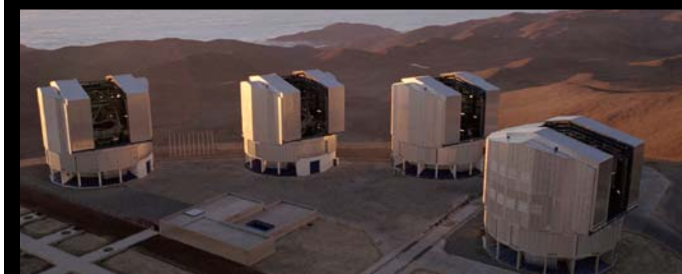
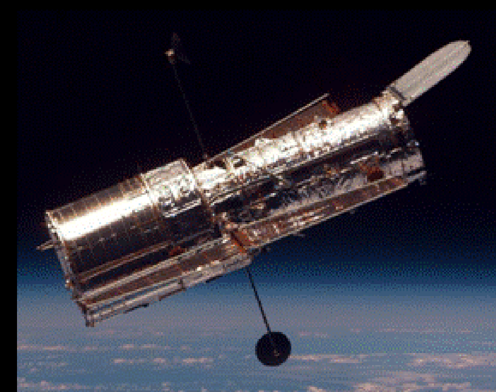
Scientific Imaging Sensors

A Short Course presented at the
"Detectors for Astronomy" workshop
Garching, Germany

12 October 2009

James W. Beletic and Markus Loose





2009 Nobel Prize in Physics awarded to the inventors of the CCD

In 1969, Willard S. Boyle and George E. Smith invented the first successful imaging technology using a digital sensor, a CCD (charge-coupled device). The two researchers came up with the idea in just an hour of brainstorming.

Bell Labs researchers Willard Boyle (left) and George Smith (right) with the charge-coupled device.
Photo taken in 1974. Photo credit: Alcatel-Lucent/Bell Labs.

The Nobel Prize in Physics 2009

"for the invention of an imaging semiconductor circuit – the CCD sensor"

Willard S. Boyle

George E. Smith

Credits and sincere thanks to all contributing parties

<u>Presentations from the workshop entitled "Scientific Detectors for Astronomy 2005"</u>

- CCDs: Barry Burke, Paul Jorden, Paul Vu
- CMOS: Markus Loose, Alan Hoffman, Vyshnavi Suntharalingham
- Pan-STARRS: John Tonry

For reference, see workshop proceedings: *Scientific Detectors for Astronomy 2005*, Jenna E. Beletic, James W. Beletic and Paola Amico (editors), Springer, (2006).

<u>Other sources</u>

- Slide set used in presentations at the NATO Advanced Studies Institute – Corsica (2002)

  For reference, see: "Optical and infrared detectors for astronomy: basic principles to state-of-the-art", James W. Beletic, chapter in book from the NATO Summer School: *Optics in Astrophysics*, Renaud Foy (editor), NATO Sciences Series II, Springer (2004).

- James Janesick CCD Course Notes
- "Substrate Removed HgCdTe-Based Focal Plane Arrays for Short Wavelength Infrared Astronomy", by Eric Piquette et al (2007)
- Wikipedia and other Internet sites
- Individual slides as identified in the presentation

<u>Disclaimer</u>

- All information presented in this slide set is accurate according to the best knowledge of the authors (James Beletic and Markus Loose). Any errors in content or presentation are solely due to the authors, and not the persons listed above.

Organization specific information denoted by text in blue box at bottom of slide

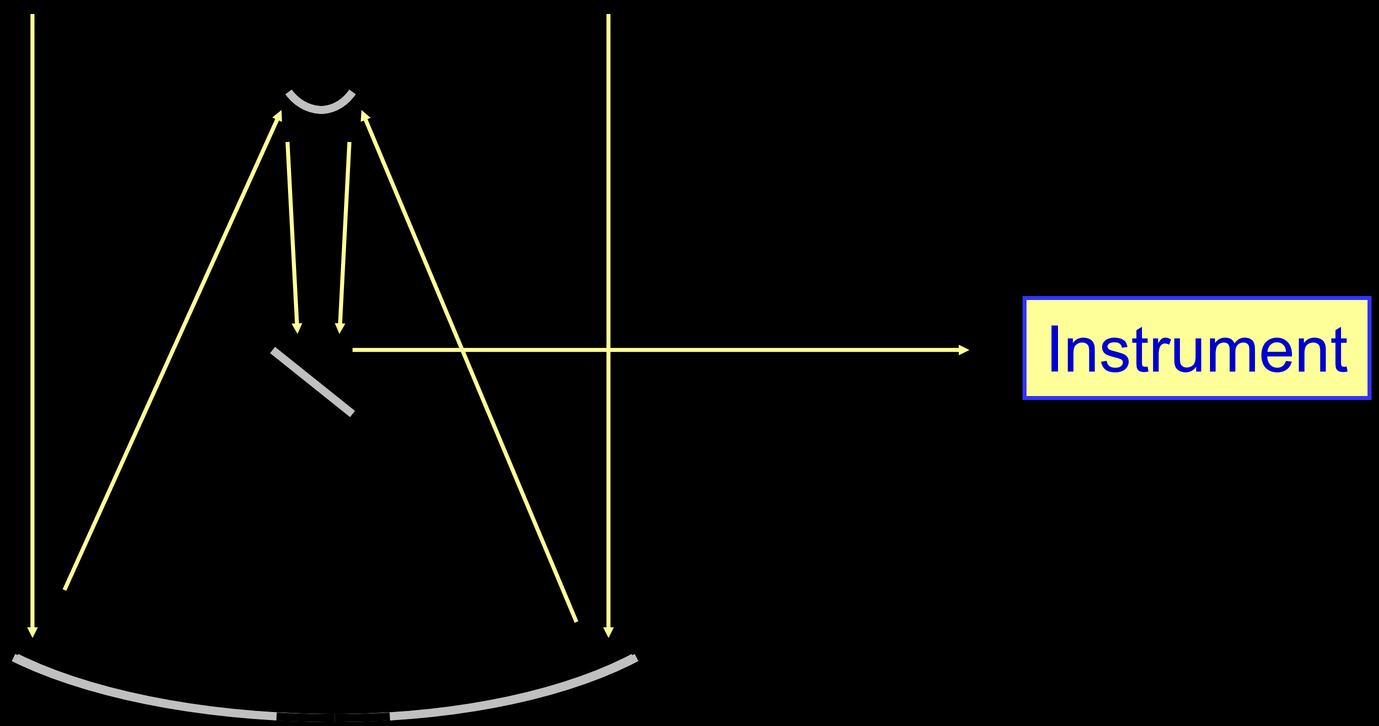
Optical and Infrared Astronomy

(0.3 to 25 μm)

Two basic parts

Telescope to collect and focus light

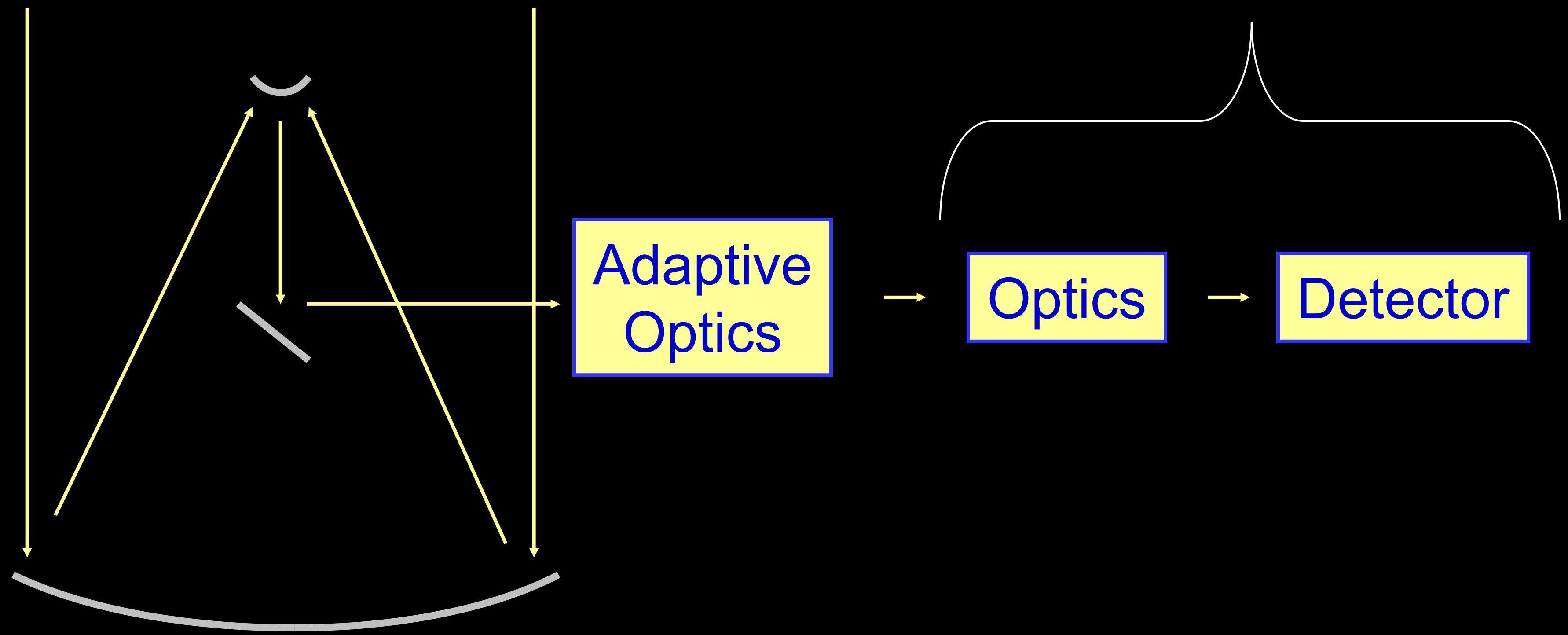
Instrument to measure light



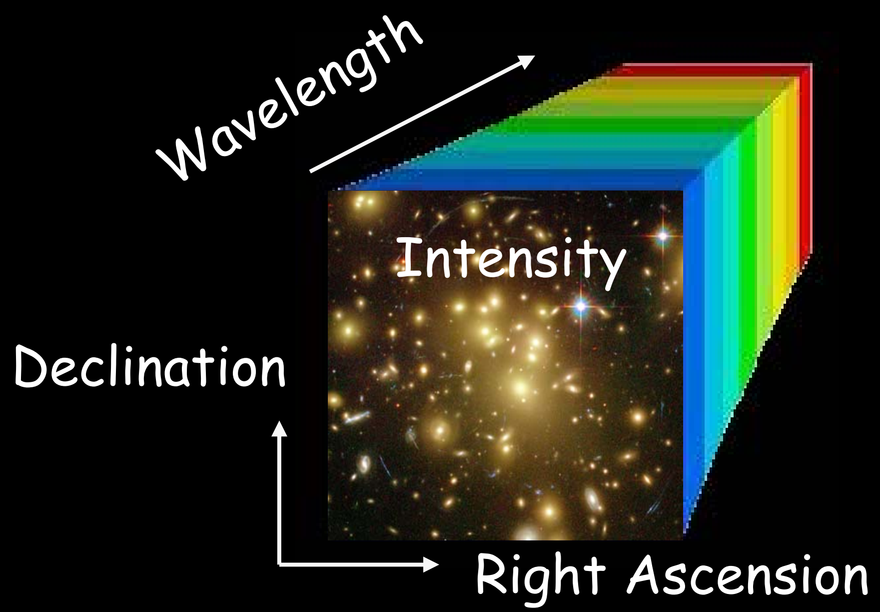
Optical and Infrared Astronomy
(0.3 to 25 μm)

Telescope to collect and focus light

Instrument to measure light



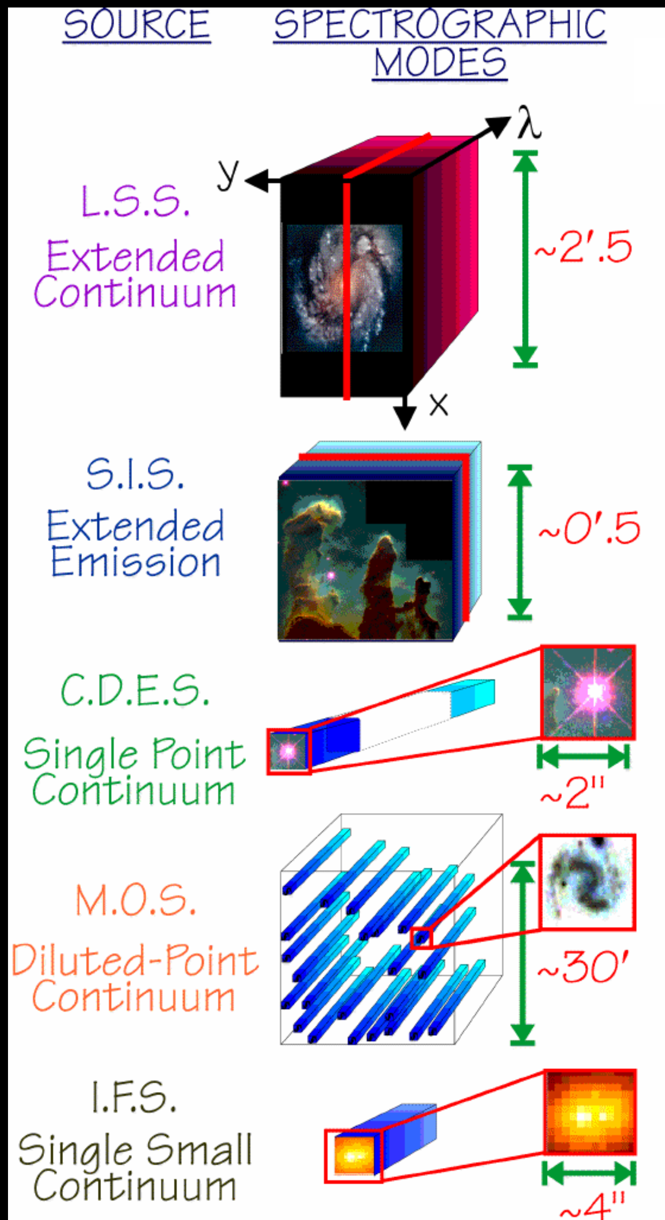
Instrument goal is to measure a 3-D data cube



But most detectors are 2-dimensional !

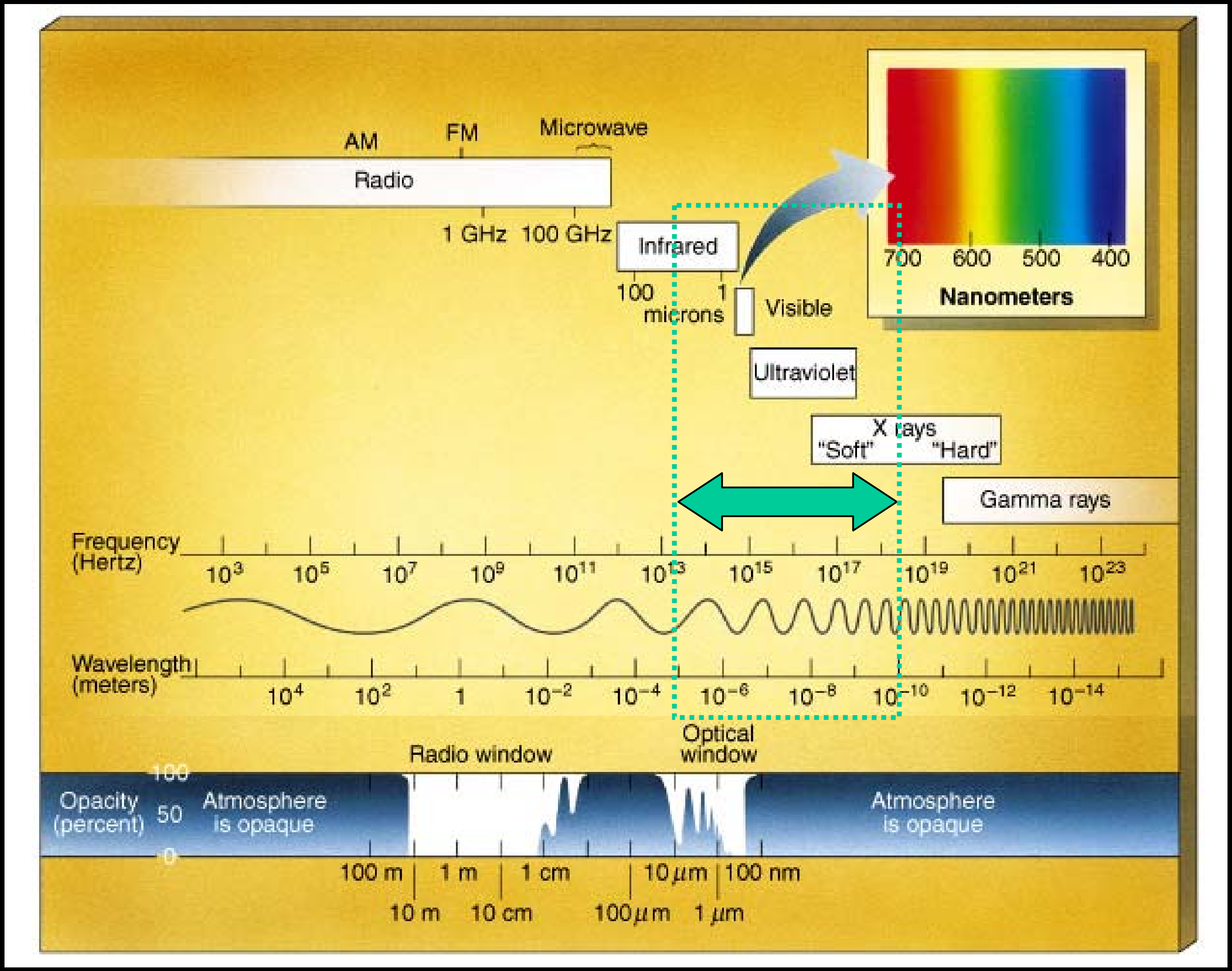
- Detectors are **BLACK & WHITE**
- Can not measure color
- Only measure intensity

Optics of the instrument are used to map a portion of the 3-D data cube onto the 2-D detector



With appropriate apologies to Foveon and 3rd Gen IR

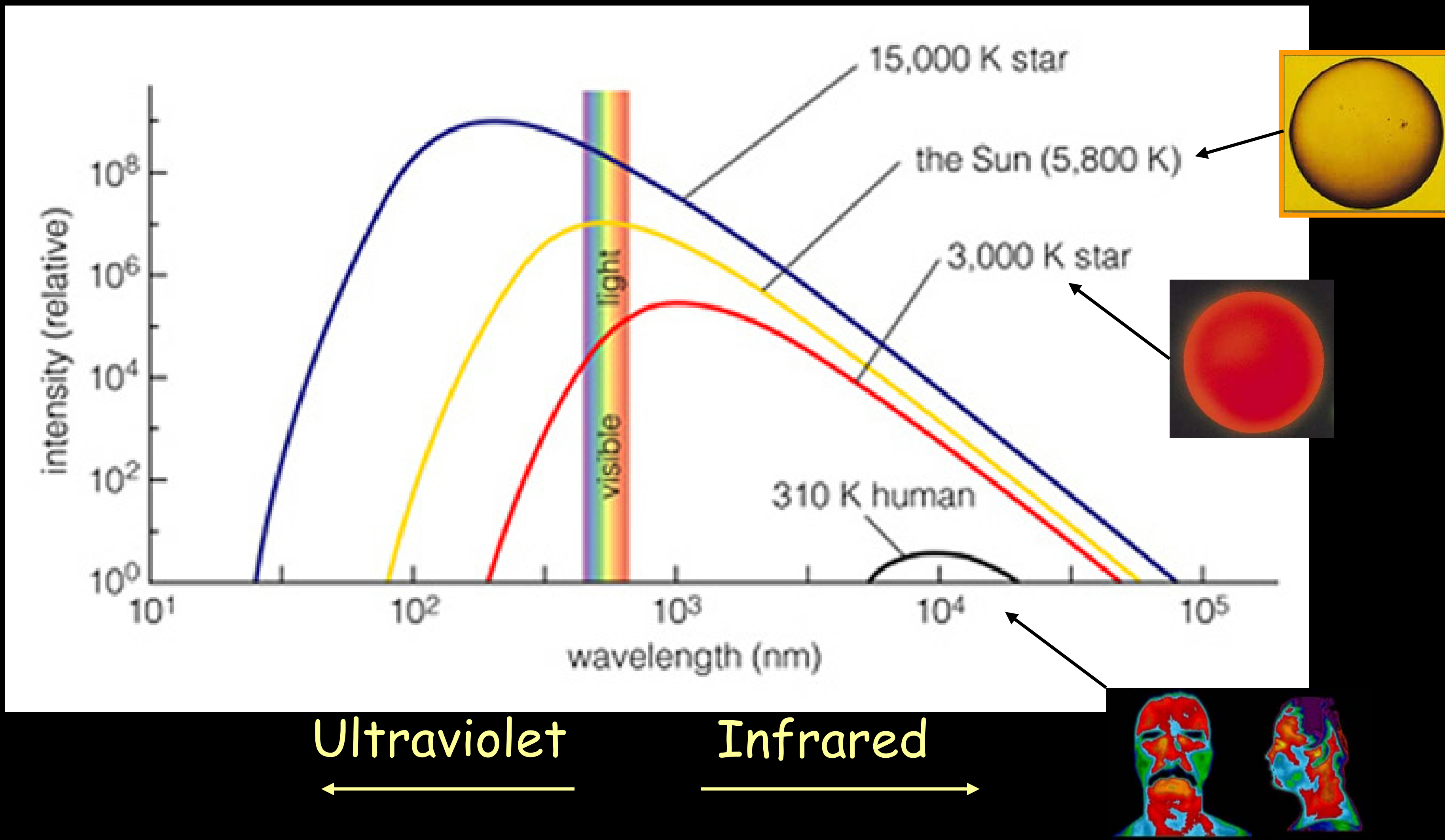
The Electromagnetic Spectrum



Orion – In visible and infrared light

Orion – by IRAS

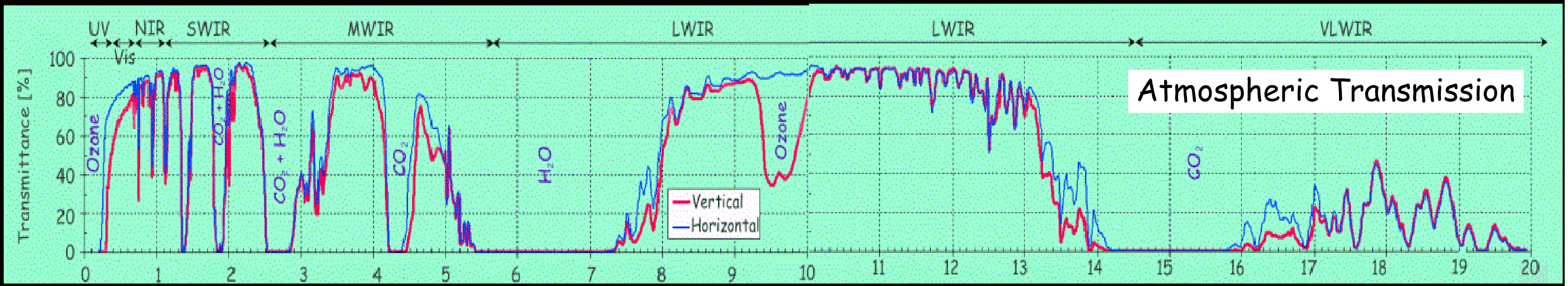
Temperature and Light



Ultraviolet ← → Infrared

Atmospheric transmission

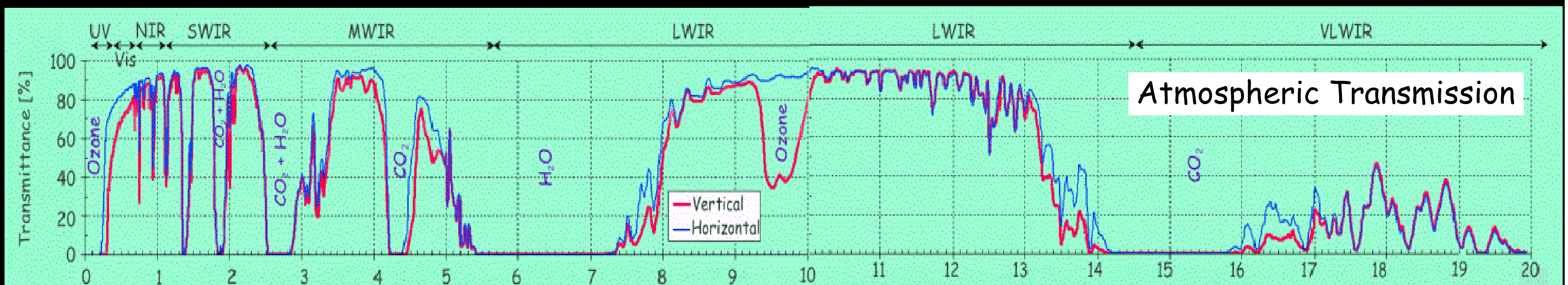
Not all of the light gets through atmosphere to ground-based telescopes



Wavelength (microns)

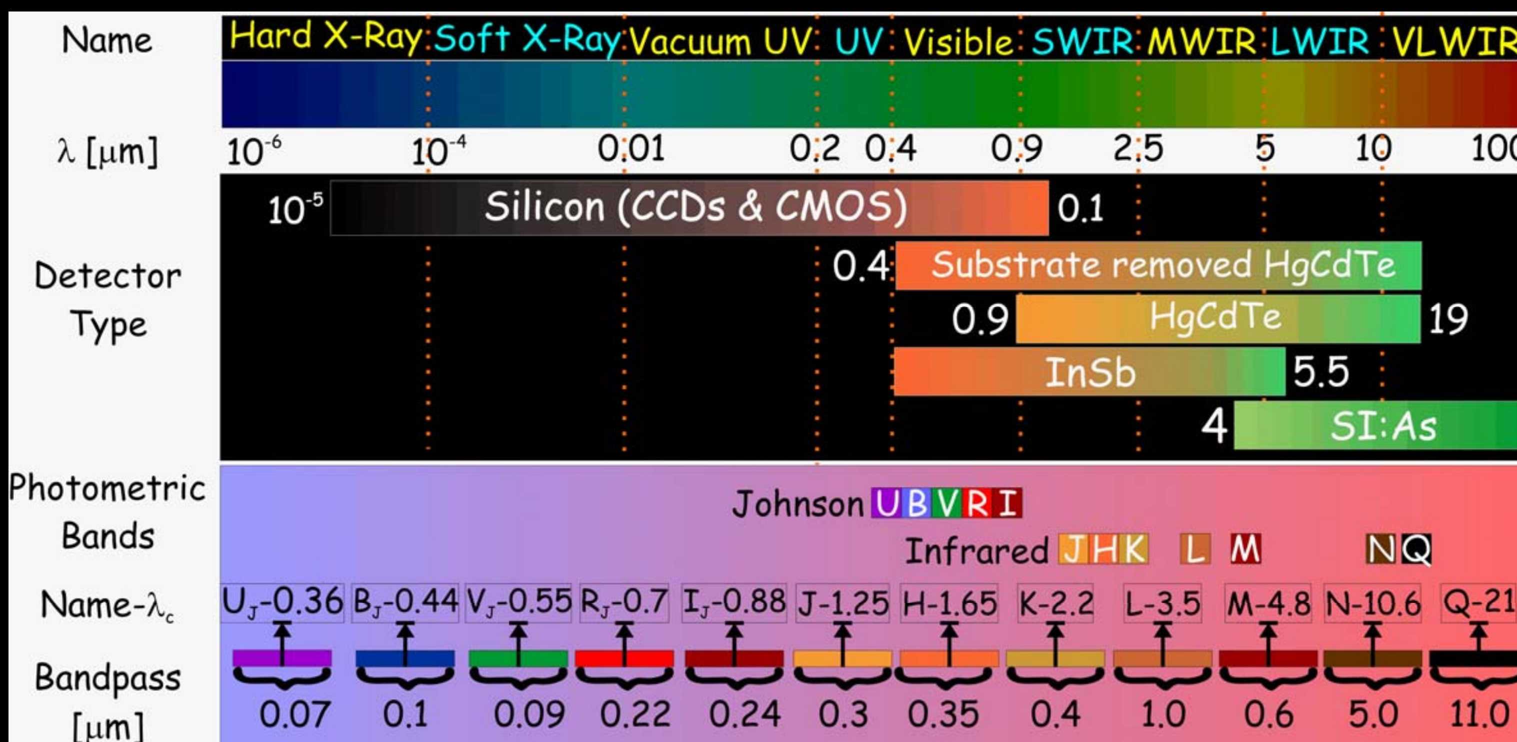
Spectral Bands

Defined by atmospheric transmission & detector material properties

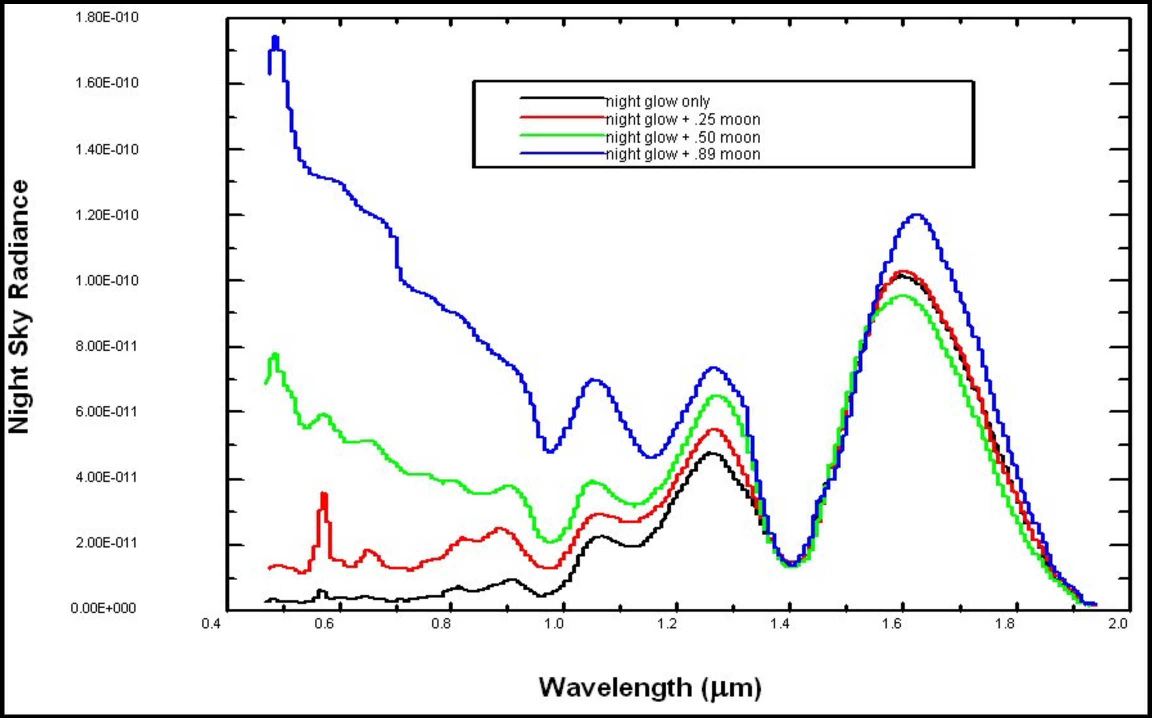


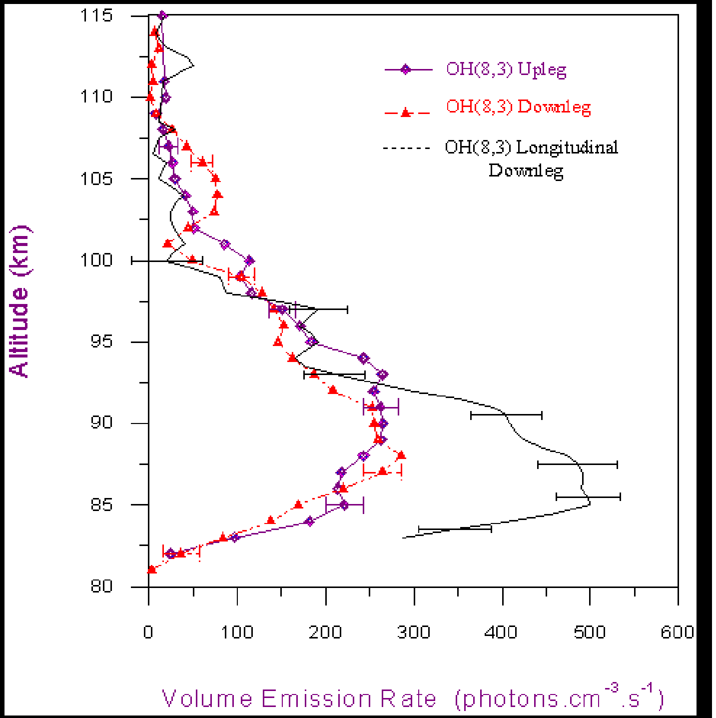
Wavelength (microns)

Detector Zoology



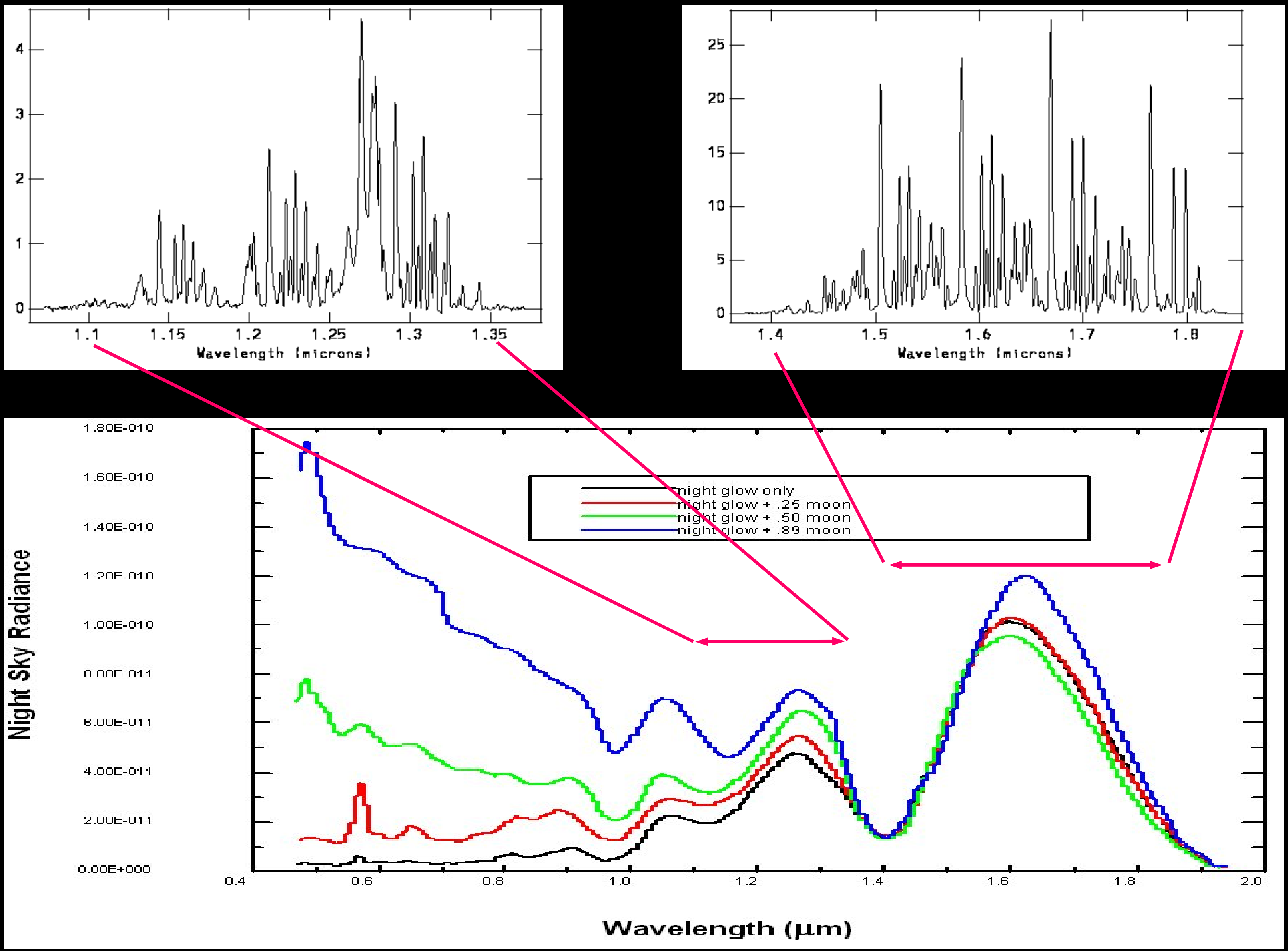
OH airglow (1.0-1.9 μm)





- OH provides a constant source of illumination in the near infrared
- OH created by the reaction: $H + O_3 \rightarrow OH + 0_2$
- Thin emitting layer at ~85 km altitude
- Daytime intensity is 3x nighttime intensity, and intensity drops 40% during the night

OH airglow (1.0-1.9 μm)



Energy of a photon

$E = h\nu$

h = Planck constant (6.6310^{-34} Joule•sec)

ν = frequency of light (cycles/sec) = λ/c

Wavelength (μm)	Energy (eV)	Band
0.3	4.13	UV
0.5	2.48	Vis
0.7	1.77	Vis
1.0	1.24	NIR
2.5	0.50	SWIR
5.0	0.25	MWIR
10.0	0.12	LWIR
20.0	0.06	VLWIR

Note Bene:

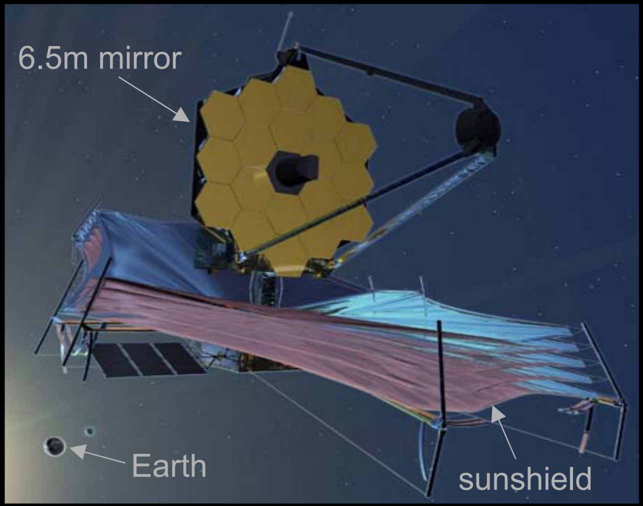
IR Industry definitions

NOT the same for astronomers !

- Energy of photons is measured in electron-volts (eV)
- eV = energy that an electron gets when it “falls” through a 1 volt potential difference.

JWST - James Webb Space Telescope

15 Teledyne 2K×2K infrared arrays on board (~63 million pixels)



- International collaboration
- 6.5 meter primary mirror and tennis court size sunshield
- 2014 launch on Ariane 5 rocket
- L2 orbit (1.5 million km from Earth)

H2RG qualified to TRL-6 and SIDECAR ASIC qualified to TRL-9

JWST will find the "first light" objects after the Big Bang, and will study how galaxies, stars and planetary systems form

FGS
(Fine Guidance Sensors)

3 individual MWIR 2Kx2K

- Acquisition and guiding
- Images guide stars for telescope stabilization
- Canadian Space Agency

NIRSpec
(Near Infrared Spectrograph)

1x2 mosaic of MWIR 2Kx2K

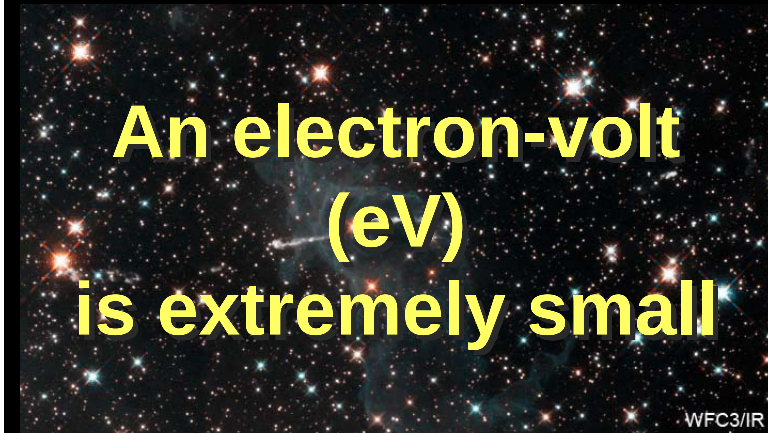
- Spectrograph
- Measures chemical composition, temperature and velocity
- European Space Agency / NASA

NIRCam
(Near Infrared Camera)

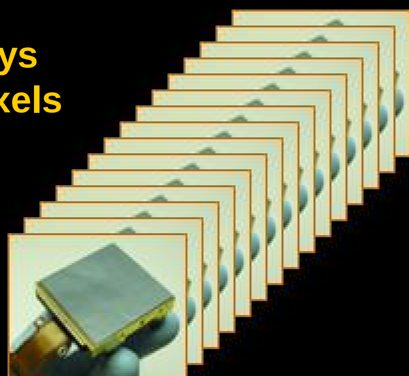
Two 2x2 mosaics of SWIR 2Kx2K

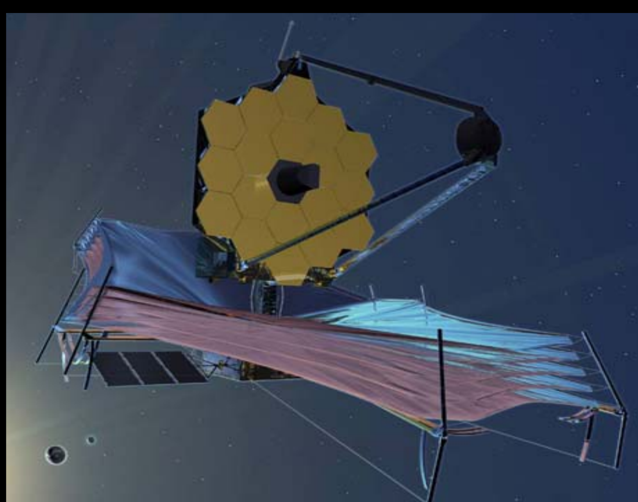
Two individual MWIR 2Kx2K

- Wide field imager
- Studies morphology of objects and structure of the universe
- U. Arizona / Lockheed Martin



15 H2RG
2K×2K arrays
63 million pixels





$1\ \text{eV} = 1.6 \bullet 10^{-19}\ \text{J}$ (J = joule)

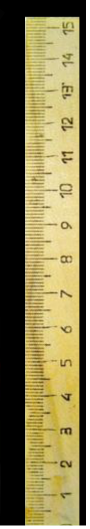
$1\ \text{J} = \text{N} \bullet \text{m} = \text{kg} \bullet \text{m} \bullet \text{sec}^{-2} \bullet \text{m}$

1 kg raised 1 meter $= 9.8\ \text{J} = 6.1 \bullet 10^{19}\ \text{eV}$

- The energy of a photon is **VERY** small
  - Energy of SWIR (2.5 μm) photon is 0.5 eV
- In 5 years, JWST will take ~1 million images
  - 1000 sec exp., 15 H2RGs, 90% duty cycle
  - Photons / H2RG image ≈ 3.6×10^{10} photons
    - 5% pixels at 85% full well
    - 10% " at 40% full well
    - 10% " at 10% full well
    - 75% " at 1% full well
  - Total # SWIR photons detected ≈ 3.6×10^{16}
  - Total energy detected ≈ 1.8×10^{16} eV

Full well
85,000 e-

- Drop peanut M&M® candy (~2g) from height of 15 cm (~6 inches)
  - Potential energy ≈ 1.8×10^{16} eV



15 cm peanut M&M® drop is equal to the energy detected during 5 year operation of the James Webb Space Telescope!

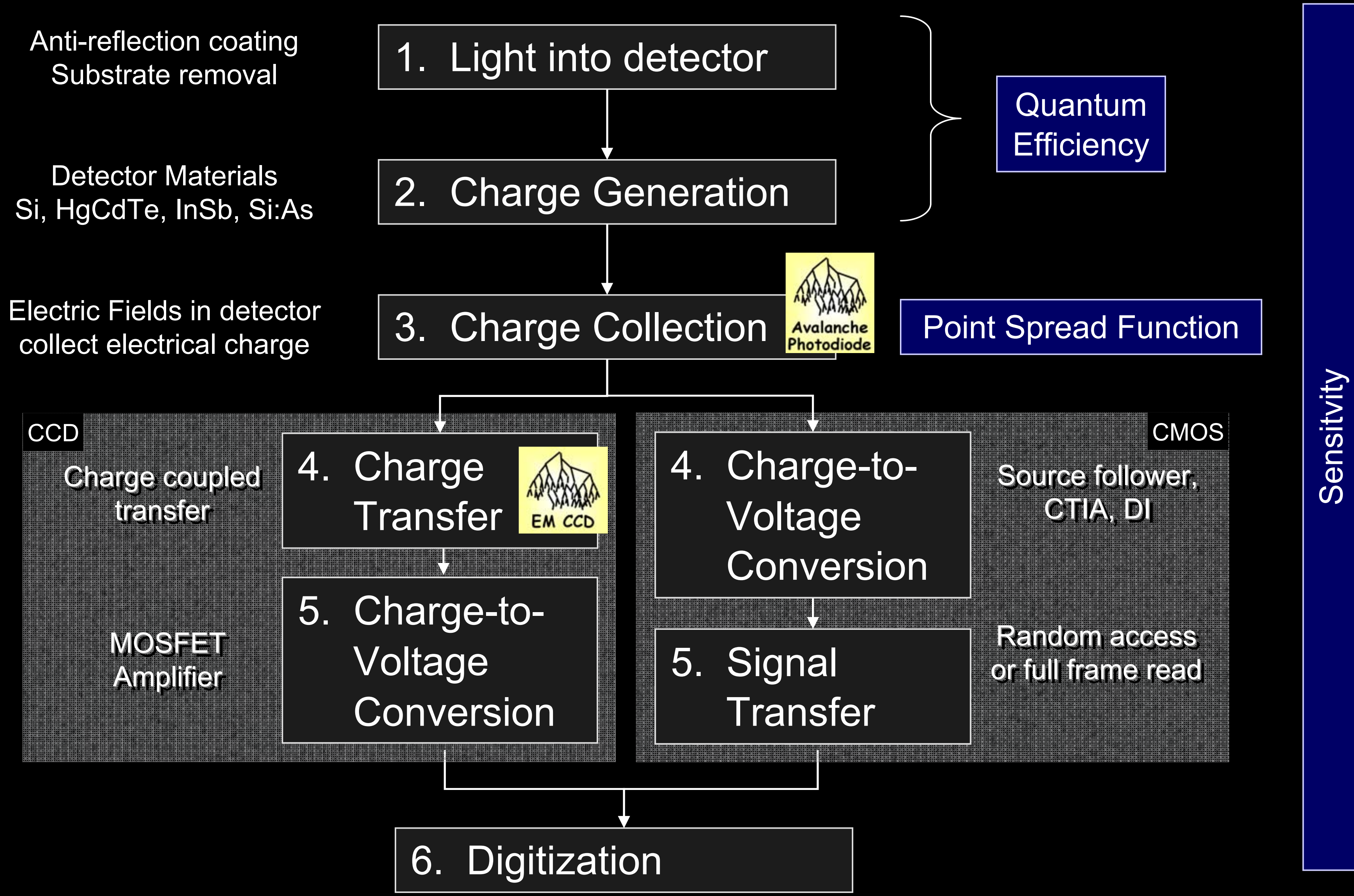

FoxTrot
by Bill Amend
DO YOU SELL ULTRAVIOLET BULL?
EXCUSE ME?
WHAT ABOUT REGULAR VIOLET BULL?
NO.
BLUE BULL?
NO.
GREEN BULL?
NO.
YELLOW BULL?
NO.
ORANGE BULL?
NO.
www.foxtrot.com
RATS. OK, I'LL TAKE A RED BULL.
I WAS HOPING FOR SOMETHING A LITTLE HIGHER-ENERGY.
AT LEAST IT ISN'T INFRARED BULL.

The Ideal Detector

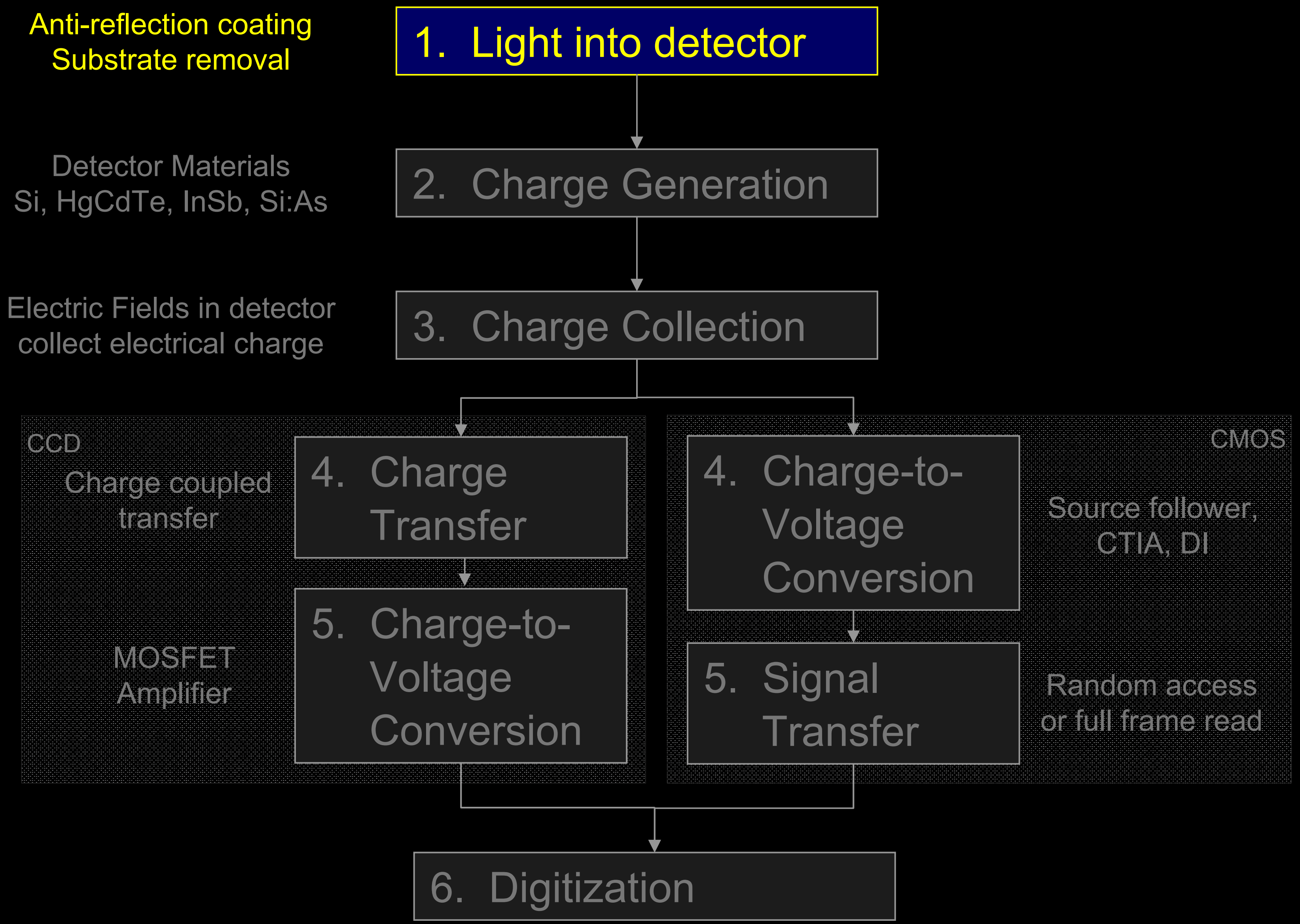
• Detect 100% of photons	✓ Up to 98% quantum efficiency
• Each photon detected as a delta function	✓ One electron for each photon
• Large number of pixels	✓~1,400 million pixels (>10^9)
• Time tag for each photon	☒ No - framing detectors ✓ APDs & event driven readout
• Measure photon wavelength	☒ No – defined by filter ✓ Foveon, 3rd Gen IR
• Measure photon polarization	☒ No – defined by filter Can place filter on detector

Plus READOUT NOISE and other “features”

6 steps of optical / IR photon detection



6 steps of optical / IR photon detection



1^{st} Step: Get light into the detector

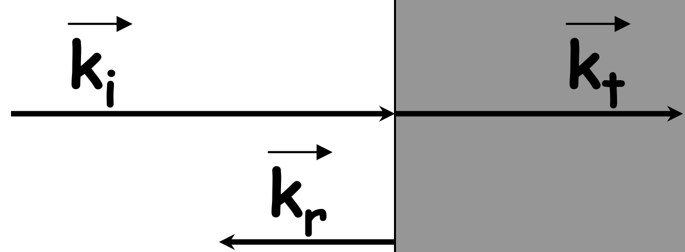
Anti-reflection coatings

Velocity of light = c / n

c = speed of light in a vacuum
n = index of refraction of medium

Light incident from this medium
n_i = index of refraction

Light transmitted into this medium
n_t = index of refraction



For transmission directly into interface (angle of incidence = 0°)

R = fraction of incident energy reflected
$= ((n_t - n_i) / (n_t + n_i))^2$

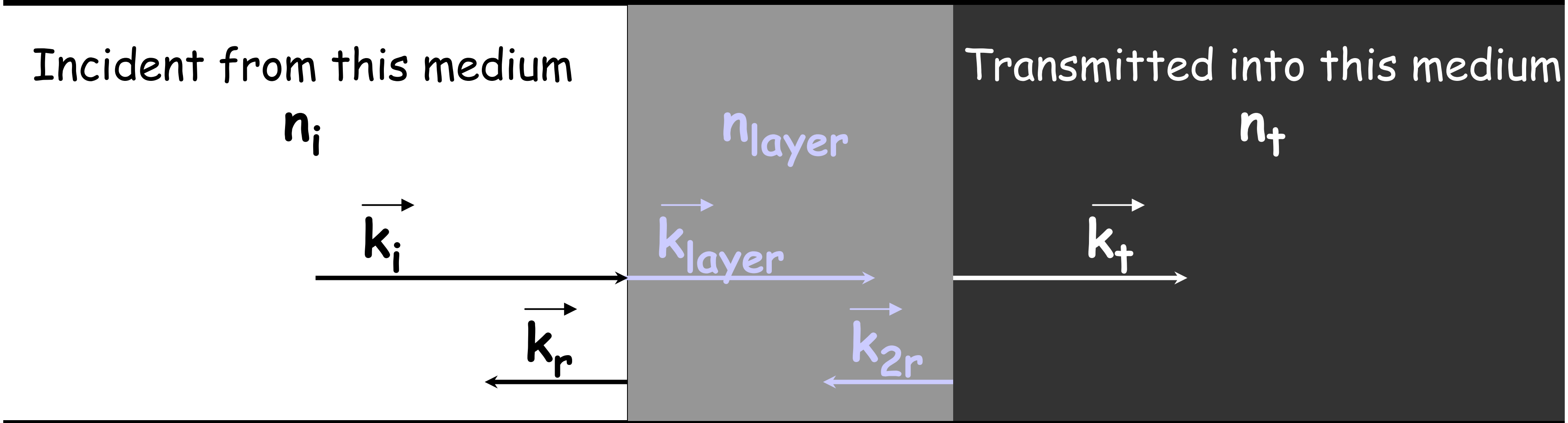
Loss at a surface

Air n_i = 1.00	Glass n_t = 1.5
4% ←	→ 96%
Air n_i = 1.00	Silicon n_t ~ 4
36% ←	→ 64%
Air n_i = 1.00	HgCdTe n_t = 3.7
33% ←	→ 67%

Silicon: Turns an 8-m telescope into an 6.4-m !

