Single Photon Counting in the X-ray, Visible and Infrared

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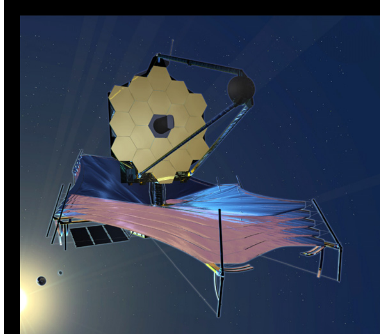
Teledyne

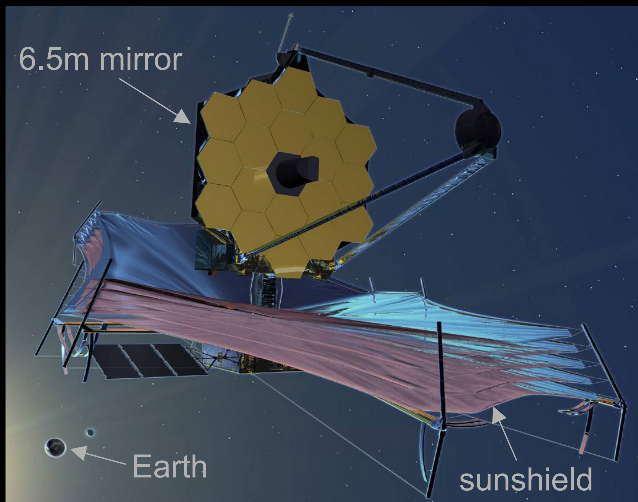
Providing the best images of the Universe




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)

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

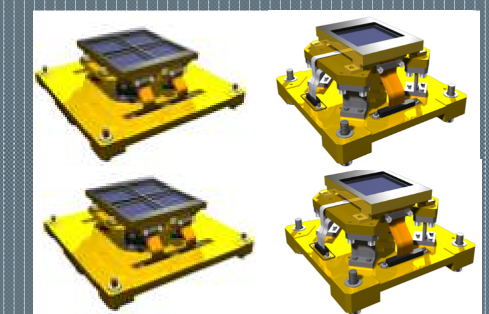
- Acquisition and guiding
- Images guide stars for telescope stabilization
- Canadian Space Agency

NIRSpec
(Near Infrared Spectrograph)

1x2 mosaic of MWIR 2Kx2K

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

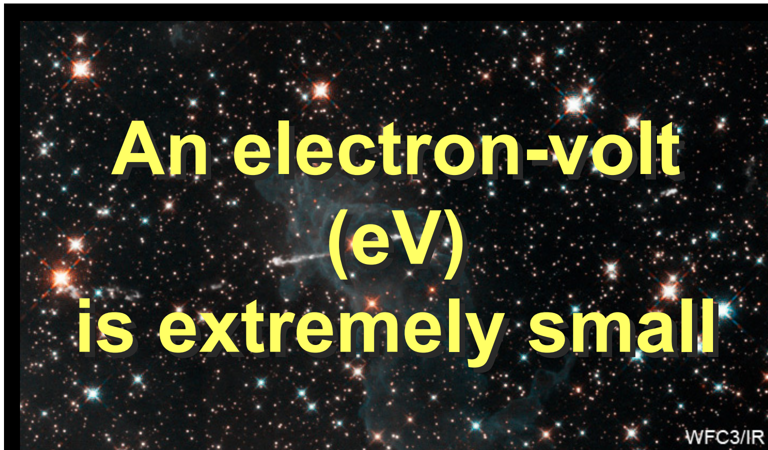
NIRCam
(Near Infrared Camera)



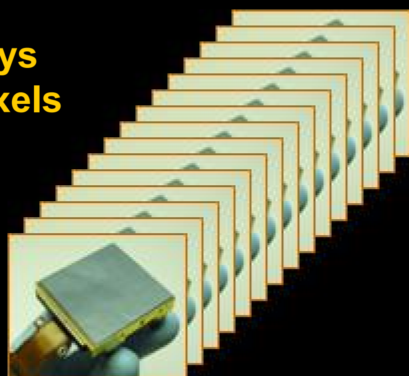
Two 2x2 mosaics of SWIR 2Kx2K

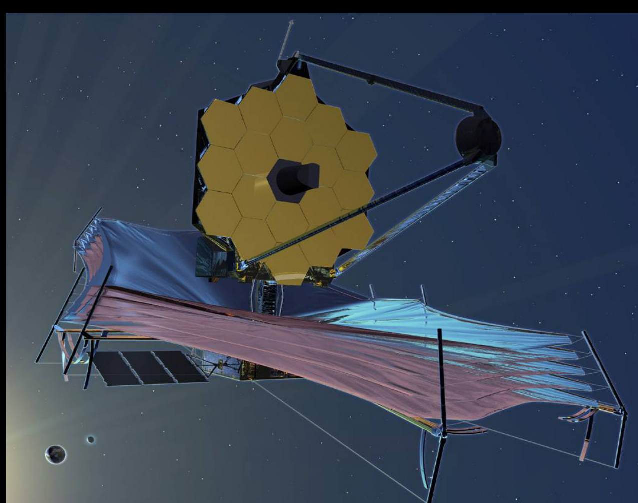
Two individual MWIR 2Kx2K

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



15 H2RG
2K×2K arrays
63 million pixels





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

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

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

- 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

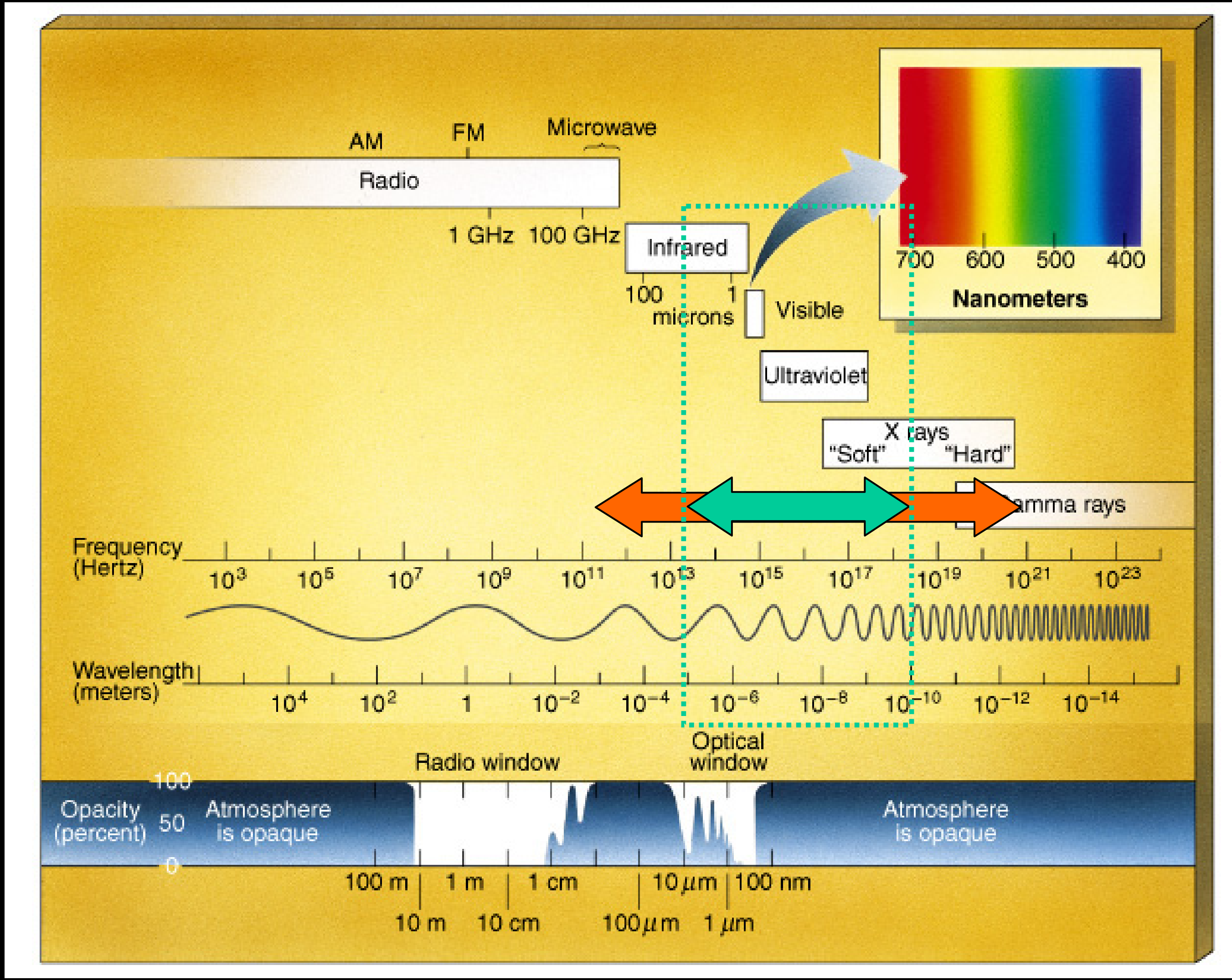
Full well
85,000 e-

  - Total # SWIR photons detected ≈ 3.6×10^{16}
  - Total energy detected ≈ 1.8×10^{16} eV
- Drop peanut M&M® candy (~2g) from height of 15 cm (~6 inches)
  - Potential energy ≈ 1.8×10^{16} eV

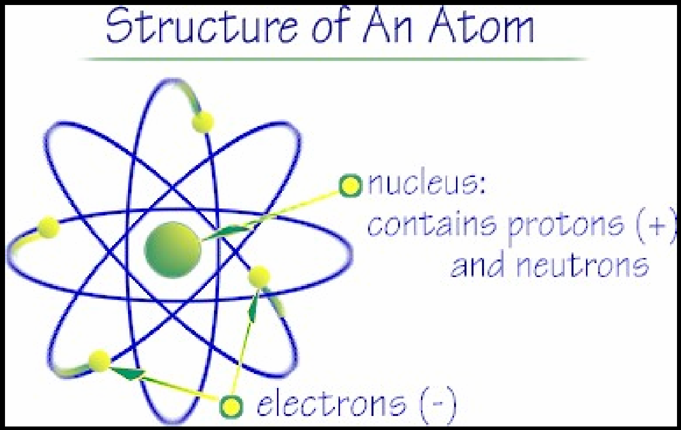
15 cm peanut M&M® drop is equal to the energy detected during 5 year operation of the James Webb Space Telescope!


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.
RATS. OK, I'LL TAKE A RED BULL.
I WAS HOPING FOR SOMETHING A LITTLE HIGHER-ENERGY.
AT LEAST IT ISN'T INFRARED BULL.
www.foxtrot.com

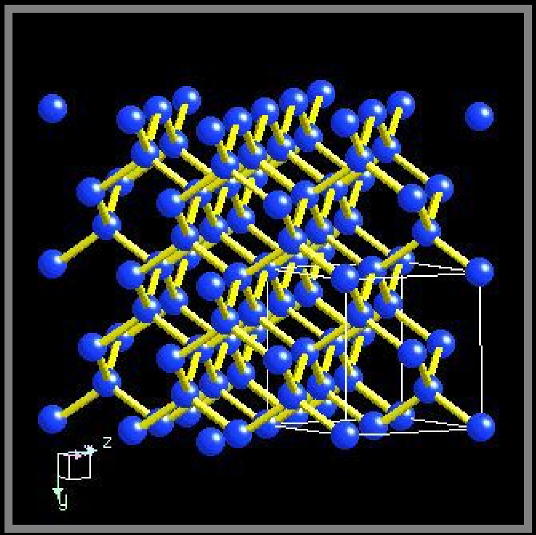
The Electromagnetic Spectrum



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.

Photon Detection…two "easy" pieces

Perfect Detector

Light Detection
$h\nu \rightarrow e^-$

- Detect 100% of the photons
- No dark current

Nearly perfect

Amplification
$e^- \rightarrow$ voltage

- Zero amplification noise
- High speed

This is the challenge

Periodic Table

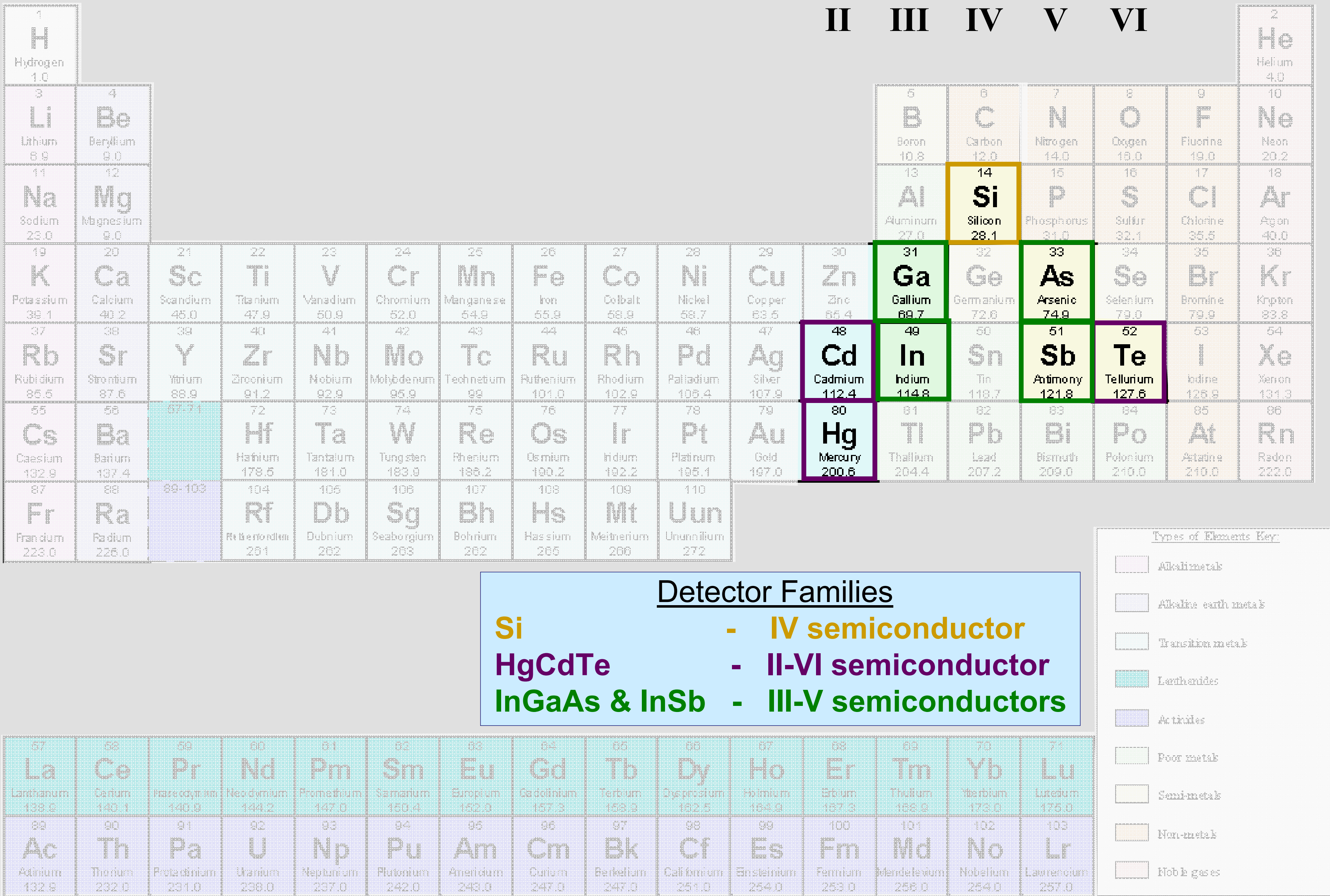
1 H Hydrogen 1.0																	2 He Helium 4.0
3 Li Lithium 6.9	4 Be Beryllium 9.0											5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2
11 Na Sodium 23.0	12 Mg Magnesium 9.0											13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	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

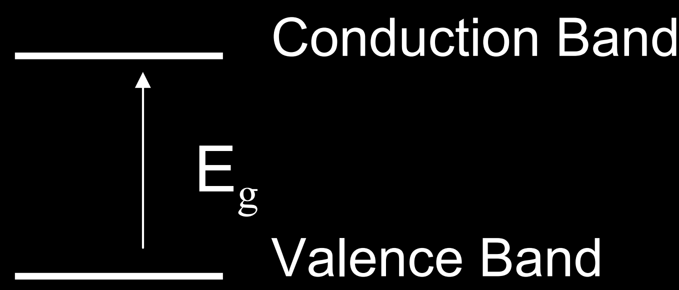
InGaAs & InSb - III-V semiconductors

Photon Detection

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

$$h\nu > E_g$$

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

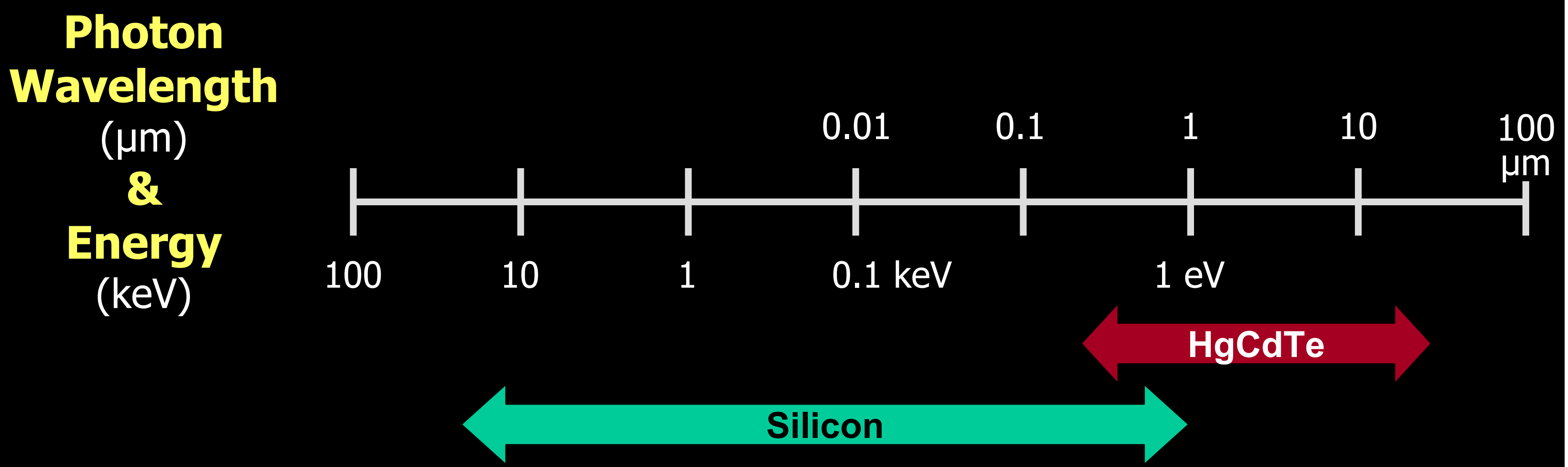


$$\lambda_c = 1.238 / E_g \text{ (eV)}$$

Material Name	Symbol	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 ($In_{0.53}Ga_{0.47}As$)

Silicon and HgCdTe – great but not yet perfect detectors of light



Silicon (Si)

- Indirect bandgap
  - Inefficient absorber of photons
- Quantum Yield
  - Multiple e^- per $h\nu$ for $\lambda \leq$
  - Single photon x-ray spectroscopy

HgCdTe

- Direct bandgap
  - Very efficient absorber of photons
  - Tunable bandgap
  - Excellent avalanche photodiode properties…the perfect APD?

