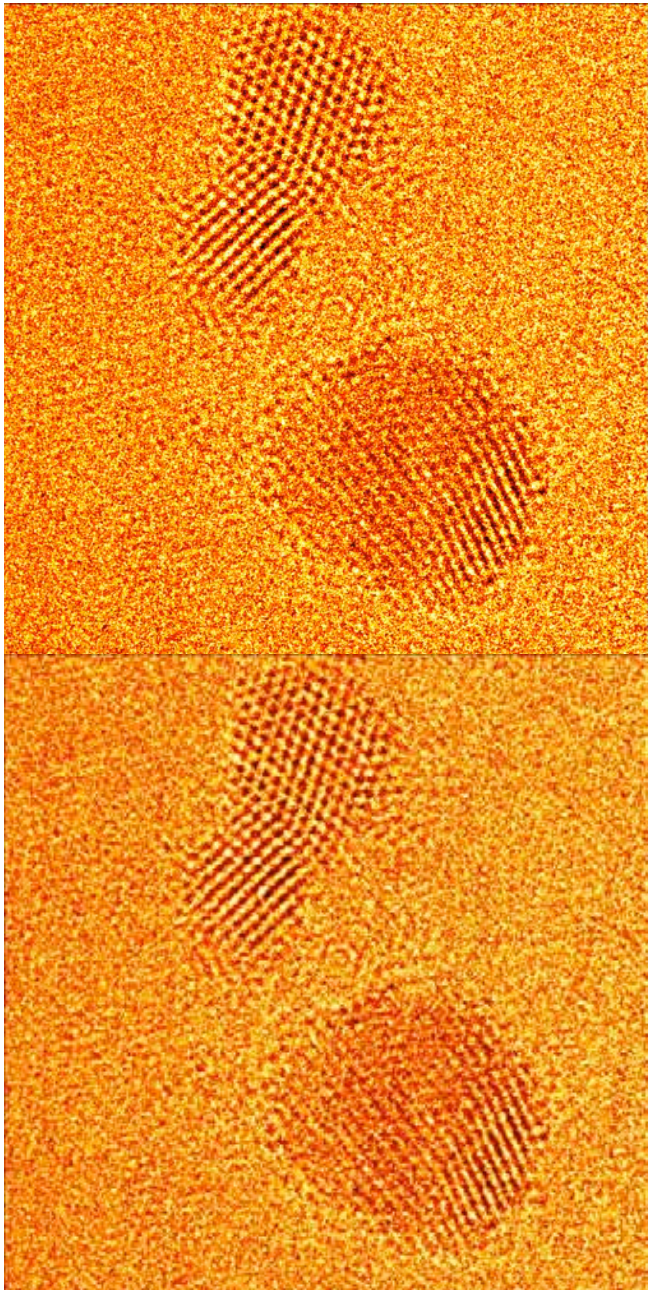
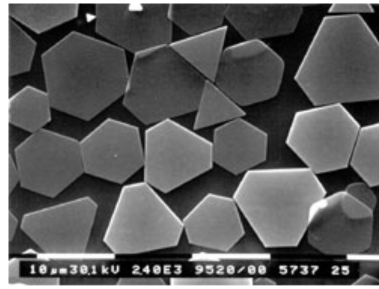
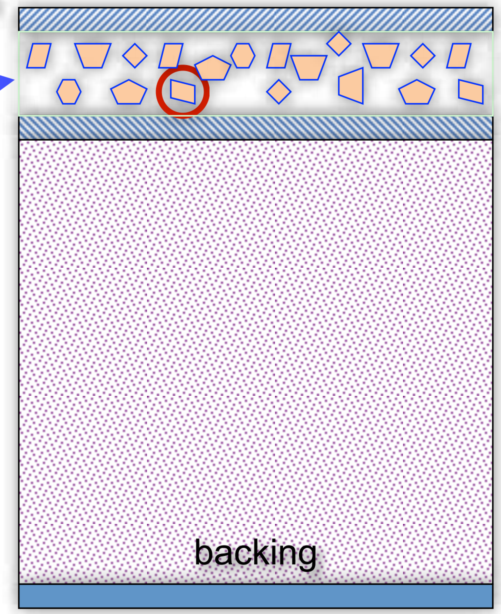
Development of Monolithic Active Pixel Sensors in 65 nm CMOS Technology



Transmission Electron Microscopy Detectors



Electron micrograph of tabular grain emulsion



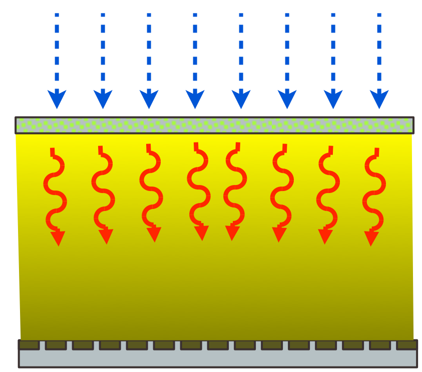
Digital

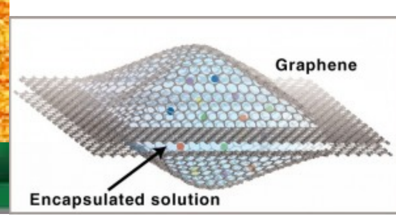
Analog

Phosphor

Fiber Optic

CCD





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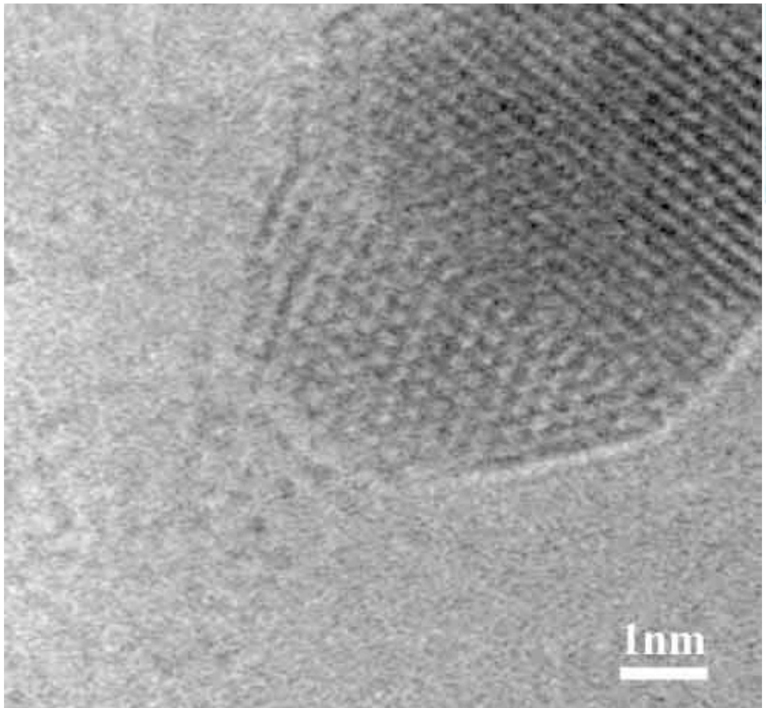
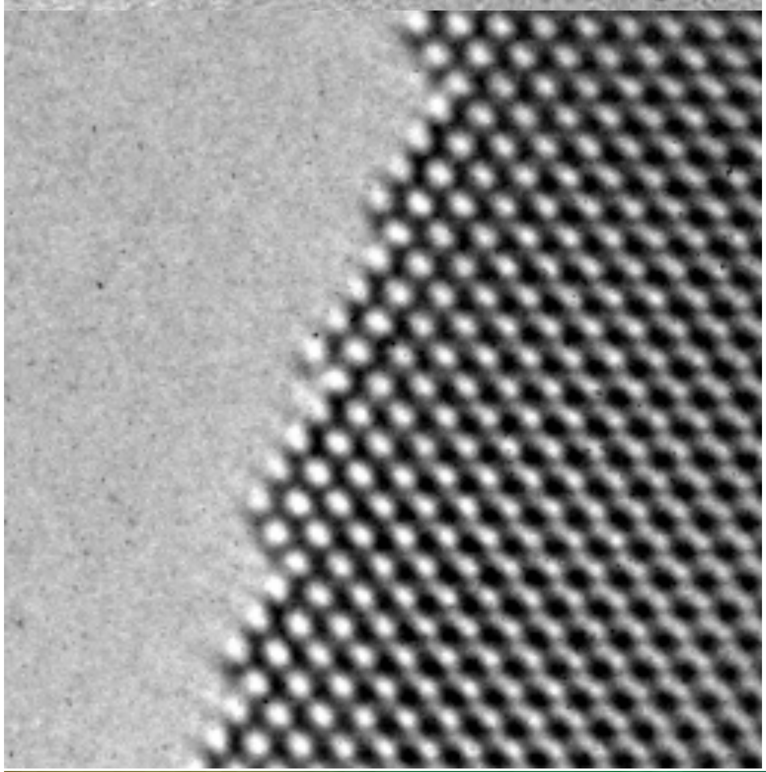


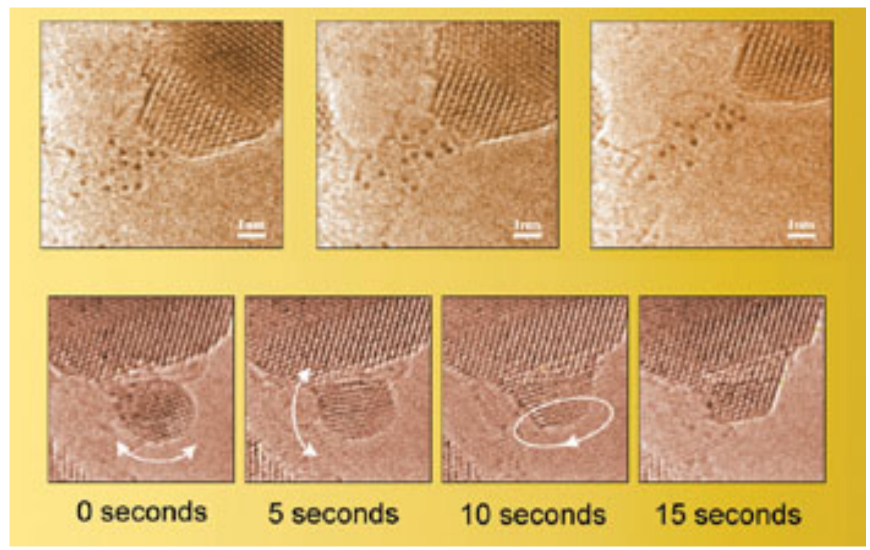


A Golden Opportunity: Watching the Atoms Dance

December 19th, 2003

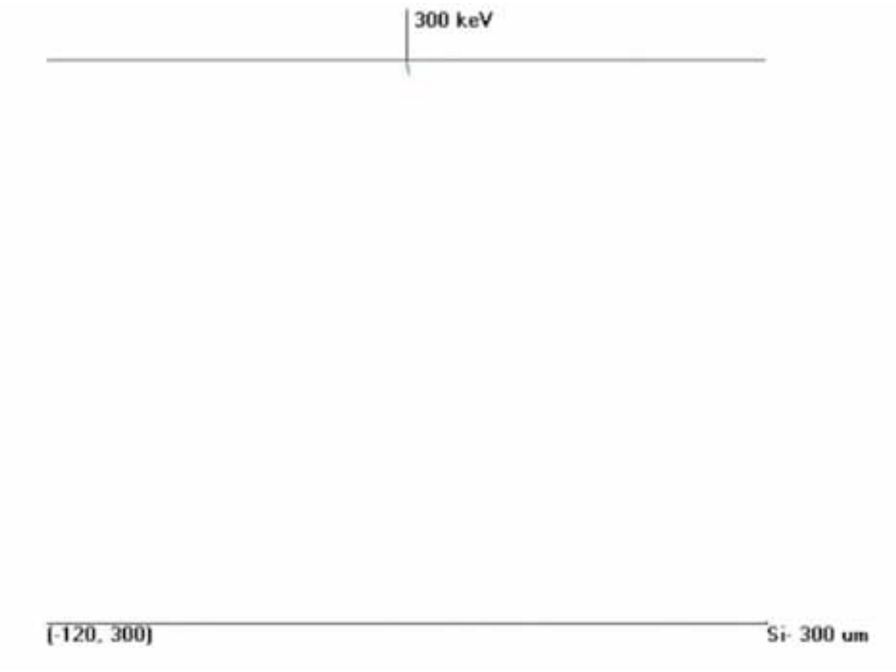
At the National Center for Electron Microscopy (NCEM) some months ago, Chris Nelson was helping a Life Sciences Division group investigate gold particles, useful for labeling protein structures. Nelson noticed unusual movement under the microscope, and when the users broke for lunch, he got their okay to record video images.

