Active Pixel Sensors for Electron Microscopy

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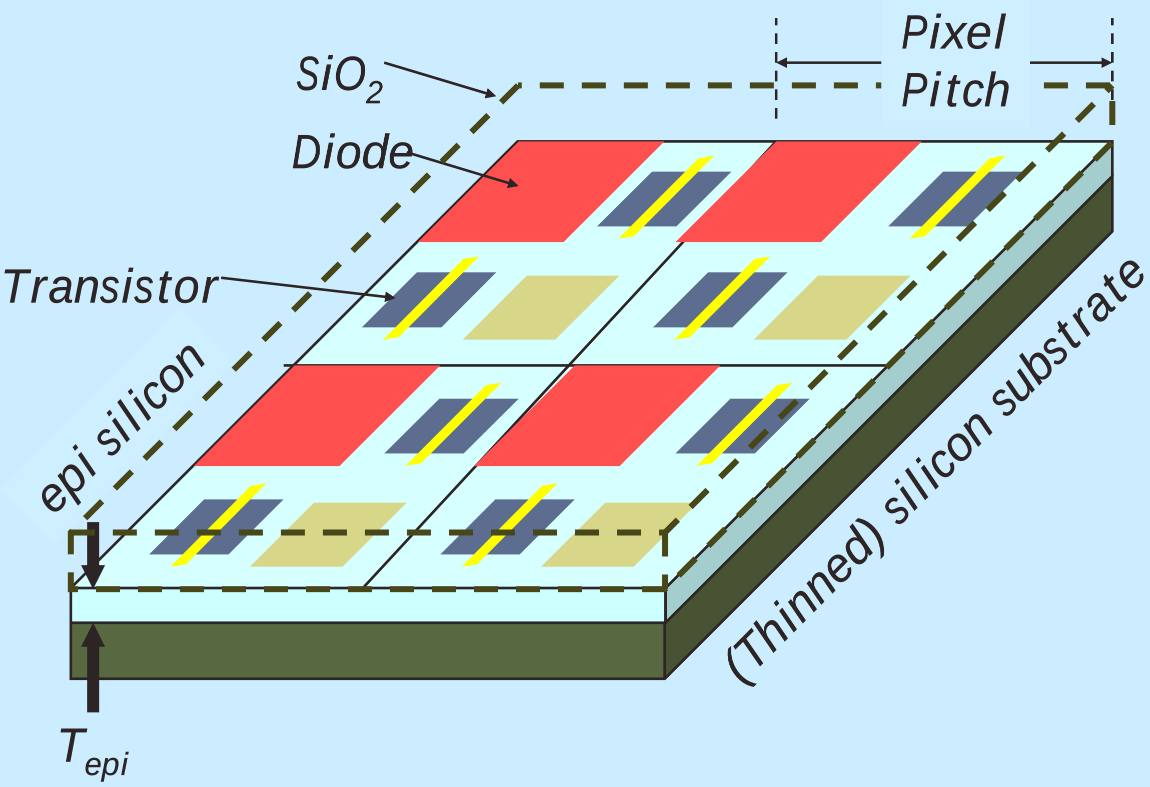
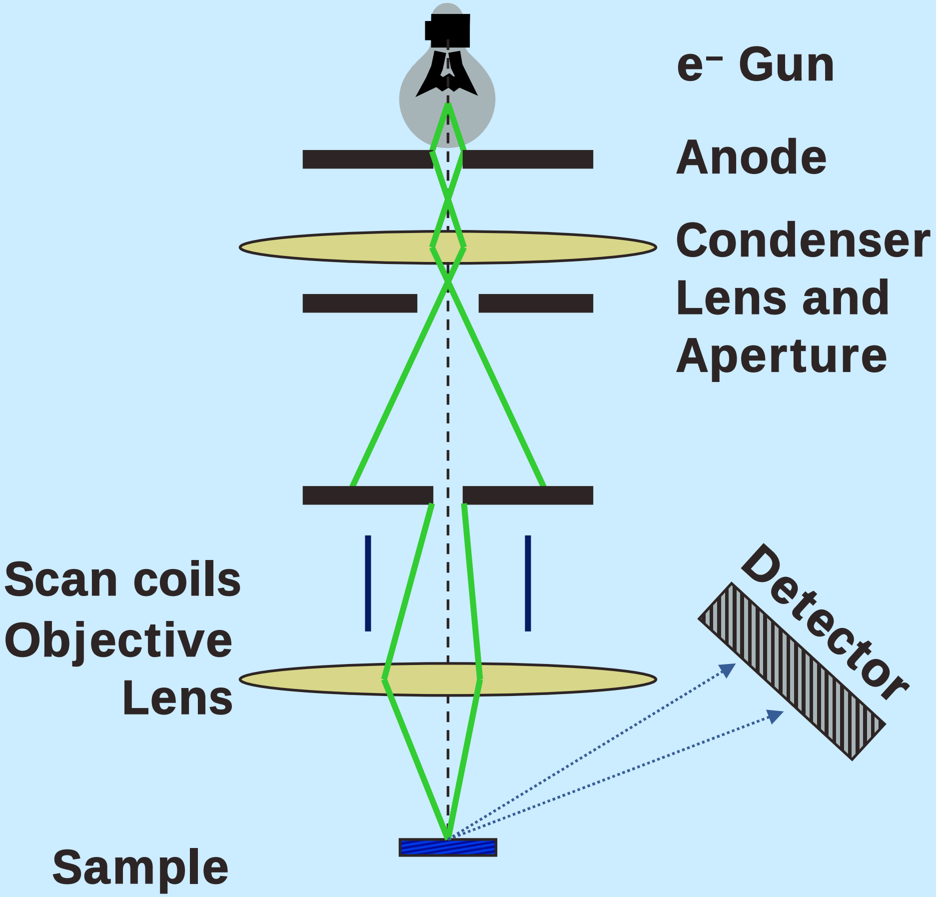
- Monolithic CMOS Active Pixel Sensors are obvious for Transmission Electron Microscopy

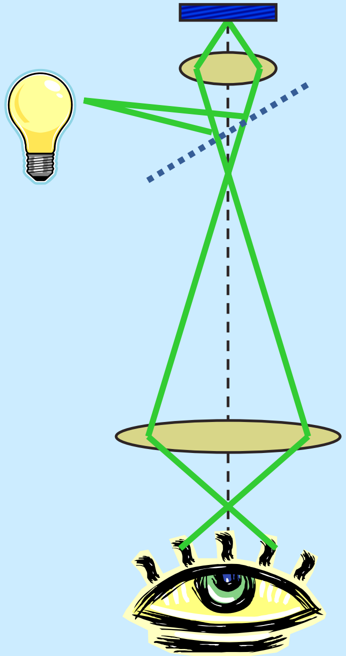
- Why?
- Challenges
- Possibilities



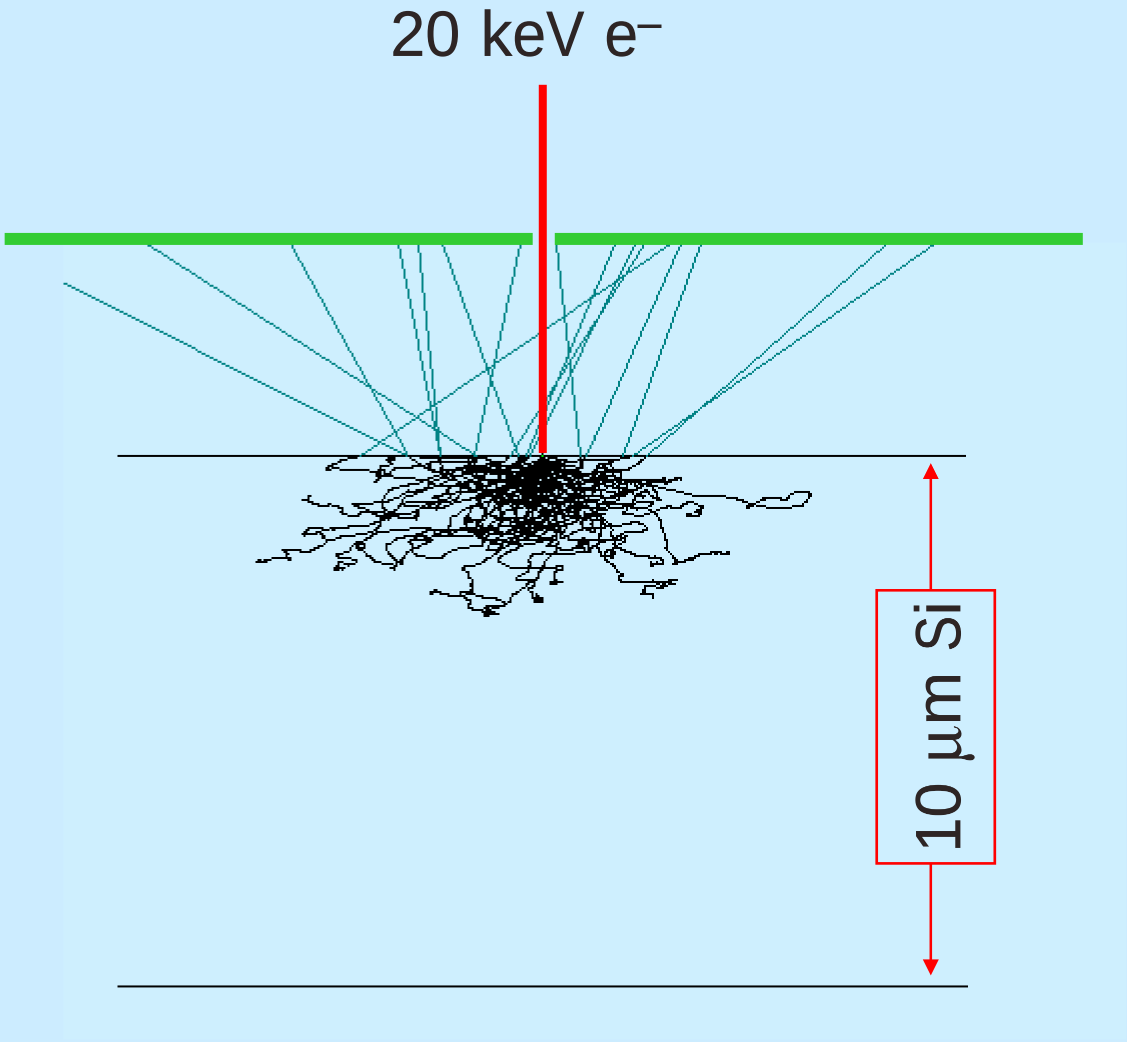
Scanning EM



- <30 keV
- Secondary or backscattered electrons
- Analogous to metallurgical light microscope