Absorption Depth

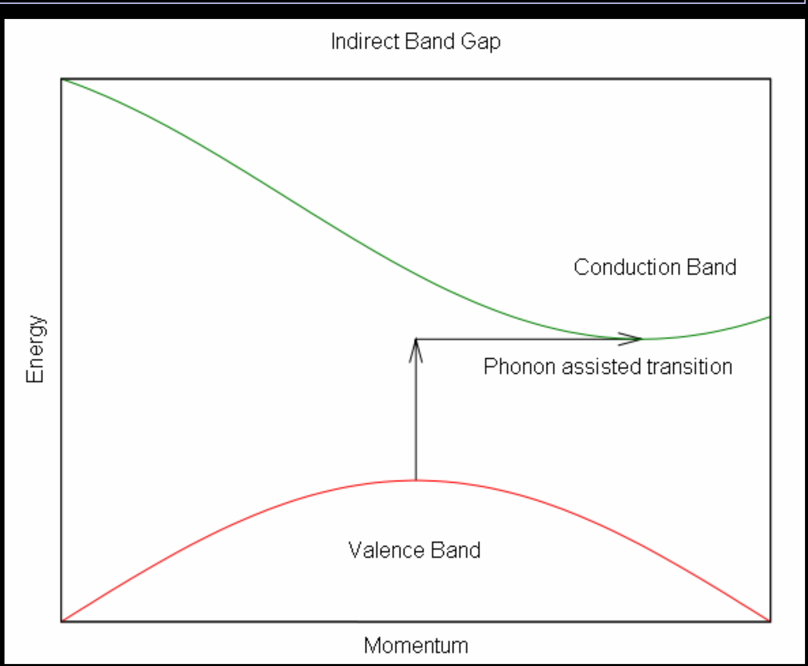
The depth of detector material that absorbs 63.2% of the radiation

(1-1/e) of the energy is absorbed

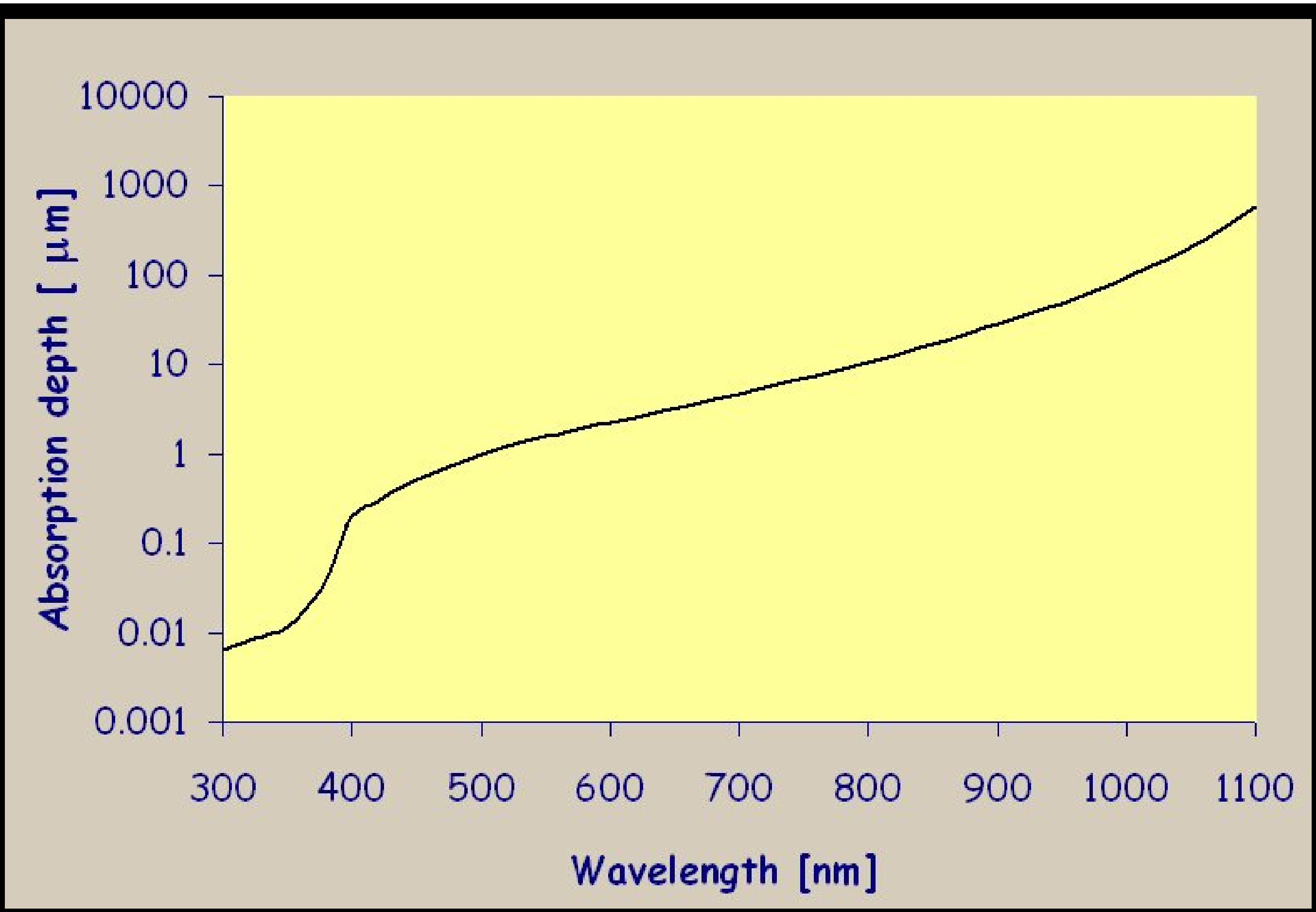
1 absorption depth(s)	63.2% of light absorbed
2	86.5%
3	95.0%
4	98.2%

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.



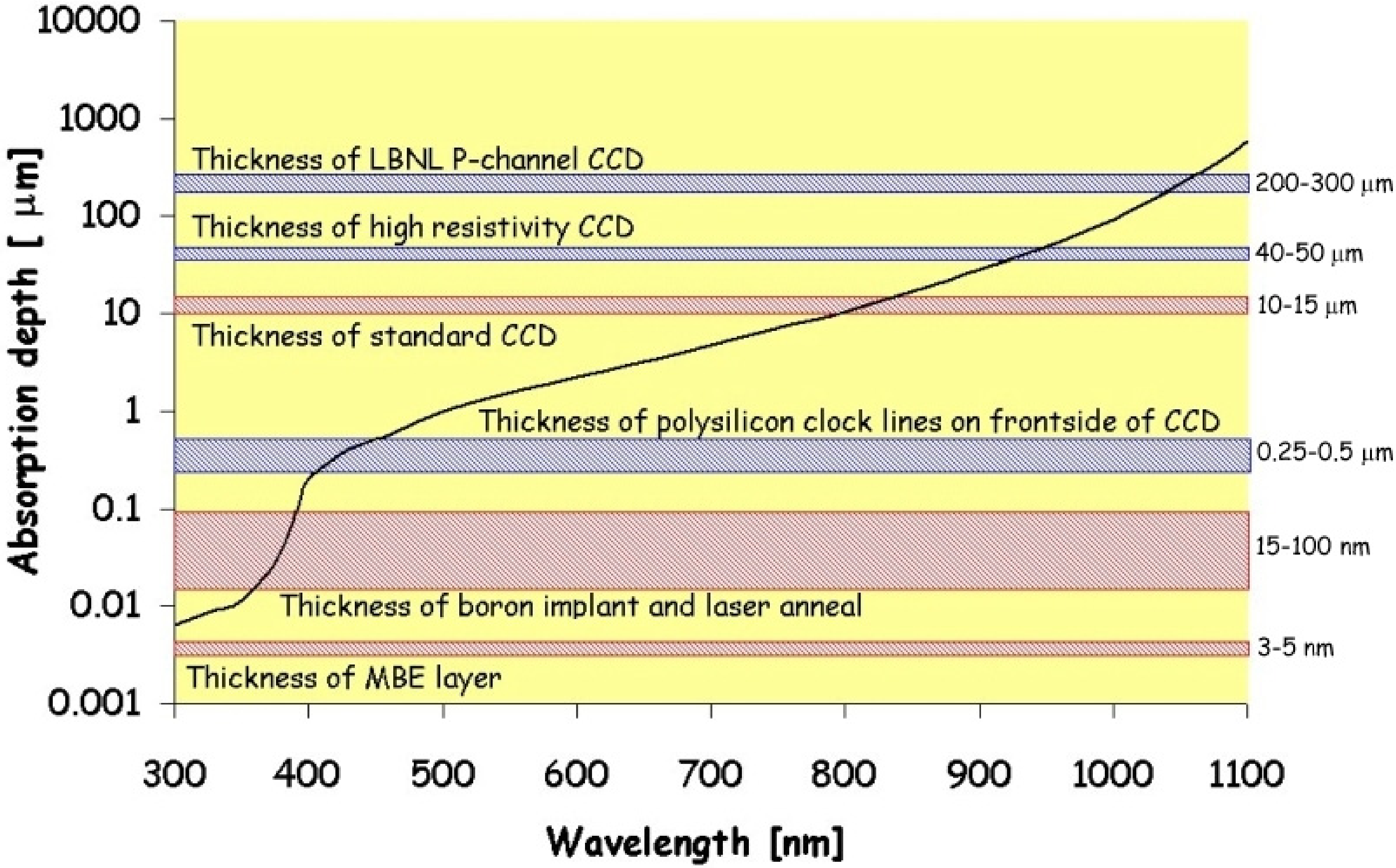
Absorption Depth of Silicon

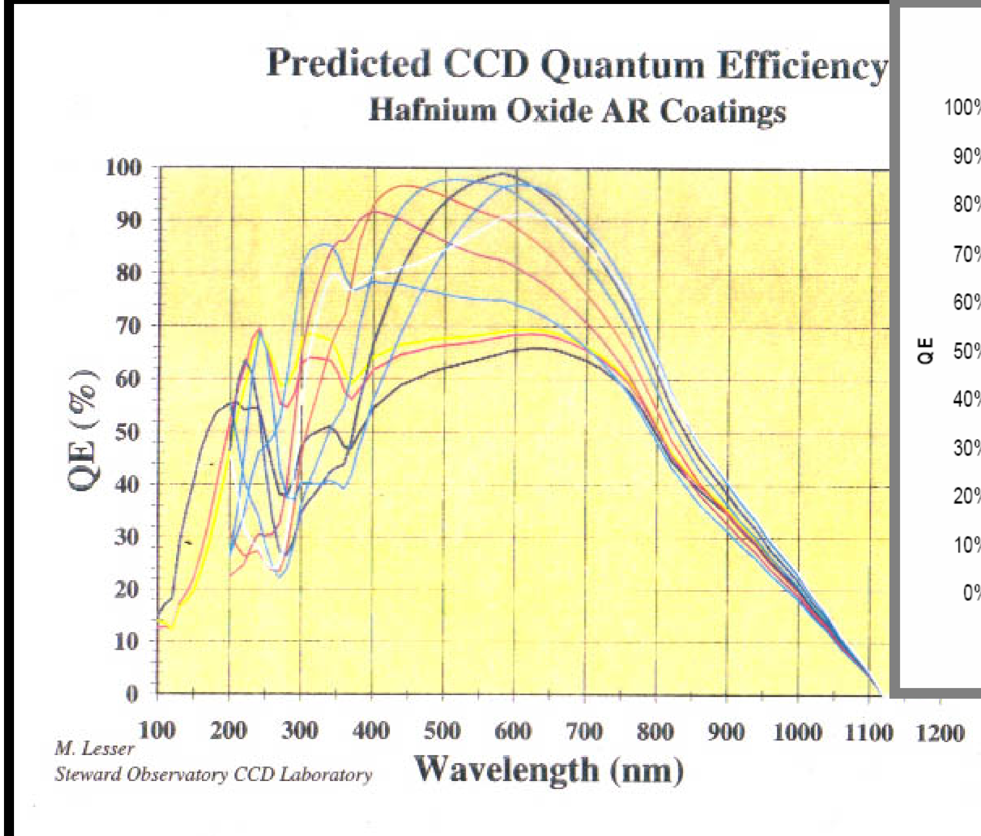


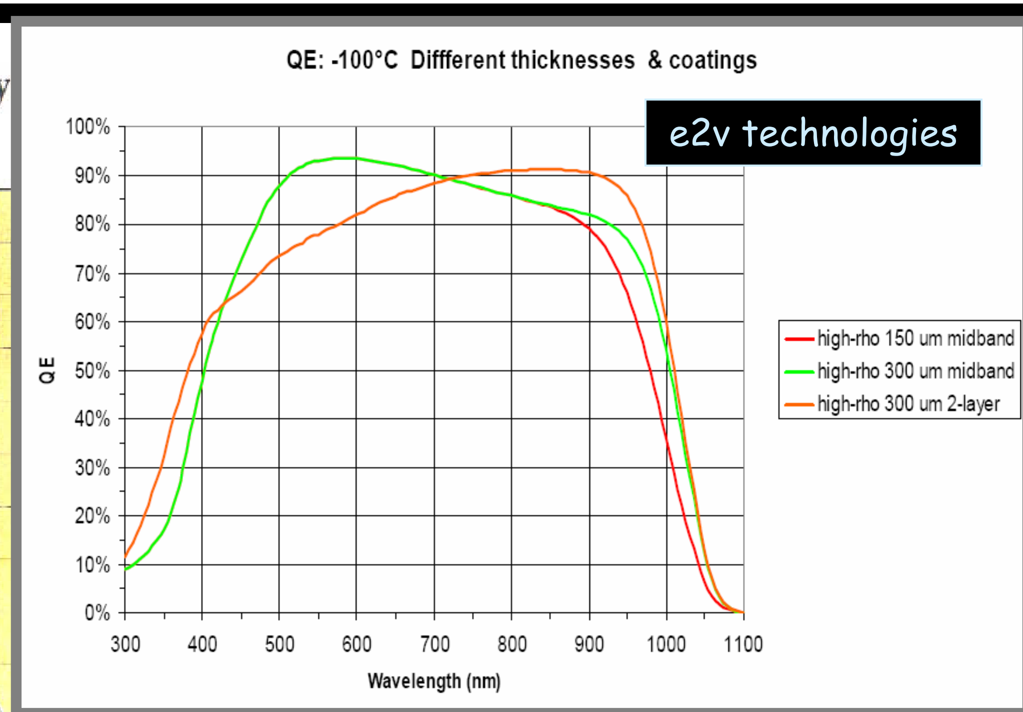
- For high QE in the near infrared, need very thick (up to 300 microns) silicon detector layer.
- For high QE in the ultraviolet, need to be able to capture photocharge created within 10 nm of the surface where light enters the detector.
- In addition, the index of refraction of silicon varies over wavelength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

Optical Absorption Depth in Silicon

(a.k.a. "The Beautiful Plot")