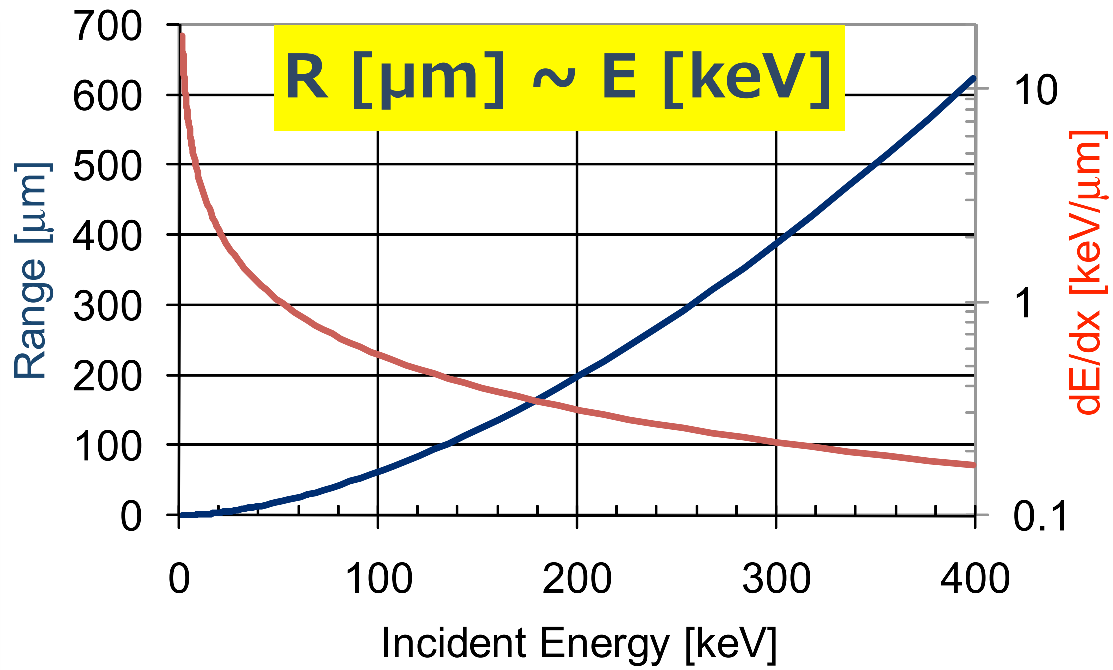
What Nelson captured on video was an extraordinary phenomenon: visible against the background of the thin carbon film that supported the samples were individual atoms of gold, moving about and attaching themselves to gold crystals.

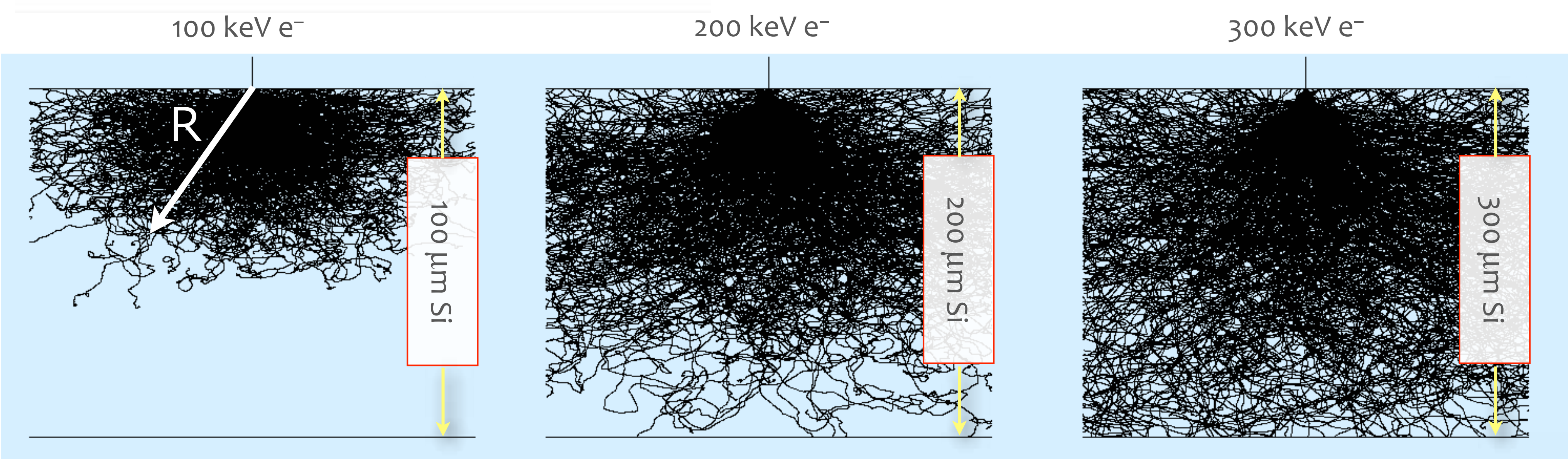


Top: In a video made by NCEM's Chris Nelson, individual atoms of gold (lower left) are seen migrating to join a growing gold crystal (upper right).
Bottom: In this video sequence, a gold nanocrystal continually reorients itself in three dimensions before finding just the right way to fit onto the larger crystal. White arrows indicate examples of the directions of this rapid movement.