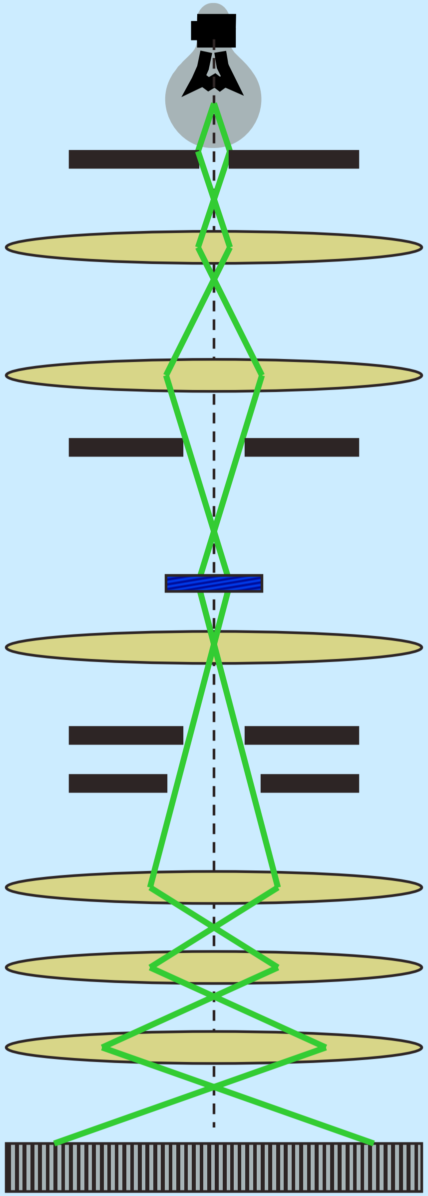


Back-scattered electrons



At energies used for microscopy, electrons really scatter!

Transmission EM



e^- Gun

Anode

Condenser Lenses

Condenser Aperture

Sample

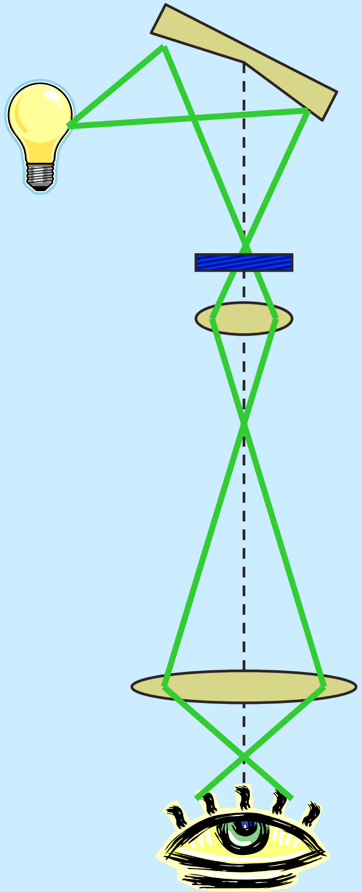
Objective Lens

Apertures

Magnification and Projection

Detector

- 100 - 400 keV
- Transparent (thin) sample
- Analogous to biological light microscope

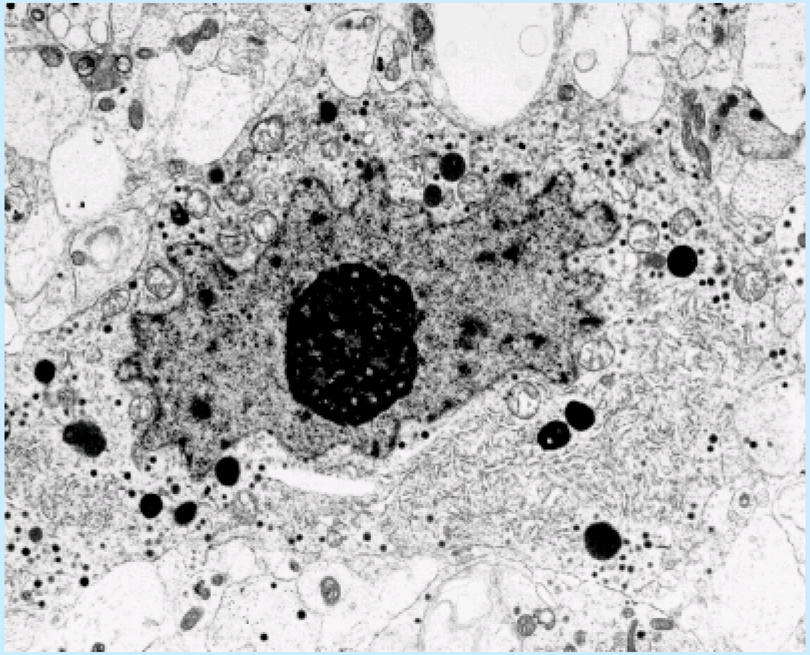


Energy vs. ...

Simple approximation:

- $P_e(>\theta) \sim (\rho t)\ (Z^2/A)\ /\ E^2\theta^2$
- $P_i(>\theta) \sim (\rho t)\ (Z/A)\ /\ E^2\theta^2$
- $P_i(>\theta)/\ P_e(>\theta) = 1/Z$

- A/Z ~2 for all elements
- $P_e(>\theta) \sim \rho t Z\ /\ E^2$
- Higher Z → more scattering
- Thinner samples or higher energies

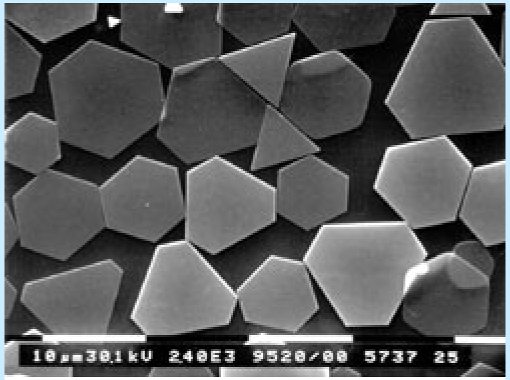


Biological samples:
Z~6 – stain
(e.g. $UO_2(CH_3COO)_2 \cdot 2H_2O$)
to increase contrast
Materials: higher E, but
displacement damage
(e.g. ~150 keV in Si)

$1\ \mathrm{pA/nm^2} \rightarrow 6\times10^{20}\ \mathrm{e^-/cm^2/s}$

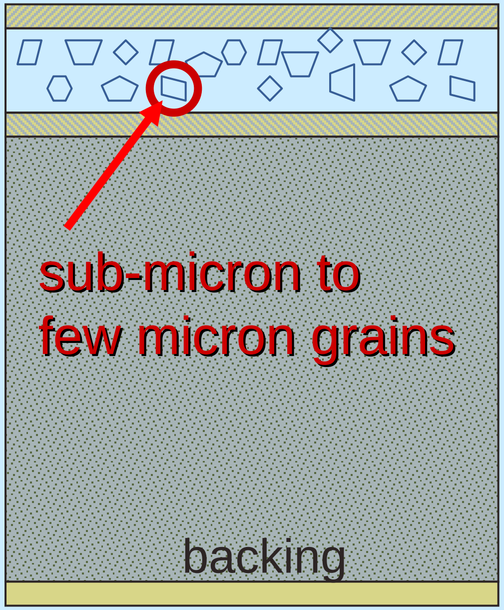
After Egerton

Traditional High-Performance EM Detectors



Electron micrograph of tabular grain emulsion

AgX + gelatin (emulsion)



sub-micron to few micron grains

backing

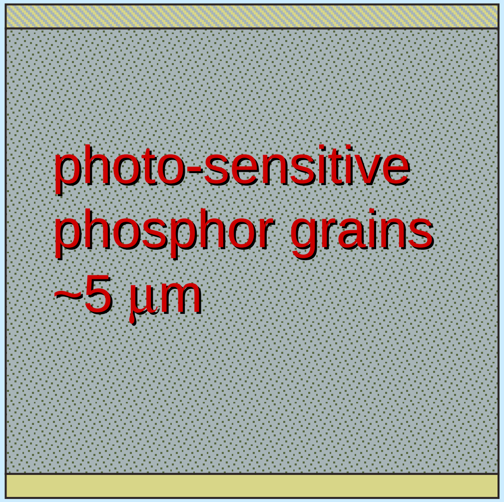
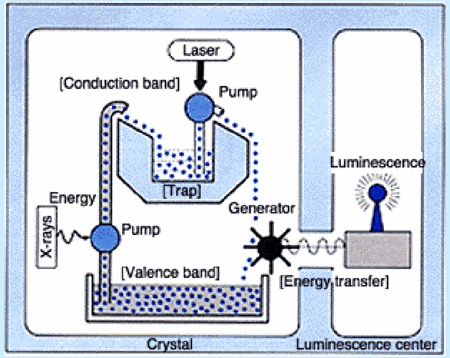
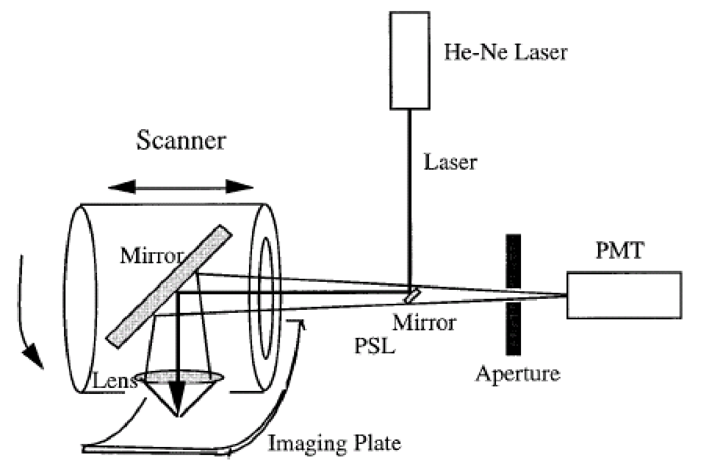