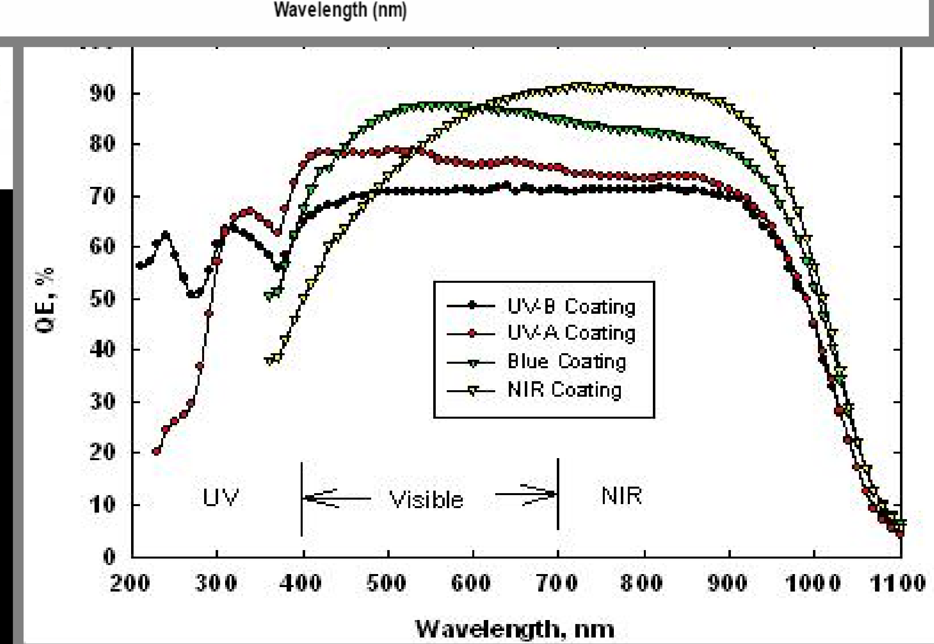






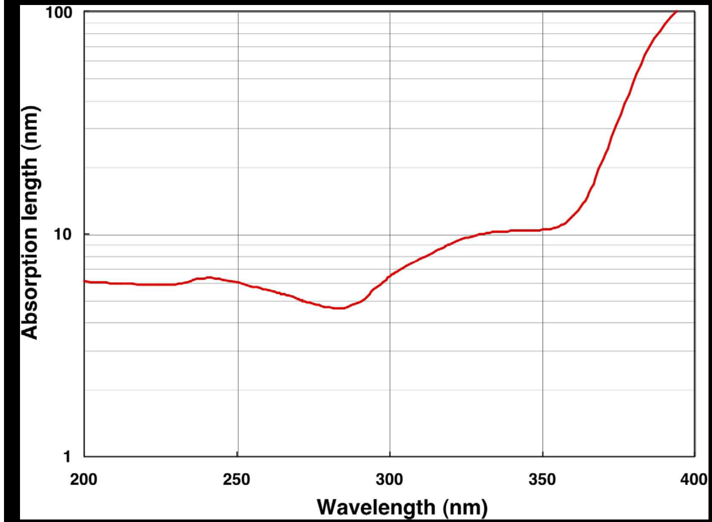
Quarter wave HfO_2 AR Coating

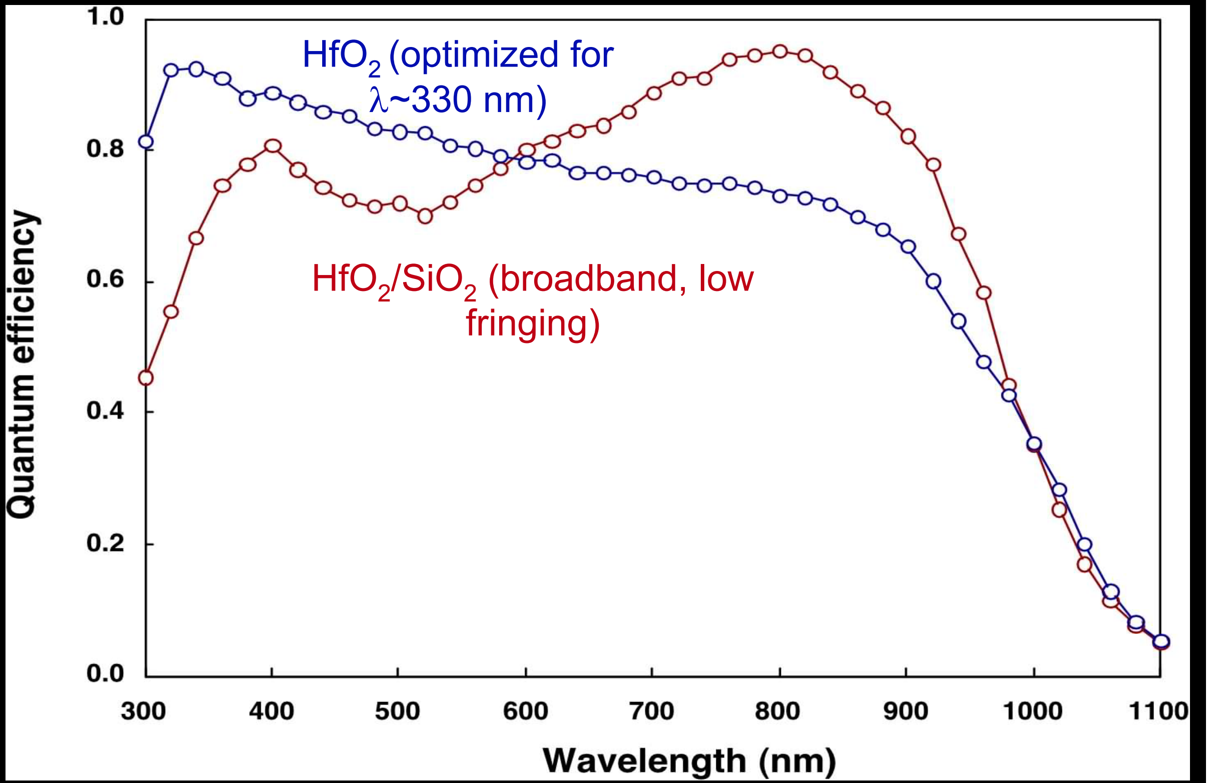
Mike Lesser, U. Arizona



Teledyne Imaging Sensors

Quantum Efficiency of AR-coated MBE Devices



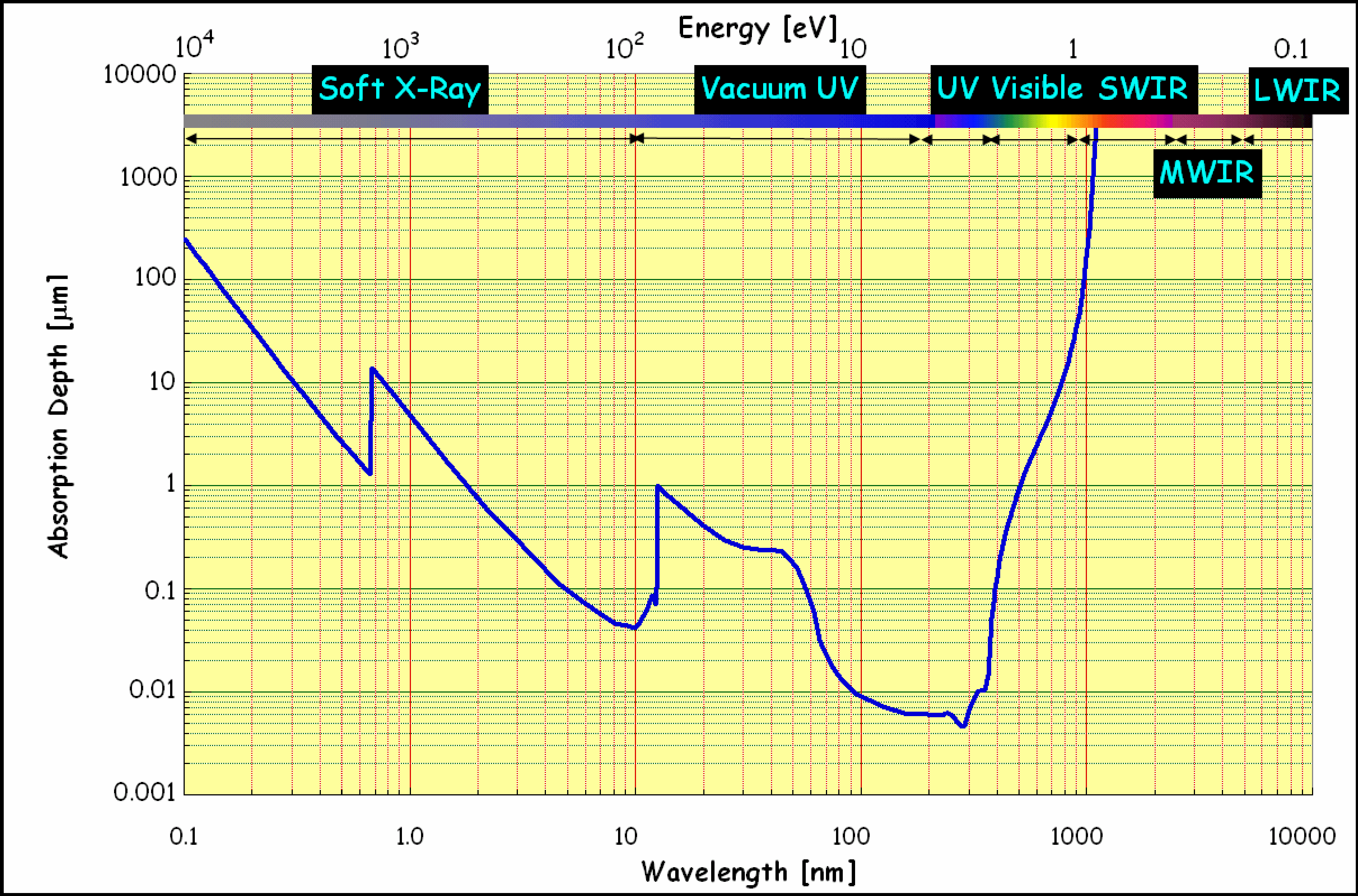


- UV (<400 nm) is challenging
  - Shallow penetration depth of radiation (<10 nm at λ=200-350 nm)
  - Requires extremely thin, doped surface layer

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

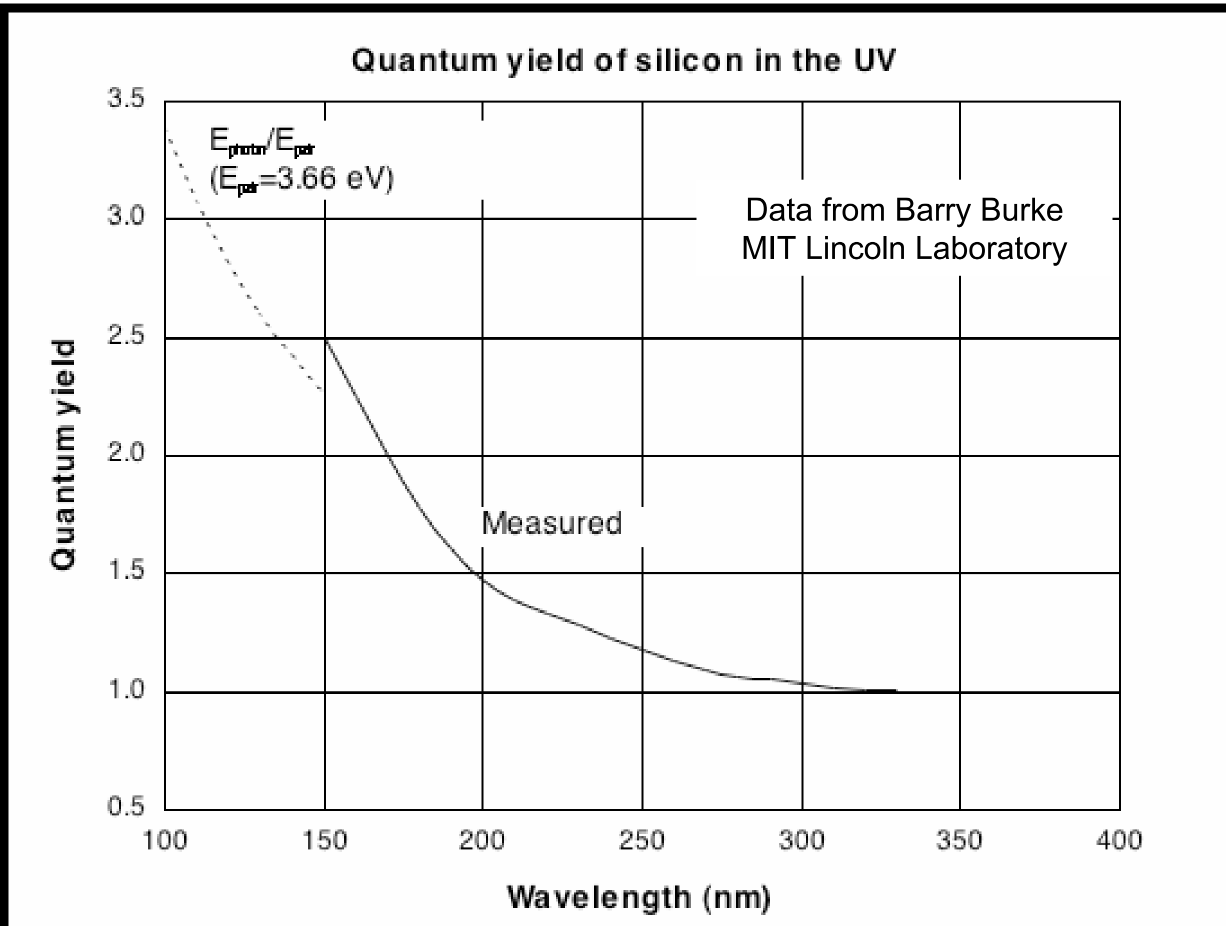
Barry Burke, MIT/LL

Absorption Depth of Light in Silicon



Quantum Yield

Number of photoelectrons for each photon



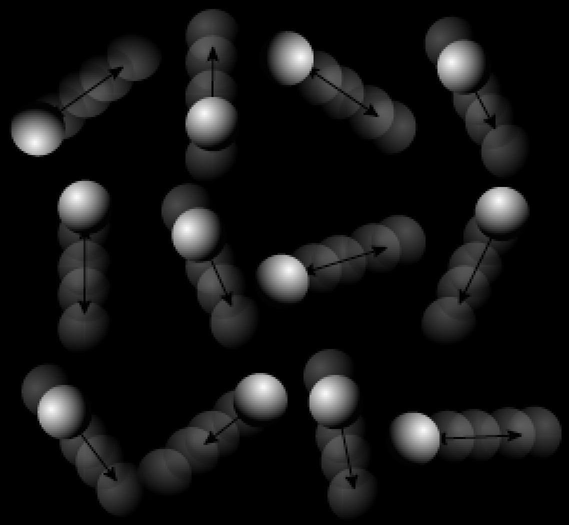
For wavelengths that are 30% to 100% of the cutoff wavelength, there will a single electron-hole pair created for every detected photon.

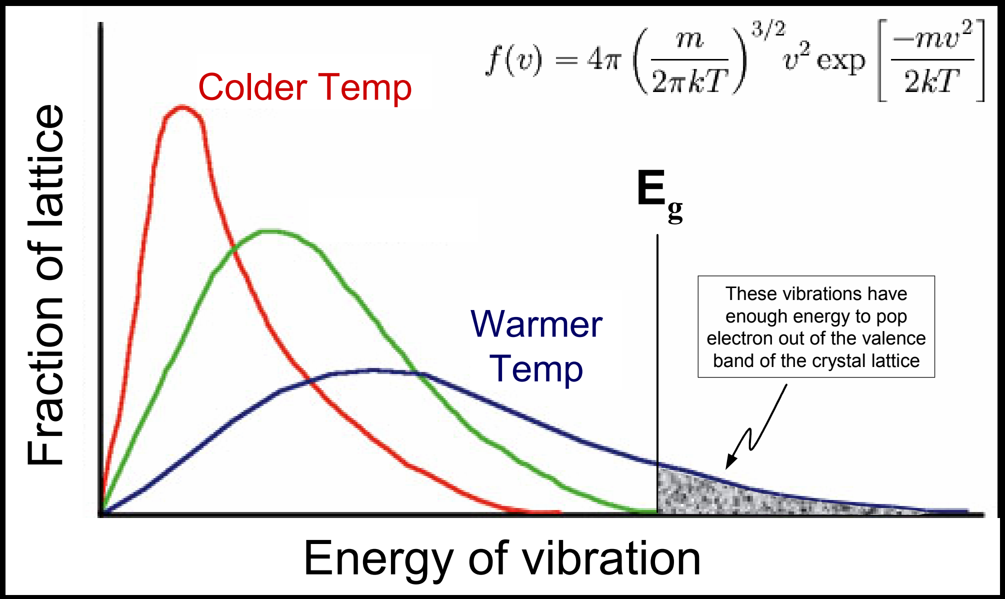
For shorter wavelengths (higher energies), there is an increasing probability of producing multiple electron-hole pairs.

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

Dark Current

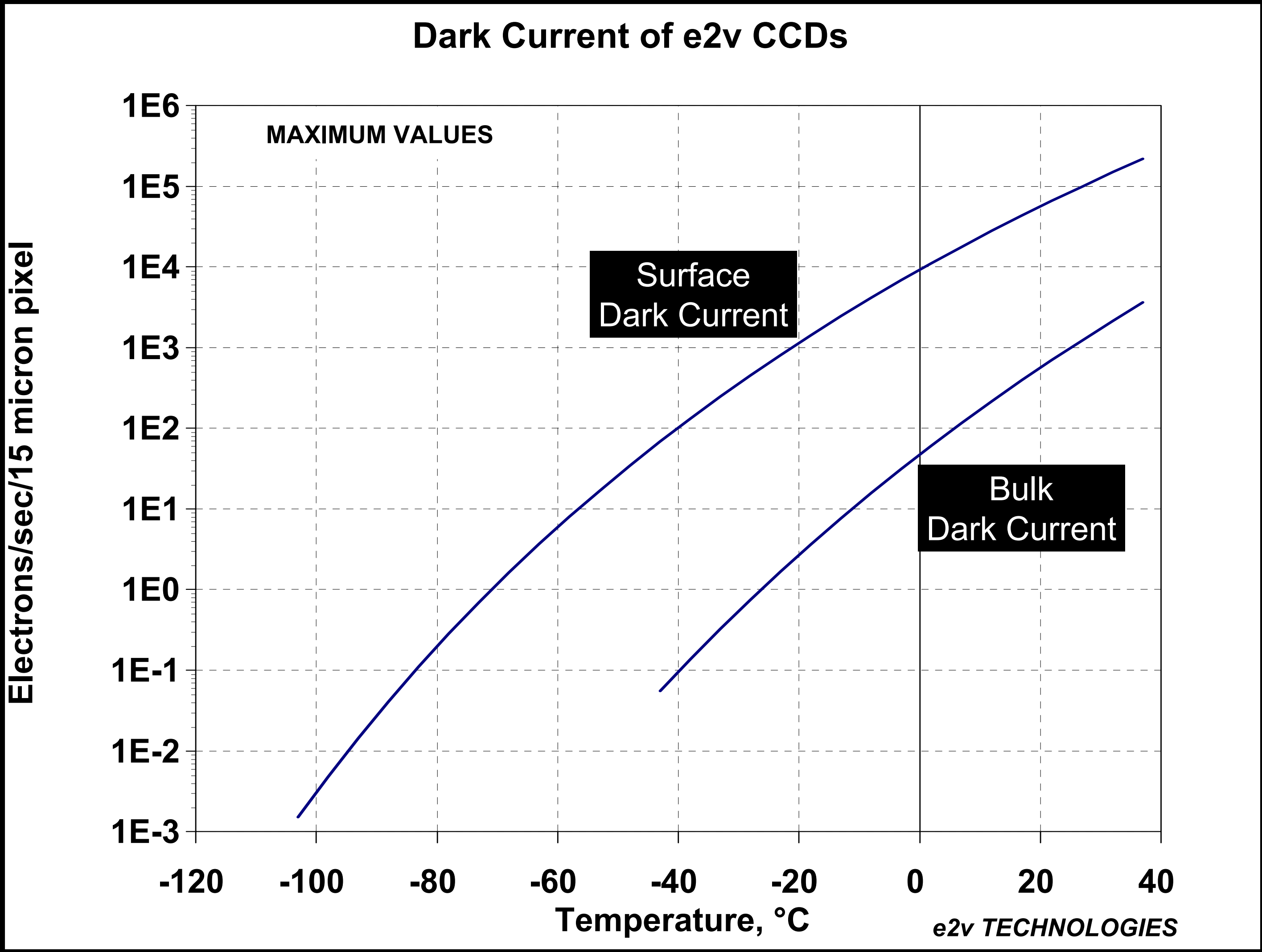
Undesirable byproduct of light detecting materials





- 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

Summary of Silicon Detector Properties

- High quantum efficiency possible
  - Need good anti-reflection coating
  - Need very thick detector layer for deep red / near IR and for soft x-ray
  - Need very good backside surface for UV

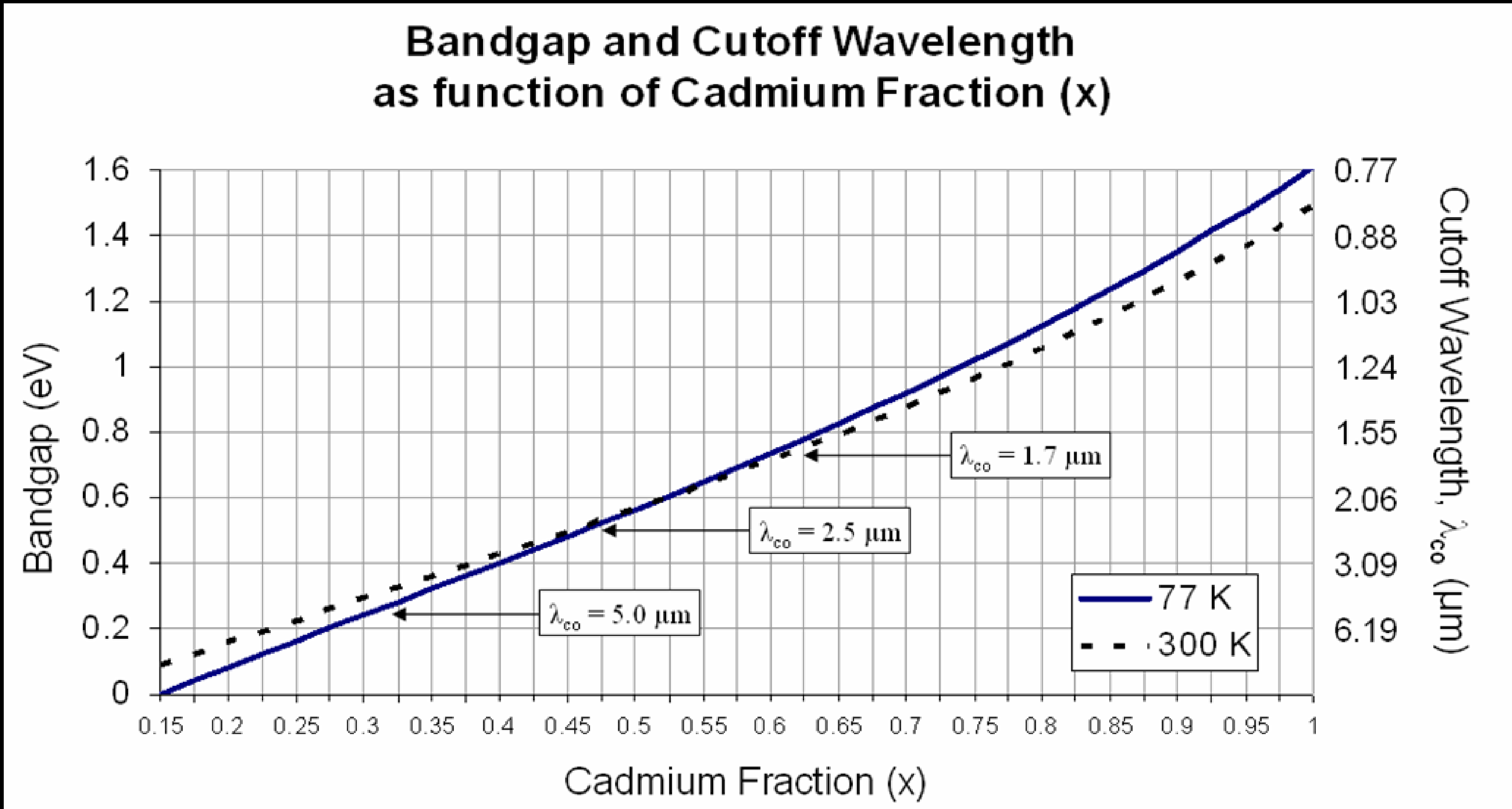
- Detectors can be cooled enough so that dark current is not an issue (<0.001 e-/pix/sec)

- Multiple electrons per x-ray photon enables x-ray spectroscopy

  ….with low noise readout circuit

Tunable Wavelength: Valuable property of HgCdTe

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



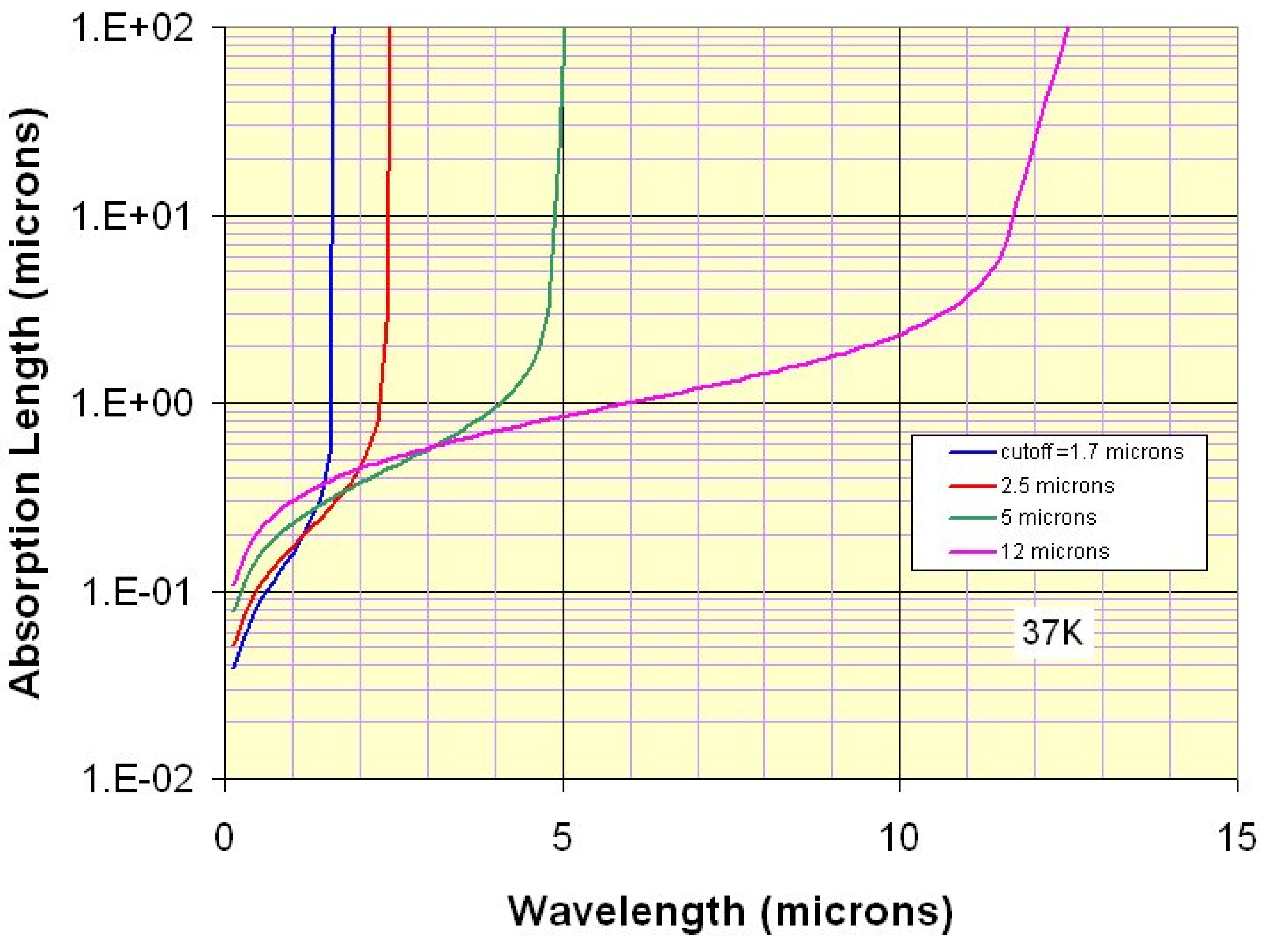
$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35\times10^{-4}\,T(1-2x)$$

