X-ray Detectors:

State-of-the-art & Future Possibilities

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simplified view of the

Evolution of Imaging Synchrotron X-ray Detectors

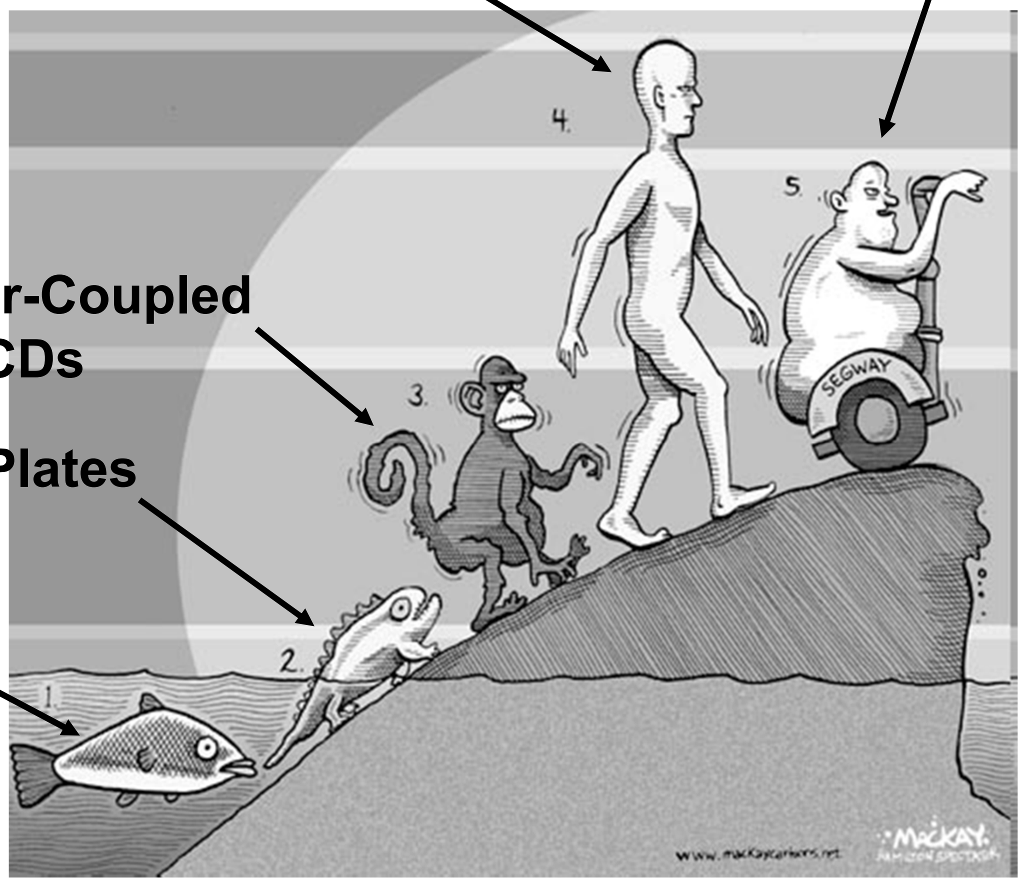
Intelligent Direct-Detection Semiconductors

Direct-Detection Semiconductors

Phosphor-Coupled CCDs

Image Plates

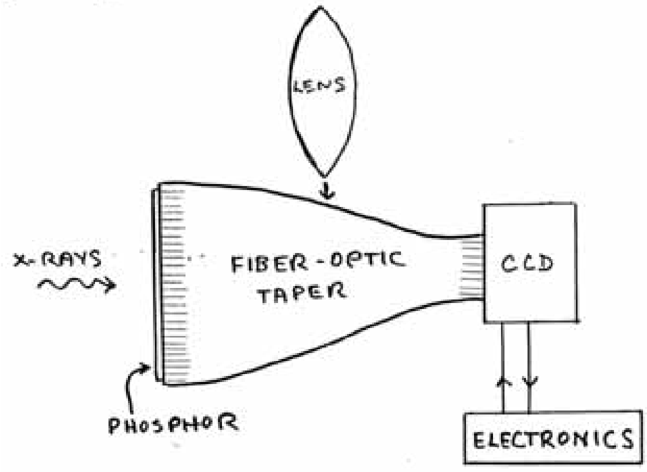
X-ray Film



What is feasible in the next decade, given sufficient R&D?

Less prevalent imaging detectors are omitted for sake of time.

Limitations arise from fundamental physical properties of detector parts



Phosphor: settled powder or single crystal garnet

- Speed (msec to μs) vs. efficiency, even for single snapshots
- Resolution vs. efficiency

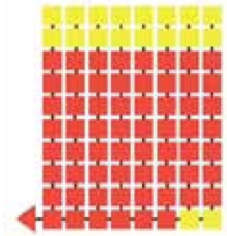
Light relay system: fiber optics bundle or lens

- Fiber optics limit resolution to several microns
- Lenses have higher resolution, but limit dynamic range

CCD

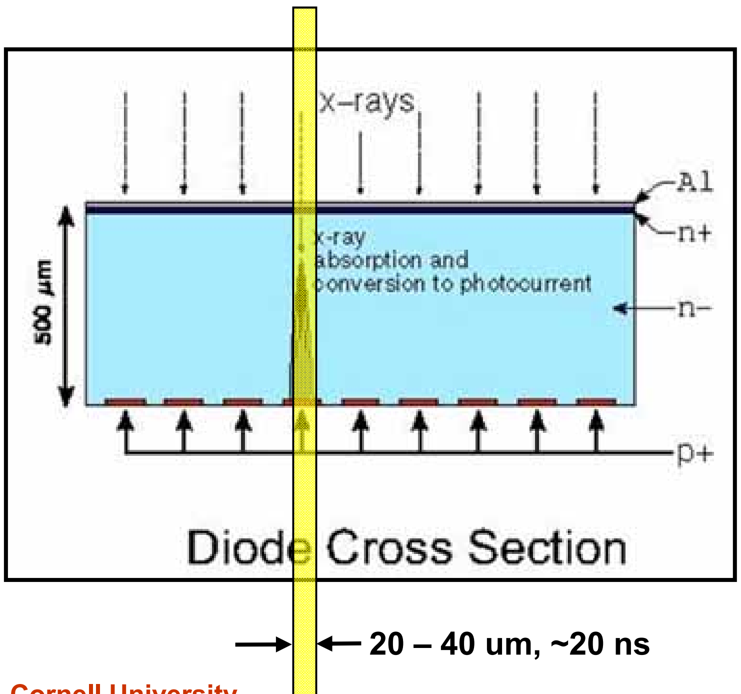
- Serial nature of readout limits frame time

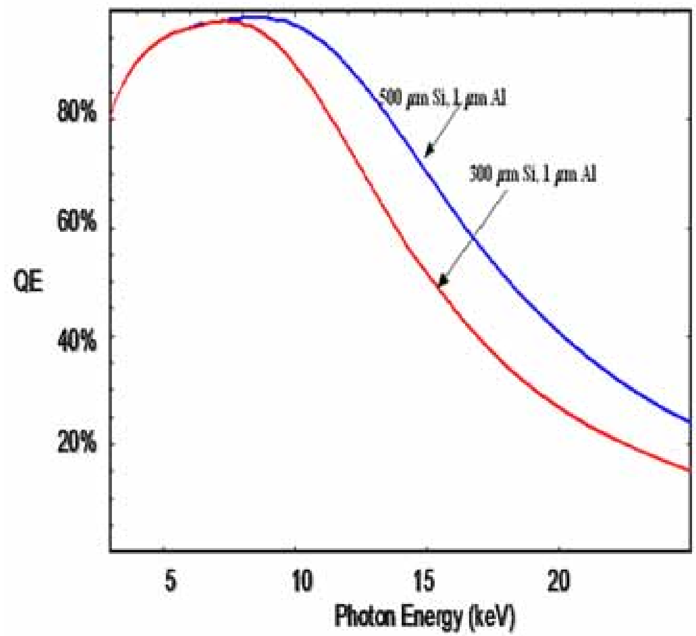
Normal depletion thickness is only a few microns



