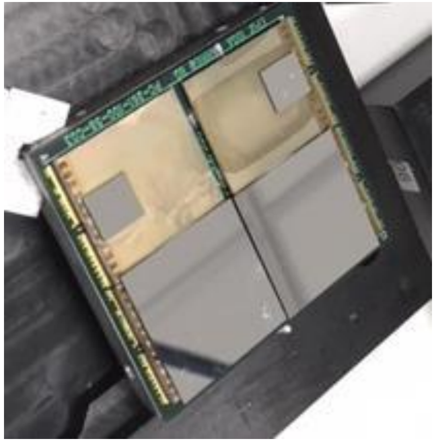


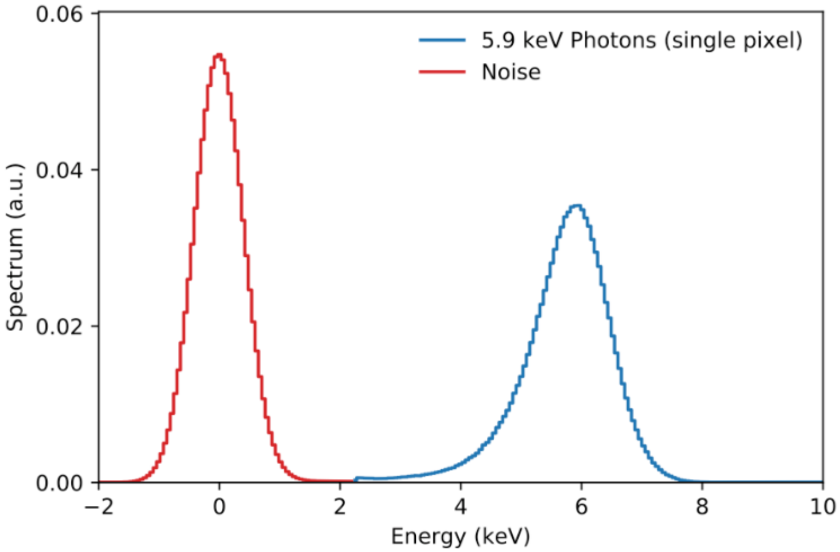
Backside of a SLAC-made sensor wafer for ePix detectors (courtesy of J. Segal, J.Hasi, L. Rosario & C. Kenney)

Results published in:

Segal J. *et al.*, Thin-Entrance Window Sensors for Soft X-rays at LCLS-II, NSS-MIC 2018

Si sensors with thin entrance window & ePix250s

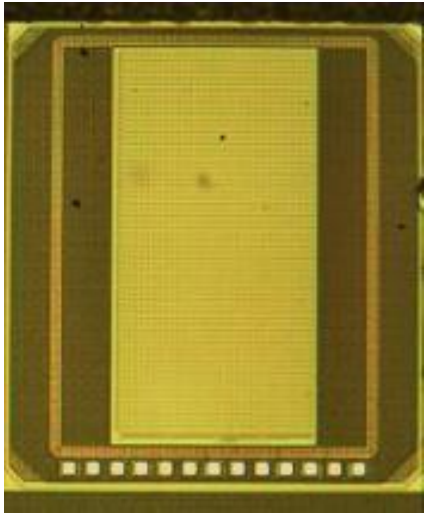




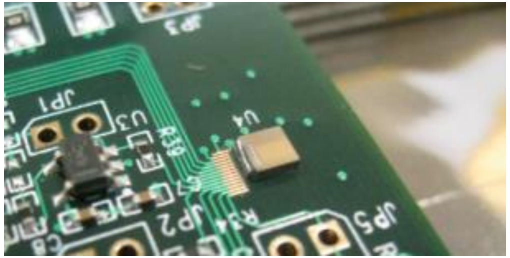
- Sensor leakage contributed 6 electrons of noise when cooled to -20C
- No damage to sensor window observed

ePixM: early prototype 2017

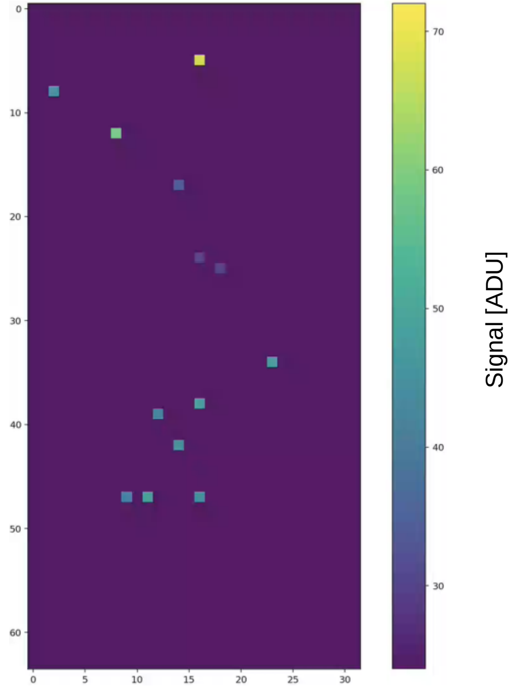
- **Purpose:** evaluate technology for X-ray applications