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

Absorption Depth of HgCdTe

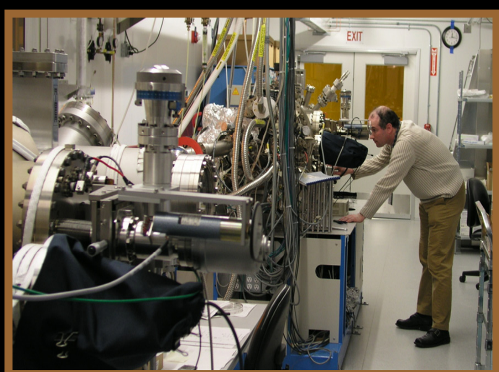
<u>Rule of Thumb</u>

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

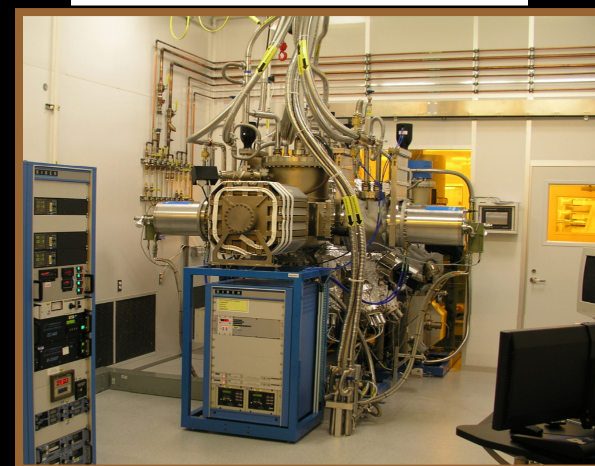


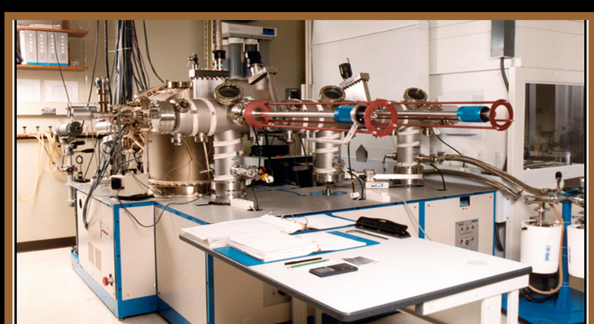
Two methods for growing HgCdTe

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



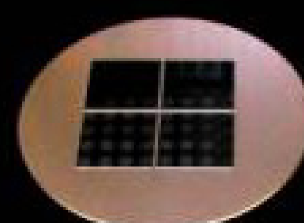
RIBER 10-in MBE 49 System





RIBER 3-in MBE Systems

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

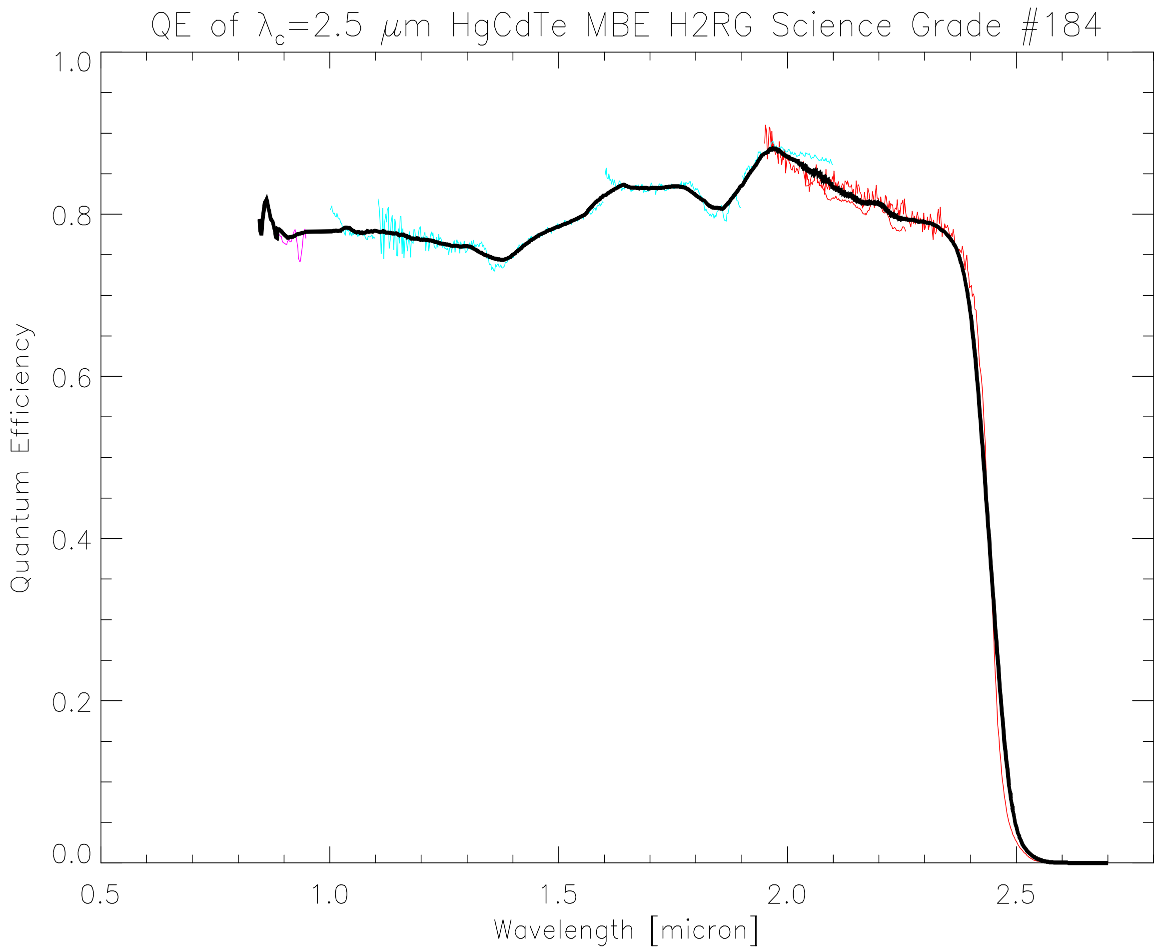


10 inch diameter platen allows simultaneous growth on four 6x6 cm substrates

More than 7500 MCT wafers grown to date

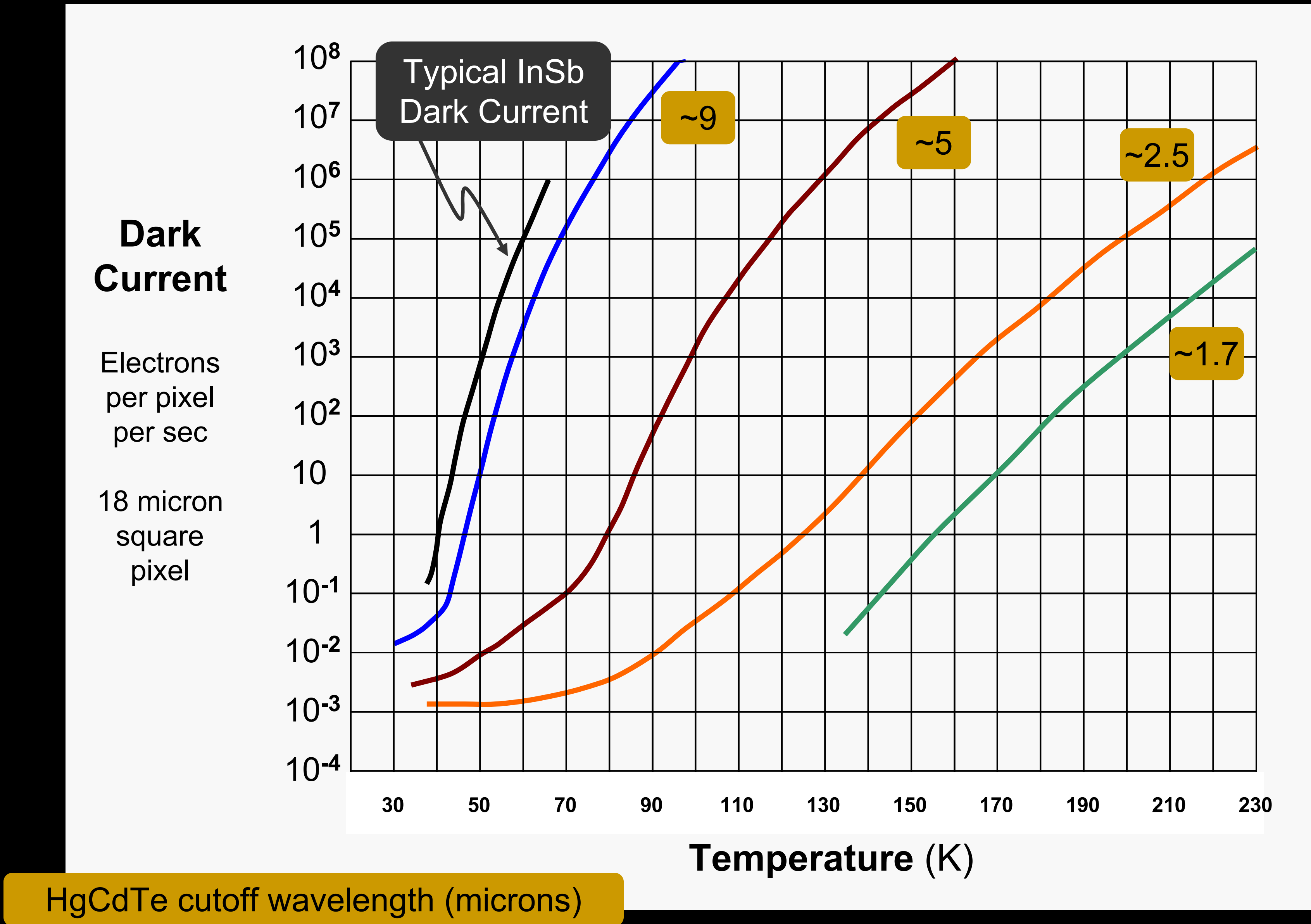
Teledyne Imaging Sensors

High Quantum Efficiency Visible – Infrared Measured by the European Southern Observatory



Data: Courtesy of ESO, KMOS project

Dark Current of HgCdTe Detectors



Summary of HgCdTe Detector Properties

- High quantum efficiency possible
  - Need good anti-reflection coating
  - Combined visible-infrared response
- Detector material is now so good that dark current is not an issue (0.005 e-/pix/sec)
- Quantum yield still under investigation
  - Some evidence shows multiple electrons start to be produced at 20% of bandgap, but data is sparse
  - For today's talk, think of HgCdTe as producing one electron-hole pair for every absorbed photon

Photon Detection…two "easy" pieces

Perfect Detector

Light Detection

$h\nu \rightarrow e^-$

- Detect 100% of the photons
- No dark current

Nearly perfect

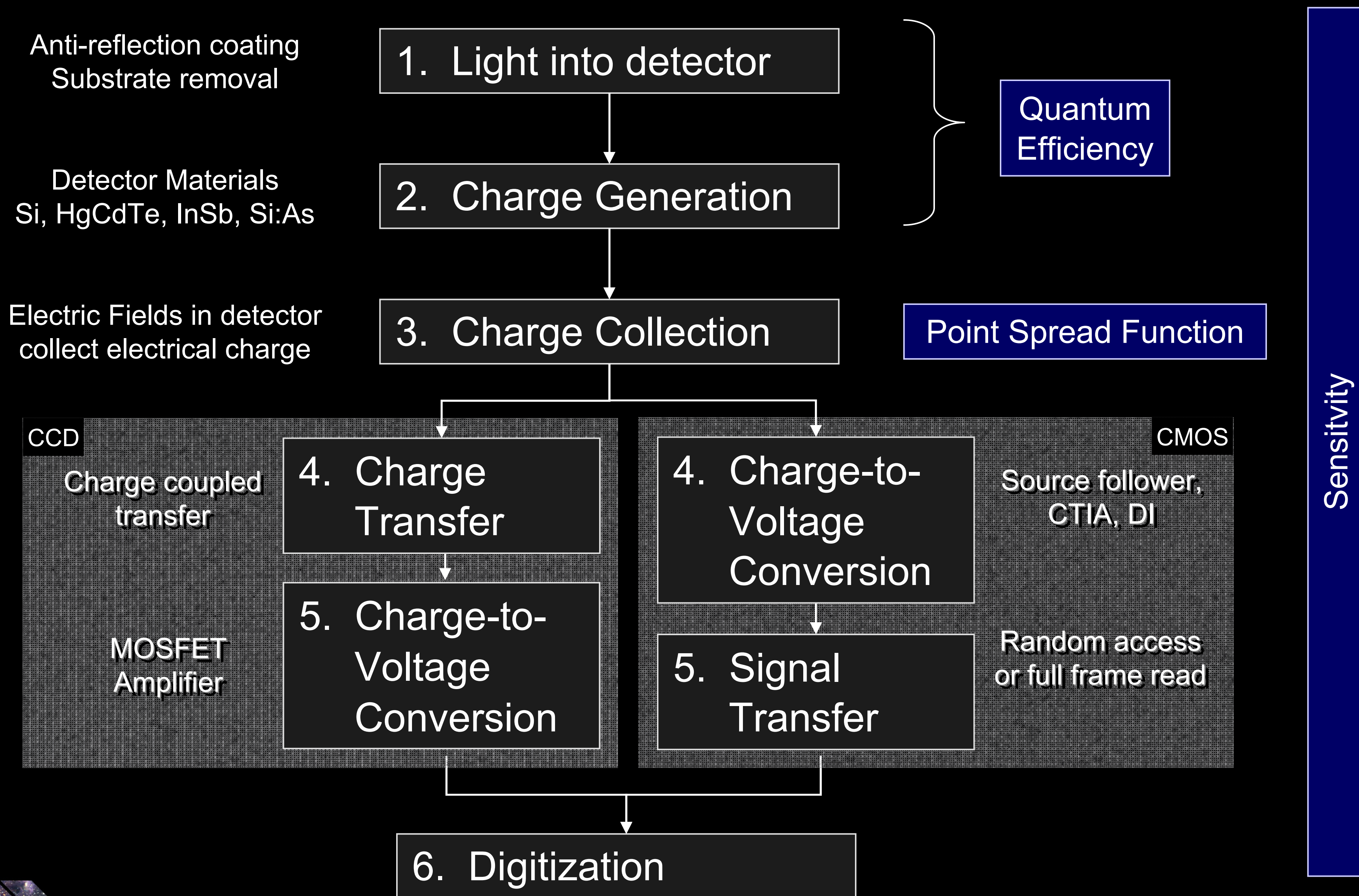
Amplification

$e^- \rightarrow$ voltage

- Zero amplification noise
- High speed

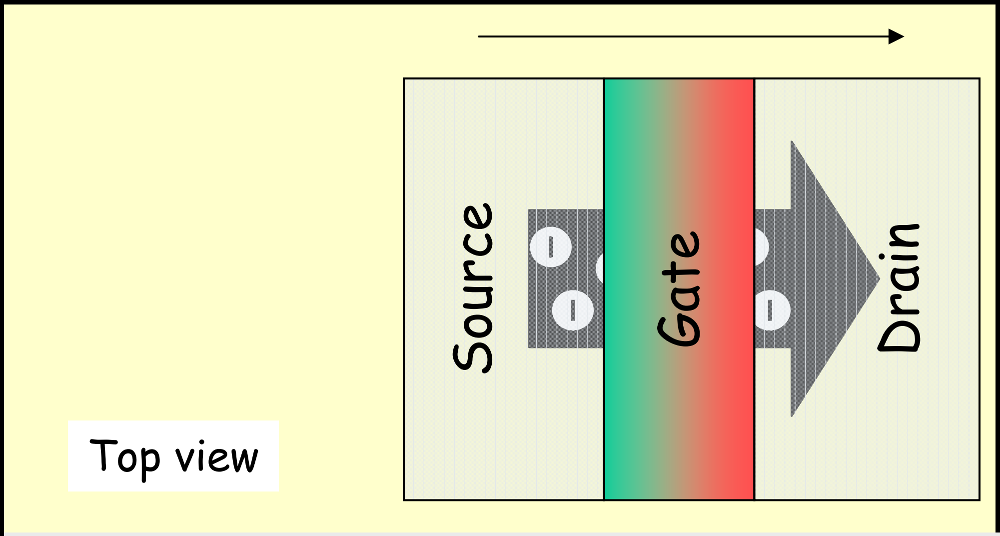
This is the challenge

6 steps of optical / IR photon detection



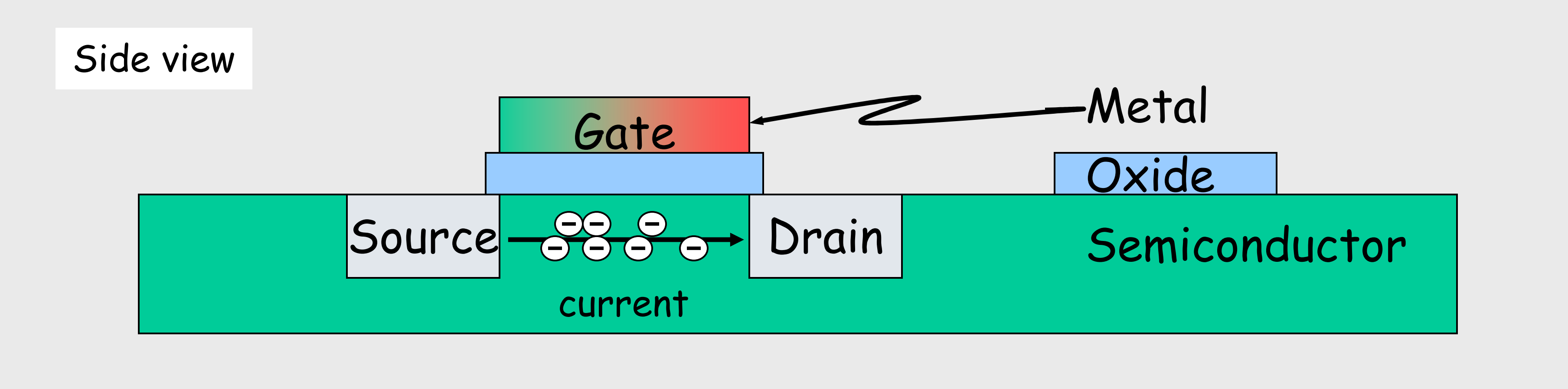
MOSFET Principles

MOSFET = metal oxide semiconductor field effect transistor



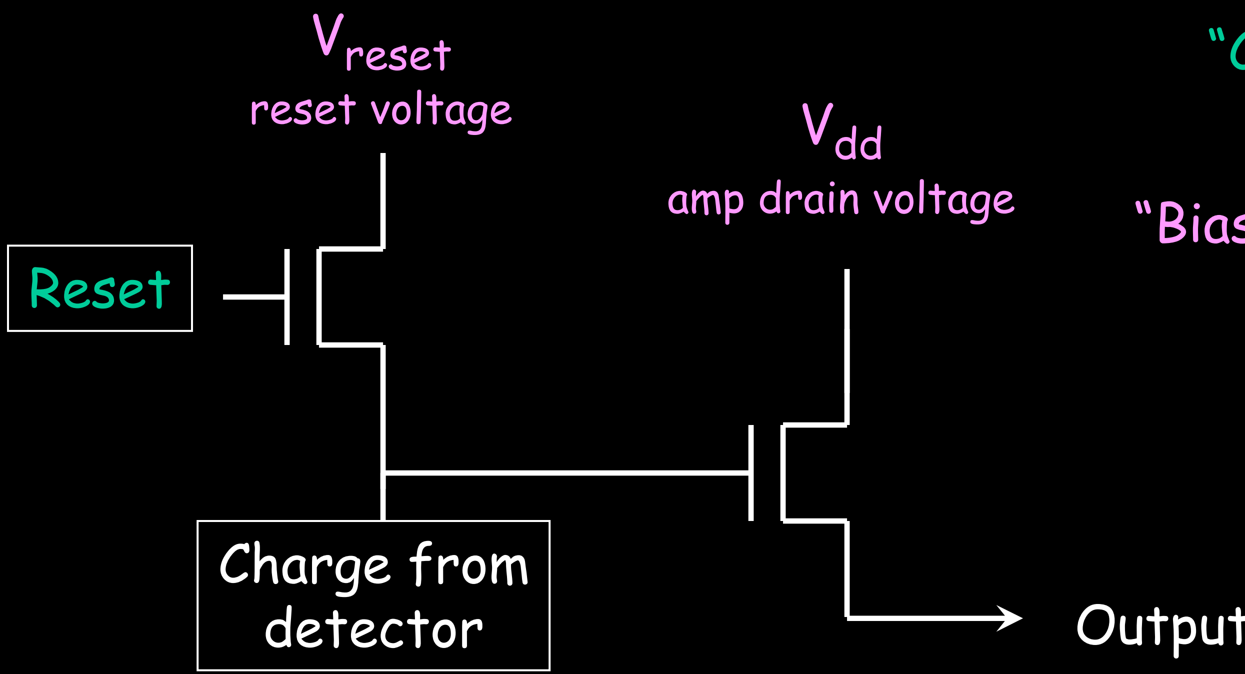
Turn on the MOSFET and current flows from source to drain

