Imaging Sensor Technologies for Astronomy, Planetary Exploration & Earth Observation

(and possibly also for particle accelerators and synchrotrons)

Fermi National Accelerator Laboratory
March 10, 2009

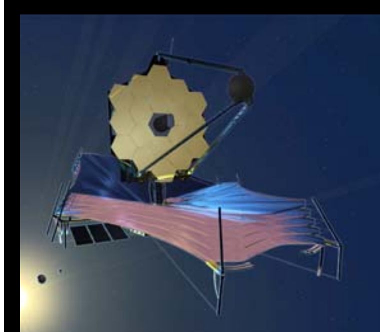
James W. Beletic

TELEDYNE
IMAGING SENSORS
A Teledyne Technologies Company

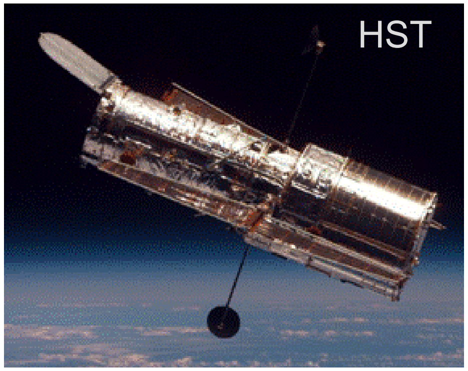
Teledyne

Providing the best images of the Universe



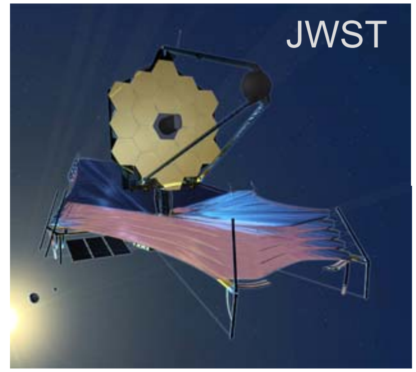




Teledyne – NASA's Partner in Astronomy



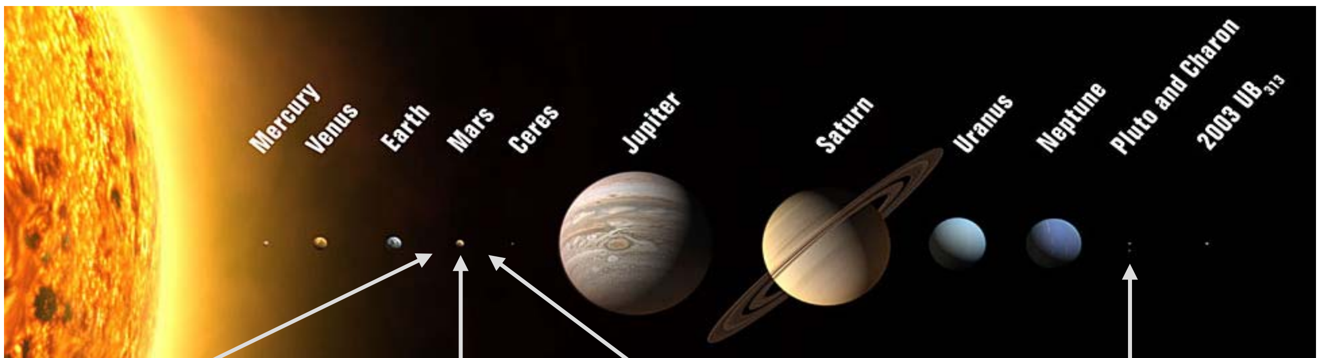
NICMOS, WFC3, ACS Repair

Bands 1 & 2



NIRCam, NIRSpec, FGS

Hubble Ultra Deep Field



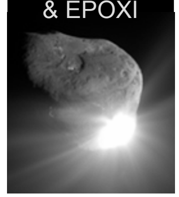
Rosetta

Lander (çiva)

Mars Reconnaissance Orbiter

CRISM (Vis & IR)

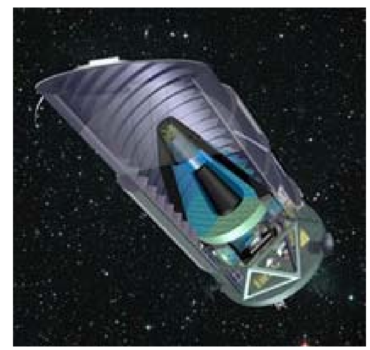
Deep Impact & EPOXI



IR spectrograph

New Horizons

IR spectrograph



JDEM

Joint Dark Energy Mission

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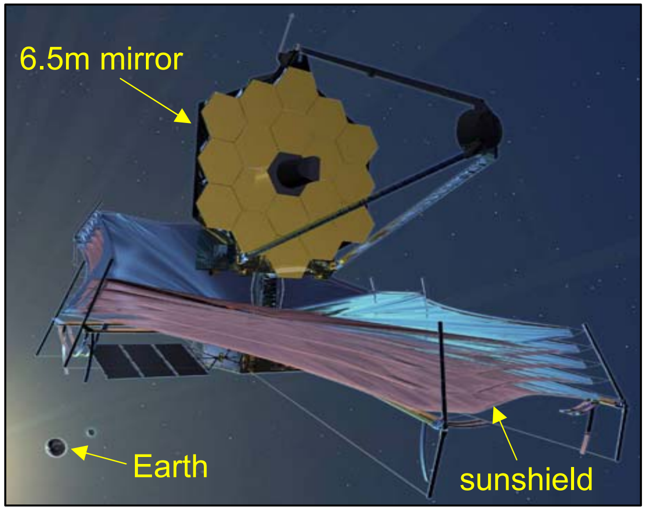
JWST - James Webb Space Telescope

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



- International collaboration
- 6.5 meter primary mirror and tennis court size sunshield
- 2013 launch on Ariane 5 rocket
- L2 orbit (1.5 million km from Earth)

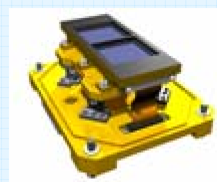
JWST will find the "first light" objects after the Big Bang, and will study how galaxies, stars and planetary systems form