Direct Detection in Silicon

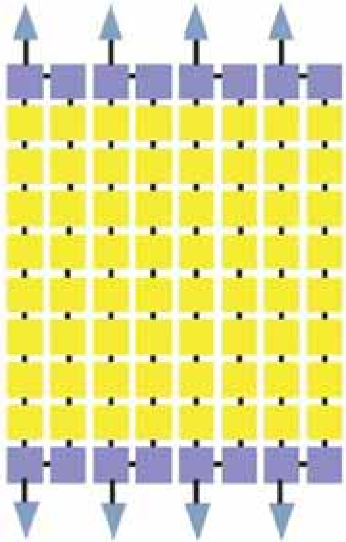
- **Si is a superb x-ray to electrical signal converter.**
- **@ 10 keV, radius of e-h cloud ~ 1 micron.**
- **Number e-h pairs, N_{eh}: $E_{x\text{-}ray}$ / 3.65 eV**
- $\sigma(N_{eh})/N_{eh} = \sqrt{F/N_{eh}}$, where $F \equiv$ Fano Factor = 0.1.
- **10 keV yields N_{eh} = 2740 ± 20. (ΔE = ±3.65 x 20 eV = 146 eV width)**





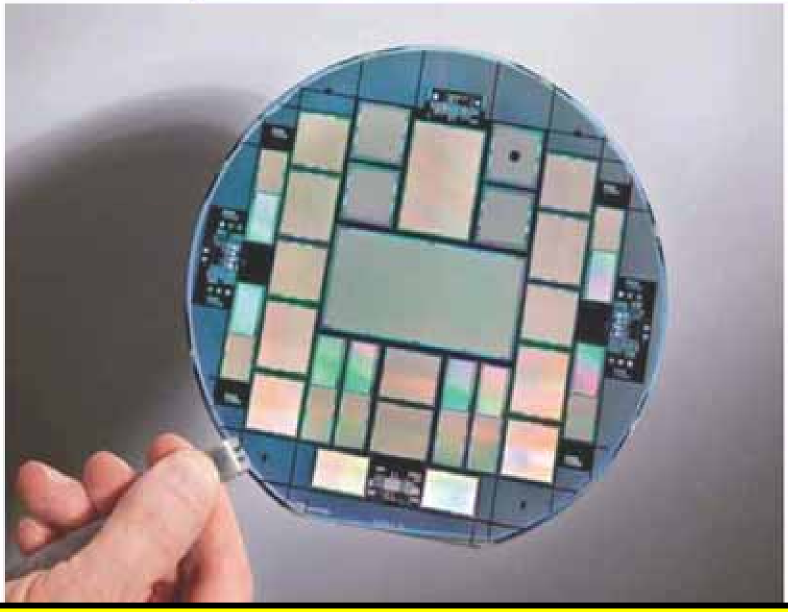
CCD output configuration

- CCDs are intrinsically slow
  - Single output CCD
  - Column parallel CCD
  - Almost column parallel CCD
- LBNL FCCD
  - Multiple outputs (ex.48 per side)
  - Faster outputs (ex.1MHz)
  - 200 fps

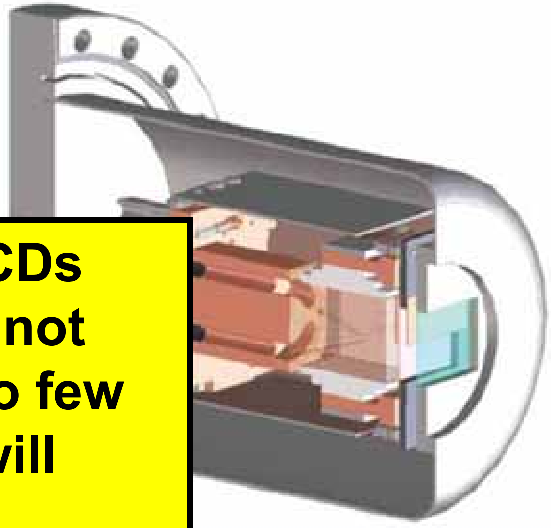


September 21, 2010 *D. Doering, LBNL @ SRI 2010 Detector workshop* *11*

(New) R&D CCD – 1k Frame Store



- 30 x 30 um pixel
- 1920x960 pixels (8 times the area of cFCCD)
- Thick 200-650um
- 200fps
- Data volume ~ 400MB/s (HD 250GB -> ~10 min)



A number of direct x-ray conversion CCDs will soon be available, though perhaps not commercially. Well depths are limited to few hundred x-rays/pix and frame speeds will likely eventually top out at ~1KHz.

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Semiconductors

Physical characteristics of the semiconductors

Semi-conductor	ρ [g/cm^3]	Z	E_{gap} [eV]	ϵ [eV]	$T_{working}$ [K]	K-edge [keV]	ρ_e [Ω cm]	$\mu_{e,h}$ $\tau_{e,h}$ [cm^2/V]
Si	2.33	14	1.12	3.6 [1]	300	1.8	$\approx 10^3$	0.42, 0.22
Ge	5.33	32	0.67	2.9 [3]	77	11.1	$\approx 10^2$	0.72, 0.84
GaSe	4.55	31, 34	2.03	4.5 [4]	300	10.3, 12.6		10^{-7}, 10^{-7}
								1.5×10^{-6}, 2.5×10^{-6}
InP	4.78	49, 15	1.30	4.2 [6]	300	27.9, 2.1	$\approx 10^7$	4.8×10^{-6}, $\leq 10^{-7}$
CdS	4.84	48, 16	2.60	7.3 [15]	300	26.7, 2.4		
GaAs	5.32	31, 33	1.43	4.3 [3]	300	10.3, 11.8	$\approx 10^7$	8.6×10^{-6}, 4.0×10^{-7}
								8.6×10^{-5}, 4.0×10^{-6}
InSb	5.77	49, 51	0.20	0.6 [15]	4	27.9, 30.4		10^{-5}, 7.5×10^{-6}
CdSe	5.80	48, 34	1.73	5.5 [a]	300	26.7, 12.6		2.0×10^{-5}, 1.5×10^{-6}
CdTe	6.20	48, 52	1.44	4.7 [3]	300	26.7, 31.8	$\approx 10^9$	2.0×10^{-3}, 4.0×10^{-4}
PbI_2	6.20	82, 53	2.55	7.7 [a]	300	88.0, 33.2	$> 10^{13}$	8.0×10^{-6}, 2.0×10^{-7}
HgI_2	6.40	80, 53	2.13	4.2 [7]	300	83.1, 33.2	10^{13}	10^{-4}, 10^{-5}
TlBr	7.56	81, 35	2.68	6.5 [18]	300	85.5, 13.5	$\approx 10^{12}$	1.6×10^{-5}, 1.5×10^{-6}

From Bencivelli et al., Nucl. Instr. Meth. Phys. Res. A310 (1991) 210-214

On a decade time scale x-ray sensors of "exotic" semiconductors are feasible, though probably only as bump-bonded sensors. High atomic number materials can extend detection to very hard x-rays.

Basic Pixel Array Detector (PAD)

Diode Detection Layer

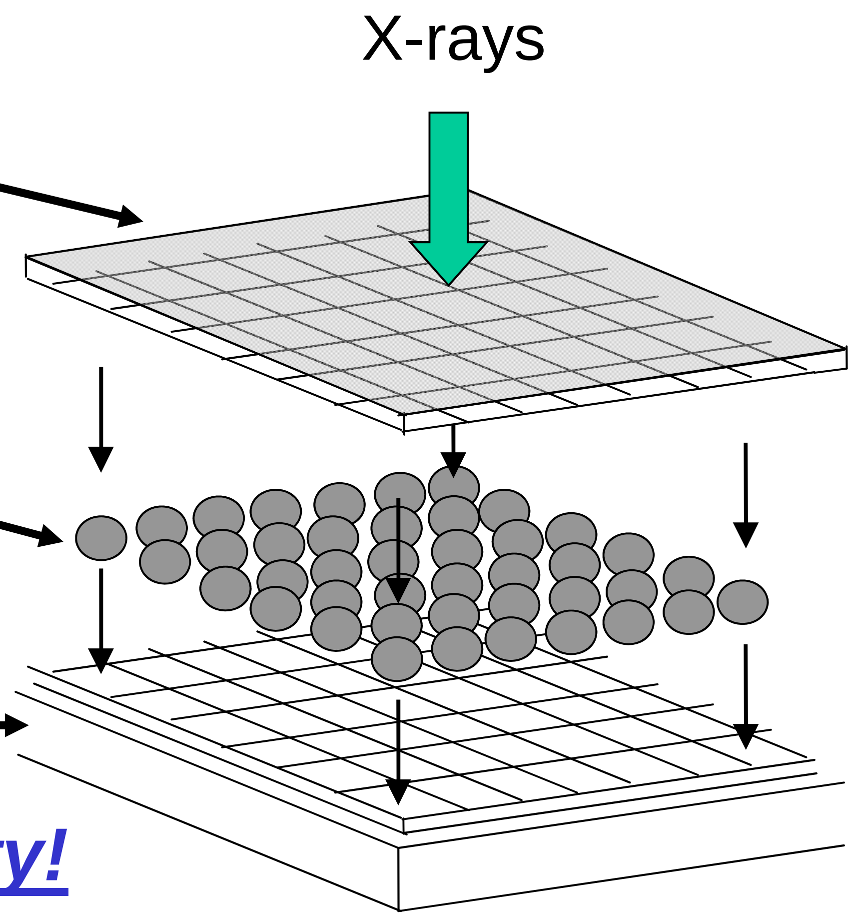
- Fully depleted, high resistivity
- Direct x-ray conversion in Si

Connecting Bumps

- Solder, 1 per pixel

CMOS Layer

- Signal processing
- Signal storage & output



Gives enormous flexibility!