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



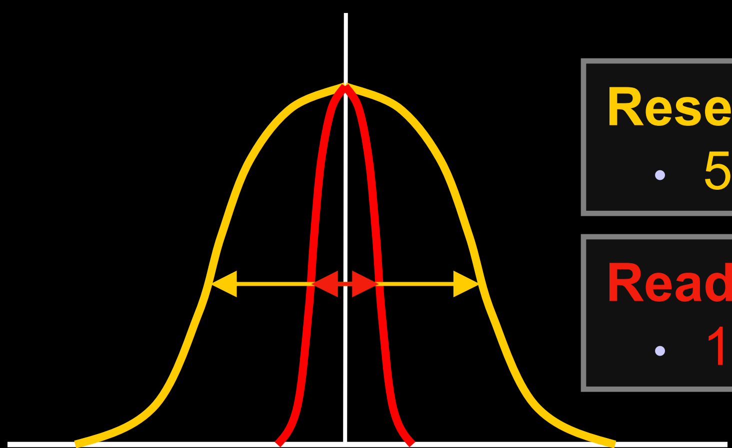
Fluctuations in current flow produce "readout noise"
Fluctuations in reset level on gate produces "reset noise"

MOSFET Amplifier



"Clock" (green)

"Bias voltage" (purple)

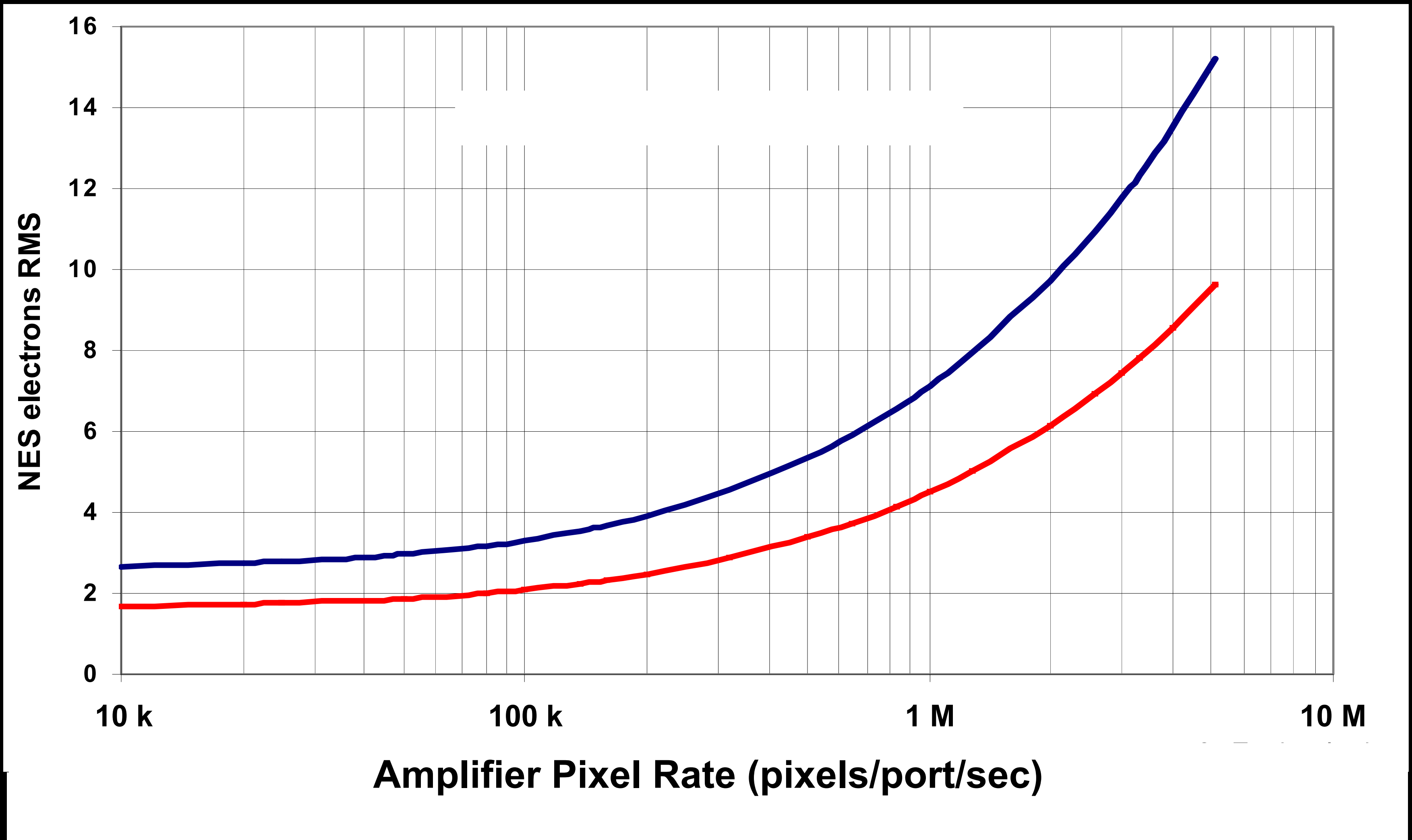


Reset Noise
- 50 to 100 e- rms

Read Noise
- 1.5 to 10 e- rms

Correlated Double Sample (CDS)
- Reset
- Read
- Put charge on gate
- Read

Typical CCD Readout Noise (single CDS)

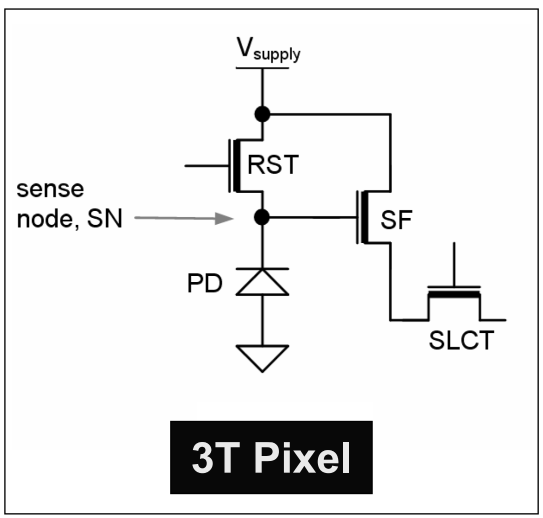


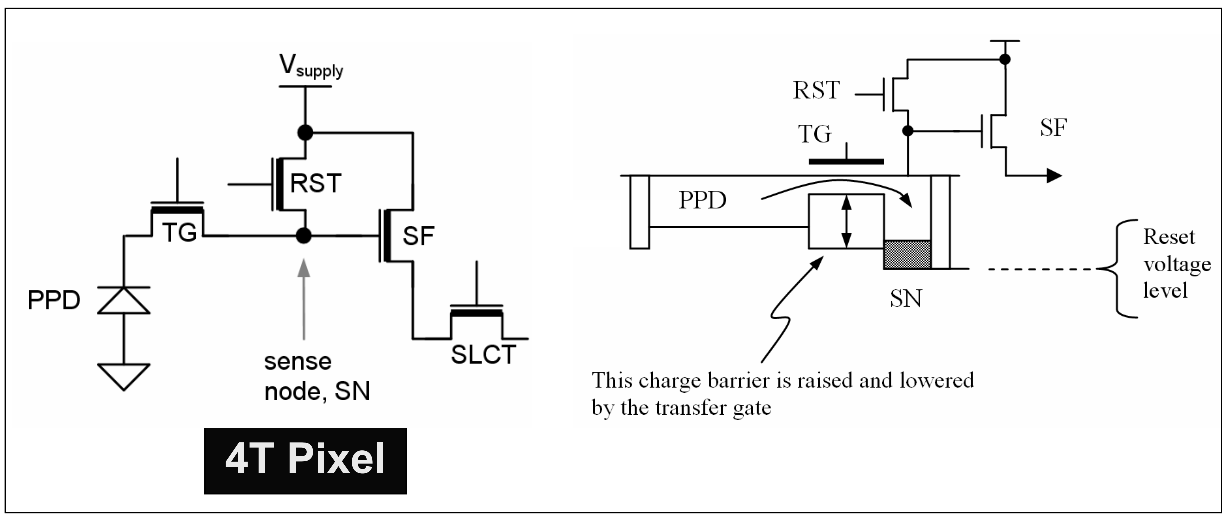
e2v technologies

Lower noise for Silicon Detectors

Lower noise CCD and CMOS Amplifiers

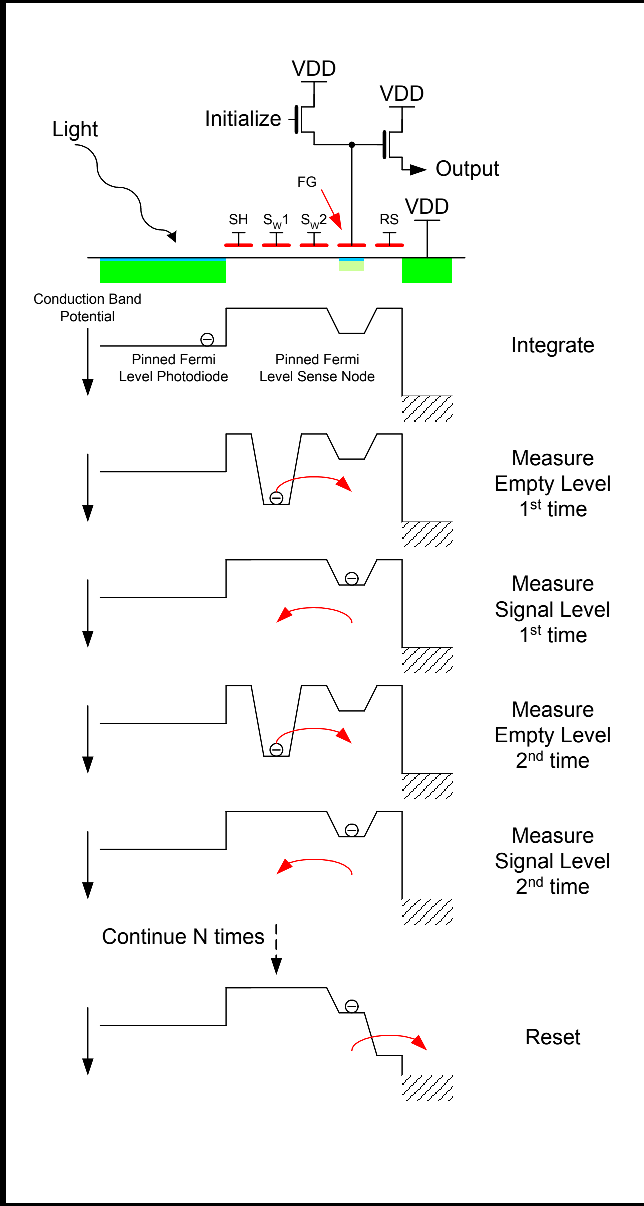
- MOSFET
  - Best performance ~2 e- rms slow (100 kHz pixel rate)
- Planar JFET (MIT Lincoln Laboratory)
  - ~2 e- noise, but faster
- Very small capacitance CMOS gate
  - 4T pixel, a.k.a. “CCD in a pixel”
  - ~2 e- noise



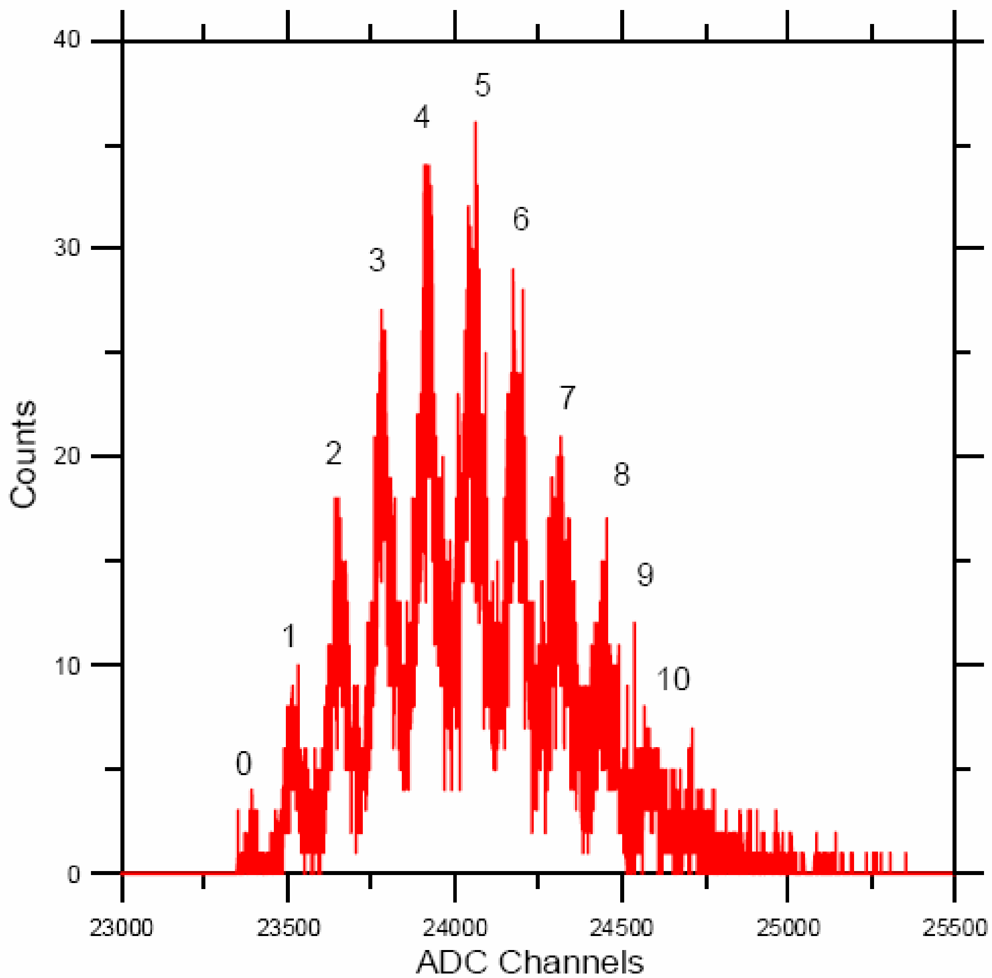


Multiple read CCD and CMOS Amplifiers

- If noise is uncorrelated, the total noise should decrease as the square root of the number of reads
- CCD Skipper amplifier
  - Jim Janesick (JPL…Sarnoff)
- Repetitive non-destructive read CMOS
  - Is basically a skipper amplifier in CMOS
  - Best example yet is Max Planck Semiconductor Laboratory (next page)



Single Photon Resolution



- A weak intensity laser has been used to inject electrons into the RNDR-DePMOS
- The laser injects in average 5 electrons
- T=- 50 °C
- A trapezoidal weighting function has been used with a total processing time of 20 µs
- ENC ~0.25 el. r.m.s.