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**

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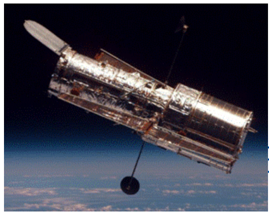
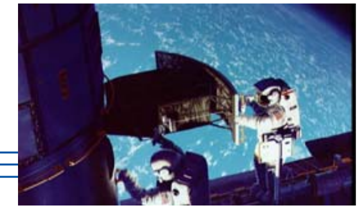
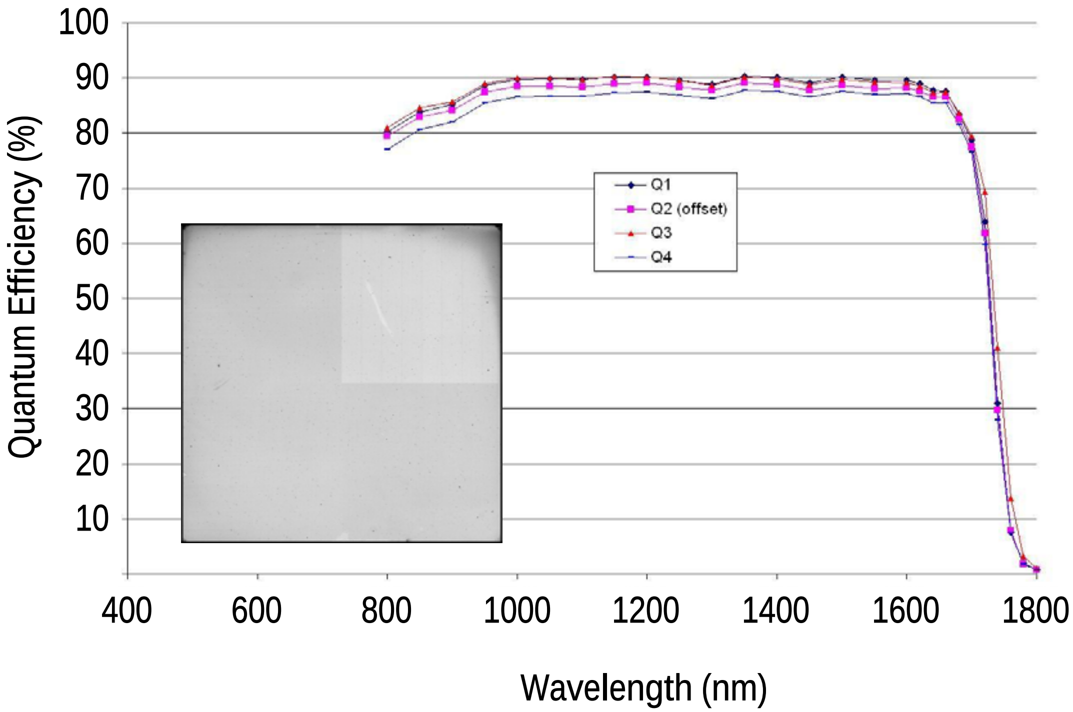
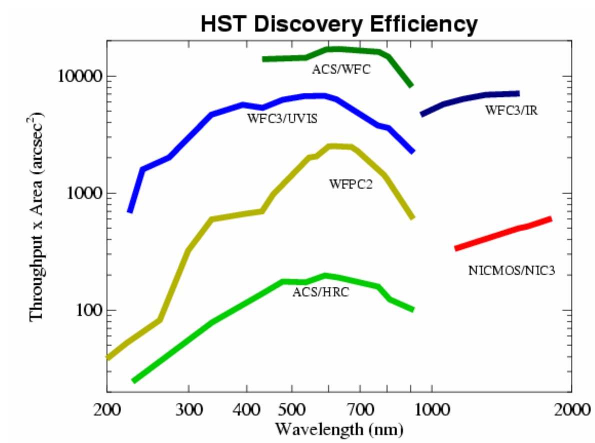


Wide Field Camera 3
Hubble Space Telescope



- **High quality, substrate-removed 1.7 µm HgCdTe arrays delivered to Goddard Space Flight Center**
- **H1RG: 1024 x 1024 pixels (18 micron pixel pitch)**
- **Will be installed in Hubble Space Telescope in 2009**
- **Nearly 30x increase in HST discovery efficiency**





Quantum Efficiency = 85-90%
Dark current (145K) = 0.02 e-/pix/sec
Readout noise = 25 e- (single CDS)

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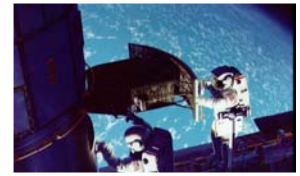
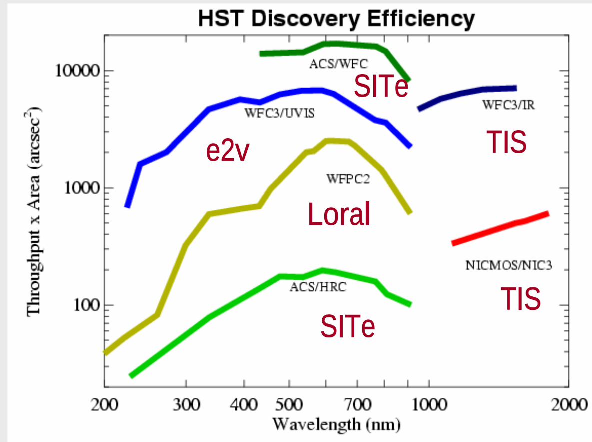
Hubble Space Telescope Servicing Mission 4



Wide Field Camera 3 (WFC3)

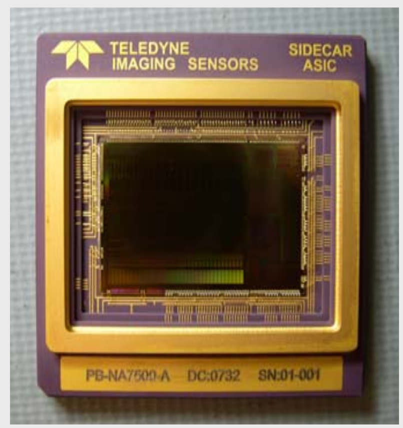
Teledyne H1R
1Kx1K
Infrared array



Advanced Camera for Surveys (ACS)

Most used instrument on HST inoperable since electronics failure in Jan 2007

Teledyne SIDECAR ASIC is heart of the repair electronics



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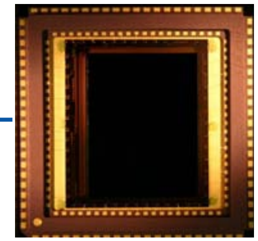
Teledyne is playing a key role in bringing wide field imaging to Hubble Space Telescope

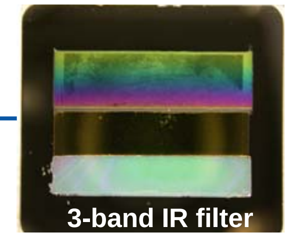
CRISM
Compact Reconnaissance Imaging Spectrometer for Mars

Detector

ROIC

Sensor Chip Assembly



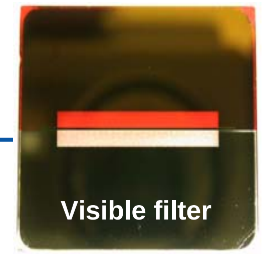


Motherboard / pedestal Subassembly

Teledyne provided both visible and mid-wave infrared detectors to CRISM instrument.