64x32 pixel
sensor picture

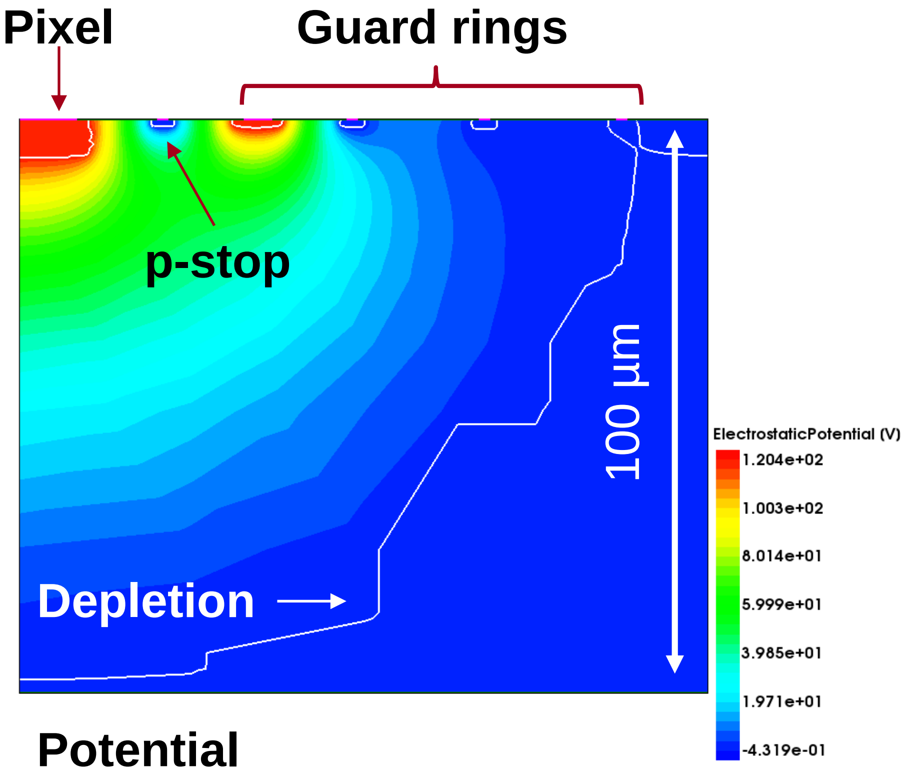


Sensor wire-bonded
to readout card

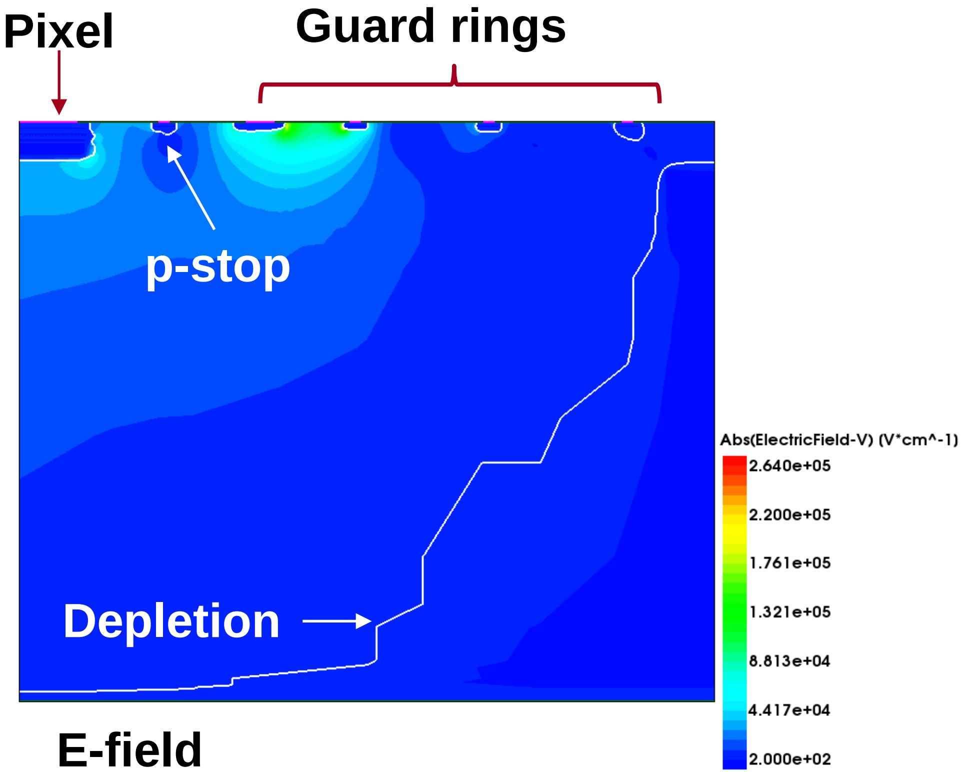


^{55}Fe live acquisition

TCAD simulations

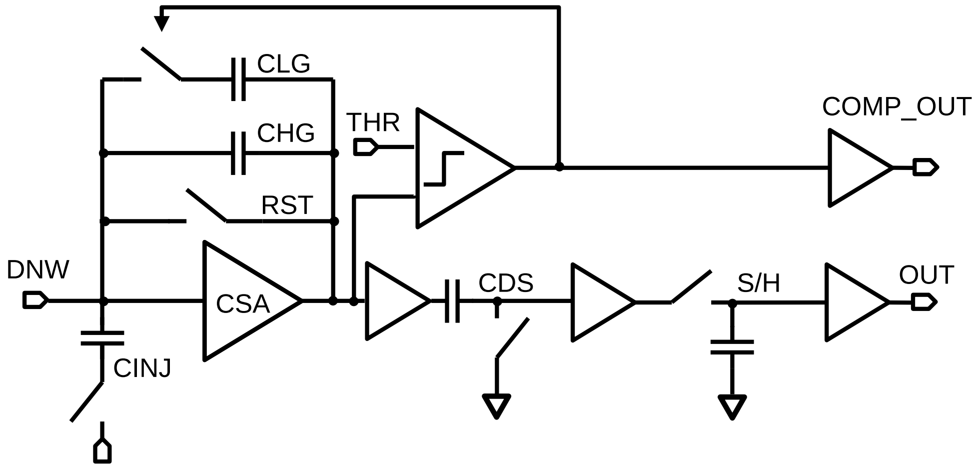


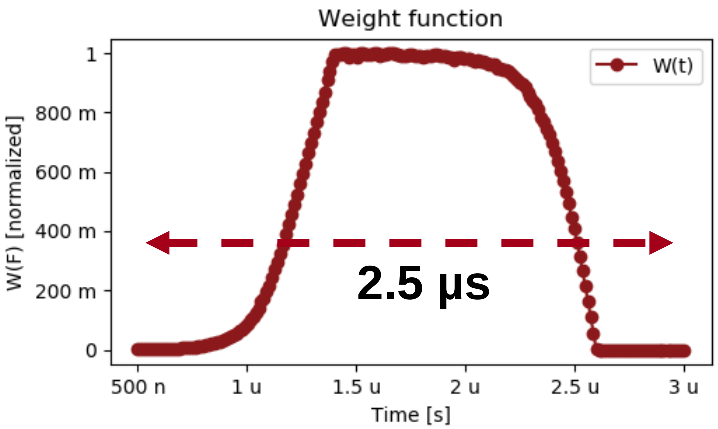
Potential



E-field

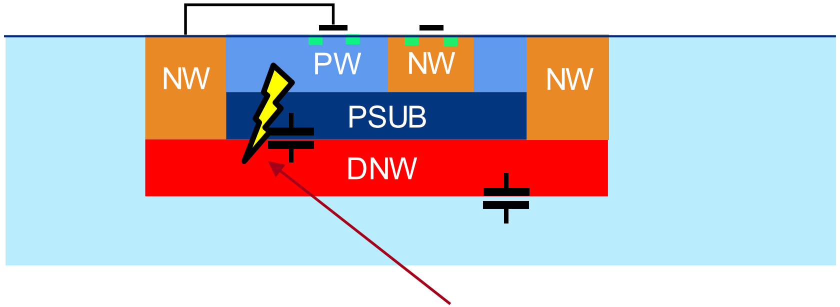
ePixM: pixel electronics





- Charge Sensitive Amplifier (CSA) with auto-ranging capability