HgCdTe: Turns an 8-m telescope into a 6.5-m !

Single layer anti-reflection coatings (angle of incidence = 0°)

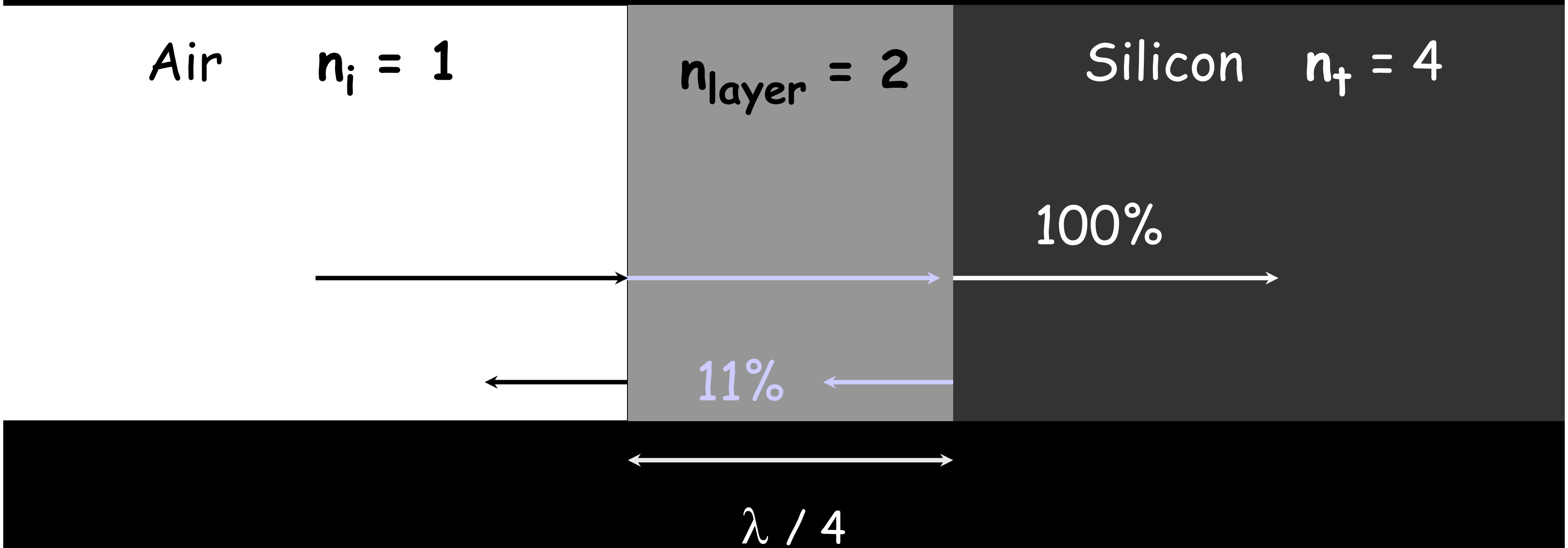


λ / 4

$$R = \left(\frac{n_i n_t - n_{layer}^2}{n_i n_t + n_{layer}^2} \right)^2$$

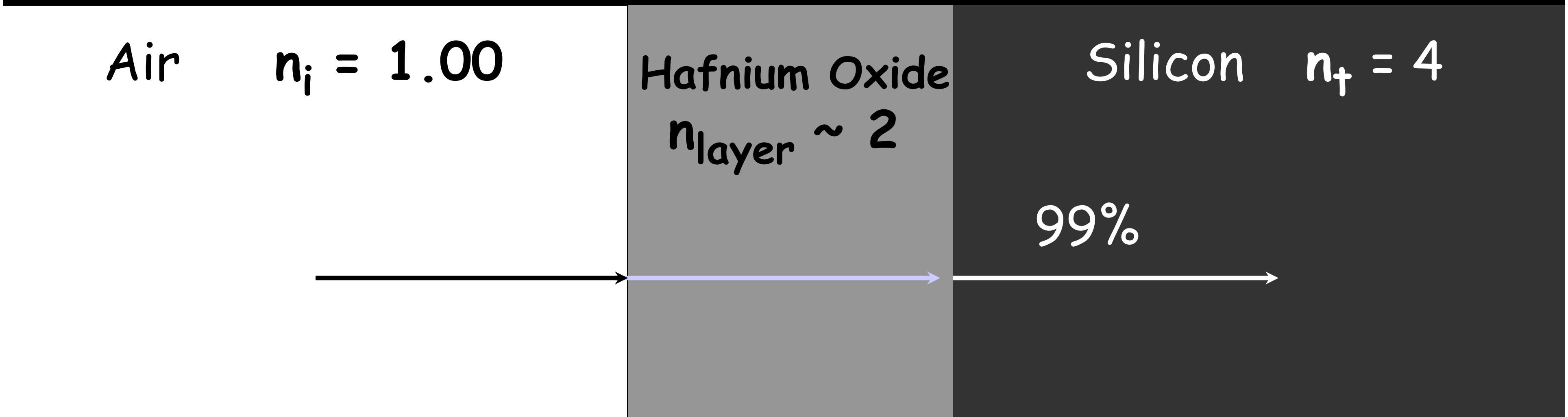
If $n_{layer}^2 = n_i n_t \Rightarrow$ 0% reflected, 100% transmitted !

Ideal CCD anti-reflection coating



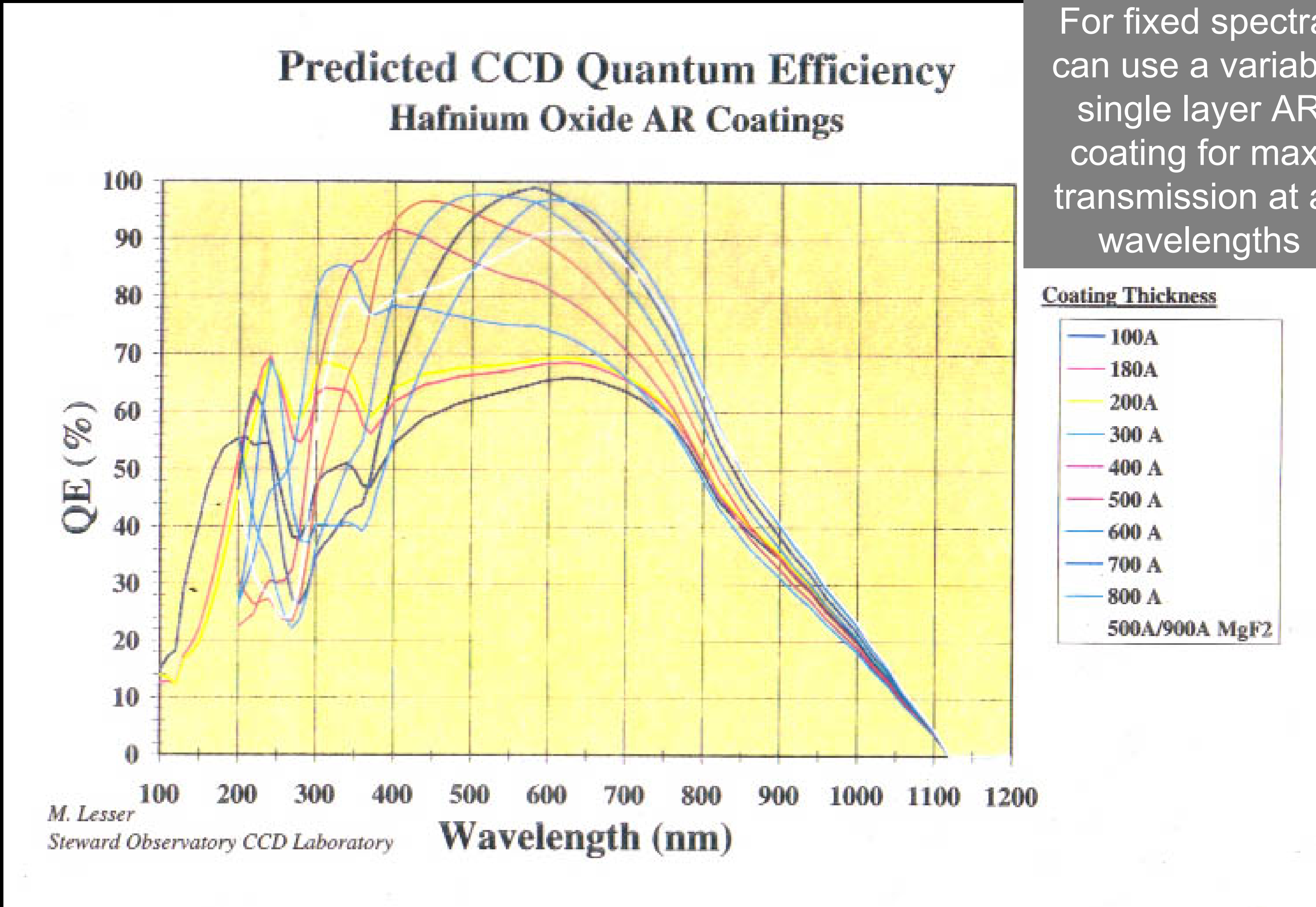
$$R = \left[\frac{1 \cdot 4 - 2^2}{1 \cdot 4 + 2^2} \right]^2 = 0$$

Actual CCD anti-reflection coating



$$R = \left[\frac{1 \cdot 4 - 2.0^2}{1 \cdot 4 + 2.0^2}\right]^2 \sim 0\ \%$$

Quarter wave HfO_2 at 560 nm is 0.25(560)/2 = 70 nm

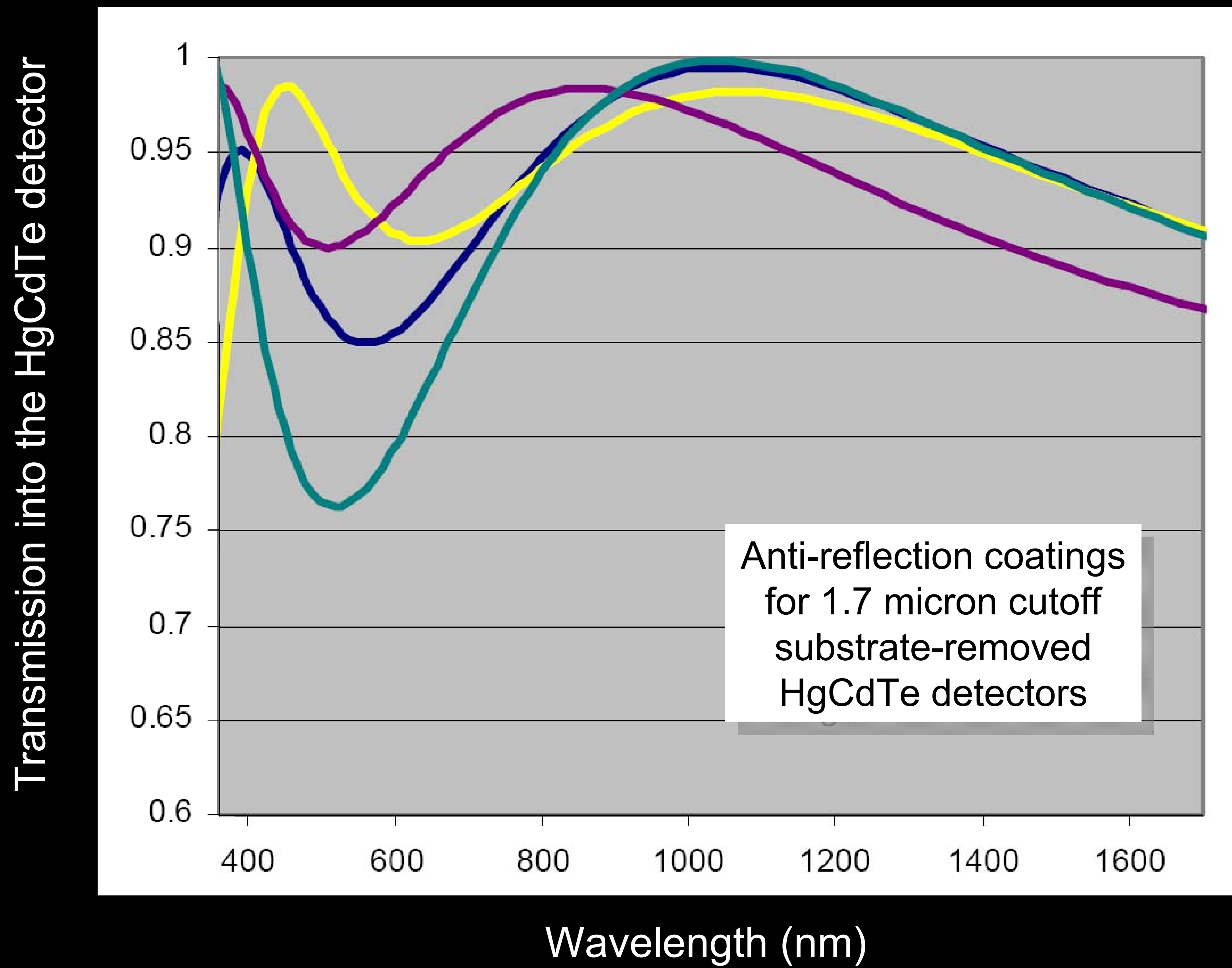


For fixed spectra, can use a variable single layer AR coating for max. transmission at all wavelengths

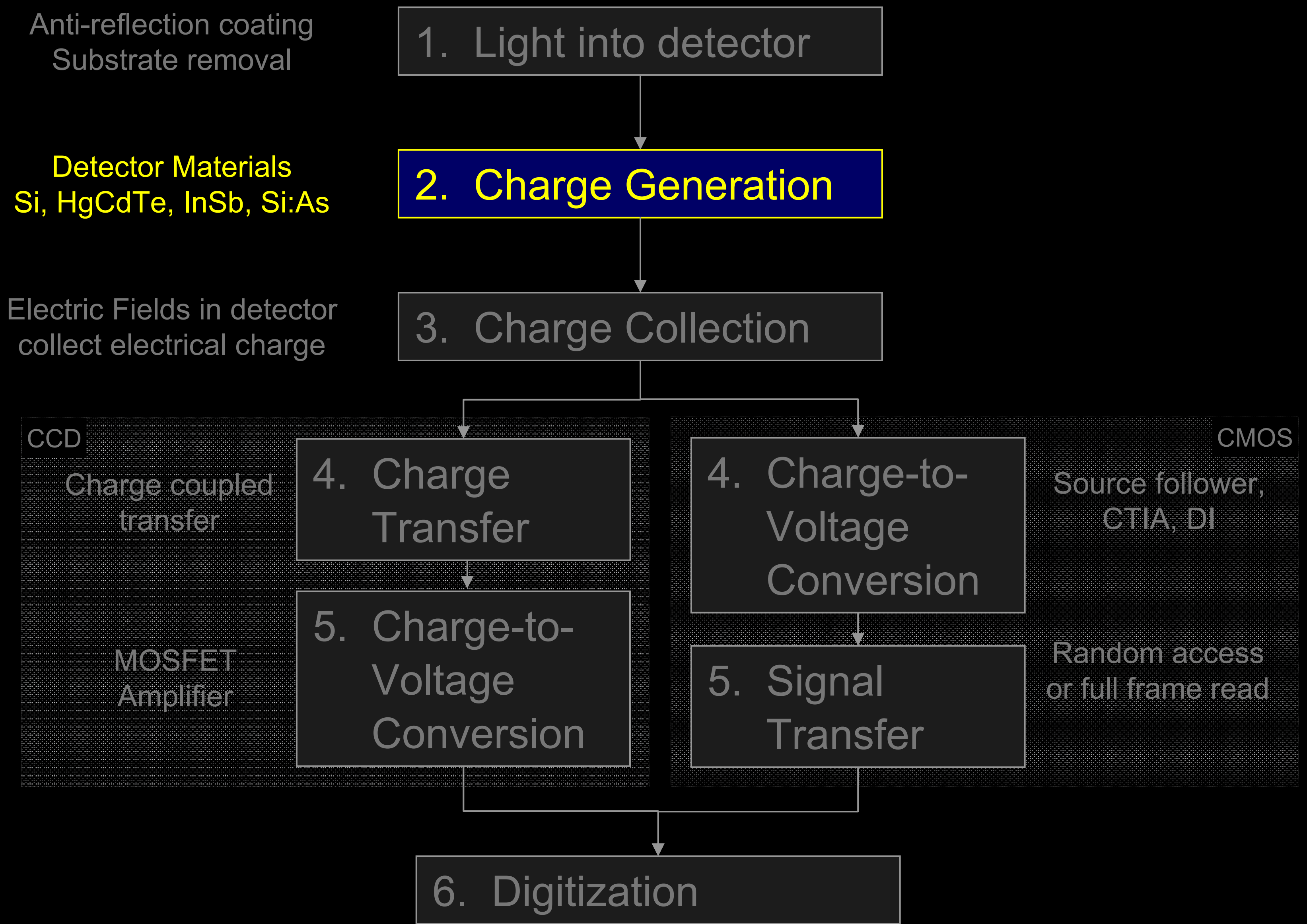
Quarter wave $Hf0_2$ at 560 nm is 0.25(560)/2 = 70 nm (700 Å)

Mike Lesser, U. Arizona

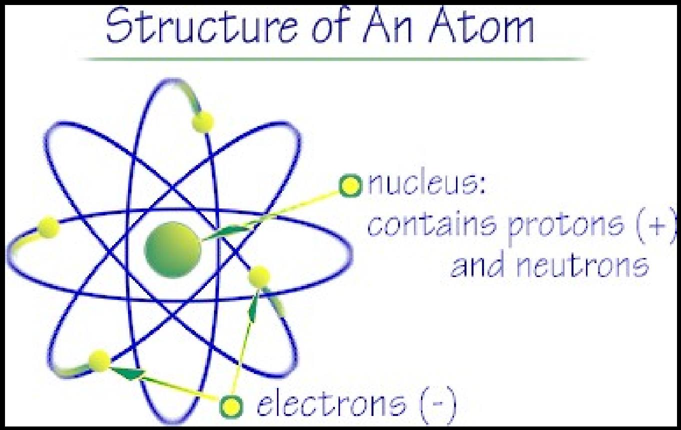
Example Anti-reflection coating for HgCdTe



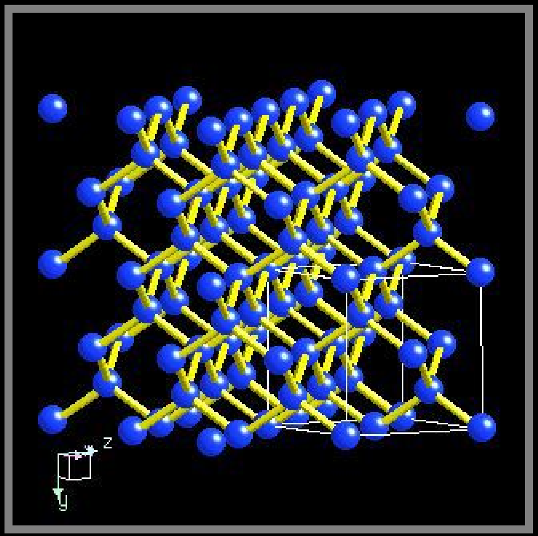
6 steps of optical / IR photon detection



Crystals are excellent detectors of light



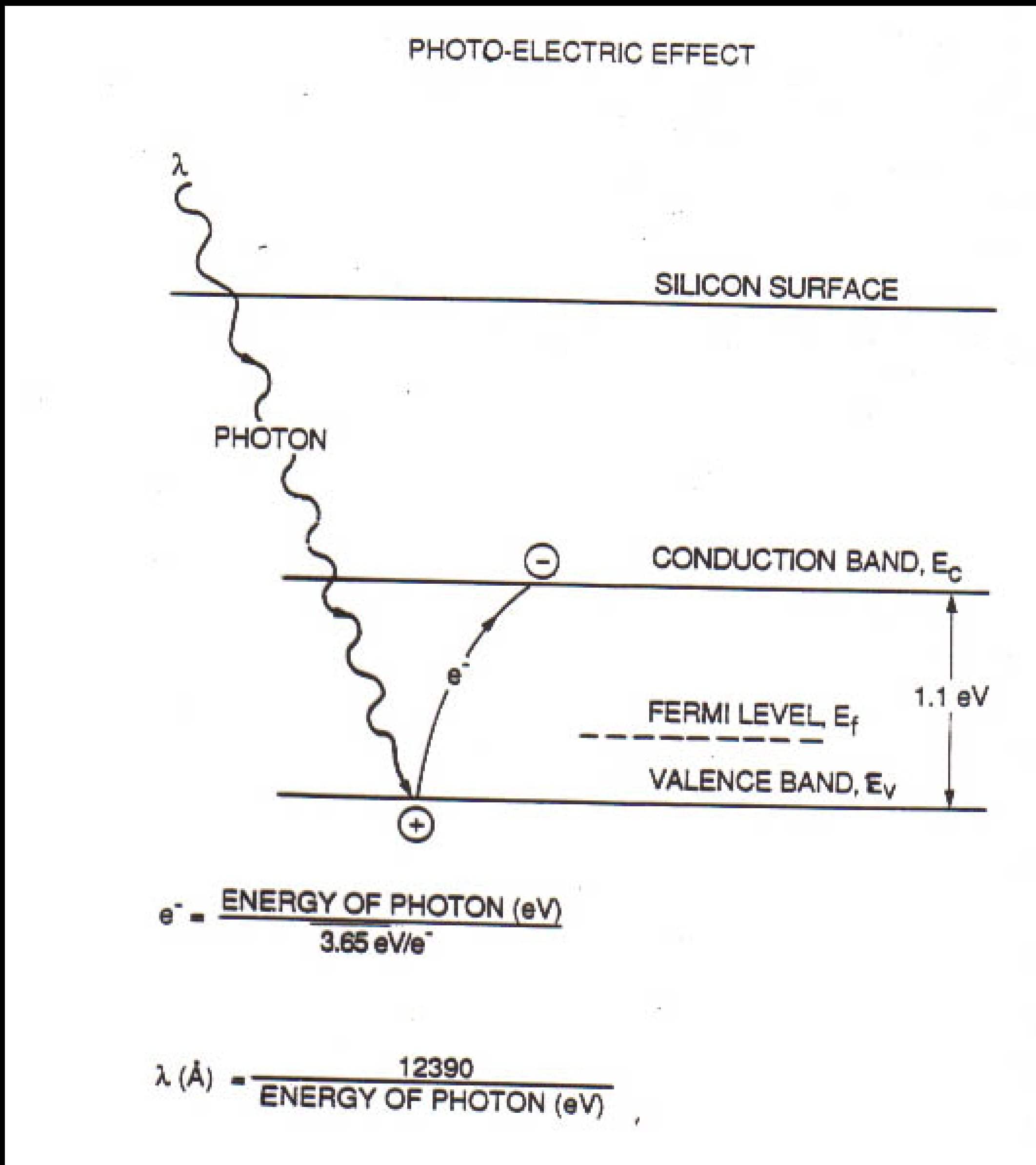
- Simple model of atom
  - Protons (+) and neutrons in the nucleus with electrons orbiting



Silicon crystal lattice

- Electrons are trapped in the crystal lattice
  - by electric field of protons
- Light energy can free an electron from the grip of the protons, allowing the electron to roam about the crystal
  - creates an “electron-hole” pair.
- The photocharge can be collected and amplified, so that light is detected
- The light energy required to free an electron depends on the material.

Charge Generation



Silicon CCD

Similar physics for IR materials

Periodic Table

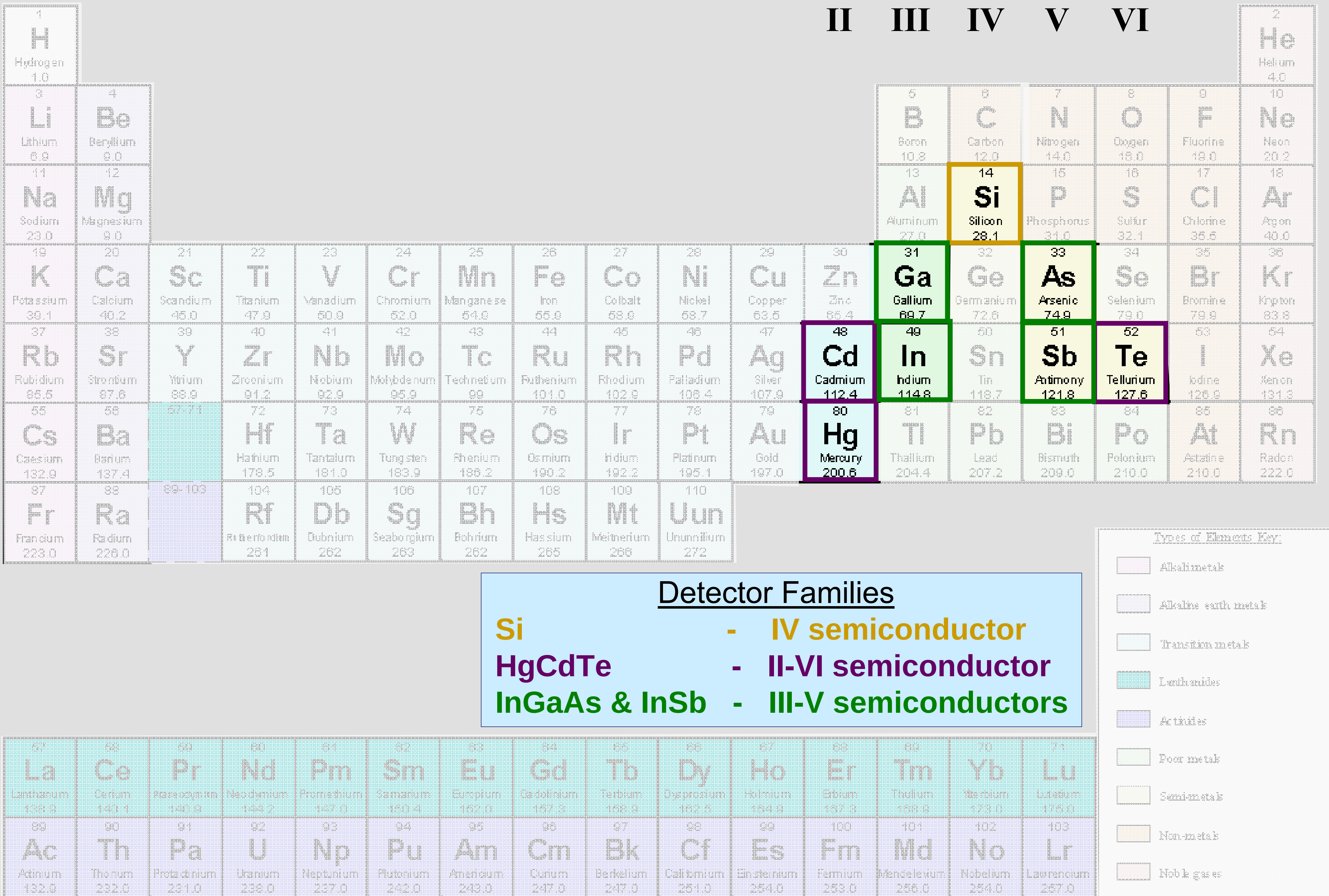
1 H Hydrogen 1.0																	2 He Helium 4.0
3 Li Lithium 6.9	4 Be Beryllium 9.0											5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2
11 Na Sodium 23.0	12 Mg Magnesium 9.0											13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 40.0
19 K Potassium 39.1	20 Ca Calcium 40.2	21 Sc Scandium 45.0	22 Ti Titanium 47.9	23 V Vanadium 50.9	24 Cr Chromium 52.0	25 Mn Manganese 54.9	26 Fe Iron 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krypton 83.8
37 Rb Rubidium 85.5	38 Sr Strontium 87.6	39 Y Yttrium 88.9	40 Zr Zirconium 91.2	41 Nb Niobium 92.9	42 Mo Molybdenum 95.9	43 Tc Technetium 99	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Caesium 132.9	56 Ba Barium 137.4	57-71	72 Hf Hafnium 178.5	73 Ta Tantalum 181.0	74 W Tungsten 183.9	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0
87 Fr Francium 223.0	88 Ra Radium 226.0	89-103	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 262	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Uun Ununnilium 272								

57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium 147.0	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium 132.9	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium 237.0	94 Pu Plutonium 242.0	95 Am Americium 243.0	96 Cm Curium 247.0	97 Bk Berkelium 247.0	98 Cf Californium 251.0	99 Es Einsteinium 254.0	100 Fm Fermium 253.0	101 Md Mendelevium 256.0	102 No Nobelium 254.0	103 Lr Lawrencium 257.0

Types of Elements Key:

- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Poor metals
- Semi-metals
- Non-metals
- Noble gases

Periodic Table



Detector Families

Si - IV semiconductor

HgCdTe - II-VI semiconductor

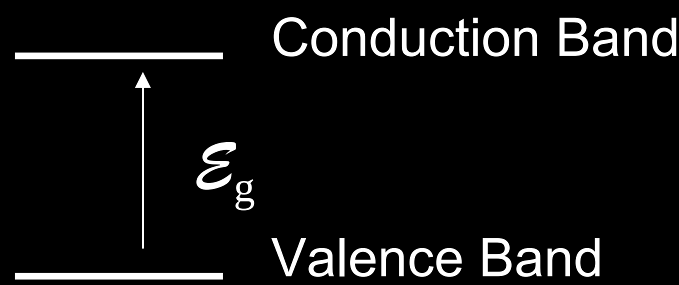
InGaAs & InSb - III-V semiconductors

Photon Detection

For an electron to be excited from the conduction band to the valence band

$$h\nu > \mathcal{E}_g$$

h = Planck constant (6.6310^{-34} Joule•sec)
ν = frequency of light (cycles/sec) = λ/c
$\mathcal{E}_g$ = energy gap of material (electron-volts)



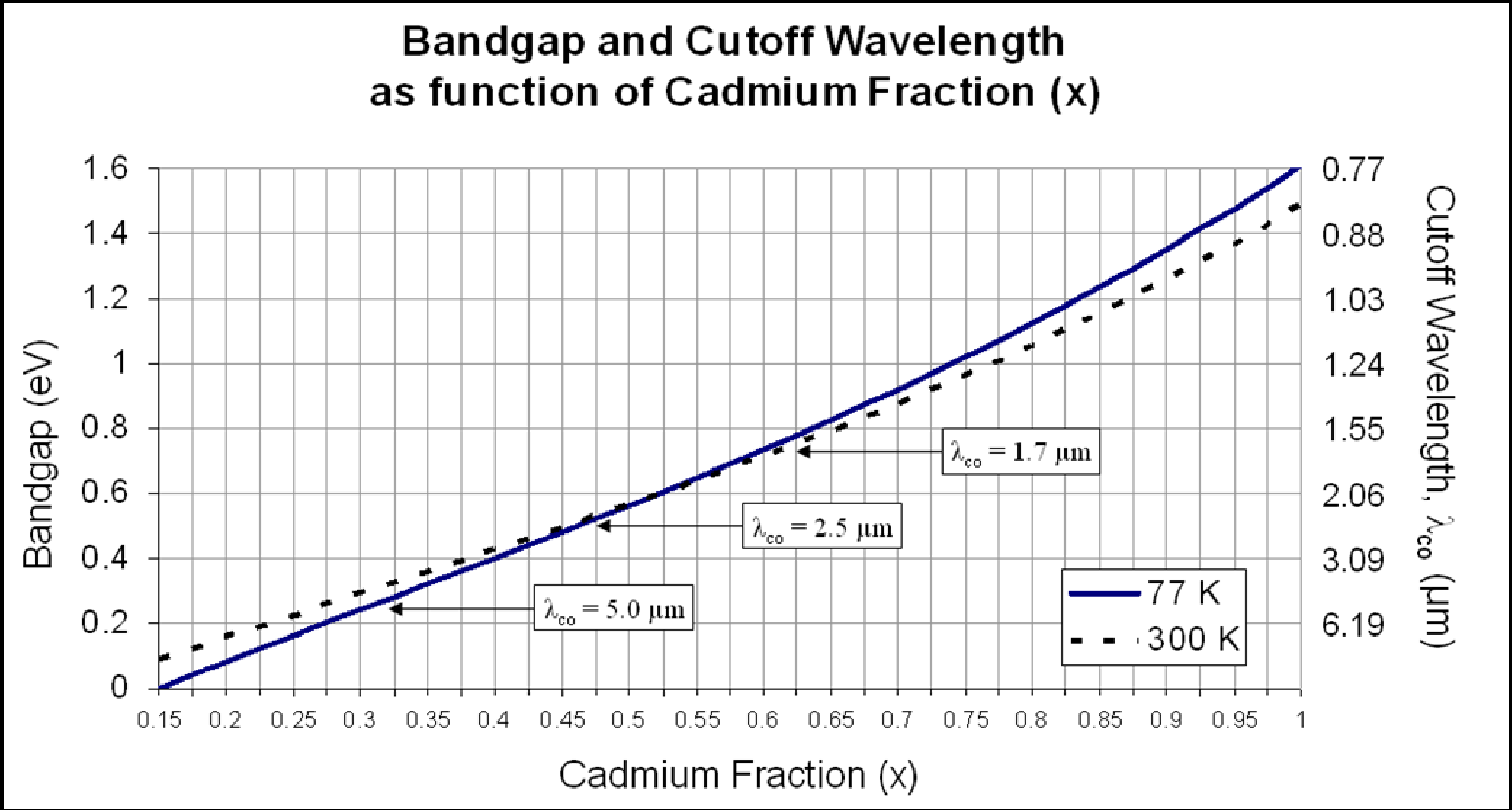
$$\lambda_c = 1.238 / \mathcal{E}_g \text{ (eV)}$$

Material Name	Symbol	$\mathcal{E}_g$ (eV)	λ_c (μm)
Silicon	Si	1.12	1.1
Indium-Gallium-Arsenide	InGaAs	0.73 – 0.48	1.68* – 2.6
Mer-Cad-Tel	HgCdTe	1.00 – 0.07	1.24 – 18
Indium Antimonide	InSb	0.23	5.5
Arsenic doped Silicon	Si:As	0.05	25

*Lattice matched InGaAs ($In_{0.53}Ga_{0.47}As$)

Tunable Wavelength: Valuable property of HgCdTe

$Hg_{1-x}Cd_xTe$ Modify ratio of Mercury and Cadmium to "tune" the bandgap energy



$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35\times10^{-4}T(1-2x)$$

G. L. Hansen, J. L. Schmidt, T. N. Casselman, J. Appl. Phys. 53(10), 1982, p. 7099

Absorption Depth

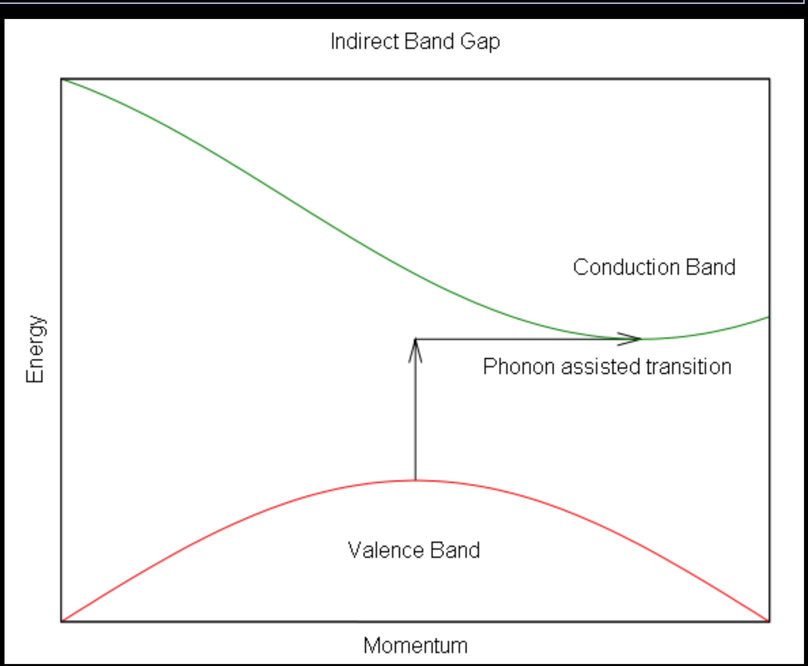
The depth of detector material that absorbs 63.2% of the radiation

1/e of the energy is absorbed

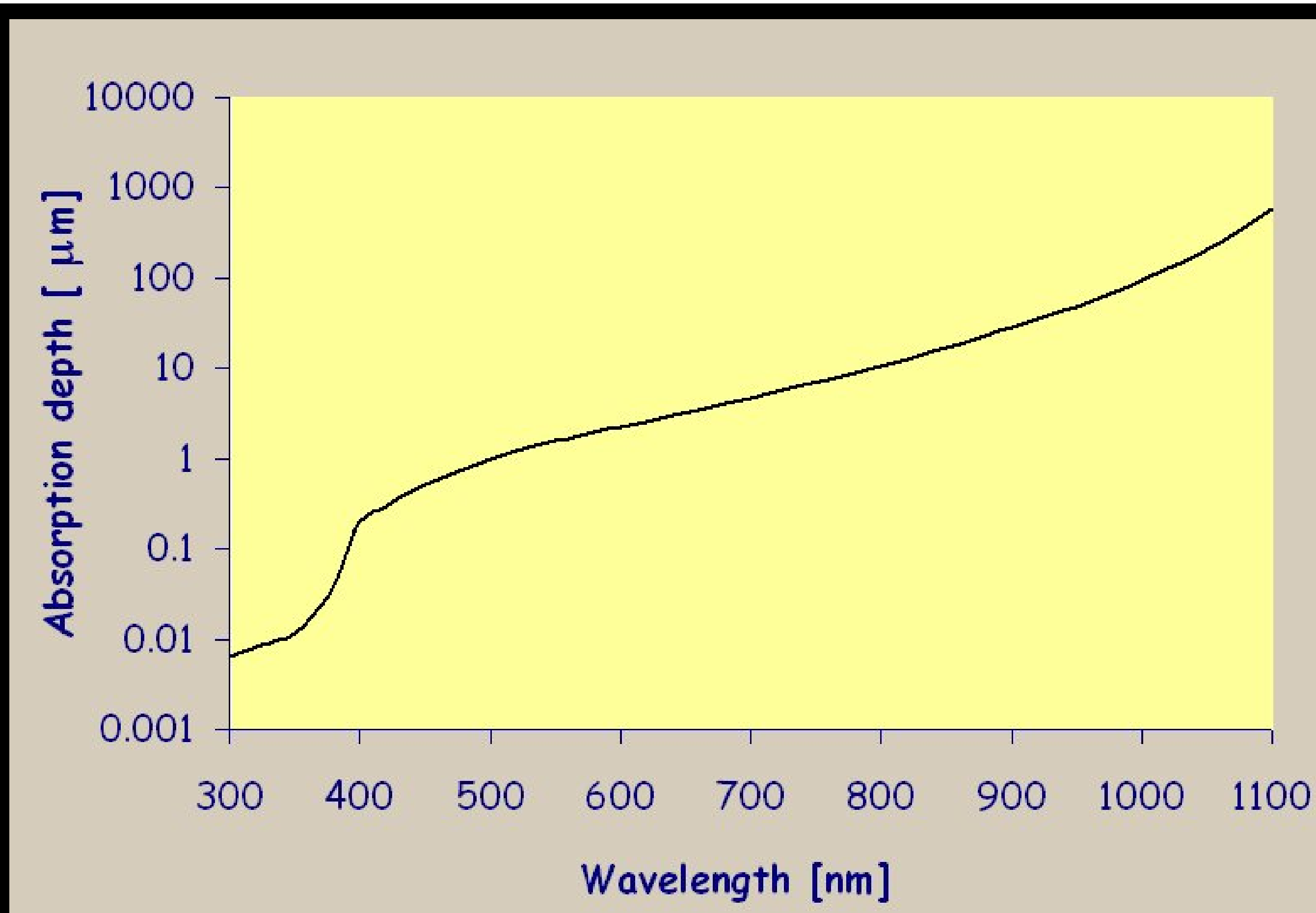
1	absorption depth(s)	63.2% of light absorbed
2		86.5%
3		95.0%
4		98.2%

For high QE, thickness of detector material should be ≥ 3 absorption depths

Silicon is an indirect bandgap material and is a poor absorber of light as the photon energy approaches the bandgap energy. For an indirect bandgap material, both the laws of conservation of energy and momentum must be observed. To excite an electron from the valence band to the conduction band, silicon must simultaneously absorb a photon and a phonon that compensates for the missing momentum vector.



Absorption Depth of Silicon

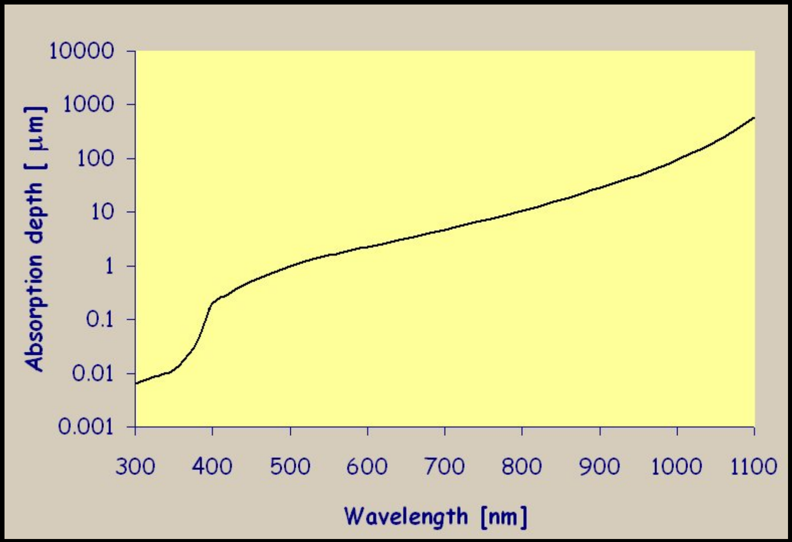


- For high QE in the near infrared, need very thick (up to 300 microns) silicon detector layer.
- For high QE in the ultraviolet, need to be able to capture photocharge created within 10 nm of the surface where light enters the detector.
- In addition, the index of refraction of silicon varies over wavelength – a challenge for anti-reflection coatings.

UV / Blue CCD Quantum Efficiency

- Need very thin backside passivation layer
- Technologies
  - Boron implant and laser anneal
    - E2V, MIT/LL
  - MBE
    - JPL, MIT/LL
  - Chemisorption coating that produces positive charge
    - University of Arizona (Lesser)

      Licensed by Fairchild



Effect of anneal process on QE

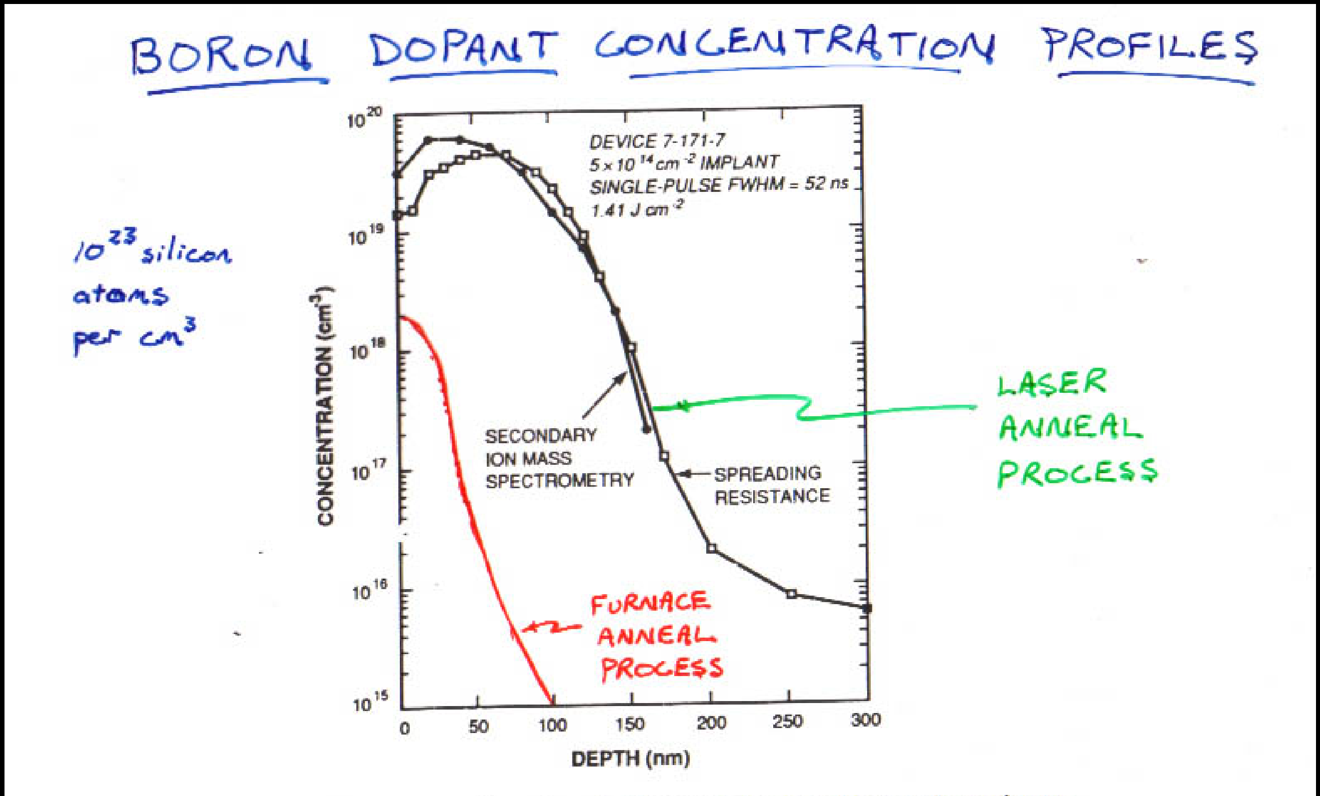
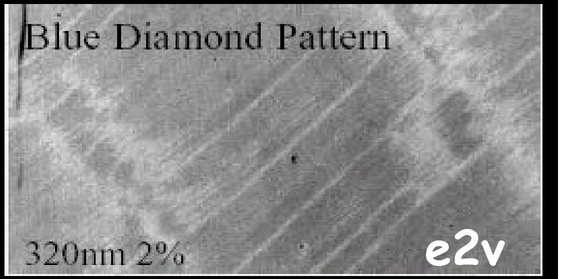
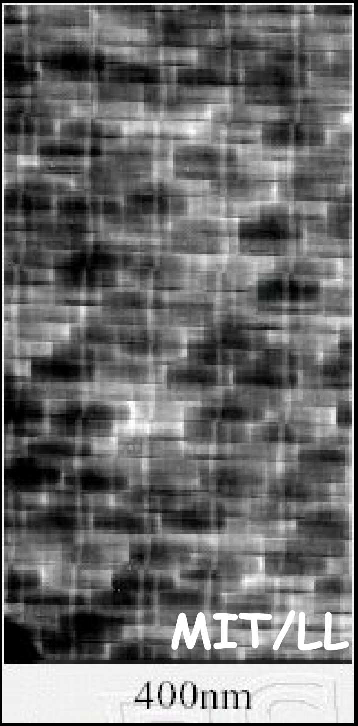


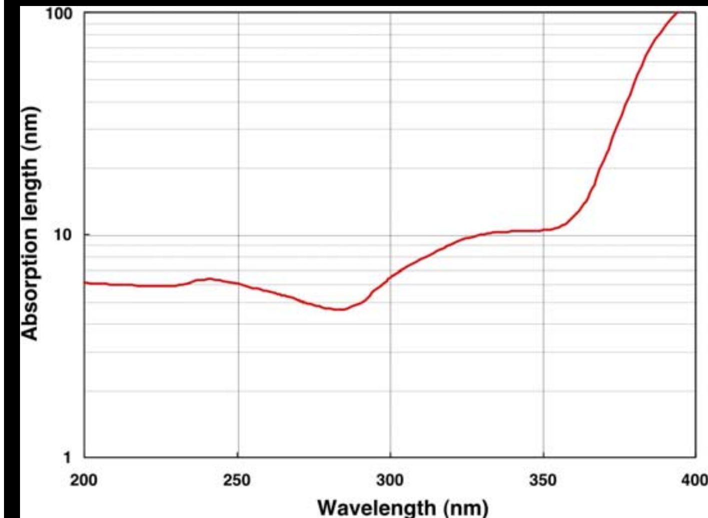
Figure 9. Plot of the active dopant (boron) vs. depth measured using both spreading resistance and secondary ion mass spectrometry (SIMS) methods. The boron was implanted and then activated by a pulsed laser anneal.