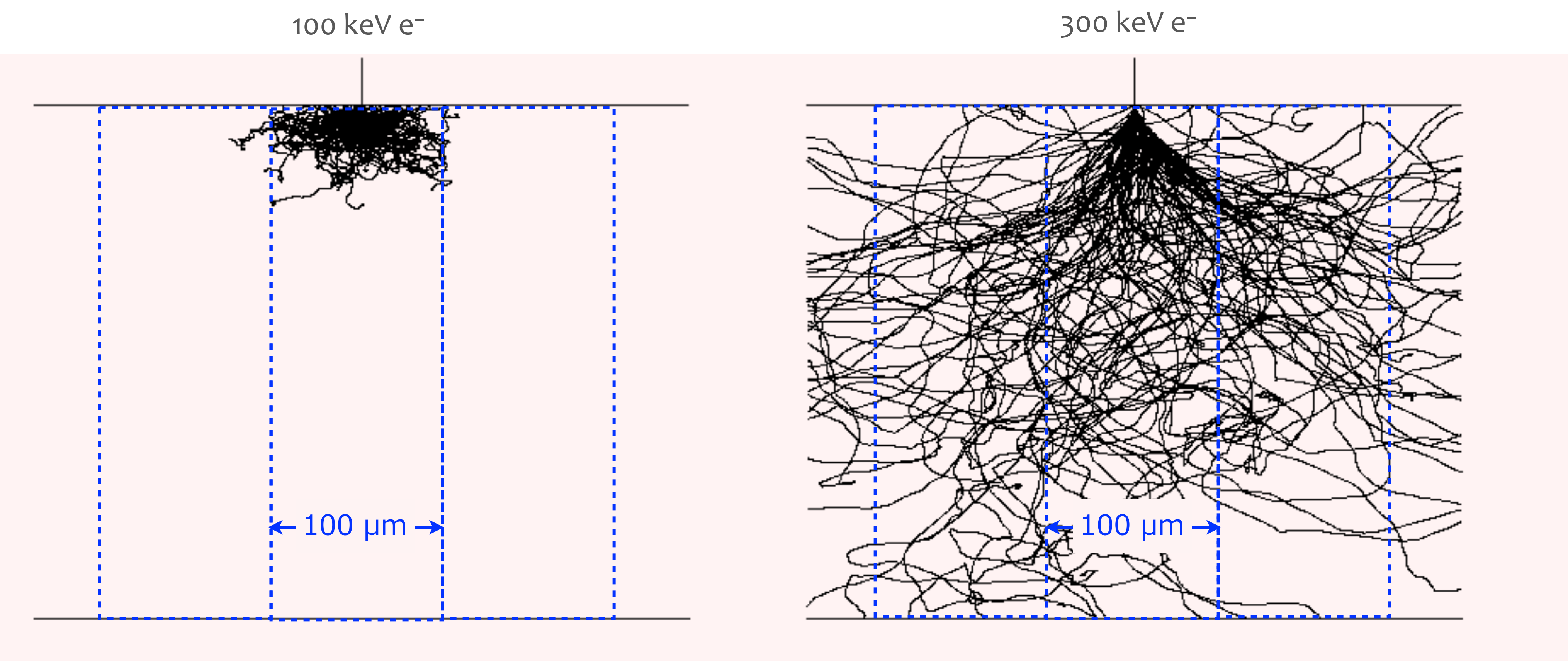
e⁻ Detection in Silicon





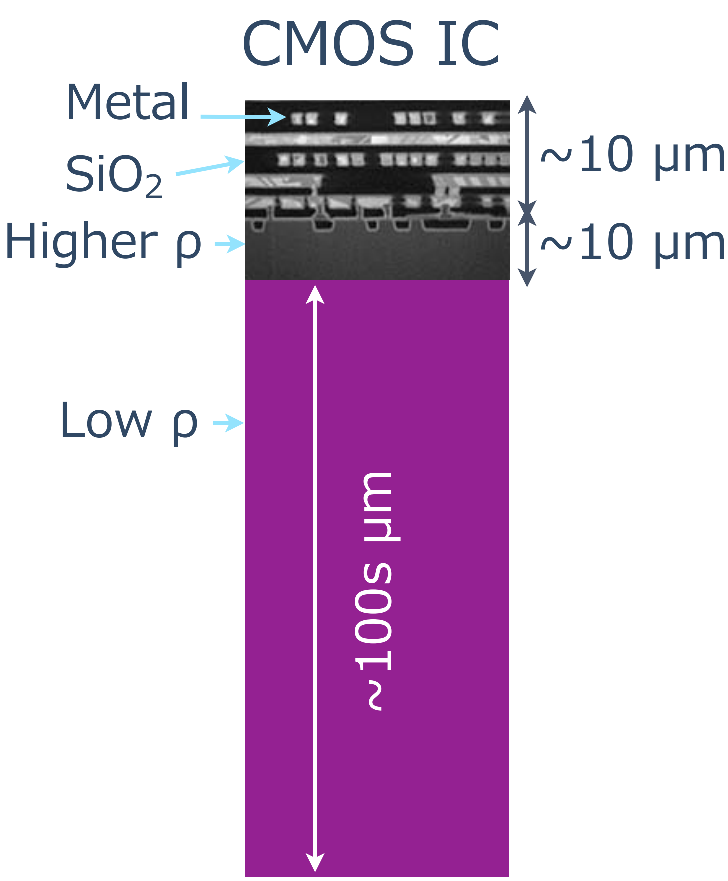


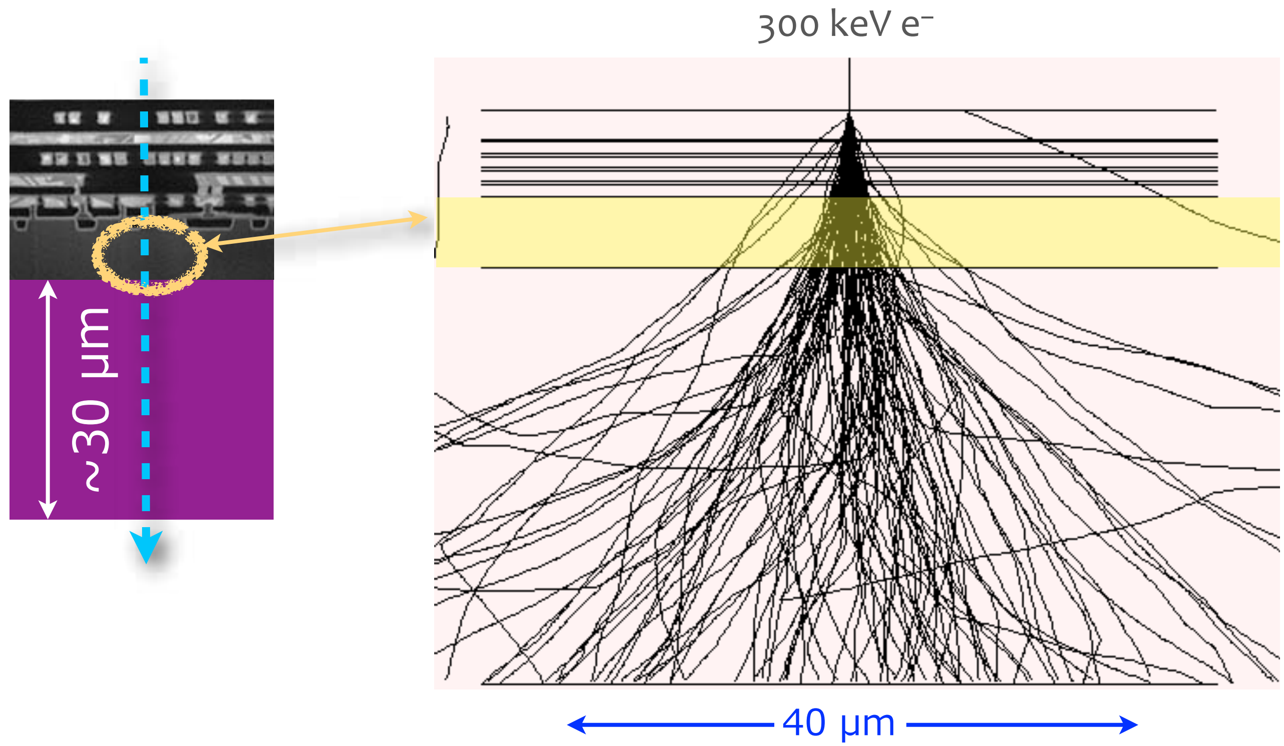
e^- Detection in Silicon



- Hybrid pixels can work at lower energies
- Not at 200+ keV (high-end TEM)

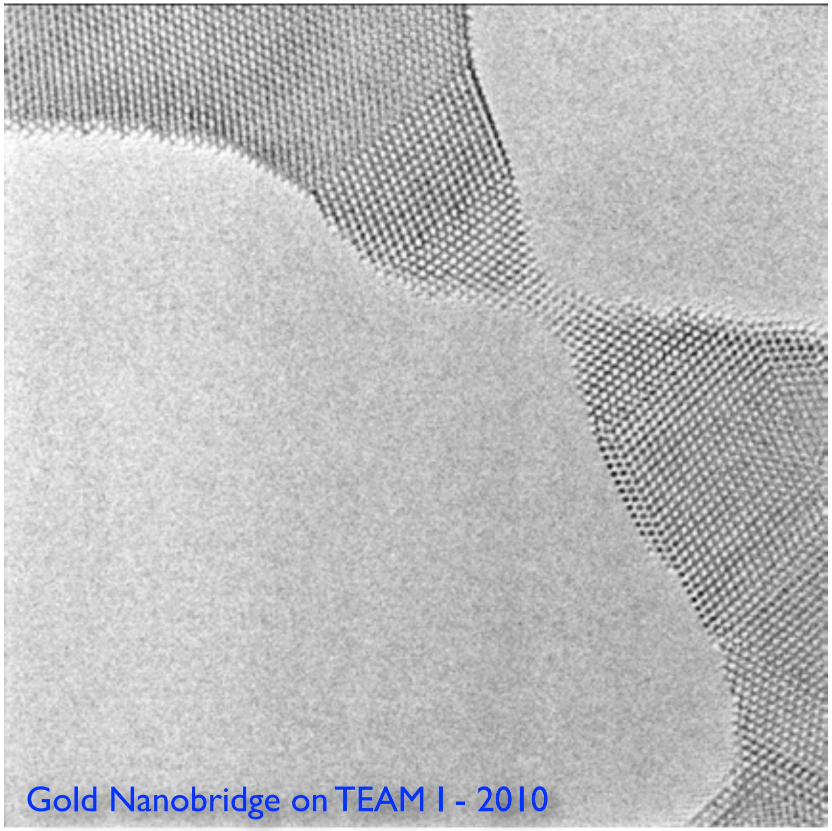
Thin CMOS Active Pixels





- Obvious solution
- Radiation hardness!

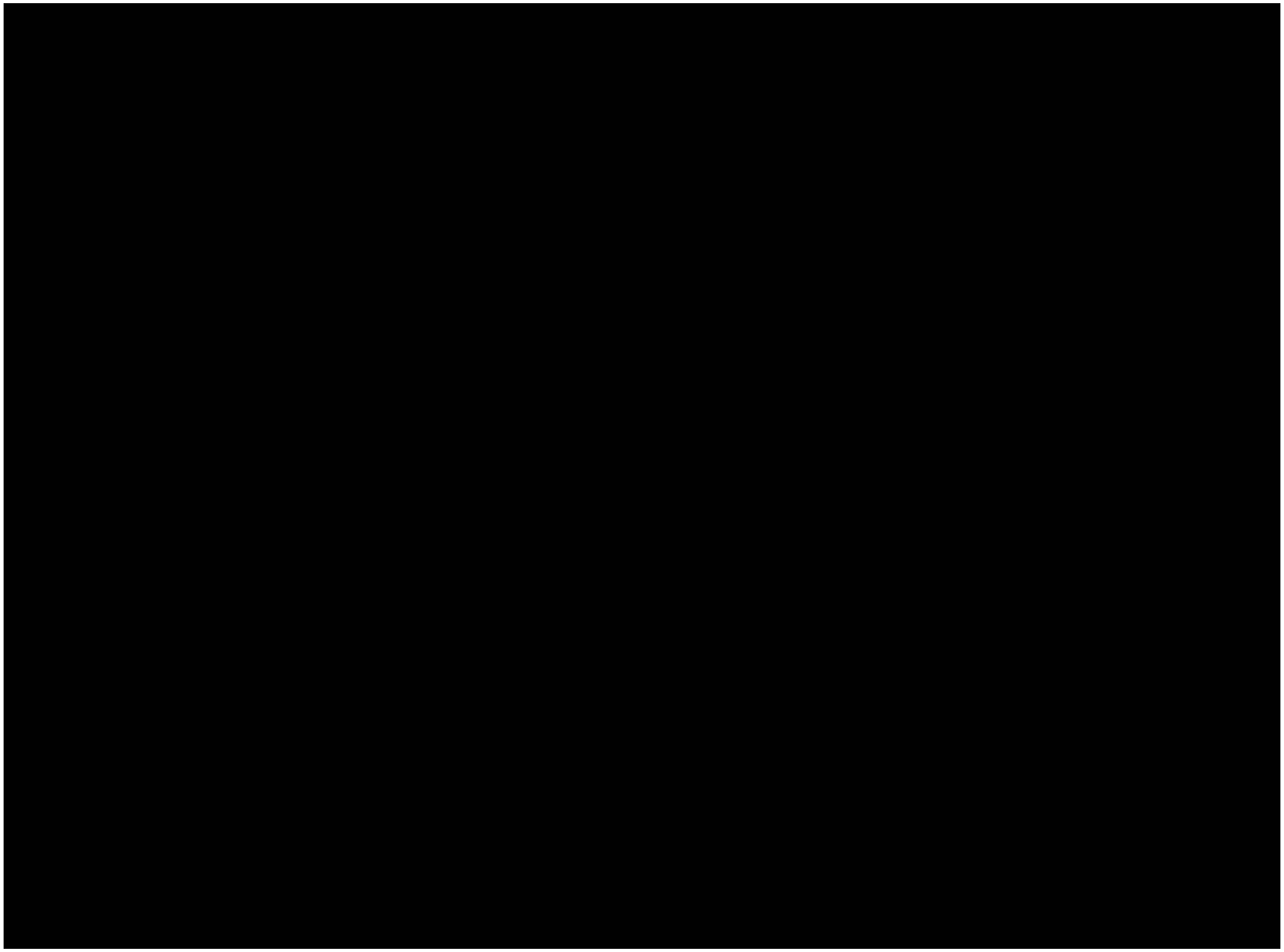
TEAM Detectors

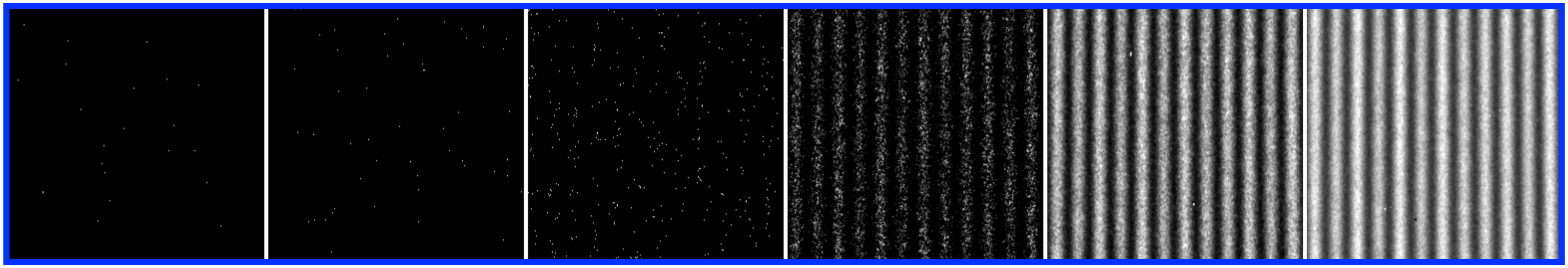


- S/N ~ 20 (single electron)
- 400 MPix/sec

- CMOS APS for TEM
  - Optimized for 300 keV
    - Developed for *TEAM*
      - Speed
        - Dynamics / in-situ
        - Dynamic range
      - Sensitivity