PADs come in two varieties

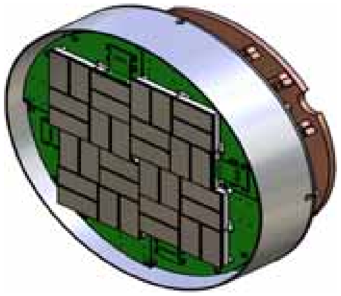
Photon counting PADs

- Front ends count each x-ray individually. (PILATUS, Medipix)
- Drawback for high-speed imaging: Count-rate limited by electronics to ~10^6 -10^7 x-rays/pix/sec.

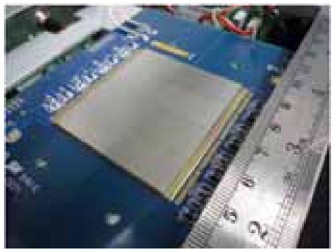
SLS PILATUS

Integrating PADs

- Use an integrating front-end to avoid the count-rate bottleneck.
- Capable of handling enormous count-rate.
- Existing variants include LCLS, ADSC, Acrorad



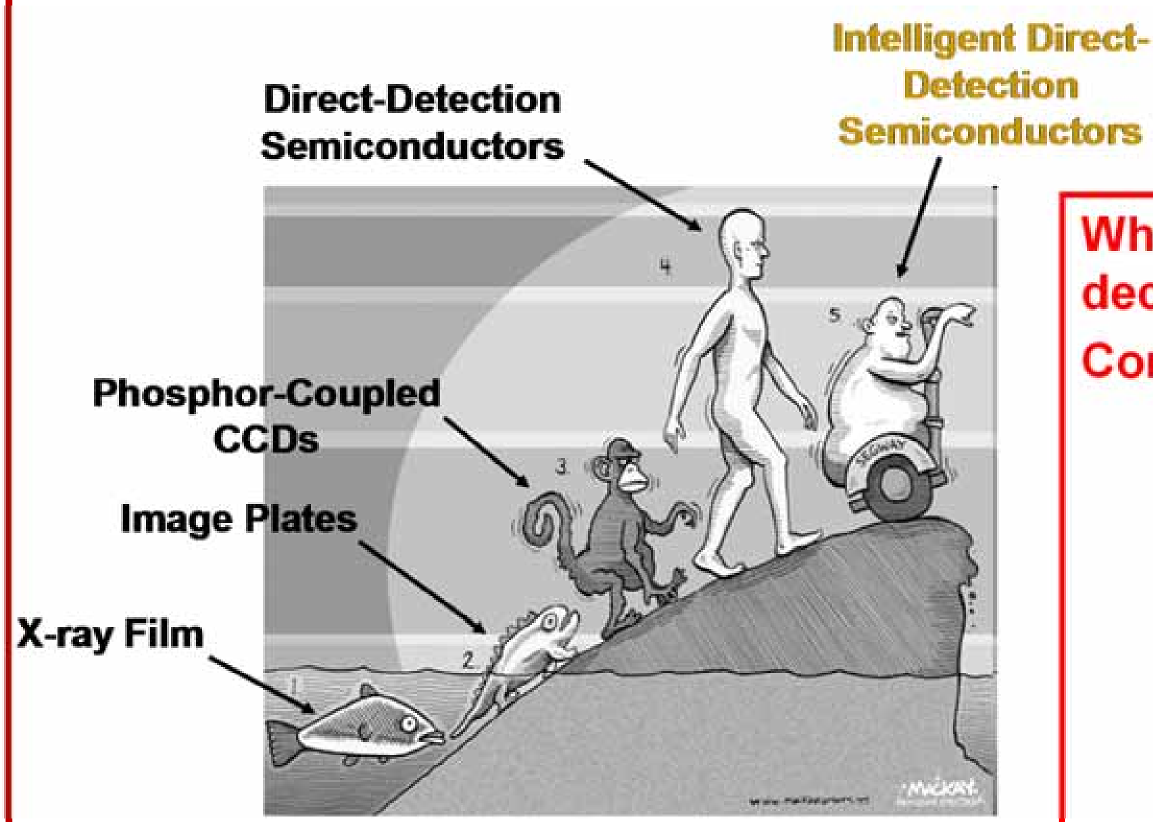
Cornell-SLAC LCLS



Acrorad CdTe

simplified view of the

Evolution of Imaging Synchrotron X-ray Detectors



What is feasible in the next decade, given sufficient R&D?

Consider:

- **Pixel size & complexity**
- **Spatial resolution**
- **Time resolution**
- **Analog dynamic range**
- **Energy resolution**

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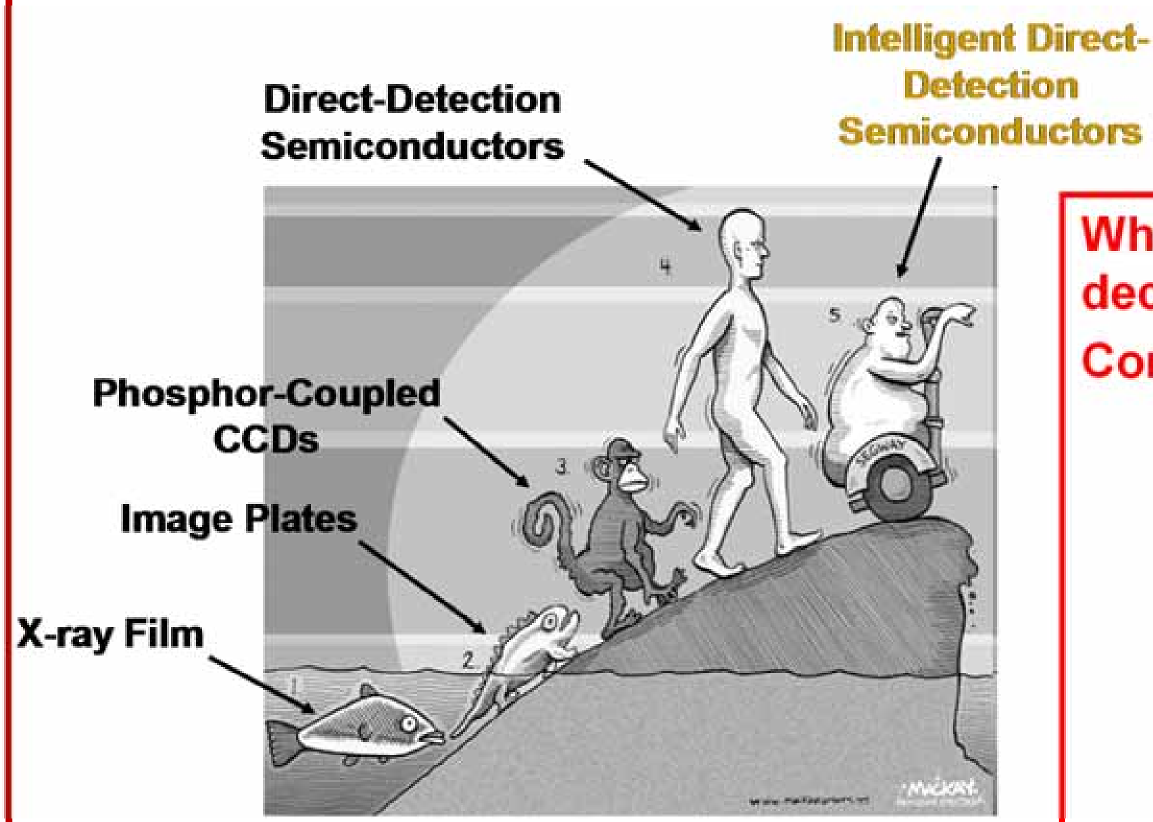