Detector / filter Assembly

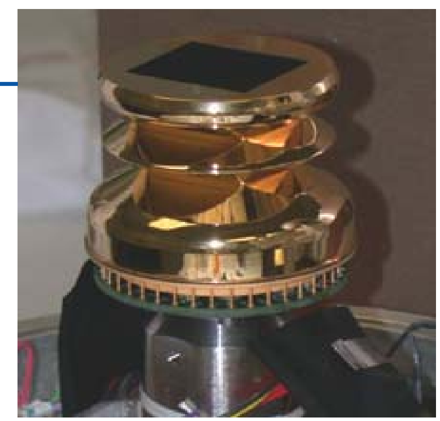
Filters



Flex cable

CRISM sensor subassembly with cold shield and cable

Visible FPA sensor subassembly



Infrared FPA sensor subassembly

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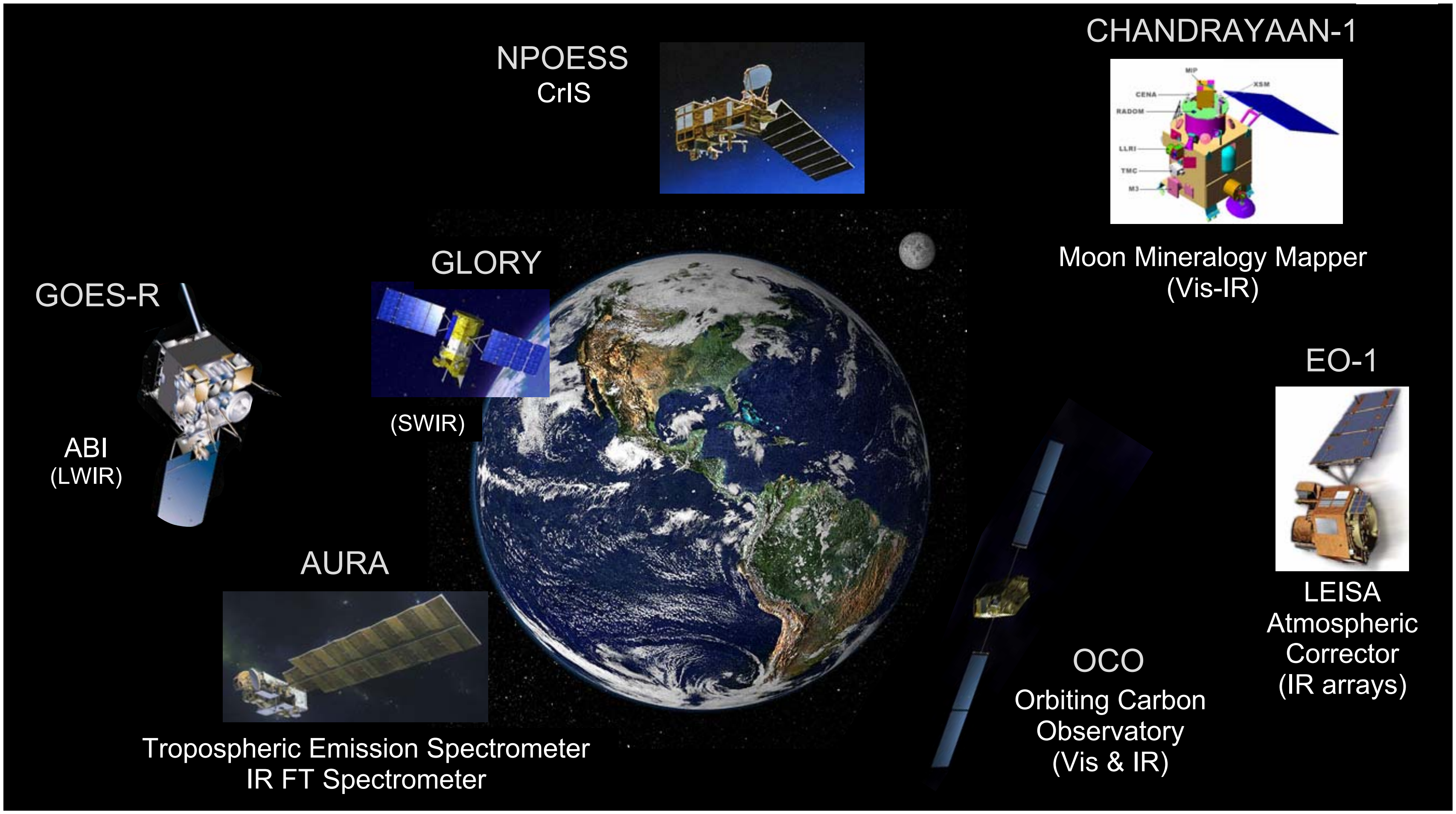
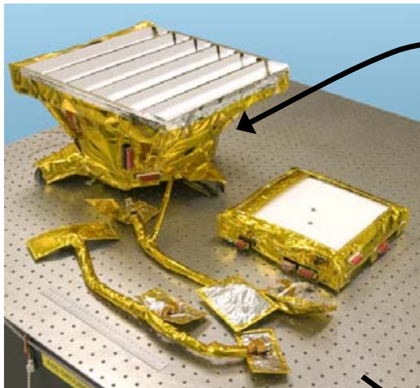
NASA's and NOAA's Partner for Earth Observation

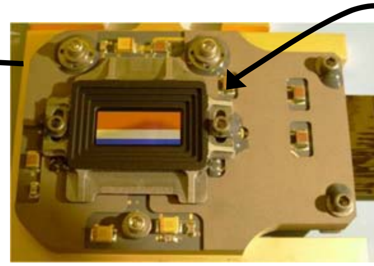


Visible to 16.5 microns

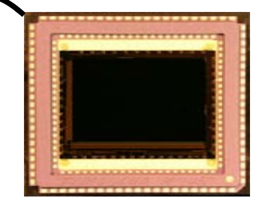
Moon Mineralogy Mapper - Visible / Near Infrared Imaging Spectrometer launched Wednesday, October 22, 2008



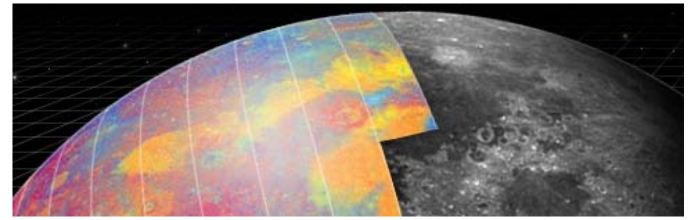
Instrument at JPL before shipment to India



Focal Plane Assembly



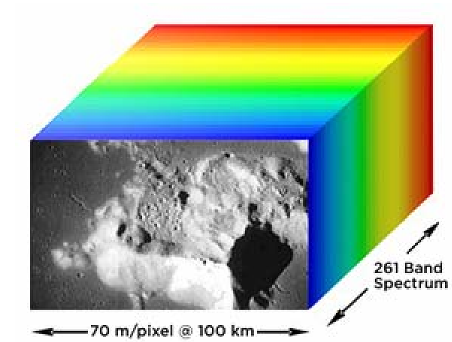
Sensor Chip Assembly



2 year mission will map the entire lunar surface

Teledyne Infrared FPA

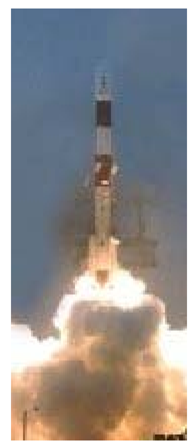
- 640 x 480 pixels (27 μm pitch)
- Substrate-removed HgCdTe (0.4 to 3.0 μm)
- 650,000 e- full well, <100 e- noise
- 100 Hz frame rate (integrate while read)
- < 70 mW power dissipation
- Package includes order sorting filter
- Total FPA mass: 58 grams