Speed + Single e^- Sensitivity



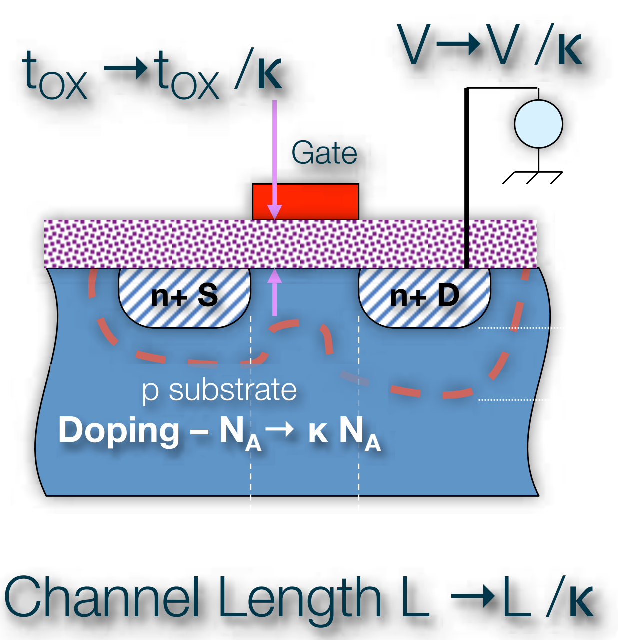


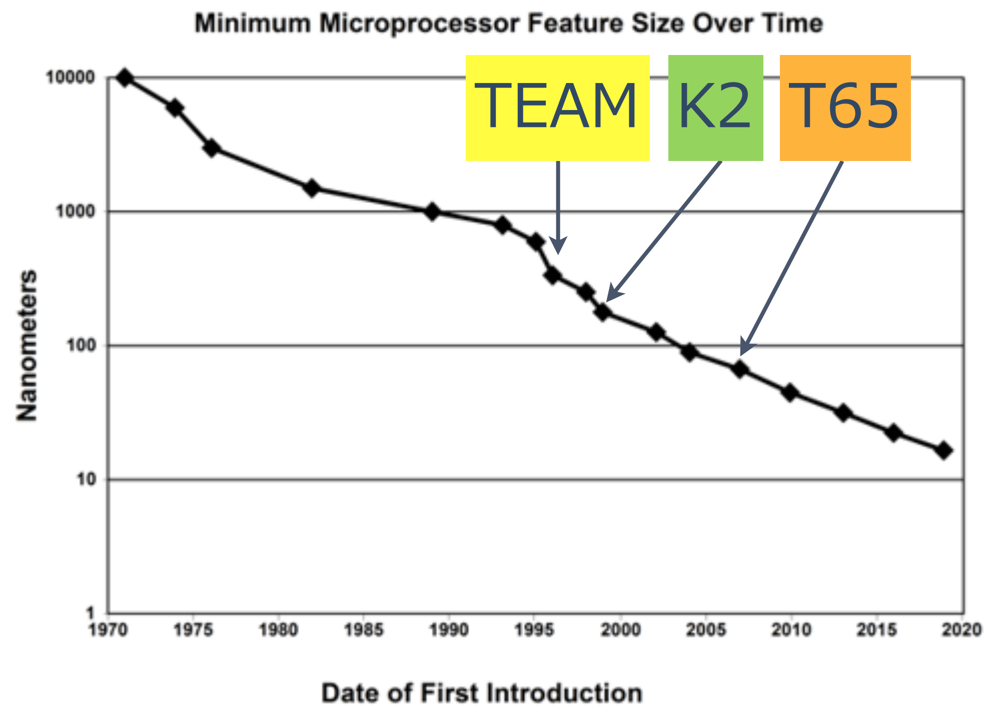
Re-creation of Akira Tonomura's "double slit" electron holography demonstration

C. Ophus et al.

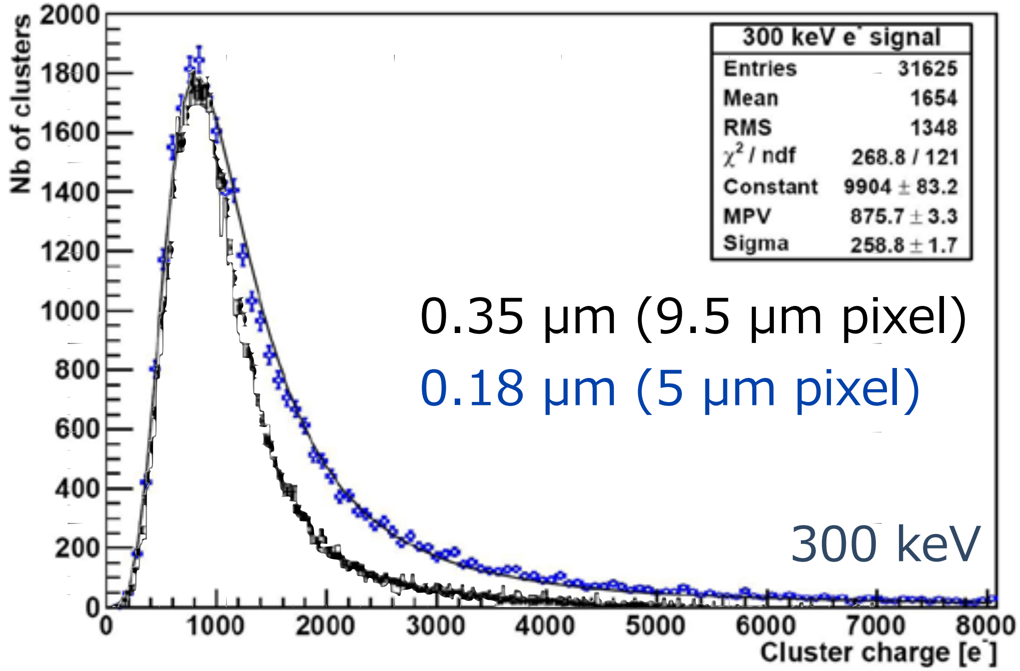
Reducing Feature Size

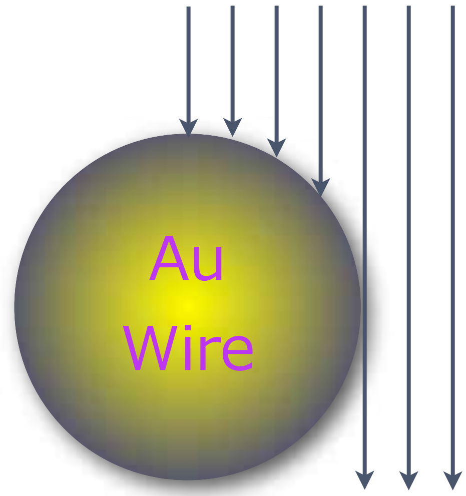
- "Moore's Law" ⇔ feature size ⬇ ("constant field scaling")
- Smaller feature size ➜
  - More radiation hard
  - Smaller pixels ➜ more pixels/chip
    - Useful if PSF scales
  - Easier to integrate intelligence
  - Less² dynamic range
    - C⬇ V/e⁻ ⬆
    - V_{DD} ⬇
  - Higher prototyping cost