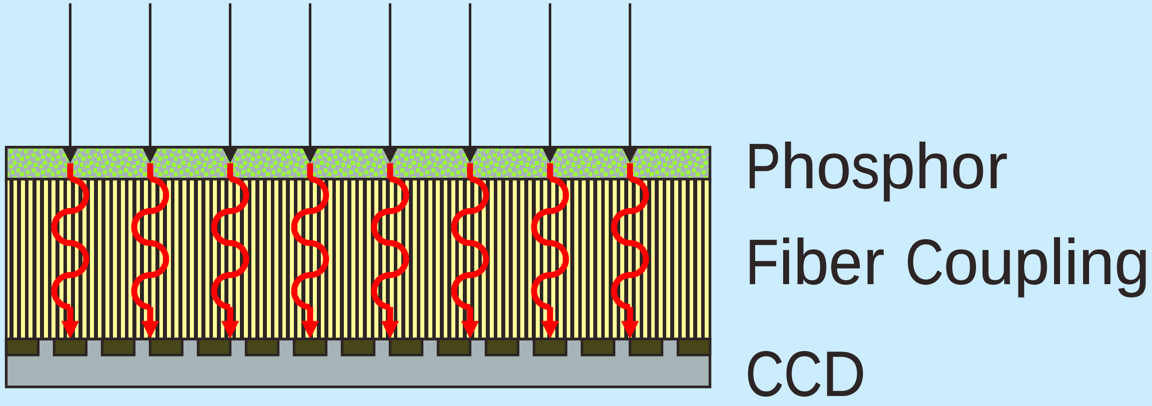
photo-sensitive phosphor grains ~5 µm

“Reuseable film”
Scanned by laser
Linear, eraseable





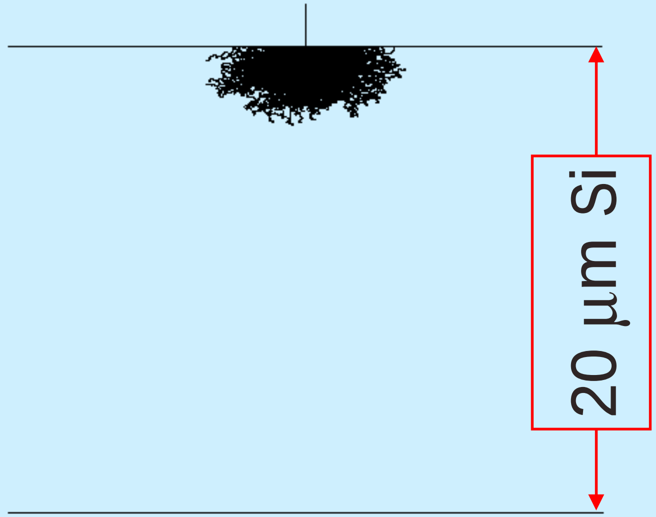
Traditional “Digital” EM Imaging Detector



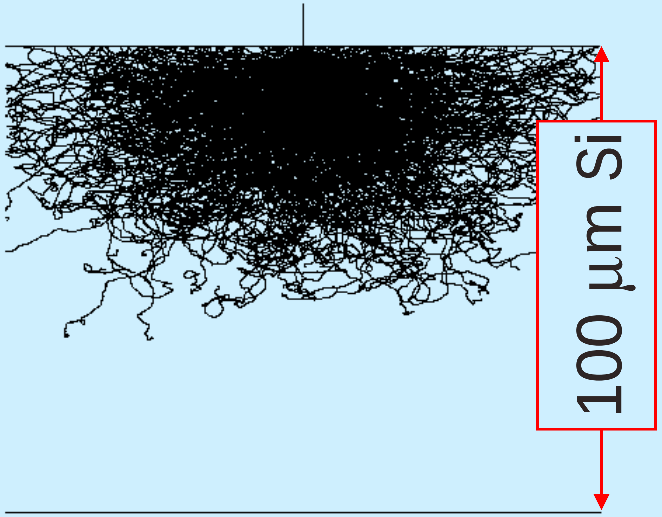
- $e^- \rightarrow \gamma$ Phosphor must be thin to minimize e^- multiple scattering
- Photons scatter
- Electrons scatter
- $\gamma \rightarrow e^-$ CCD QE