- Injection capacitance for calibration
- Correlated Double Sampling (CDS) → quasi-trapezoidal shaping
- Pre-charge feedback cap to extend DR and reduce noise when switching gain
- Sampling stage and 2x column buffers for analog and comparator (gain)

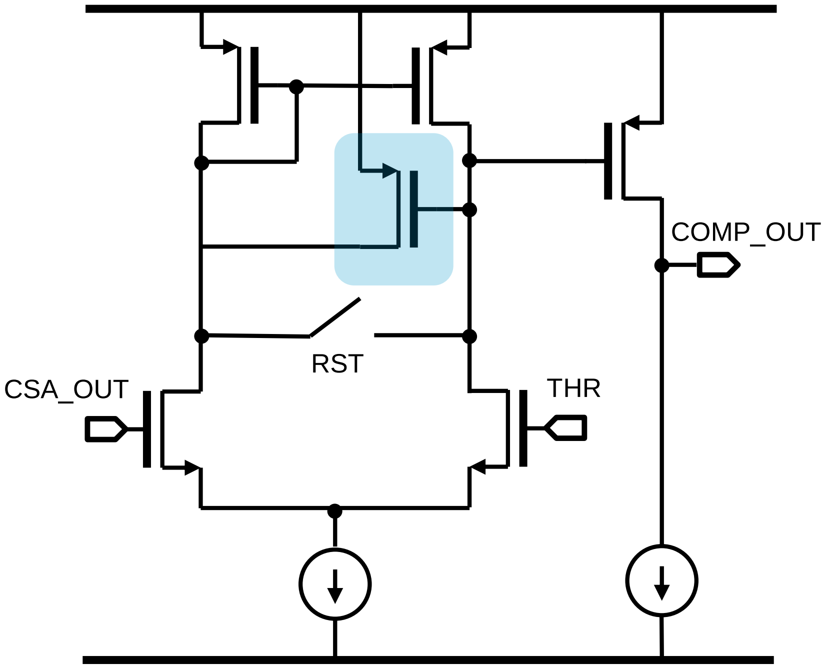
Comparator + SR latch



Noise from digital circuits couples through $C_{DNW\text{-}PSUB}$ to DNW (input!)