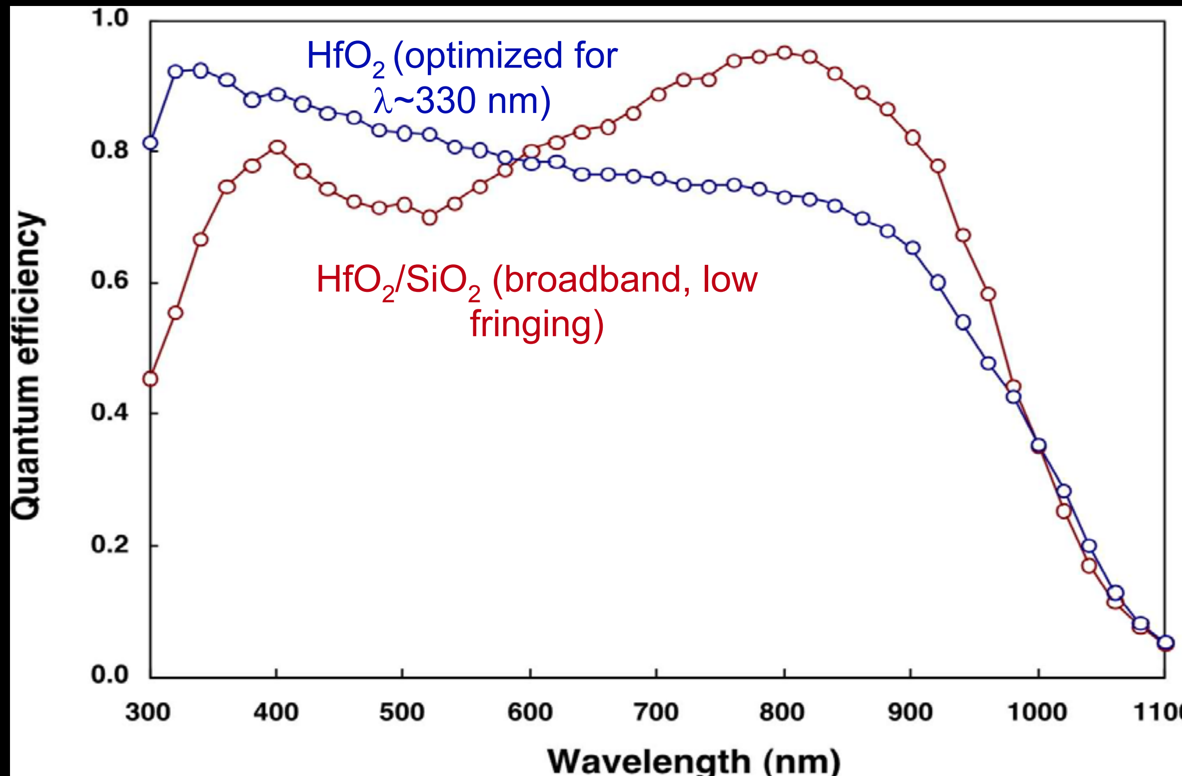




Cyril Cavadore, ESO

Quantum Efficiency of AR-coated MBE Devices





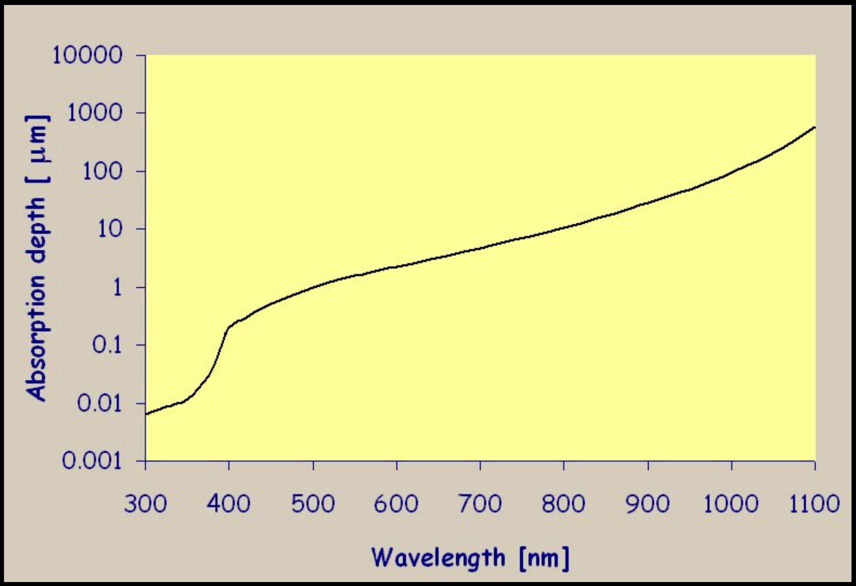
- UV (<400 nm) is challenging
  - Shallow penetration depth of radiation (<10 nm at λ=200-350 nm)
  - Requires extremely thin, doped surface layer

MBE processed
Device thickness = 45µm, T = 20°C

Barry Burke, MIT/LL

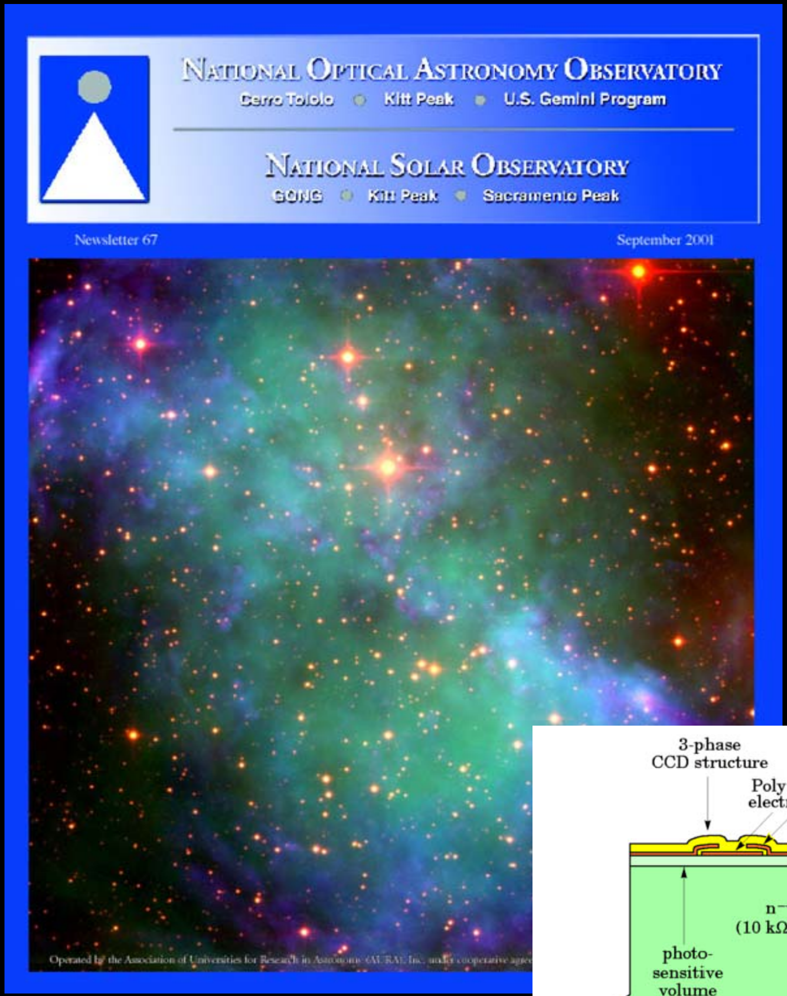
NIR Silicon CCD Quantum Efficiency

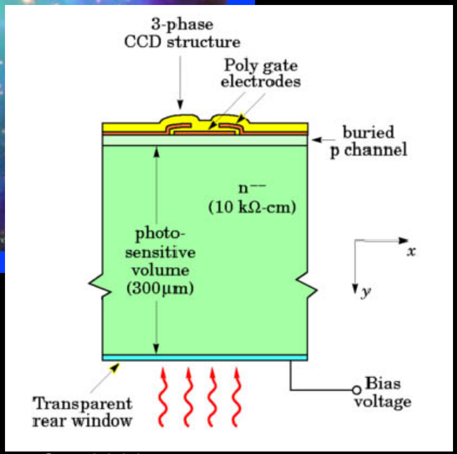
- Optical absorption depth
  - 800 nm 11 μm
  - 900 nm 29 μm
  - 1000 nm 94 μm

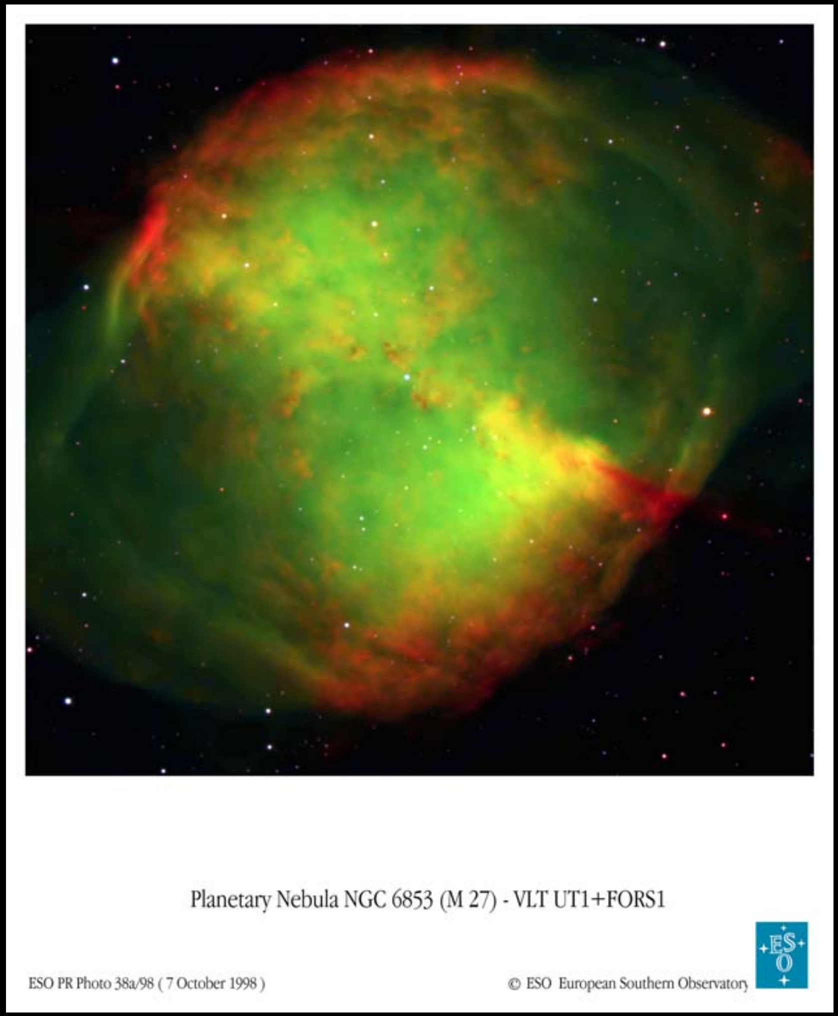


- N-channel CCD (collect electrons)
  - Standard CCDs 10-15 μm thick
  - Thick high-resistivity 40-50 μm thick
    - MIT/LL, e2v
- P-channel CCD (collect holes)
  - Very thick 200-300 μm thick
    - LBNL

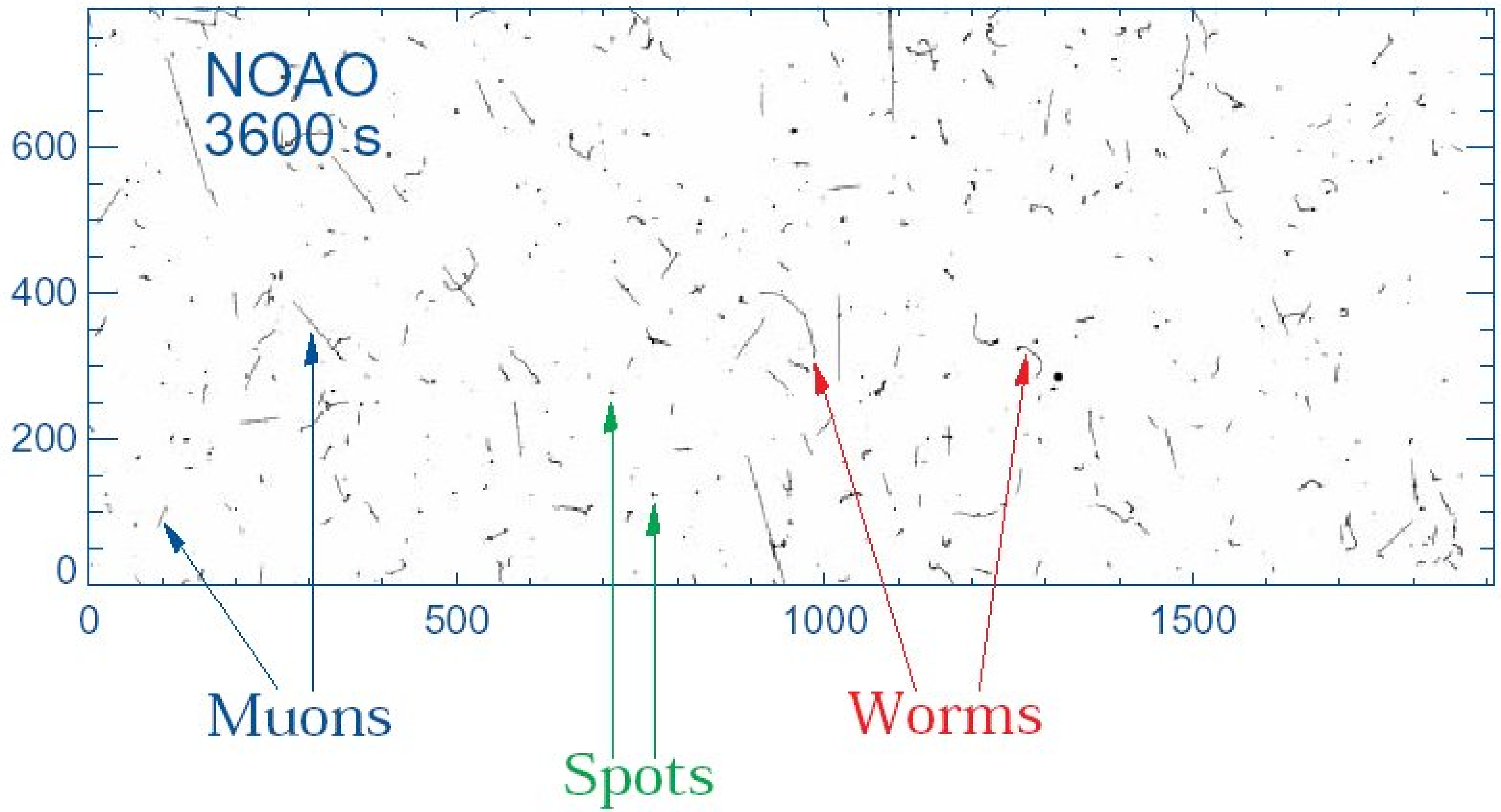
Near-IR Imaging enabled by very thick silicon sensors







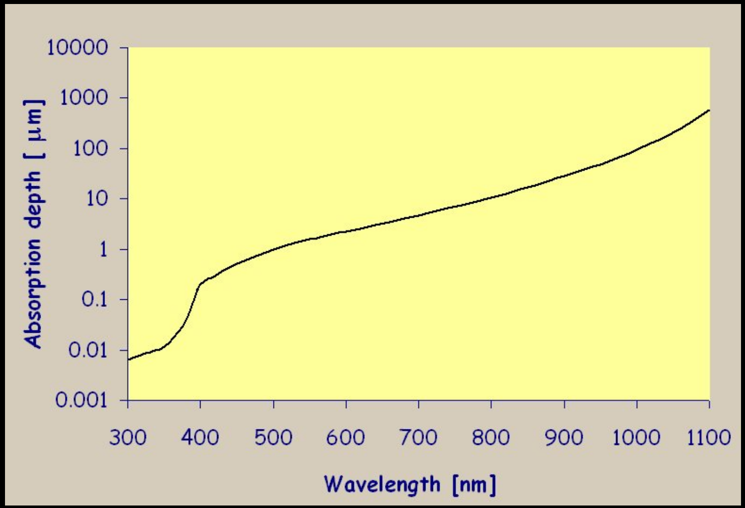
A very thick silicon detector is also a very good sensor of cosmic rays

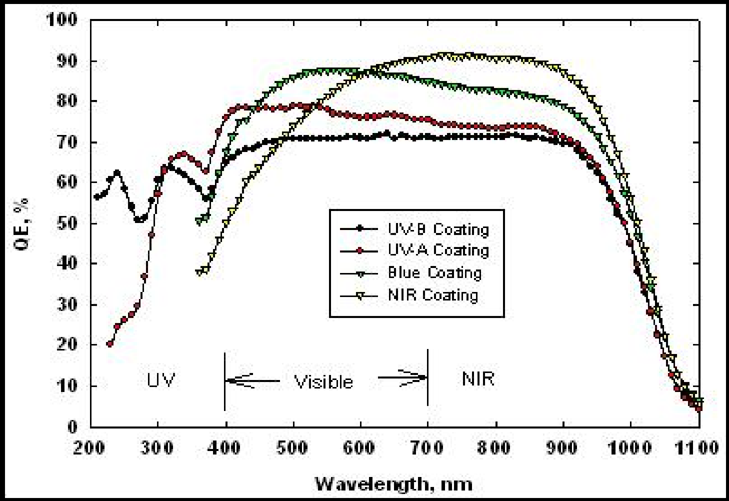


Our 300-μm thick depleted CCD gives us the great advantage (curse?) that we can see the events in new detail

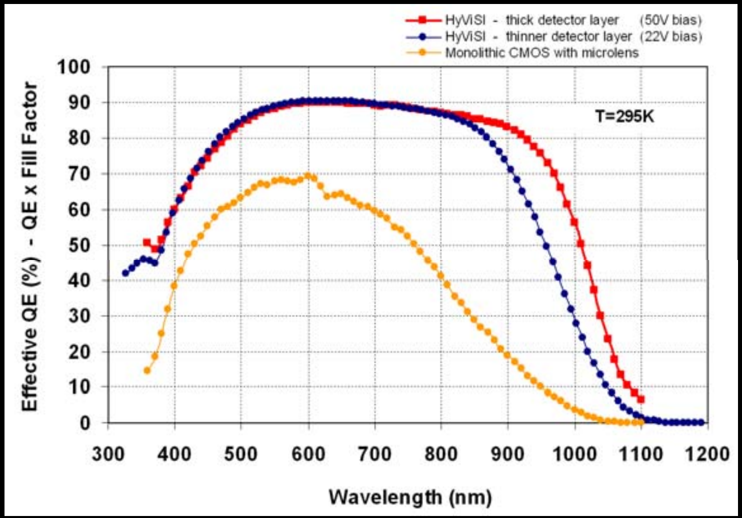
Hybrid Silicon PIN Quantum Efficiency

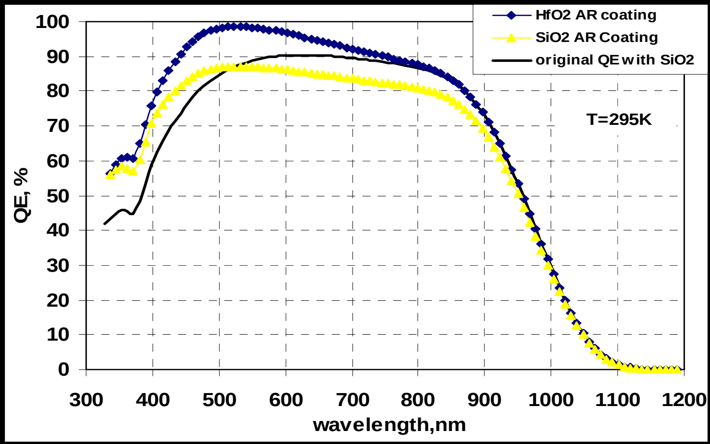
achieves as high QE as CCDs in the NIR





Measured data





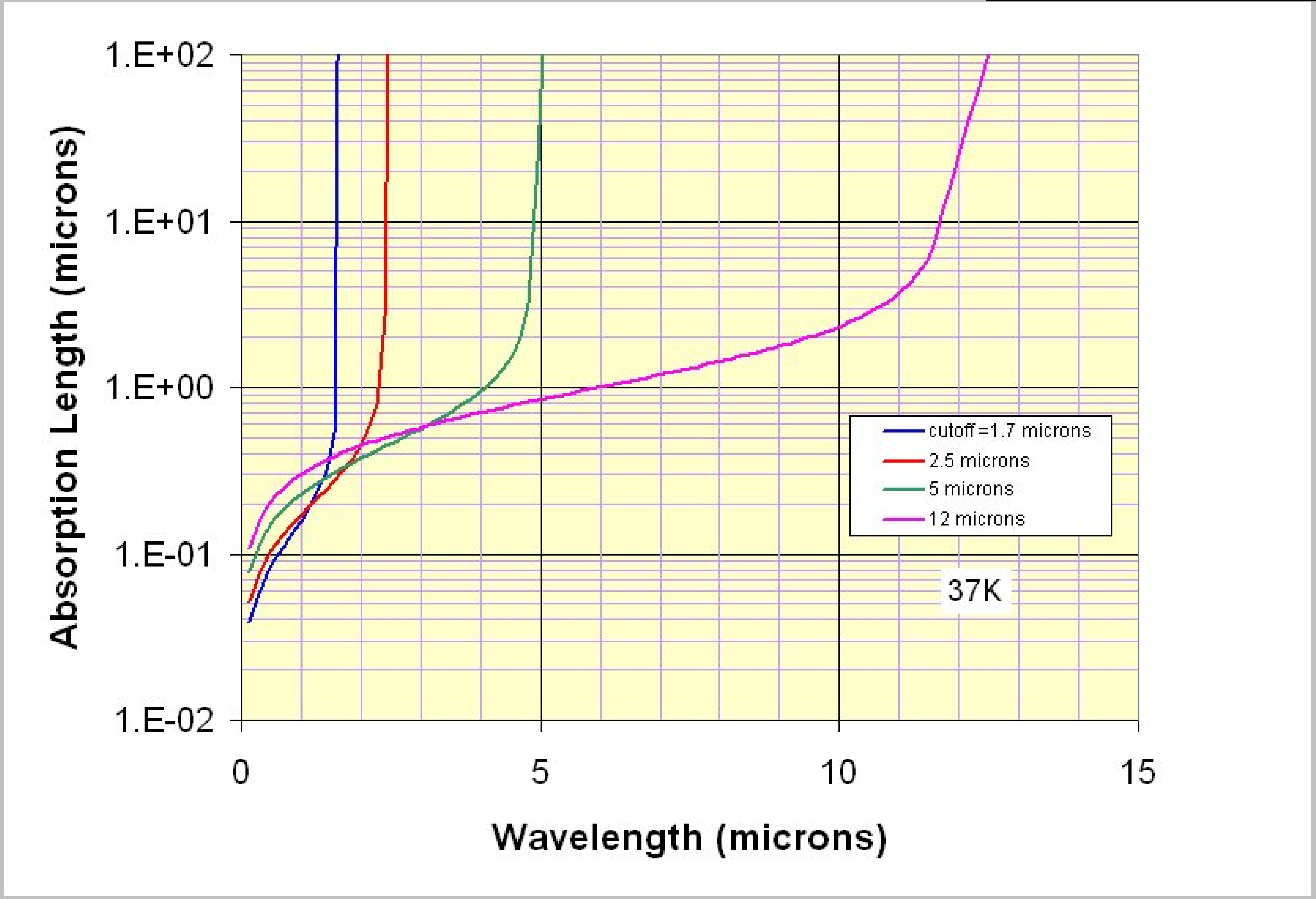
Computed QE curves

Teledyne Imaging Sensors

Absorption Depth of HgCdTe

Rule of Thumb

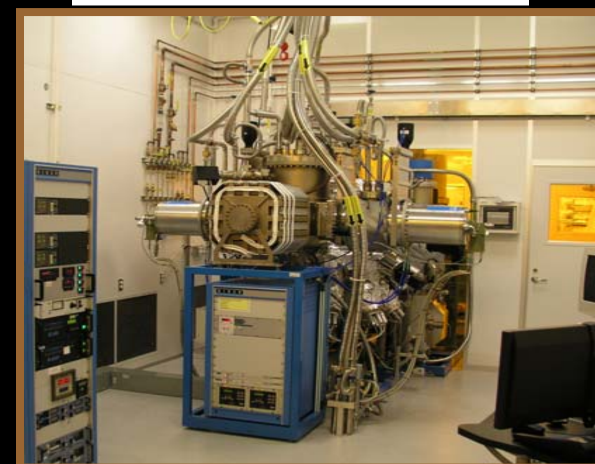
Thickness of HgCdTe layer needs to be about equal to the cutoff wavelength



Two methods for growing HgCdTe

1. Liquid Phase Epitaxy (LPE)
2. Molecular Beam Epitaxy (MBE)
   - Enables very accurate deposition ⇒ “bandgap engineering”
   - Teledyne has 4 MBE machines for detector growth

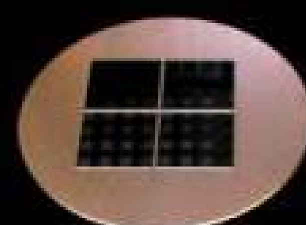
RIBER 10-in MBE 49 System



RIBER 3-in MBE Systems

3 inch diameter platen allows growth on one 6x6 cm substrate

More than 7500 MCT wafers grown to date



10 inch diameter platen allows simultaneous growth on four 6x6 cm substrates

Teledyne Imaging Sensors

Quantum Yield: One photoelectron for every detected photon

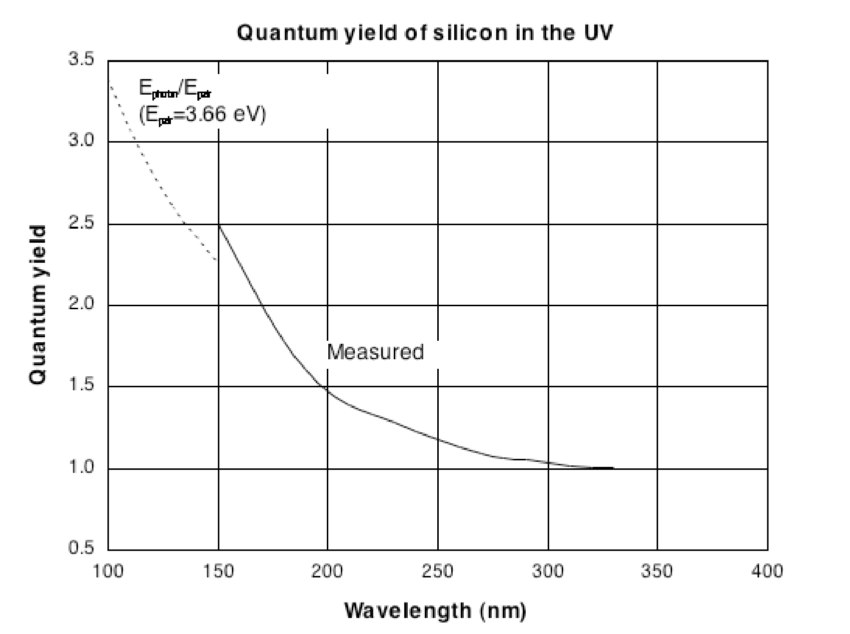
…for most wavelengths of interest to ground-based astronomy

Silicon

For wavelengths that are 30% to 100% of the cutoff wavelength, there will a single electron-hole pair created for every detected photon.

For shorter wavelengths (higher energies), there is an increasing probability of producing multiple electron-hole pairs.

For silicon, this effect commences at ~30% of the cutoff wavelength (λ < 330 nm).



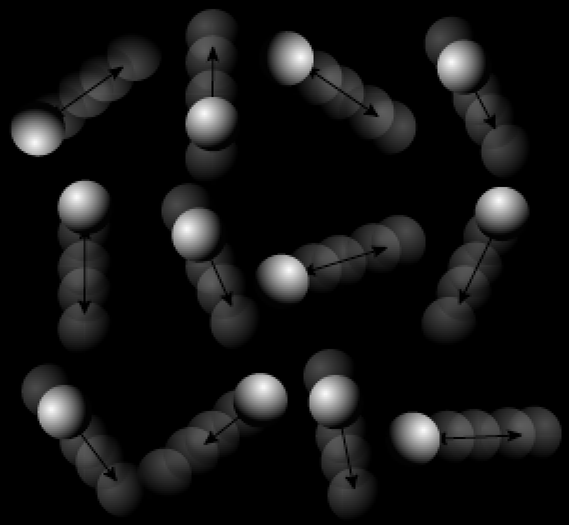
Data from Barry Burke, MIT Lincoln Laboratory

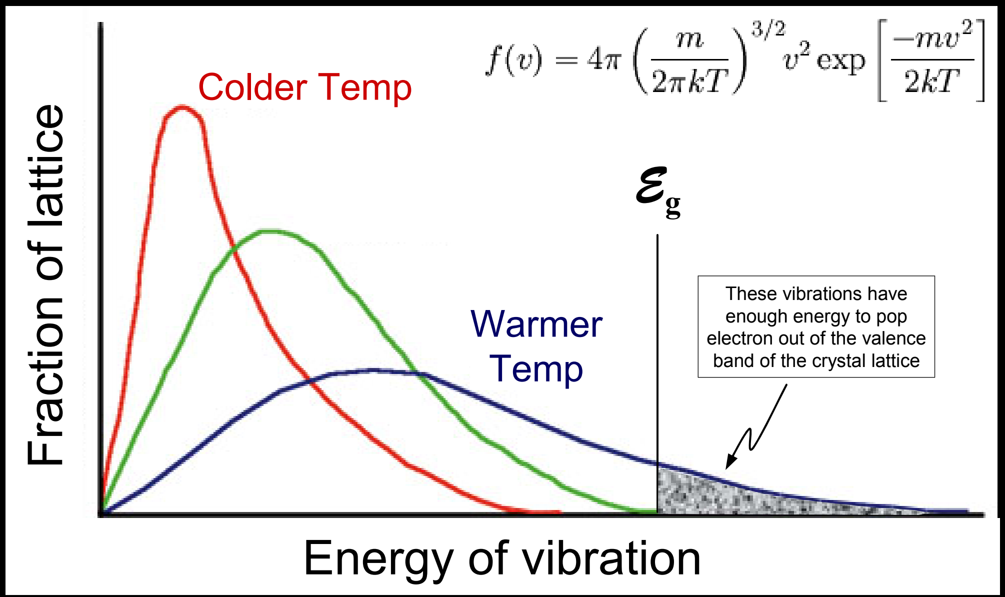
HgCdTe

- Limited data from HgCdTe detectors shows that quantum yield is not significant at 800 nm for a 5400 nm cutoff detector (11% of cutoff wavelength).
- The quantum yield of HgCdTe is still being investigated.

Dark Current

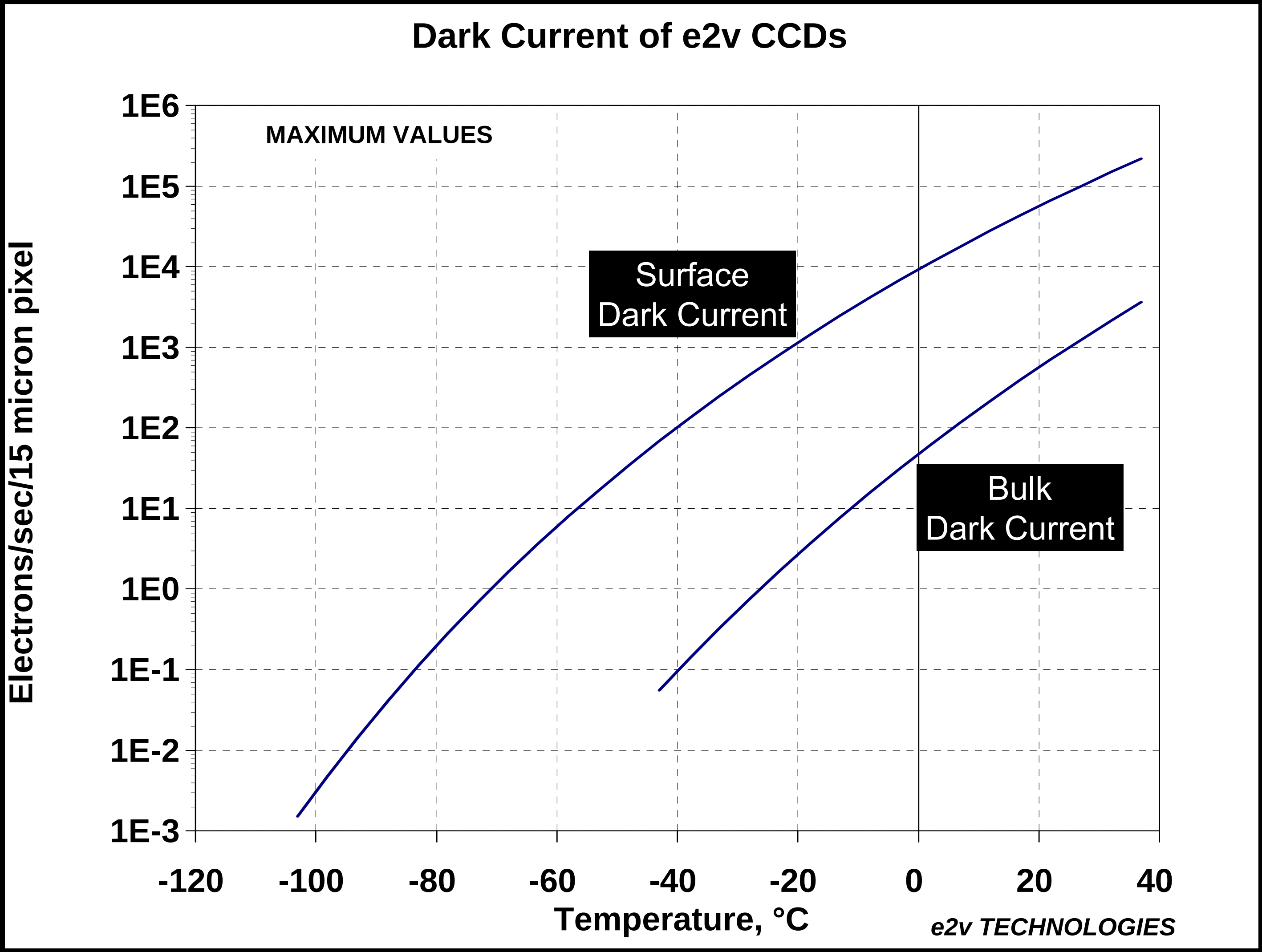
Undesirable byproduct of light detecting materials





- The vibration of particles (includes crystal lattice phonons, electrons and holes) has energies described by the Maxwell-Boltzmann distribution. Above absolute zero, some vibration energies may be larger than the bandgap energy, and will cause electron transitions from valence to conduction band.
- Need to cool detectors to limit the flow of electrons due to temperature, i.e. the **dark current** that exists in the absence of light.
- The smaller the bandgap, the colder the required temperature to limit dark current below other noise sources (e.g. readout noise)

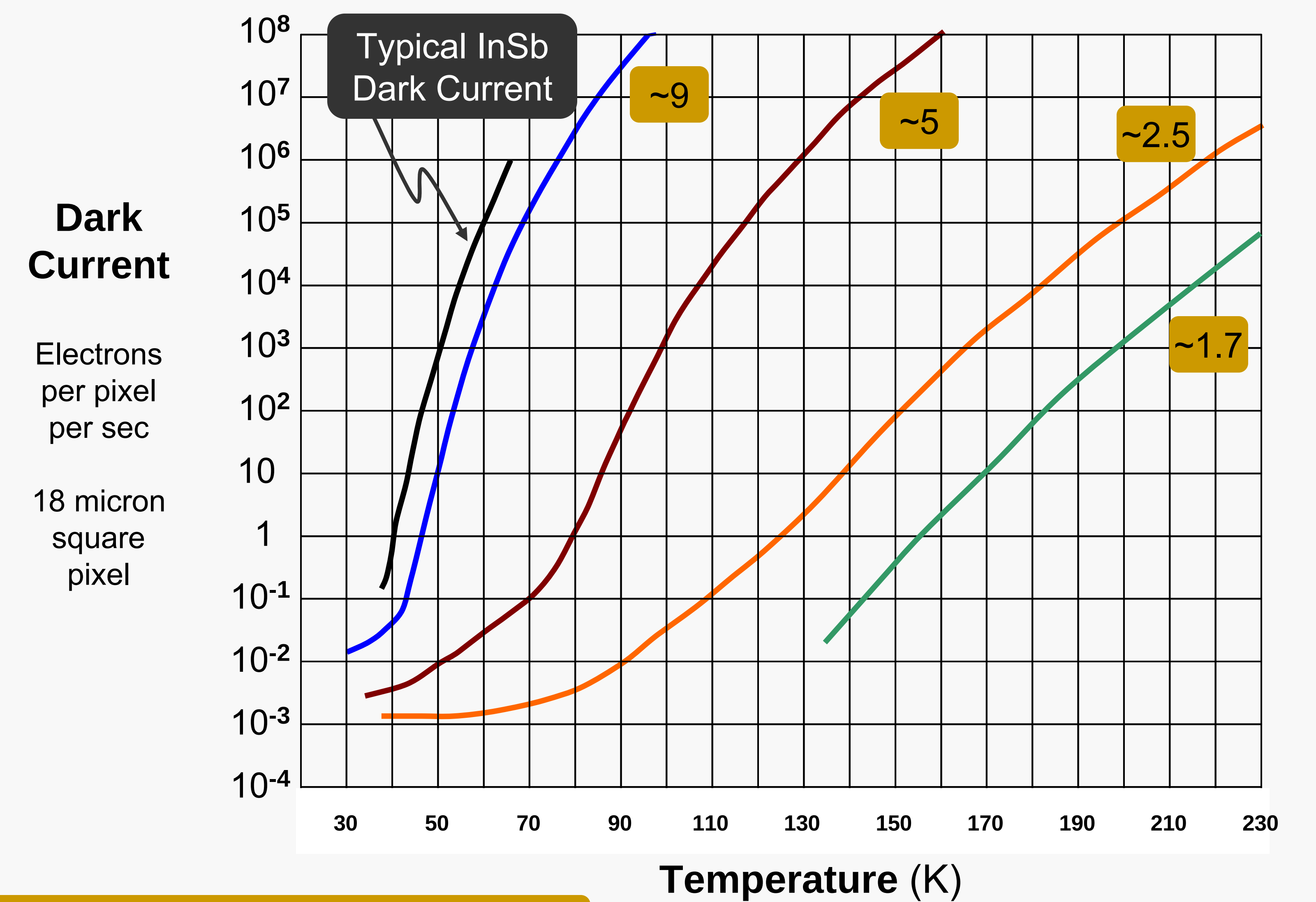
Dark Current of Silicon-based Detectors



In silicon, dark current usually dominated by surface defects

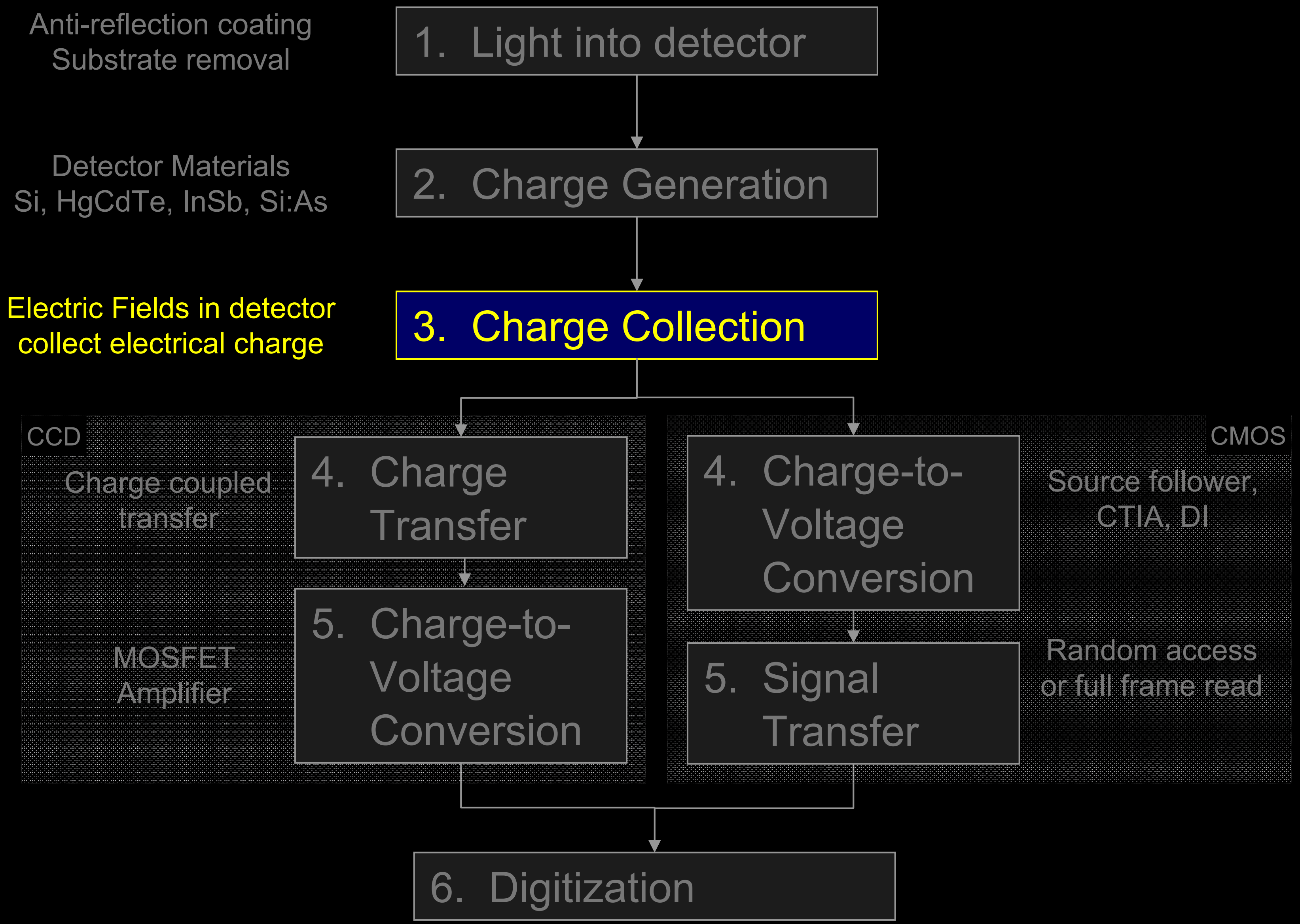
e2v technologies

Dark Current of HgCdTe Detectors



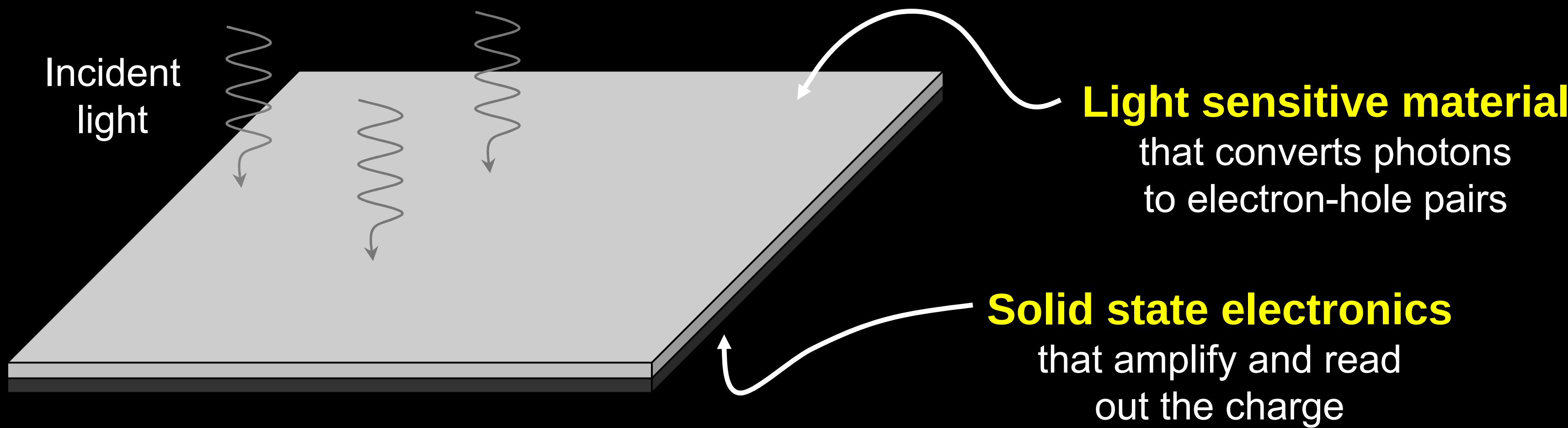
HgCdTe cutoff wavelength (microns)

6 steps of optical / IR photon detection

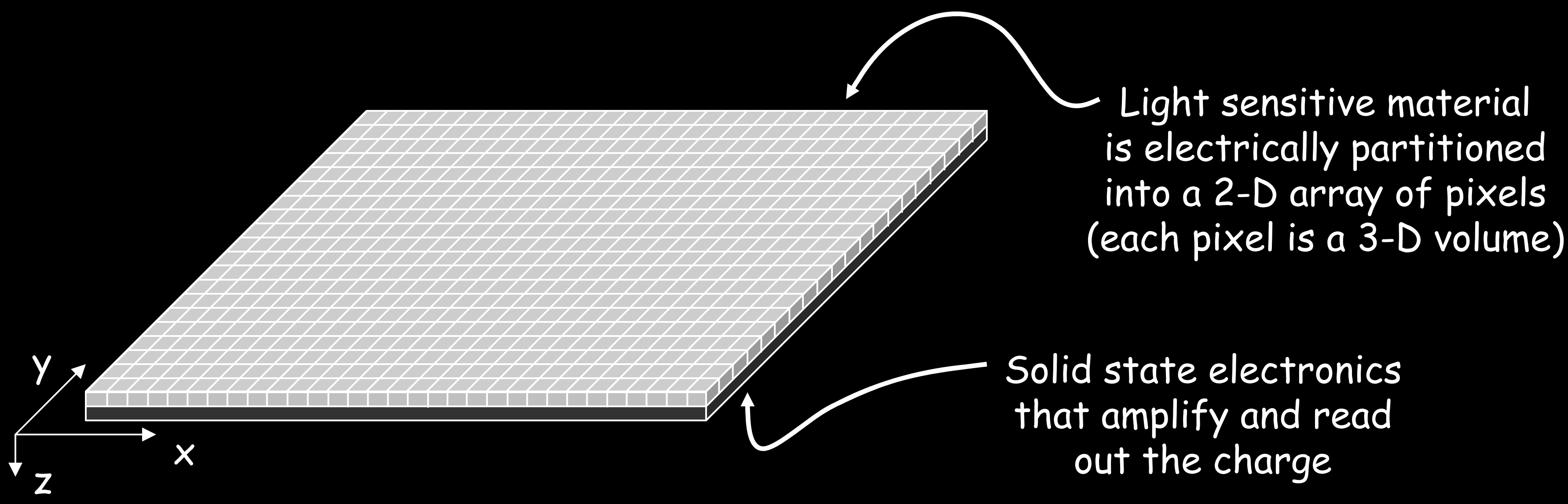


Two main parts of an imaging detector

Detector material & Solid state electronics



3. Charge Collection



- Intensity image is generated by collecting photocharge generated in 3-D volume into 2-D array of pixels.
- Optical and IR focal plane arrays both collect charges via electric fields.
- In the z-direction, optical and IR use a p-n junction to “sweep” charge toward pixel collection nodes.

Periodic Table

Number of electrons in outer shell

						3	4	5			
											2 He Helium 4.0
						5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2
						13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 40.0
n ese	26 Fe Iron 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krypton 83.8
c um	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
e m 2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0
n m	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Uun Ununnilium 272								

Types of Elements Key:

Alkalimetals

Periodic Table

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						13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 40.0
n ese	26 Fe Iron 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krypton 83.8
c um	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
e m 2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0
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Types of Elements Key:

Alkalimetals

Periodic Table

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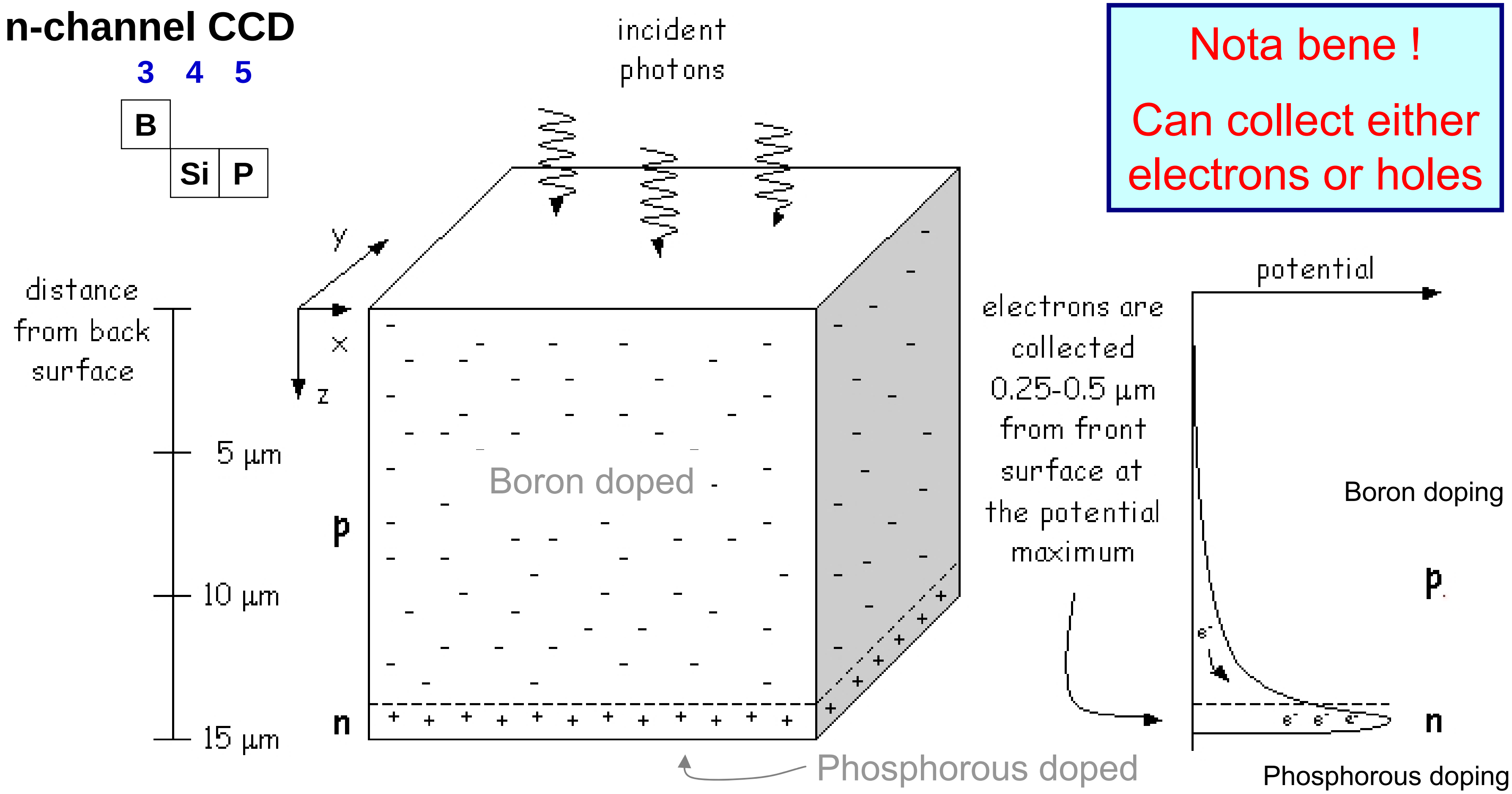
e m 2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0
n m	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Uun Ununnilium 272								

Types of Elements Key:

Alkali metals

Photovoltaic Detector Potential Well



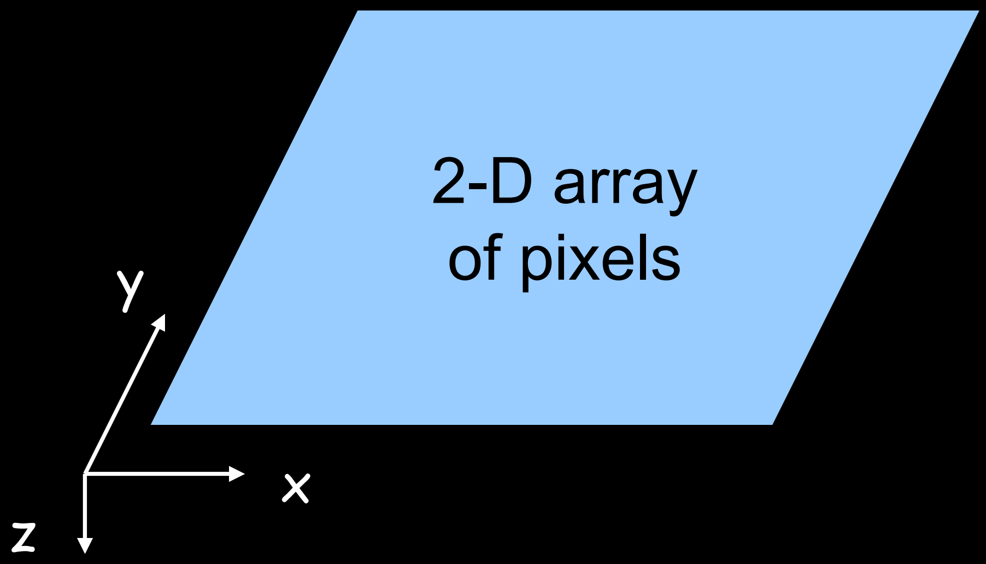
Nota bene !

Can collect either electrons or holes

Silicon, HgCdTe and InSb are photovoltaic detectors. All use a pn-junction to generate E-field in the z-direction of each pixel. This electric field separates the electron-hole pairs generated by a photon.

Charge Collection

- CCD and CMOS focal plane arrays are different for charge collection in the x and y dimensions.
- CMOS – collect charge at each pixel and have amplifiers and readout multiplexer
- CCD – collect charge in array of pixels. At end of frame, move charge to edge of array where one (or more) amplifier (s) read out the pixels.



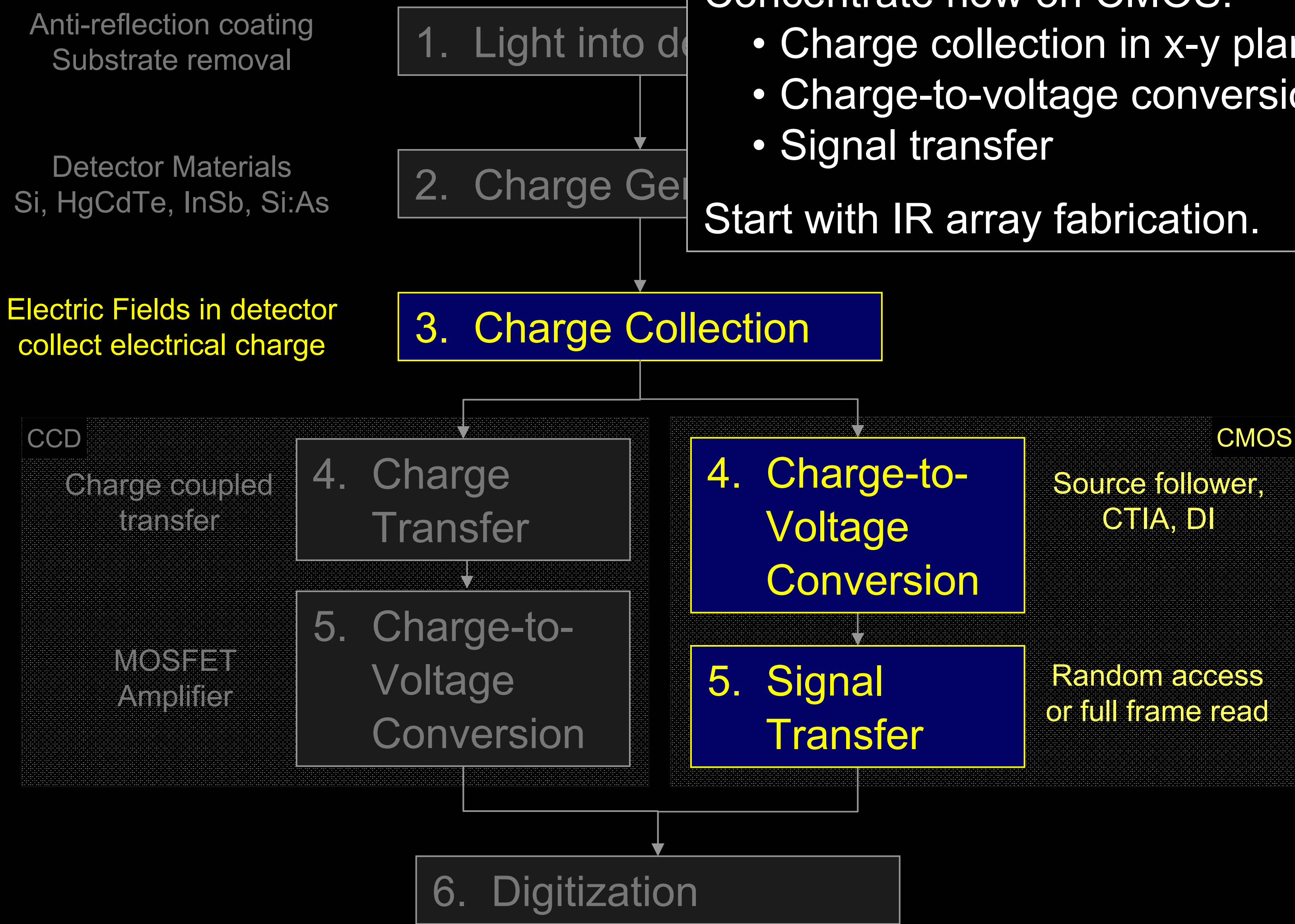
6 steps of optical / IR

Charge collection in the x-y plane is where CCD and CMOS diverge.