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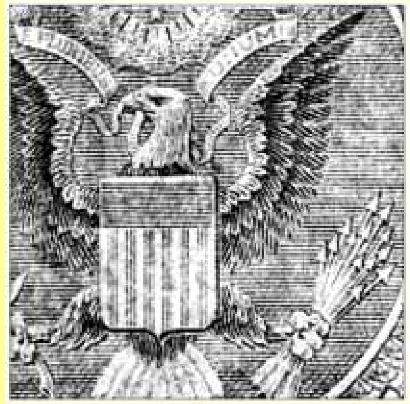
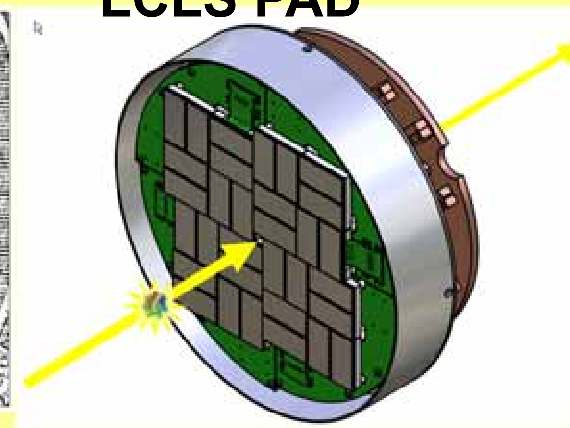
KECK PAD	
Parameter	**Target Value**
Noise	< 0.5 x-ray/pixel/accumulation
Minimum exposure time	<150 ns for 12-bit imaging
Capacitor well depth	2000 – 4000 x-rays
Nonlinearity (% full well)	< 0.2%
Diode conversion layer	500 µm thick Si
Number of capacitor wells/pix	8
Full chip frame time	1 msec/frame, e.g., 8 msec for 8 capacitors
Radiation lifetime	> 50 Mrad at detector face @ 8 keV
Pixel size	150 µm on a side, or 128 x 128 pixels per IC
Detector chip format	2 x 4 chips = 256 x 512 pixels

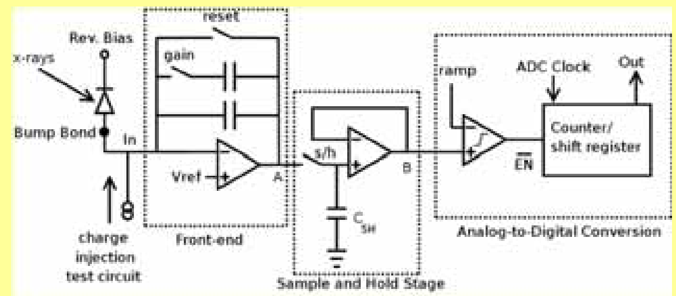
Complexity at the level of 200 – 300 transistors/pixel. 0.25 um process.

Pixel sizes of 110 & 150 um across.

LCLS PAD

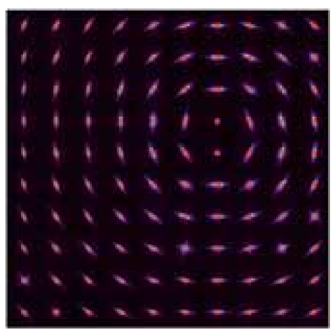


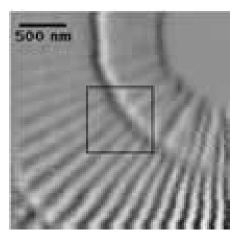


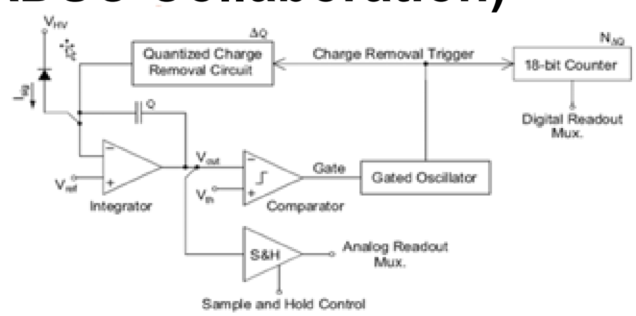


Mixed-Mode PAD (ADSC Collaboration)

PAD Tile Format	128 x 128 pixels
Pixel Size	150 µm x 150 µm
Frame Rate	Up to 1,000 Hz
Read Noise	0.3 X-ray [12 keV] / pix
Well Capacity	2.6 x 10^7 X-ray [12 keV]/pix/frame





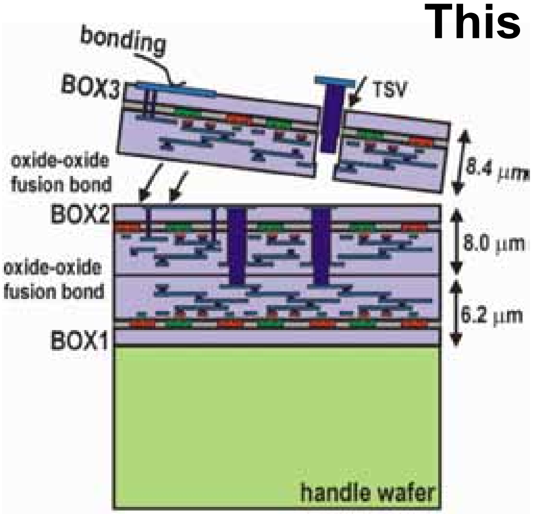


3D-ICs based on Silicon-on-Insulator (SOI) Wafers

"…Small prototypes of VIPs are extendable to sizes of 1024×1024 pixels, bearing the actual needs of the application. The top tier contains a gated charge integrator, a single ended AC-coupled offset corrected discriminator with capacitively injected threshold, an analog memory for reference sample, an analog memory for post discriminator sample, a pulse generator for time stamping lock and hit information lock, a receiving part of test-charge injection capacitance and a bonding pad to the detector. The intermediate tier features an analog memory cell for time stamping (distributed voltage ramp), a 7-bit SRAM-like digital time stamping memory with output enable control to read on the same lines on which time ticks in Gray code are distributed. The bottom tier hosts the sparsification system: token propagation logic, wiredOR line access logic for X-line/Y-line of a hit pixel address generator, test-charge injection logic and a peripheral serialization and output part."

This is ~200 transistor level of complexity in 20 um pixel.

From: Deptuch et al, FERMILAB-CONF-10-401-PPD

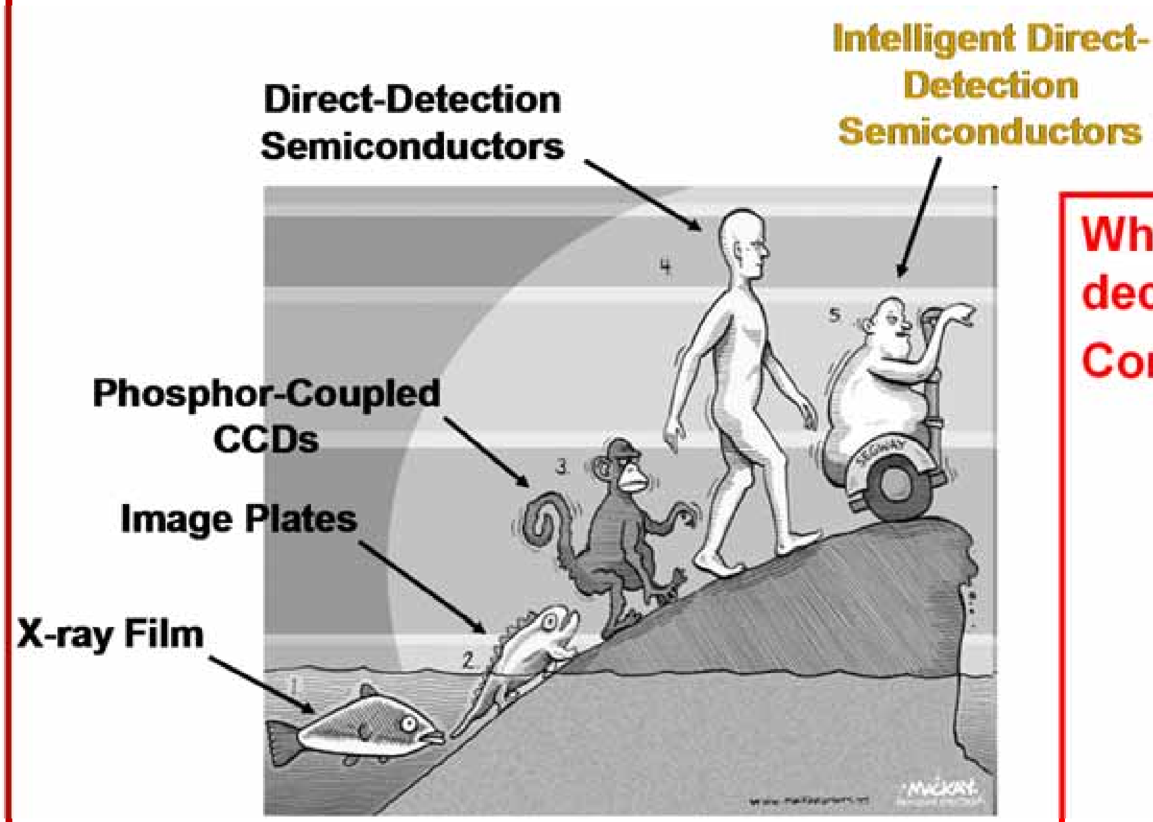


Deptuch et al, FERMILAB-PUB-10-314-ppd

On a decade time scale pixels with reasonable levels of complexity and 10 – 20um pixel sizes are feasible.