The Problem

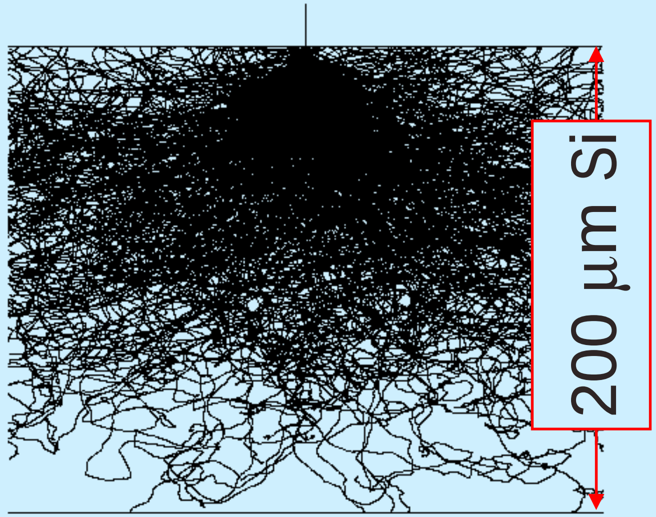
20 keV e$^-$



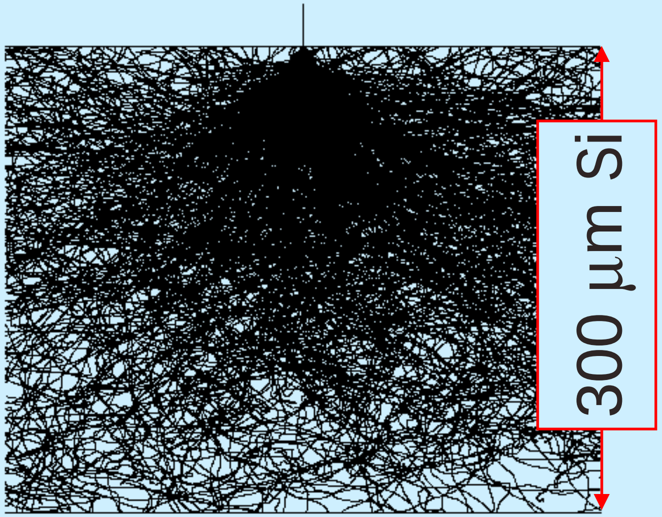
100 keV e$^-$



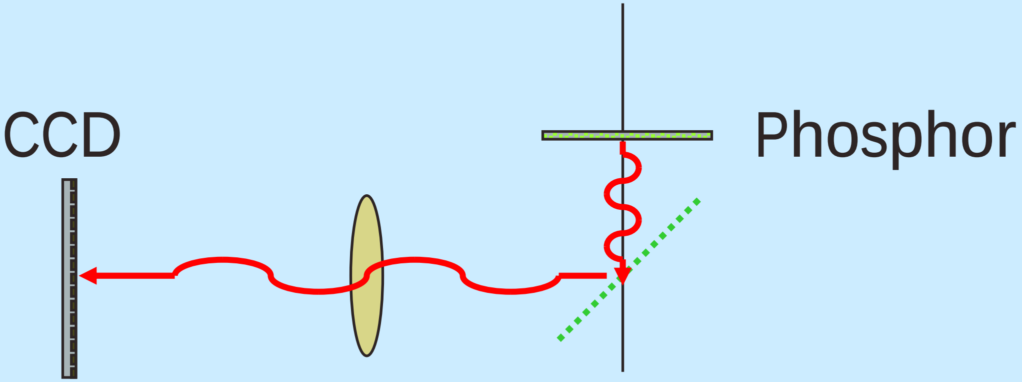
200 keV e$^-$

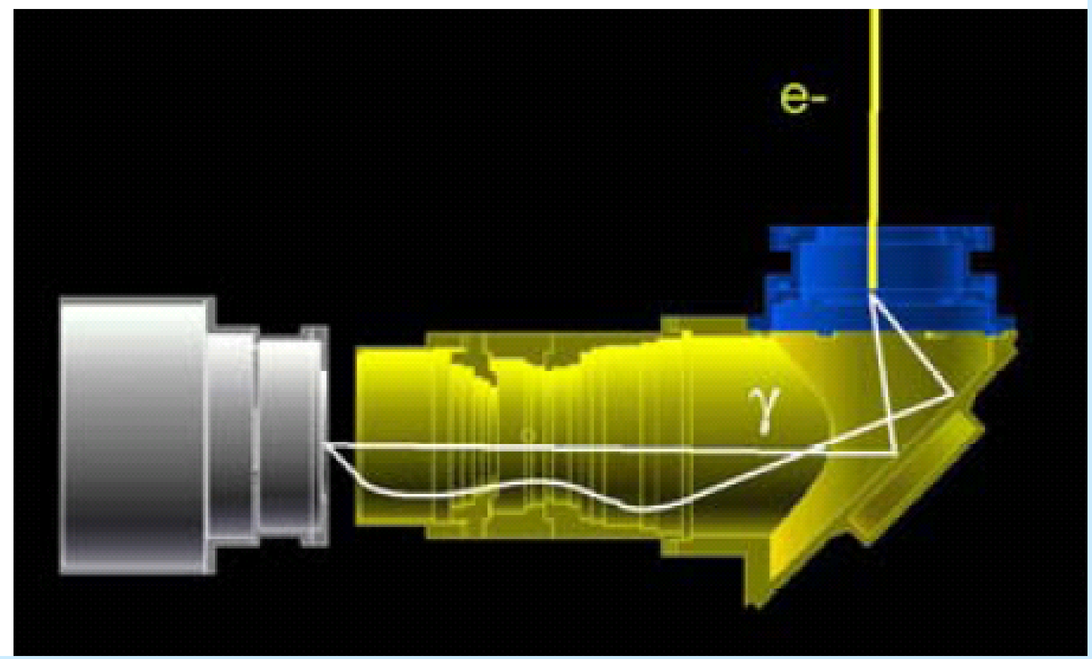


300 keV e$^-$



Lens-coupled CCD

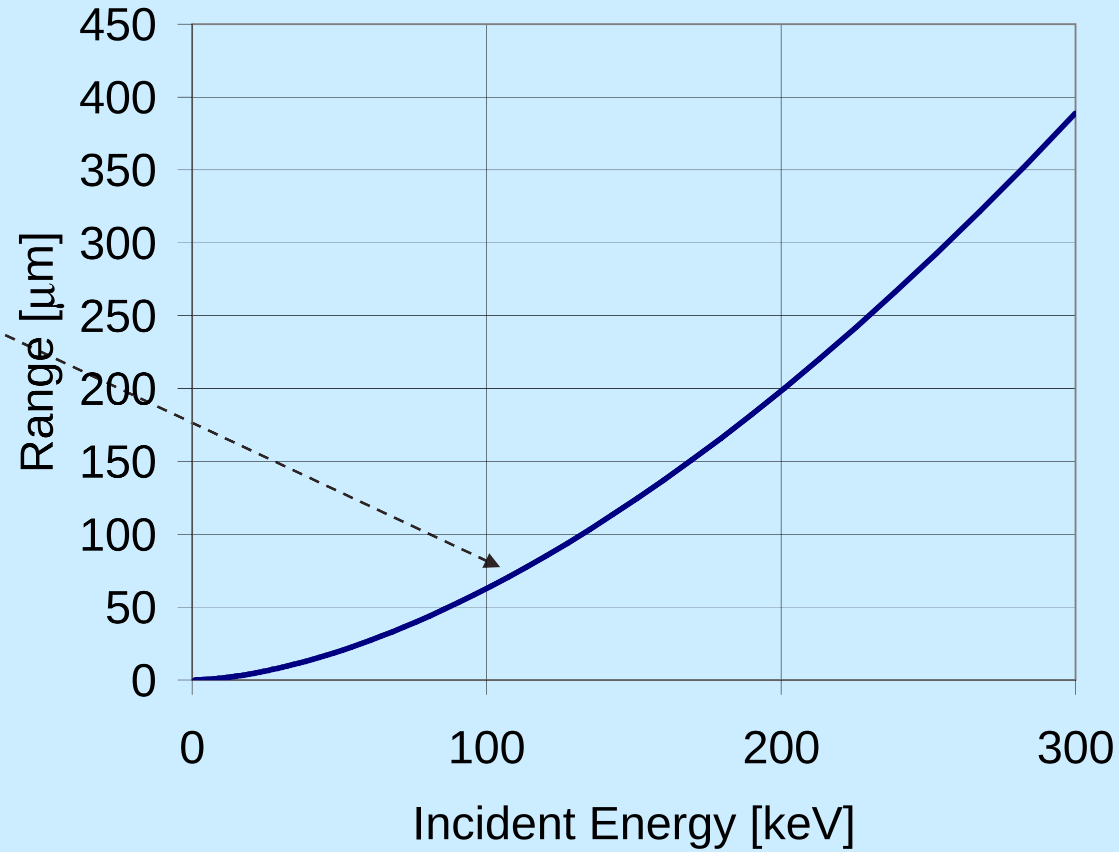




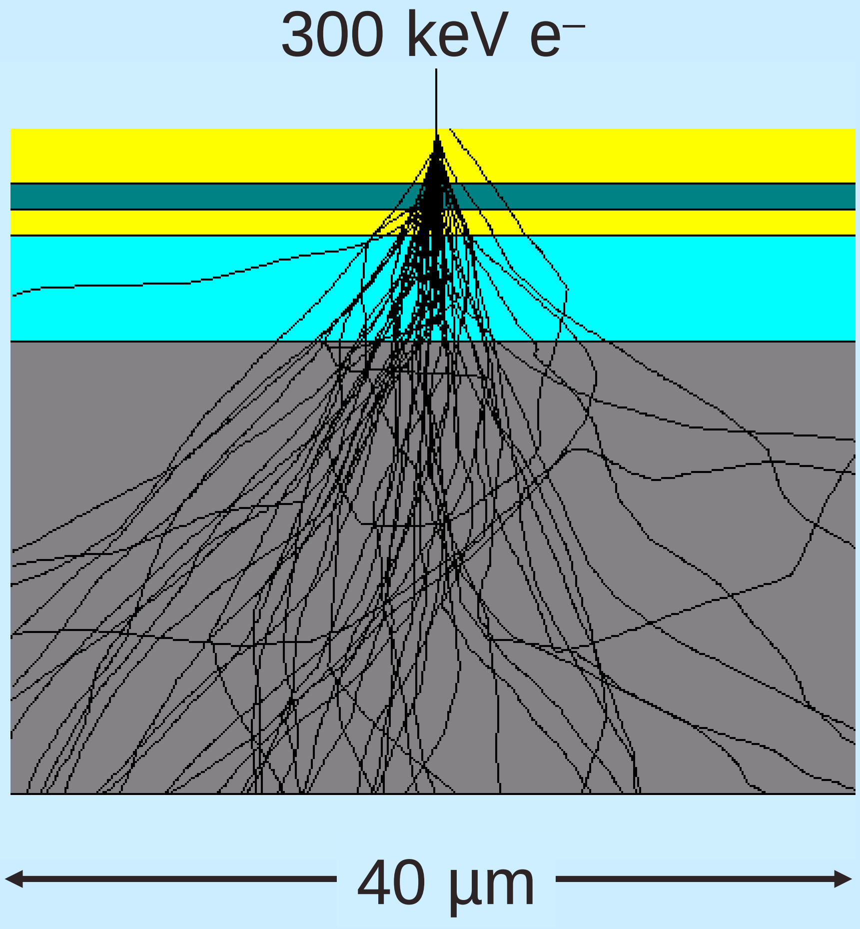
In the Past 10+ Years

"Direct detection in silicon"

- Direct detection in CCDs – radiation damage
- Hybrid pixels
  - *Fan et al. - 1998*
  - *Faruqi et al.*
    - *Medipix at 120 keV Pixel size ~ "blob" size*
- CMOS APS

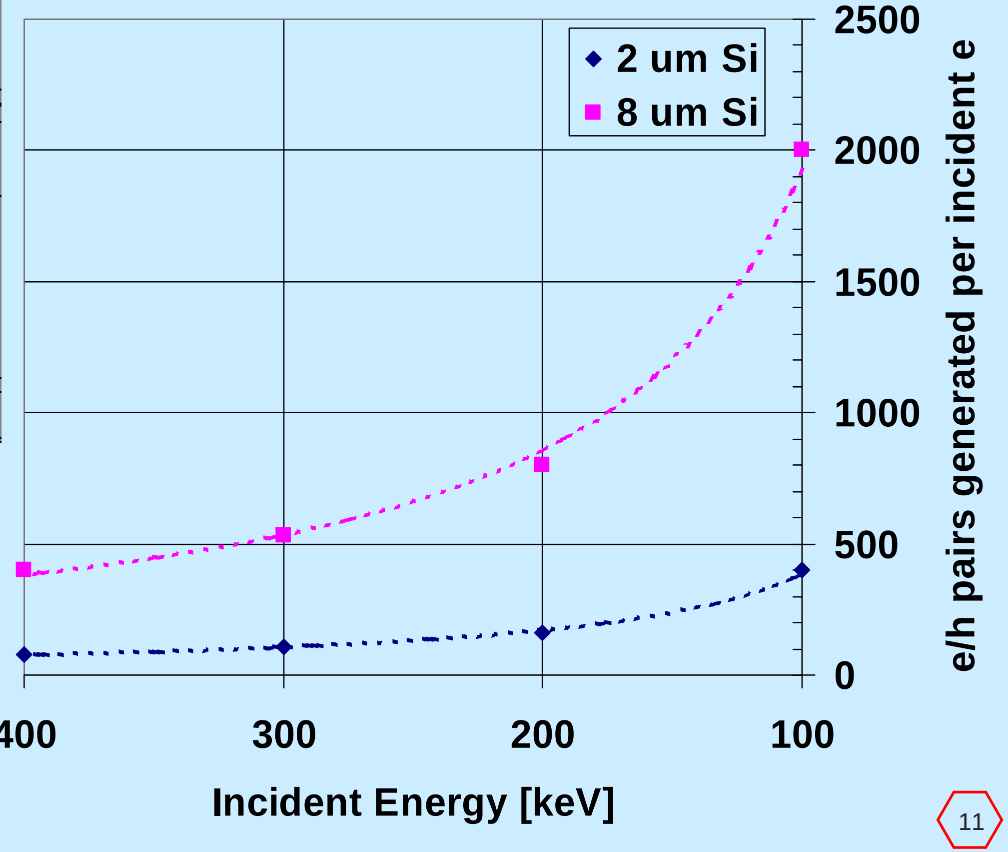


Why APS?