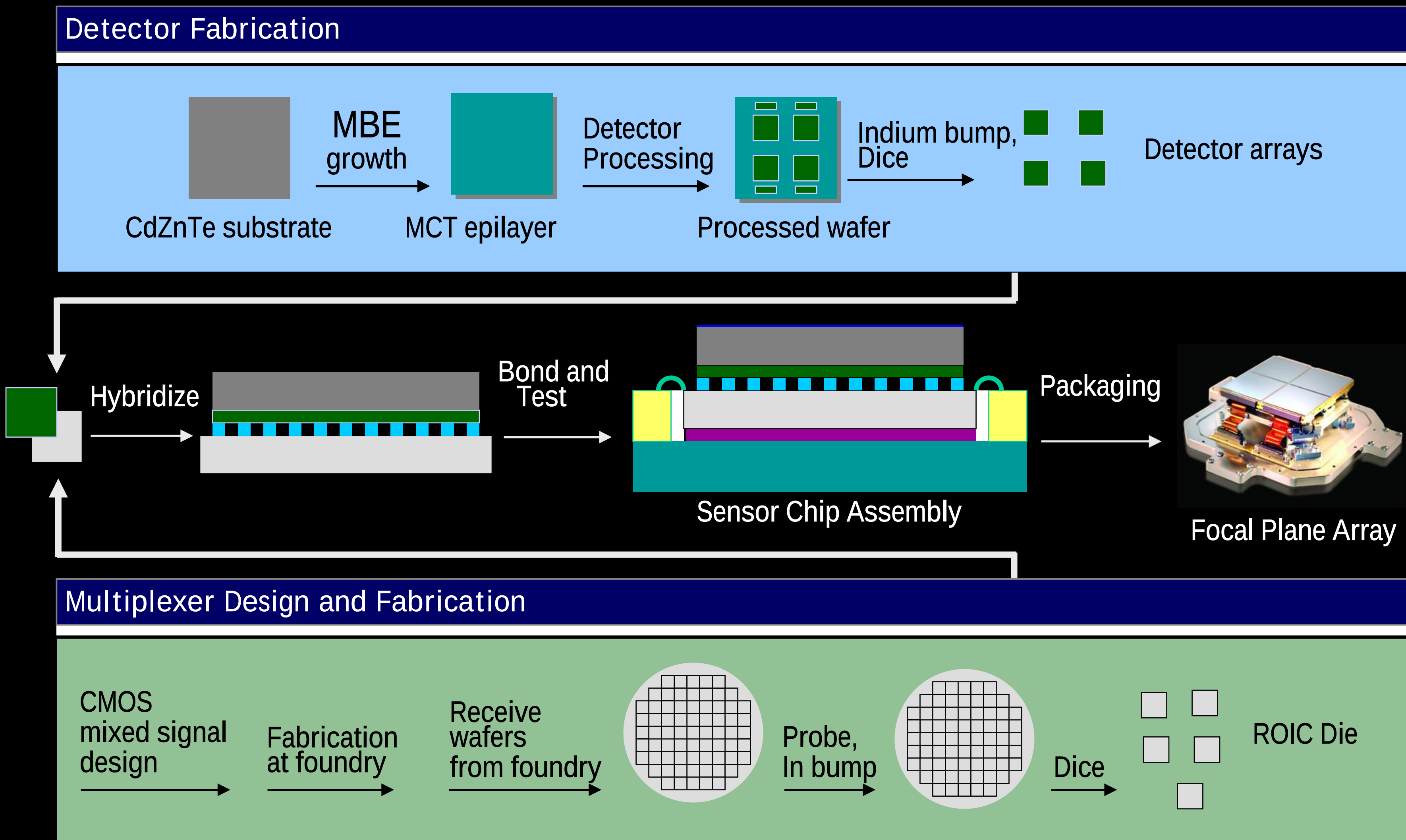
Concentrate now on CMOS:

- Charge collection in x-y plane
- Charge-to-voltage conversion
- Signal transfer

Start with IR array fabrication.



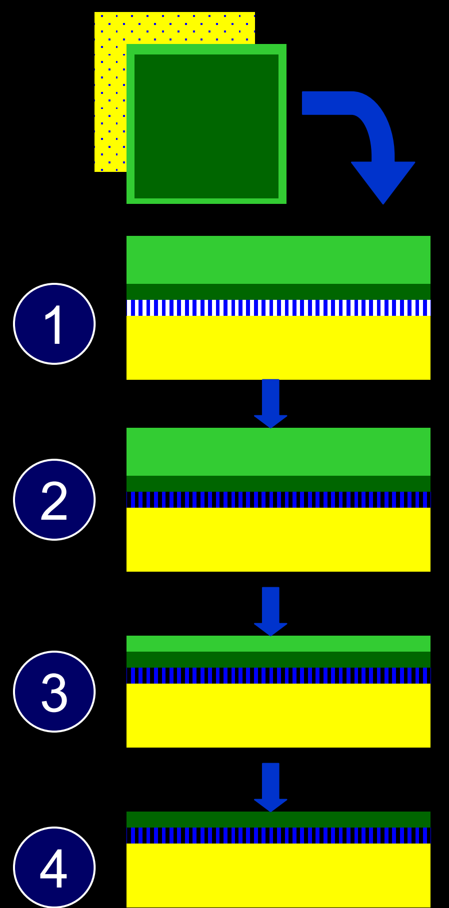
HgCdTe IR FPA Manufacturing Process



Teledyne Imaging Sensors

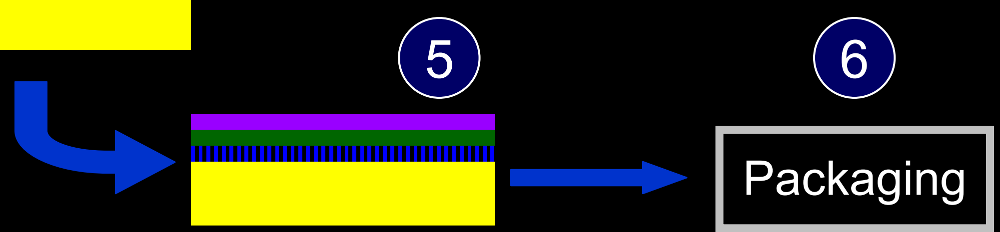
Substrate Removal of HgCdTe

The new standard in astronomy

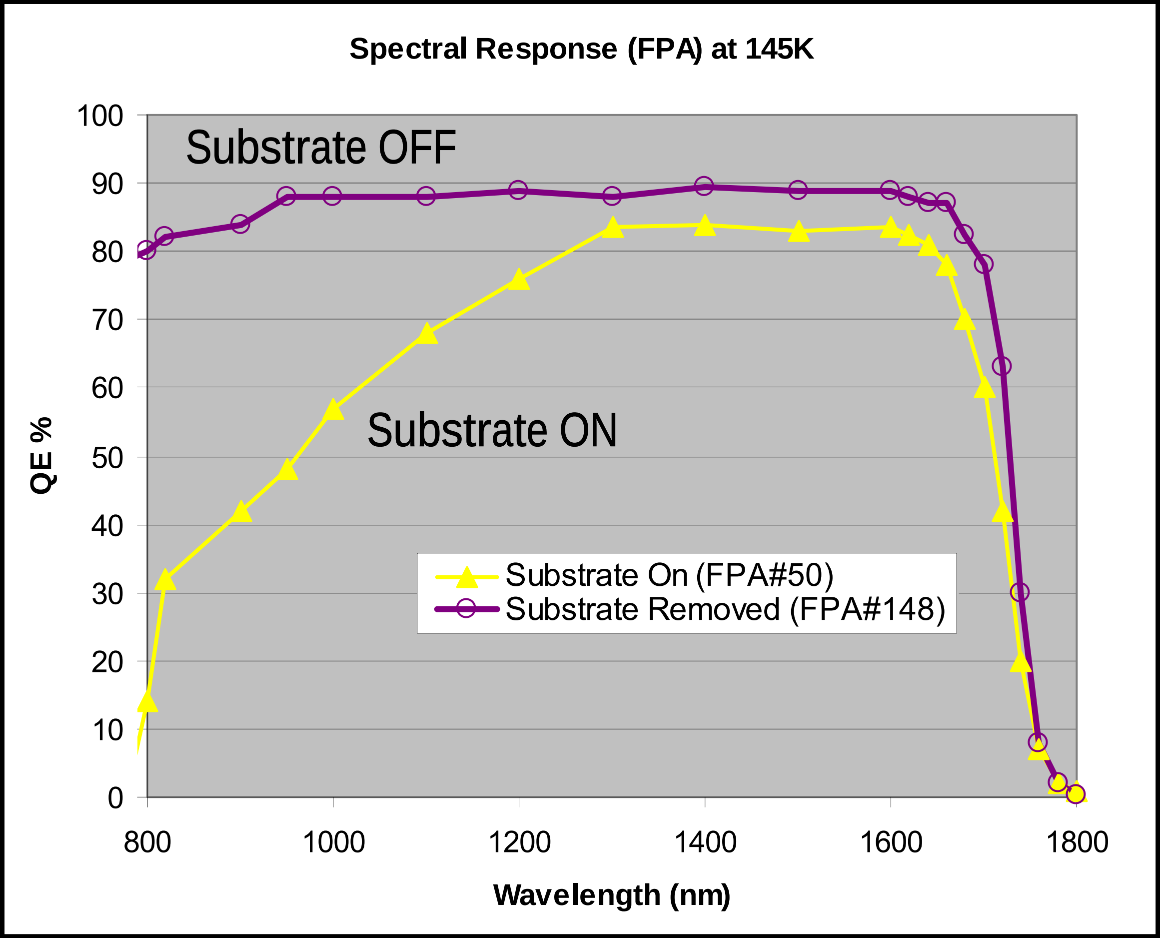


Substrate Removal Process

1. Detectors are hybridized
2. The hybrids are epoxy backfilled
3. CdZnTe substrates are then mechanically thinned
4. Remaining substrate is removed by etching, stopping in the HgCdTe layer
5. The etched surface is passivated and AR coated
6. The hybrid packaging is completed



QE Improvement With Substrate Removal

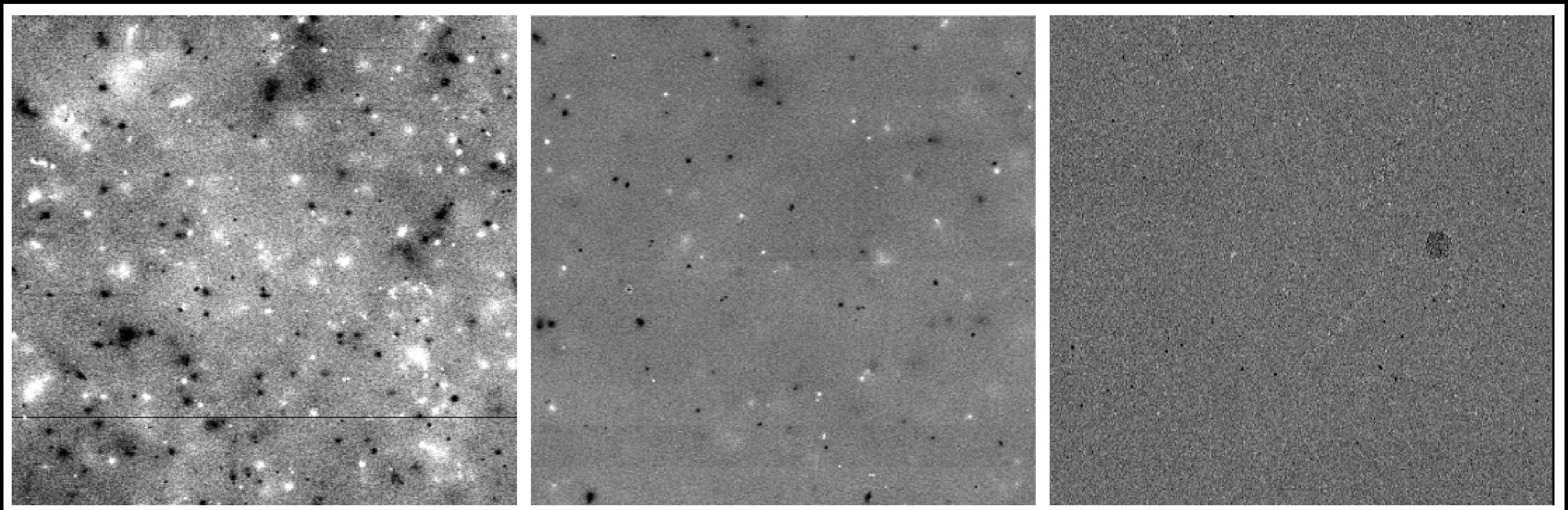


Quantum efficiency improves across the IR band after substrate removal, particularly at short wavelengths, and HgCdTe is sensitive to visible light.

FPA QE measured by NASA Goddard Detector Characterization Laboratory (no IPCC)

Cosmic Rays and Substrate Removal

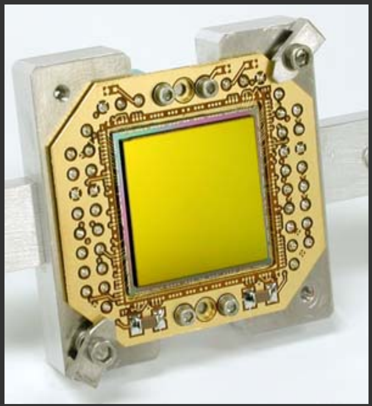
- Cosmic ray events produce clouds of detected signal due to particle-induced flashes of infrared light in the CdZnTe substrate; removal of the substrate eliminates the effect

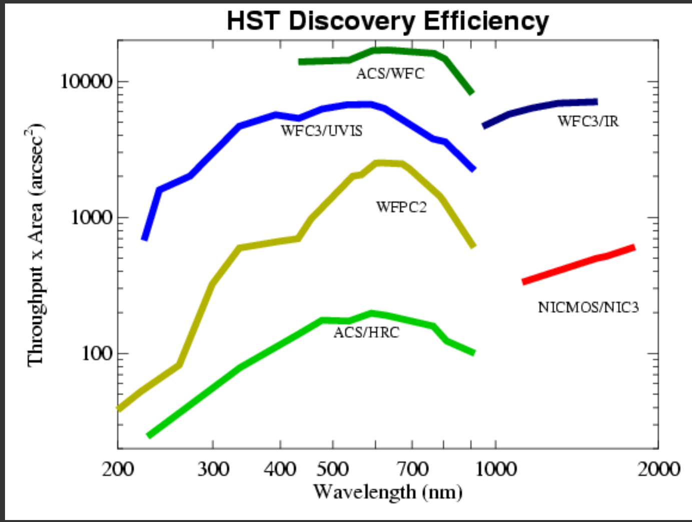


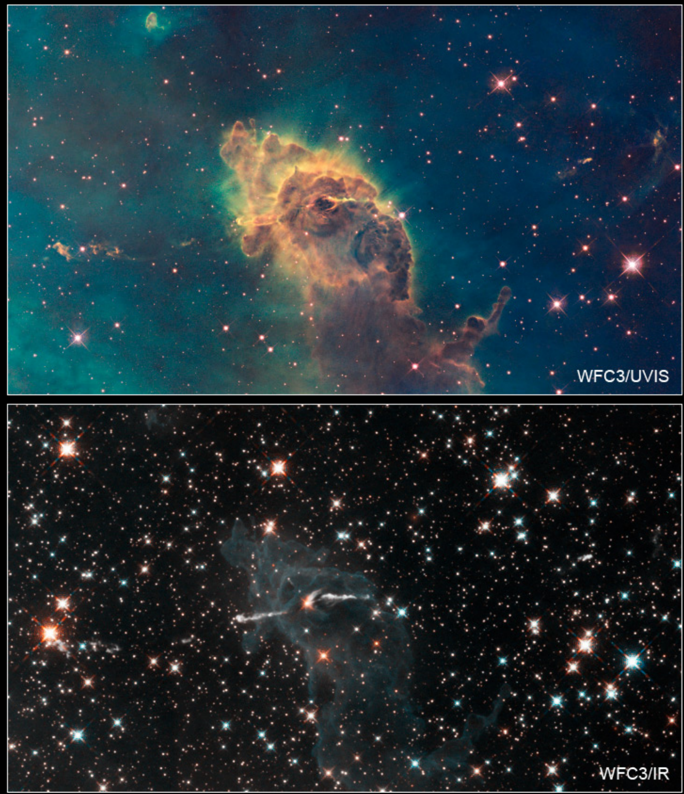
2.5um cutoff, substrate on | 1.7um cutoff, substrate on | 1.7um cutoff, substrate off

*Roger Smith (Caltech) SPIE 5-25-2006

Hubble Space Telescope
Wide Field Camera 3

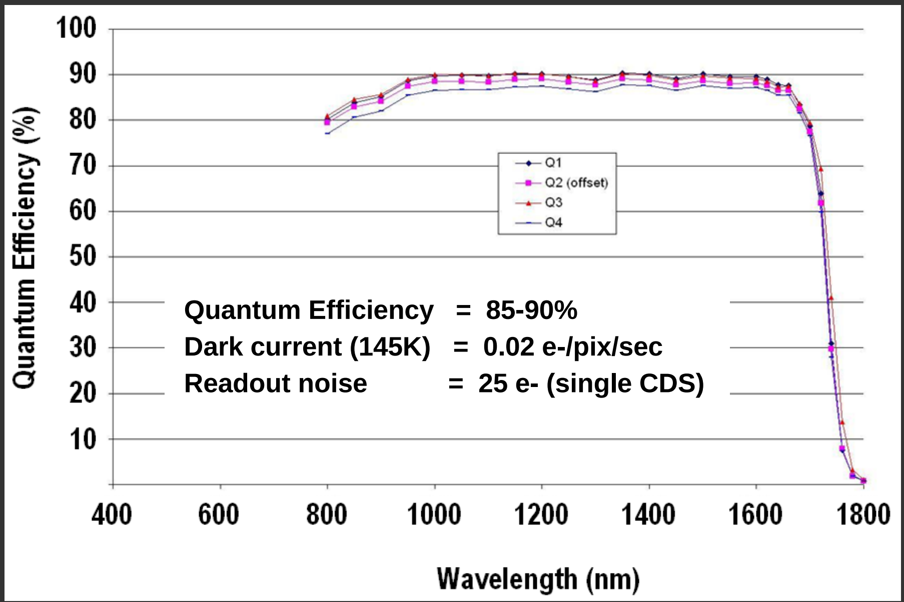






Stellar Jet in the Carina Nebula
Hubble Space Telescope • WFC3/UVIS/IR

NASA, ESA, and the Hubble SM4 ERO Team STScI-PRC09-25b



- **1024×1024 pixels, 18.5 micron pitch**
- **Substrate-removed 1.7 µm HgCdTe arrays**
- **Nearly 30x increase in HST discovery efficiency**

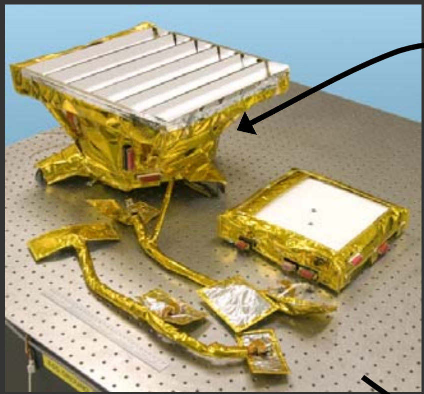
Moon Mineralogy Mapper Discovers Water on the Moon

Moon water findings are a game-changer

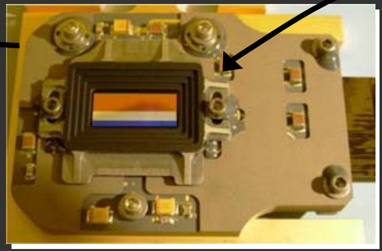
Discovery calls into question 40 years of assumptions about lunar surface

By Andrea Thompson
SPACE
updated 12:38 p.m. PT, Thurs., Sept . 24, 2009

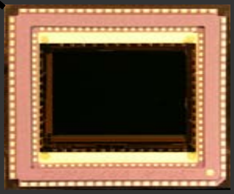
The discovery of widespread but small amounts water on the surface of the moon, announced Wednesday, stands as one of the most surprising findings in planetary science.



Instrument at JPL before shipment to India



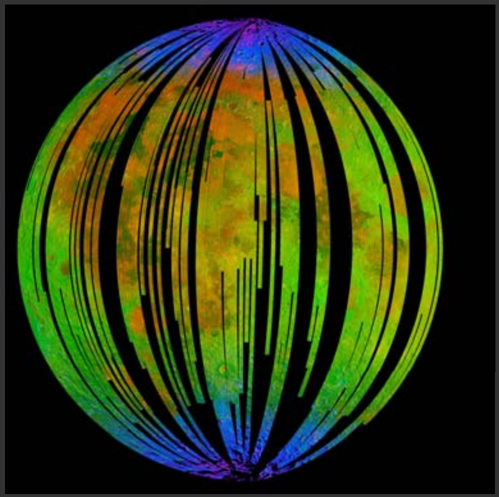
Focal Plane Assembly



Sensor Chip Assembly

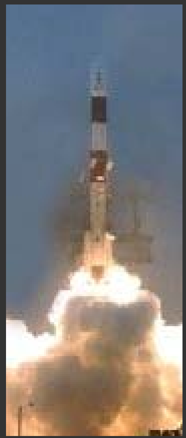
Teledyne Infrared FPA

- 640 x 480 pixels (27 μm pitch)
- Substrate-removed HgCdTe (0.4 to 3.0 μm)
- 650,000 e- full well, <100 e- noise
- 100 Hz frame rate (integrate while read)
- < 70 mW power dissipation
- Package includes order sorting filter
- Total FPA mass: 58 grams

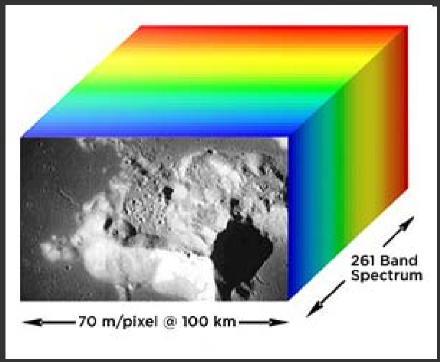


Completion of Chandrayaan-1 spacecraft integration
Moon Mineralogy Mapper is white square at end of arrow

Chandrayaan-1 in the Polar Satellite Launch Vehicle



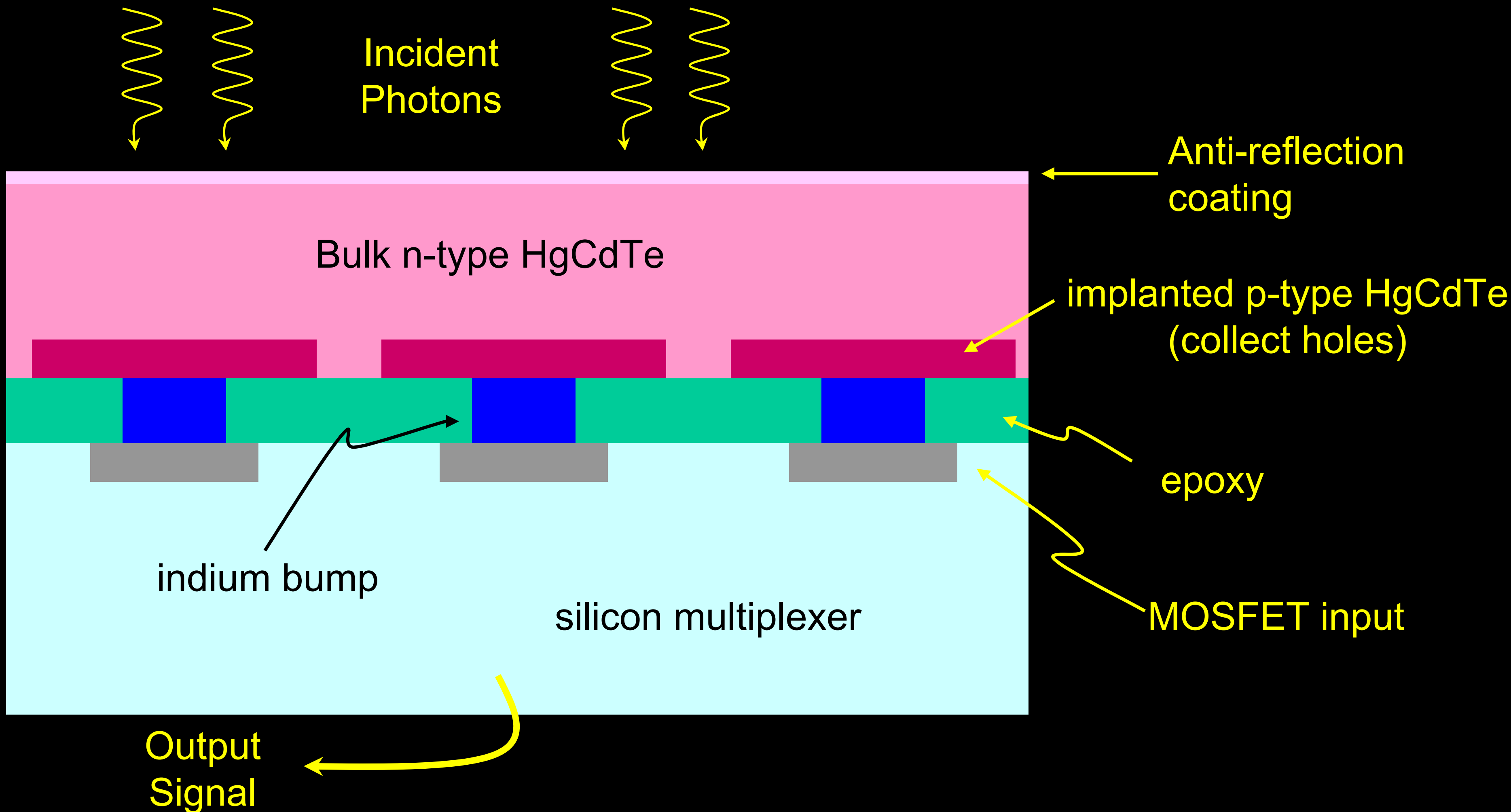
Launch from Satish Dhawan Space Centre



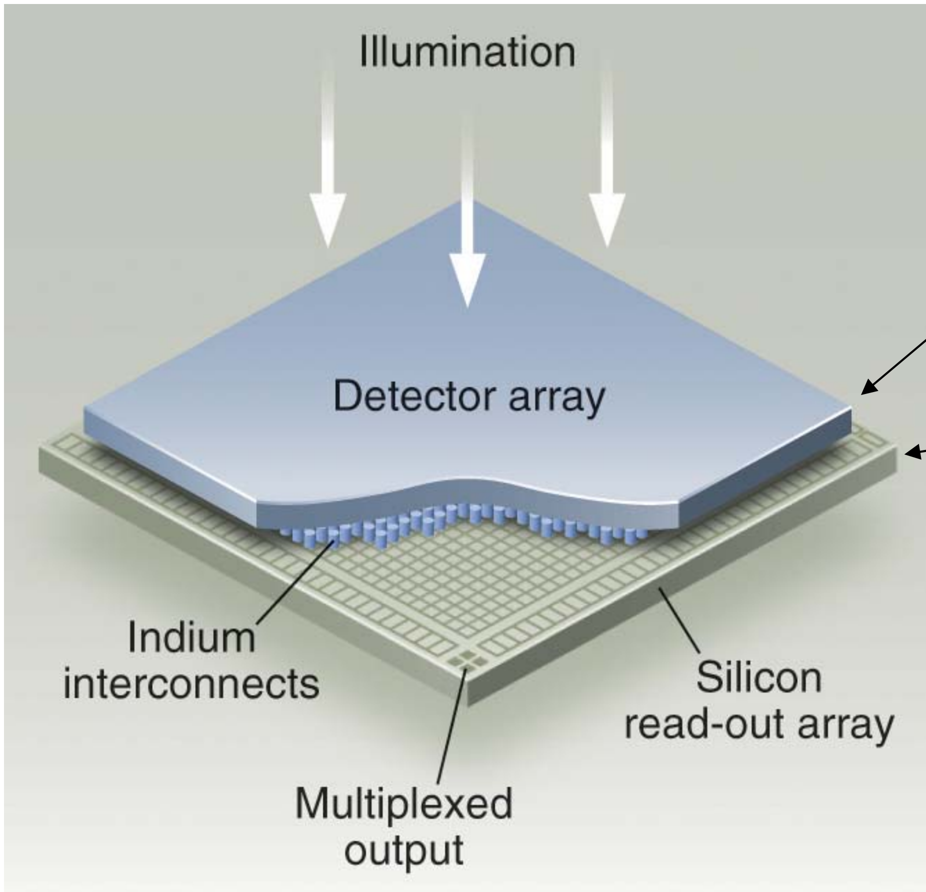
Moon Mineralogy Mapper resolves visible and infrared to 10 nm spectral resolution, 70 m spatial resolution
100 km altitude lunar orbit

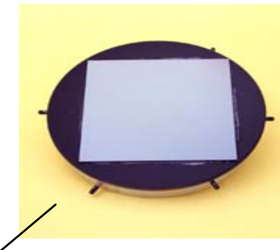
HgCdTe hybrid FPA cross-section

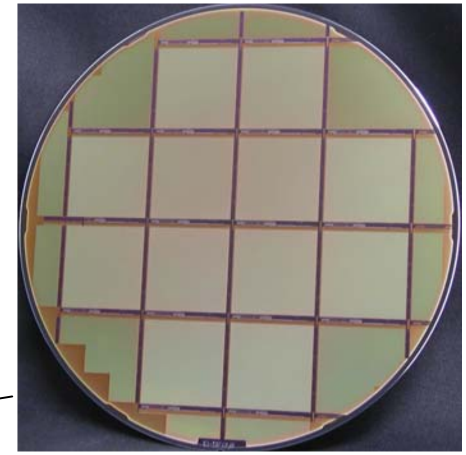
(substrate removed)



Hybrid CMOS Infrared Imaging Sensors







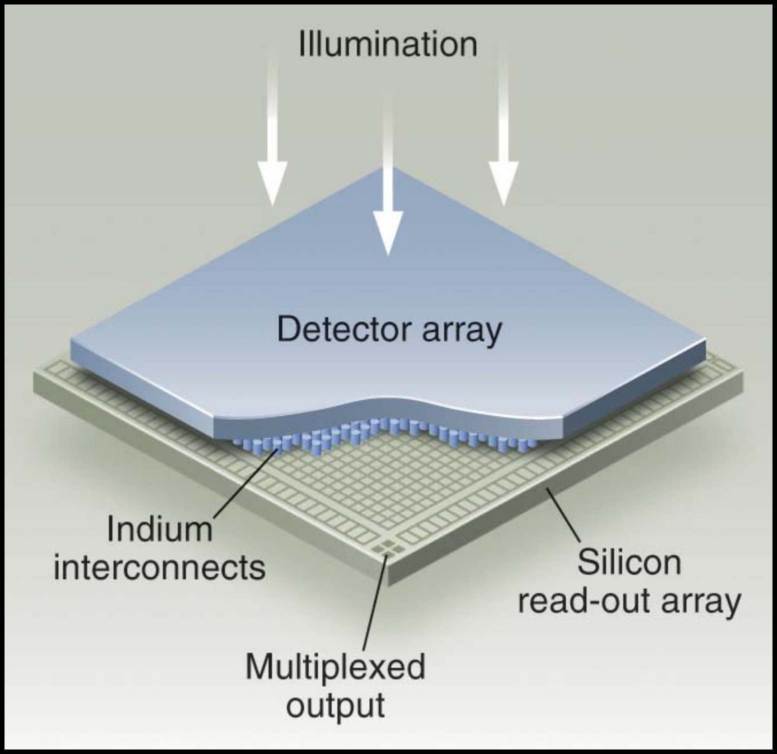
Large, high performance IR arrays

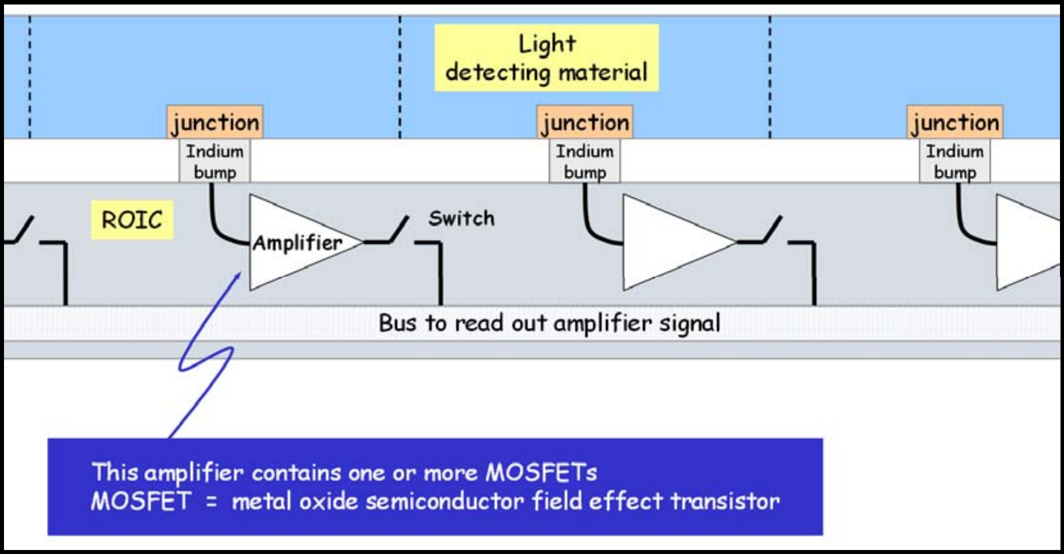
Three Key Technologies

1. Growth and processing of the HgCdTe detector layer
2. Design and fabrication of the CMOS readout integrated circuit (ROIC)
3. Hybridization of the detector layer to the CMOS ROIC

TELEDYNE IMAGING SENSORS
A Teledyne Technologies Company

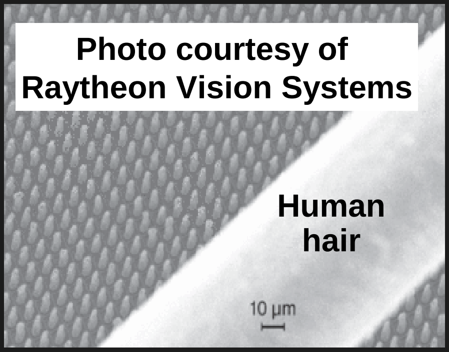
Hybrid Imager Architecture



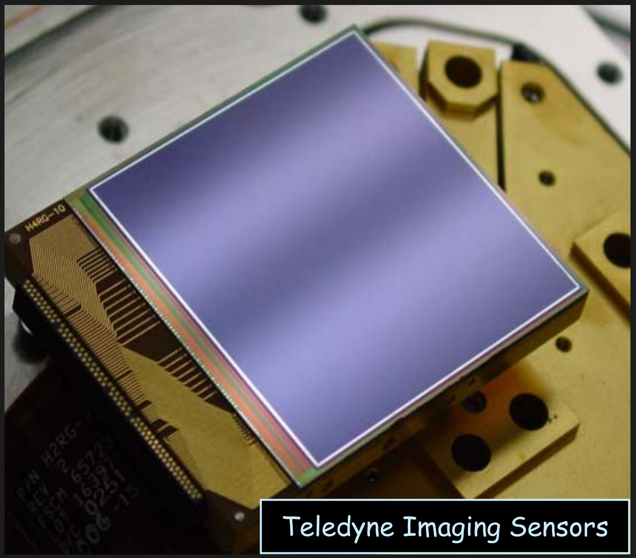


Mature interconnect technique:

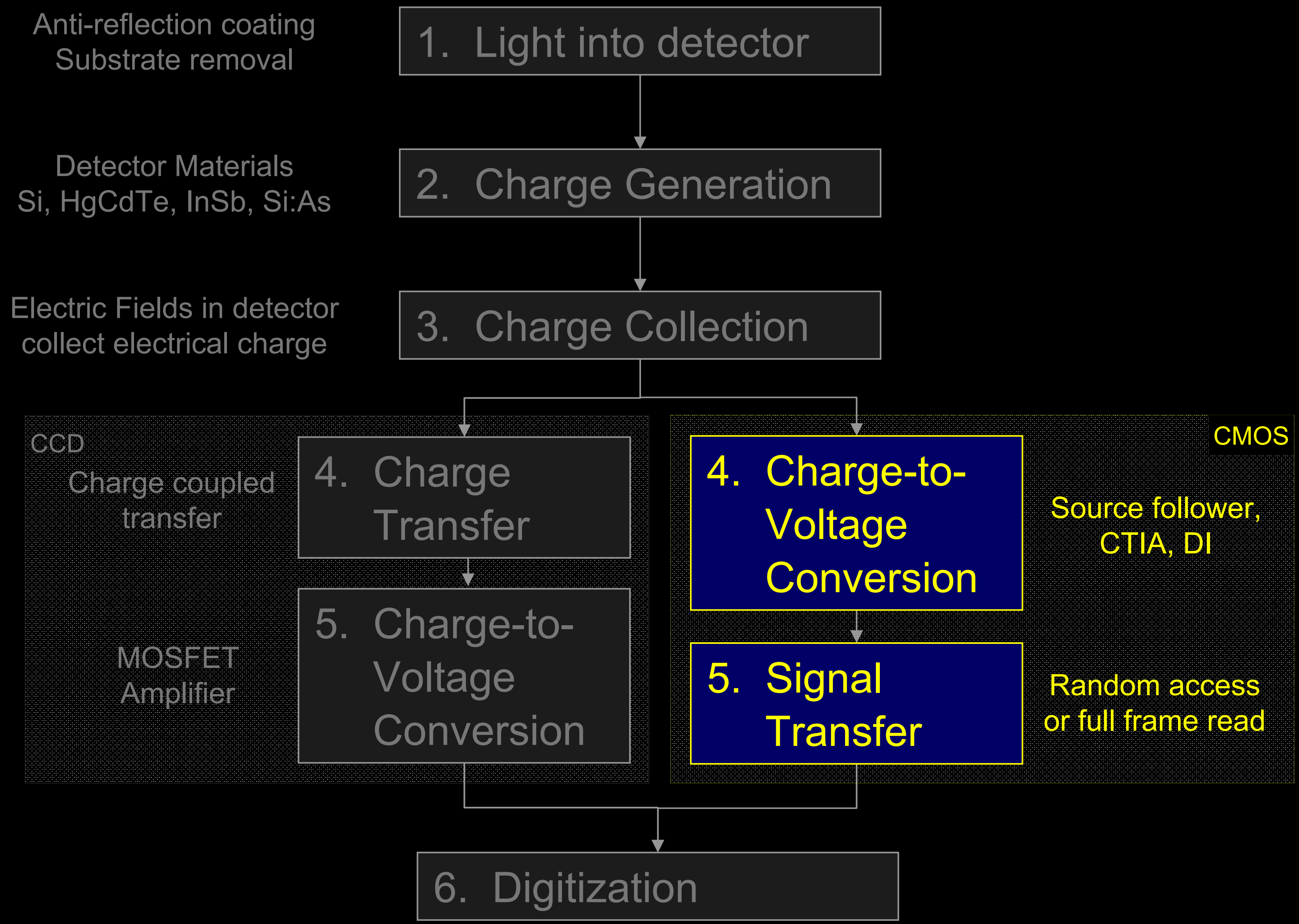
- Over 16,000,000 indium bumps per Sensor Chip Assembly (SCA) demonstrated
- >99.9% interconnect yield



H4RG-10
4096x4096 pixels
10 micron pixel pitch
HyViSI silicon PIN

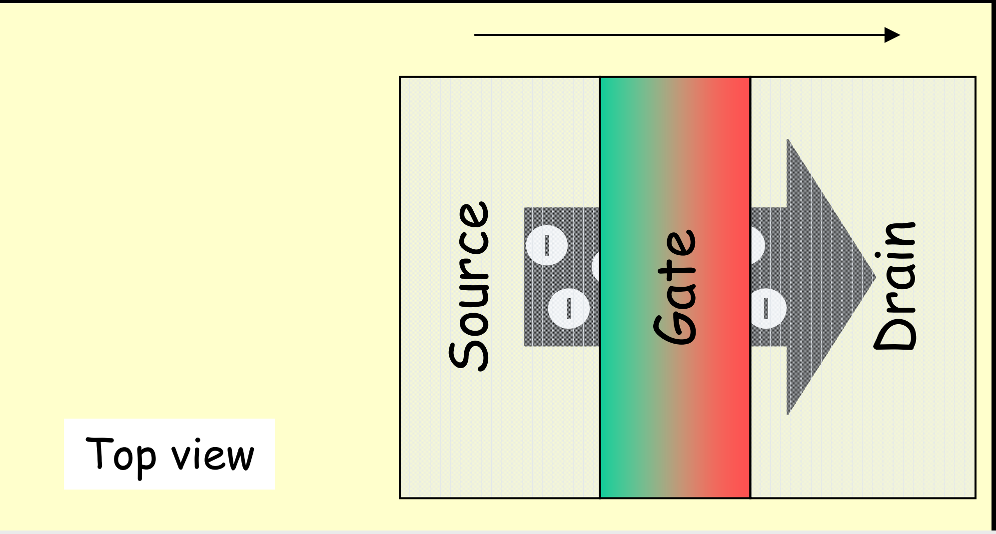


6 steps of optical / IR photon detection



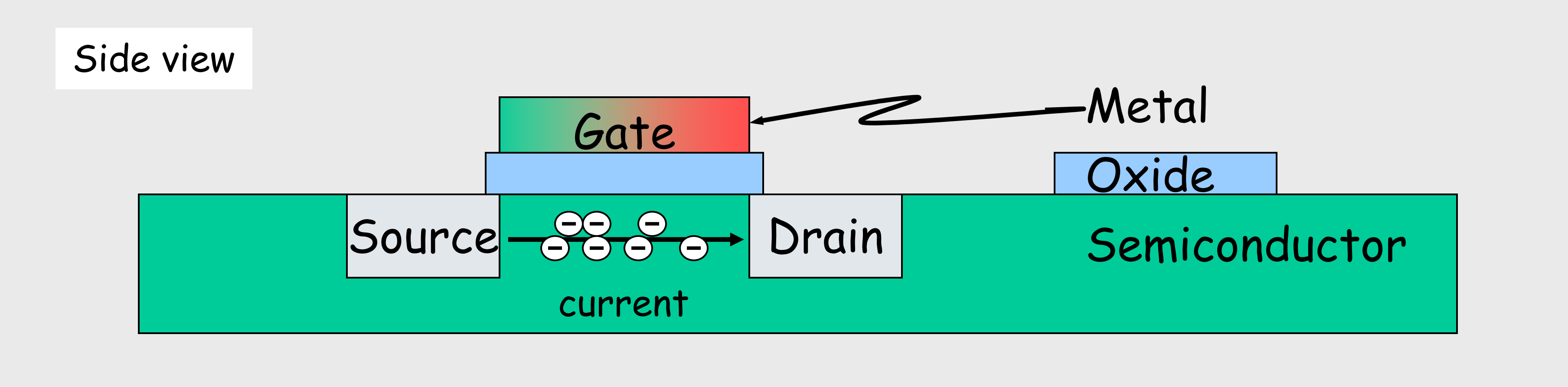
MOSFET Principles

MOSFET = metal oxide semiconductor field effect transistor



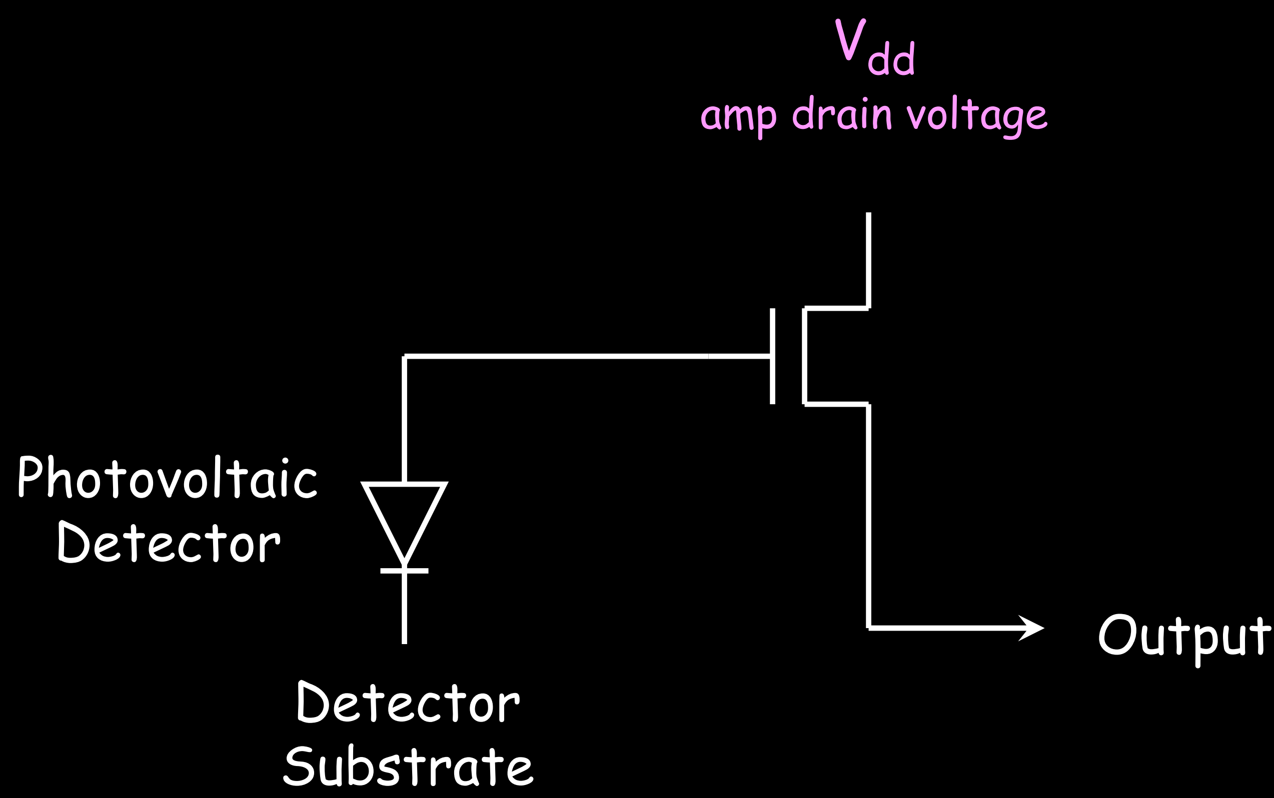
Turn on the MOSFET and current flows from source to drain

Add charge to gate & the current flow changes since the effect of the field of the charge will reduce the current

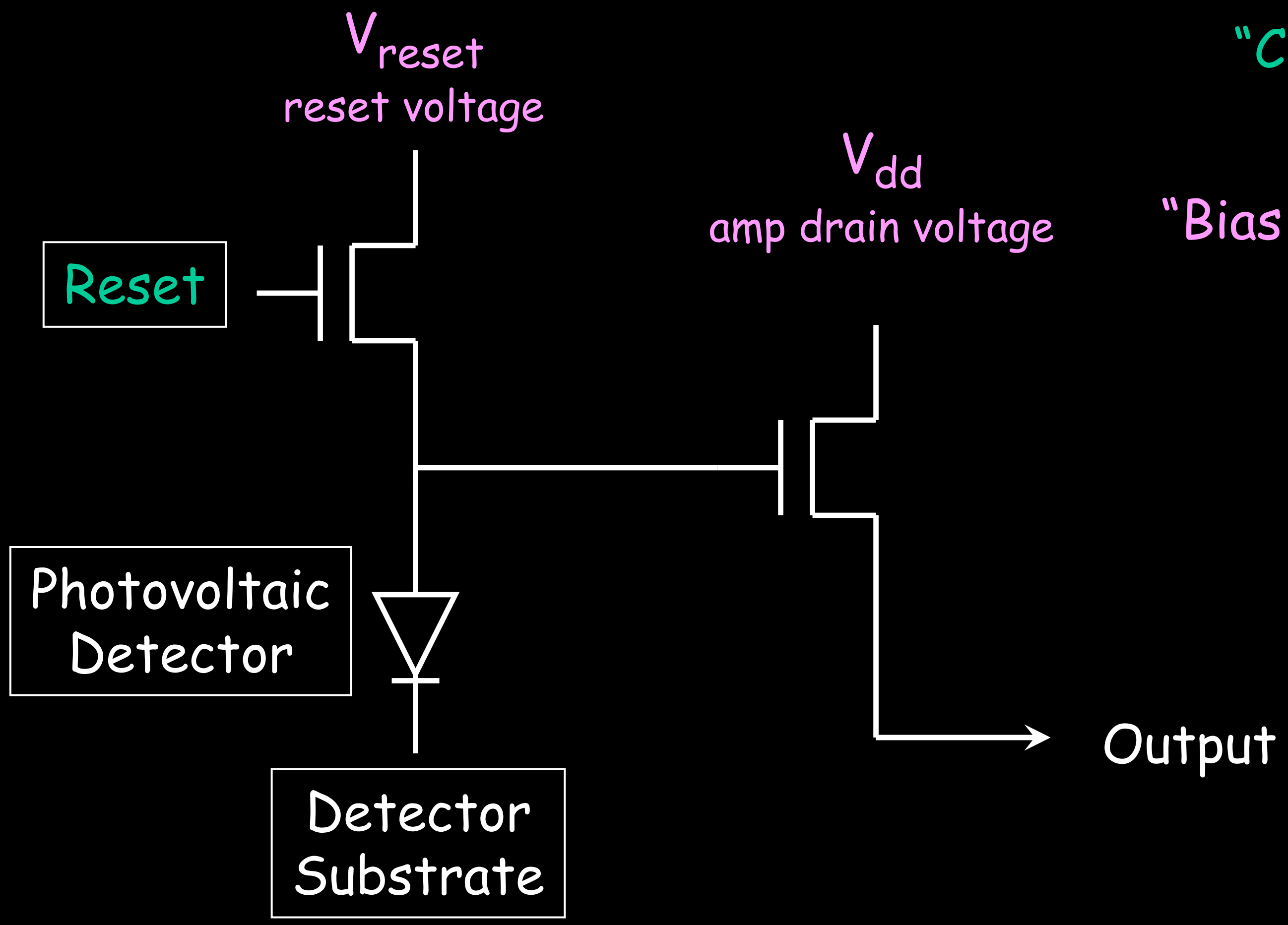


Fluctuations in current flow produce "readout noise"
Fluctuations in reset level on gate produces "reset noise"

IR multiplexer pixel architecture



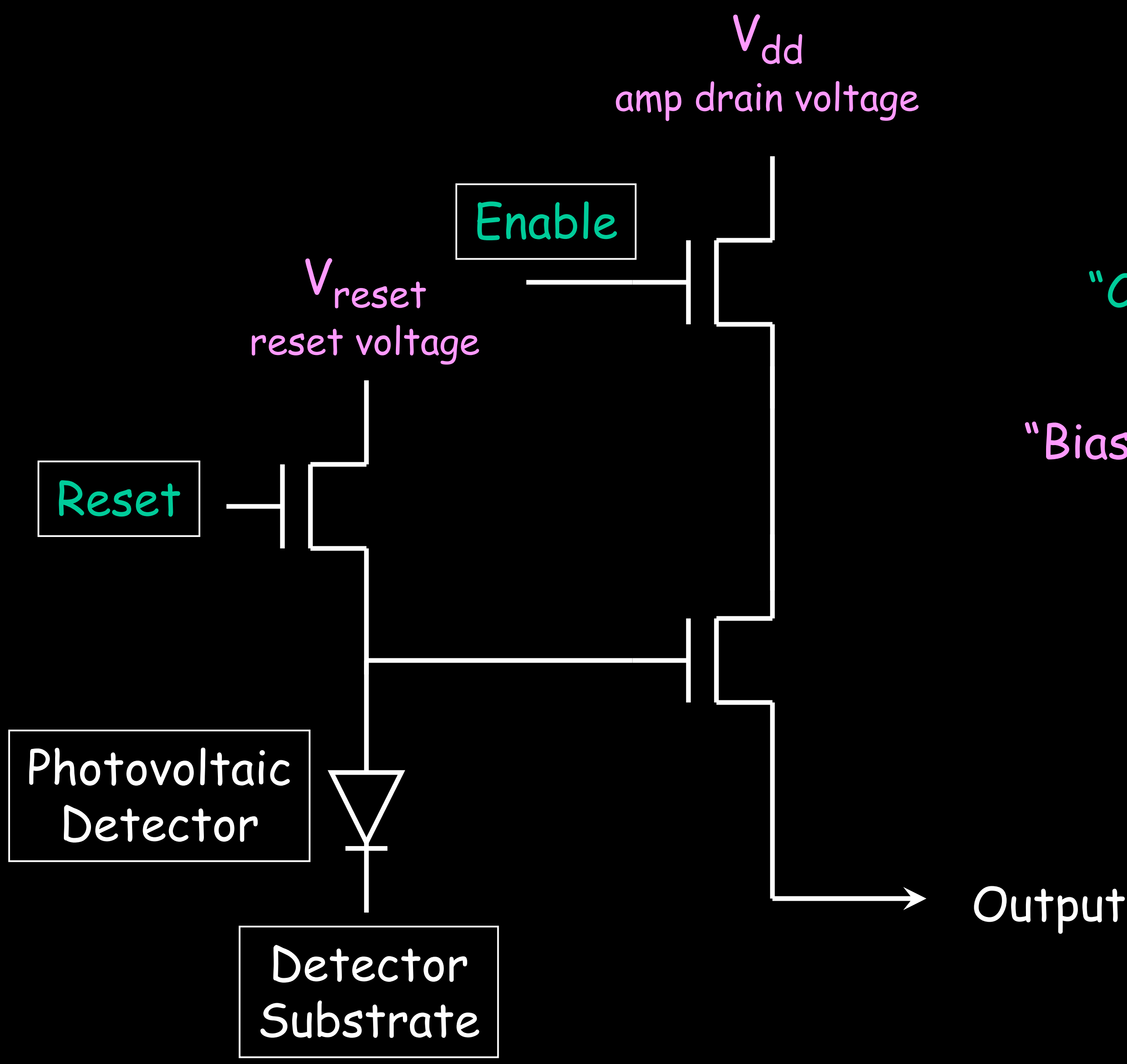
IR multiplexer pixel architecture



"Clock" (green)