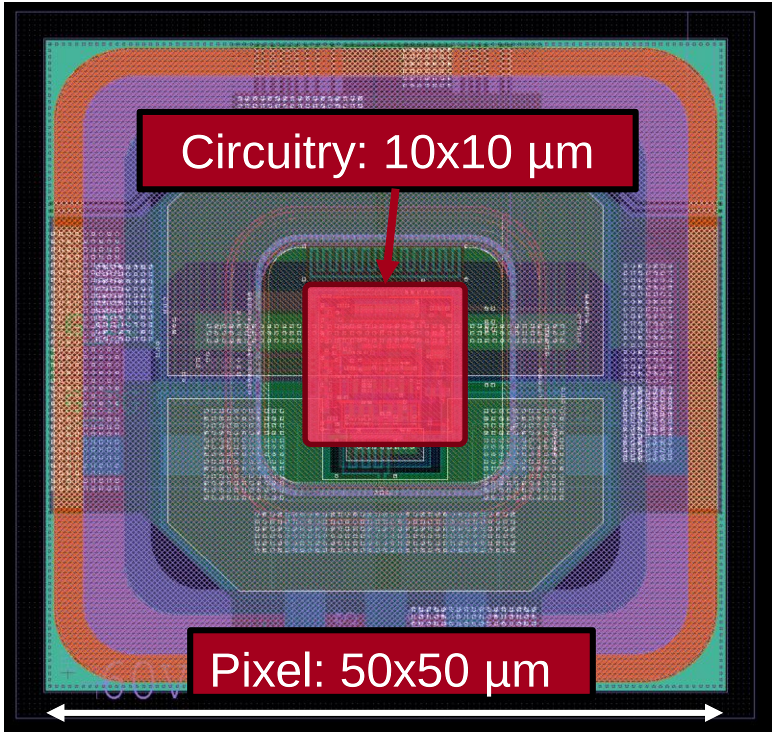
→ **Minimize area**: uses only 9 transistors
→ **Reduce PW noise**: avoid std CMOS logic

“SR latch” functionality added to comparator with positive feedback loop + RST switch