simplified view of the

Evolution of Imaging Synchrotron X-ray Detectors

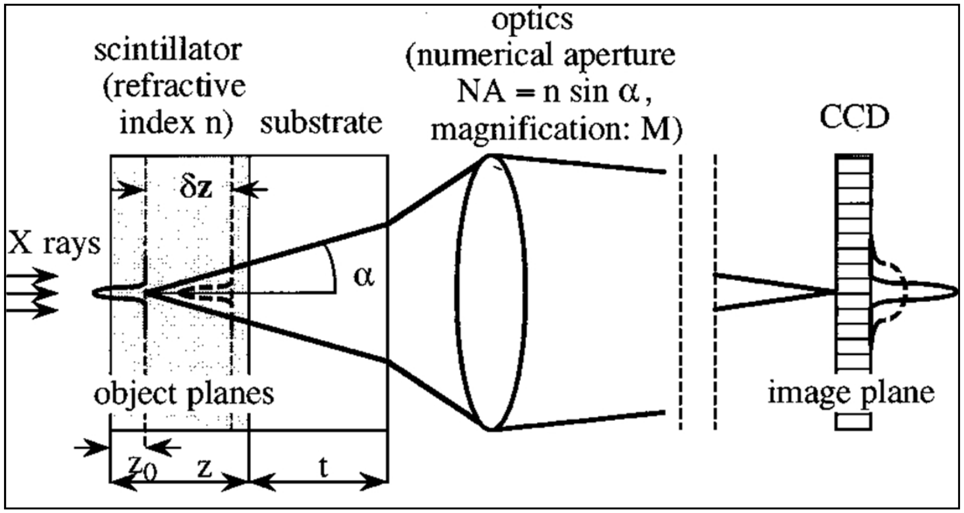


What is feasible in the next decade, given sufficient R&D?

Consider:

- Pixel size & complexity
- **Spatial resolution**
- Time resolution
- Analog dynamic range
- Energy resolution

High Spatial Resolution Using Doped Garnets



Single crystal YAG:Ce and GGG:Eu screens with doped layers microns thick are commercially available (e.g., ESRF; laser vendors).

Present spatial resolutions of ~0.7um are available with reasonable efficiencies. The wavelength of light and photoelectron emission will likely limit this to small digit improvements, at best.

From: Koch at al., J. Opt. Soc. Am. A 15 (1998) 1940

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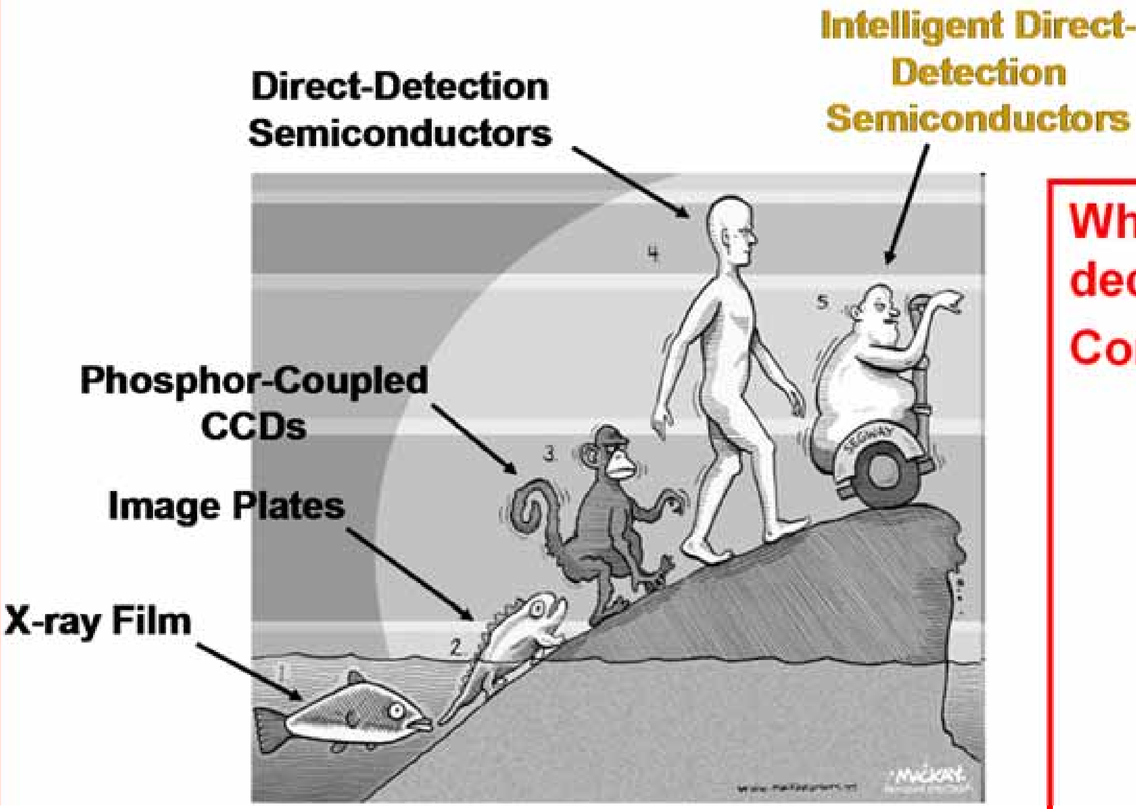

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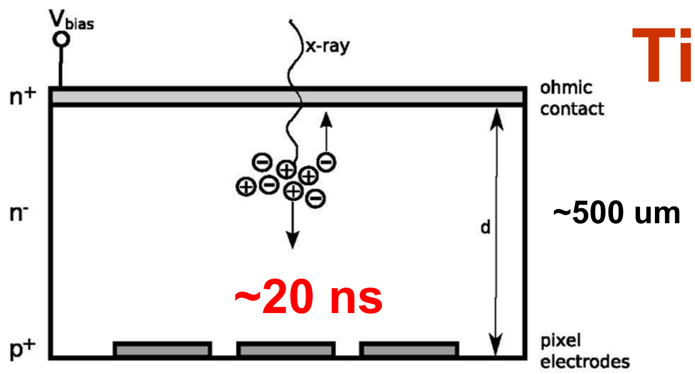
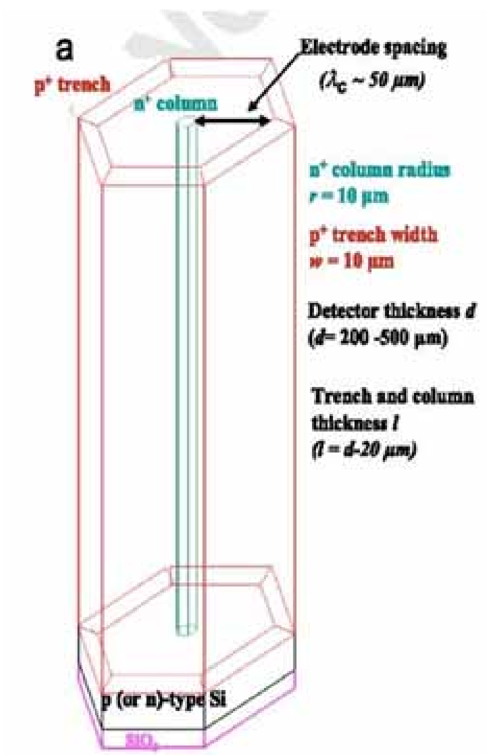
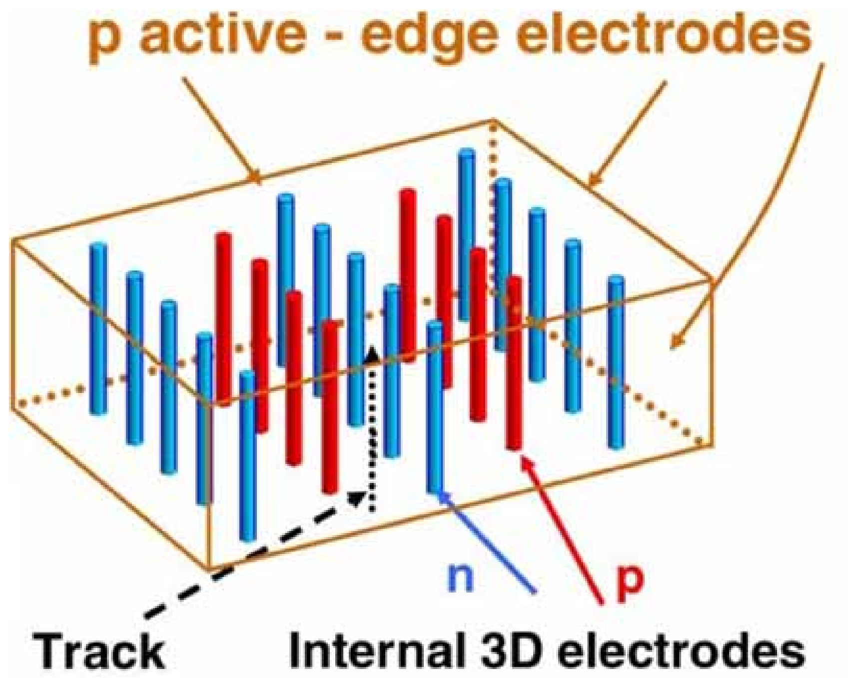
Time Resolution