6 steps of optical / IR photon detection

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

CCD

Charge coupled transfer

4. Charge Transfer

MOSFET Amplifier

5. Charge-to-Voltage Conversion

CMOS

Source follower, CTIA, DI

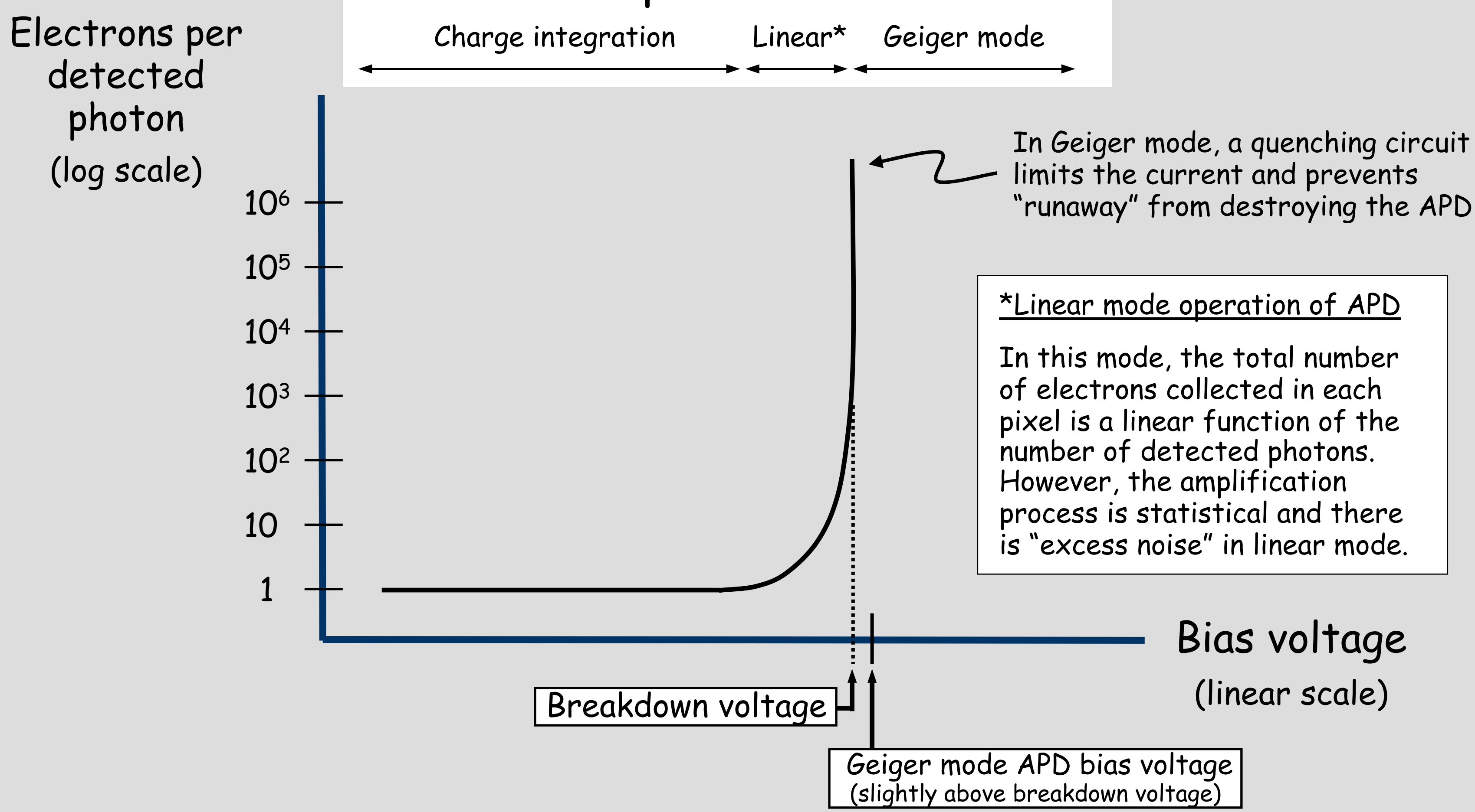
4. Charge-to-Voltage Conversion

Random access or full frame read

5. Signal Transfer

6. Digitization

Mode of operation of an APD

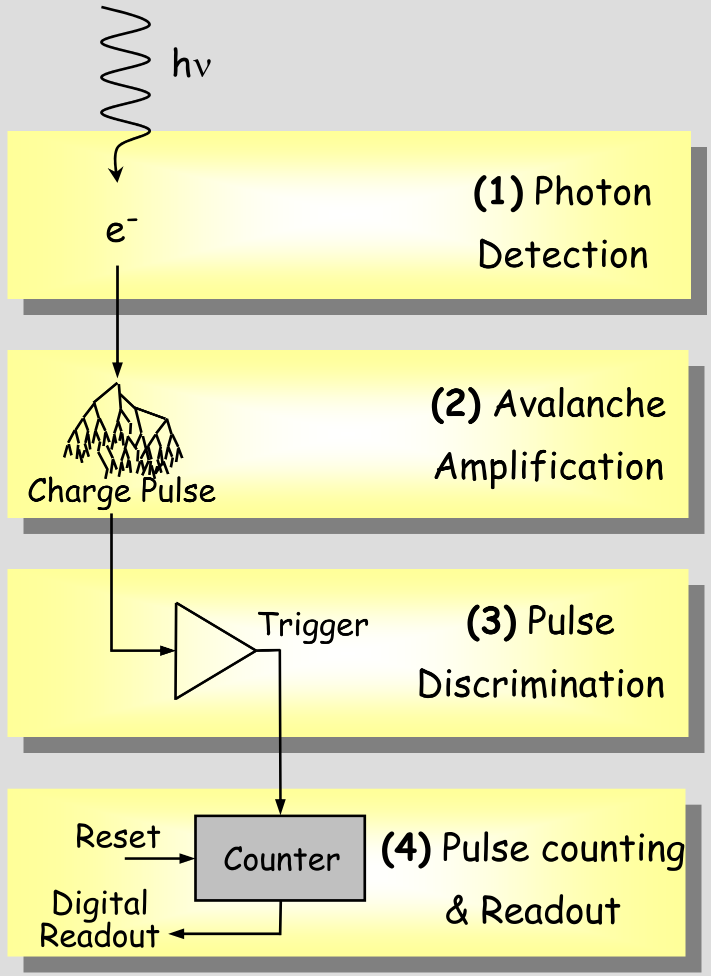


*Linear mode operation of APD

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.

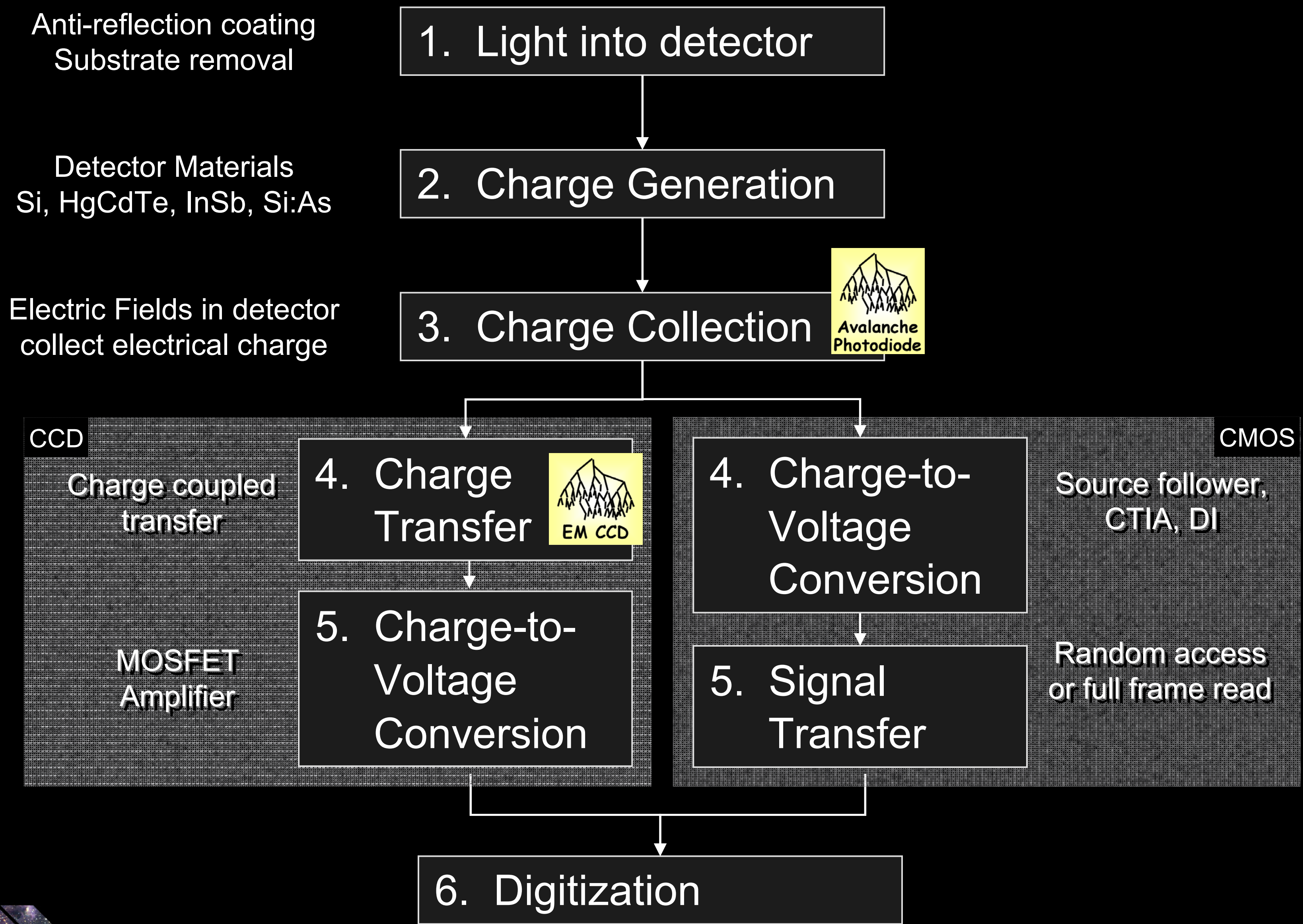
Geiger APD Sensor architecture

- **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:**
  1) Part of CMOS circuit
  2) Put APD into detector material and hybridize to CMOS circuitry

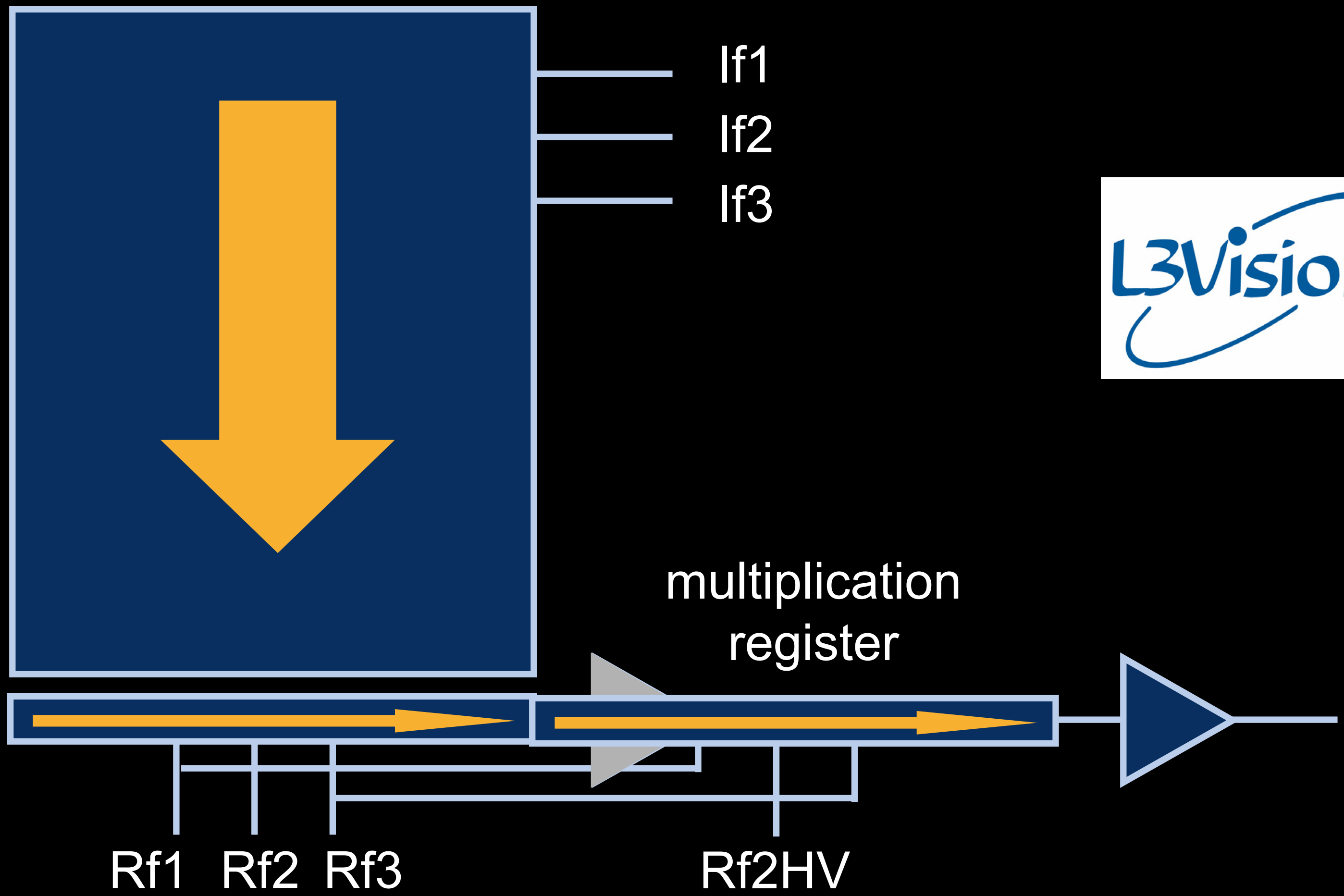


Probability of Avalanche ~50%

6 steps of optical / IR photon detection

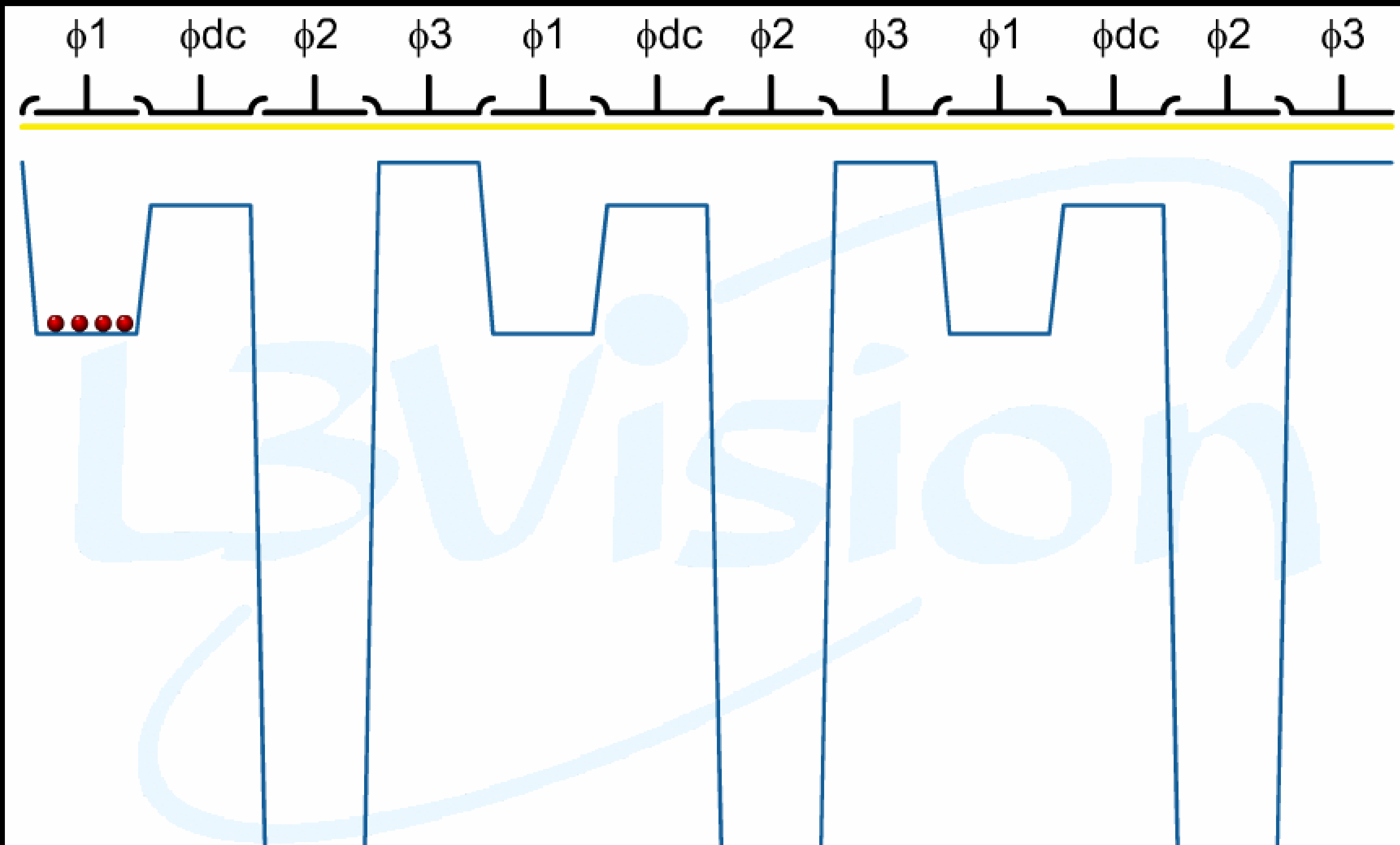


L3Vision CCD



e2v technologies

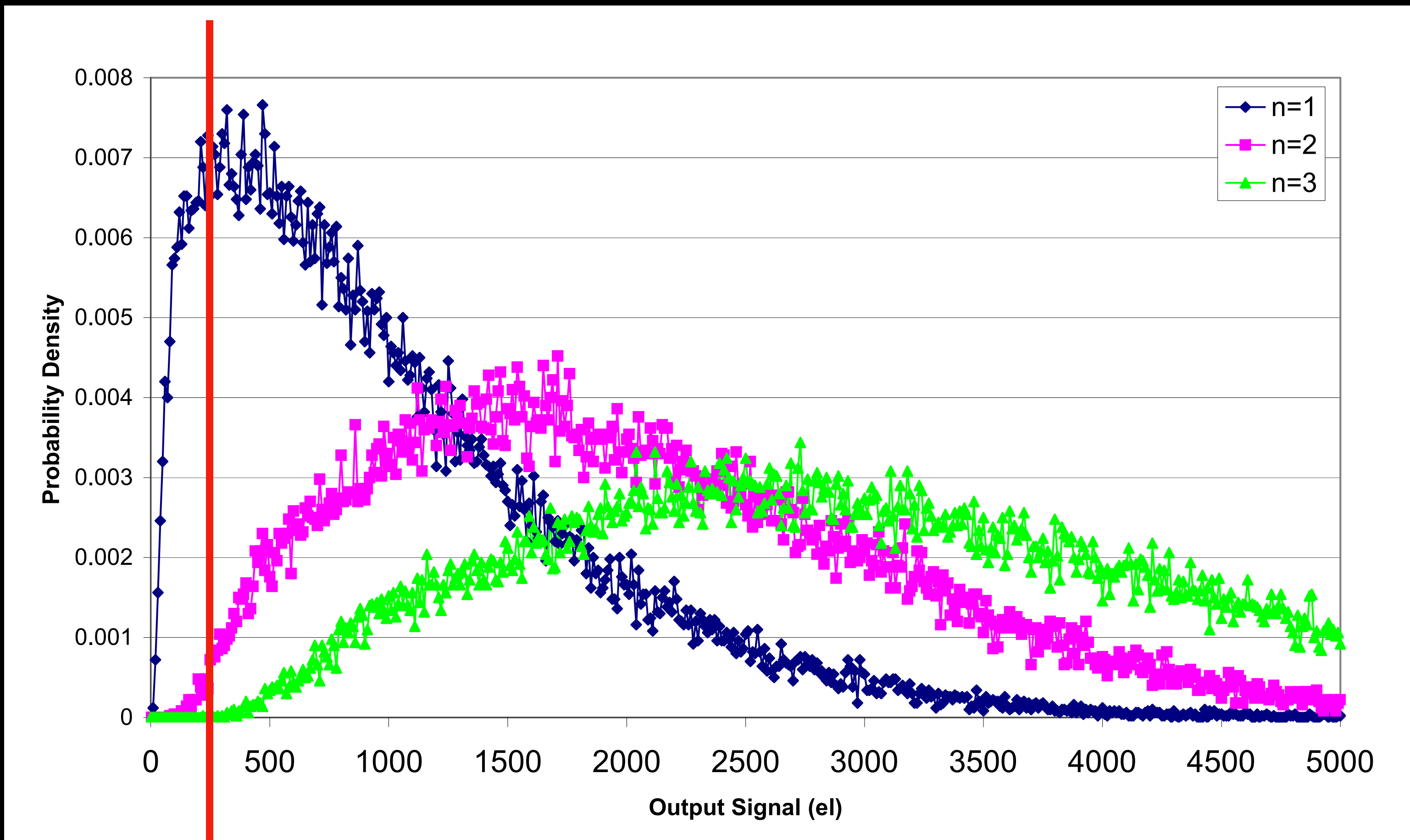
Amplification in the CCD serial register
e2v's L3Vision technology



e2v technologies

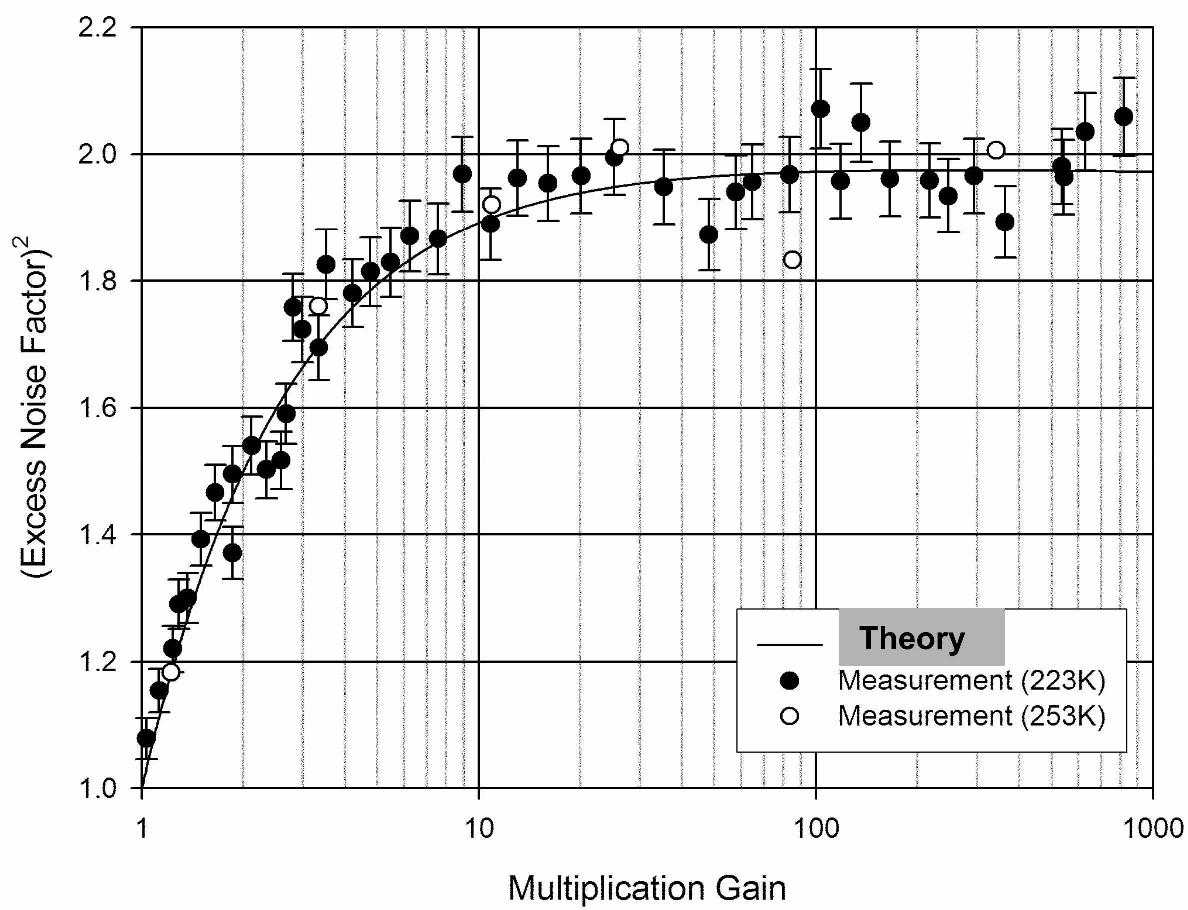
Limit for Silicon Linear APDs and EMCCD

- Excess Noise due to poor pulse height distribution
  - Similar to a negative exponential
  - Increases photon noise by square root of 2



Must set threshold a few sigma above readout amplifier noise

Read Noise of EMCCD



The excess noise factor of $\sqrt{2}$ has been shown to be present for the gain factors used in most applications.