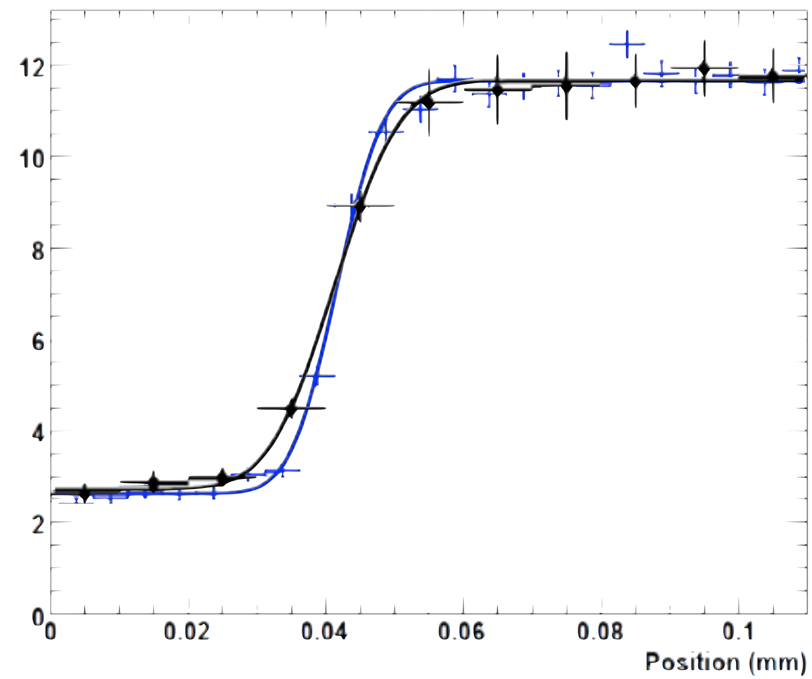




Compare Feature Size



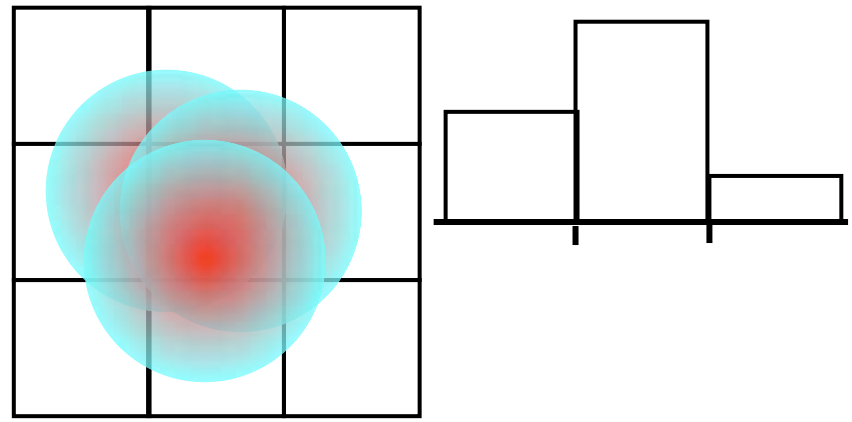


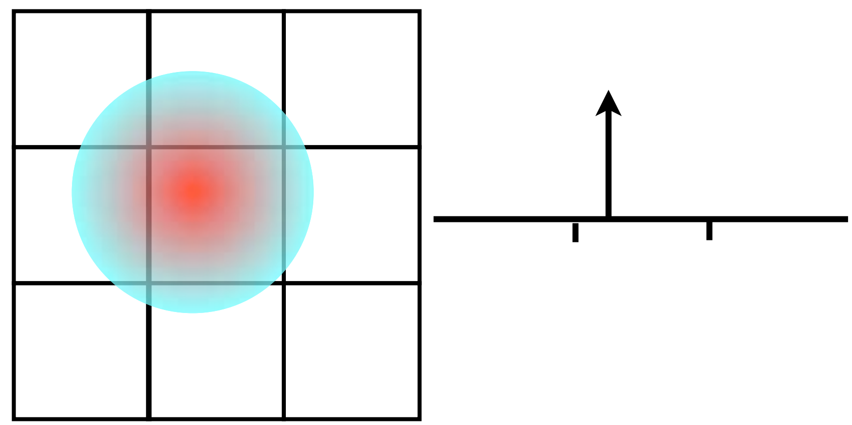


- Equivalent Signal-to-Noise
  - S/N ~ 15
  - Longer Landau tail
- Better PSF

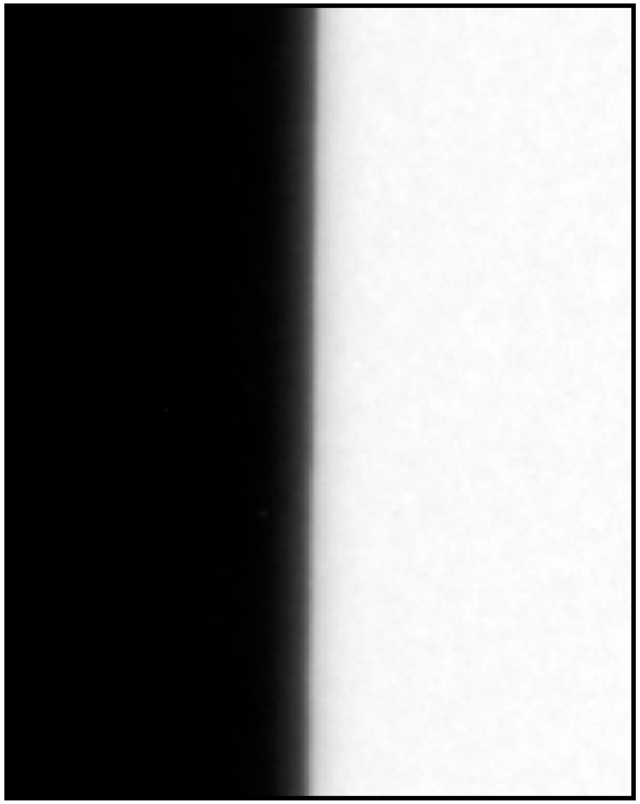
Imaging Modes

- σ_{DIFF} ~ pixel size
- >1 particle / pixel / frame
  - peak gives impact point to within a pixel
  - energy distribution across pixels
- <1 particle / pixel / frame
  - simple: localize to a pixel -- count e^-
  - **Cluster Imaging**: sub-pixel resolution
- High speed readout - to enable cluster imaging

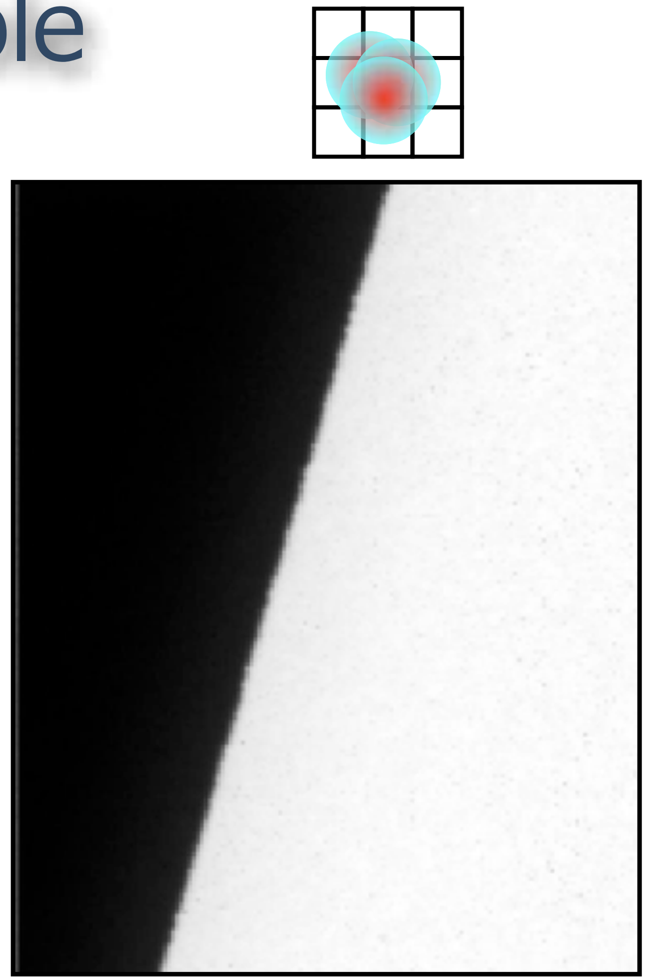




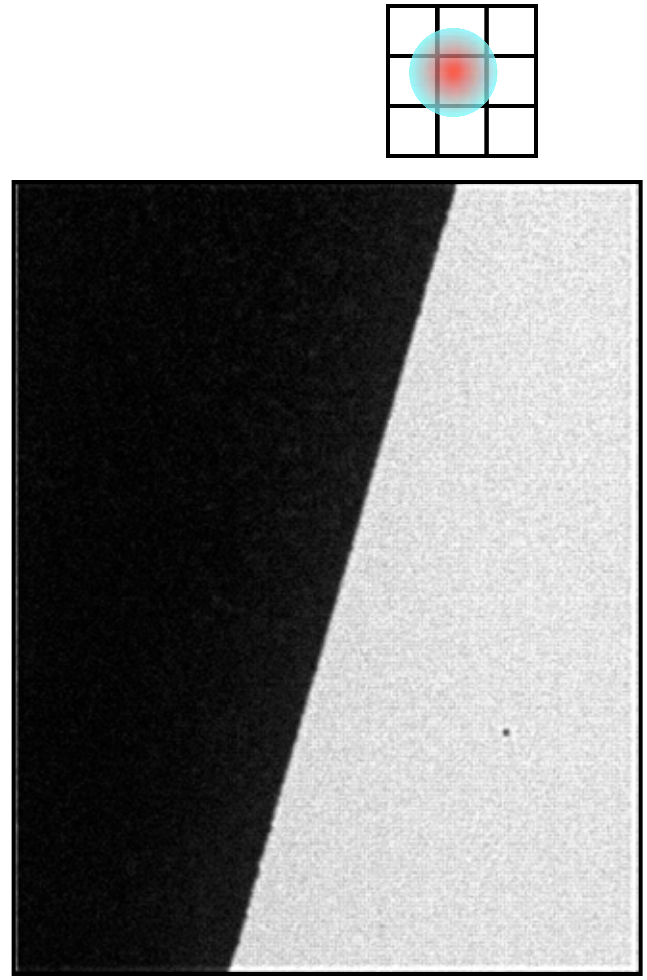
Spatial Example



Commercial (indirect)
“14 μm” pixels



0.18 μm
5 μm pixels

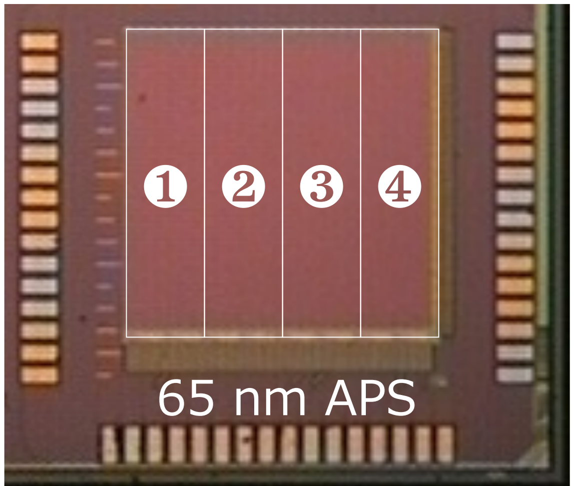


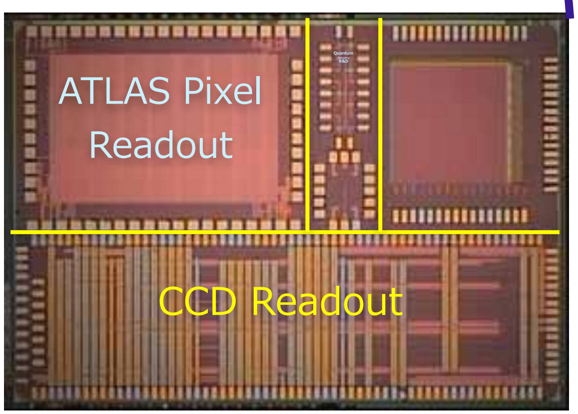
0.18 μm
Clusterized

Feature Size Progression

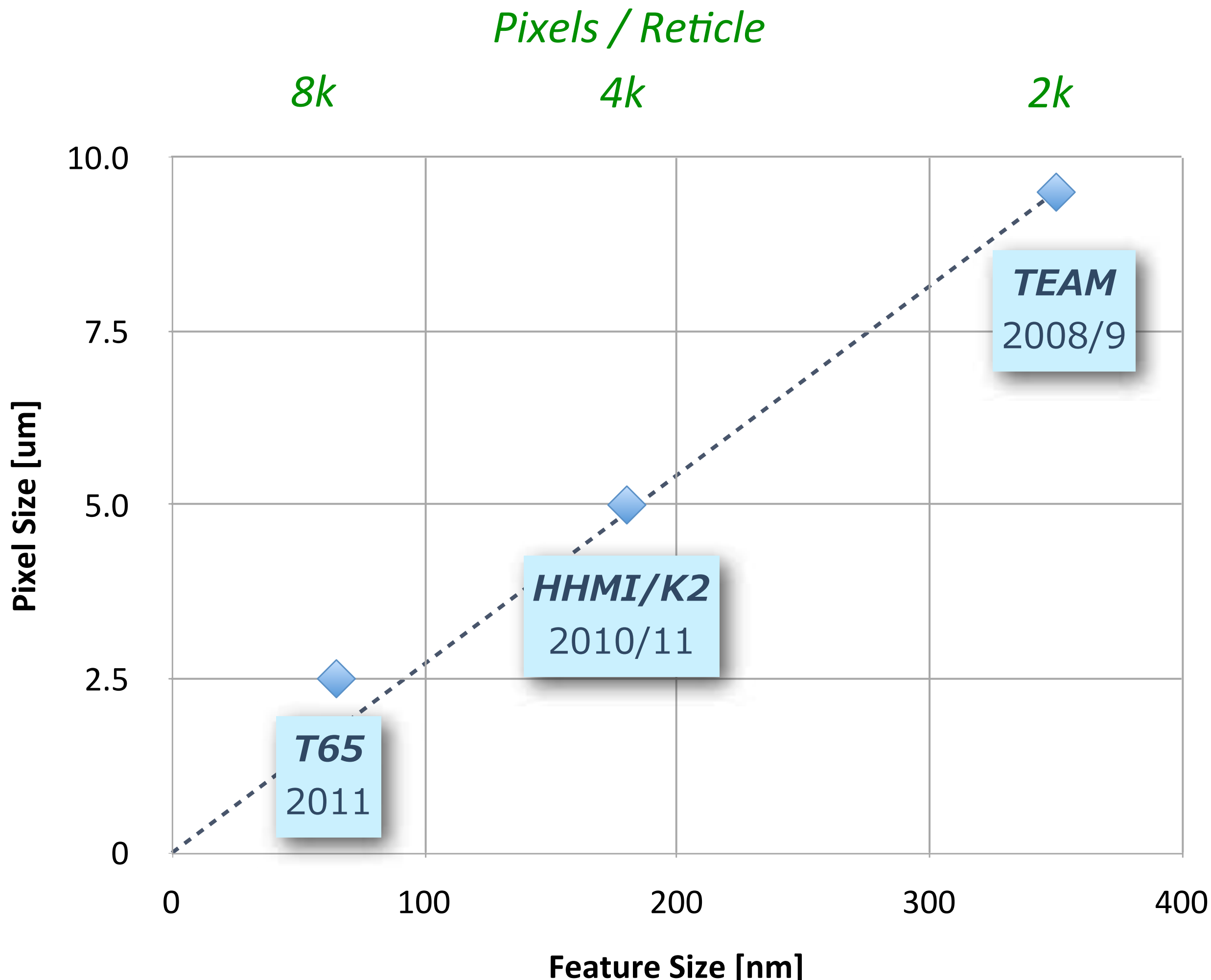
400 x 400
2.5 µm pixels

- ❶-❸ TEAM-like pixels
- ❹"pseudo-pinned"