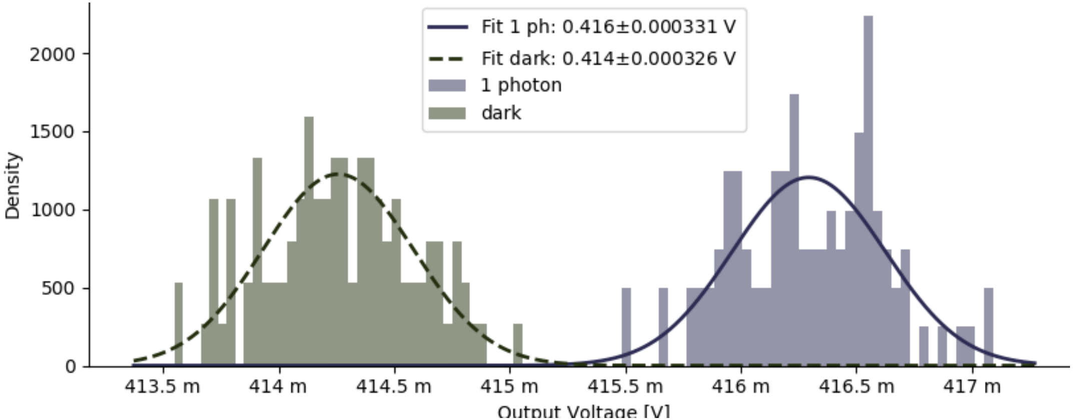
Post-layout simulations: noise

Layout of one pixel



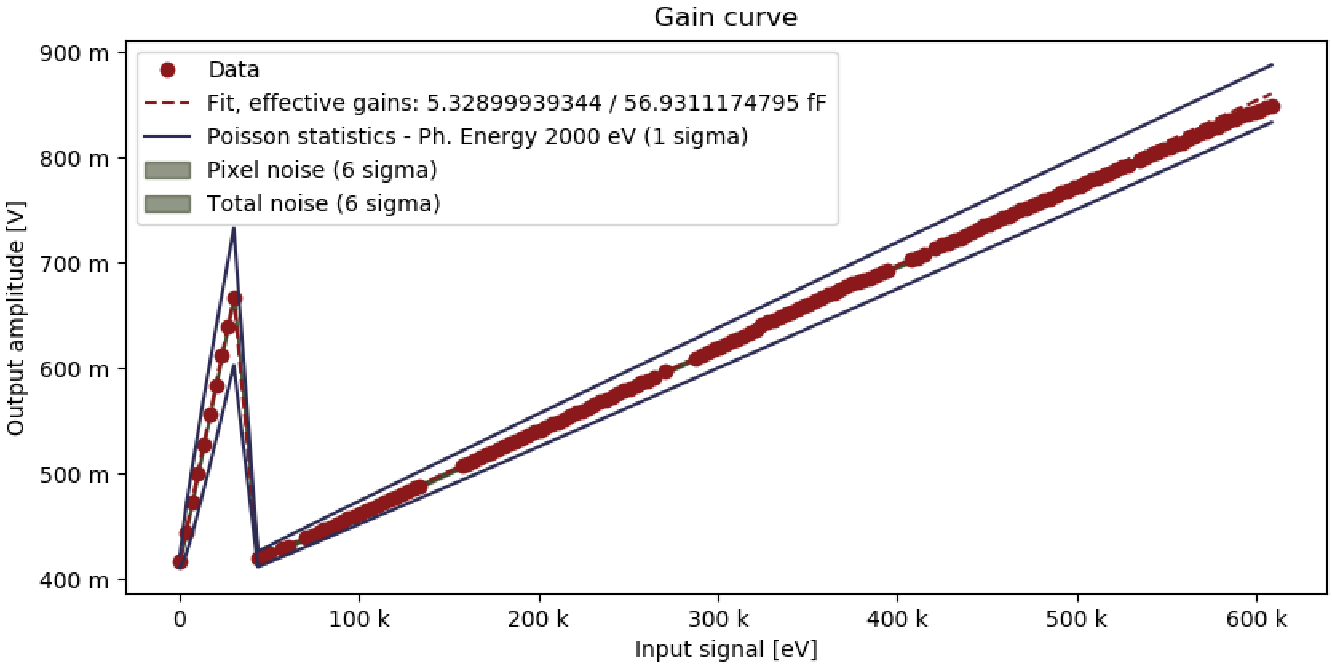
Equivalent Noise Charge (ENC) simulated at room temp, assuming C_{Det} = 70 fF:

- High-Gain = 11.3 e^-
- Low-Gain = 90 e^-



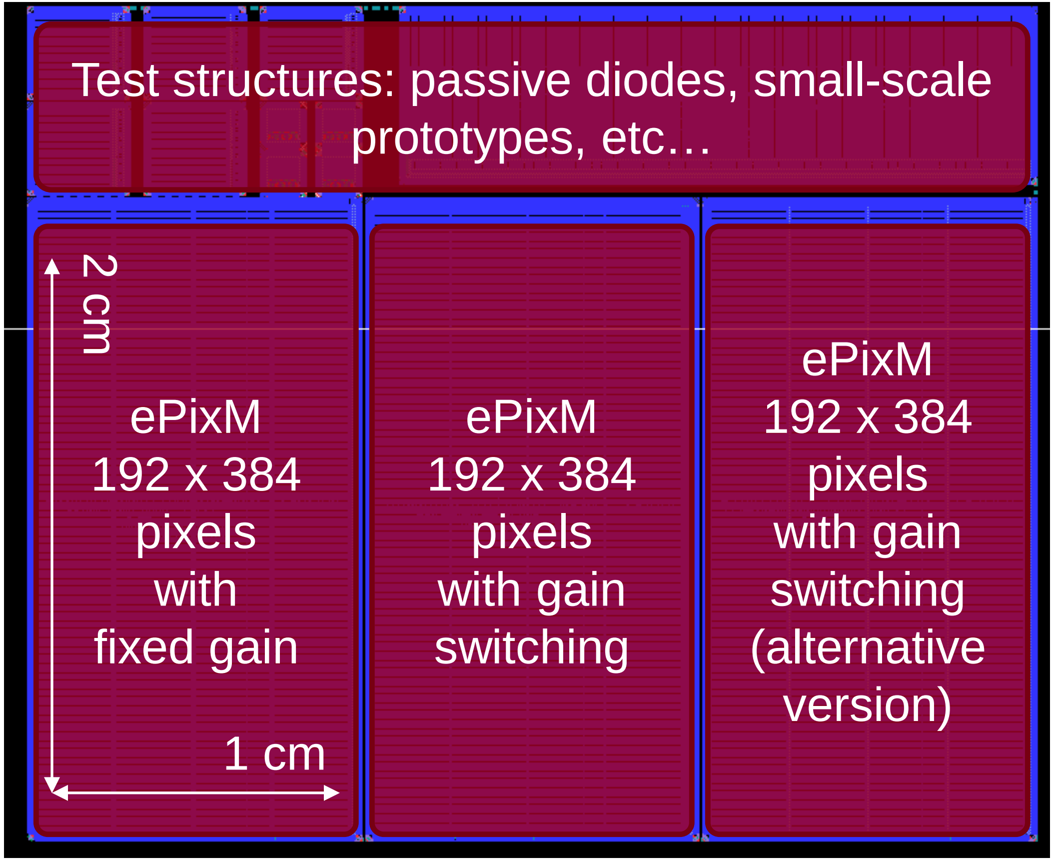
Post-layout simulations: automatic gain-ranging

- Noise and non-linearity well below Poisson limit over whole range 250 eV – 500 keV (limit shown for worst-case: photons @ 2 keV)