Summary of Silicon Detector Properties

- High quantum efficiency possible
- Dark current low enough to be negligible
- Quantum yield enables single photon x-ray spectroscopy

- Noise
  - Standard CCD & CMOS ~ 2 e- (may get close to 1 e-)
  - Multiple non-destructive read (skipper) CMOS shows <1 e-
  - Electron multiplied CCD (EMCCD)
    - Good for photon counting, but loss of QE due to threshold
    - Worse than std. amplifier for >5 detected photons, like 50% QE loss
  - Linear APD
    - Same noise issues as EMCCD
  - Geiger APD
    - Could be best of all worlds
    - But avalanche probability now is ~50% (effectively reduces QE)

Low noise for the Infrared HgCdTe Detectors

6 steps of optical / IR photon detection

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

No Infrared CCD

5. Charge-to-Voltage Conversion

MOSFET Amplifier

CMOS

4. Charge-to-Voltage Conversion

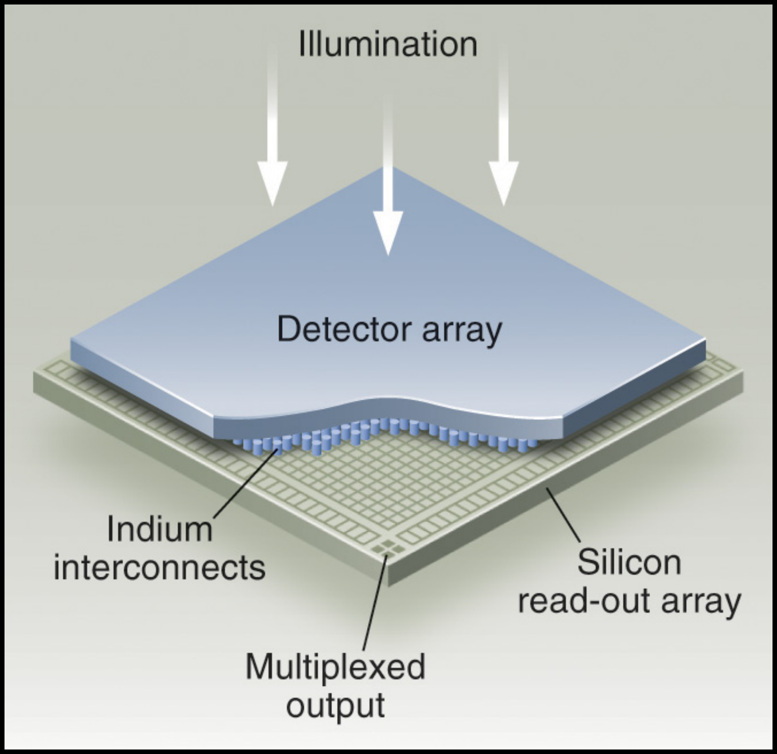
Source follower, CTIA, DI

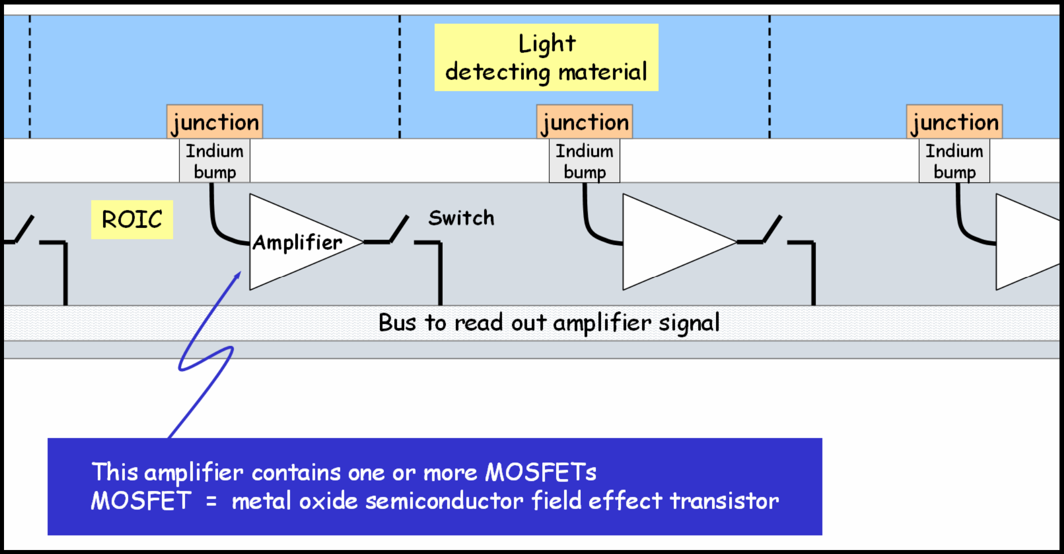
5. Signal Transfer

Random access or full frame read

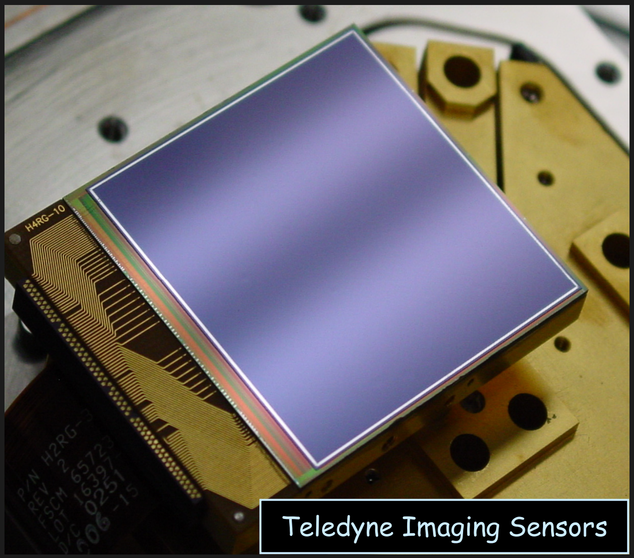
6. Digitization

Hybrid Imager Architecture



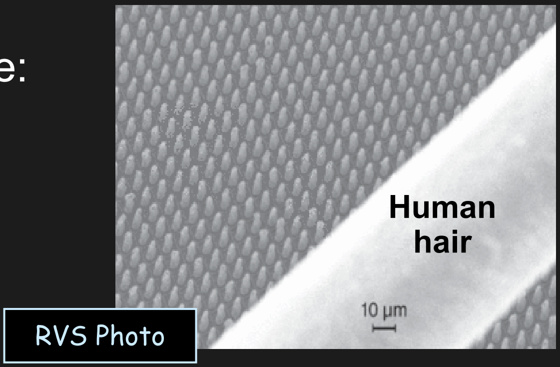


H4RG-10
4096x4096 pixels
10 micron pixel pitch
HyViSI silicon PIN



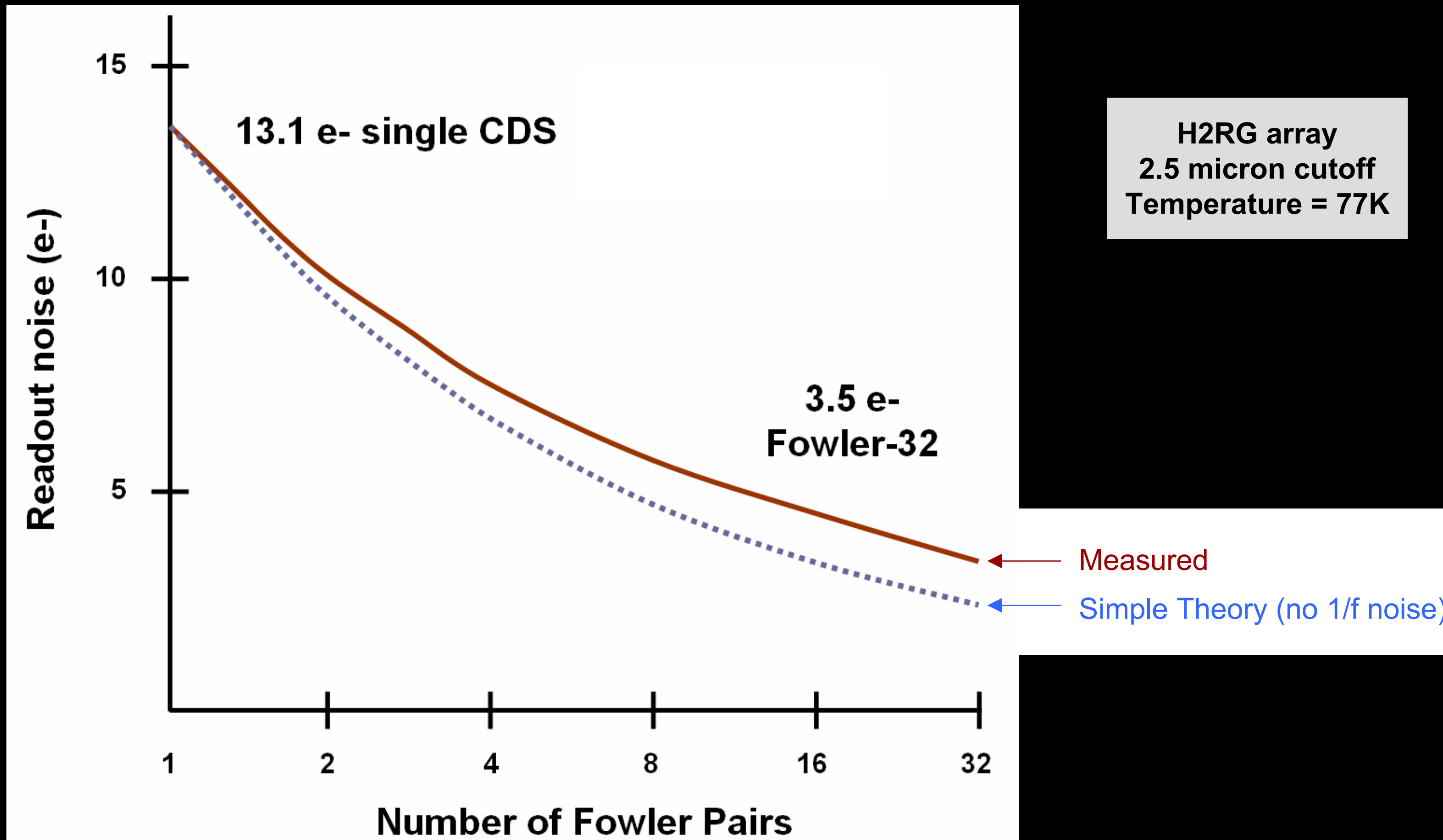
Mature interconnect technique:

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



Multiple Sampling (Fowler Sampling)

Non-destructive readout enables reduction of noise from multiple samples



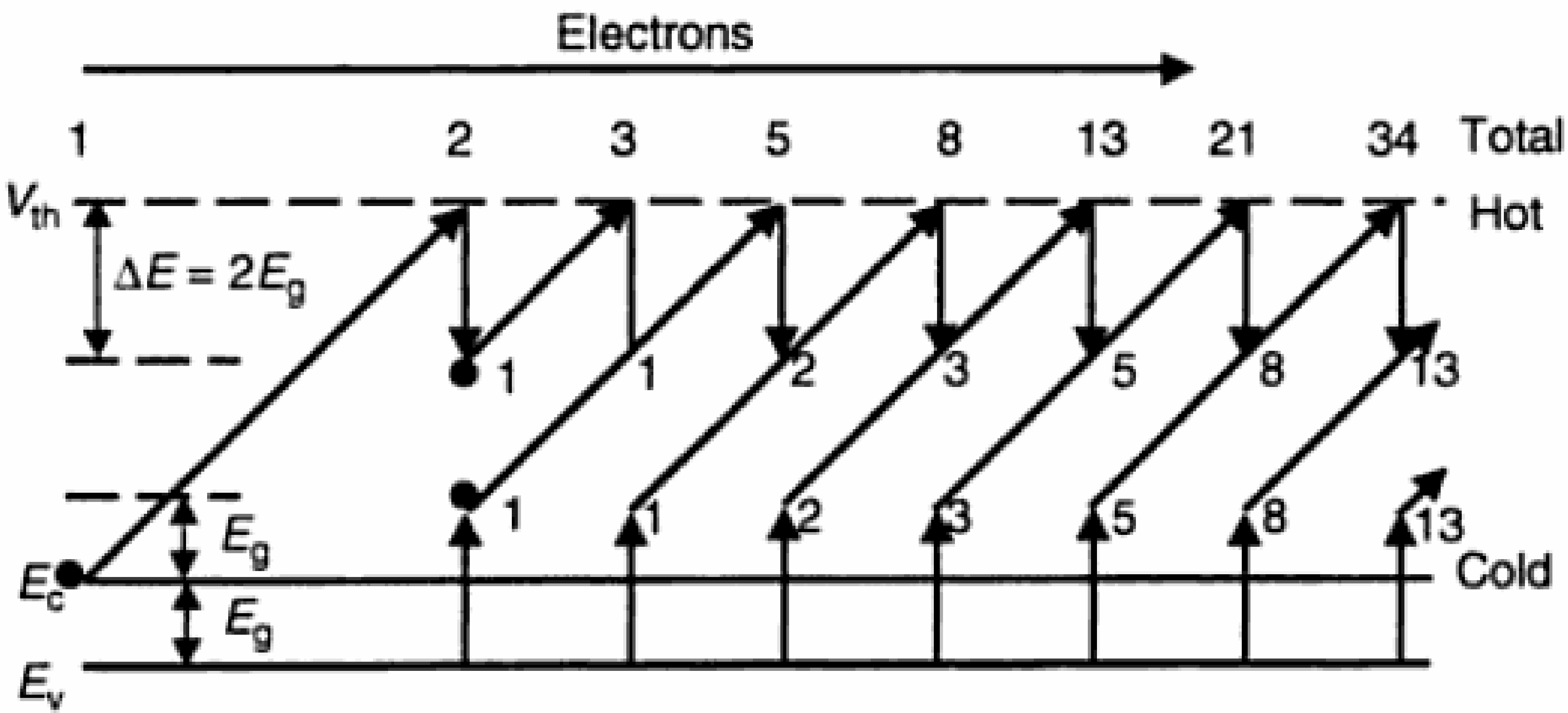
H2RG array
2.5 micron cutoff
Temperature = 77K

HgCdTe – an ideal APD ?

HgCdTe is a very unique material

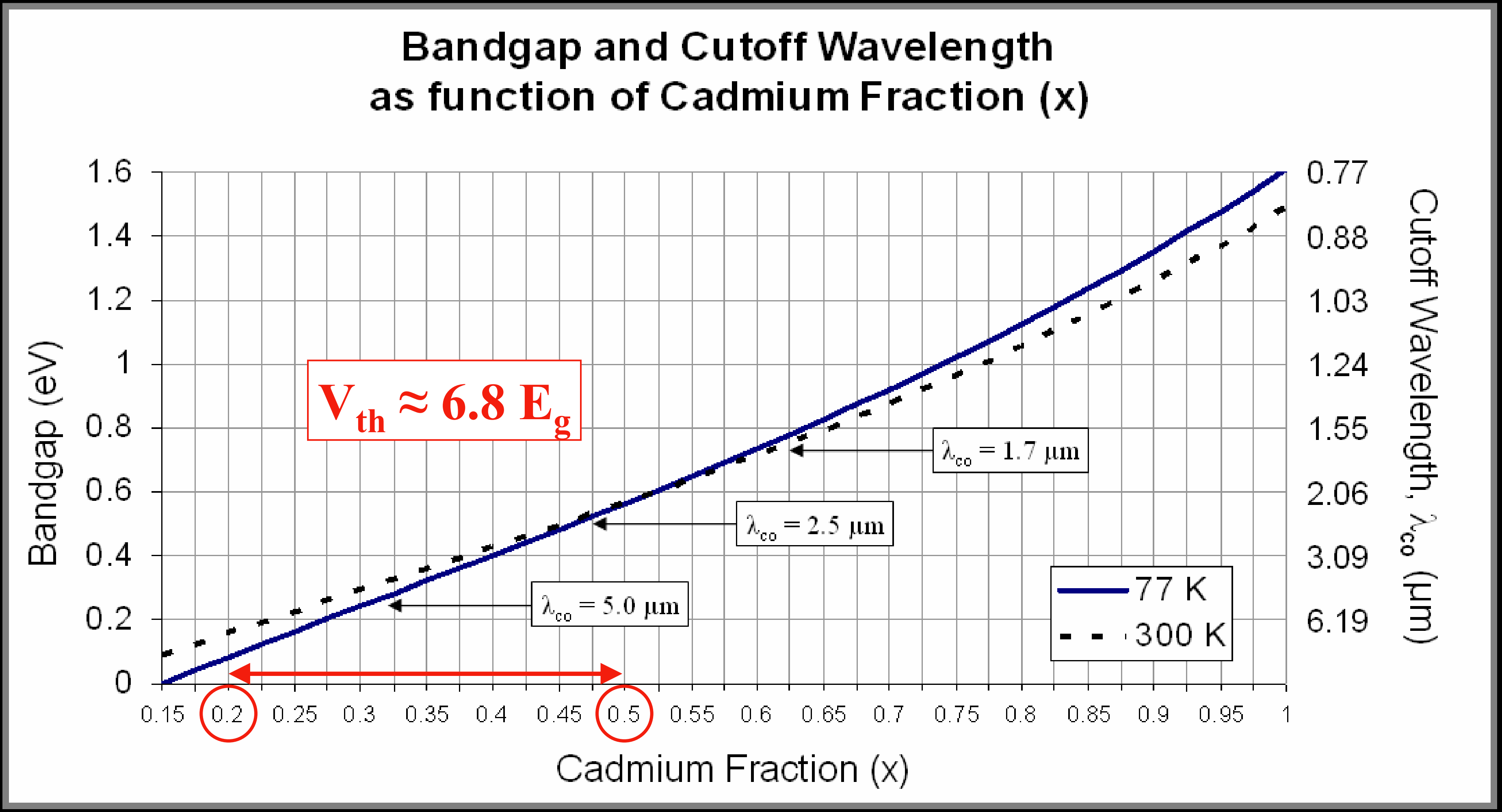
- The bandgap is tunable
- Direct bandgap semiconductor with very efficient conversion of photon energy to electron-hole pairs
- High probability of electron impact ionization to convert electron energy into additional electron-hole pairs
  - Avalanche process
- The hole-to-electron ionization coefficient ratio ≈ 0
  - Narrow pulse height distribution
  - Excess noise ≈ 0

HgCdTe e-APD (electron avalanche)