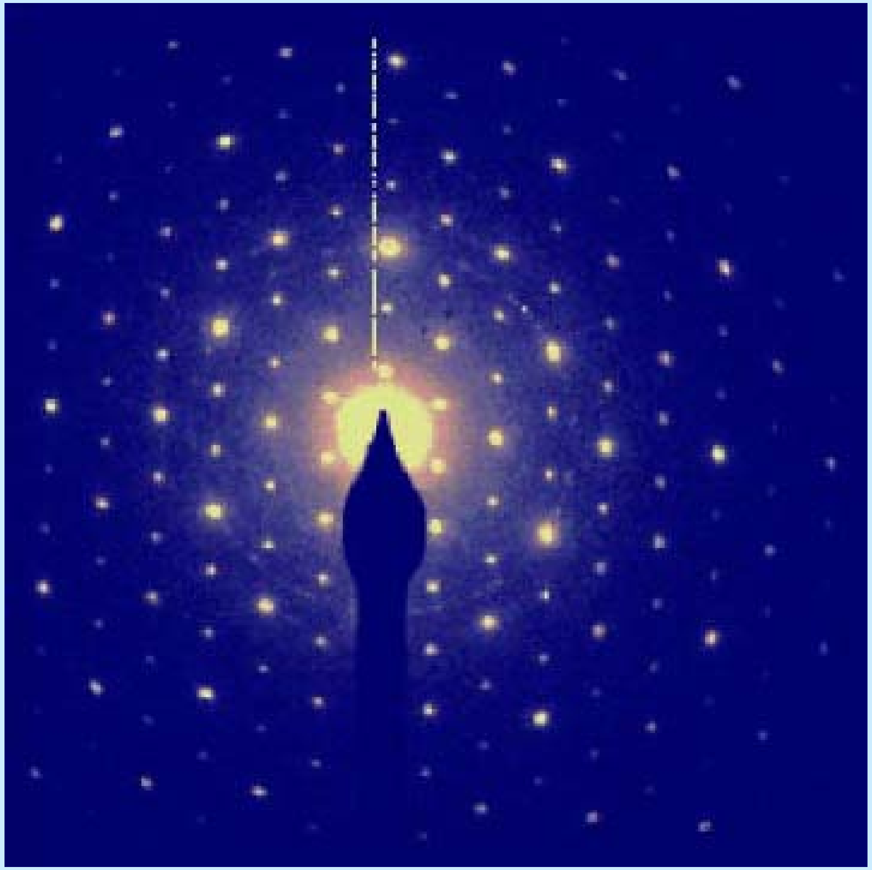


SiO$_2$ + metal

Si epi



An Example



525 x 525
25 μm pixels
0.5 μm CMOS
from RAL

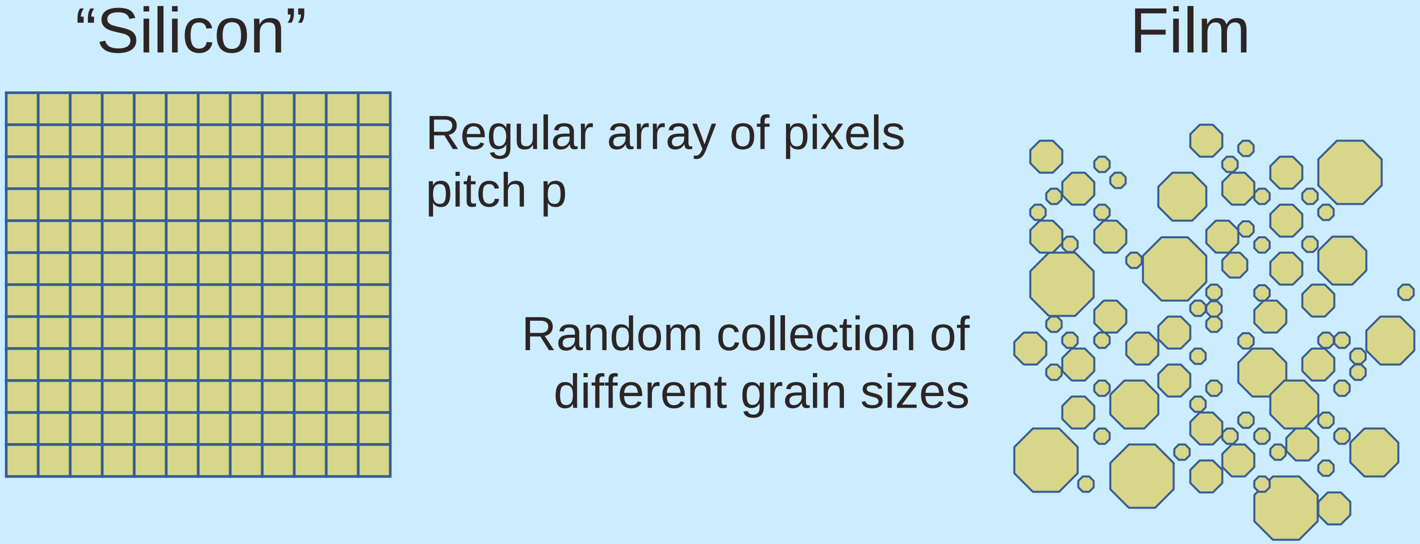
Diffraction pattern from vermiculite

Faruqi IWORID 2004

Pros and Cons

	“Digital” [Si]	Film [or I.P.]
♦ Processing	Electronic	Chemical
♦ Linearity	“ideal” $n(e^-) = QE \times n(\gamma)$	non-linear – n γ required to flip a grain; thermal fluctuations vs grain size; linear
♦ Resolution	Larger [smaller] pixels	Smaller grains
♦ Dynamic range	CCDs – 16 bits [APS – speed]	Locally, ~4 bits; [16 bits]
♦ MTF	Regular pattern – aliasing	Given by smallest grains, no aliasing
♦ MTF x S/N	Better	Worse; [best – at low rate]

Who Wins?



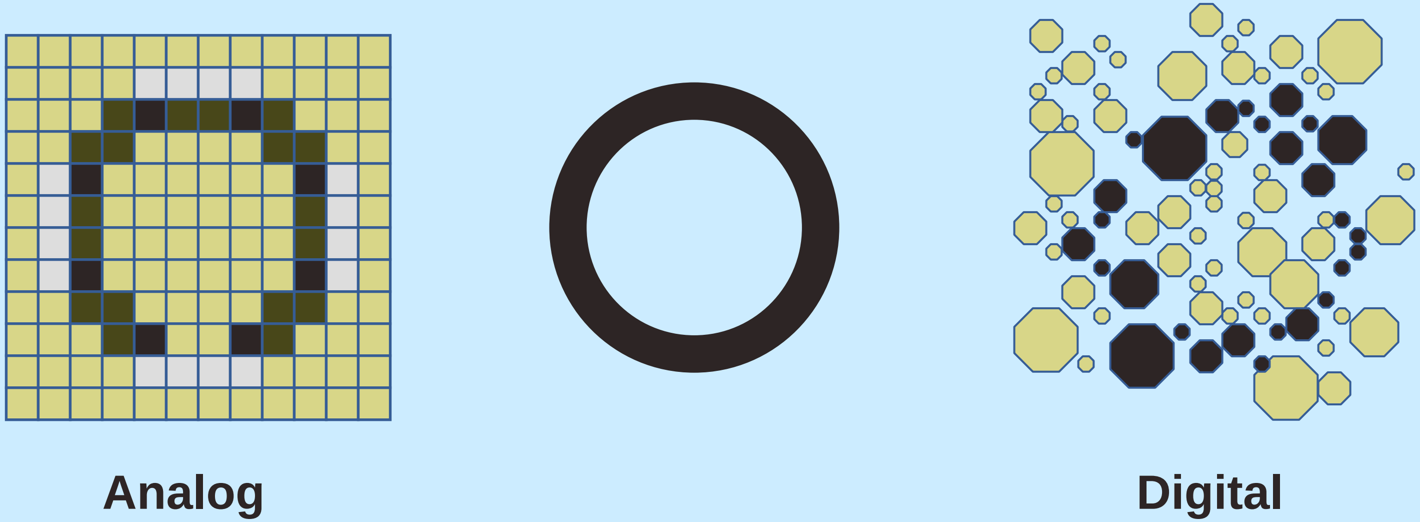
"Silicon"

Film

Regular array of pixels
pitch p

Random collection of
different grain sizes

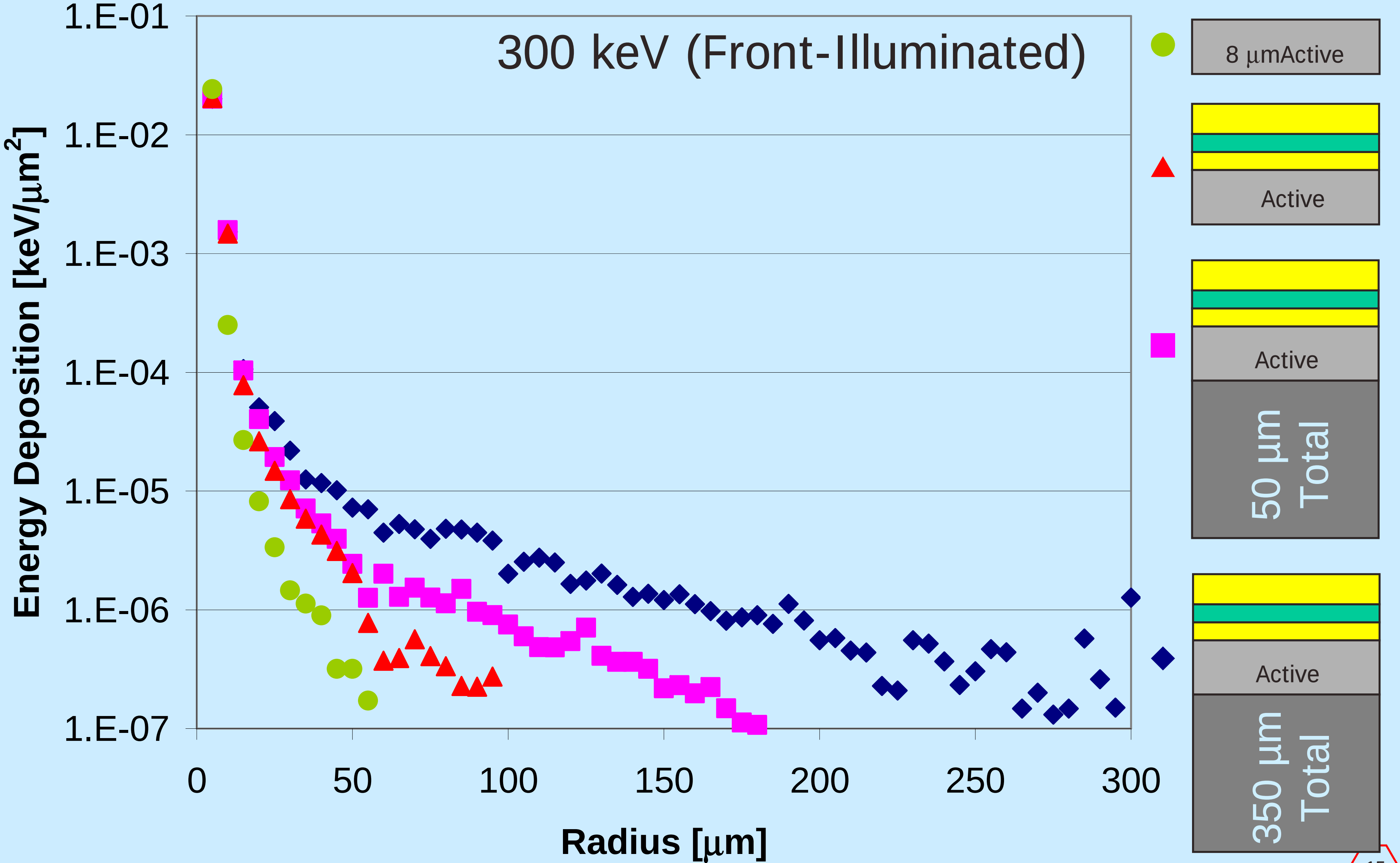
For now film grains smaller than silicon pixels