Conclusion

- Early prototype: demonstrated that technology is suitable for X-ray applications
- ePixM: results from post-layout simulations meet design specs in terms of noise, dynamic range and functionality
- Dedicated run in March 2018



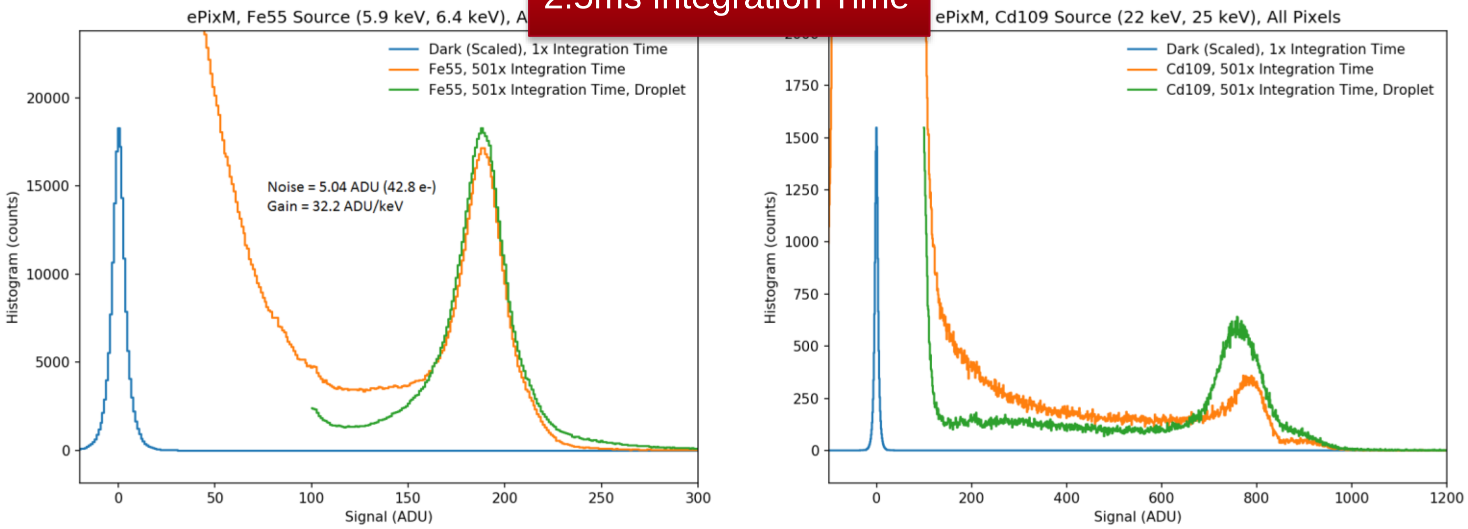
Outlook:

- Readout ASIC for ePixM is being submitted this week
- First measurements: Q4 2019

BACKUP SLIDES

Prototype results - bench test with sources

2.5ms Integration Time

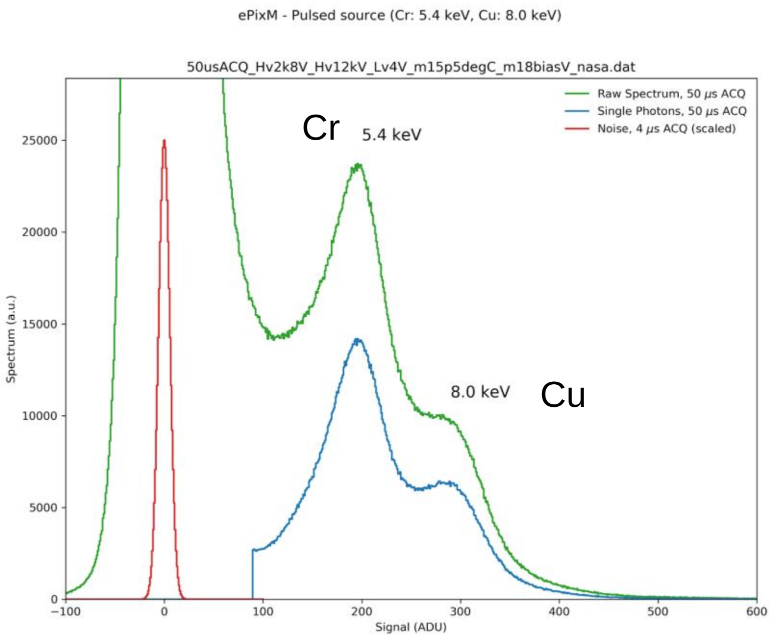


Bias voltage 20V only (instead of 120V):

- Not fully depleted-higher capacitance-higher noise
- Charge sharing also limits resolution

Spectra resolution affected by the long integration time of 2.5 ms vs 5 µs (expected at LCLS)

Prototype results - pulsed



- Synchronized measurement with 50us integration
- Resolution dominated by charge sharing and partial gain calibration

Noise at LCLS integration time: 42 e- (spectra at 50 us higher noise 68e- but n/a for LCLS)