"Bias voltage" (purple)

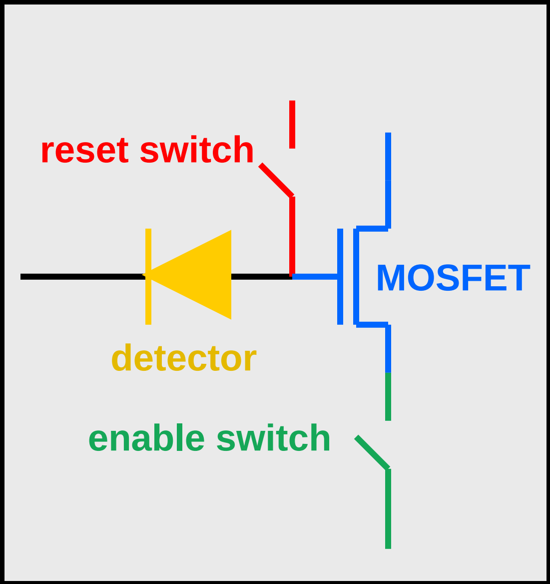
IR multiplexer pixel architecture



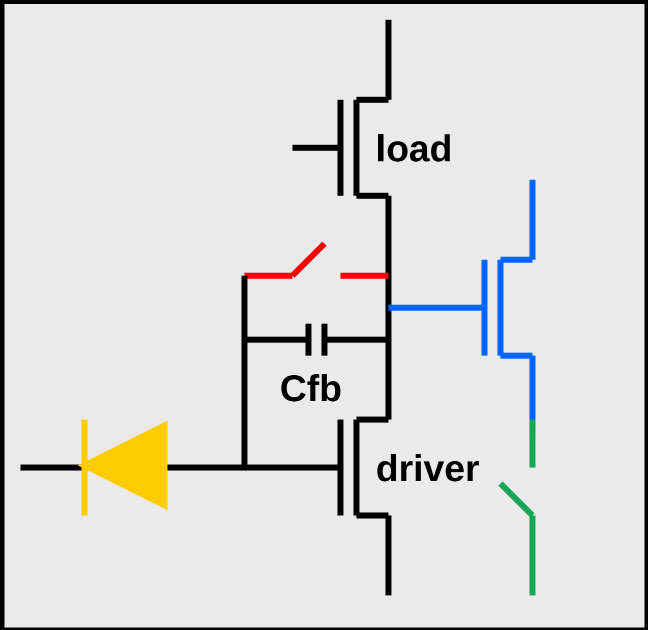
"Clock" (green)

"Bias voltage" (purple)

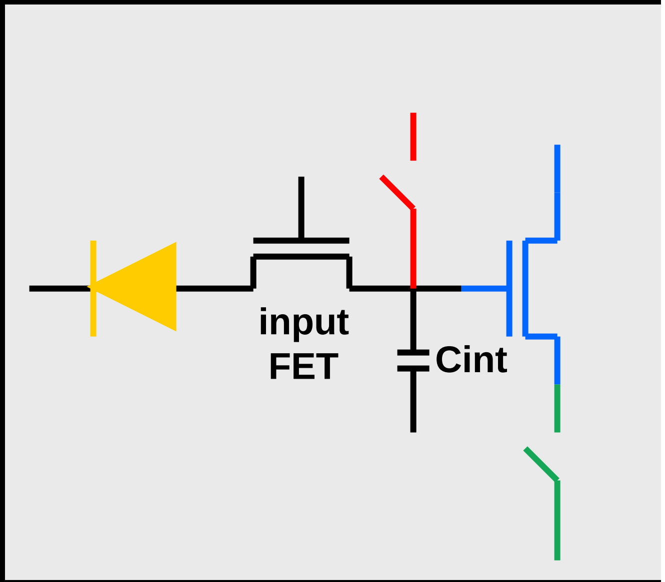
CMOS Pixel Amplifier Types



Source follower per Detector (SFD)



Capacitive TransImpedance Amplifier (CTIA)



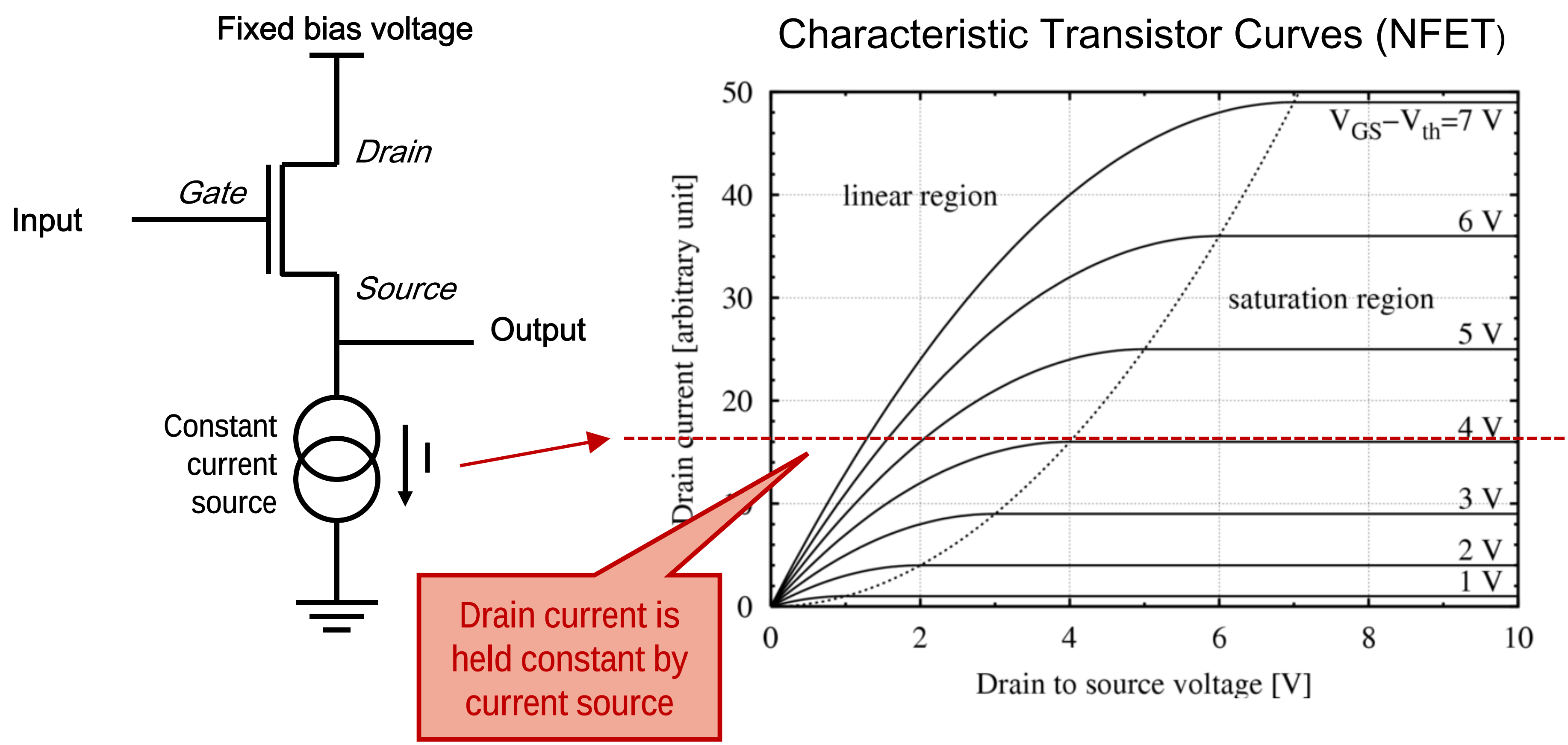
Direct Injection (DI)

- Integration on detector node
- Low power & compact
  (3 FETs / pixel)
- Ideal for small pixels and low flux
- Poor performance for high flux

- Versatile circuit suitable for all backgrounds and detectors
- High linearity
- High power, higher noise and larger circuit than SFD for low flux
- Difficult for high flux due to the need for a large capacitor and high operating current

- Extremely small circuit
- Large integration density in pixel
- High well capacity for high flux applications
- Ultra low power
- Poor injection efficiency for low flux applications

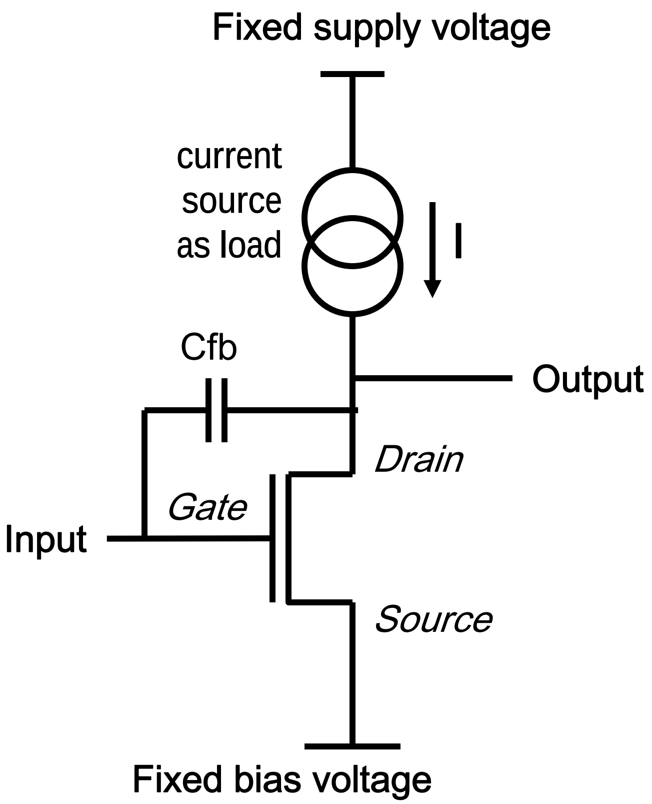
Source Follower Operation



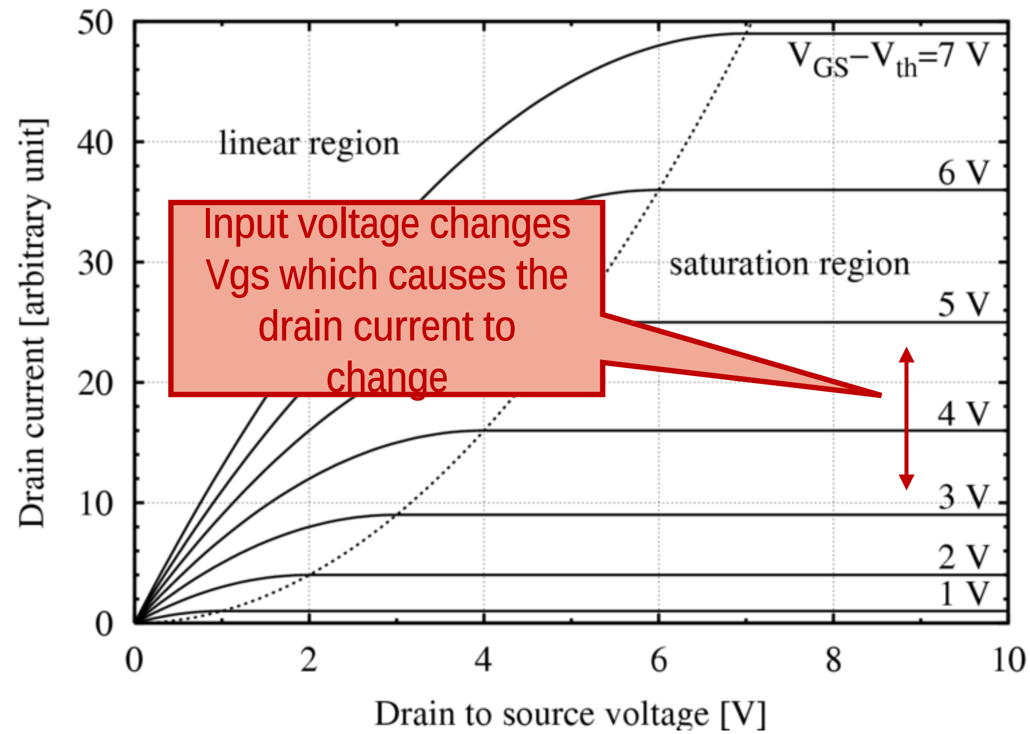
If the drain current is constant, the gate-source voltage (Vgs) is constant as long as the transistor operates in saturation:

=> If Vg moves, Vs will follow to keep Vgs constant

Capacitive Trans-Impedance Amplifier Operation



Characteristic Transistor Curves (NFET)



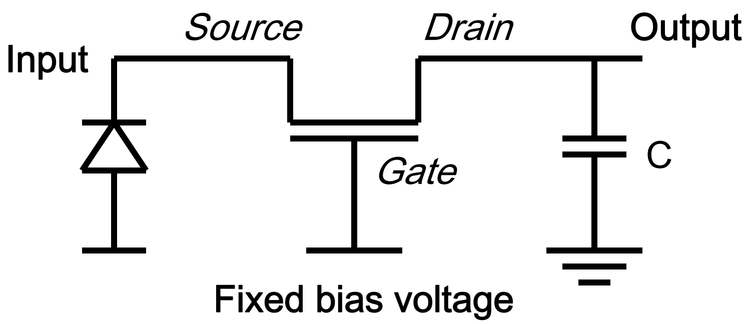
Inverting amplifier:

When the input increases, the drain current increases => The output node is pulled down by the transistor
When the input decreases, the drain current decreases => The output node is pulled up by the current source

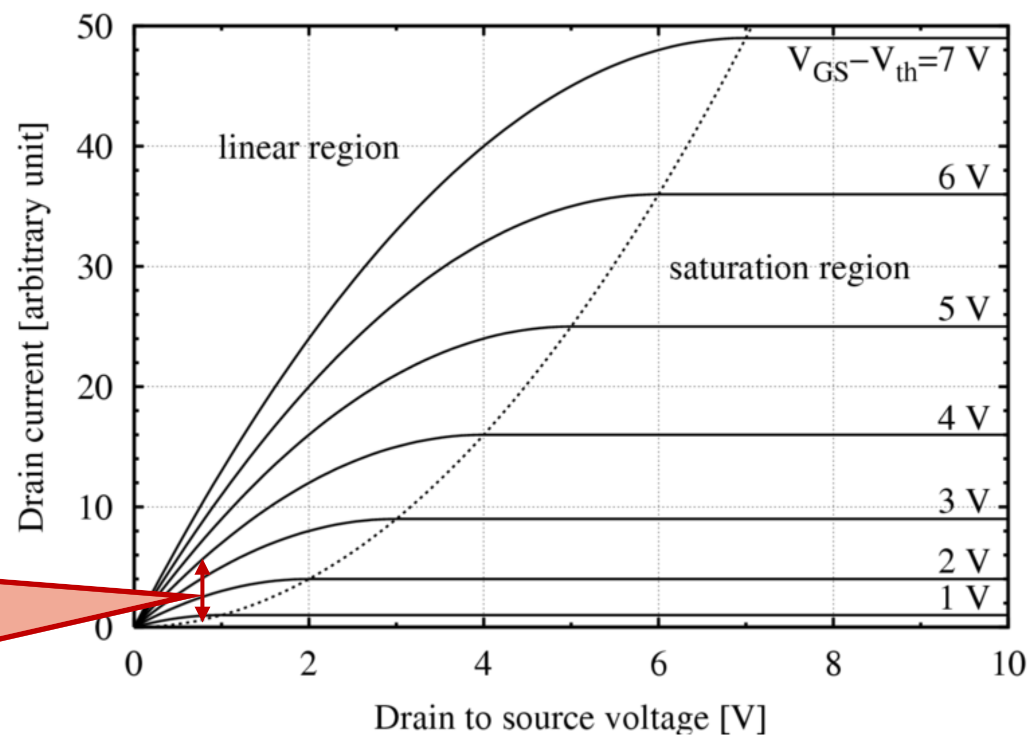
Capacitive feedback:

negative feedback that counteracts the initial input voltage change
=> charge at the input is converted to a voltage at the output, the input voltage is held constant by the feedback.

Direct Injection Operation



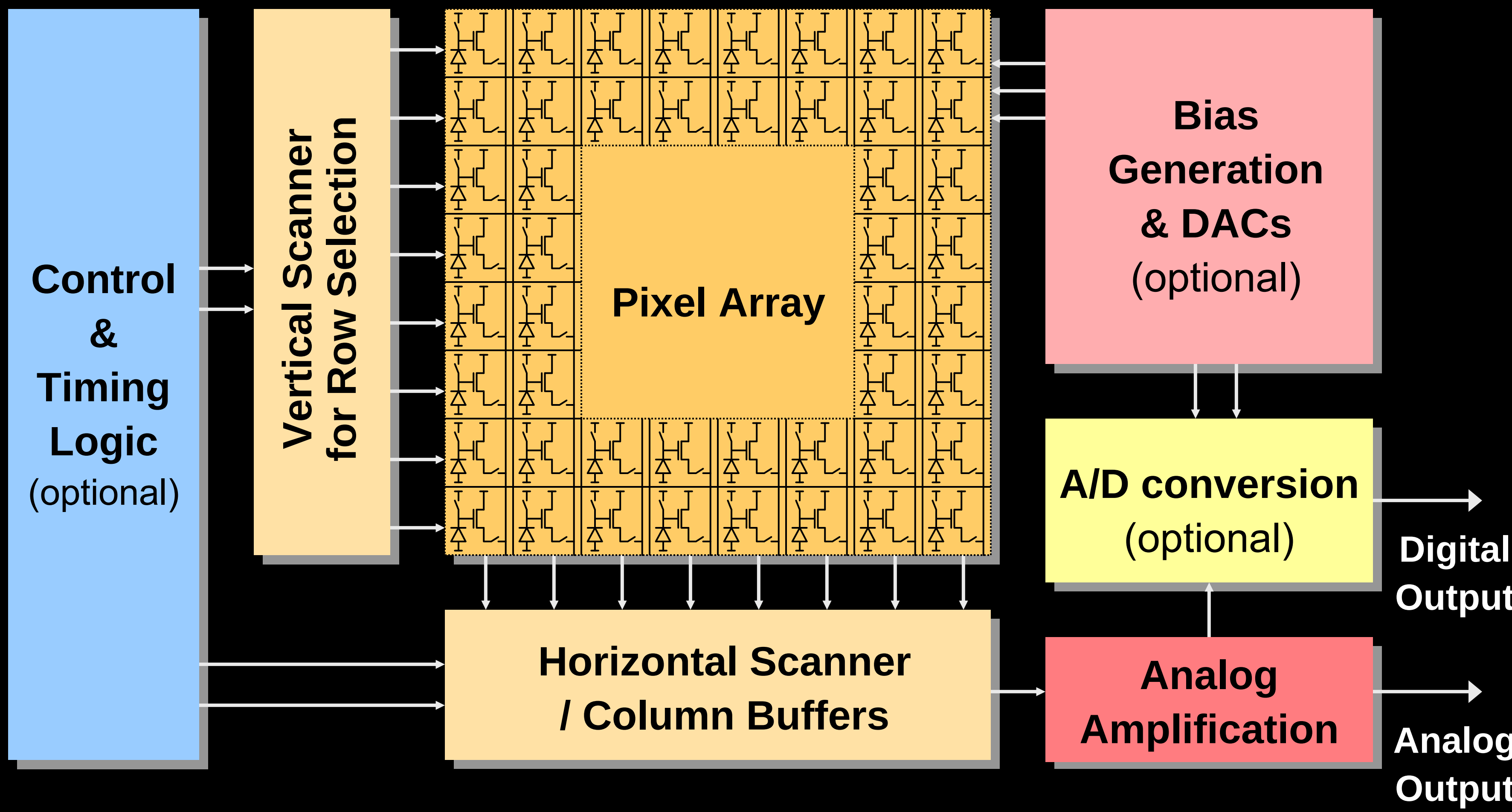
Characteristic Transistor Curves (NFET)



Decrease of input voltage (source) increases Vgs which increases the drain current.
Usually operates in subthreshold region (small currents)

- DI transistor does not work as amplifier, works more like a passgate
  - Whenever the detector diode generates photo charges, its voltage decreases (due to built-in capacitance)
  - This will increase Vgs which in turn will allow an increased drain current through the transistor
  - This current moves the collected charges from the photodiode into the integration capacitor C
  - Removing charges from the detector increases its voltage again, causing the drain current to decrease

General Architecture of CMOS-Based Image Sensors

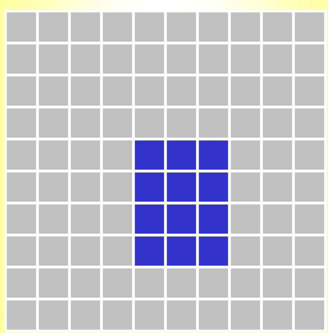


Special Scanning Techniques Supported by CMOS

- **Different scanning methods are available to reduce the number of pixels being read:**
  - **Allows for higher frame rate or lower pixel rate (reduction in noise)**
  - **Can reduce power consumption due to reduced data**

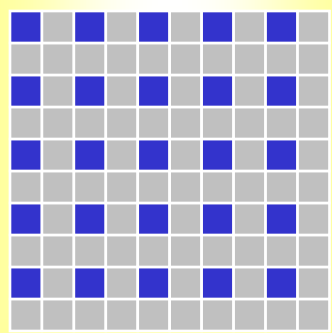
Windowing

- Reading of one or multiple rectangular subwindows
- Used to achieve higher frame rates (e.g. AO, guiding)



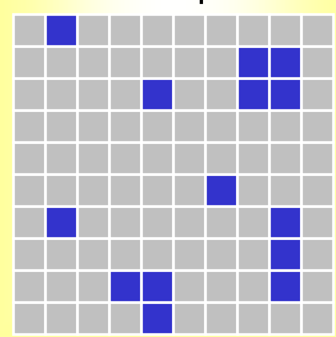
Subsampling

- Skipping of certain pixels/rows when reading the array
- Used to obtain higher frame rates on full-field images



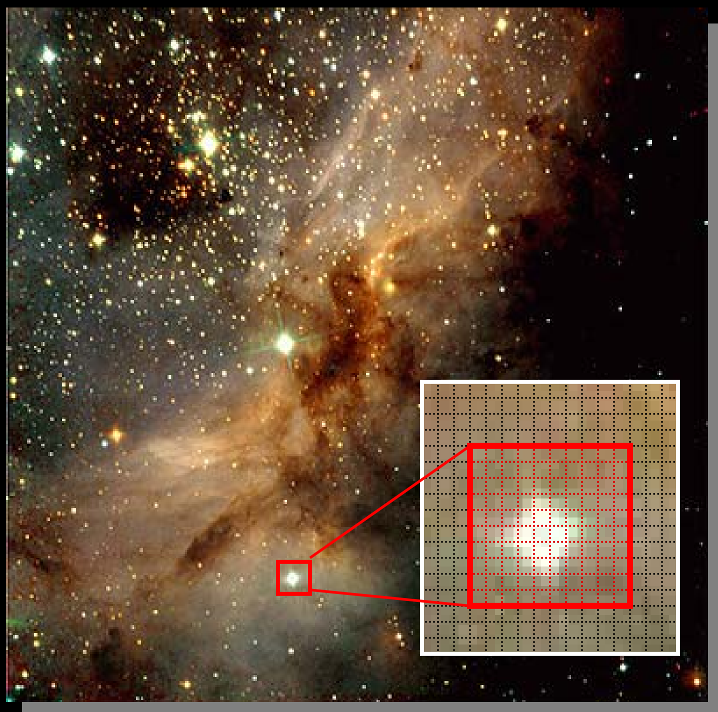
Random Read

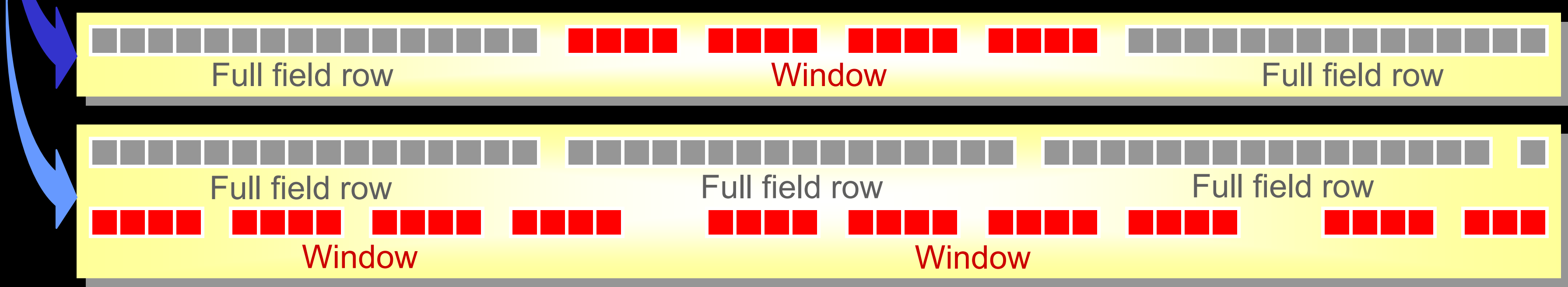
- Random access (read or reset) of certain pixels
- Selective reset of saturated pixels
- Fast reads of selected pixels



Astronomy Application: Guiding

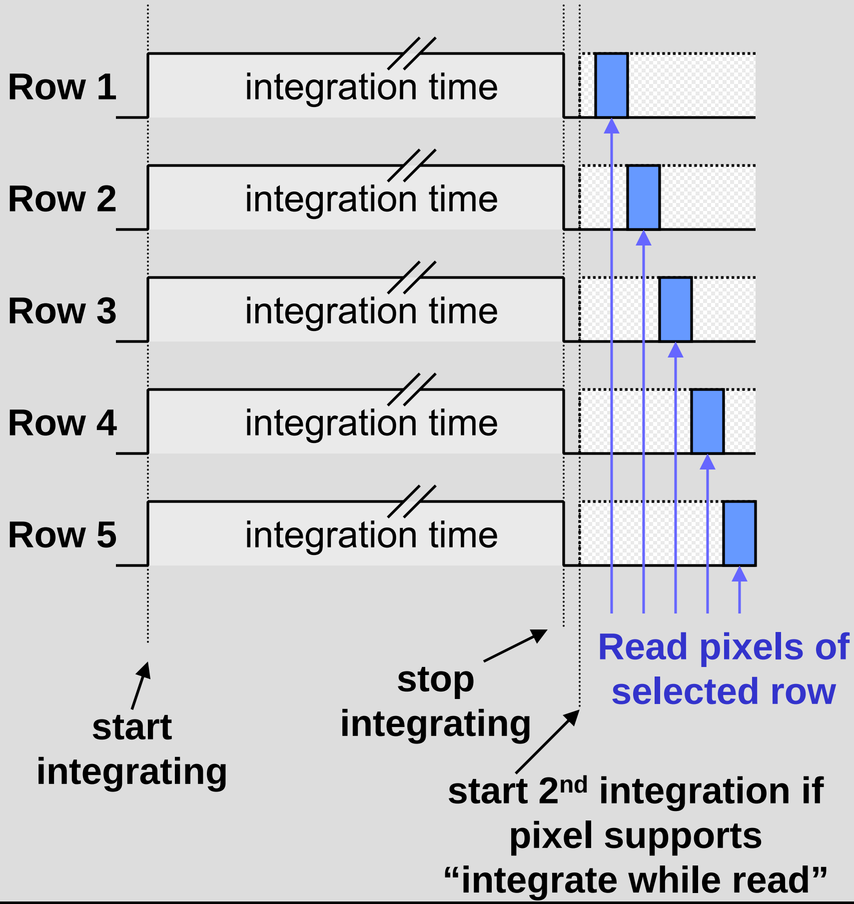
- **Special windowing can be used to perform full-field science integration in parallel with fast window reads.**
  - ⇒ **Simultaneous guide operation and science data capture within the same detector.**
- **Two methods possible:**
  - **Interleaved reading of full-field and window**
    - **No scanning restrictions or crosstalk issues**
    - **Overhead reduces full-field frame rate**
  - **Parallel reading of full-field and window**
    - **Requires additional output channel**
    - **Parallel read may cause crosstalk or conflict**
    - **No overhead ⇒ maintains maximum full-field frame rate**

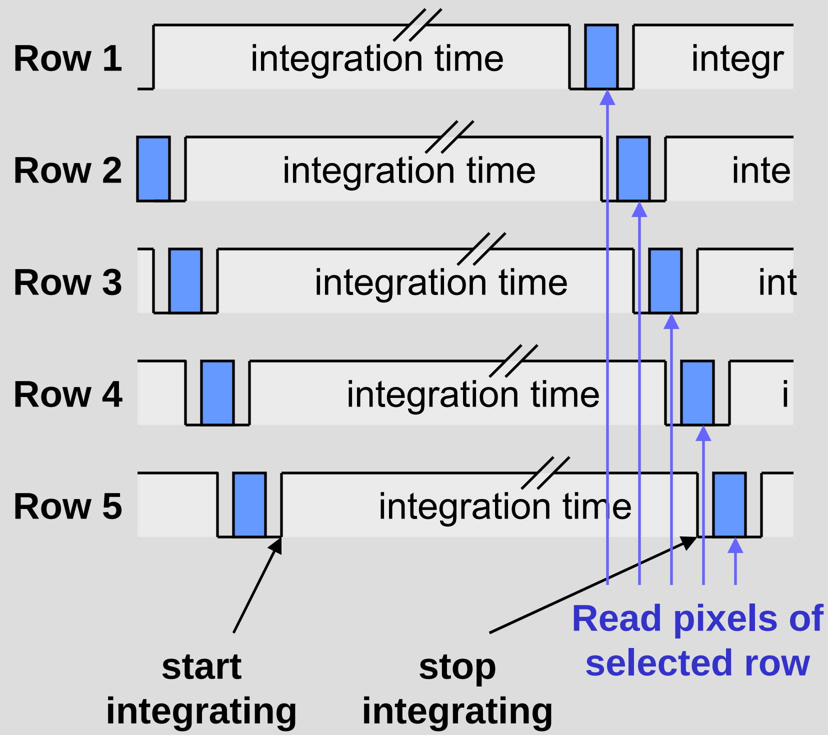




Electronic Shutter: Snapshot vs. Rolling Shutter

- **Snapshot Shutter**
  - **All rows are integrating at the same time.**
  - **Typically more transistors per pixel and higher noise.**
- **Rolling Shutter (Ripple Read)**
  - **Each row starts and stops integrating at a different time (progressively).**
  - **Typically less transistors per pixel and lower noise.**



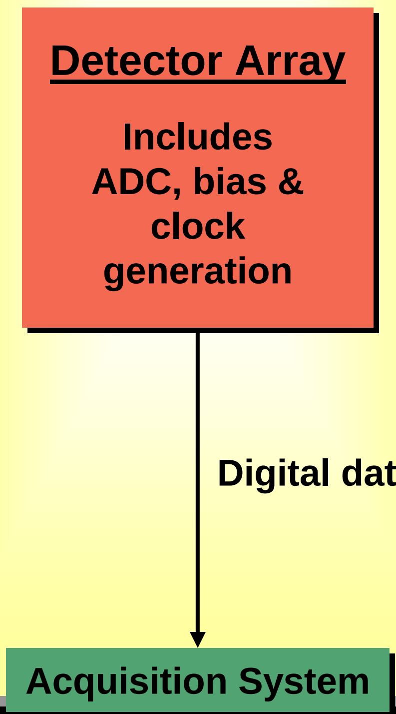


CMOS-Based Detector Systems

- Three possible CMOS Detector Electronics Configurations

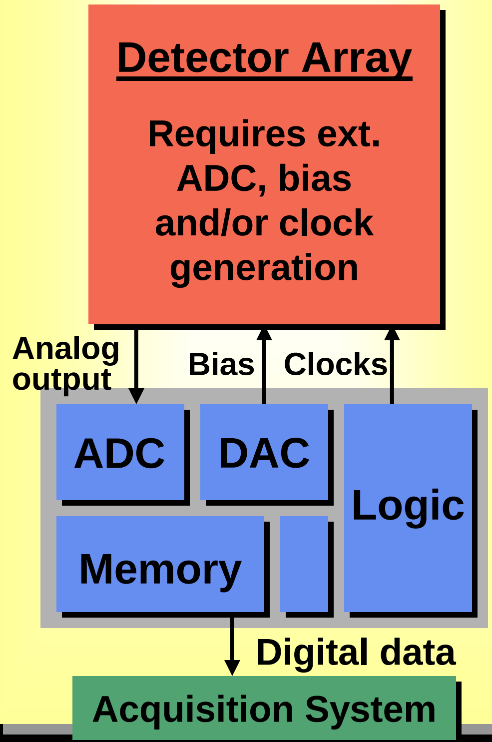
Single Chip

- All electronics integrated in sensor chip
- Small, low system power
- Not always desirable (high design effort, glow)



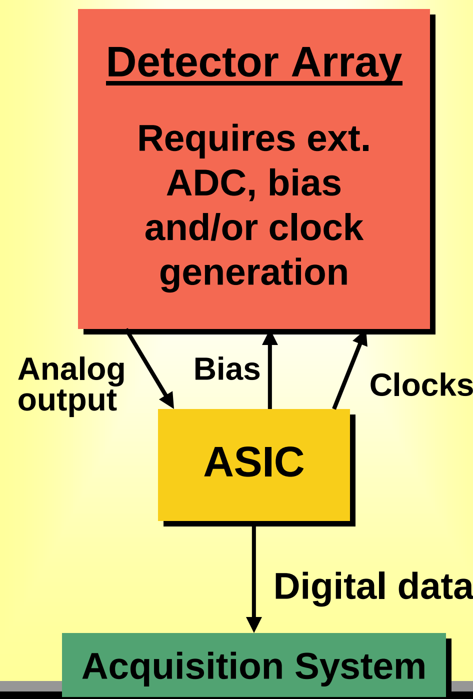
Discrete Electronics

- Assembly of discrete chips and boards
- Large, higher power
- Reusable, modular, only PCB design required



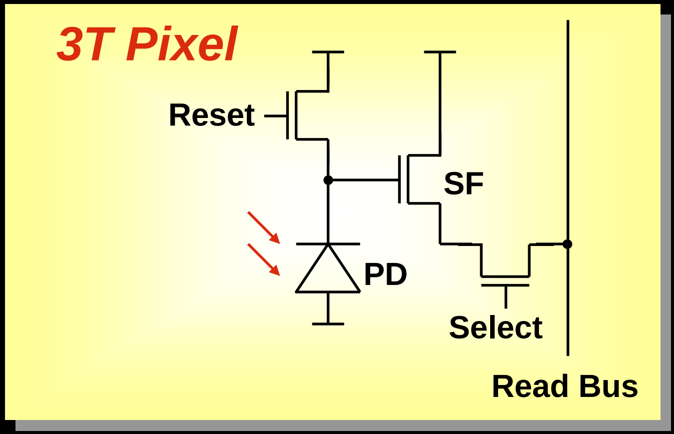
Dual Chip

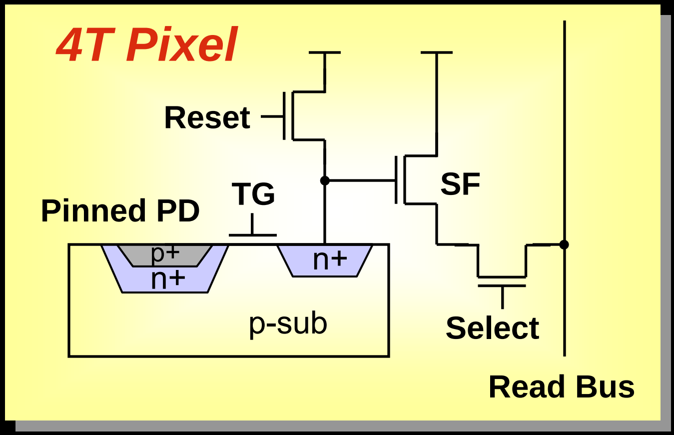
- All electronics integrated in a single companion chip
- Small, low system power
- Can be placed next to detector => low noise

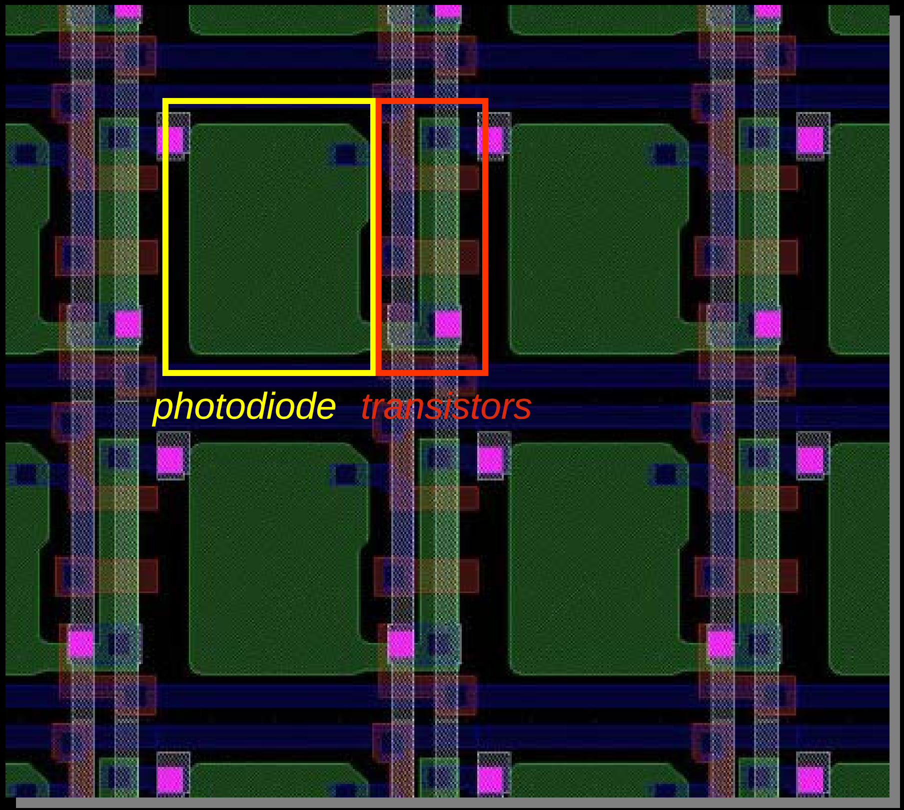


Monolithic CMOS

- A monolithic CMOS image sensor combines the photodiode and the readout circuitry in one piece of silicon
  - Photodiode and transistors share the area => less than 100% fill factor
  - Small pixels and large arrays can be produced at low cost => consumer applications (digital cameras, cell phones, etc.)

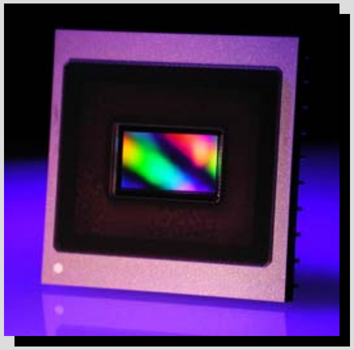




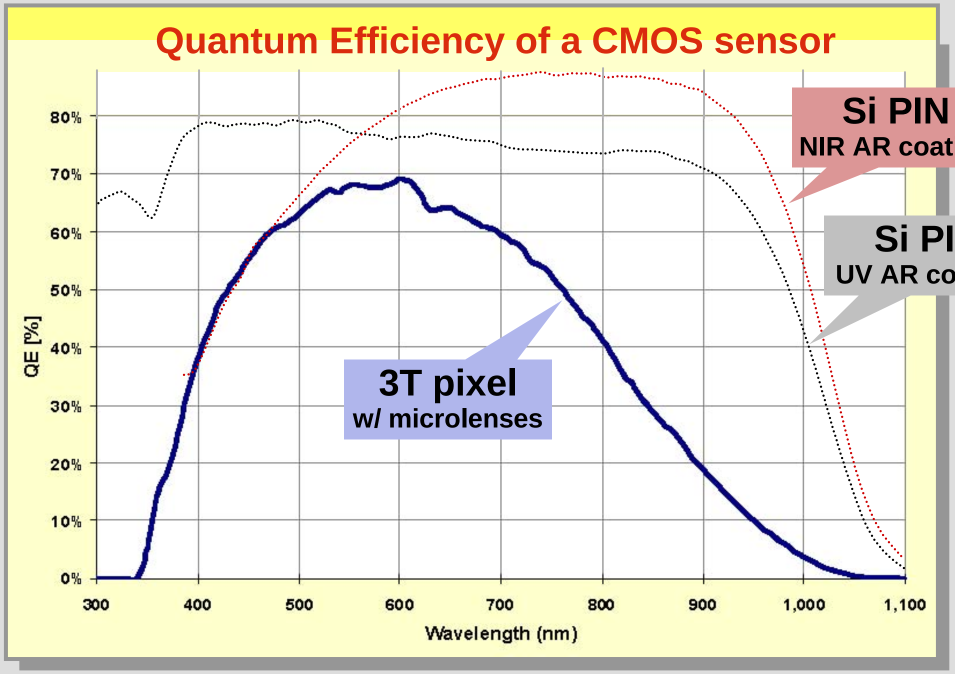


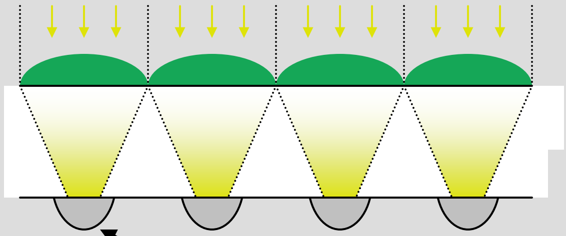
Complete Imaging Systems-on-a-Chip

- **Monolithic CMOS technology has enabled highly integrated, complete imaging systems-on-a-chip:**
  - **Single chip cameras for video and digital still photography**
  - **Performance has significantly improved over last decade and is better or comparable to CCDs for many applications.**
  - **Especially suited for high frame rate sensors (> Gigapixel/s) or other special features (windowing, high dynamic range, etc.)**
- **However, monolithic CMOS is still limited with respect to quantum efficiency:**
  - **Photodiode is relatively shallow => low red response**
  - **Metal and dielectric layers on top of the diode absorb or reflect light => low overall QE**
  - **Backside illumination possible, but requires modification of CMOS process**
- **Microlenses increase fill factor:**

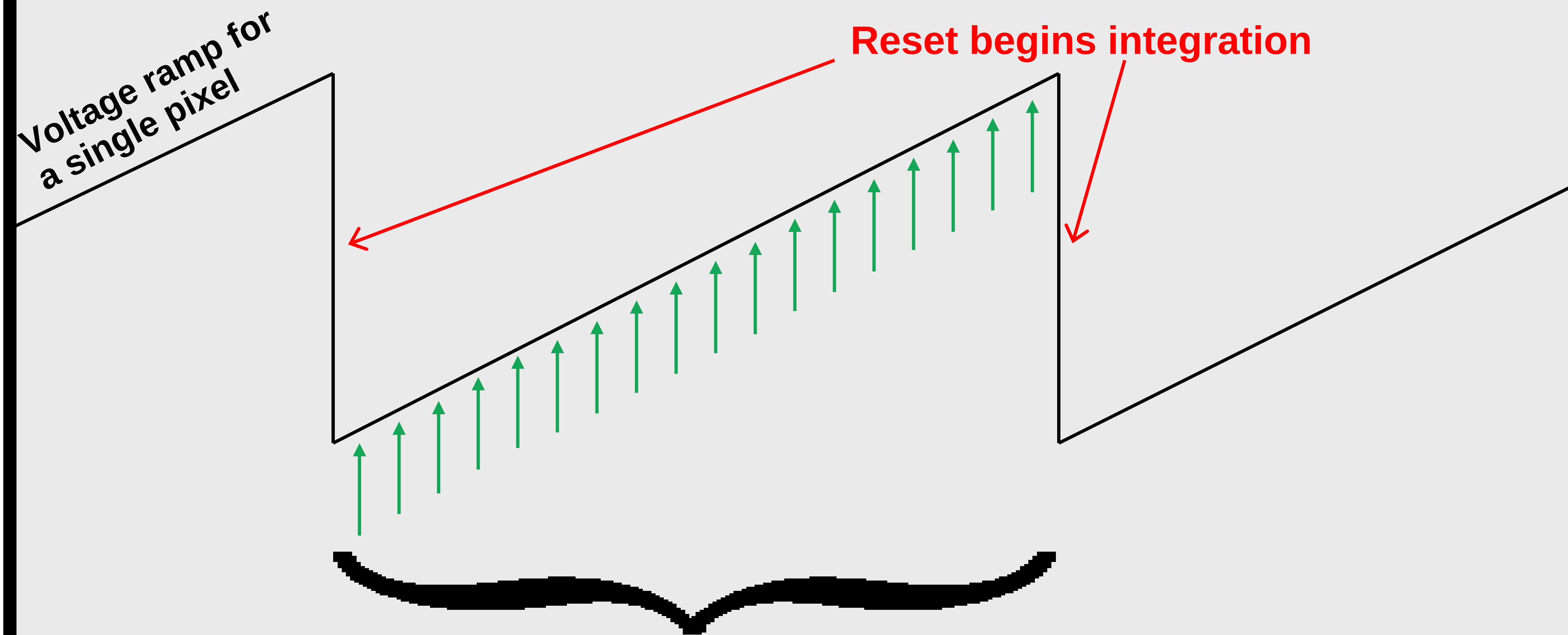


2 Mpixel HDTV CMOS Sensor





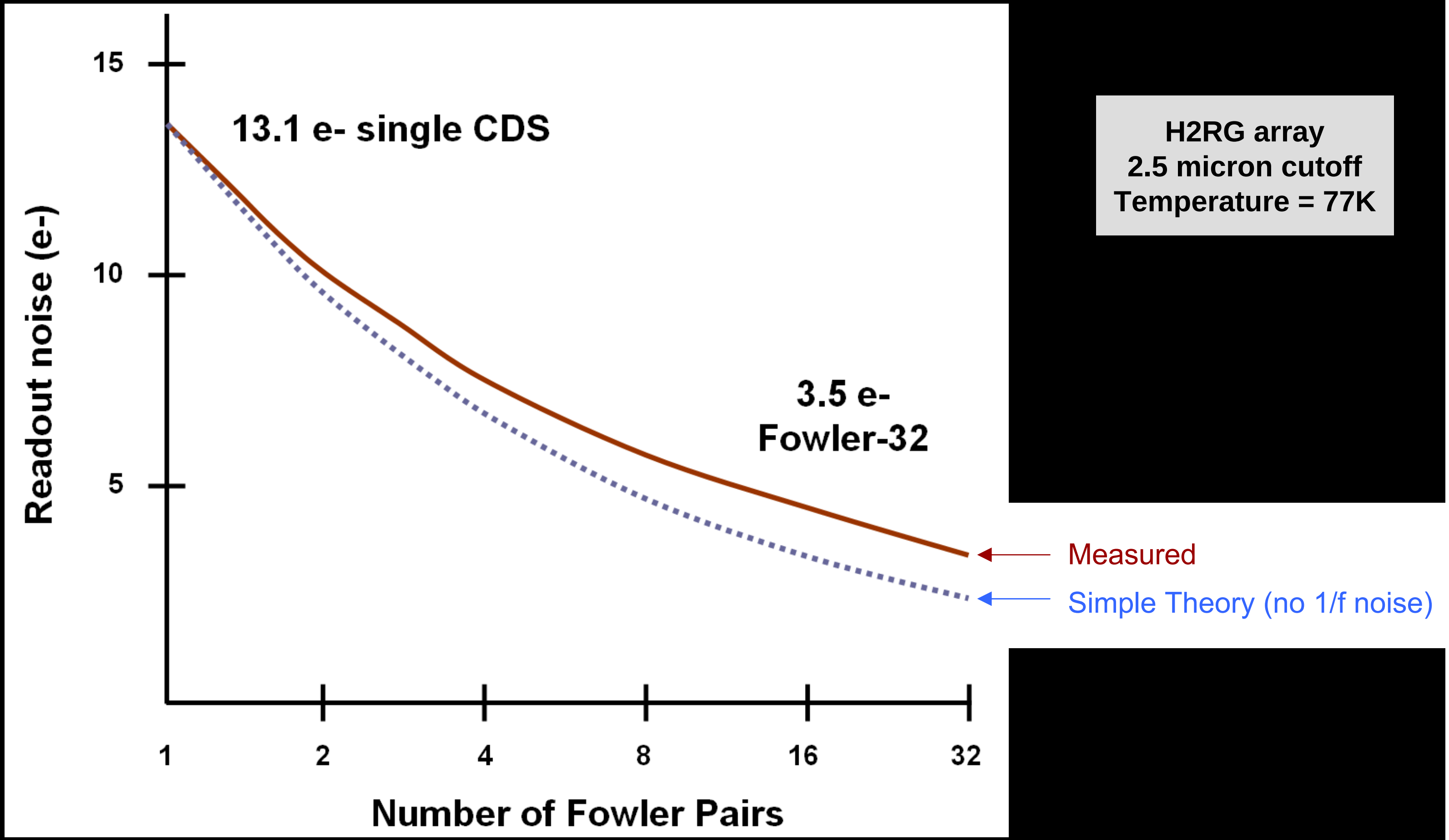
CMOS SCA Sampling Techniques



- Periodic sampling of detector signal possible during a long integration
- Two general methods of white noise reduction by multiple sampling
  - Fowler sampling: average 1st N samples and last N samples; then subtract
  - Sample up the ramp (SUTR): fit line (or polynomial) to all samples

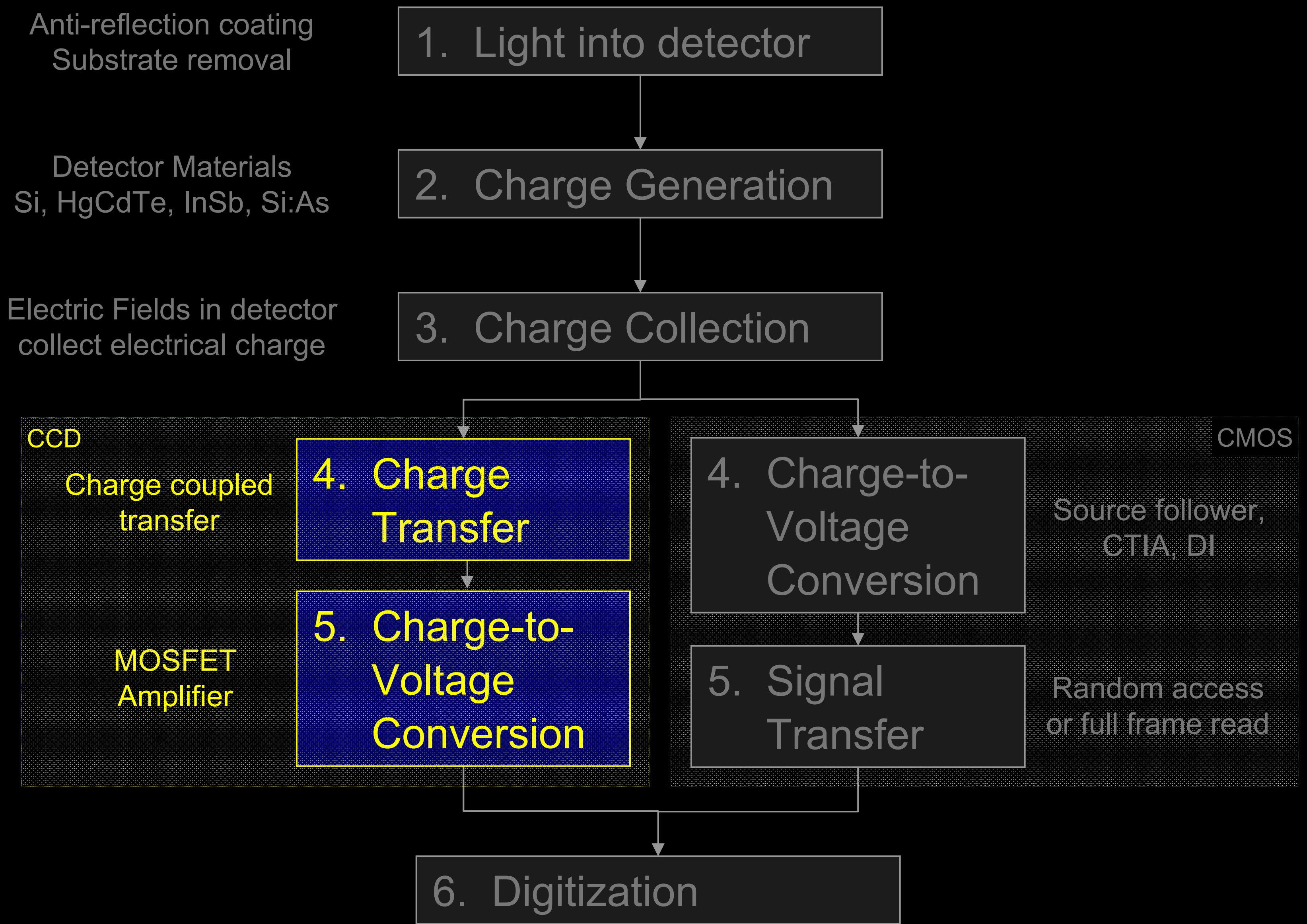
Example of Noise vs Number of Fowler Samples