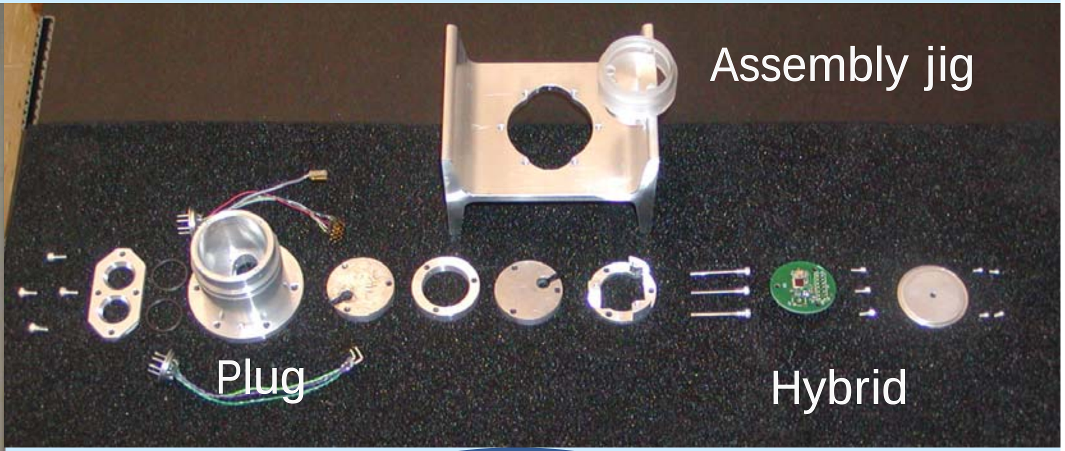
Analog

Digital

Some Thinning Helps



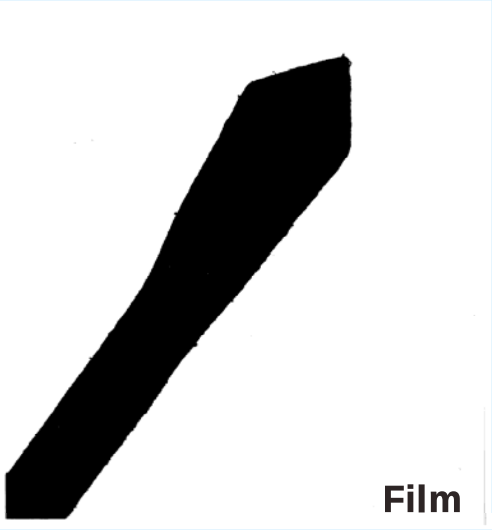
Tests on 200CX at NCEM



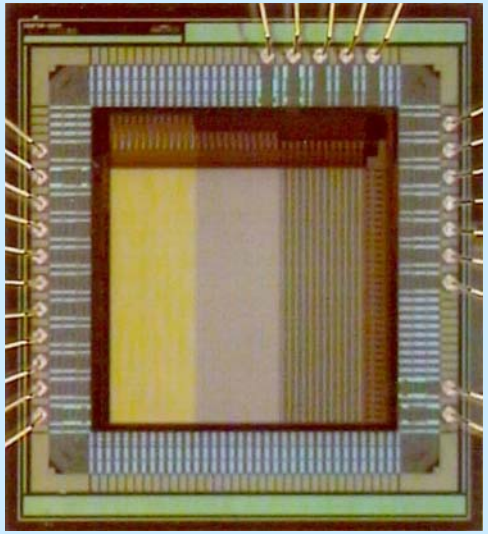
Modified GATAN bright field STEM detector housing at the bottom of the JEOL 200CX TEM

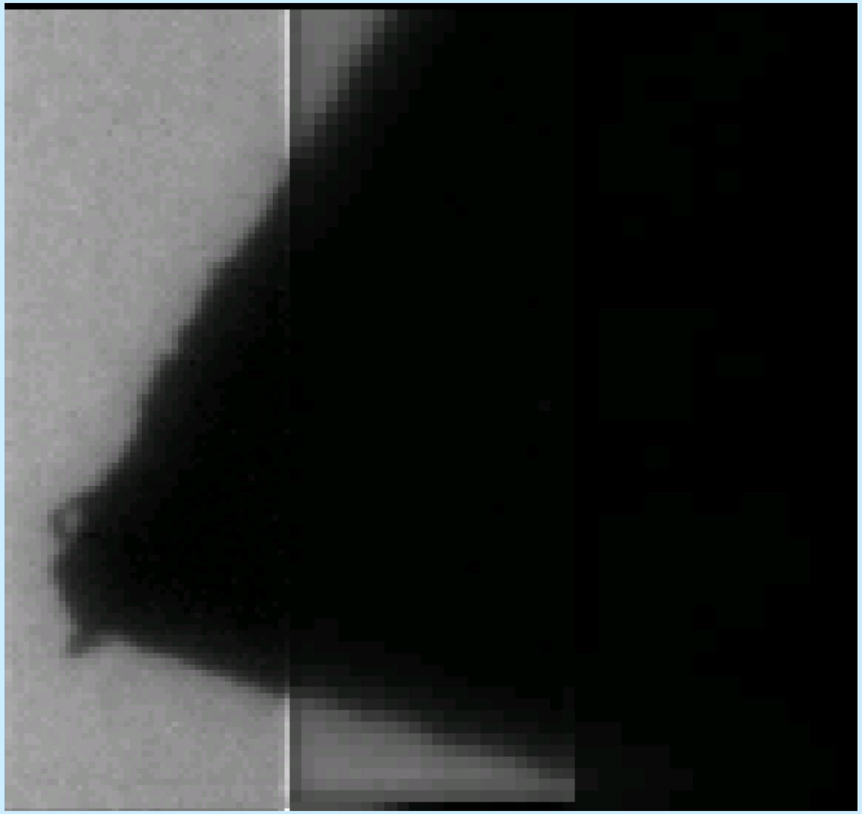
An Example

Beamstop
on 200CX
(imaged at
200 keV)



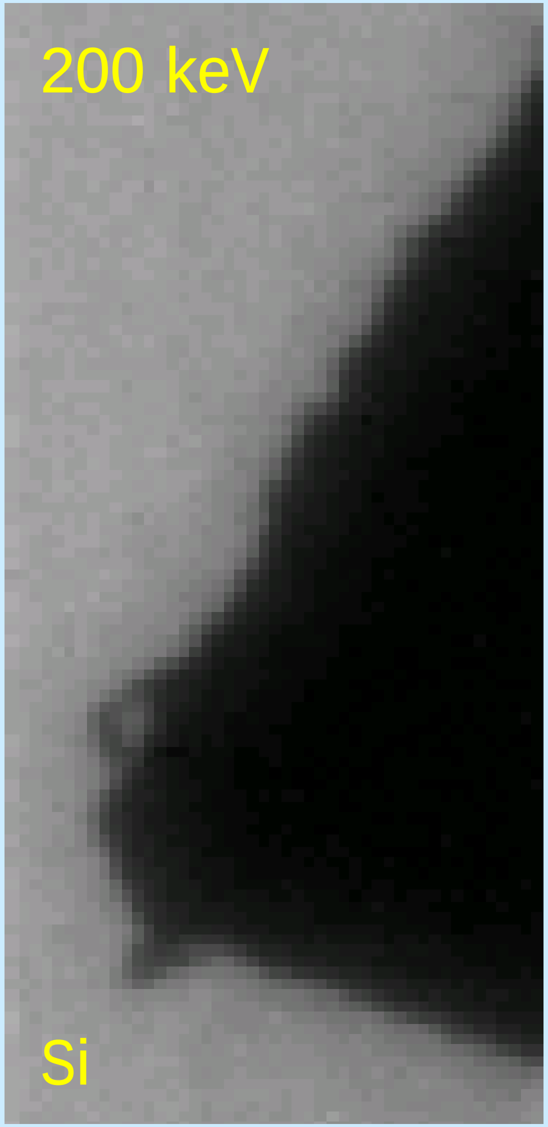
APS in
0.35 µm

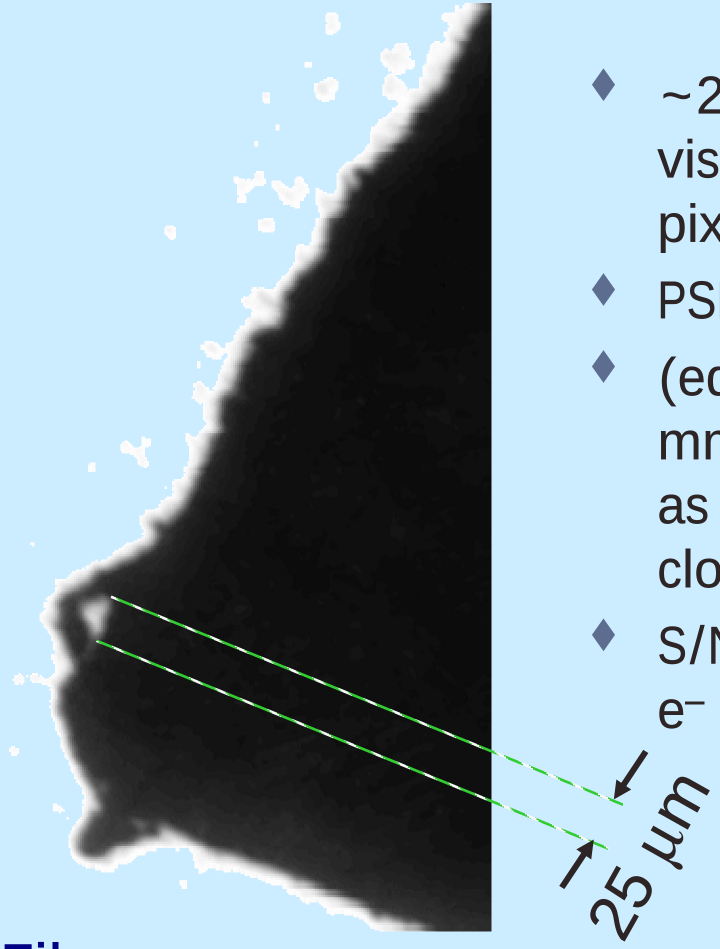




48x144	24x72	12x36
10 µm Pixels	20 µm Pixels	40 µm Pixels

Small Features Visible





Film

- ~20 μm features visible with 10 μm pixels
- PSF ~15 μm
- (equiv. MTF at 40-50 mm^{-1} ~ 20% - not as good as film, but close*)
- S/N ~8.3 → single e^- sensitivity