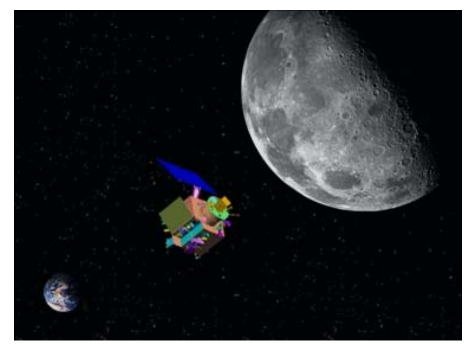
Moon Mineralogy Mapper resolves visible and infrared to 10 nm spectral resolution, 70 m spatial resolution

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



Journey Earth to Moon
100 km altitude lunar orbit

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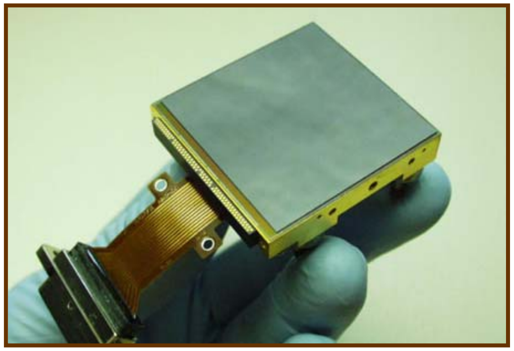
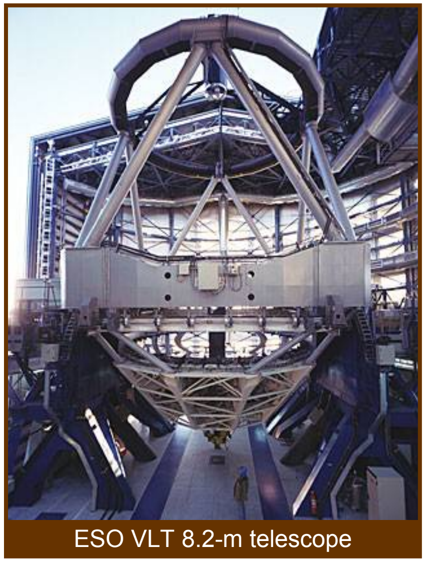
Leading Supplier of IR Arrays To Ground-based Astronomy

- H2RG (2048×2048 pixels) is the leading IR FPA in ground-based IR astronomy
- 4096×4096 pixel mosaic commissioned at European Southern Observatory in July 2007
  - 6th mosaic at major telescope, two more mosaics to be commissioned in 2009



ESO Very Large Telescope (VLT) Facility - Chile



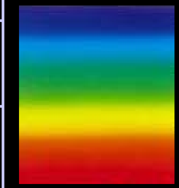
ESO VLT 8.2-m telescope

Energy of a photon

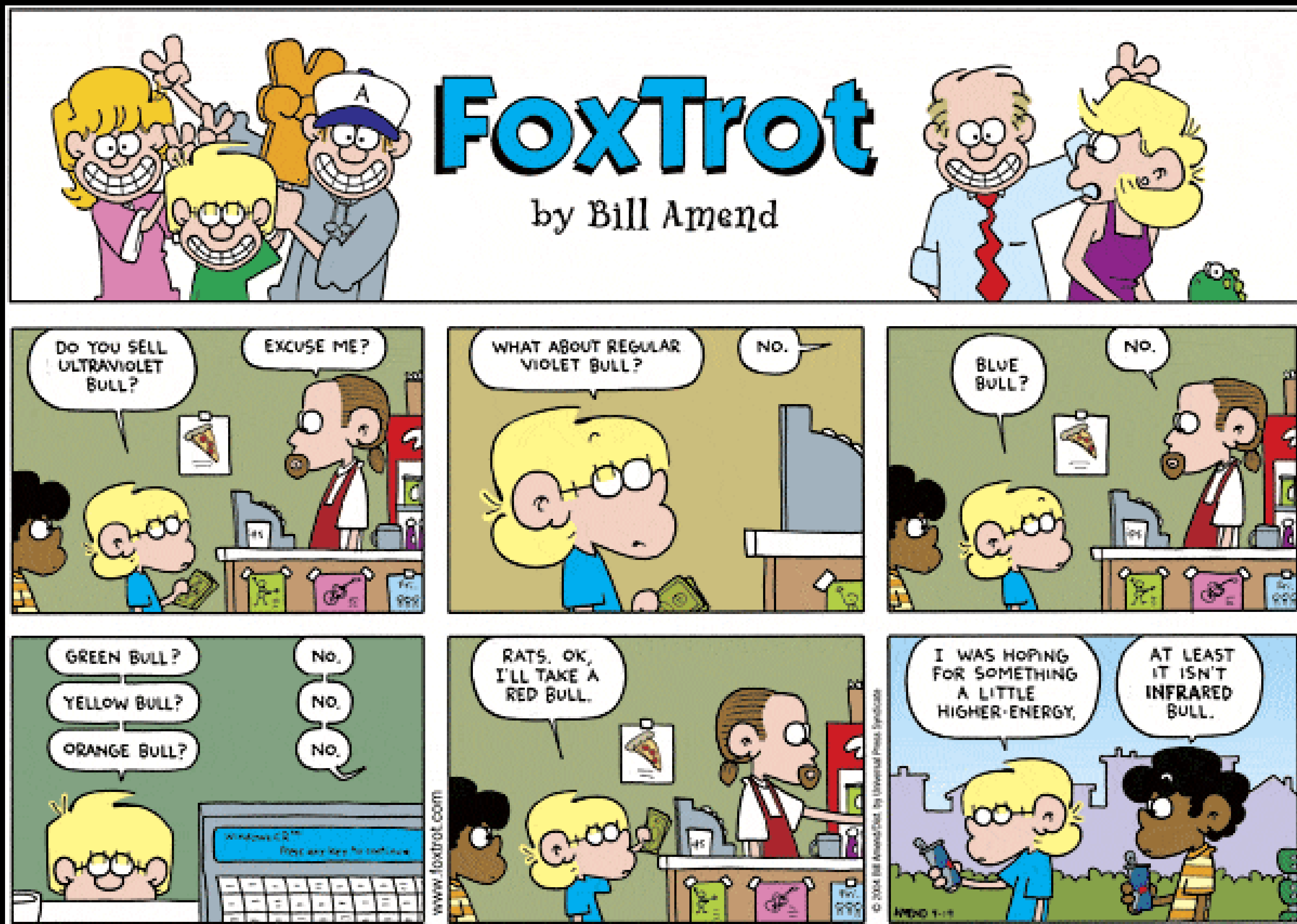
$$E = h\nu$$

h = Planck constant ($6.63 \cdot 10^{-34}$ Joule•sec)
ν = frequency of light (cycles/sec) = λ/c
1 eV = $1.6 \cdot 10^{-19}$ J (J = joule)

Wavelength (μm)	Energy (eV)	Band
0.3	4.13	Ultraviolet
0.5	2.48	Visible
0.7	1.77	Visible
1.0	1.24	Near IR
2.5	0.50	Short Wave IR
5.0	0.25	Mid Wave IR
10.0	0.12	Long Wave IR
20.0	0.06	Very Long Wave IR



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


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.