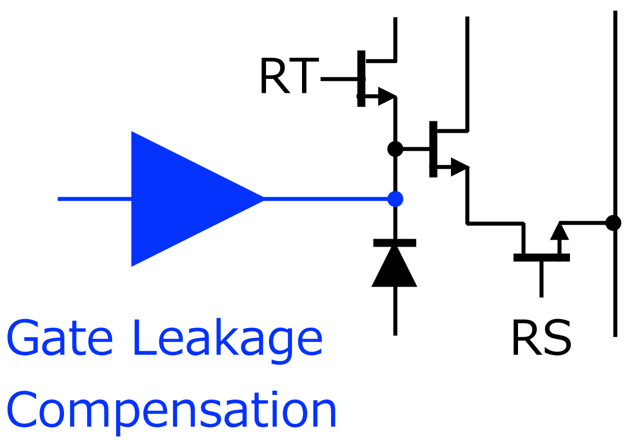


- Line width scales, but not implants
  - Pixels do not quite decrease ∝ feature size

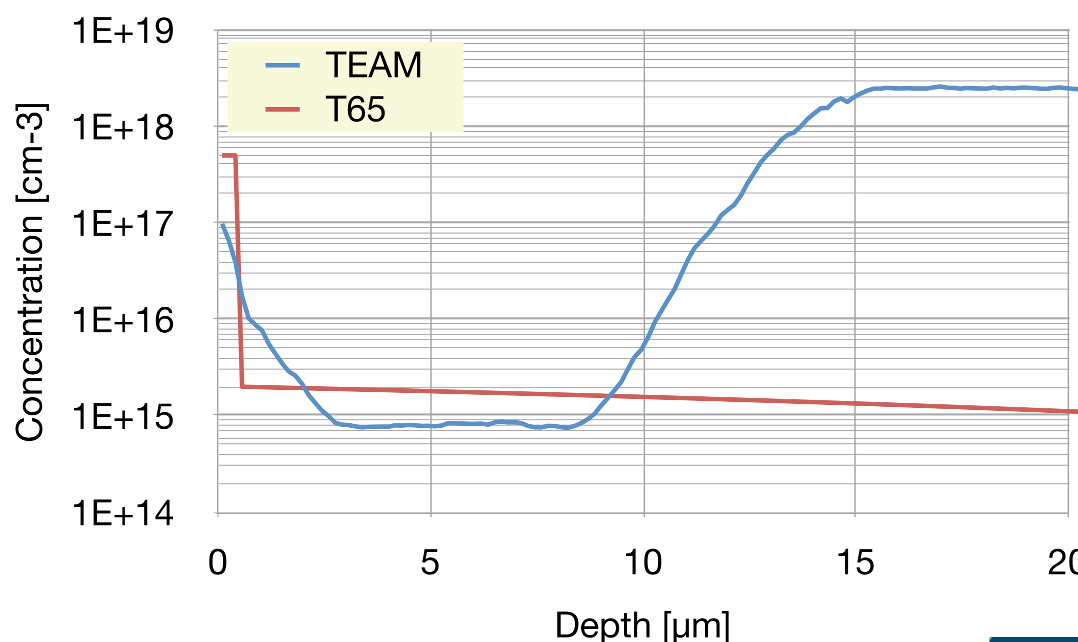


Features of 65 nm Pixels

- Gate Leakage!
  - Gate oxides a handful of atoms thick → tunneling
    - Good for radiation hardness, bad for leakage

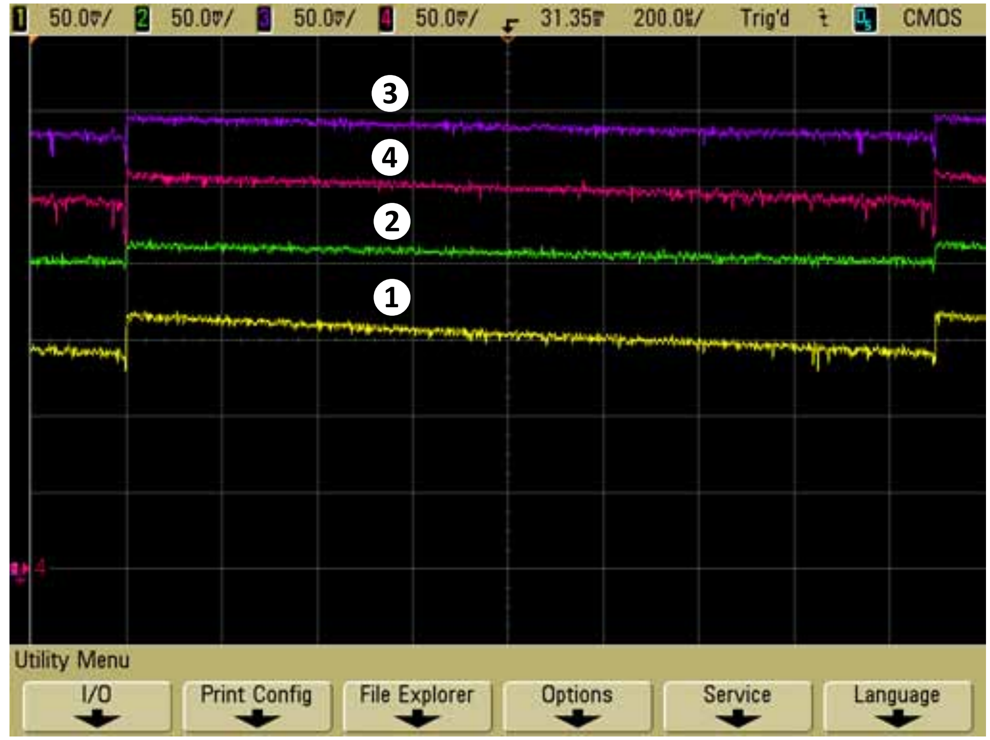


- Doping profile
  - Un-expected



Gate Leakage Compensation

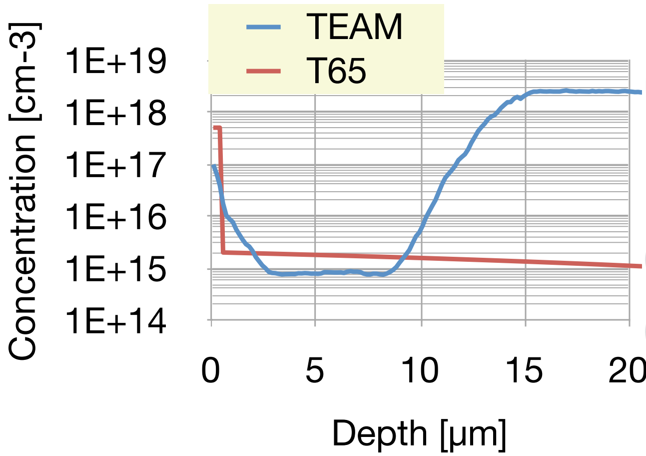
Uncompensated



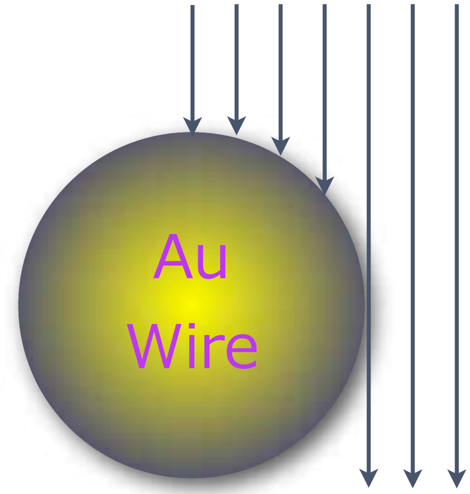
Compensated

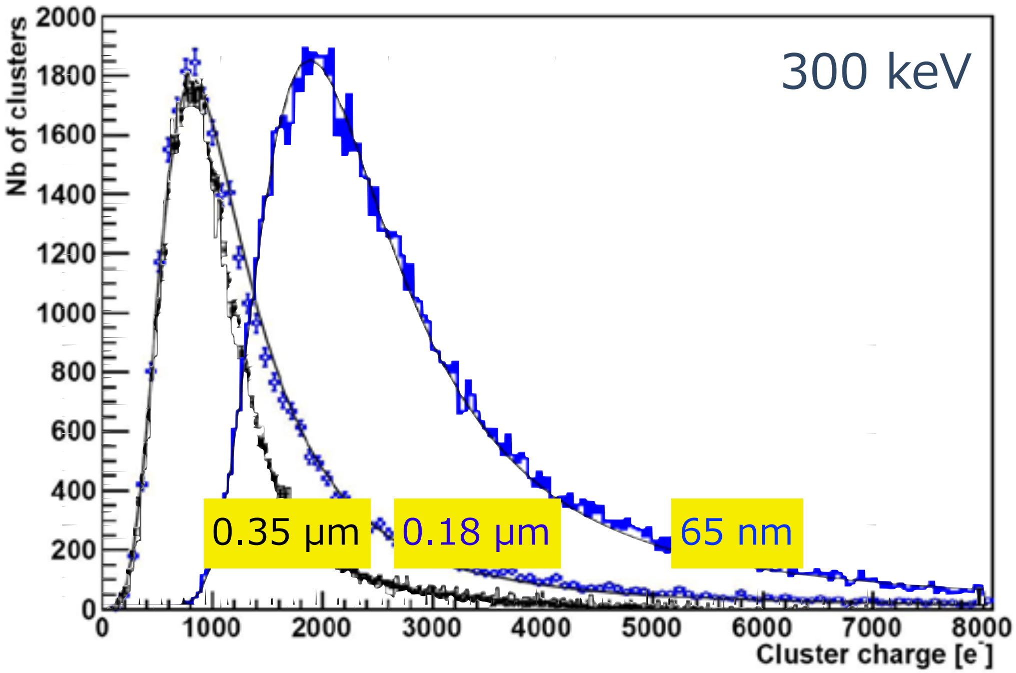
- Must compensate gate leakage in 65 nm APS
- Can be effectively performed
- Also helps radiation tolerance