Z. Li, Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.05.003

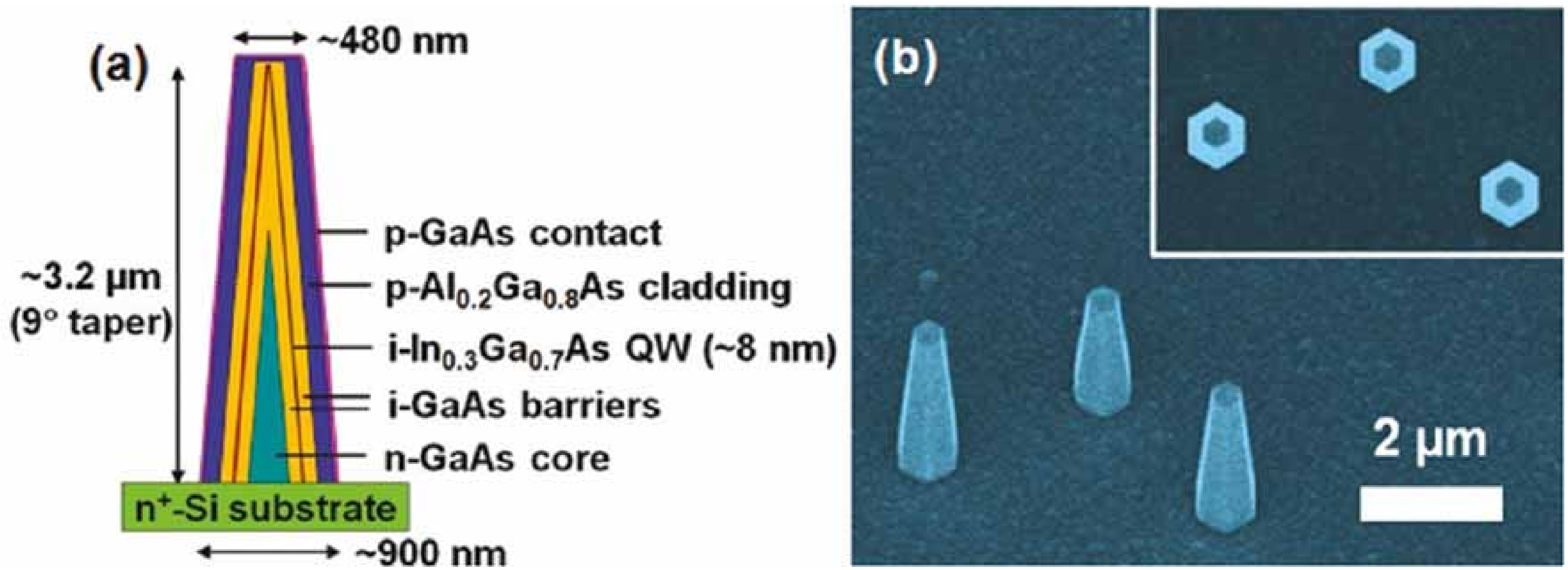
few ns using Si



Parker et al., IEEE Trans. Nucl. Sci. 58 (2011) 404.

3D silicon sensors capable of a few ns response are in advanced R&D. On a decade time scale, use of "exotic" semiconductors and few hundred ps response may be feasible.

Time Resolution: Use Nanopillars



From: Chuang et al., NANO Letters 11 (2011) 385

This is an LED, but they also report on Avalanche Photodiodes (APD)

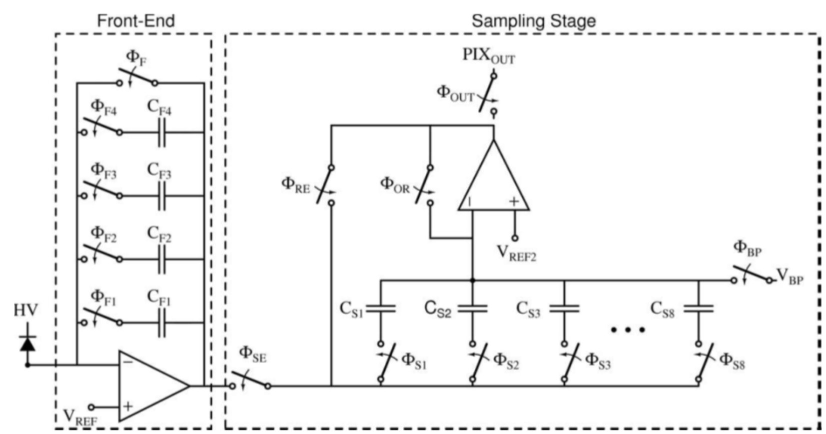
A dense forest of nanopillar APDs are in principle capable of few ps response. With sufficient R&D fill factors of ~25% may become feasible. Readout electronics then become limiting.

Frame Time

Considerations:

- **Front-end amplifier settling time.**
- **Time to transfer data to off-ASIC digital memory. Parallelize!**

KECK PAD	
Parameter	**Target Value**
Noise	< 0.5 x-ray/pixel/accumulation
Minimum exposure time	<150 ns for 12-bit imaging
Capacitor well depth	2000 – 4000 x-rays
Nonlinearity (% full well)	< 0.2%
Diode conversion layer	500 µm thick Si
Number of capacitor wells/pix	8
Full chip frame time	1 msec/frame, e.g., 8 msec for 8 capacitors
Radiation lifetime	> 50 Mrad at detector face @ 8 keV
Pixel size	150 µm on a side, or 128 x 128 pixels per IC
Detector chip format	2 x 4 chips = 256 x 512 pixels
Dark current	2 x-rays/pix/sec



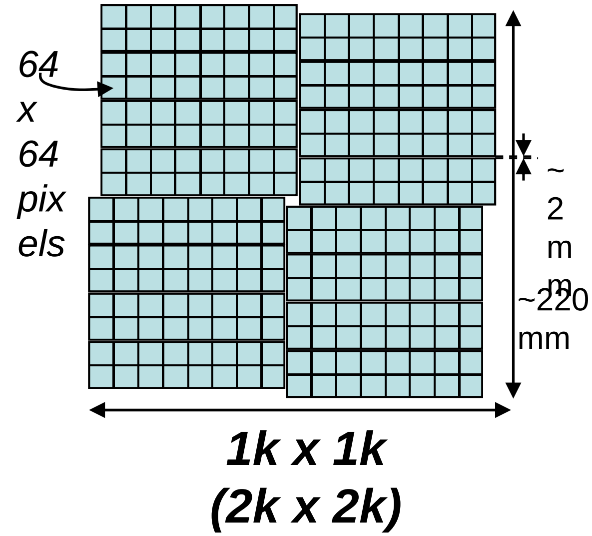
Koerner & Gruner, J. Synchro. Rad. 18 (2011) 157.