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
- 2013 launch on Ariane 5 rocket
- L2 orbit (1.5 million km from Earth)

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The energy of a photon is VERY small

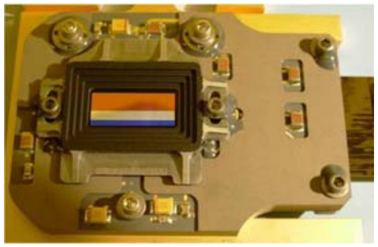
- The number of photons that will be detected by the James Webb Space Telescope in 5 years is about **4×10^{16} photons**
  - One image every 20 minutes (~150,000 images)
  - 15 arrays, each ~4 million pixels (63 million pixels)
  - Average pixel is at 4% full well (FW): ~4000 photons
    - 1% at 100% FW, 10% at 20% FW, 10% at 5% FW, 50% at 1% FW
- Total photon energy is 2×10^{16} eV
  - 2.5 micron IR photon is 0.5 eV
- Potential energy of a peanut M&M® candy dropped from a height of 6 inches is ~ 2×10^{16} eV
  - A peanut M&M® is ~2 g
  - mgh = $(2\times10^{-3}) \cdot (9.8\ m/s^2) \cdot (1.5\times10^{-1}) / (1.6\times10^{-19}$J per eV) ≈ 2×10^{16} eV
- **The amount of IR photon energy absorbed by the JWST over 5 years is the same energy as dropping a peanut M&M® candy 6 inches !**

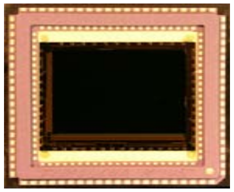
1 eV = $1.6 \cdot 10^{-19}$ J (J = joule)

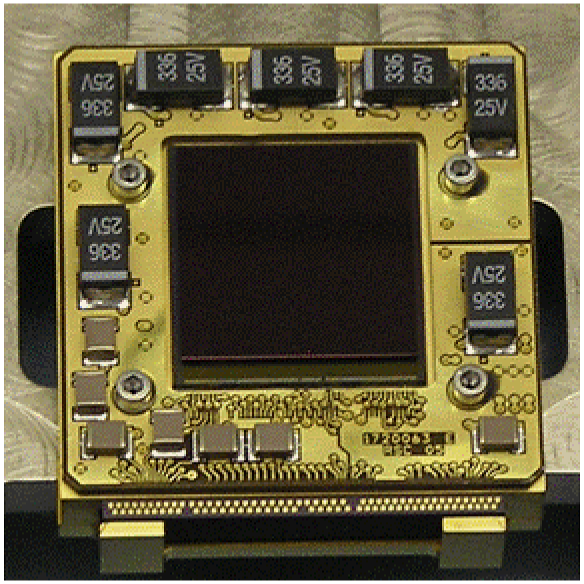
1 J = N • m = kg • m • sec^{-2} • m

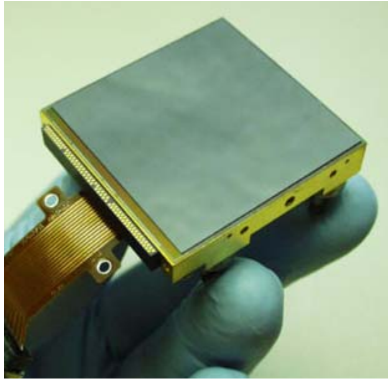
1 kg raised 1 meter = 9.8 J = $6.1 \cdot 10^{19}$ eV

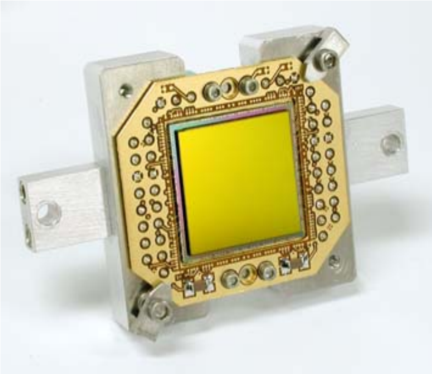
The Technologies of High Performance Imagers