High quantum efficiency at carbon edge

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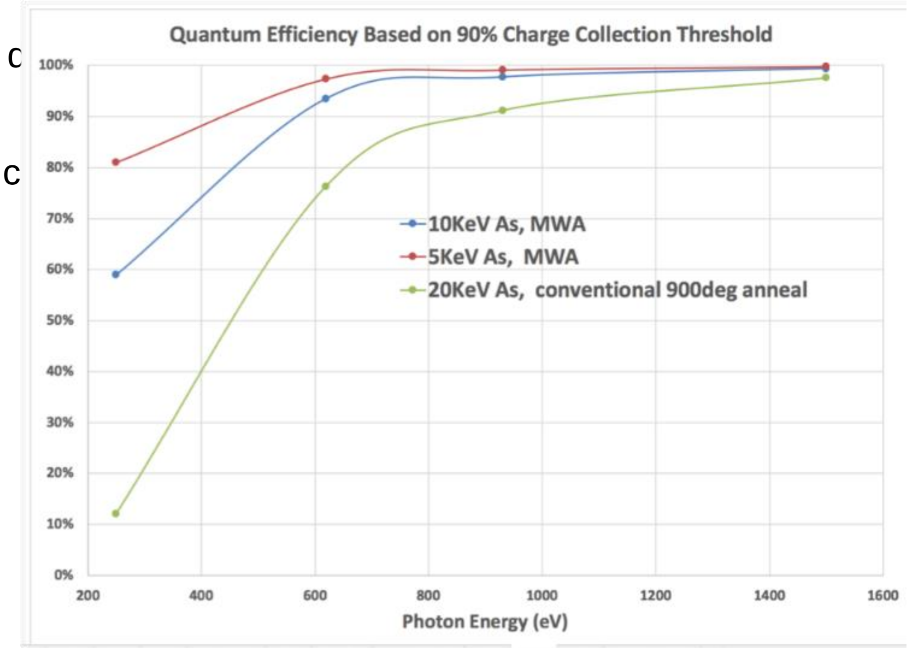
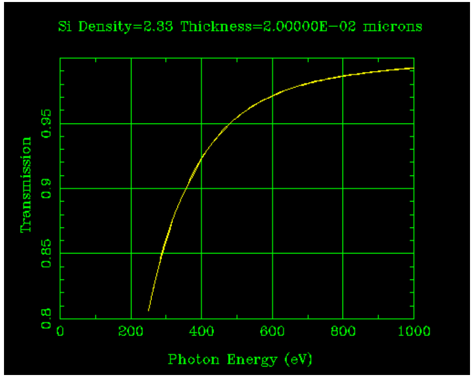
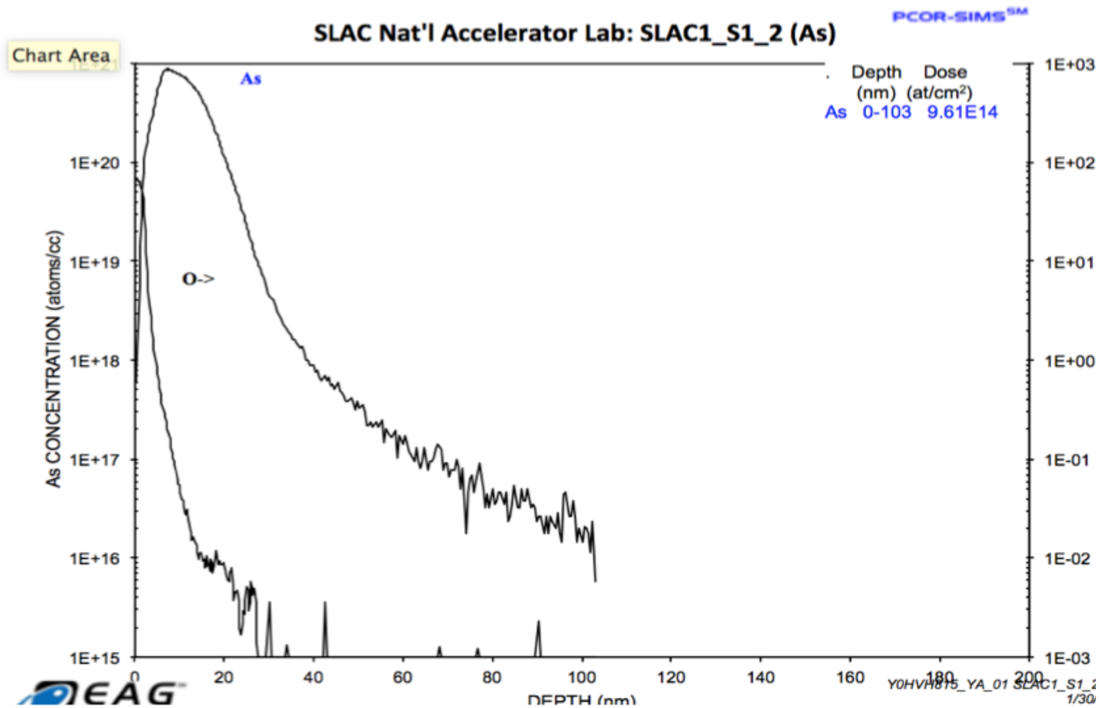
- 20 nm is 84% transmission at 279 eV
- Sensors usually have to have a thin aluminum film c
  protect detector from sample material
- Both of the above can be the dominant attenuating c