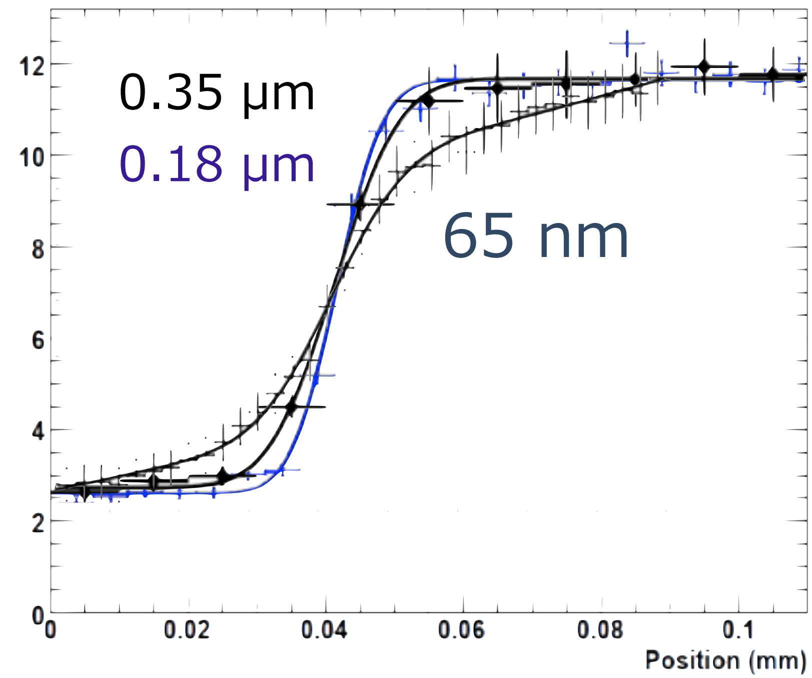
Compare Feature Size



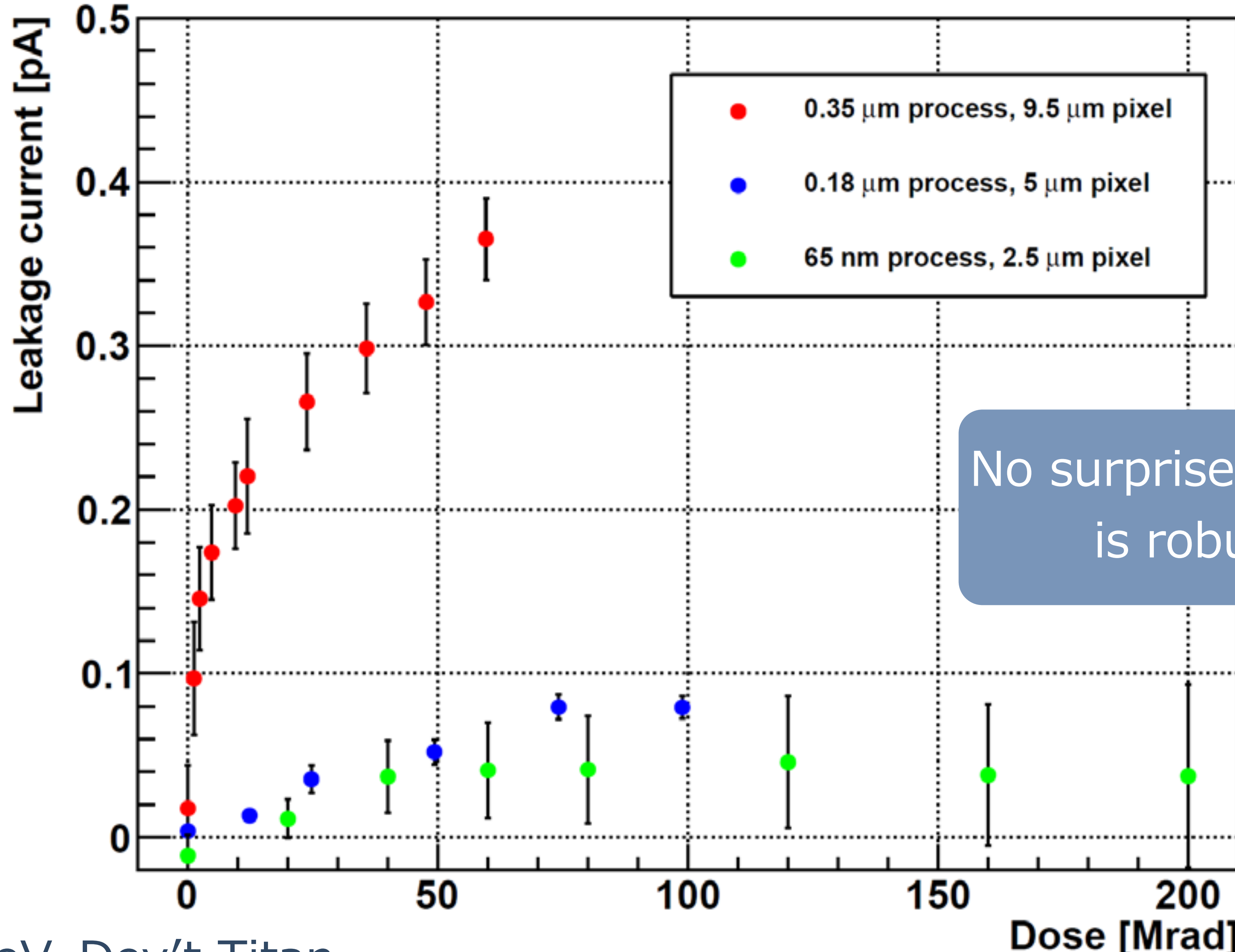
- Doping profile of 65 nm APS
- More signal
- More diffusion (worse PSF)







Radiation Hardness



No surprise, 65 nm is robust

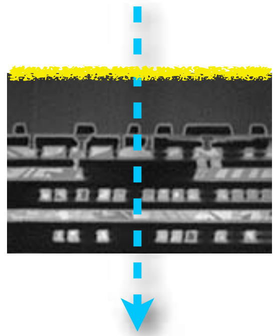
300 keV, Dev't Titan

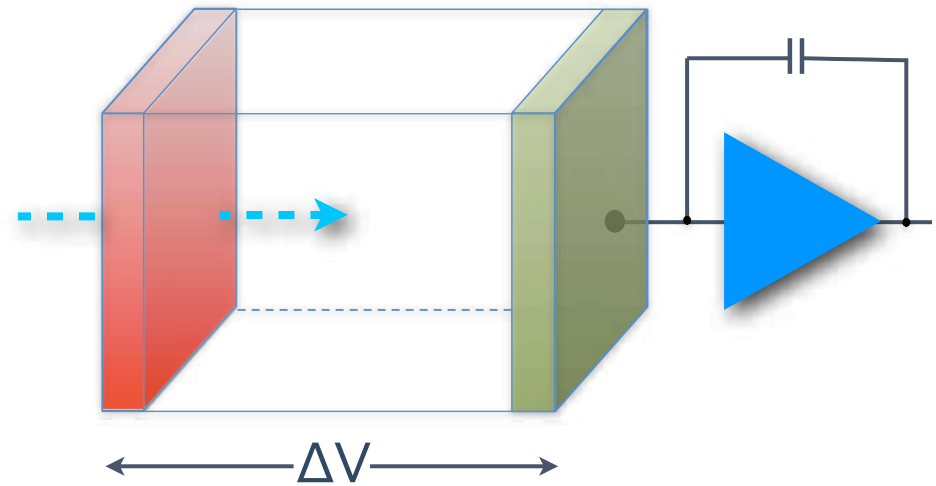
Comparison

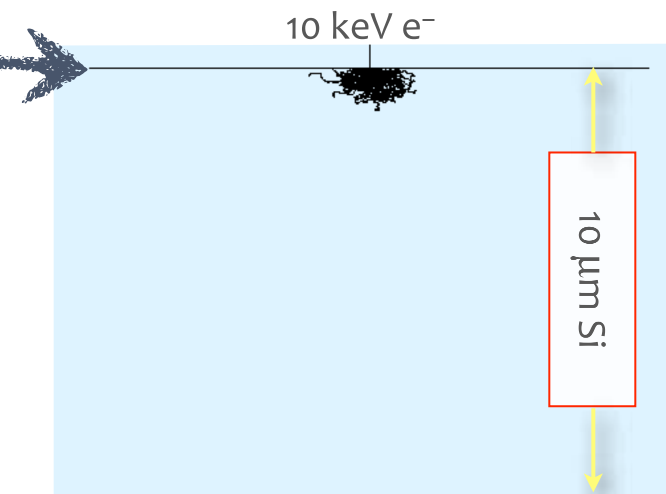
Process / Pixel	Pixel pitch [µV]	Gain [µV/e-]	Noise @ RT [e-]	Ileak [fA]
0.35 µm (TEAM)	9.5	9.4	30	10
0.18 µm (TEAM-like)	5.0	15.5	35-40	4
0.18 µm (photogate)	5.0	23.3	12	< 1
65 nm (TEAM-like)	2.5	7-10	70-80	< 1 (Gate Leak Comp)
65 nm (pseudo-pinned)	2.5	21	50	8

Optimized electron detector

- Technology
  - Thinned
  - Thin-window
  - Back-illuminated
  - Fully-depleted
  - 65 nm (?) sensor
- *Even better* for high-E e⁻
- Excellent for low-E e⁻

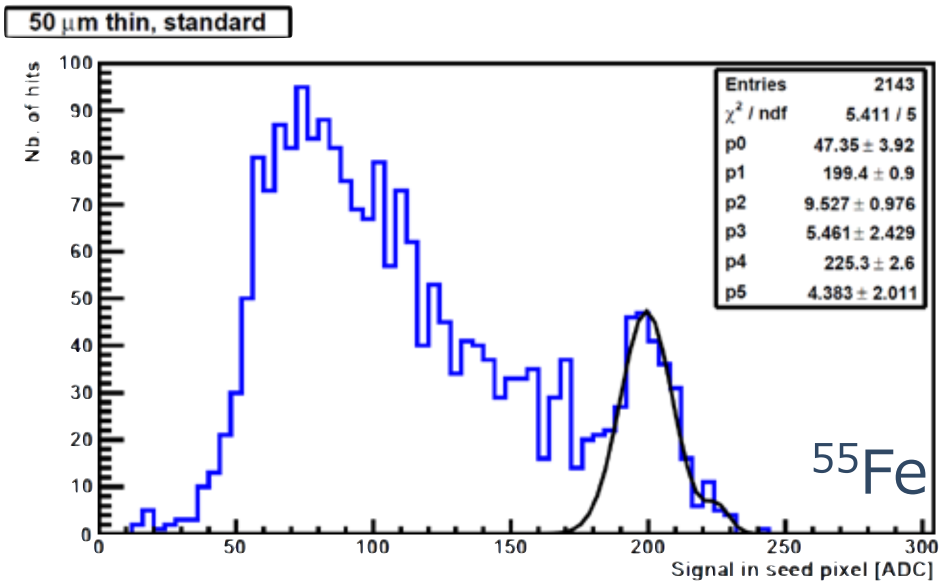


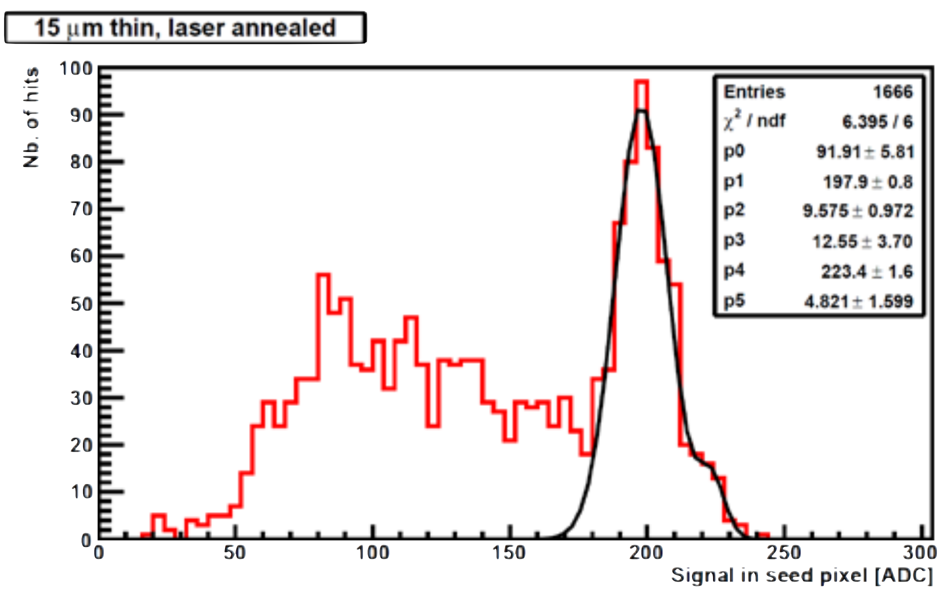




- Develop:
  - Device thinning (very thin devices ~10 µm)
  - Ultra-thin conductive entrance windows
  - Substrate engineering