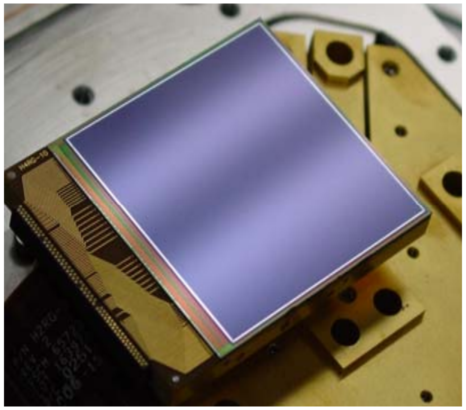












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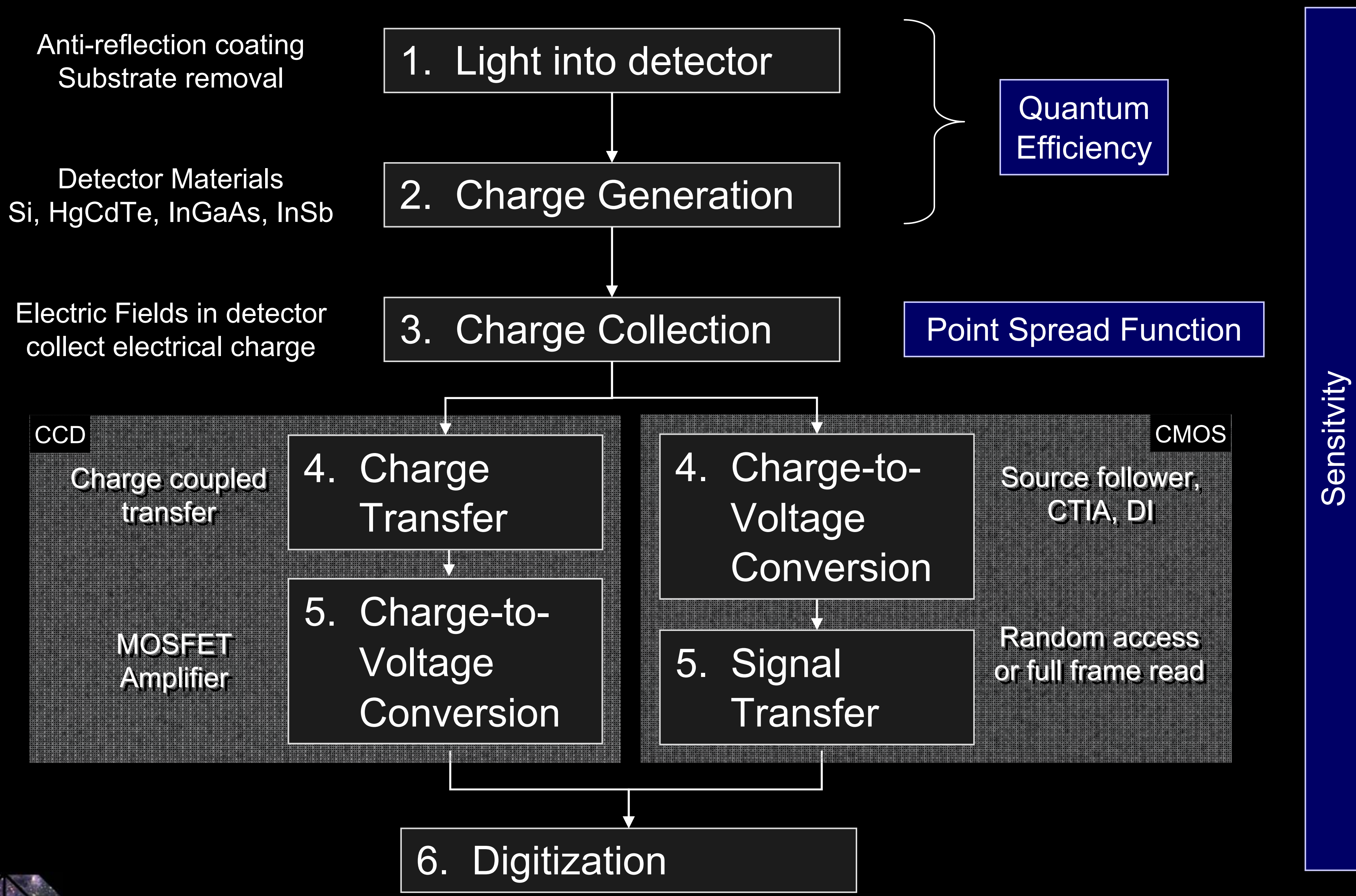
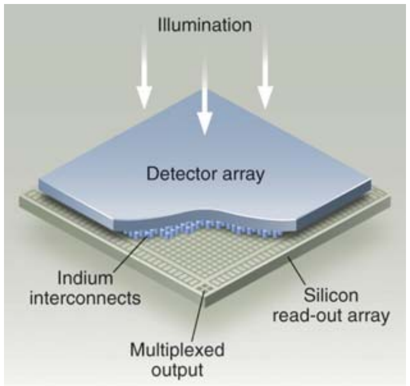
6 steps of optical / IR photon detection



6 Steps of CMOS-based X-ray → IR Photon Detection



HYBRID SENSOR CHIP ASSEMBLY (SCA)

SIDECAR ASIC

Anti-reflection coating
Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InGaAs

2. Charge Generation

Quantum Efficiency

Electric Fields in detector collect electrical charge p-n junction

3. Charge Collection

Point Spread Function

Source follower, CTIA, Direct Injection

4. Charge-to-Voltage Conversion

Random access or full frame read

5. Signal Transfer

SIDECAR ASIC

6. Digitization

Sensitivity

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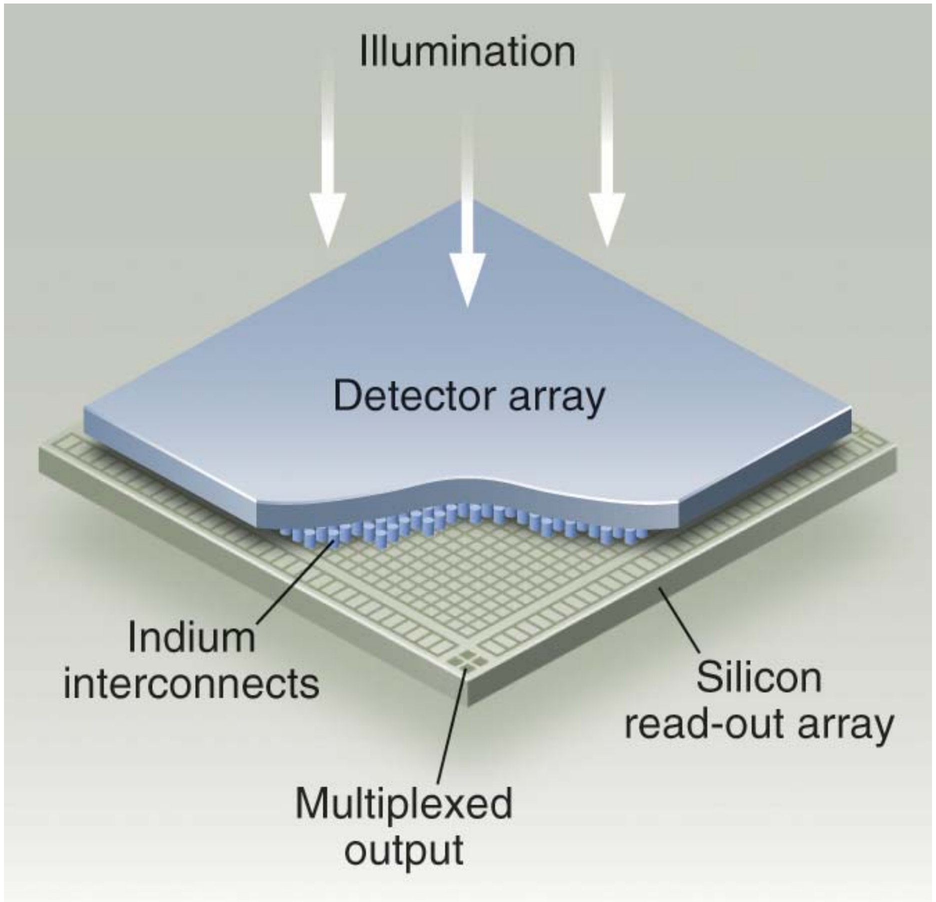
Hybrid CMOS Infrared Imaging Sensors