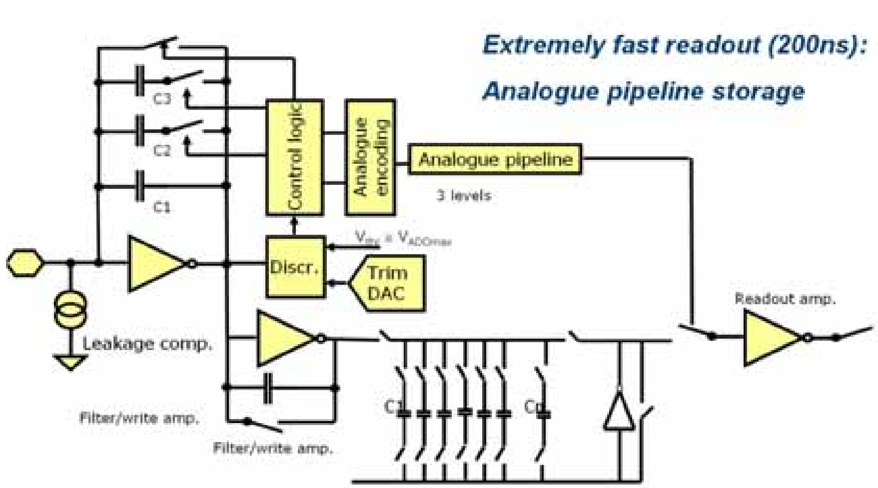
< 150 ns for 12 bit settling shown. Equivalent to ~4000 8 keV x-rays. Faster for fewer bits. A few bits in 10's of ns should be feasible.

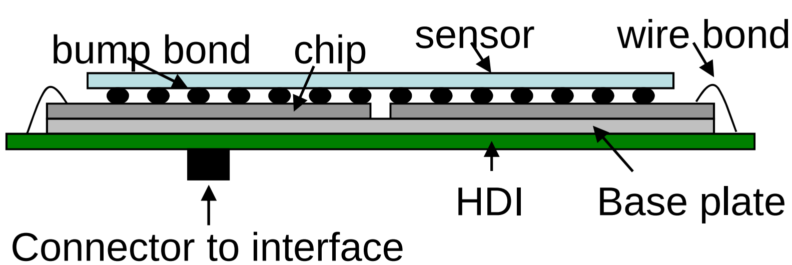
The Adaptive Gain Integrating Pixel Detector

<u>Basic parameters</u>

- 1 Megapixel detector (1k × 1k)
- 200mm × 200mm pixels
- Flat detector
- Sensor: Silicon 128 x 512 pixel tiles
- Single shot 2D-imaging
- 5MHz frame rate
- 2×10^4 photons dynamic range
- Adaptive gain switching
- Single photon sensitivity at 12keV
- Noise ≤200e (50×10^{-3} photons @ 12keV)
- Storage depth ≥200 images
- Analogue readout between bunch-trains







On the 10 year time scale, detectors of large format (>10^6 pixels), wide dynamic range (>10^4 10 keV x-rays/pix/frame), frame rates of ~100ns, and frame depths of hundreds of frames are likely feasible. If the dynamic range is reduced to ~10's of x-rays/pix/frame, frame rates can likely fall to a few 10's of ns.

simplified view of the

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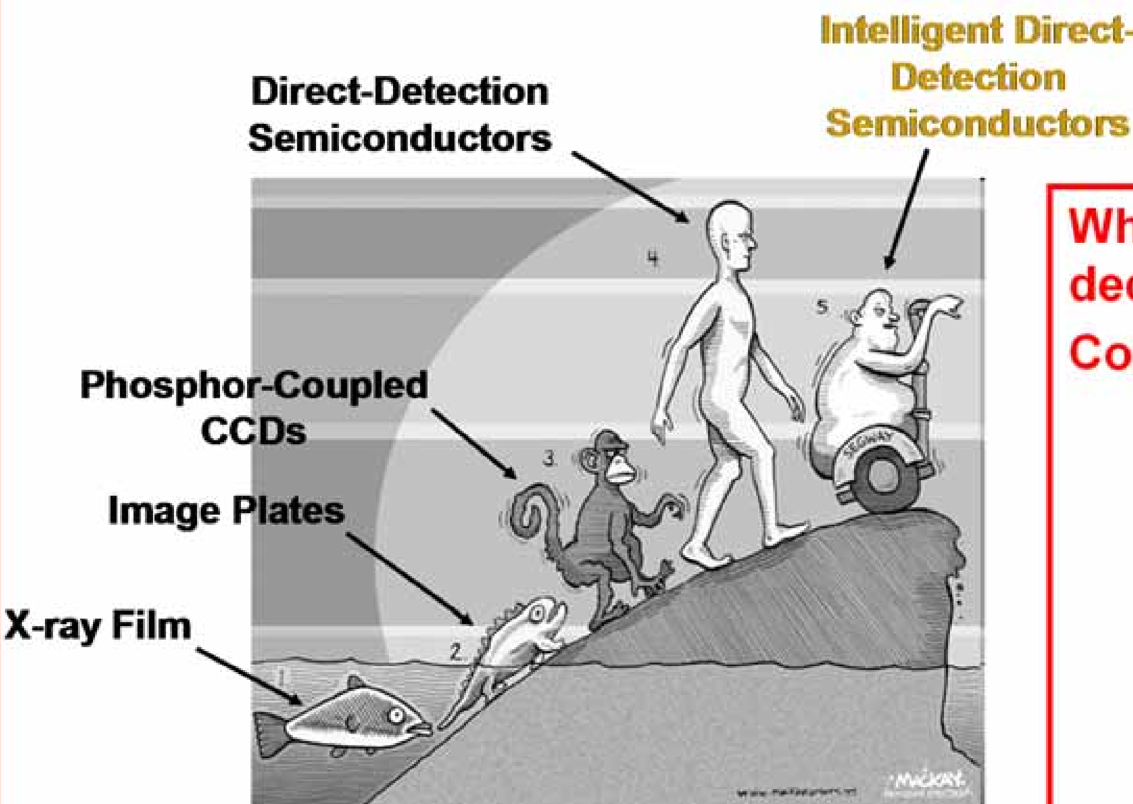

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Consider:

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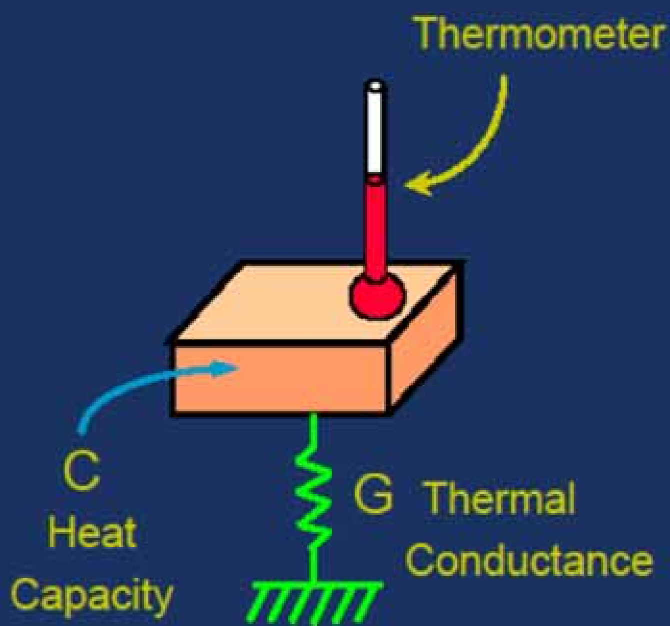
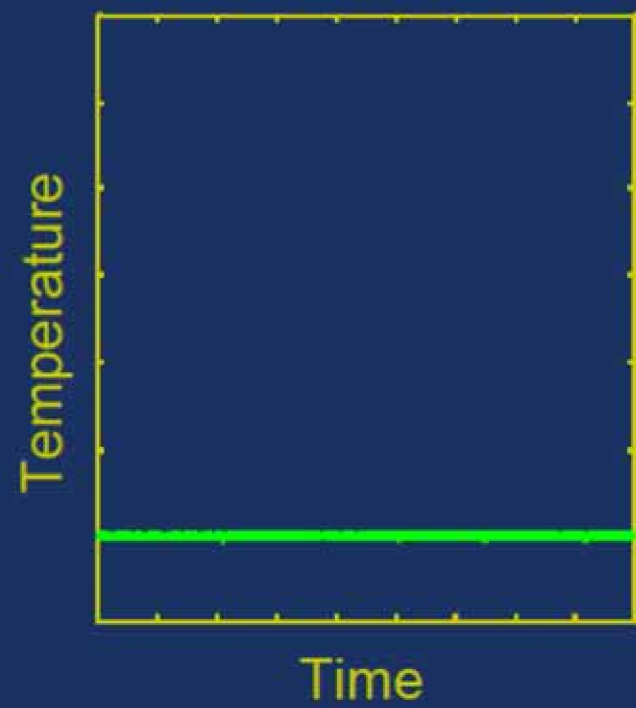
- **Energy resolution**