Thinning

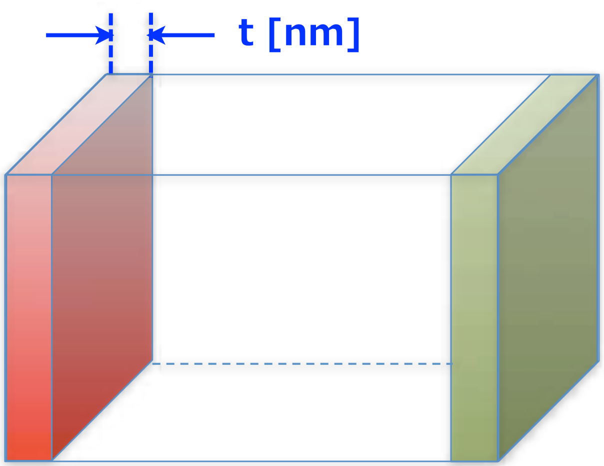


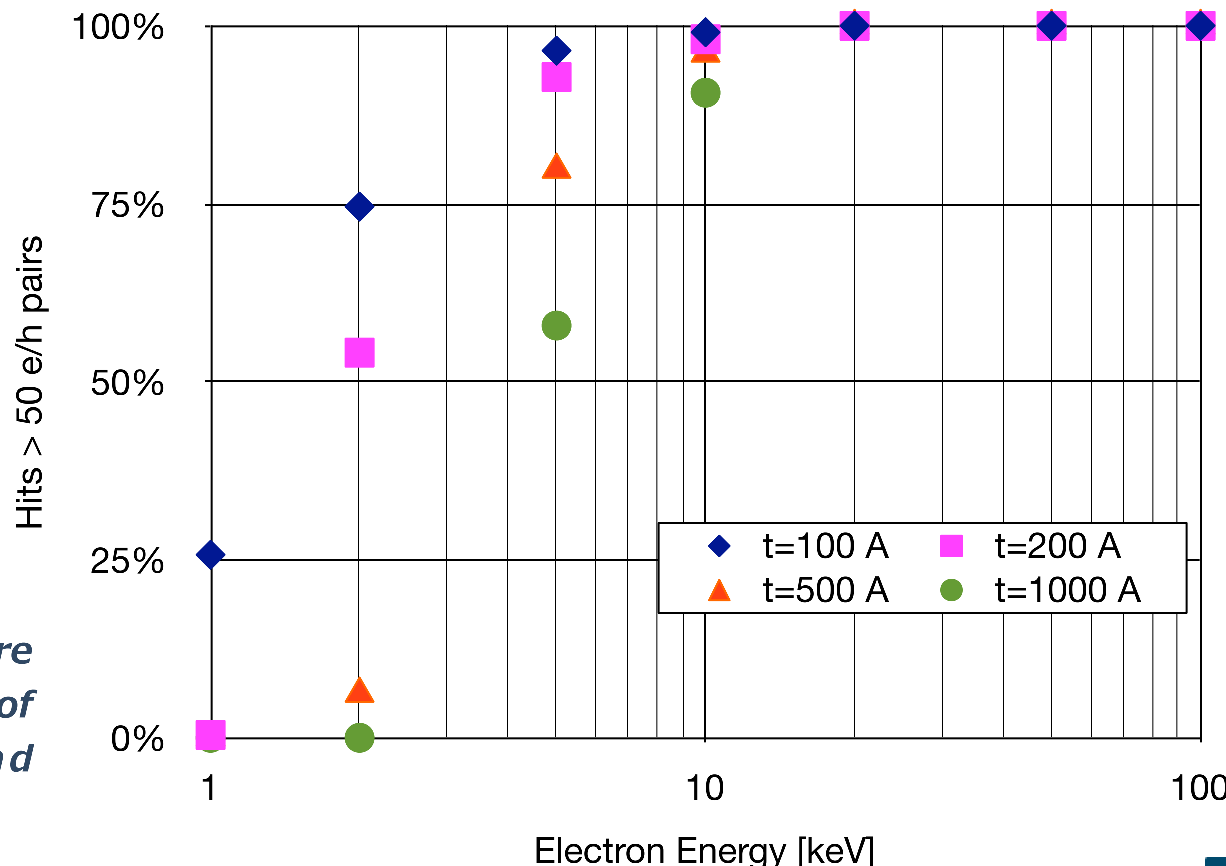


- For thin sensor applications
- Compare 50 μm TEAM chip and same chip thinned to epi
- Work in progress

Thin Window Processes (Depleted Detector)

Process	Window thickness	Status
Low energy implantation + 500 C annealing	1,000-2,000 Å	Process dependent, several SOI prototypes functional
Low energy implantation + laser annealing	400-700 Å	Several SOI prototypes functional after processing
a-Si contact deposition by sputtering	300 Å	Prototypes functional after processing, high leakage
In-situ doped poly (ISDP)	100-200 Å	Standard MSL process - first use without AR coating
Molecular Beam Epitaxy	50-75 Å	Developing in-house capability (2013)

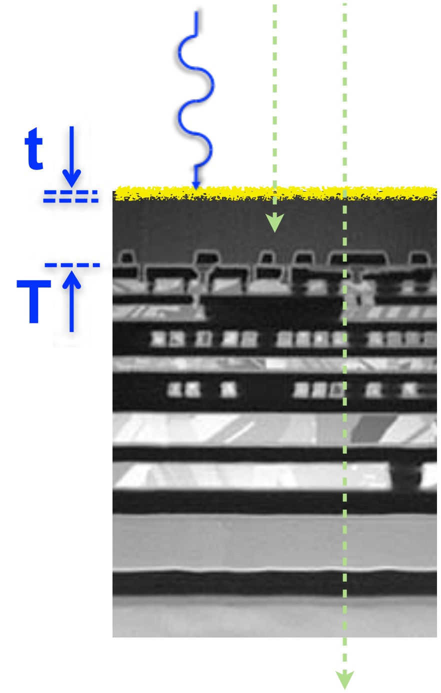




Fraction of events generating more than 50 e/h pairs as a function of incident electron energy and contact thickness

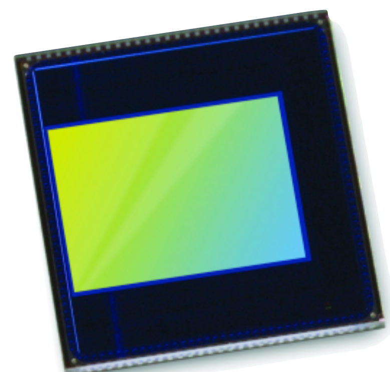
Conclusions

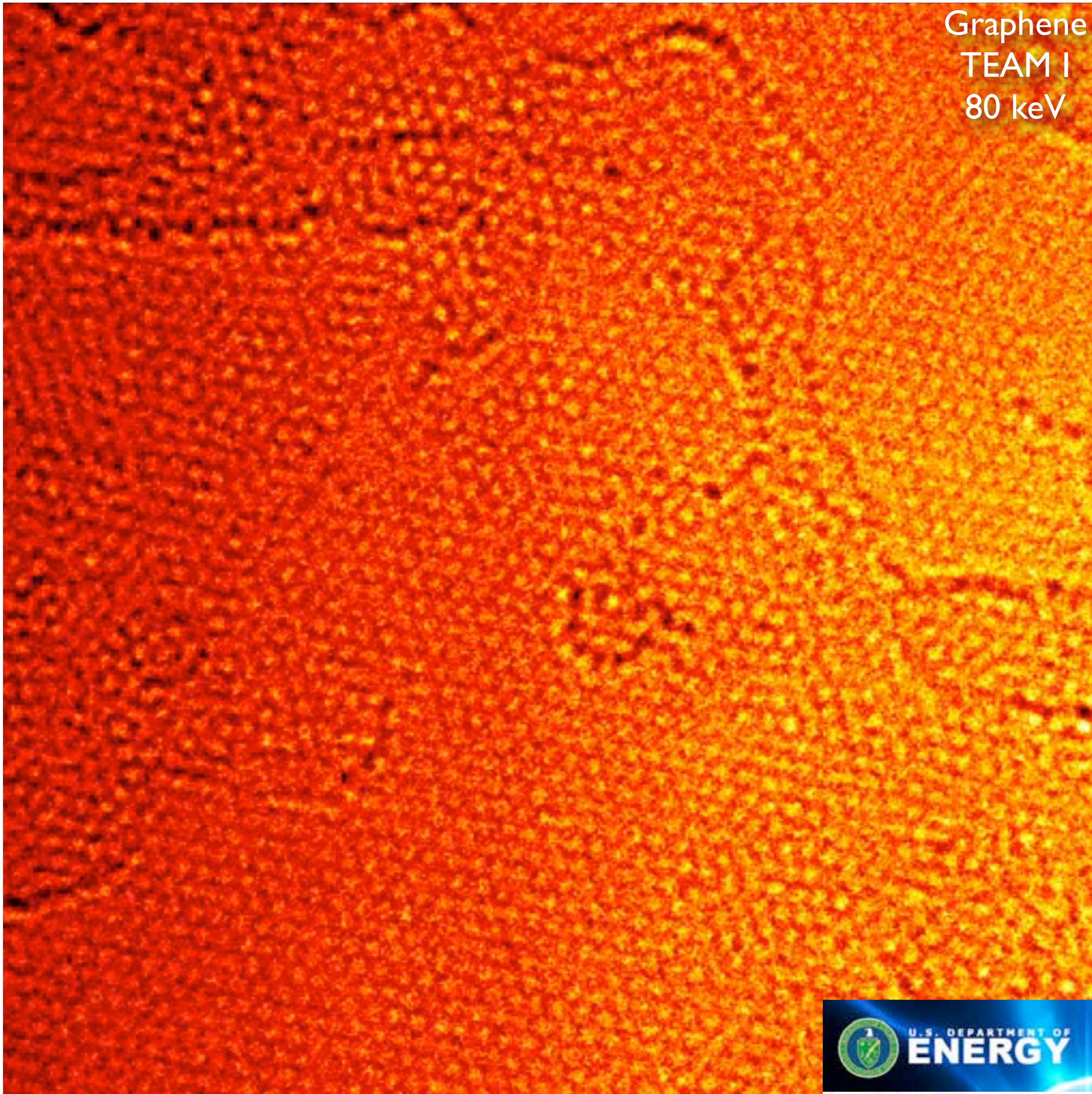
- CMOS APS - High efficiency charged particle sensor
  - Single particle sensitivity with good S/N
    - Analog counting for N>1
  - Spatial resolution
    - Intrinsically good
    - Better with single particle cluster imaging
- Feature size ⬇
  - Density, Radiation Hardness ⬆
- 65 nm
  - 😊 Robust
  - 😞 Gate leakage
  - 😏 Substrate
  - Thinned, back-illuminated detector
- This is also an interesting soft X-ray detector



iPhone 4 Camera

- Photons in
- JPEG out





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