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

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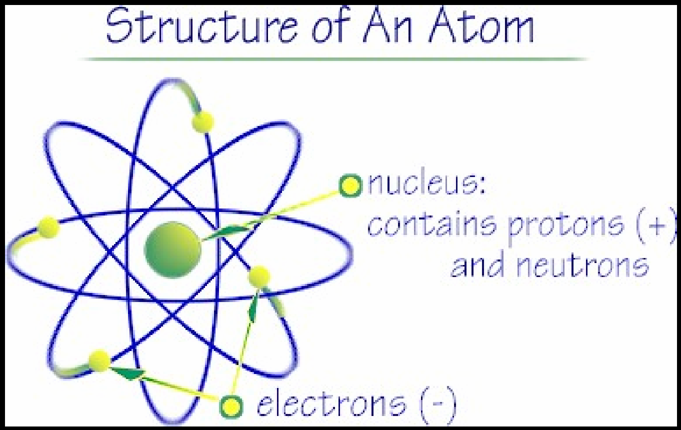
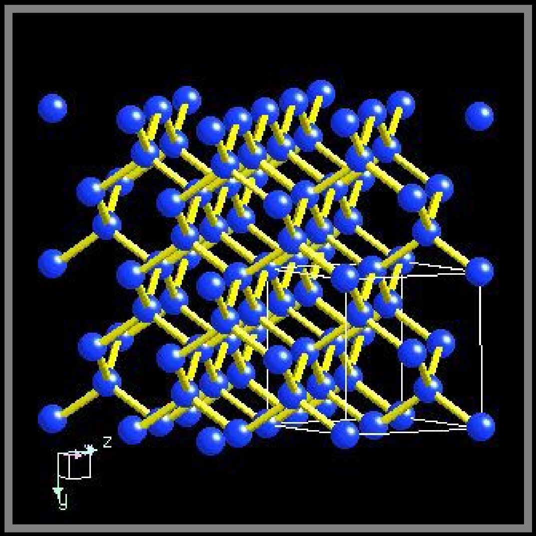
Crystals are excellent detectors of light



- 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.

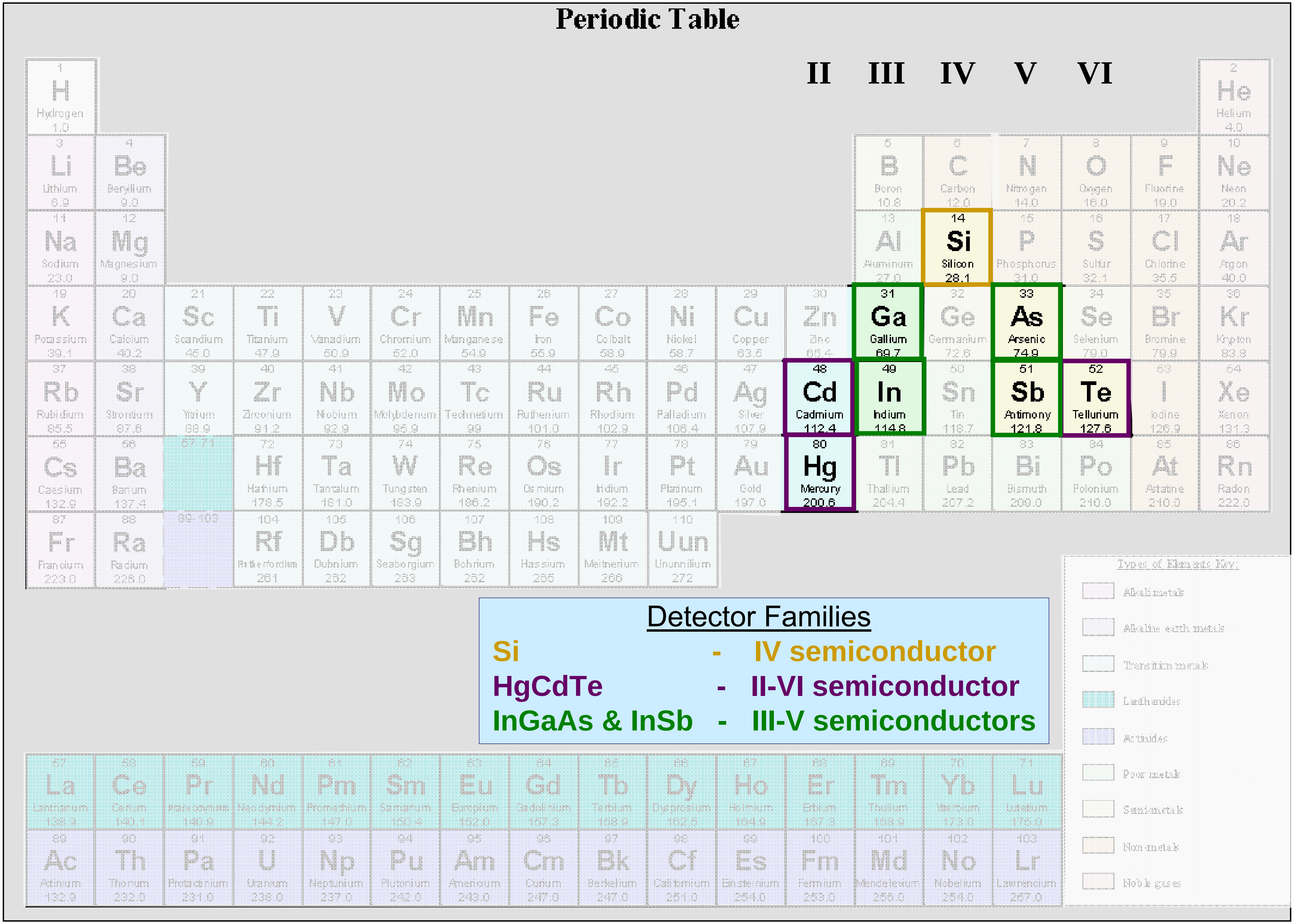
Periodic Table

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
II
III
IV
V
VI
14 Si Silicon 28.1
31 Ga Gallium 69.7
33 As Arsenic 74.9
48 Cd Cadmium 112.4
49 In Indium 114.8
51 Sb Antimony 121.8
52 Te Tellurium 127.6
80 Hg Mercury 200.6
Detector Families
Si - IV semiconductor
HgCdTe - II-VI semiconductor
InGaAs & InSb - III-V semiconductors