Non-destructive readout enables reduction of noise from multiple samples

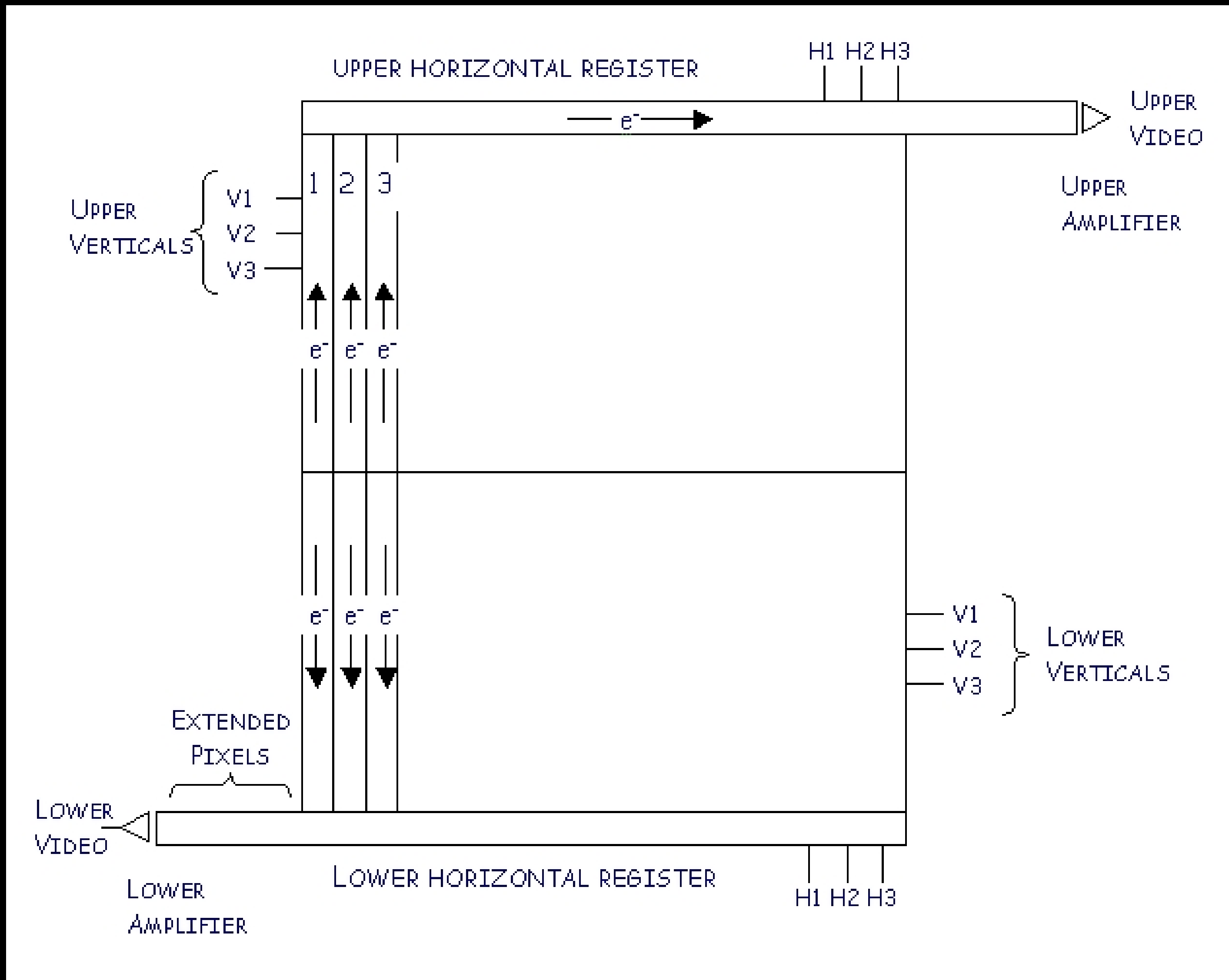


H2RG array
2.5 micron cutoff
Temperature = 77K

6 steps of optical / IR photon detection

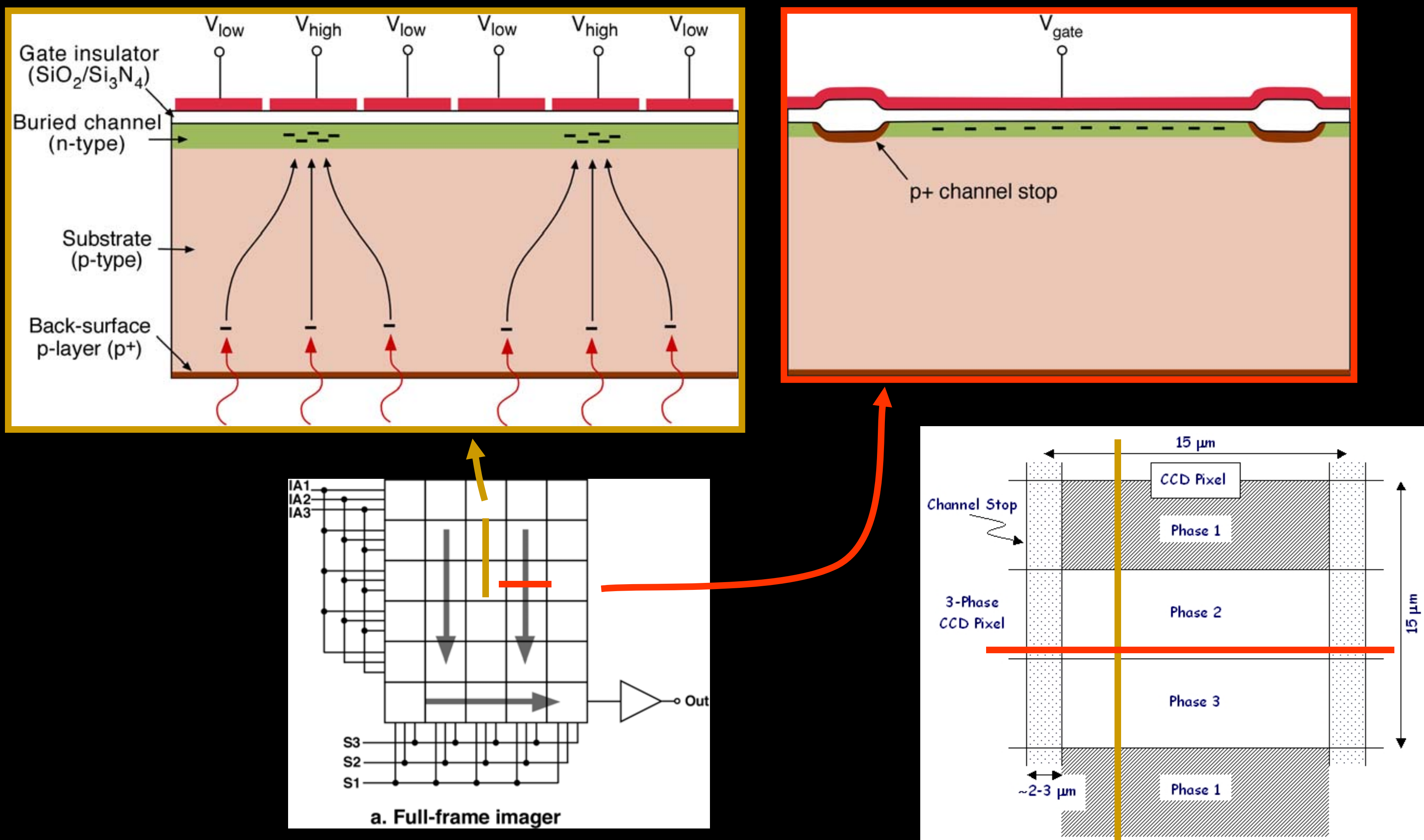


CCD Architecture



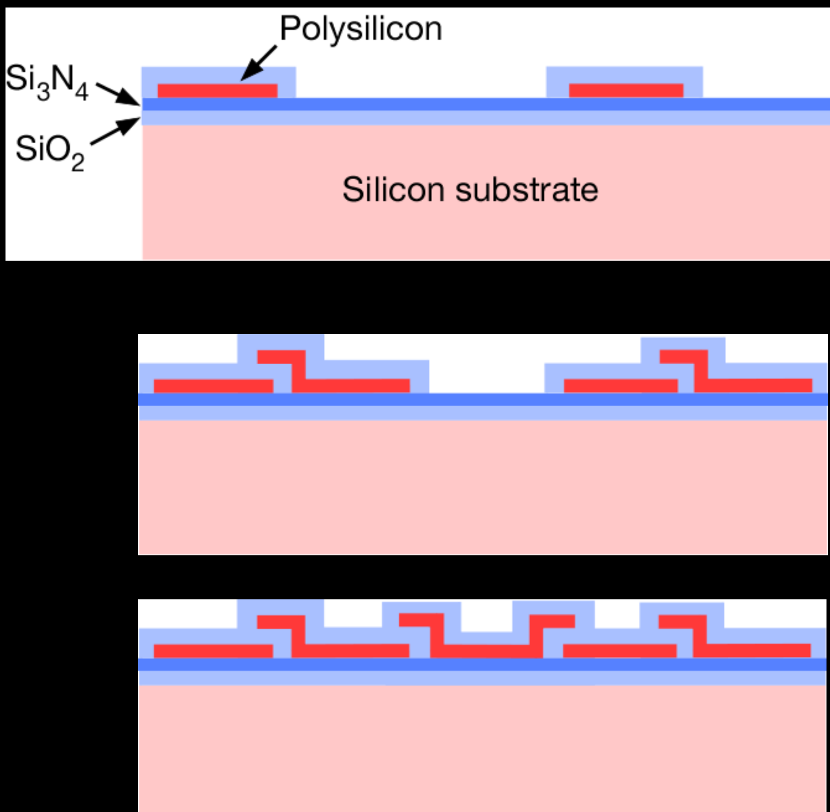
Basic CCD Structure

View along charge-transfer direction | **View across CCD channel**

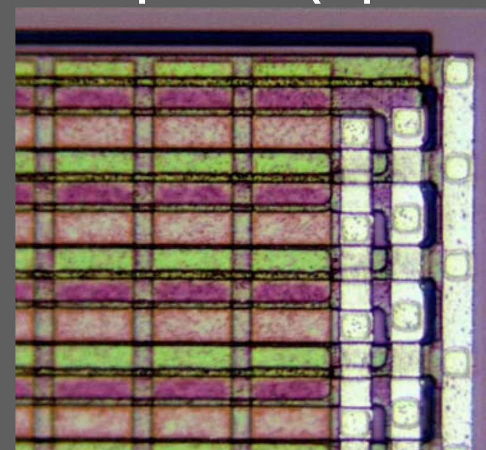


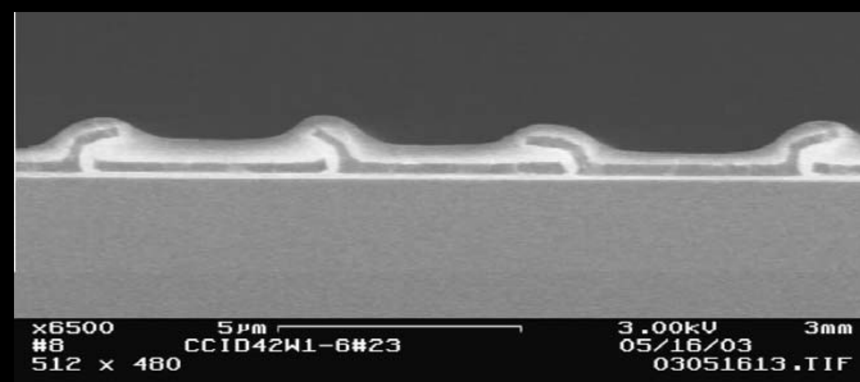
Basic CCD Manufacturing Process

Process: three phase, triple poly



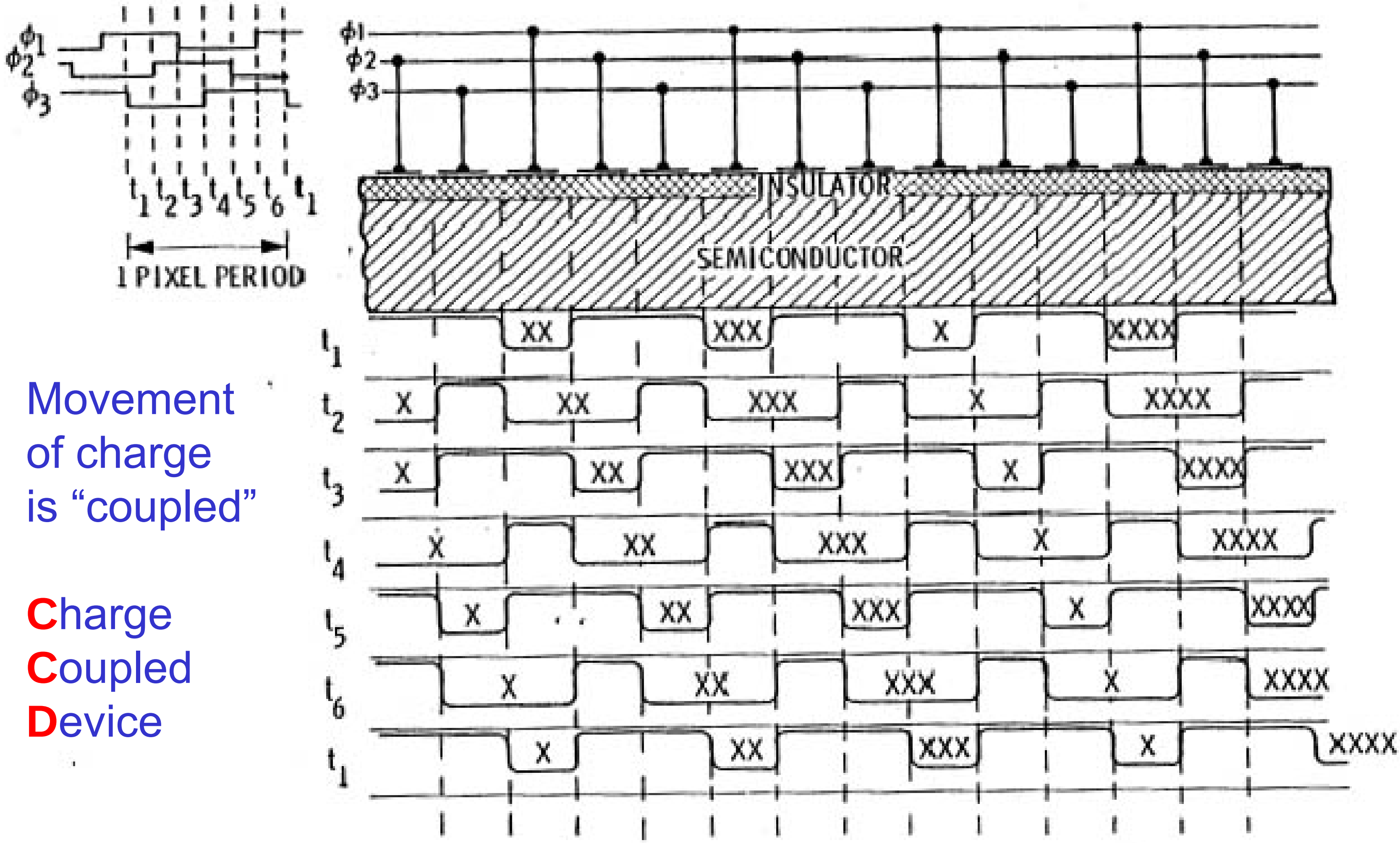
Final product (top view)





SEM cross section

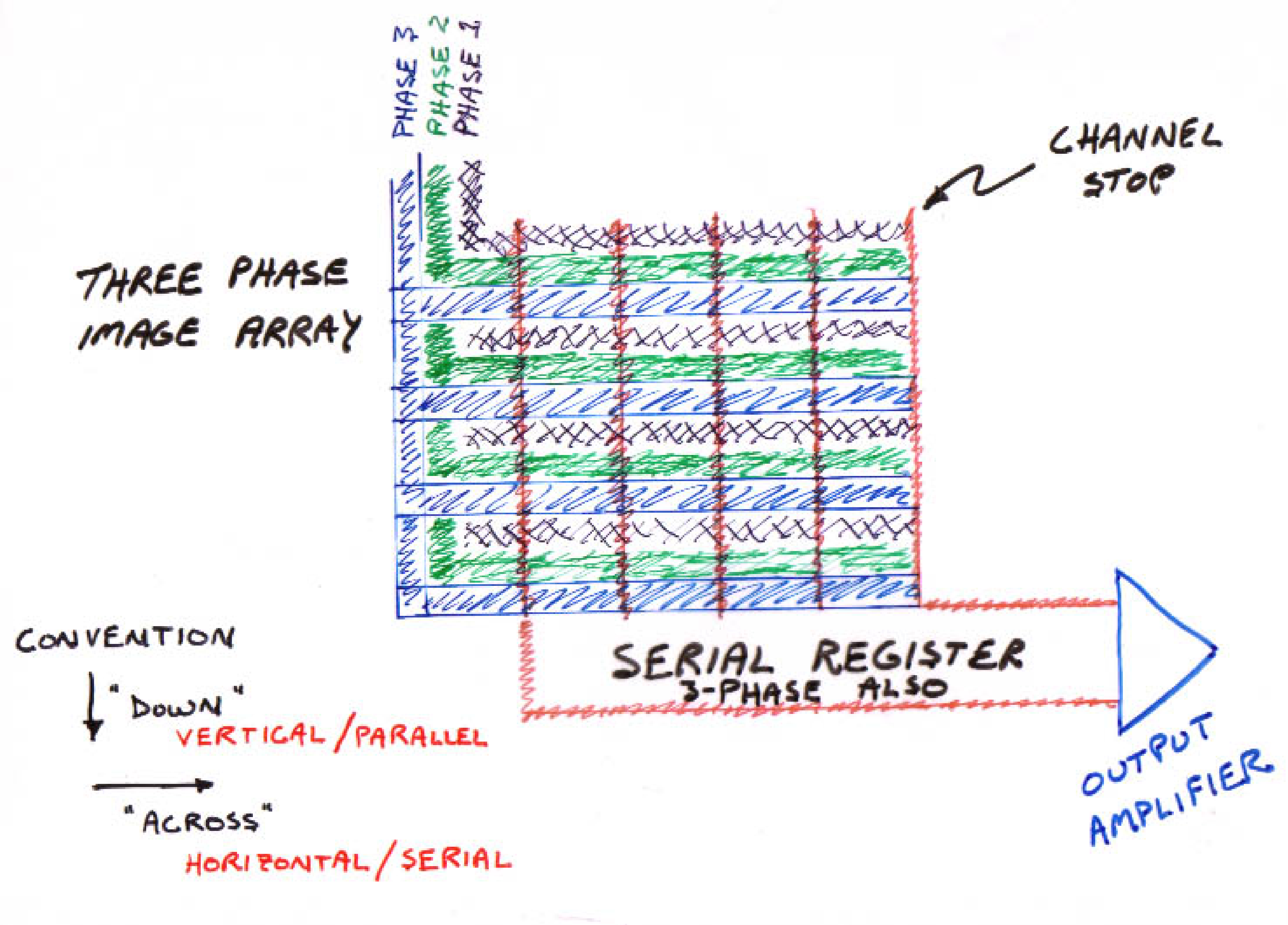
CCD Timing

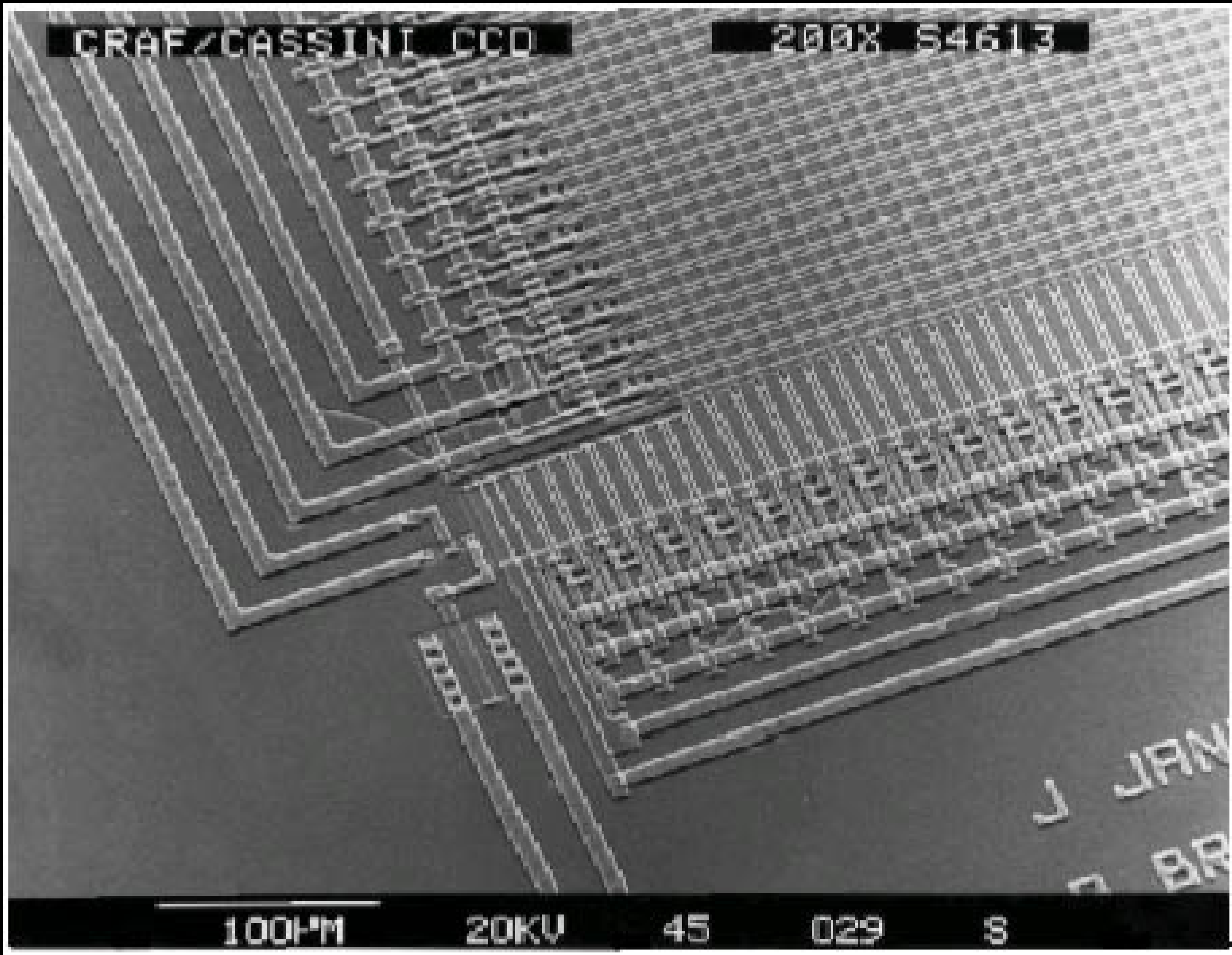


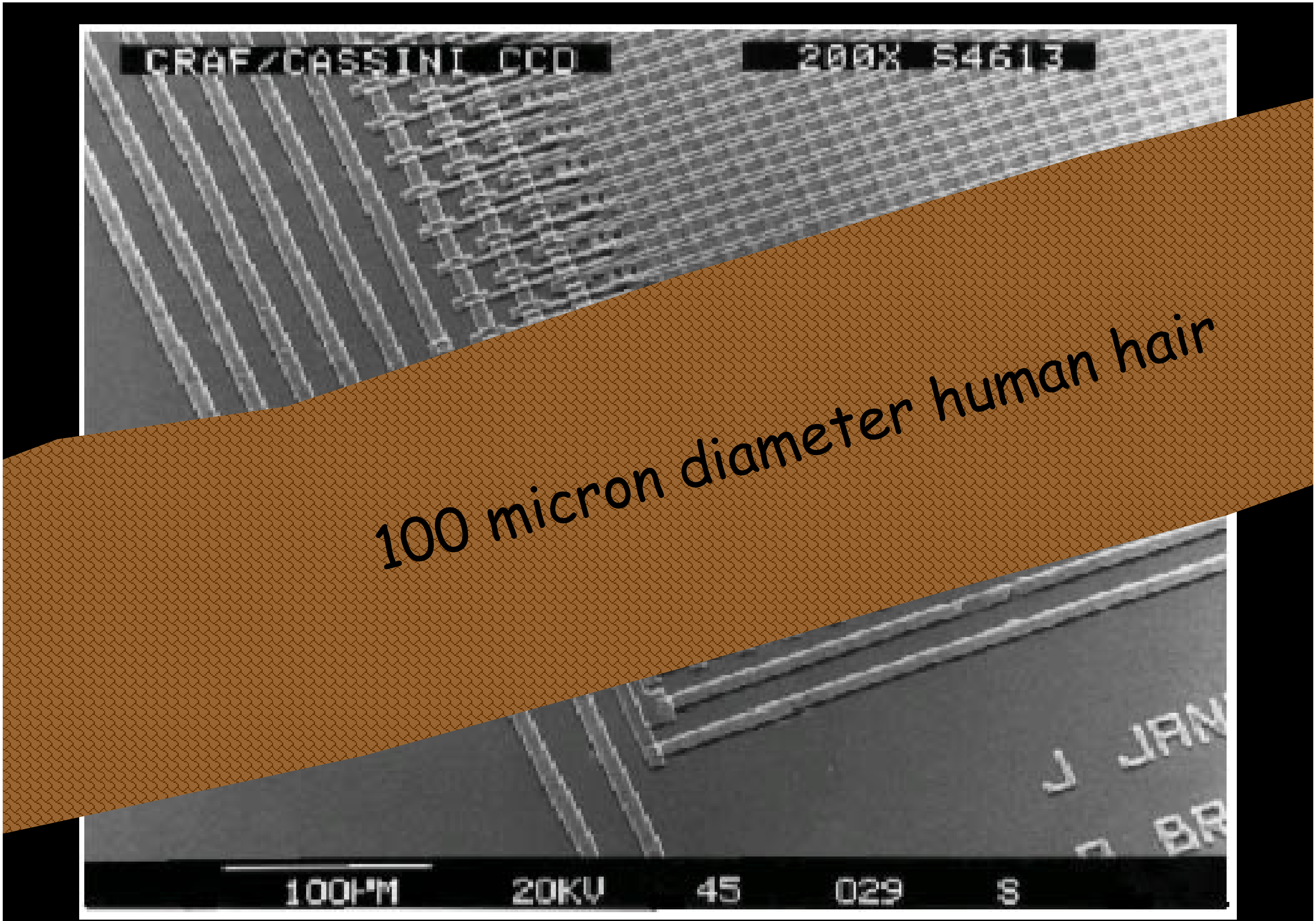
Movement of charge is "coupled"

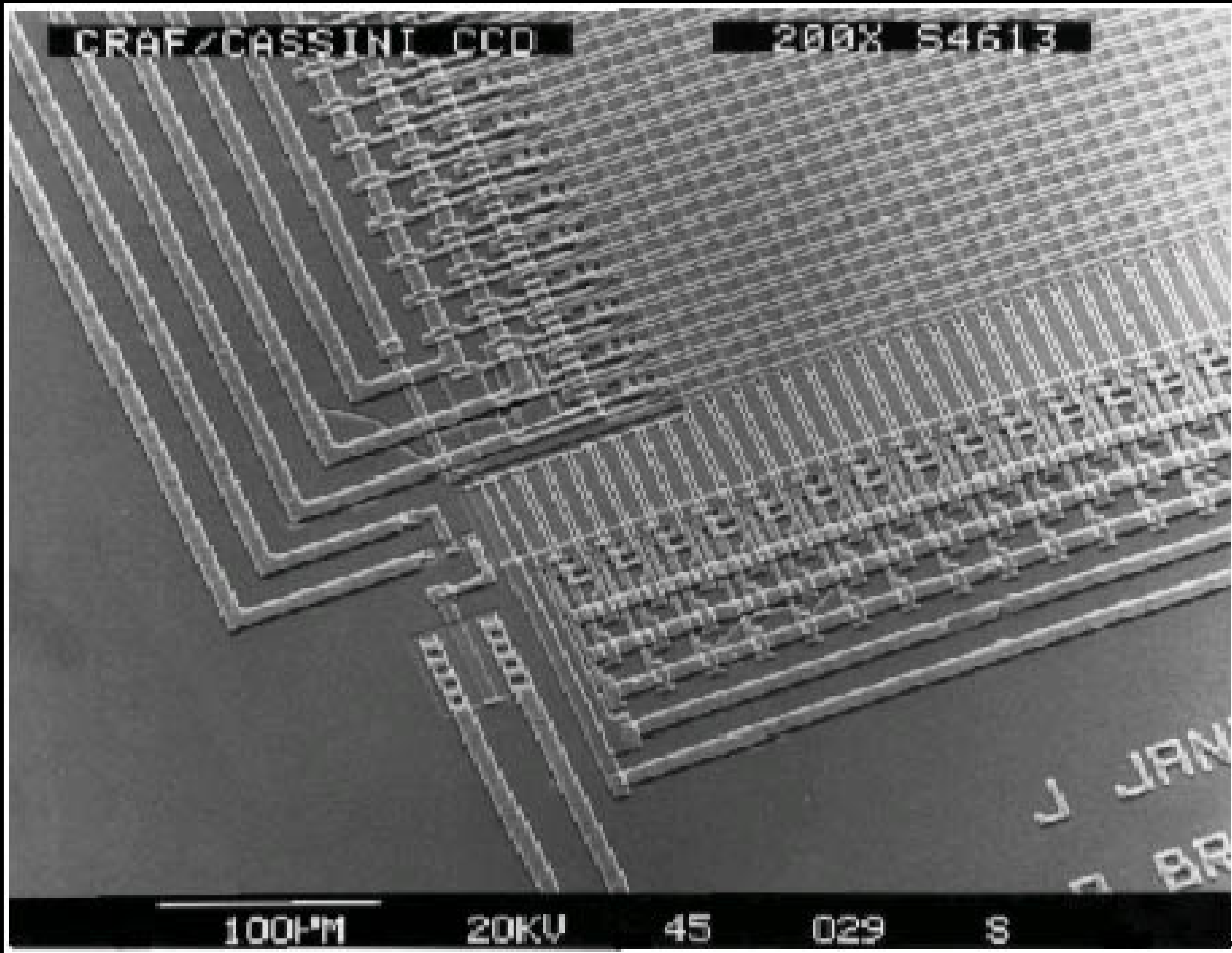
Charge **C**oupled **D**evice

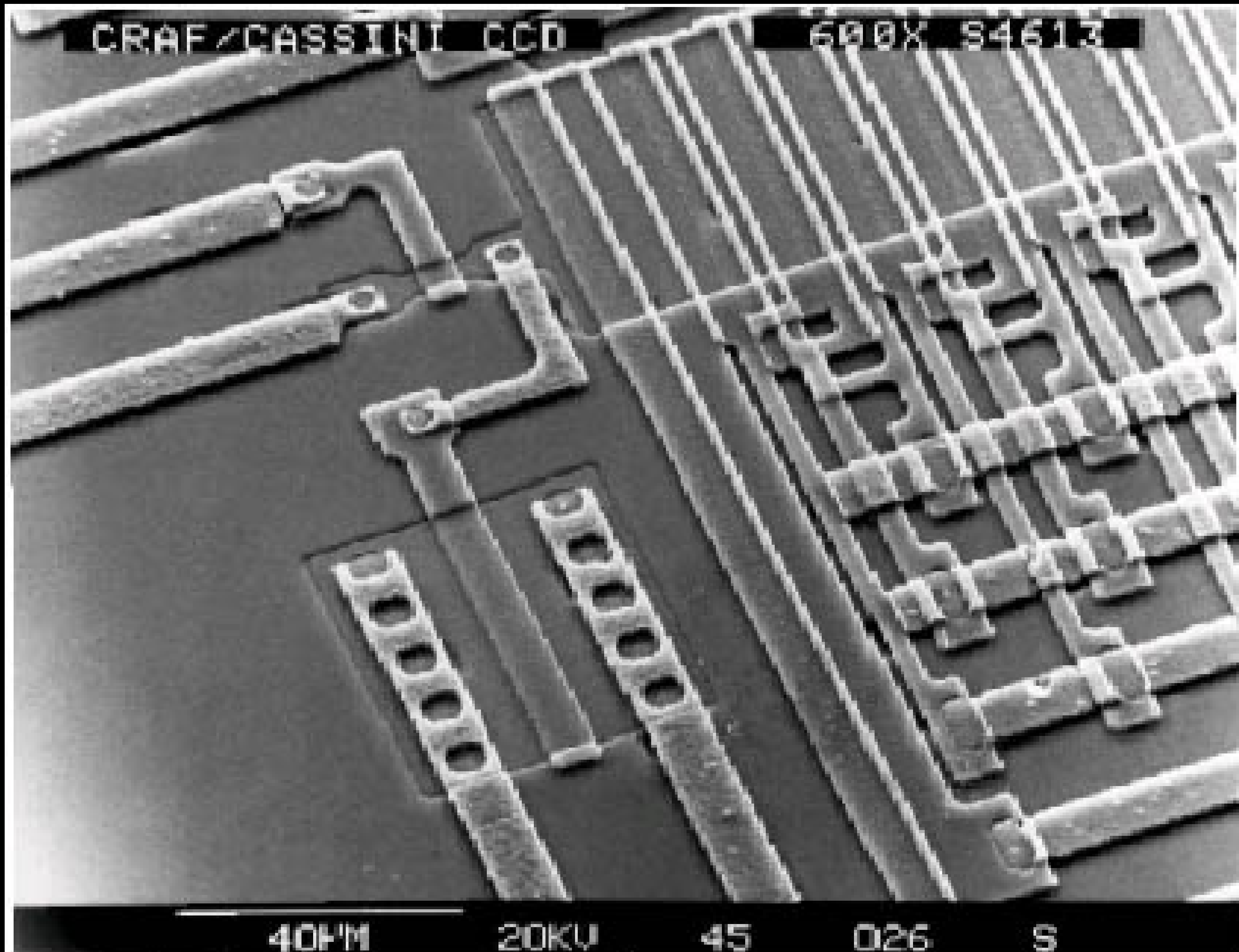
CCD – 3 Phase Serial Register

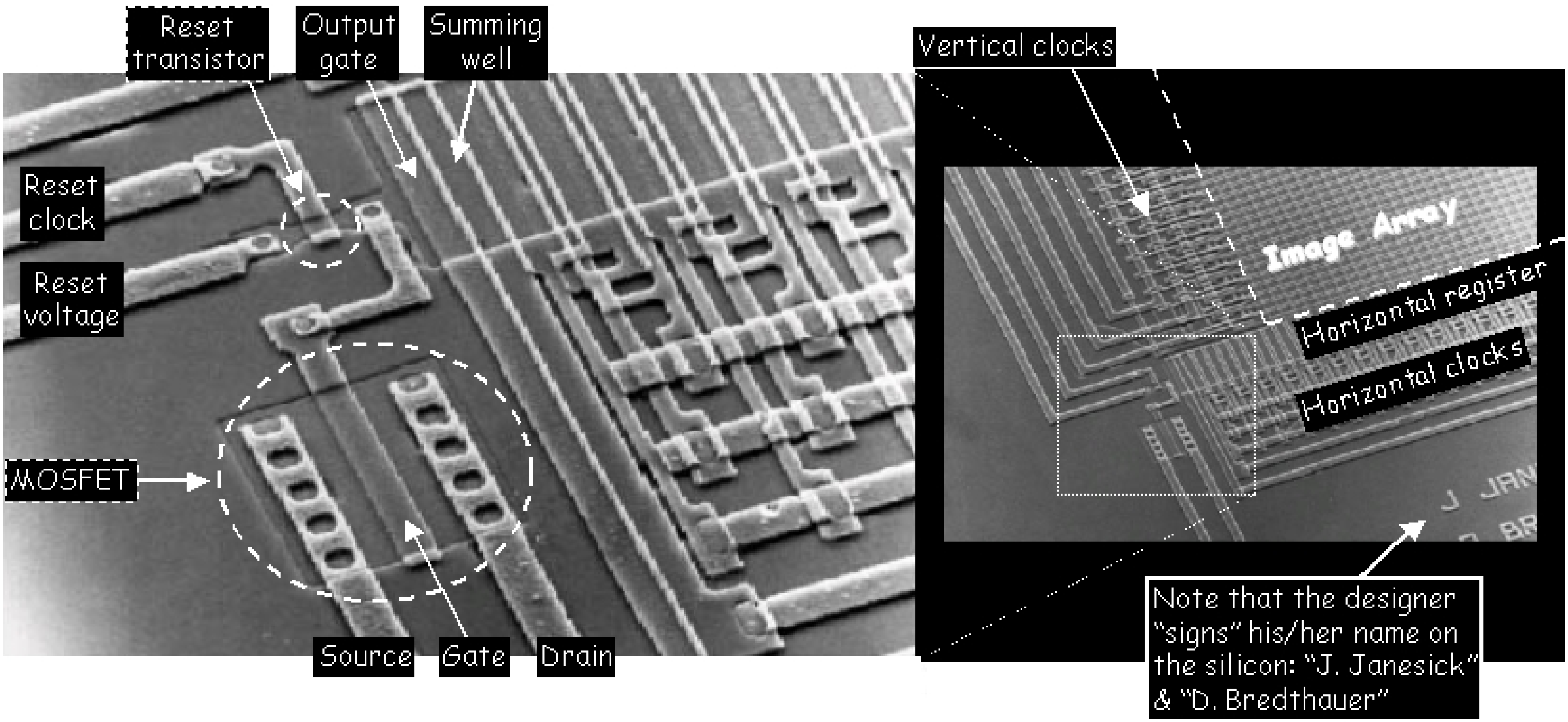



CRAF/CASSINI CCD
200X S4613
100HM 20KV 45 029 S

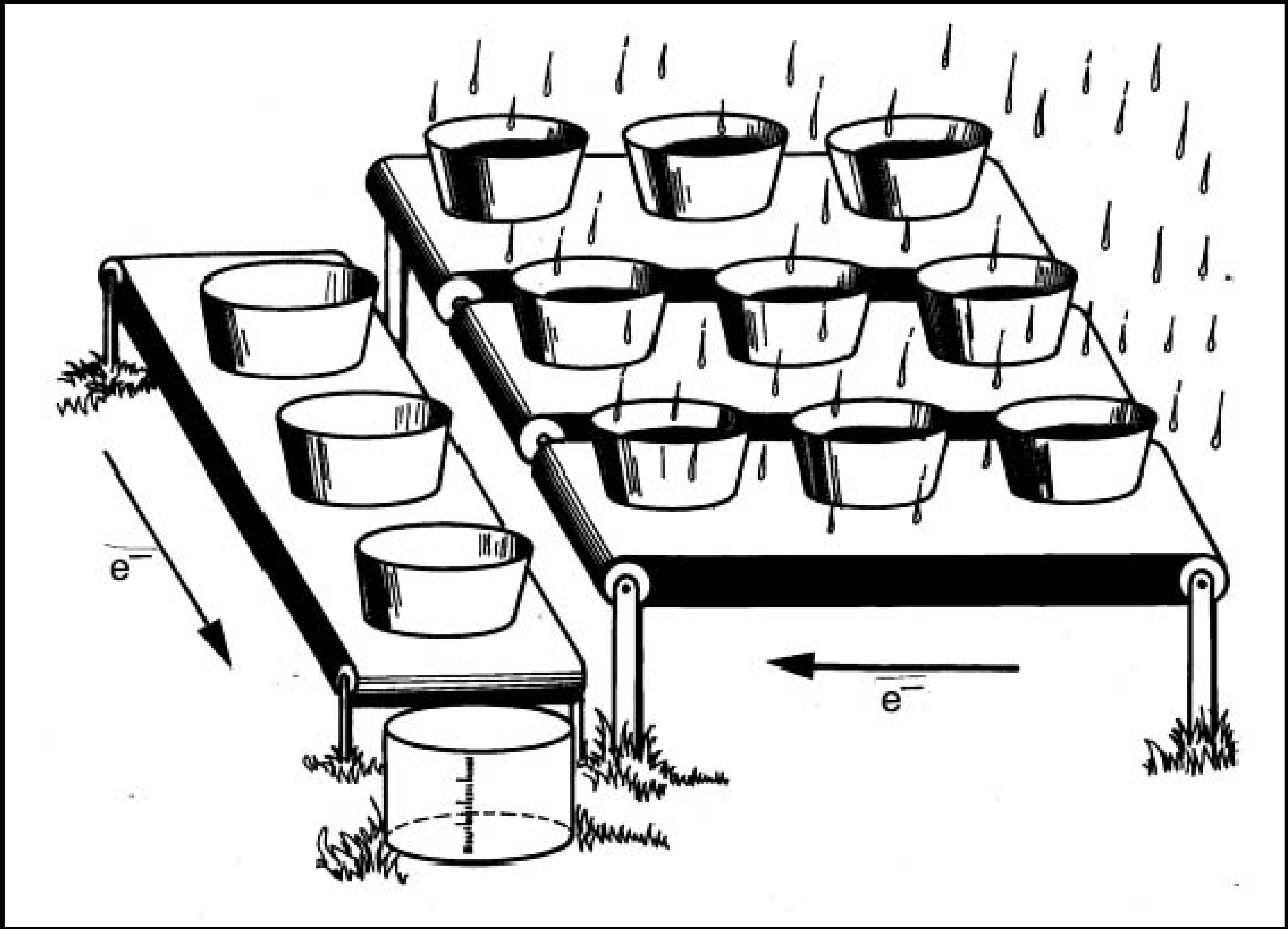

CRAF/CASSINI CCD
200X S4613
100 micron diameter human hair
100HM 20KV 45 029 S


CRAF/CASSINI CCD
200X S4613
100µM
20KV
45
029
S


CRAF/CASSINI CCD
600X S4613
40PM
20KV
45
026
S

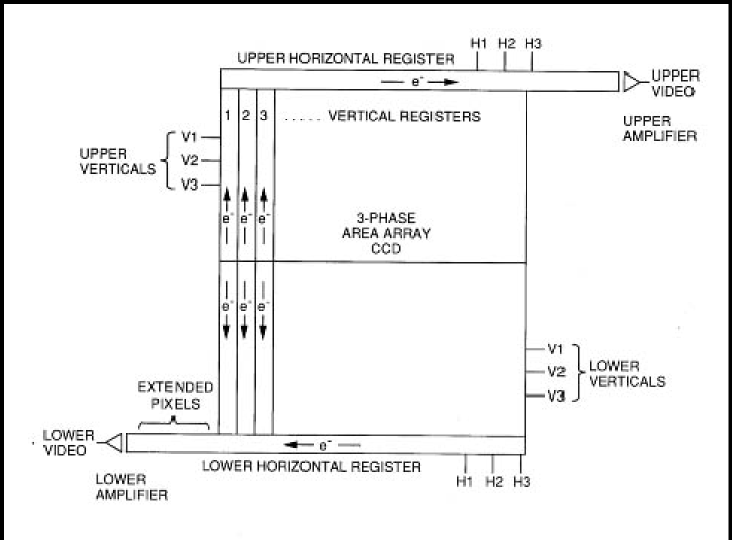

Reset transistor
Output gate
Summing well
Reset clock
Reset voltage
MOSFET
Source
Gate
Drain
Vertical clocks
Image Array
Horizontal register
Horizontal clocks
Note that the designer "signs" his/her name on the silicon: "J. Janesick" & "D. Bredthauer"

CCD Rain bucket analogy



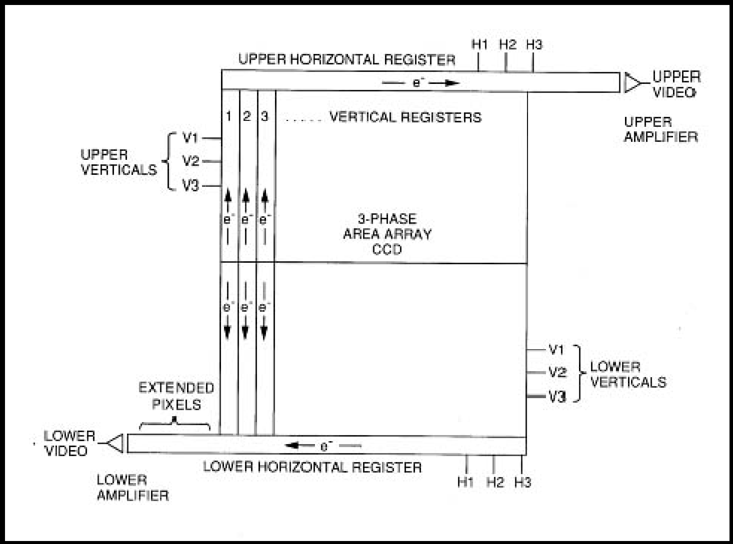
CCD Charge transfer

The good, the bad & the ugly



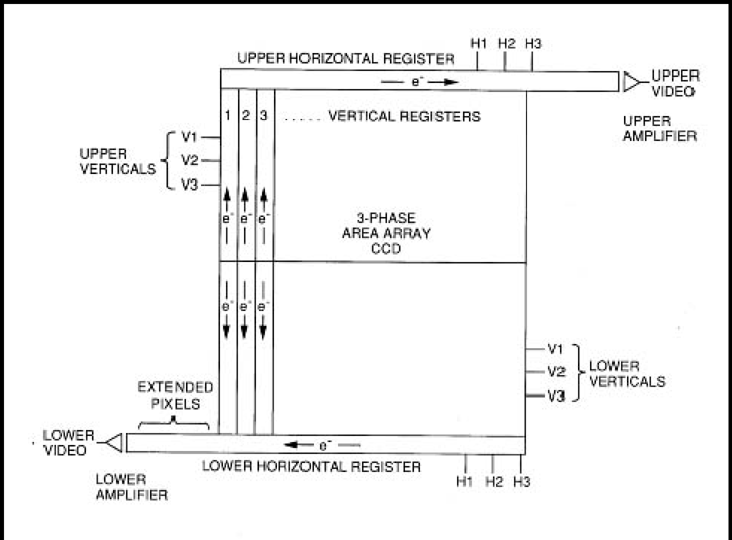
CCD Charge transfer
The good, the bad & the ugly

- "Bad & ugly" aspects of charge transfer
  - Takes time (limited max frame rate)
  - Can blur image if no shutter used
  - Can lose / blur charge during move (may limit astrometry accuracy)
  - Can bleed charge from saturated pixel up/down column
  - Can have a blocked column
  - Can have a hot pixel that releases charge into all passing pixels

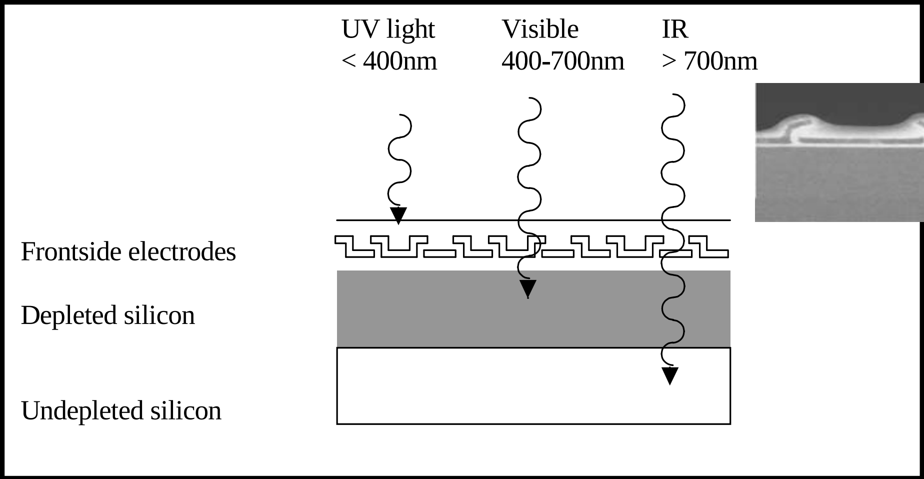


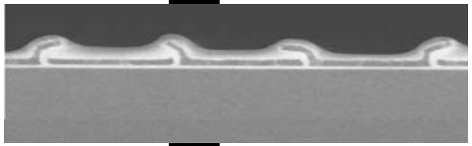
CCD Charge transfer
The good, the bad & the ugly

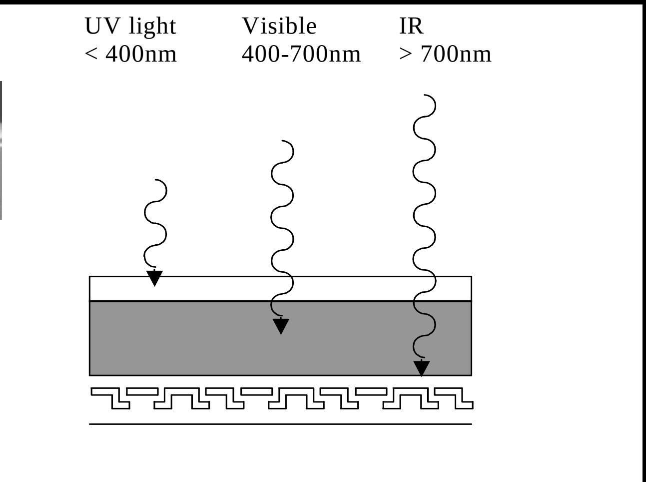
- "Good" aspects of charge transfer
  - Can bin charge "on-chip" – noiseless process
  - Can charge shift for tip/tilt correction or to eliminate systematic errors
    - "va-et-vient", "nod-and-shuffle"
  - Can build special purpose designs that integrate different areas (curvature wavefront sensing, Shack-Hartmann laser guide star wavefront sensing)
  - Can do drift scanning
  - No indium bump issues that can cause inoperable pixels
  - **Have space to build a great low noise amplifier !**



Frontside & Backside illuminated CCD







Frontside

Backside

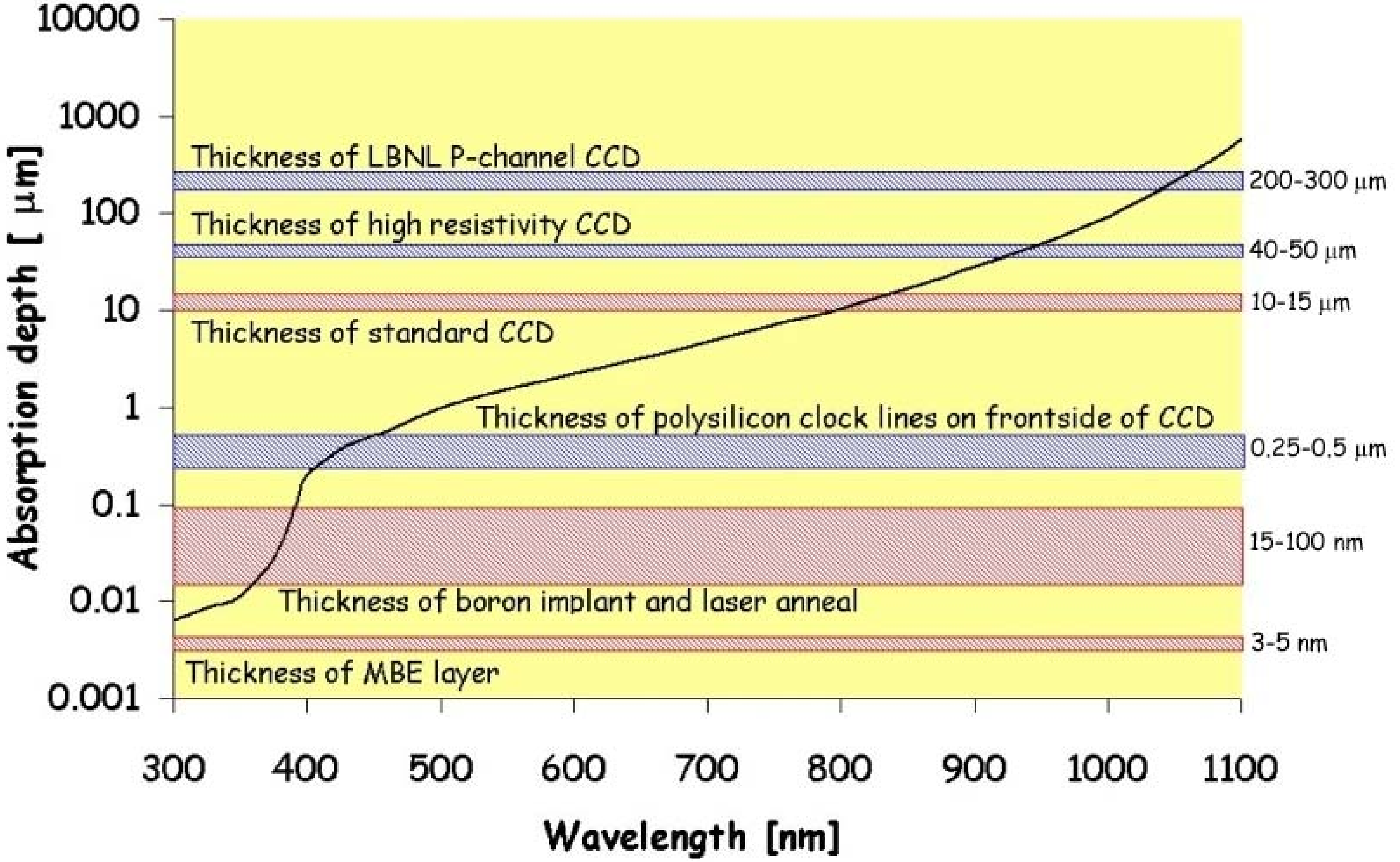
Backside illuminated CCDs have high spectral response…if processed correctly.