Bolometers / Microcalorimeters

Slide from Kent Irwin of NIST, shown at SRI-2005 at ANL





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Bolometers / Microcalorimeters

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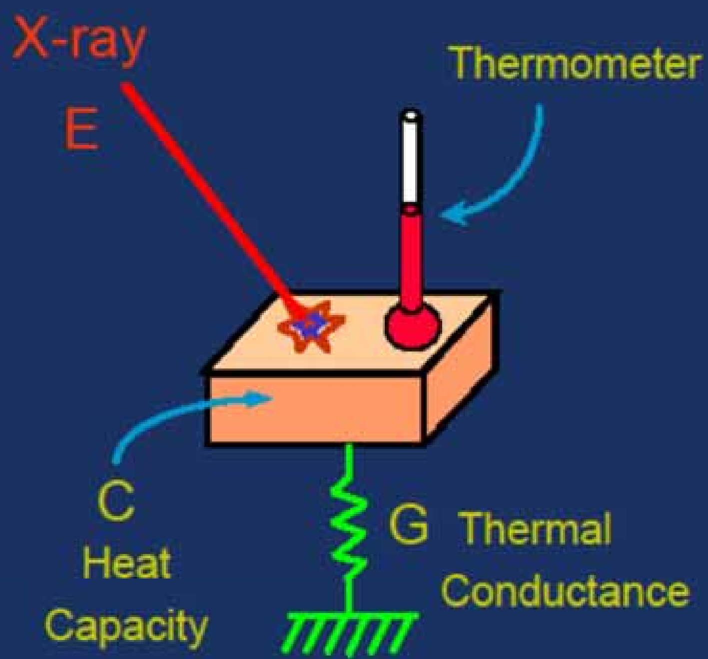

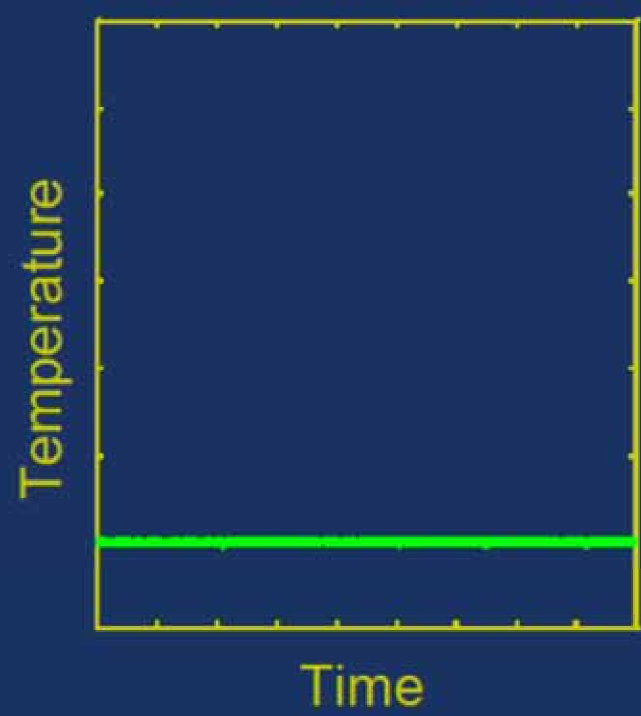

Photon

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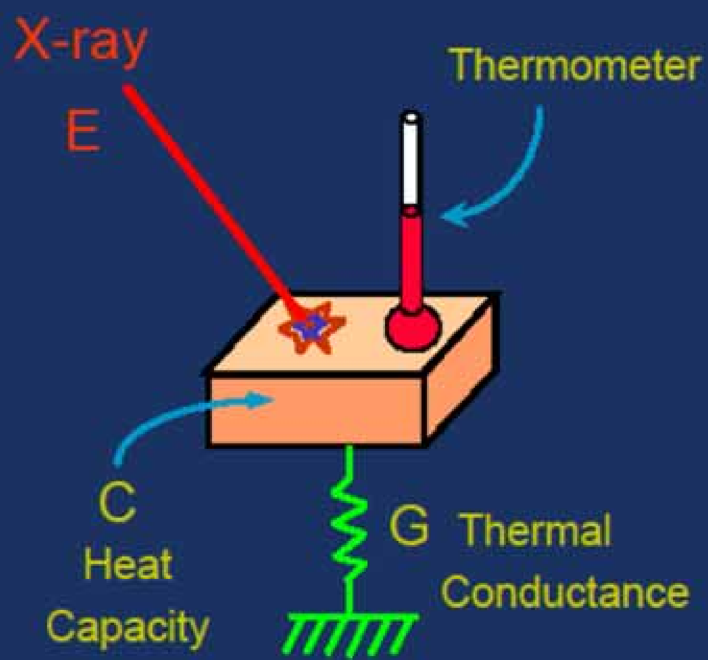
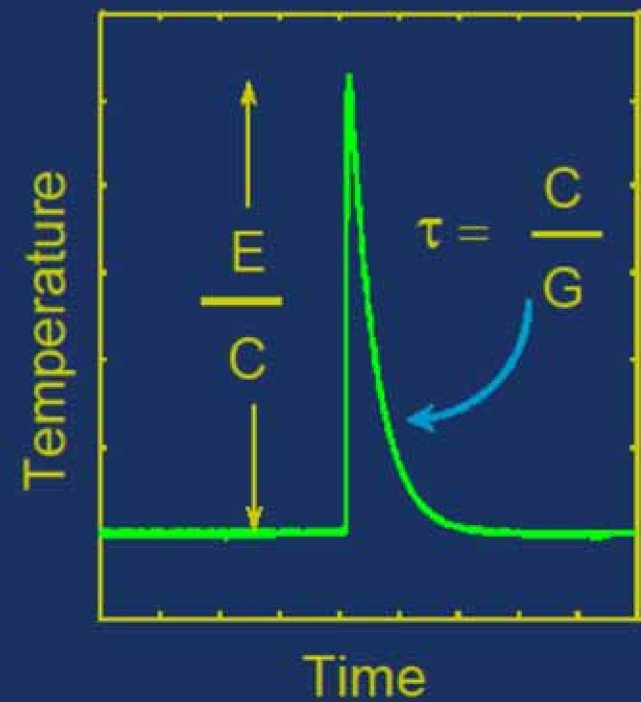
Bolometers / Microcalorimeters

Slide from Kent Irwin of NIST, shown at SRI-2005 at ANL





Photon → Heat

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Development possible over 5-10 years

Slide from Kent Irwin of NIST, shown at SRI-2005 at ANL

All pixels 250 μm in size…

Optimization	E	ΔE_{FWHM}	array size	Array count rate	Timescale
Best resolution	0.1 – 10 keV	3 eV	32 × 32	200 kHz	~ 3 years
Best count rate 1 keV	0.1 – 1 keV	6 eV	100 × 100	20 MHz	~ 5 years
Best count rate 10 keV	0.1 – 10 keV	20 eV	100 × 100	5 MHz	~ 5 years
Microwave	0.1 – 10 keV	5 eV	100,000	100 MHz	5 - 10 years

Can also make instruments for THz, IR, visible & UV, γ-ray

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Warnings!

1. **Difference between feasibility and reality: $**
2. **No one detector will have all the characteristics discussed.**

Cornell PAD Group

- **Actively working on PAD projects at Cornell:**
  - Darol Chamberlain
  - Kate Green
  - Marianne Hromalik
  - Hugh Philipp
  - Mark Tate
  - Sol Gruner
- **PAD Design Collaborators:**
  - Area Detector Systems Corp.
  - SLAC
- **Past PAD Group Members:**
  - Dan Schuette
  - Alper Ercan
  - Tom Caswell
  - Matt Renzi
  - Guiseppe Rossi
  - Sandor Barna
  - Bob Wixted
  - Eric Eikenberry
  - Lucas Koerner
- **Support:**
  - U.S. Dept. of Energy
  - U.S. National Inst. Health
  - U.S. National Science Found.
  - Keck Foundation

END

The ideal detector

Should have:

- 10^9 pixels
- 1um spatial resolution
- 1eV energy resolution
- 1 fs time resolution
- count rates up to 10^9 / pixel
- Efficient from 100eV out to 100keV
- **And it should be free!**

Shamelessly stolen from Peter Siddons