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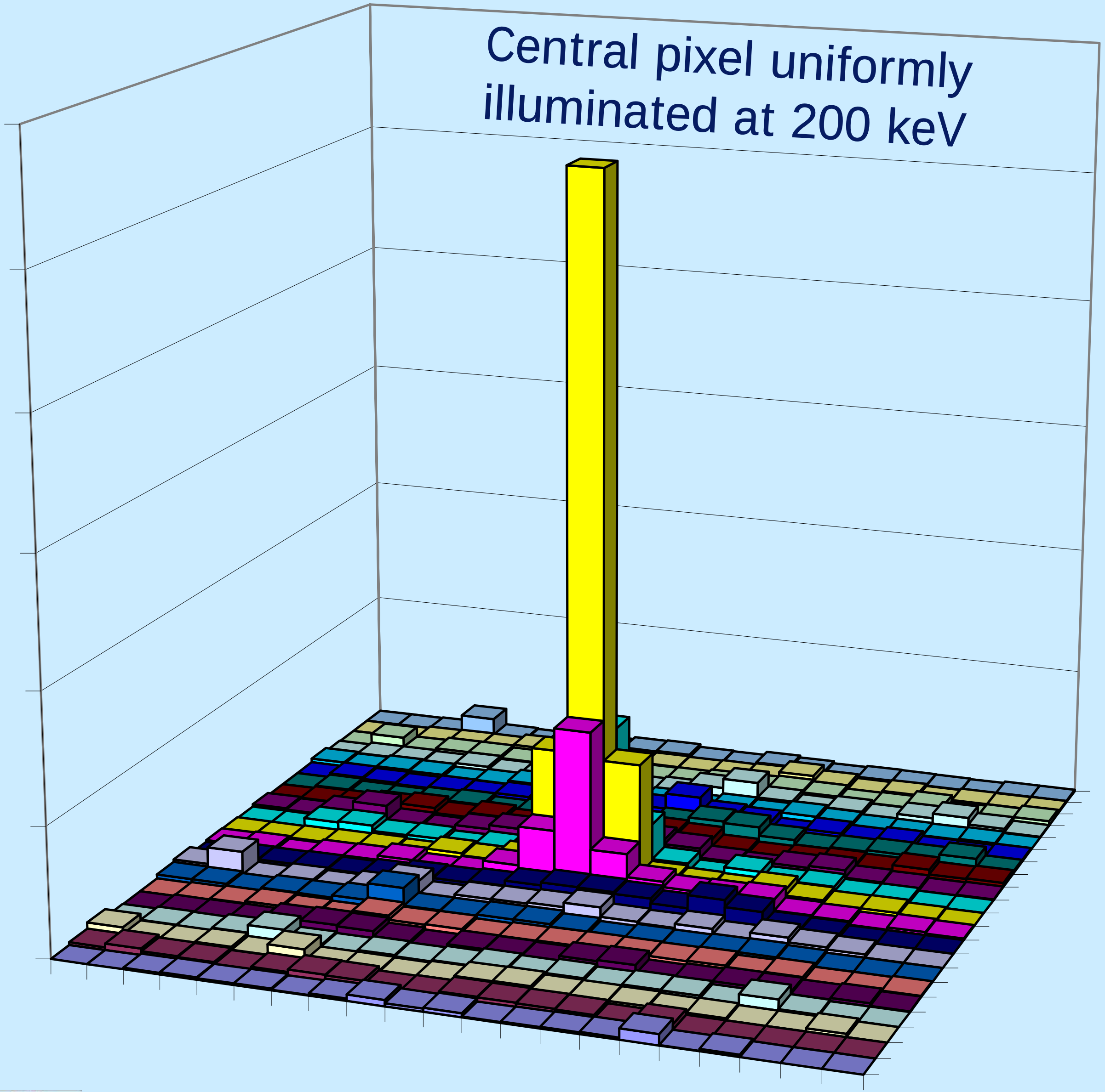
*Zuo 2000

vs. Prediction



- PSF due to e$^-$ multiple scattering at 200 keV ~6 μm
- Diffusion dominant

“Specifications”

Next-generation materials microscope

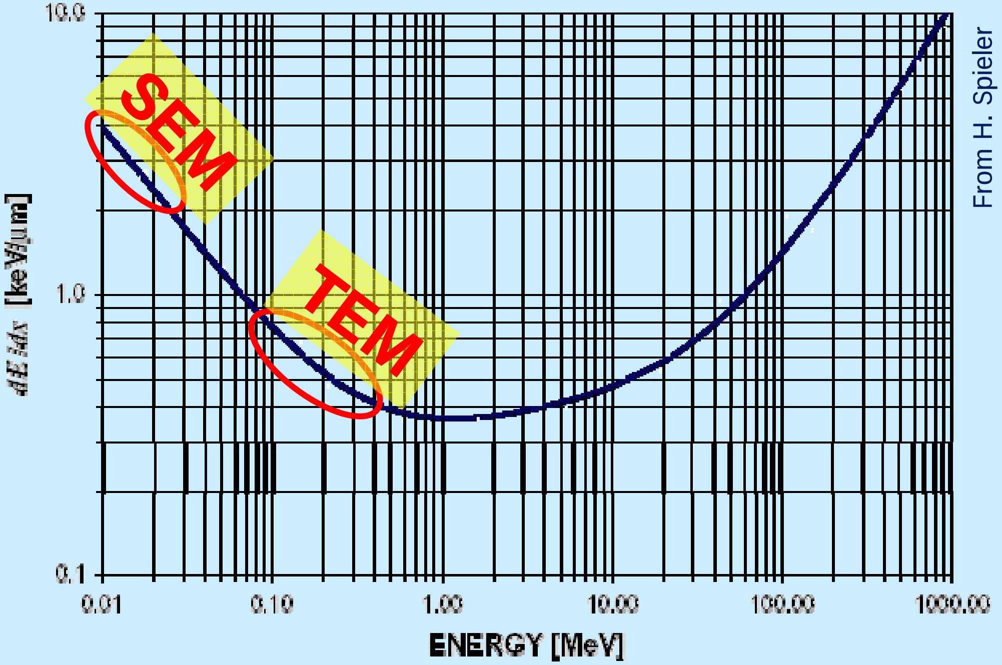
Parameter	**Spec.**	**Units**	**Comment**
Incident energy	100-300	keV	
Radiation hardness	300	images/day	min.
	10^5	images/day	desired
	~1	year lifetime	
e-/pixel/image	500		“imaging”
	10^5		“diffraction”
Elements	1200^2	pixels	200Å field-of-view with pixel size 0.5/3 Å
PSF	25%		(value at ½ Nyquist)
Resolution	$\sqrt{N}$		i.e. “shot noise limited”
Full scale	(given by frame rate)		e-/pixel/s x frame rate
Frame rate	<10	ms	

Biology not so different, except desire to have ∞ pixels

Challenges

- High S/N is desirable, but need to accommodate 100 (bio) 500 (materials) 10^5 (diffraction) primary e^- per pixel per image (readout rate dependent)
- “Resolution” is not the issue (optics set field of view), just number of pixels
- Readout speed helps in all applications
- **Radiation damage!**

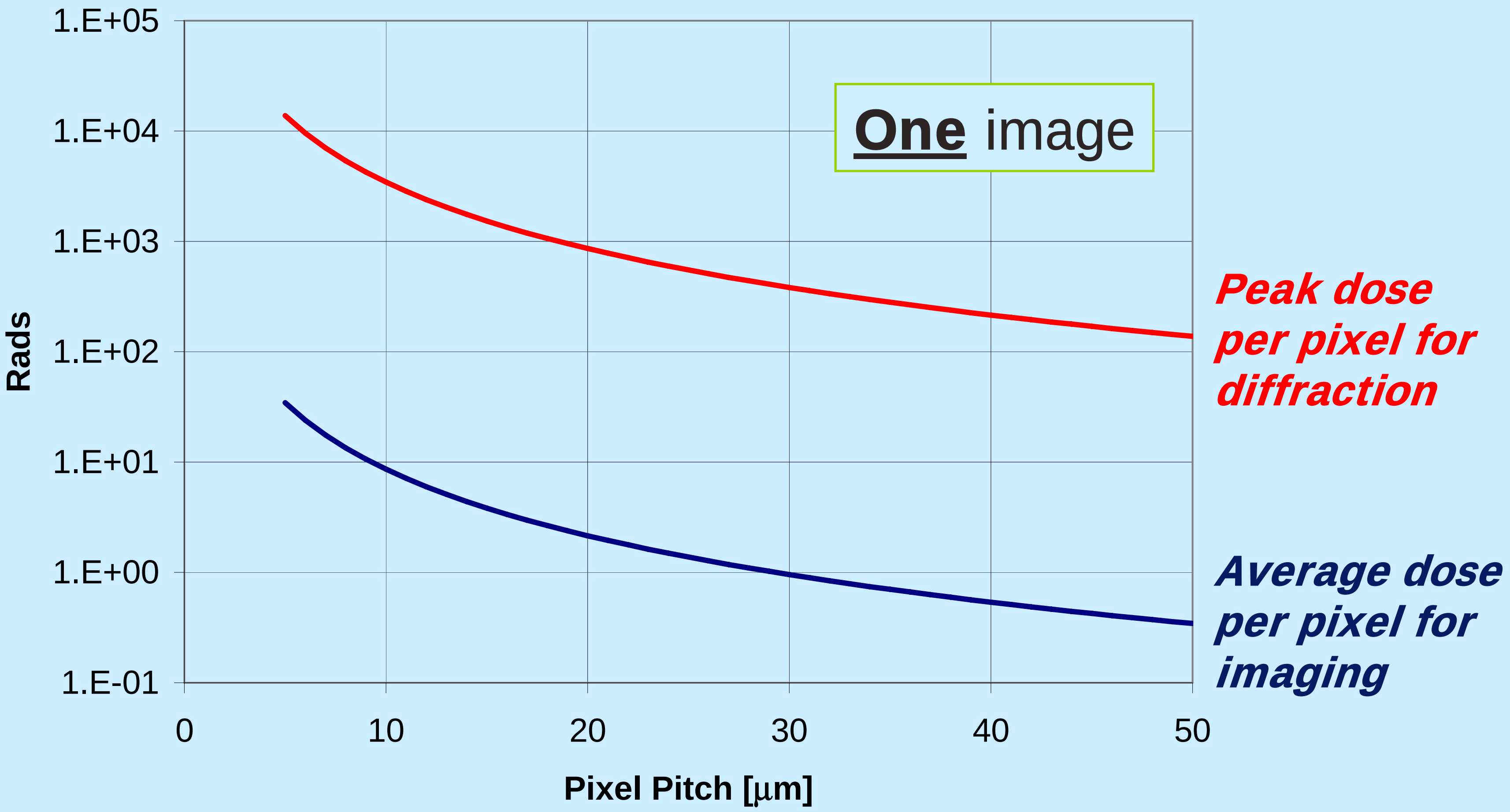
- Region of interest:
  1 – few x M.I.