Thin to 10-20 microns, and **backsurface treatment** to ensure that photons absorbed near the back surface are collected. Surface treatments include:

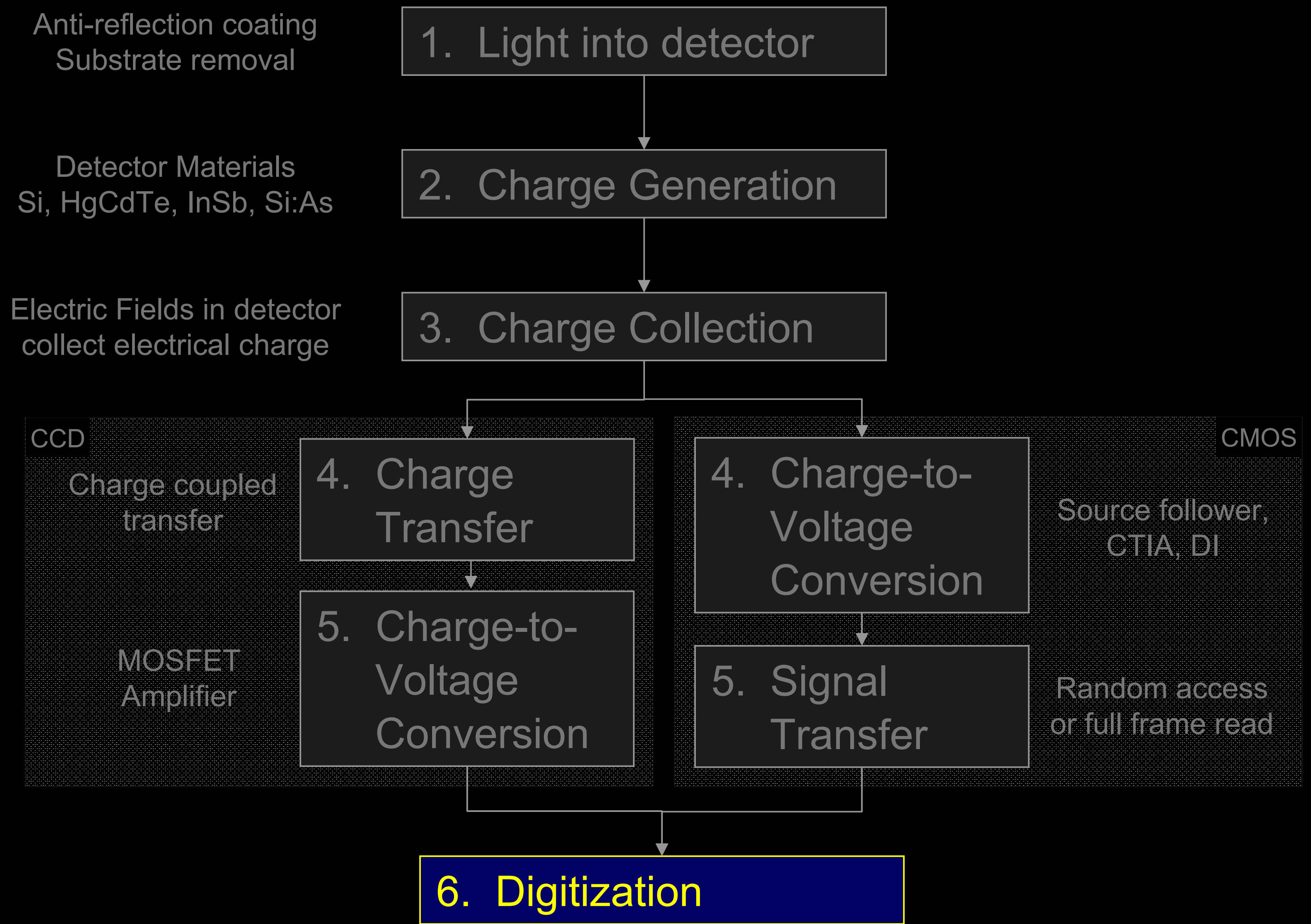
- Ion implantation followed by laser annealing
- Ion implantation followed by furnace annealing
- Chemisorption charging
- Molecular beam epitaxy (MBE) / delta doping

Optical Absorption Depth in Silicon

(a.k.a. “The Beautiful Plot”)



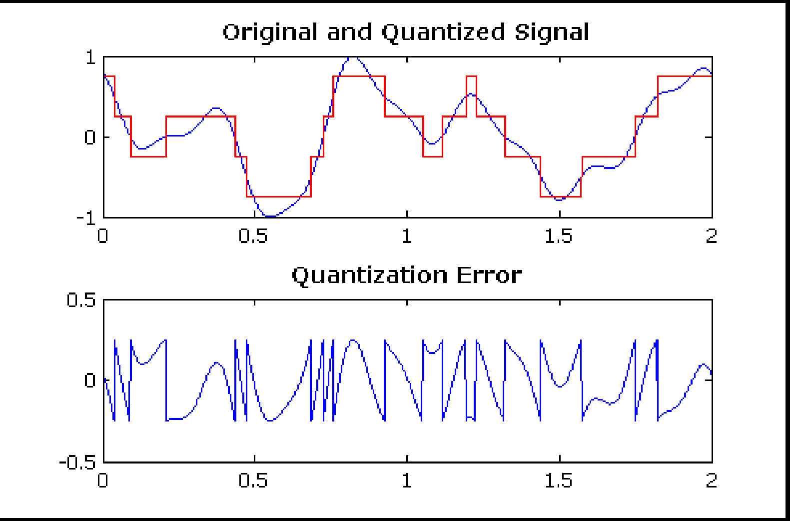
6 steps of optical / IR photon detection



Analog-to-digital converters

"Convert the analog signal (voltage or current) into a digital number"

- Quantization noise of an ADC is (1/√12) Least Significant Bit = 0.289 LSB
- Typically set gain of amplifier chain so that quantization noise is much less than readout noise. If readout noise is 4 electrons, set gain so that LSB equals ~2 electrons
- 16 bit ADC is most commonly used in astronomy. At ~2 electrons per ADU (analog to digital unit), or LSB, full well of a 16 bit ADC will be ~130,000 electrons; good match to the typical full well of a CCD or Short-Wave IR detector of 100,000 electrons.

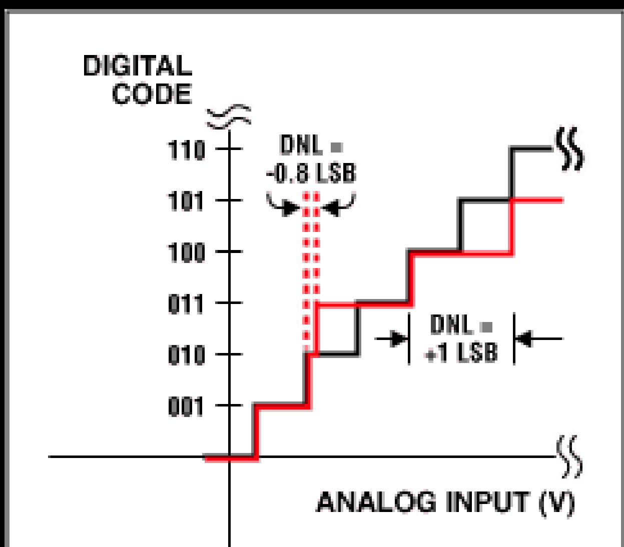


Highly exaggerated quantization noise

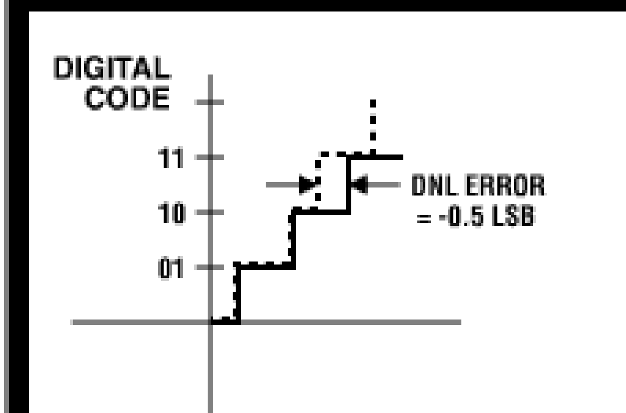
Differential Non-Linearity (DNL)

- DNL describes the distance of an ADC code from its adjacent code.
- It is measured as a change in input voltage magnitude, and then converted to number of Least Significant Bits (LSBs).

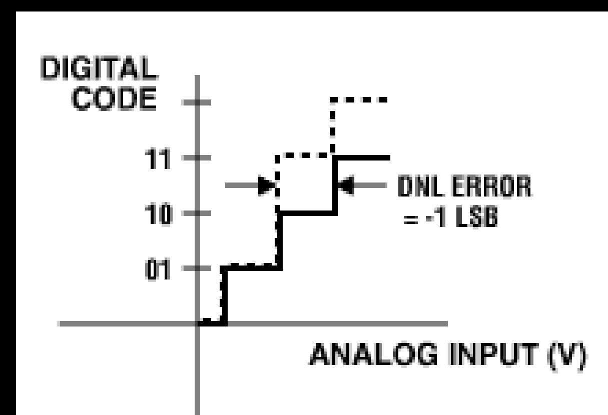
$$DNL = (V_{D+1} - V_D) / V_{LSB\text{-}Ideal} - 1$$



Code 100 is increased
DNL = +1



Code 10 is reduced
DNL = -0.5

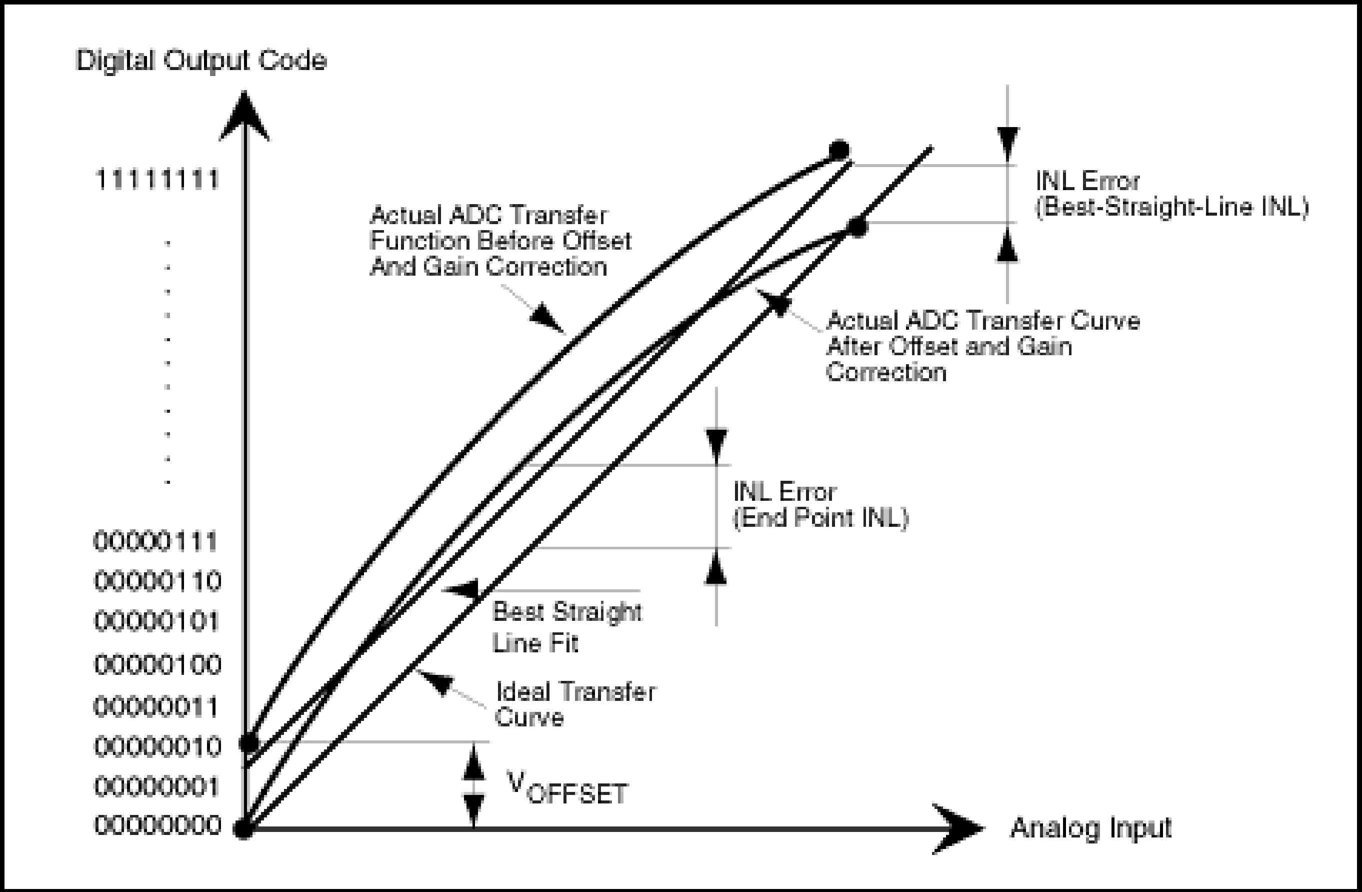


Code 10 is missing
DNL = -1

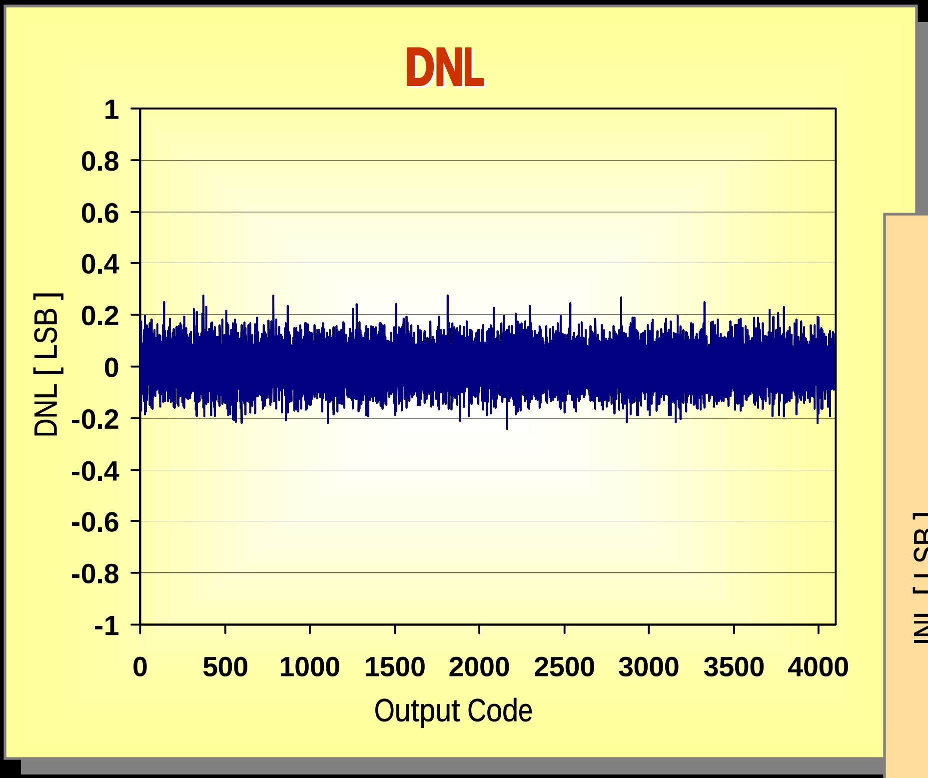
Integral Non-Linearity (INL)

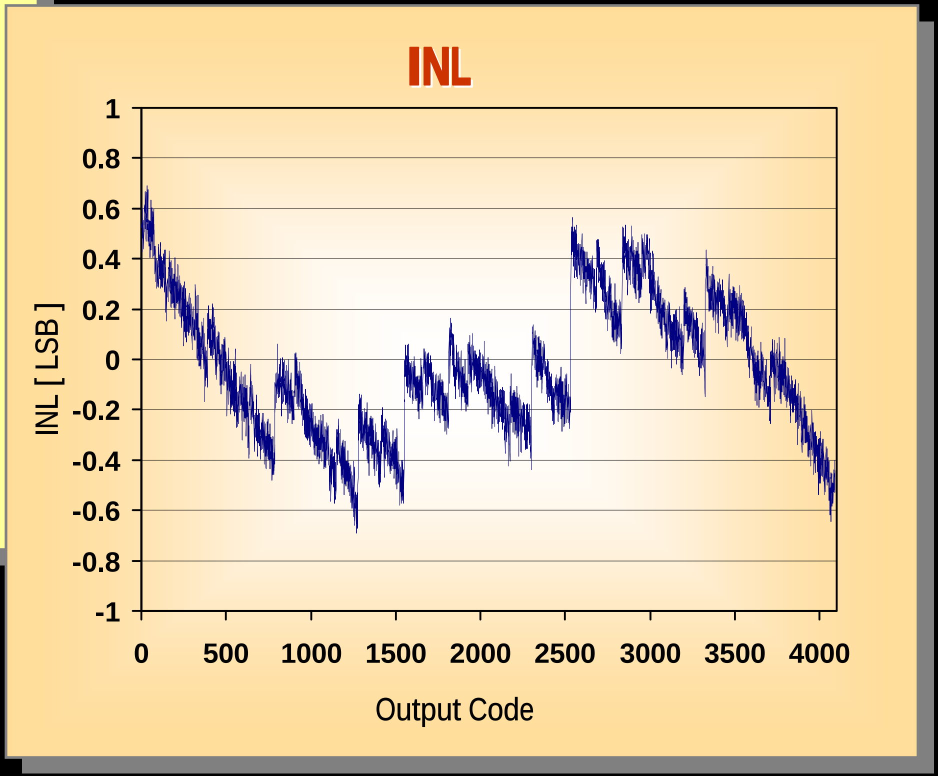
- INL describes the deviation of the ADC transfer function from a straight line
- It can be computed as the integral of the DNL, and is expressed in LSB

$$INL = (V_D - V_{Zero}) / V_{LSB\text{-}Ideal} - D$$



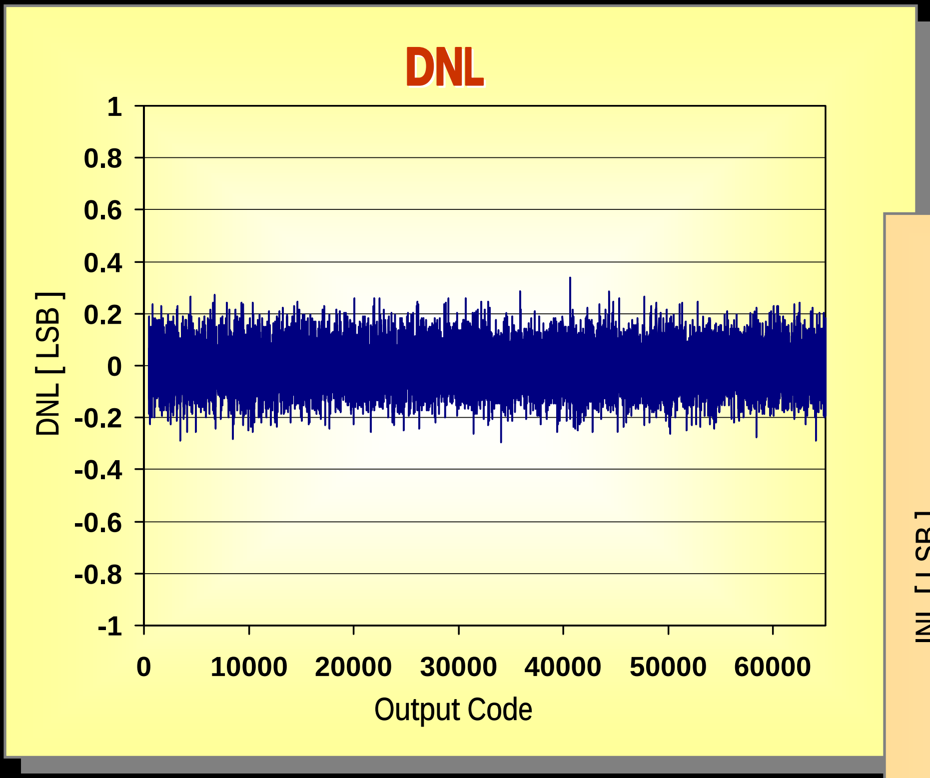
DNL and INL Plots of a 12-bit ADC
(from SIDECAR ASIC, at 7.5 MHz rate)

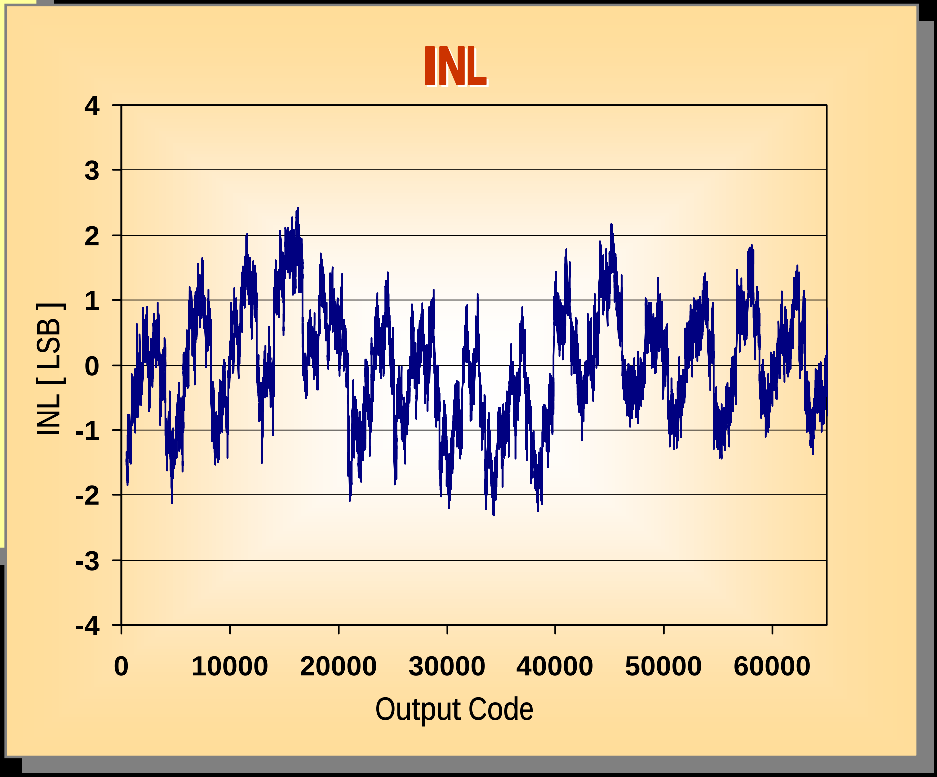




- Differential Non-Linearity: < ± 0.3 LSB
- Integral Non-Linearity: < ± 0.7 LSB

DNL and INL Plots of a 16-bit ADC
(from SIDECAR ASIC, at 125 kHz rate)

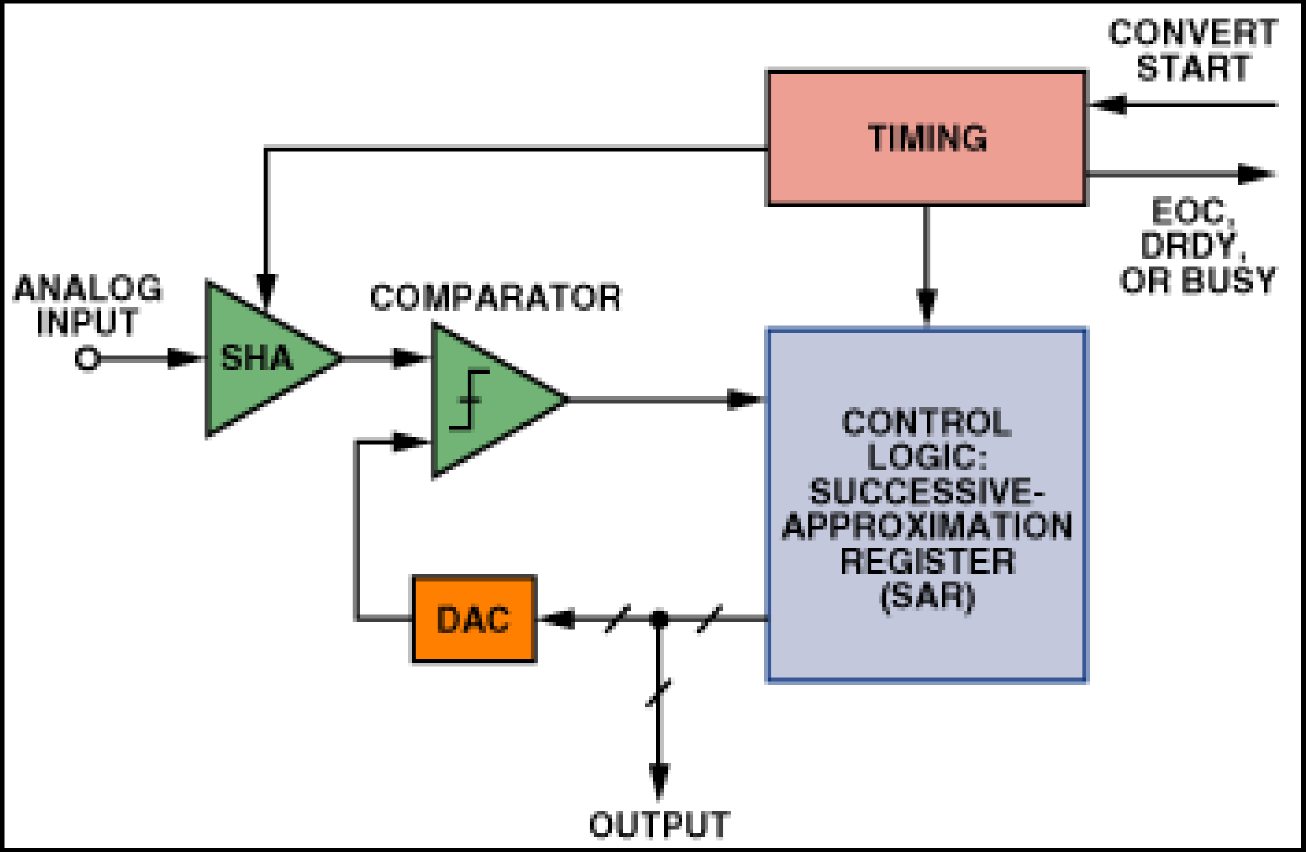




- Differential Non-Linearity: < ± 0.3 LSB
- Integral Non-Linearity: < ± 0.7 LSB

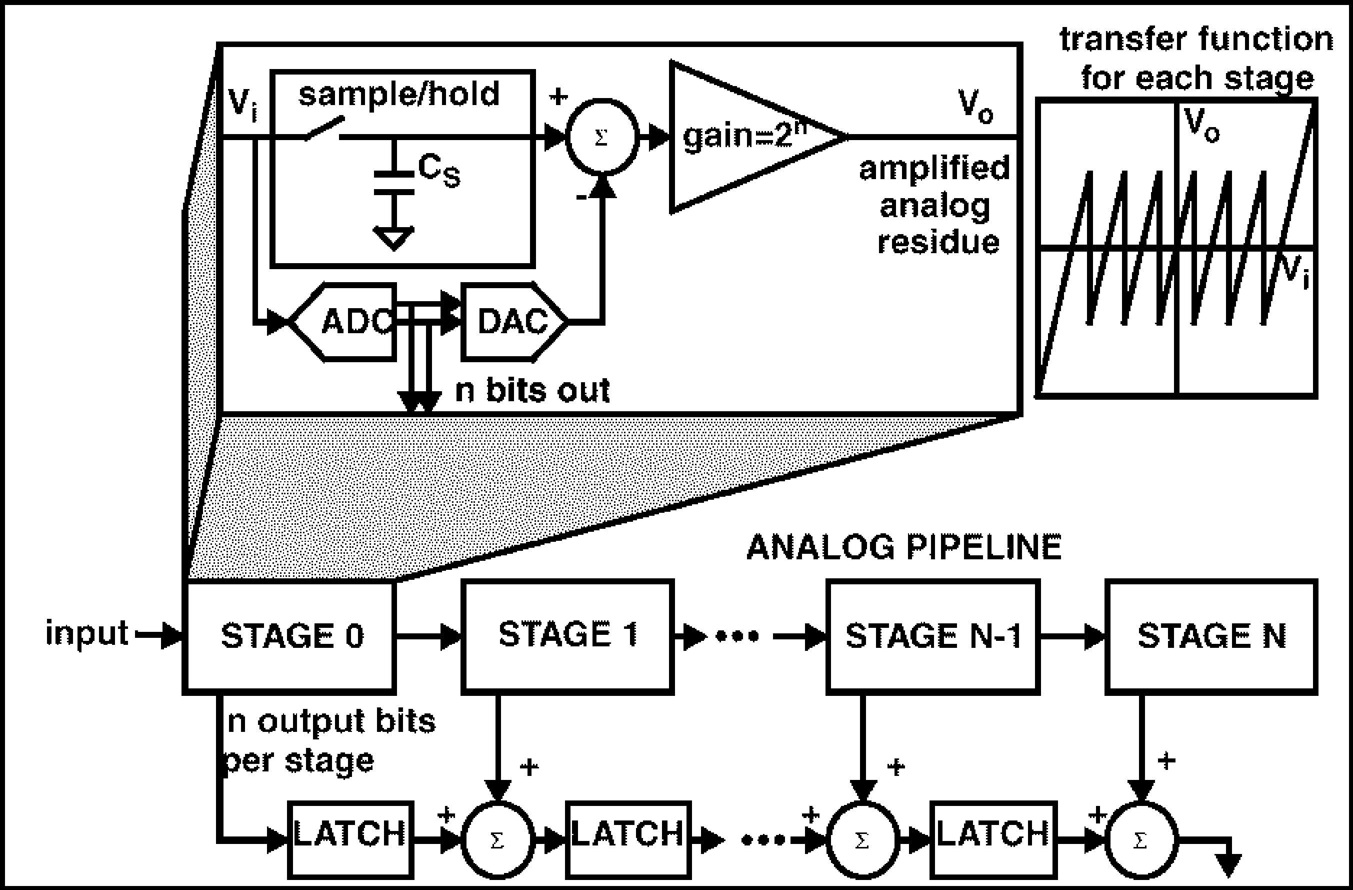
Sample ADC Architectures

Successive Approximation Register (SAR)



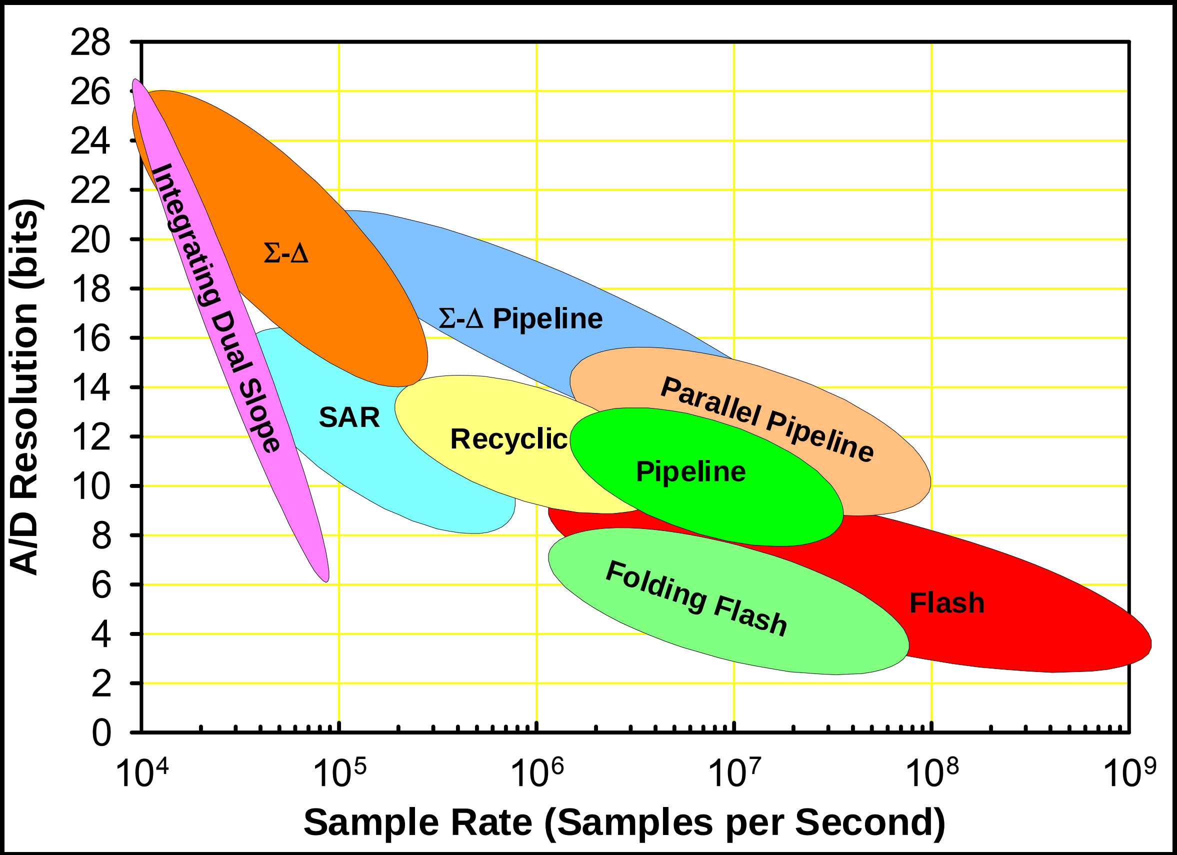
Sample ADC Architectures

Pipeline ADC



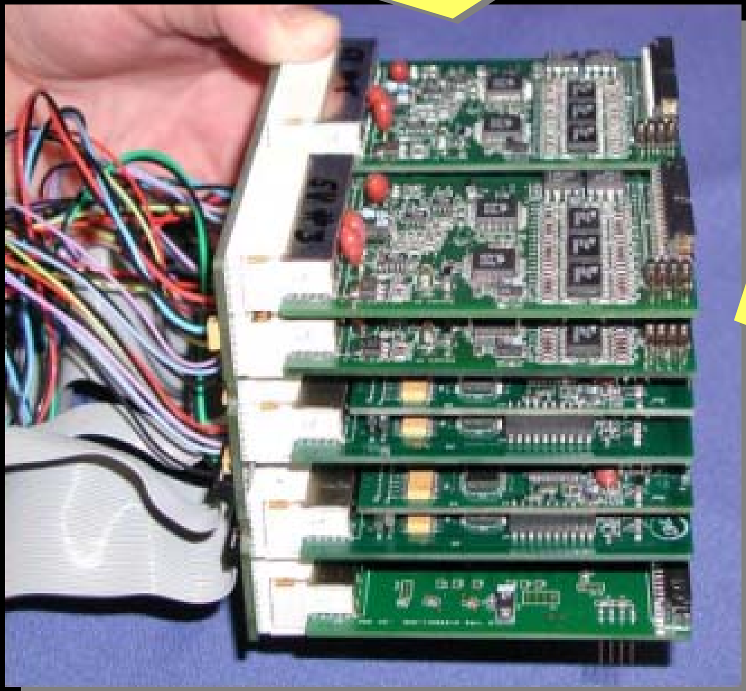
ADC Development Optimized for Applications

- Depending on resolution, sample rate and power consumption requirement, different architectures for ADCs are used.
- Pipeline ADCs used for video rate applications.
- Successive Approximation Register (SAR) ADCs are used for medium speed, higher resolution applications.
- Sigma-Delta ADCs are used for slow speed, very high resolution applications.

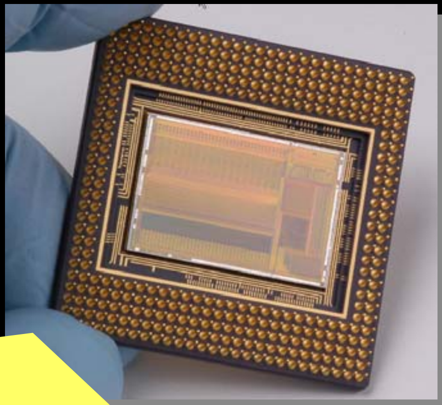


The SIDECAR ASIC
Complete Electronics on a Chip

Replace this



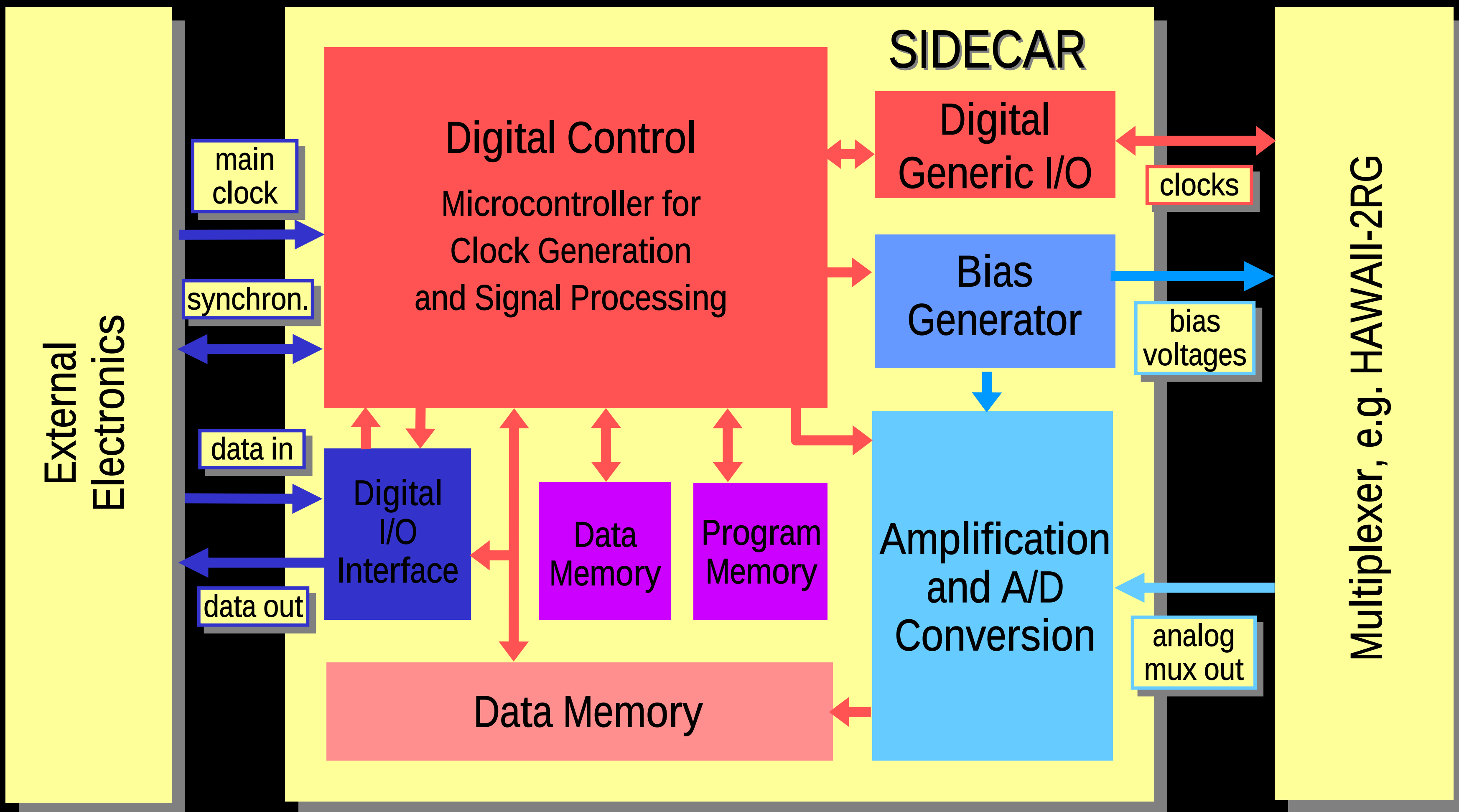
with this!



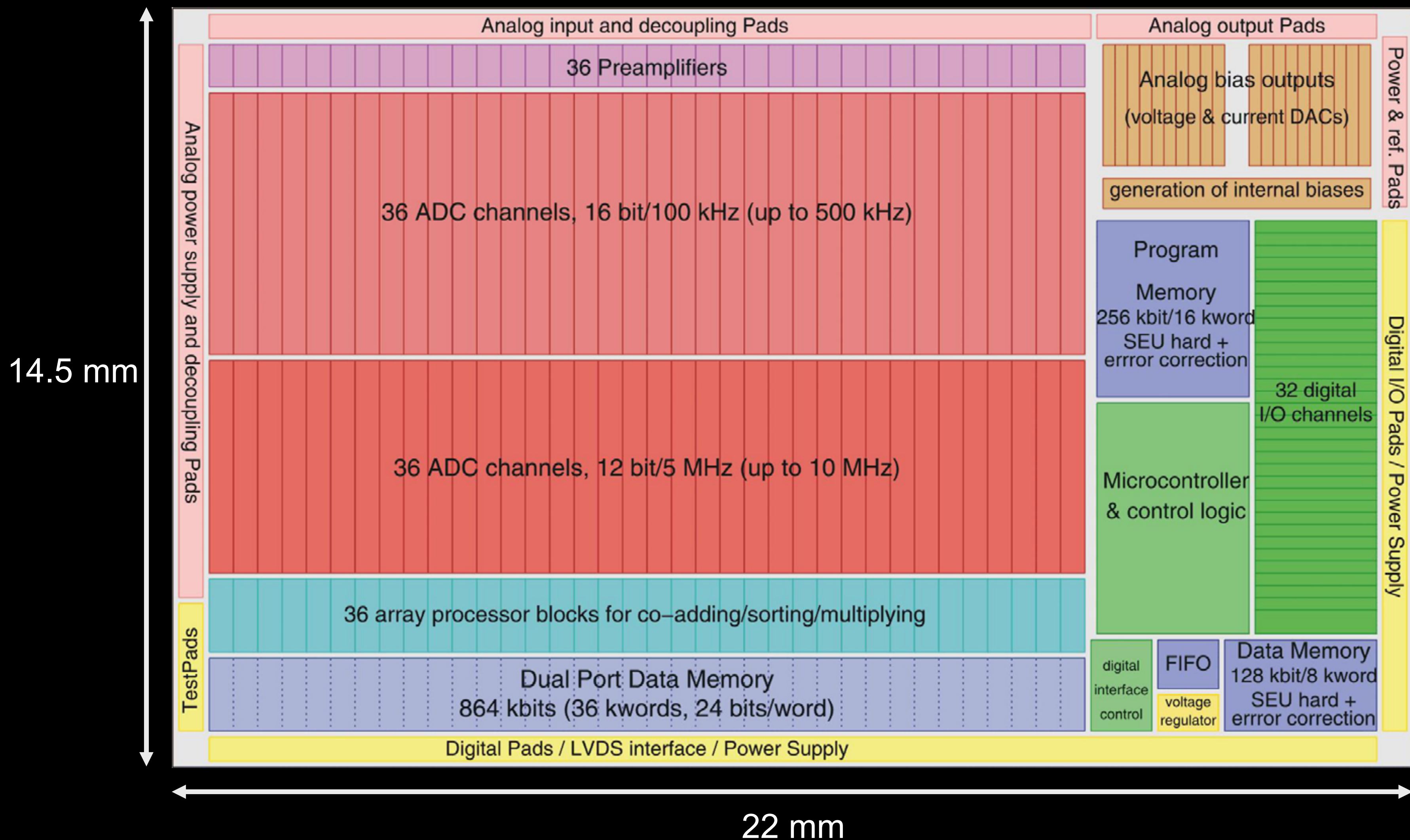
1% volume
1% power
less hassle

SIDECAR: System for Image Digitization, Enhancement, Control And Retrieval

SIDECAR ASIC Functionality



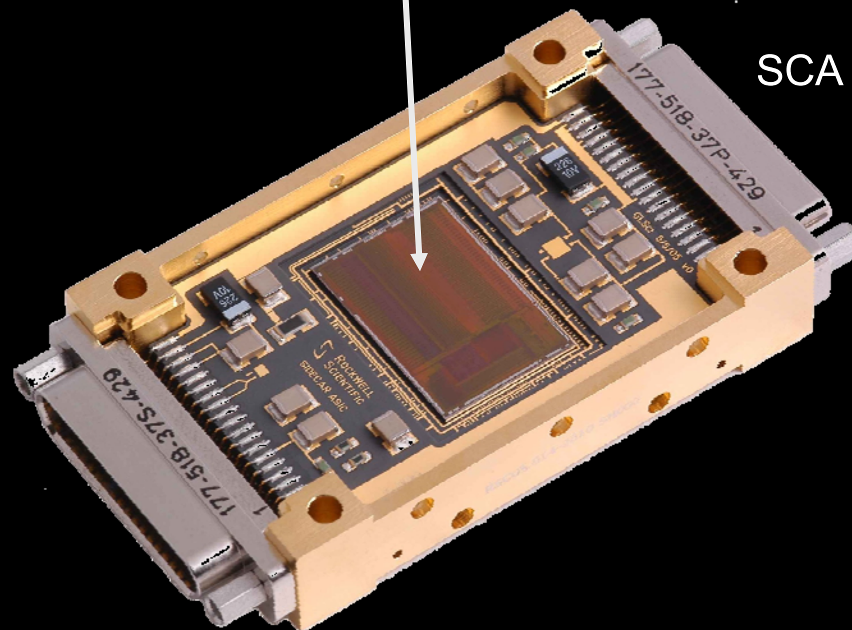
SIDECAR ASIC Floorplan



Teledyne Imaging Sensors

SIDECAR ASIC Flight Package for JWST

- Ceramic board with ASIC die and decoupling caps
- Invar box with top and bottom lid
- Two 37-pin MDM connectors
  - FPE-to-ASIC connection
  - ASIC-to-SCA connection
- Qualified to NASA Technology Readiness Level 6 (TRL-6)
- 11 mW power when reading out of four ports in parallel, with 16 bit digitization at 100 kHz per port.

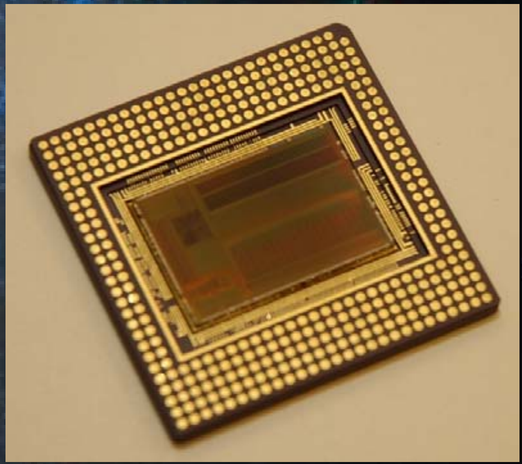


SIDECAR ASIC LGA Package

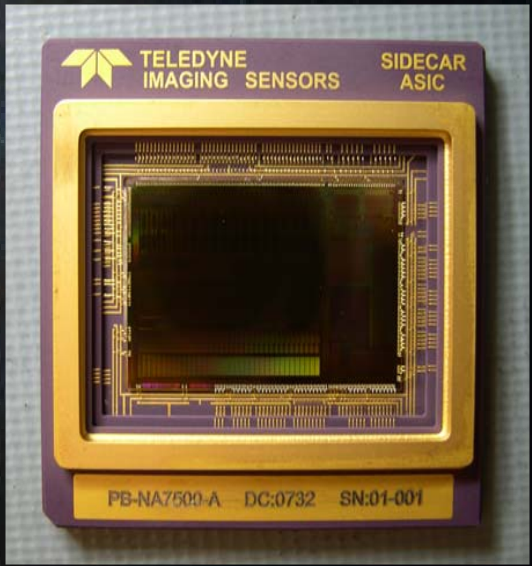
- Package for board level mounting:
  - 337-pin LGA ceramic carrier
- Currently used for all ground-based applications
- Existing LGA package cannot be hermetically sealed: not enough room to attach the seal ring.