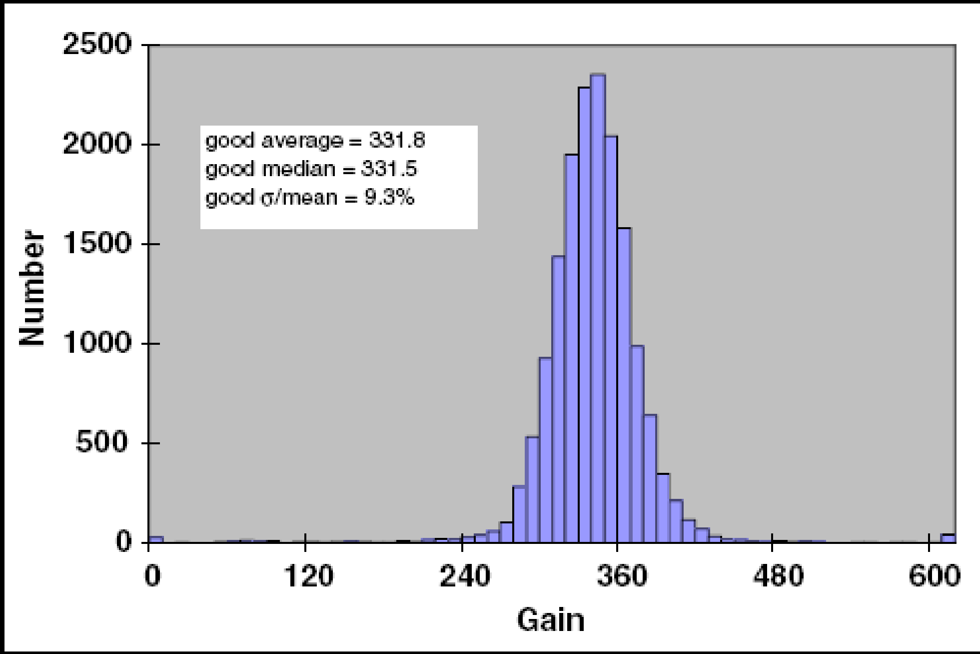


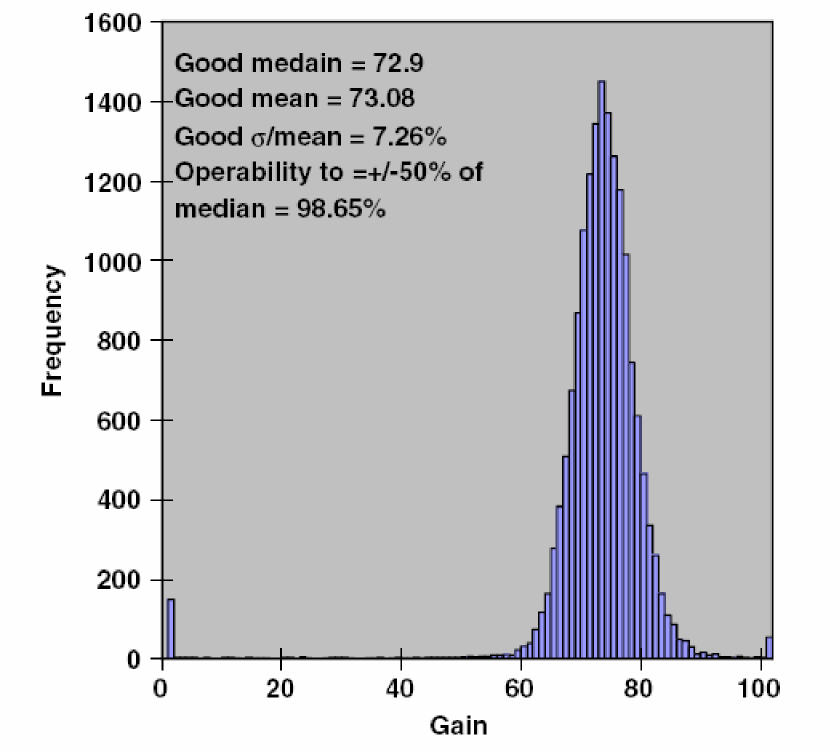
M. Kinch, *Fundamentals of Infrared Detector Materials*, p. 122, Fig. 7.13

HgCdTe e-APD (electron avalanche)



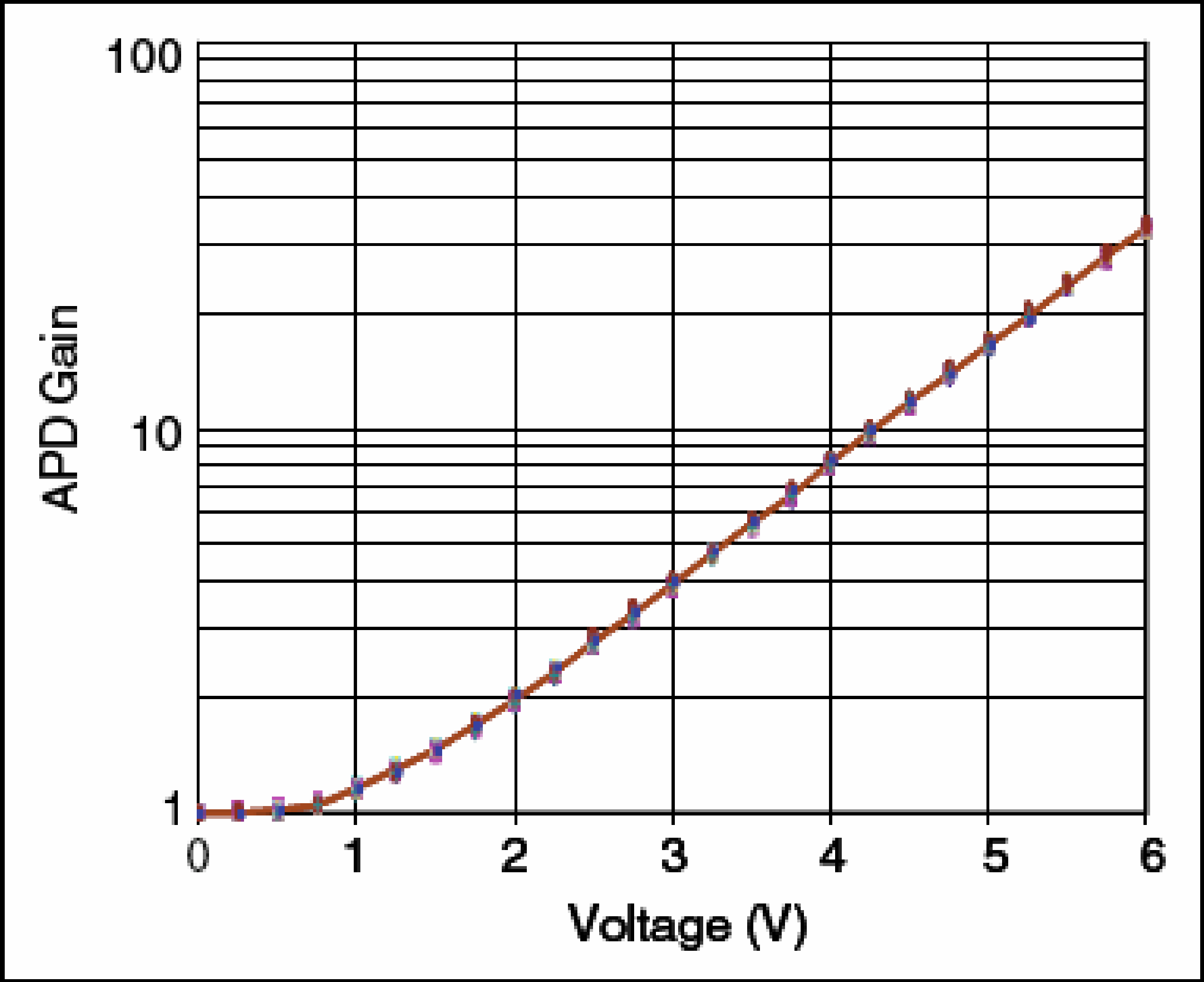
HgCdTe e-APD data





DRS

HgCdTe e-APD (electron avalanche)



e-APD gain M varies with V as:

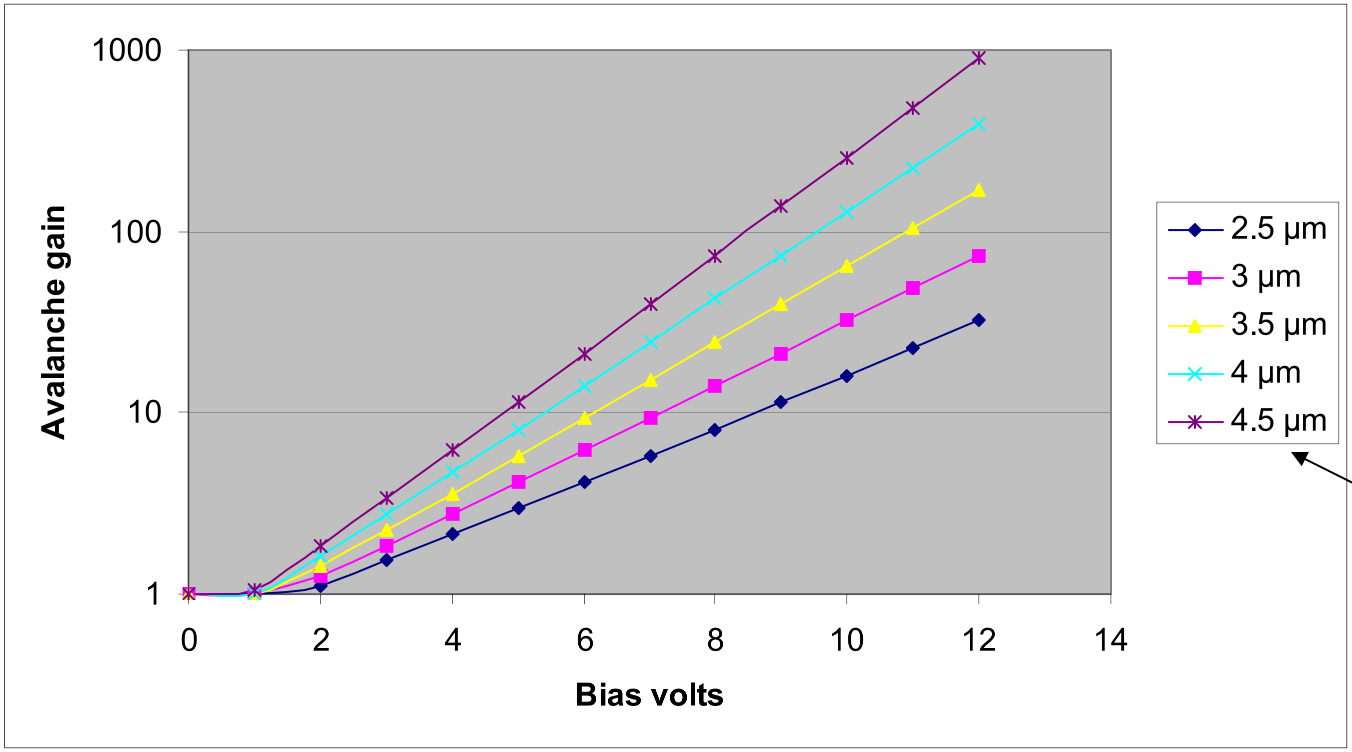
$$M = 2^{(V - V_{th})/(V_{th}/2)}$$

M. Kinch, *Fundamentals of Infrared Detector Materials*, p. 124, Fig. 7.15

Avalanche gain vs. bias voltage and cutoff wavelength

SELEX GALILEO

HgCdTe avalanche photodiodes at 77K



$V_{th} \approx 6.8\ E_g$

e-APD gain M varies with V as:

$M = 2^{(V-Vth)/(Vth/2)}$

Cut-off wavelength

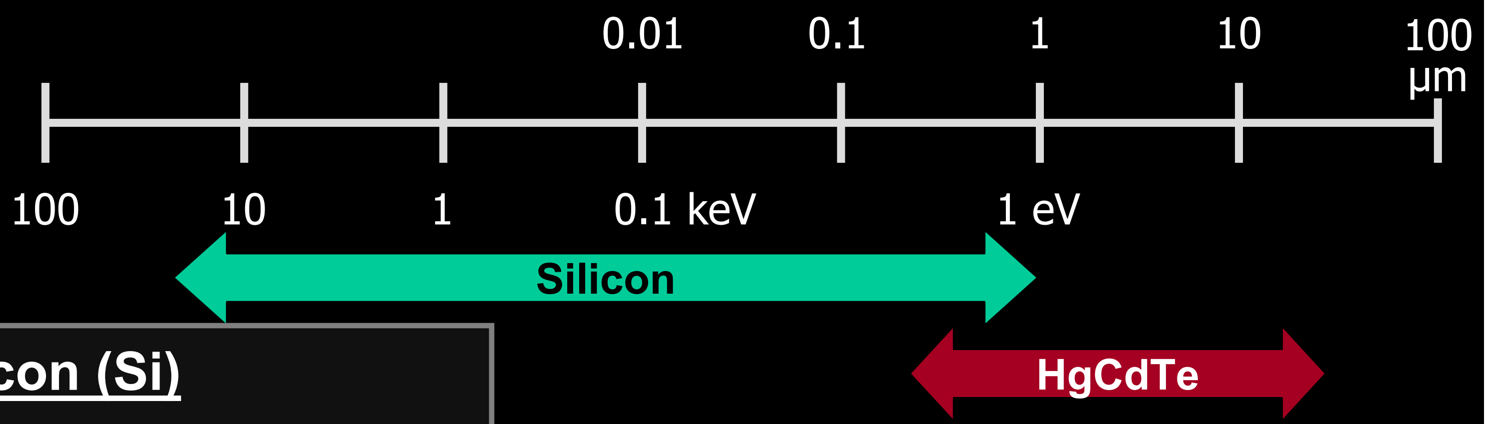
[µm]

Selex

Silicon and HgCdTe

Prospects for single photon detectors

Photon Wavelength (µm) **& Energy** (keV)



Silicon (Si)

- Single photon x-ray spectroscopy
  - Lower noise readout → smaller ΔE
- Standard CCD & CMOS (2 e- noise)
- EMCCD & linear APD
  - Photon counting, with loss of QE
  - Excess noise: not good >5 photons
- Skipper CMOS & CCD
  - Is single photon counting here?!
- Geiger APD
  - Single photon counting, but need to increase avalanche probability

HgCdTe

- Standard hybrid CMOS
  - 10 e- single CDS
  - 2.5 e- Fowler-32 (average 32 reads)
- Electron avalanche APD (e-APD)
  - Single photon counting
  - Very low excess noise allows addition of multiple events in a pixel while retaining ability to count photons

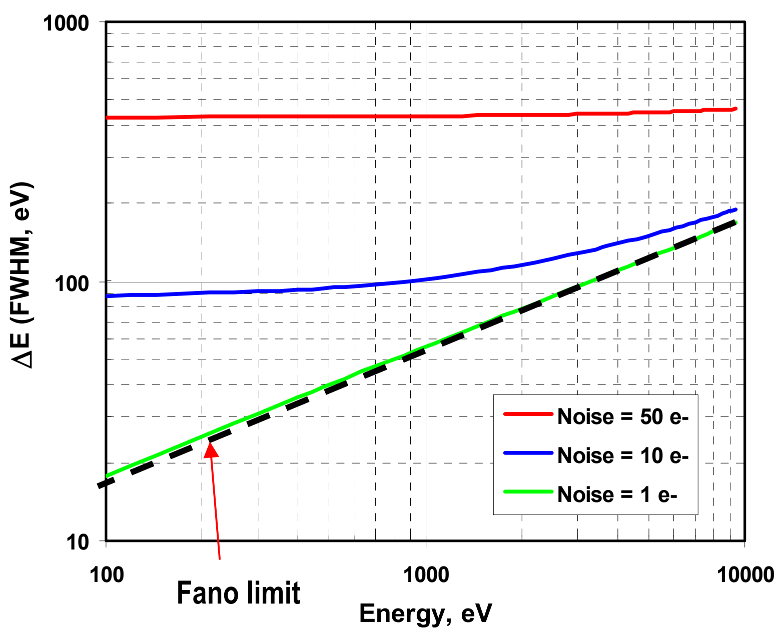
Thank you for your attention

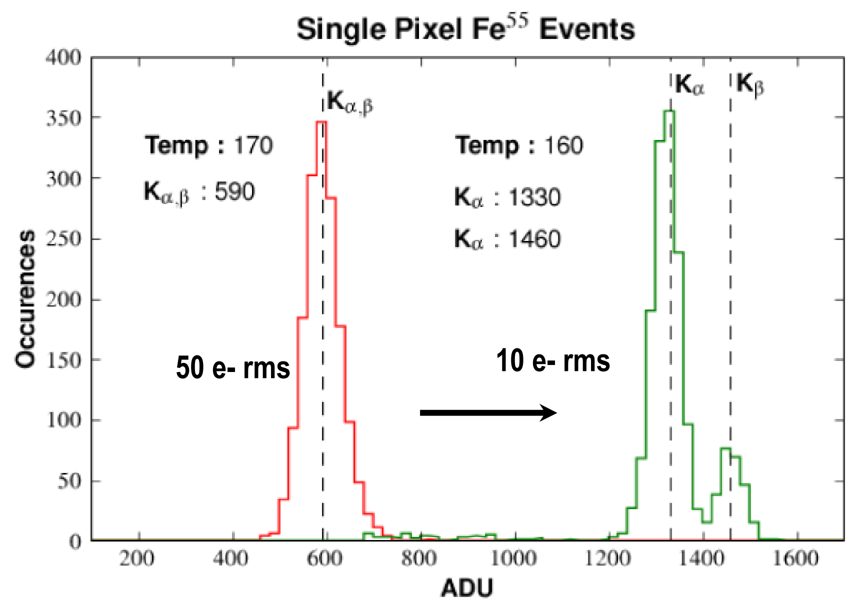
X-ray Energy Resolution

- Non-dispersive energy resolution of detector

$$\Delta E(FWHM) = 2.35 \times \omega \sqrt{\frac{f \times E}{\omega} + n^2} \, (eV)$$

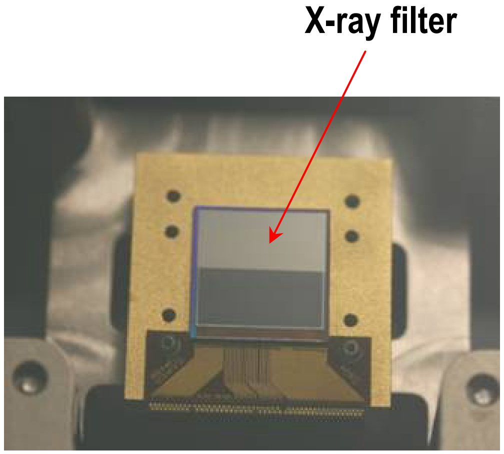
ω =3.65 eV/e- for Si
F= 0.12 for Si
n = sensor noise
E = photon energy





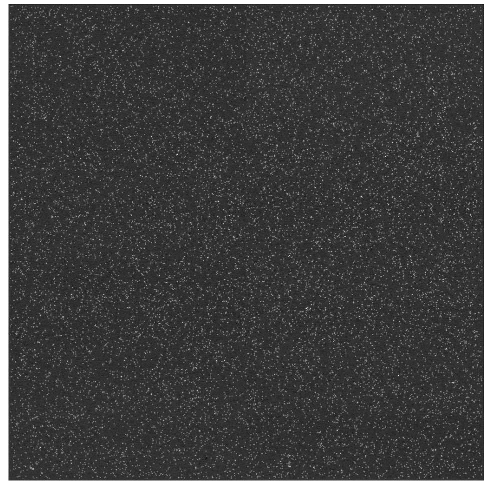
2Kx2K H2RG HyViSI data (L.Simms, et al, SPIE Aug 2009)

X-ray Response



1Kx1K format, 18µm pixel hybrid CMOS detector

Fe-55 X-ray Response Map



$$\frac{T_A}{T_B} \approx 100\%$$

700nm Optical Response Map

$$\frac{T_A}{T_B} = 0.11\%$$

- Aluminum optical blocking filter is deposited directly at detector surface
  - Transmission for Fe-55 X-ray photons: ~100%
  - Optical blocking ratio: 1000 to 1 @ 700nm wavelength

Event Driven X-ray sensor

Large format x-ray sensors detect a small number of x-rays per frame

X-rays produce hundreds to thousands of electron-hole pairs per absorbed x-ray

Event driven readout being developed to:

- Only read out pixels where x-rays detected
- Single event readout provides x-ray energy measurement
- High time resolution