From H. Spieler

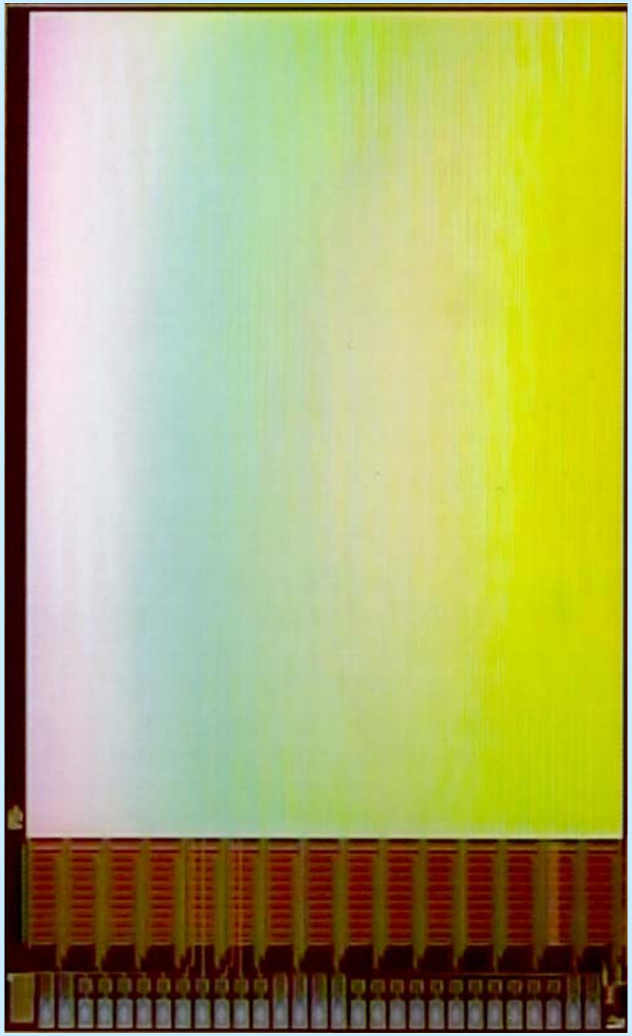
Radiation Damage

- Displacement damage not significant
- Ionizing dose not negligible



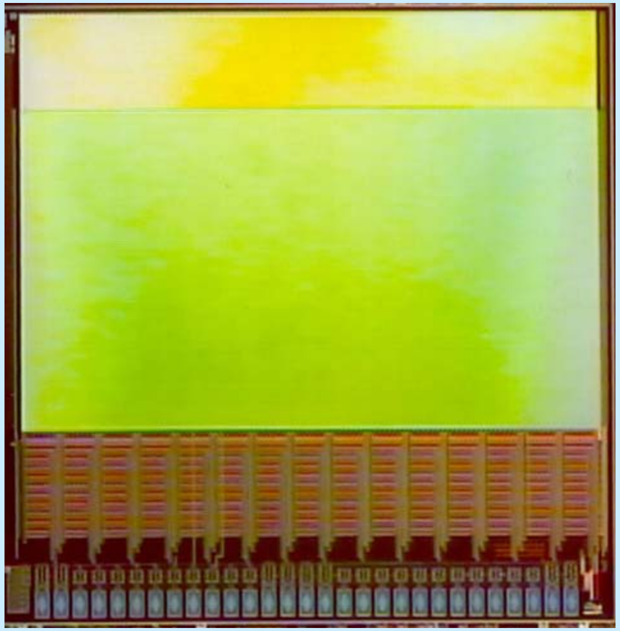
What We've Been Up To

Two 0.25 µm CMOS Prototypes (2005)



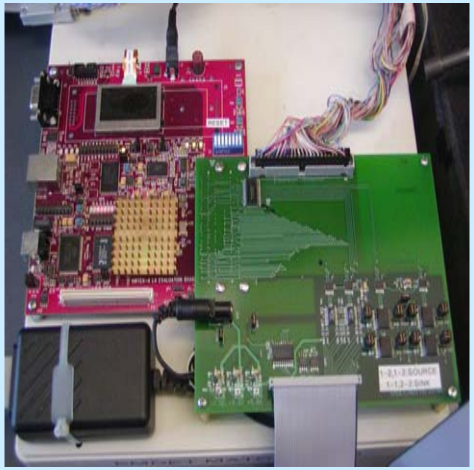
19 µm pixels
in-pixel CDS

6 µm pixels



on-chip
digitizers

← 5 mm →

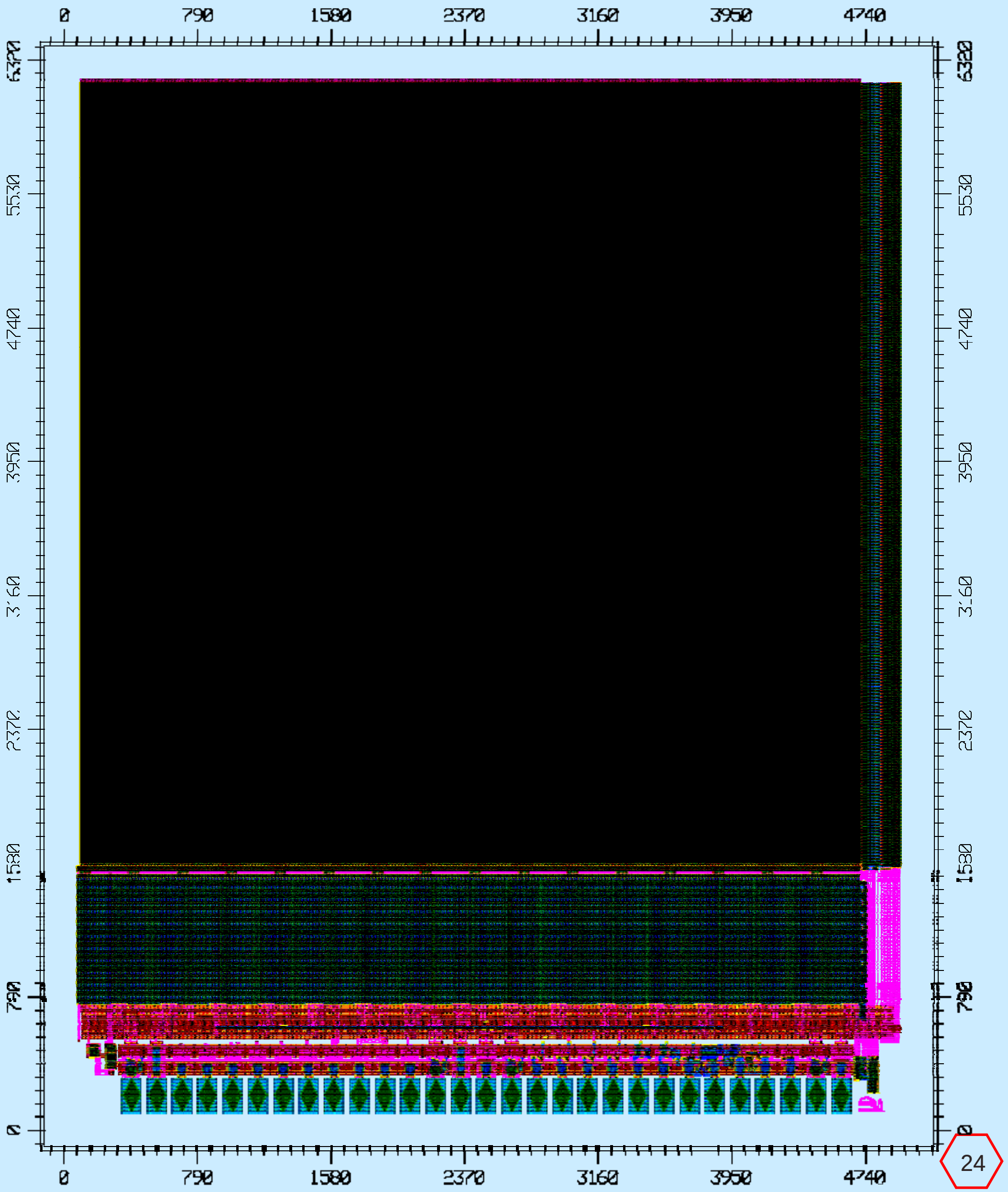


Readout System

Now in Fab

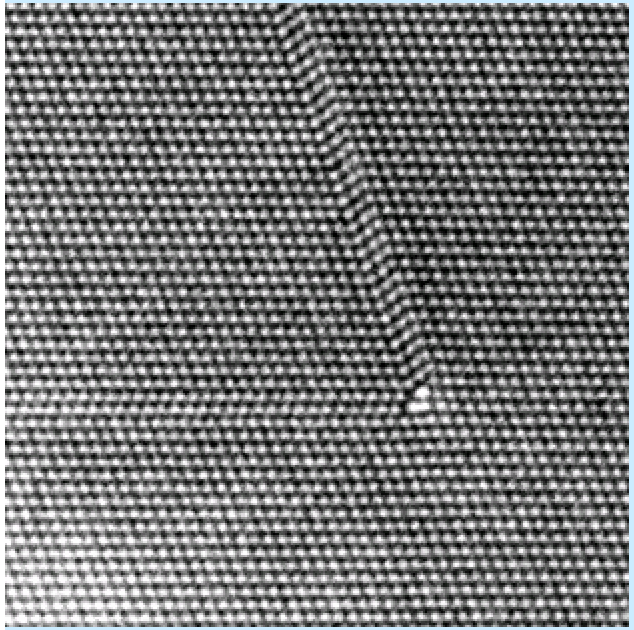
- 9 µm pixels
- 512 x 512
- Adjustable gain
- Same backend (digitizers and readout)

- Prototype for 2k x 2k



What This Achieves

- Unprecedented speed
  - *Visualize catalysis*
  - *Reduce beam-induced motion of biological samples*
- High DQE
  - *Good single e^- sensitivity and good PSF*
  - *DQE = 1 if variance of input signal faithfully transmitted*
- Spatial resolution better than fiber-coupled phosphor + CCD
  - *Eventually approach film*
- Uniformity and linearity
- Radiation hardness requirement not negligible



Atomic resolution image of stacking faults in Gold

(An) Ultimate Goal