- Modified version is operating on the Hubble Space Telescope:
  - Uses "cavity-up" instead of "cavity-down"
  - Provides large seal ring for hermetic seal
  - Pinout is exactly mirrored compared to original LGA package
  - Used by Hubble Space Telescope Advanced Camera for Surveys (ACS) Repair (image in background is from first light press release)

LGA (old)

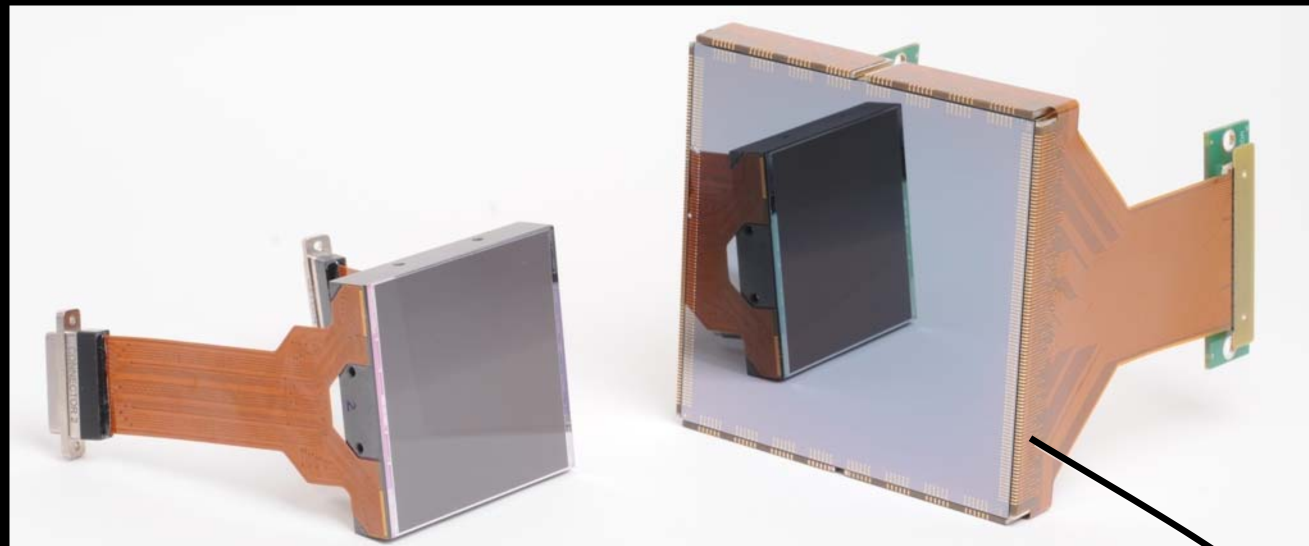


LGA (new)



World’s Largest Monolithic CCDs

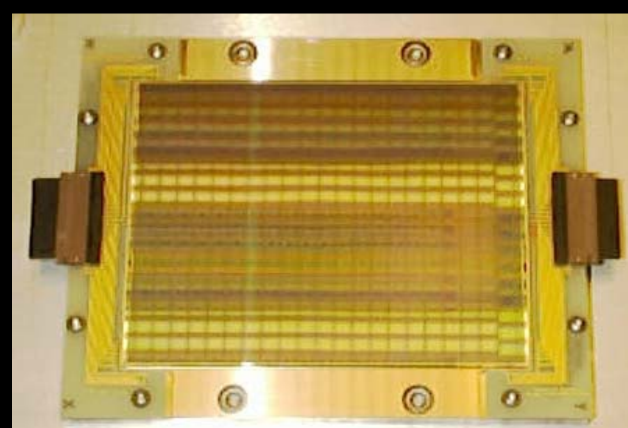
e2v
8.4 million pixels
2048×4096, 15 µm
18.9 cm2



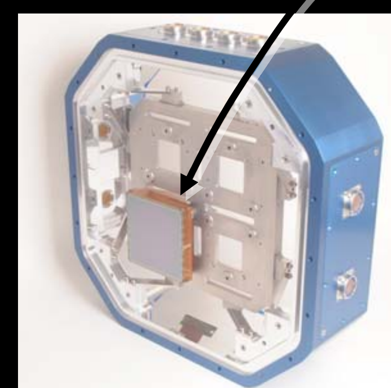
e2v
16.8 million pixels
4096×4096, 15 µm
37.7 cm2

STA
111.5 million pixels
10,240×10,240, 9 µm
90.3 cm2

Dalsa
48 million pixels
6000×8000, 6 µm
17.3 cm^2

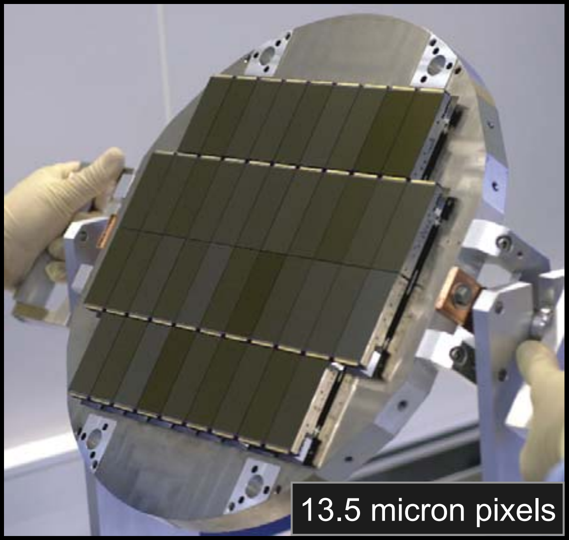


Philips
66.1 million pixels
7168×9216, 12 µm
95.1 cm2



445 Mpixel mosaic

CCD Mosaics

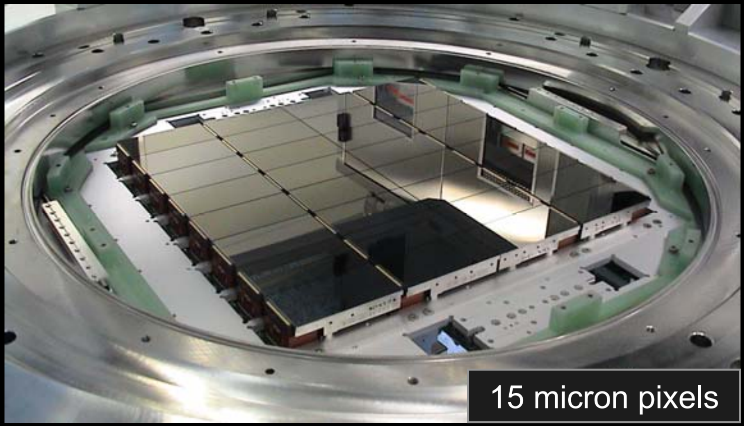


13.5 micron pixels

MegaCam on the CFHT - 378 million pixels

10 micron pixels

Pan-STARRS 1
1,397 million pixels



15 micron pixels

OmegaCam on the VST - 268 million pixels

LSST
3,171 million pixels

10 micron pixels

Growth of CCD mosaics

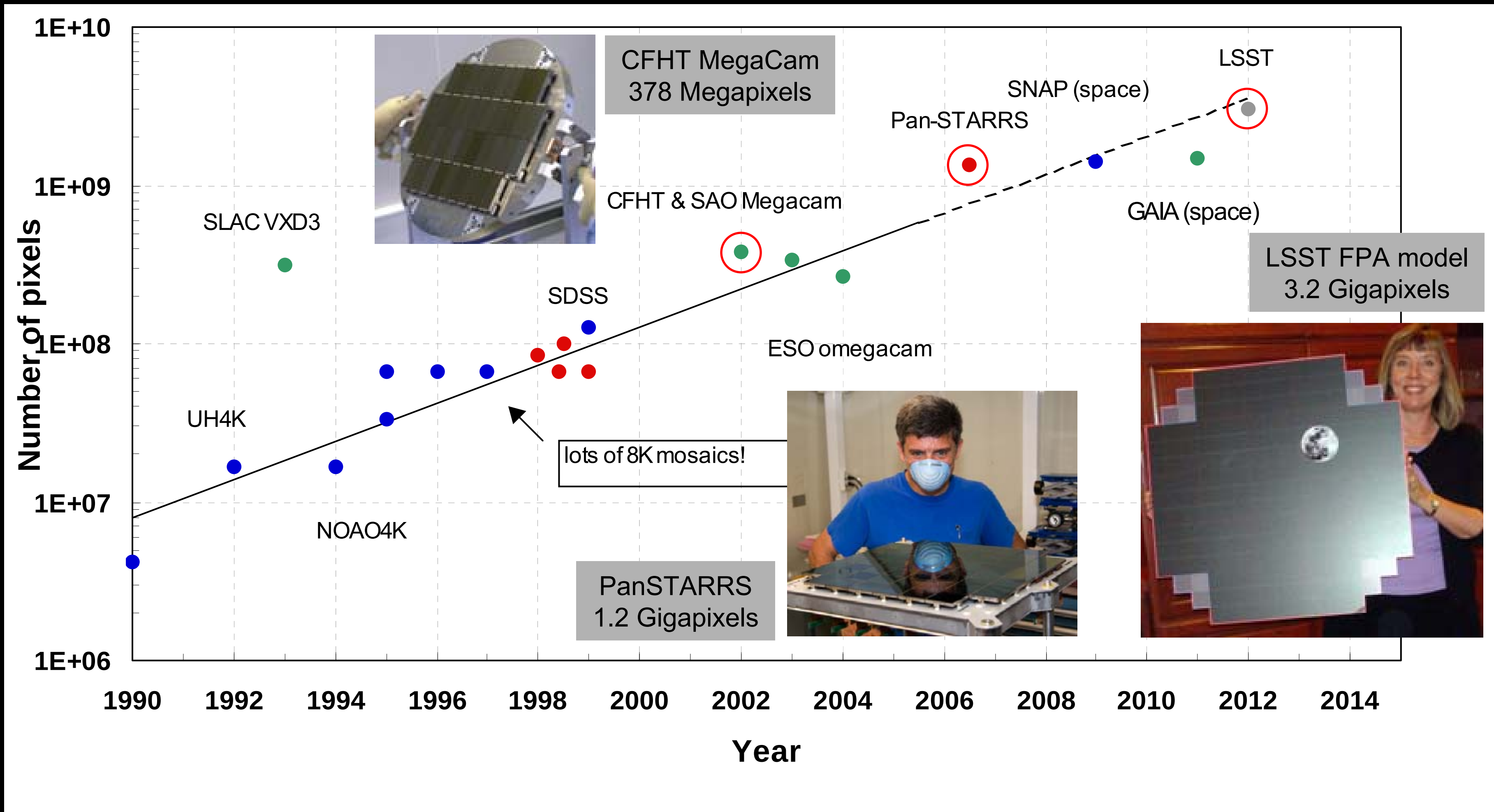


Illustration of large focal plane sizes, from Luppino 'Moore's' law

Focal plane size doubles every 2.5 years

Infrared Mosaics

HgCdTe 2K x 2K, 18 µm pixels

2×2

HgCdTe 4K x 4K mosaic, 18 µm pixels

Teledyne Imaging Sensors

Another 4096 x 4096 pixel IR mosaic comes on-line

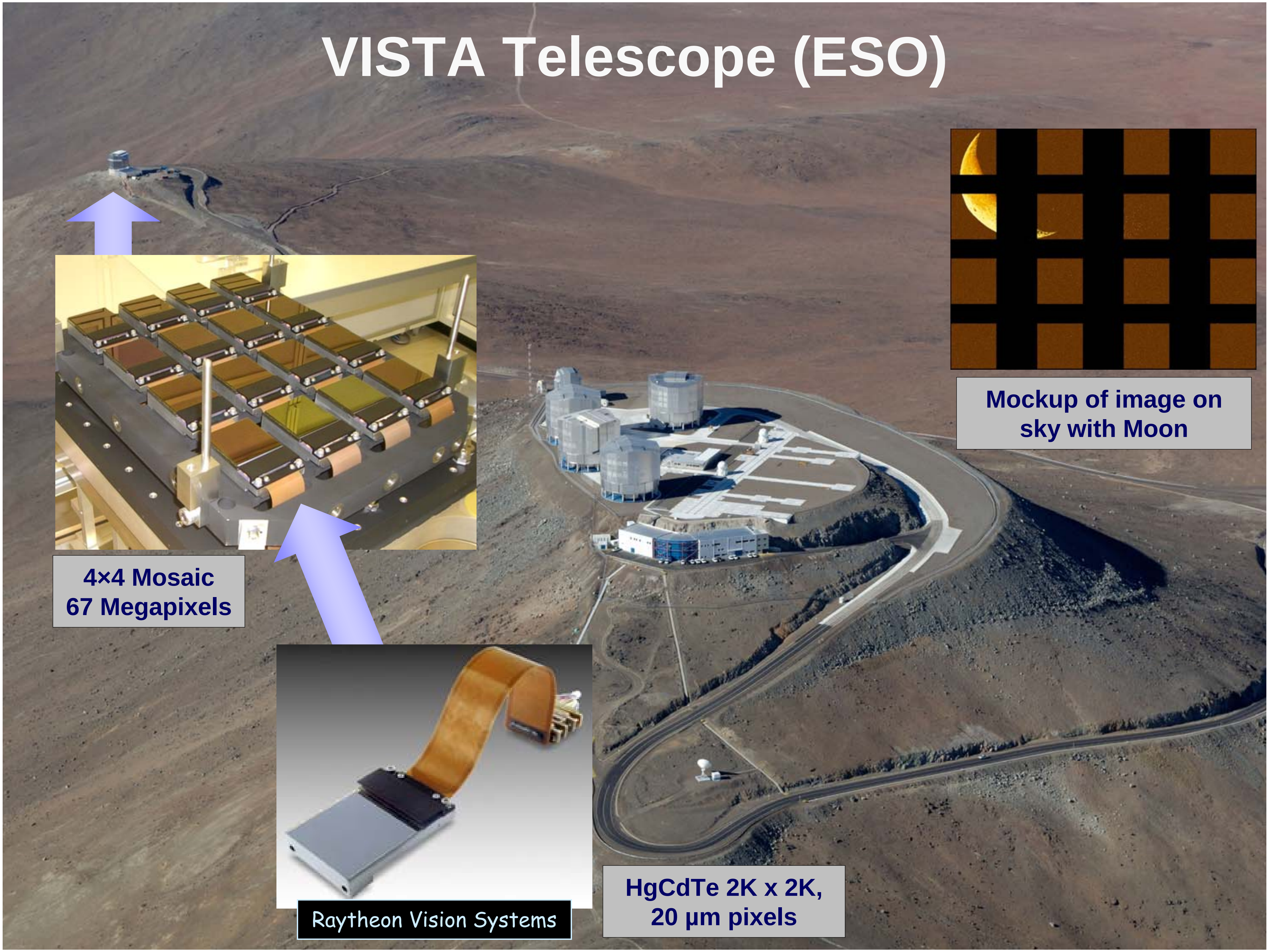
July 2007 - First light of HAWK-I (High Acuity, Wide field K-band Imaging)

European Southern Observatory 4096x4096 pixel mosaic of H2RGs

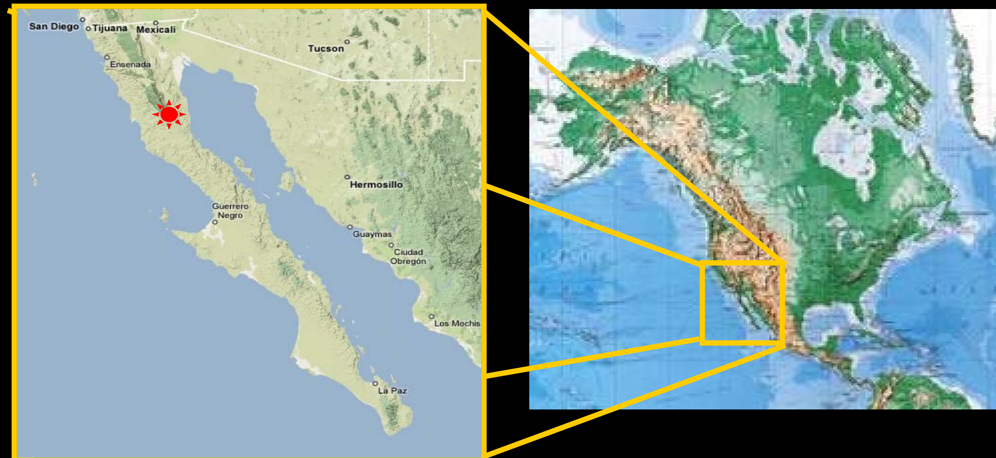
- 6th operational 4K×4K mosaic of H2 / H2RGs: ESO, Gemini, CFHT, UH, UKIRT, SOAR
- Two more 4K×4K mosaics to be commissioned in 2010: OCIW, MPIA

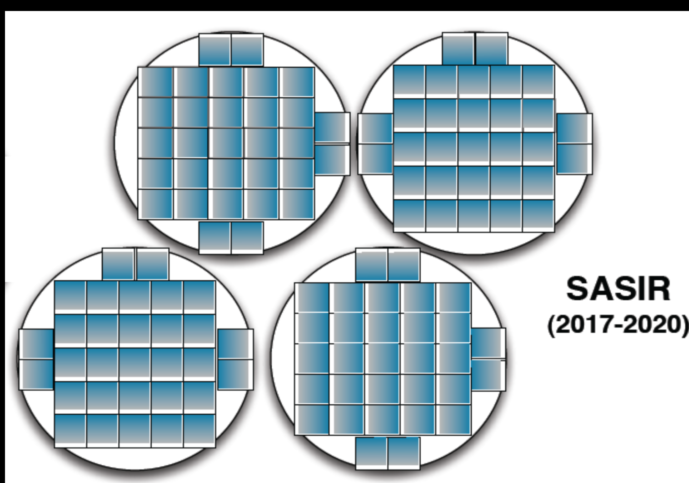
Serpens Star Forming Region
1 million year old stars

VISTA Telescope (ESO)



Synoptic All-Sky InfraRed (SASIR) Telescope





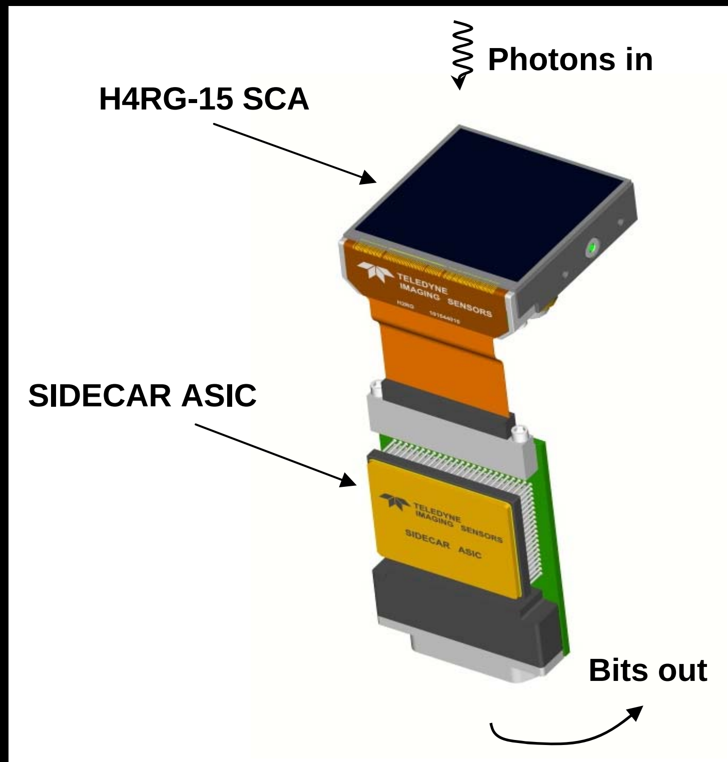
- 6.5-meter primary
- Four color camera
  - Y, J, H, K
- 31 2K×2K IR arrays for each channel
- 520 million IR pixels

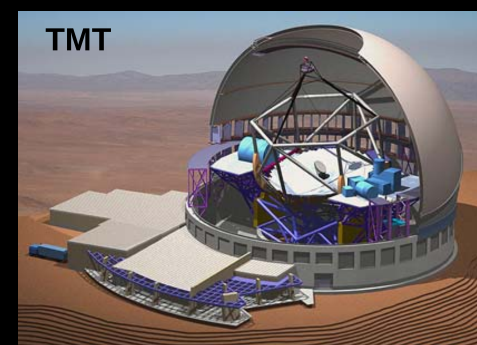
UNAM Universidad Nacional Autónoma de México

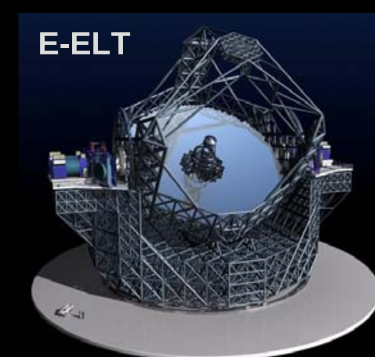
Instituto Nacional de Astrofísica, Óptica y Electrónica

ARIZONA

Large IR Astronomy Focal Plane Development
The Next Step: 4096×4096 pixels

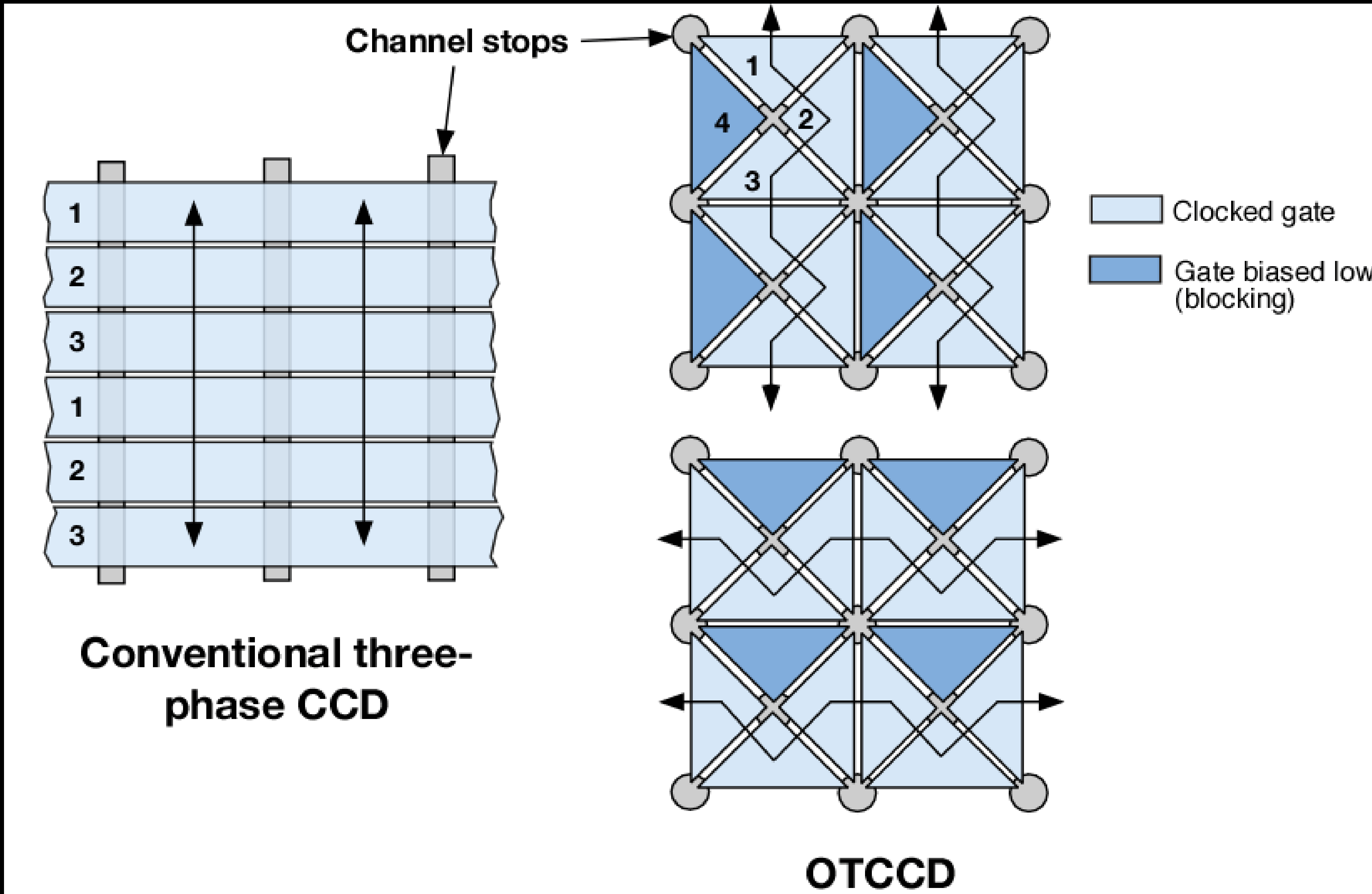






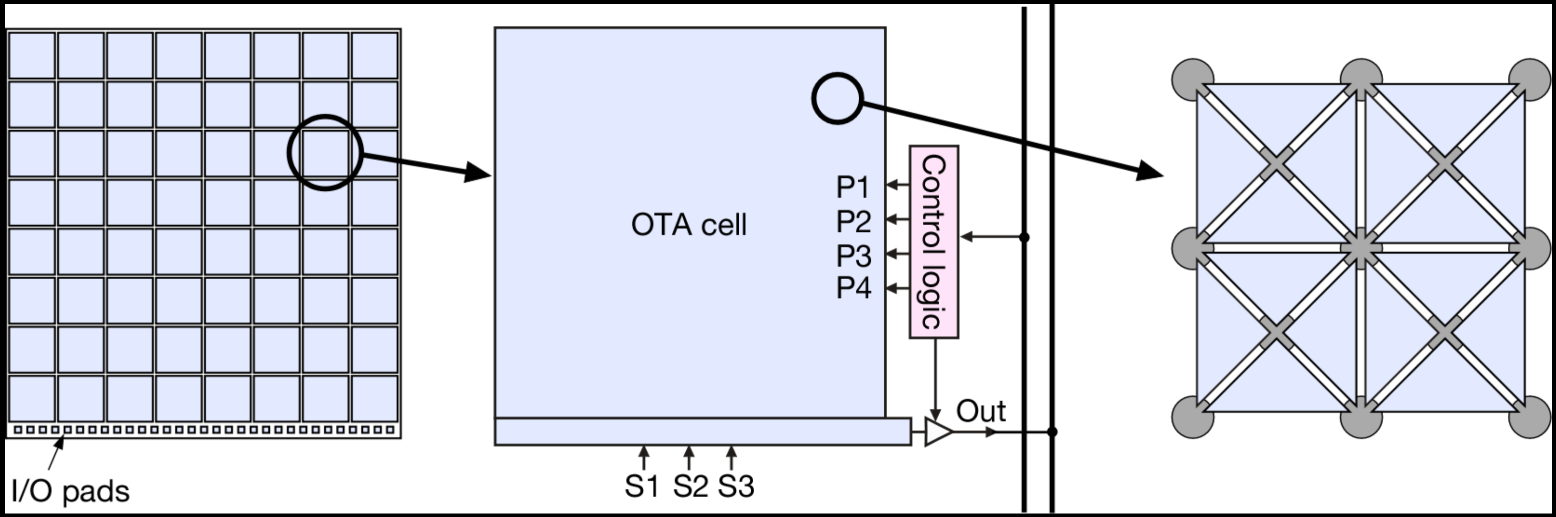
- **4096×4096, 15 µm array**
- **Design readout circuit for high yield**
  - 4 ROICs per 8-inch wafer
- **4-side buttable for large mosaics**
- **Developed for the Extremely Large Telescopes**

Conventional vs. Orthogonal-Transfer CCDs



MIT Lincoln Laboratory

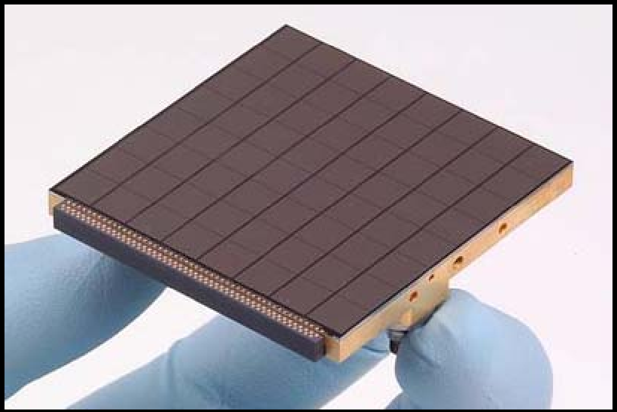
Orthogonal Transfer Array



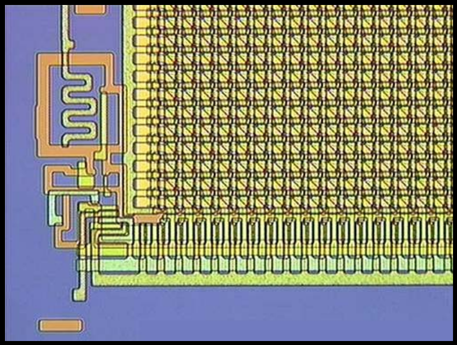
OTA: 8×8 array of OTCCD cells

OTA cell with I/O control

Four-phase OTCCD structure



- **New device paradigm**
  - 2D array of independent OTCCDs
  - Independent clocking and readout of OTCCDs
- **Advantages**
  - Enables spatially varying tip-tilt correction
  - Isolated defective cells tolerable (higher yield)

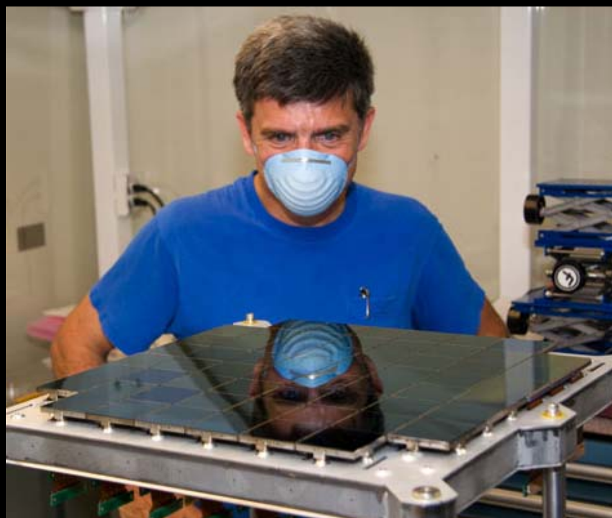


~250 microns

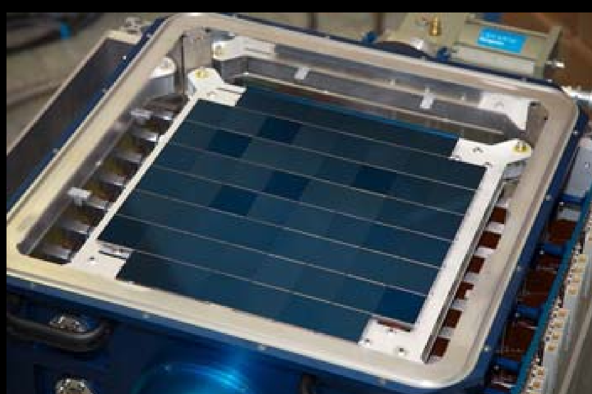
MIT Lincoln Laboratory

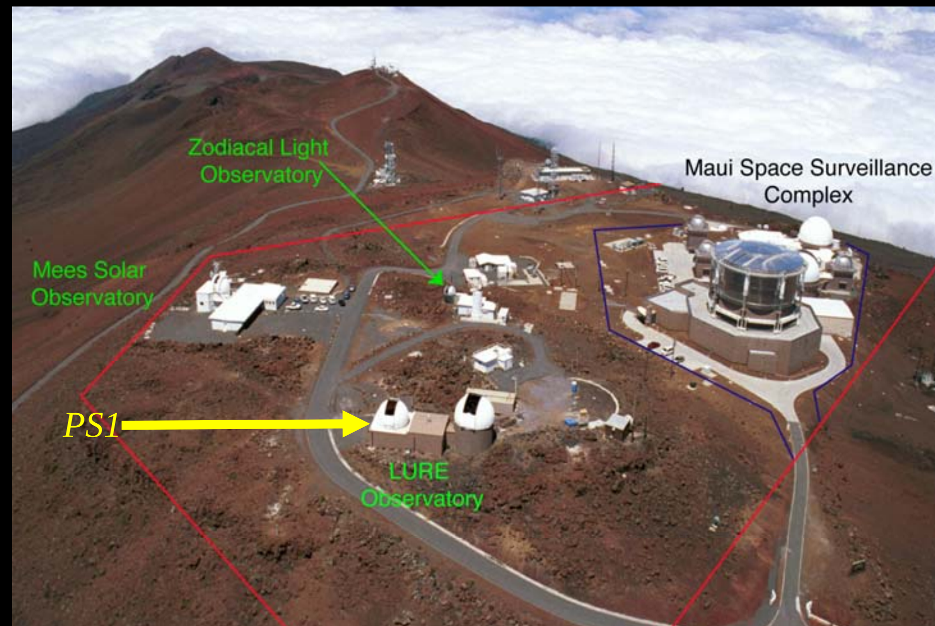
Pan-STARRS 1 on Haleakala (Maui)

1.4 Gigapixel array of orthogonal transfer CCDs

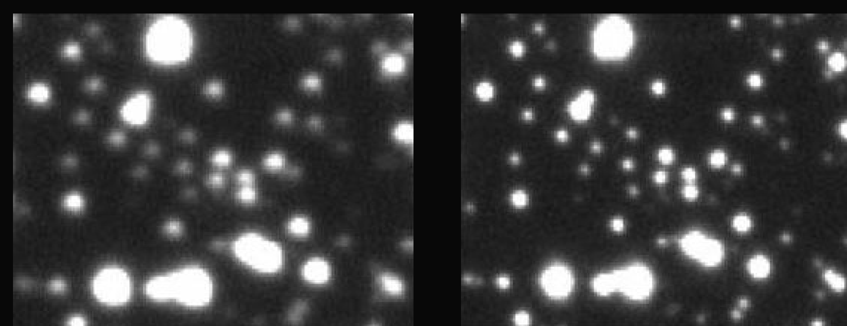


John Tonry & his masterpiece



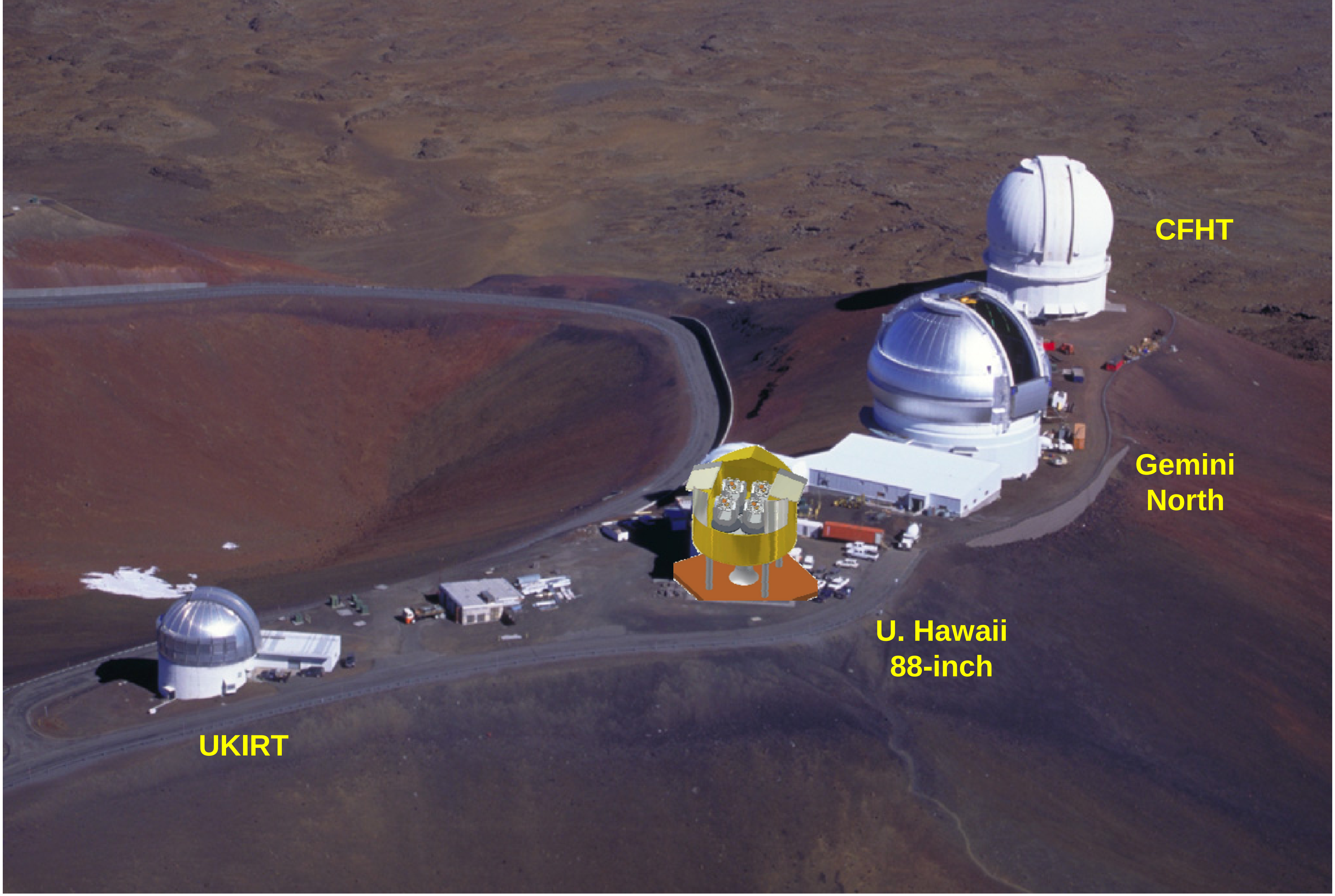


First Gigapixel array installed in August 2007



Improved resolution from OTCCD Tip-Tilt Correction

Pan-STARRS4 on Mauna Kea



Avalanche Process before Charge-to-Voltage Conversion

Potential for noiseless photon counting

Anti-reflection coating
Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InSb, Si:As

2. Charge Generation

Electric Fields in detector
collect electrical charge

3. Charge Collection

Avalanche Photodiode

CCD

Charge coupled transfer

4. Charge Transfer

EM CCD

MOSFET Amplifier

5. Charge-to-Voltage Conversion

CMOS

4. Charge-to-Voltage Conversion

Source follower, CTIA, DI

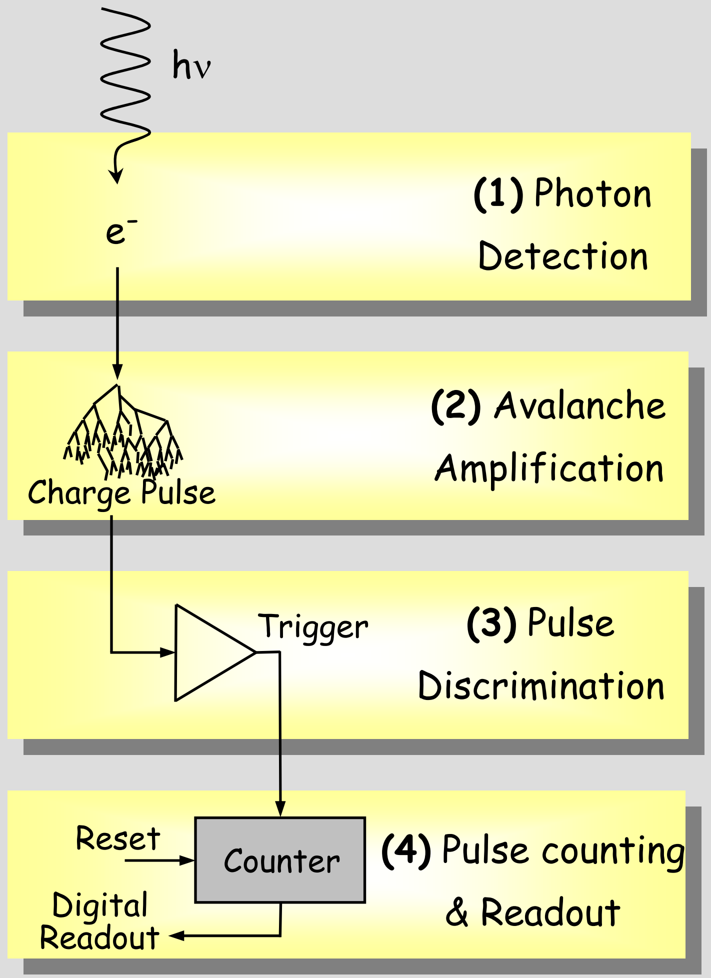
5. Signal Transfer

Random access or full frame read

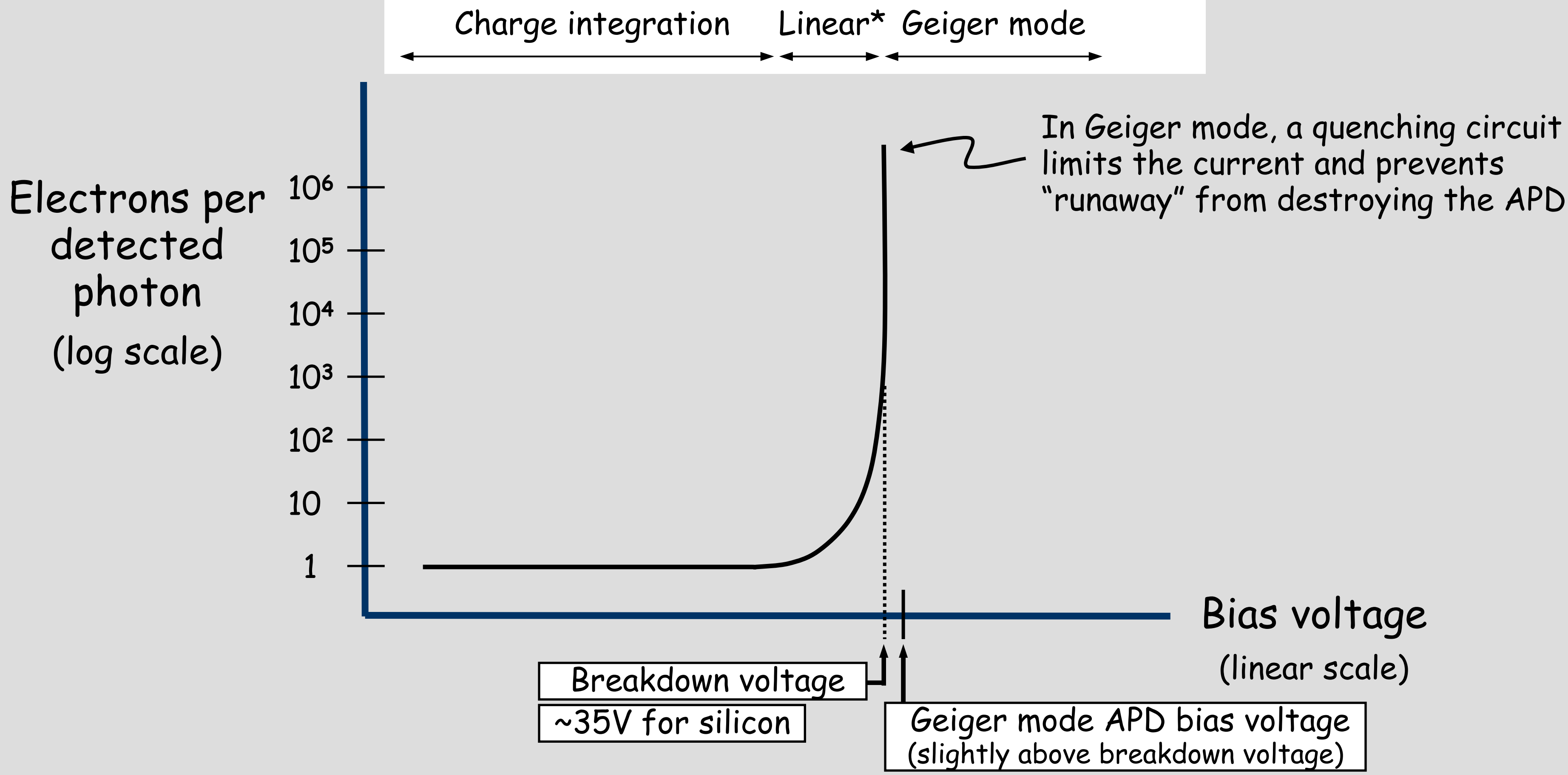
6. Digitization

Geiger APD Sensor architecture

- Four main parts
  1) Photon detection
  2) Avalanche amplification (pulse generation)
  3) Pulse discrimination
  4) Photon counting and readout circuitry
- CMOS circuit used for (3) and (4)
- For (1) and (2) - two options:
  a) Part of CMOS circuit
  b) Put APD into detector material and hybridize to CMOS circuitry



Mode of operation of an APD



*Linear mode operation of APD

In this mode, the total number of electrons collected in each pixel is a linear function of the number of detected photons.

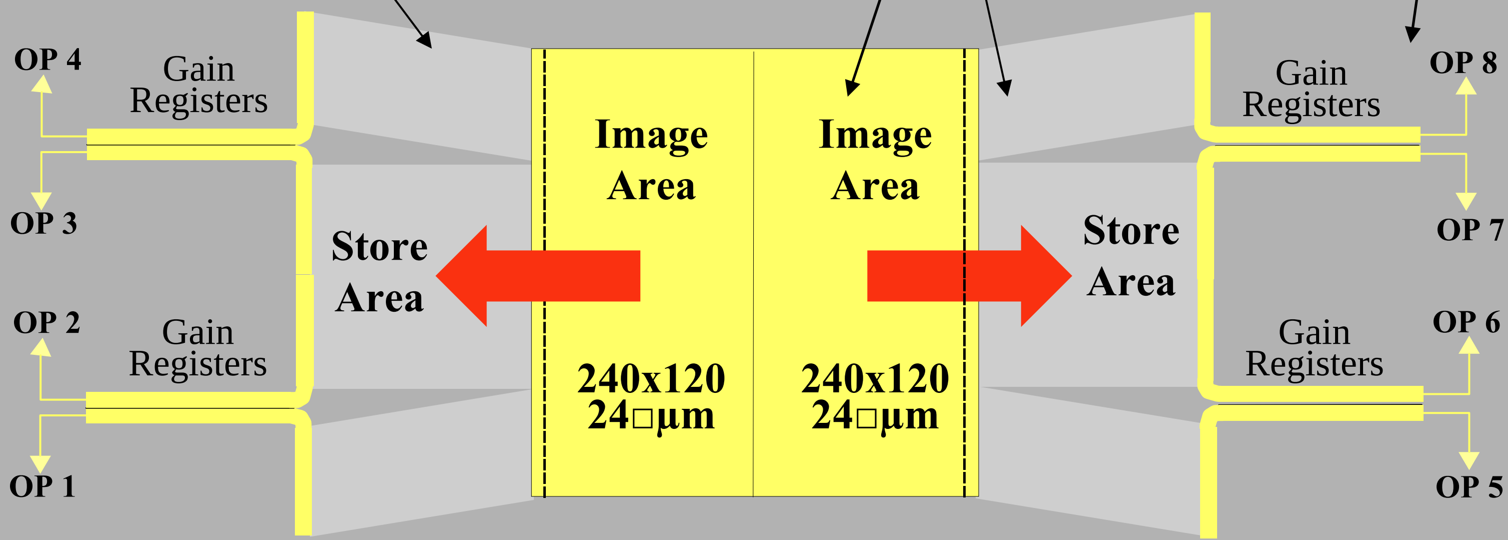
- However, the amplification process is statistical and there is "excess noise" in linear mode.
- HgCdTe may be a special material with very little excess noise (few %) for avalanching under the appropriate conditions.
    - Electron avalanche HgCdTe (e-APD) with ~5 micron cutoff material (X ~ 0.33)
    - Hole avalanche HgCdTe (h APD) with ~1.7 micron cutoff material (X ~ 0.63)

e2v L3CCD – Serial Gain Register

Store slanted
to allow multiple outputs.

Metal Buttressed 2Φ 10 Mhz
For fast image to store transfer rates.

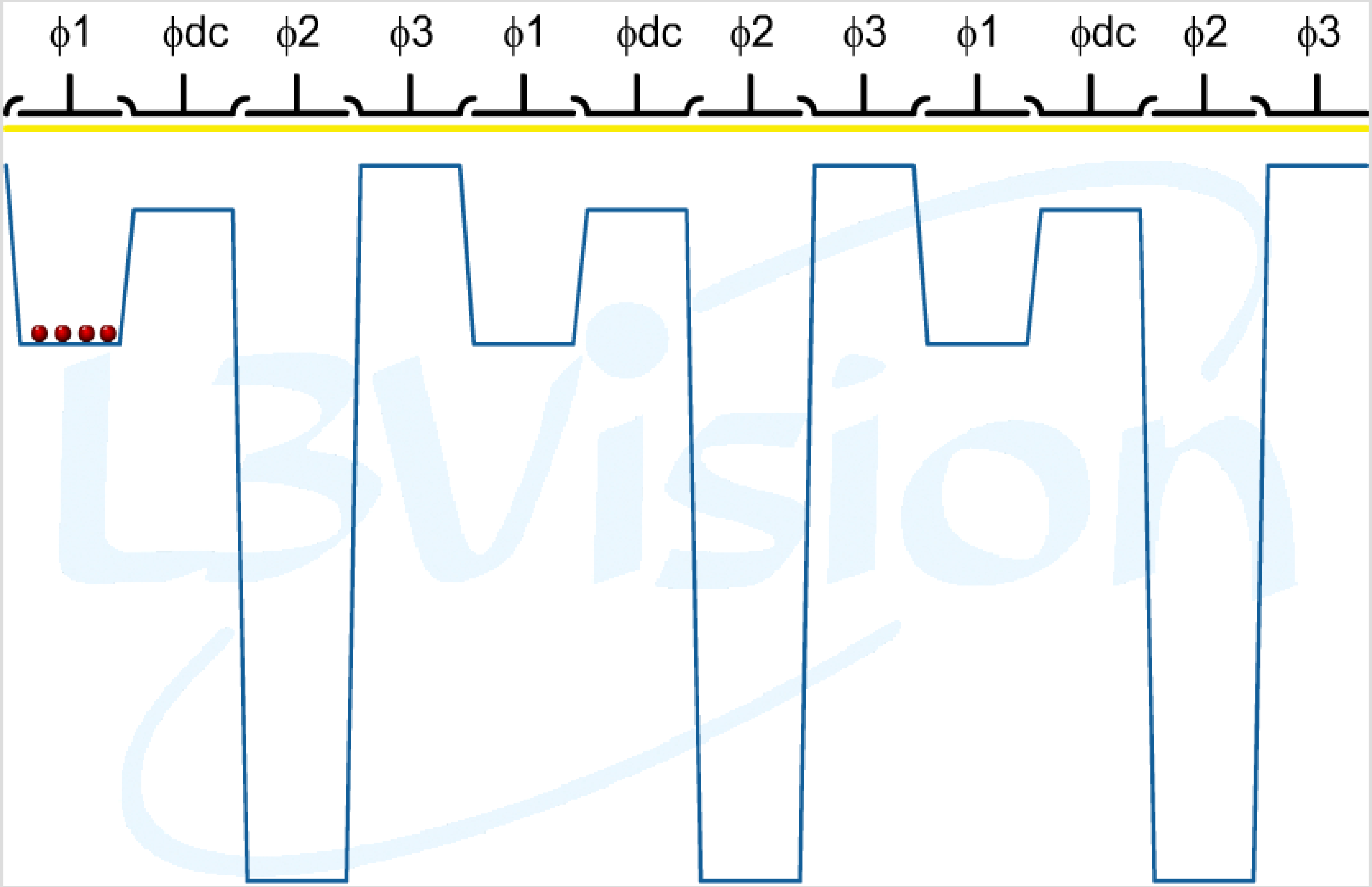
8 L3Vision Gain Registers/Outputs.
Each 15Mpix./s.



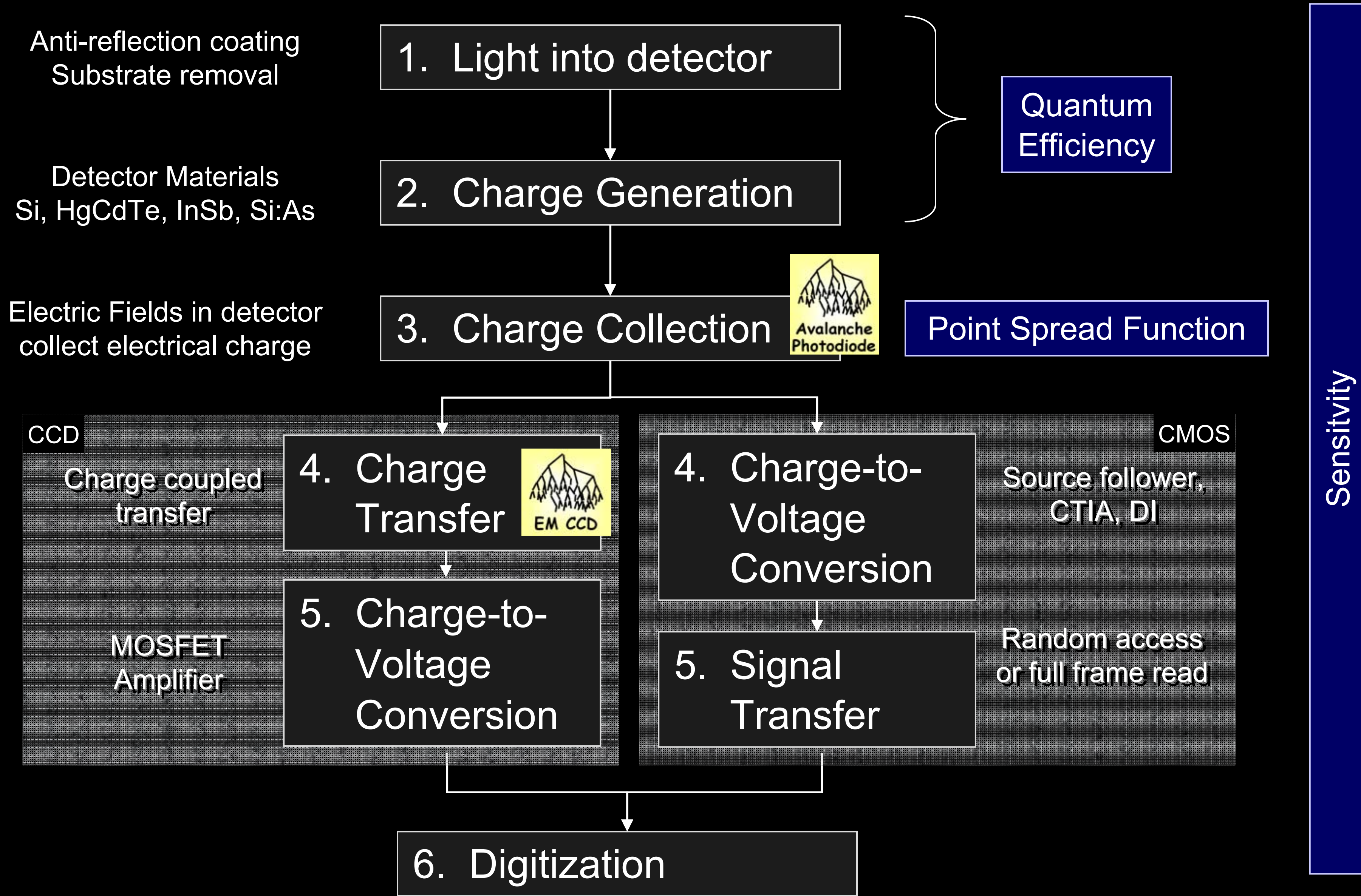
Split frame transfer 8-output back-illuminated e2v L3Vision CCD.

e2v L3Vision Technology

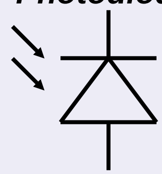
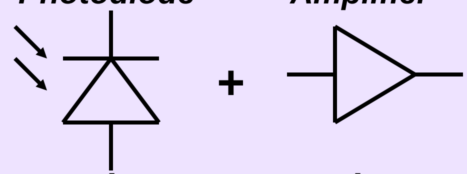
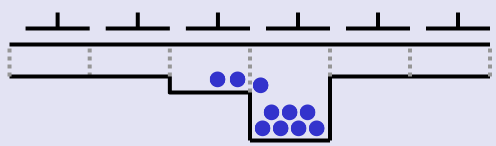
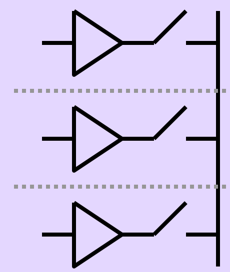
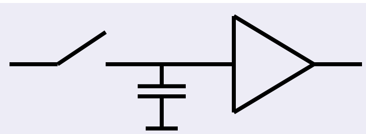
Effective noise is $\sqrt{2}$ photon noise



6 steps of optical / IR photon detection



CCD / CMOS Comparison

	CCD Approach	CMOS Approach
Pixel	*Photodiode*  Charge generation & charge integration	*Photodiode* *Amplifier*  Charge generation, charge integration & charge-to-voltage conversion
Array Readout	 Charge transfer from pixel to pixel	 Multiplexing of pixel voltages: Successively connect amplifiers to common bus
Sensor Output	 Output amplifier performs charge-to-voltage conversion	Various options possible: - no further circuitry (analog out) - add. amplifiers (analog output) - A/D conversion (digital output)

CMOS = Complimentary Metal Oxide Semiconductor

Comparison CMOS vs. CCD for Astronomy

Property	CCD	Hybrid CMOS
Resolution	> 4K x 4K	up to 4K x 4K
Pixel pitch	10 – 20 µm	10 – 40 µm (up to 100 µm if required)
Typical wavelength coverage	400 – 1050 nm	400 – 1050 nm with Si PIN 400 – 18,000 nm with HgCdTe 400 – 5,000 nm with InSb
Noise	Few electrons	Few electrons with multiple sampling
Shutter	Mechanical	Electronic, rolling shutter, snapshot
Power Consumption	High	Typ. 10x lower than CCD
Radiation	Sensitive	Much less susceptible to radiation
Control Electronics	High voltage clocks, at least 2 chips needed	Low voltage only Can be integrated into single chip
Special Modes	Orthogonal Transfer Binning	Windowing, Guide Mode, Random Access, Reference Pixels, Large dynamic range (up the ramp)

- Silicon PIN hybrid detectors have become a serious alternative to CCDs providing a number of advantages, especially for space applications.
- **Backside illuminated monolithic CMOS** which combines the best of CMOS and CCD features will make major strides before the next detector workshop.

Thank you for your attention