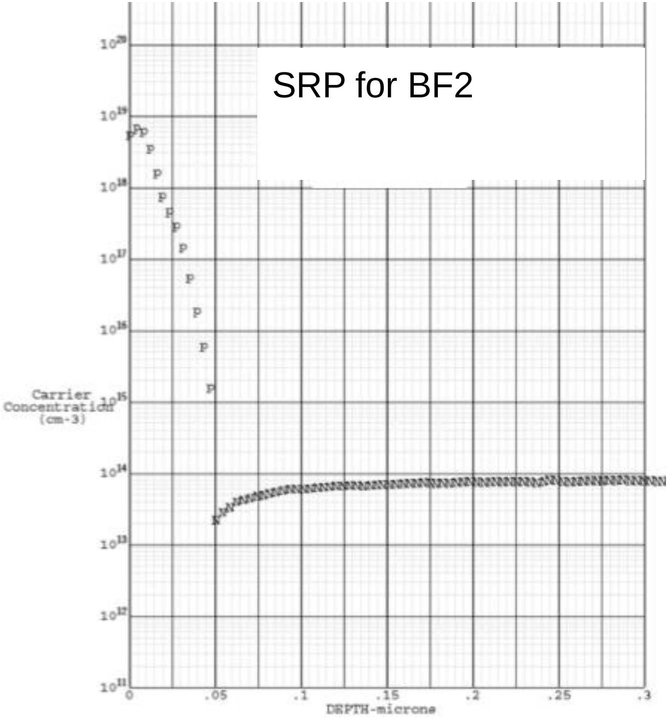


Synopsys simulations (J. Segal)



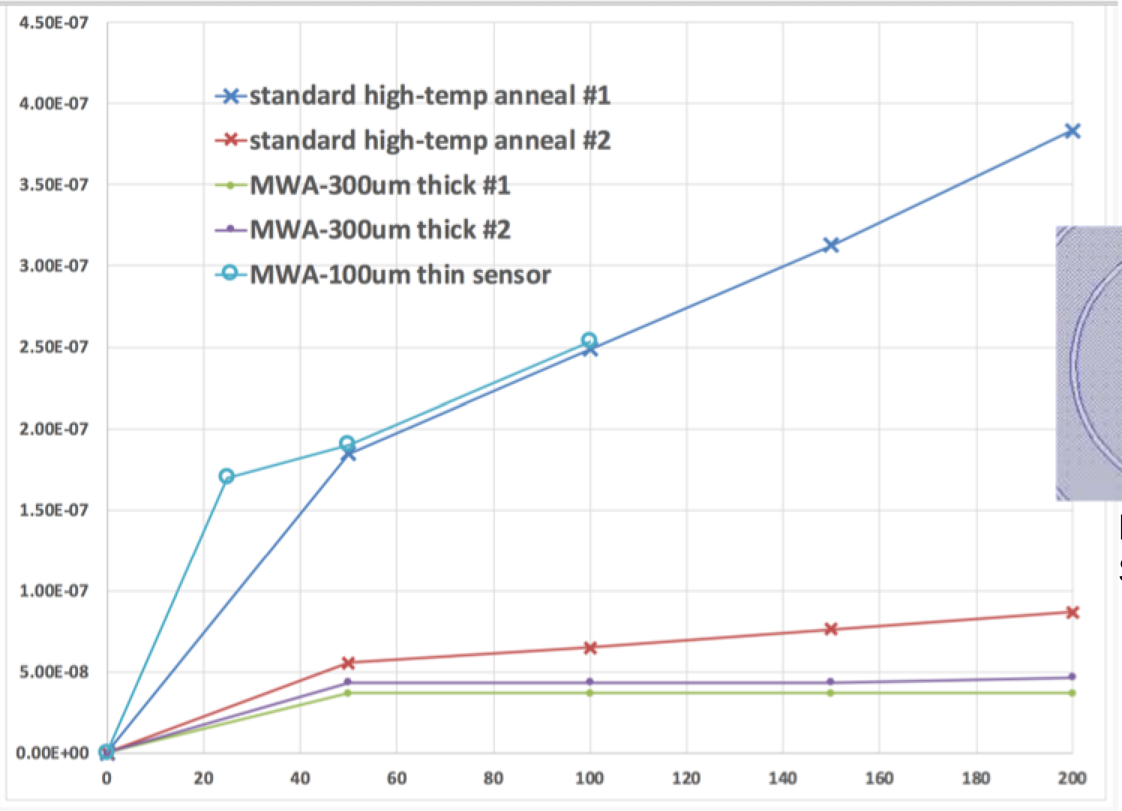
Shallow As distribution shown by SIMS and SRP

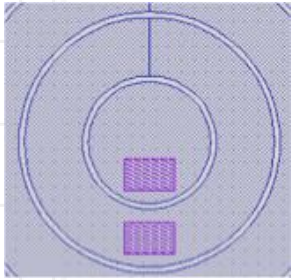




50 nm

No degradation in sensor due to window process





IV Test Structure