Photon Detection

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

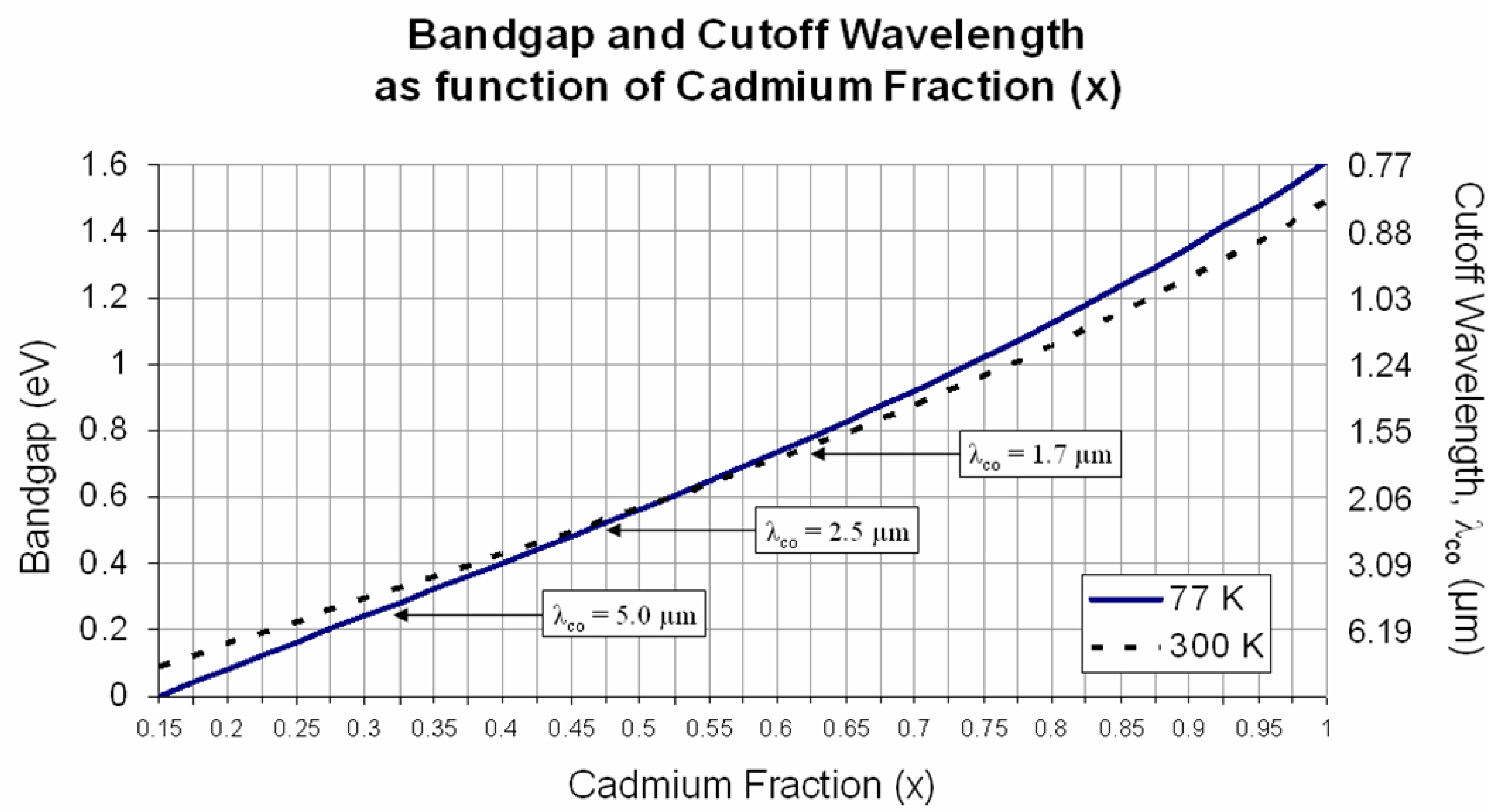
$$\lambda_c = 1.238 / E_g \text{ (eV)}$$

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 ($In_{0.53}Ga_{0.47}As$)

Tunable Wavelength: Unique property of HgCdTe

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



$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35 \times 10^{-4} T(1-2x)$$

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

Absorption Depth

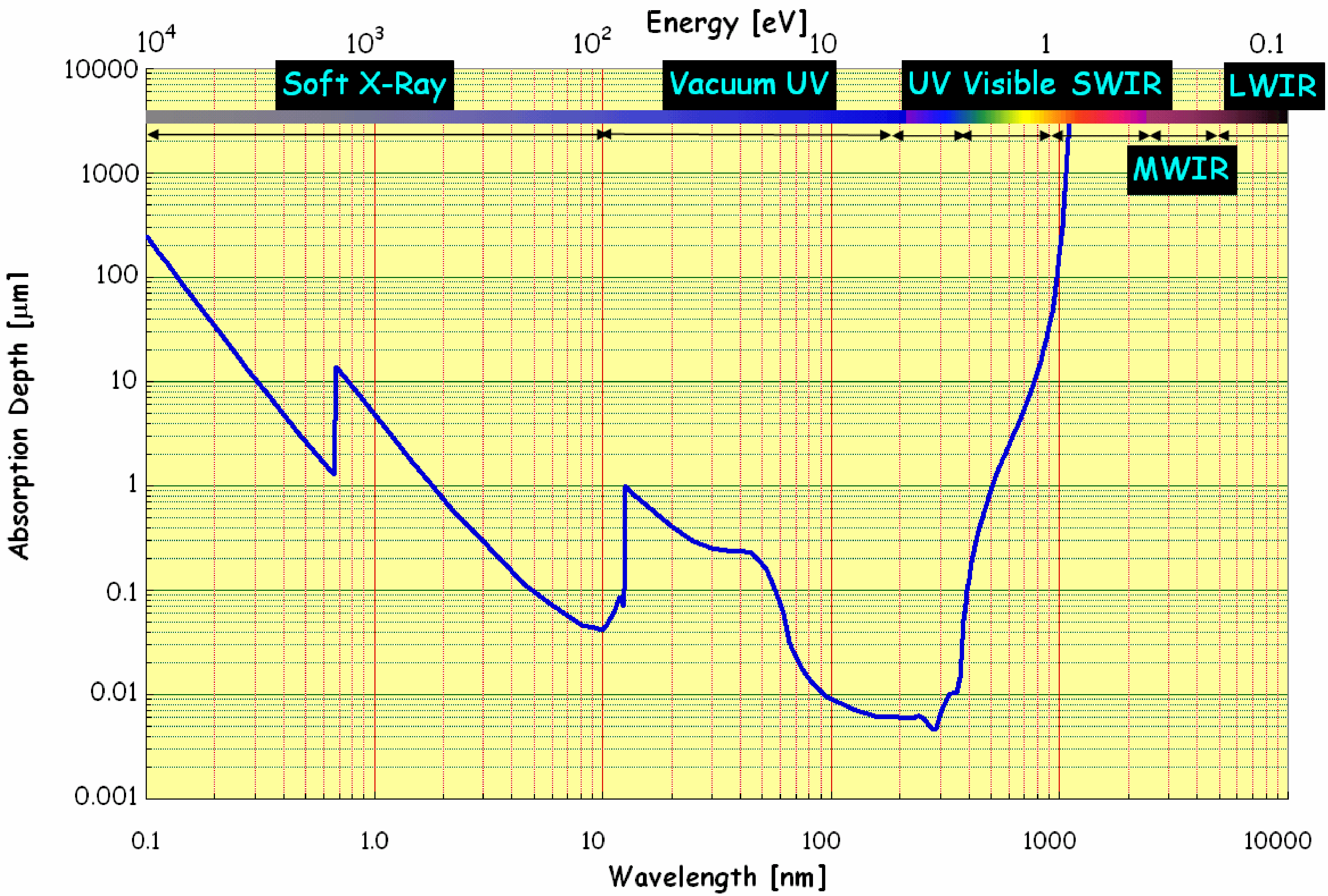
The depth of detector material that absorbs 63.2% of the radiation

1/e of the energy is absorbed

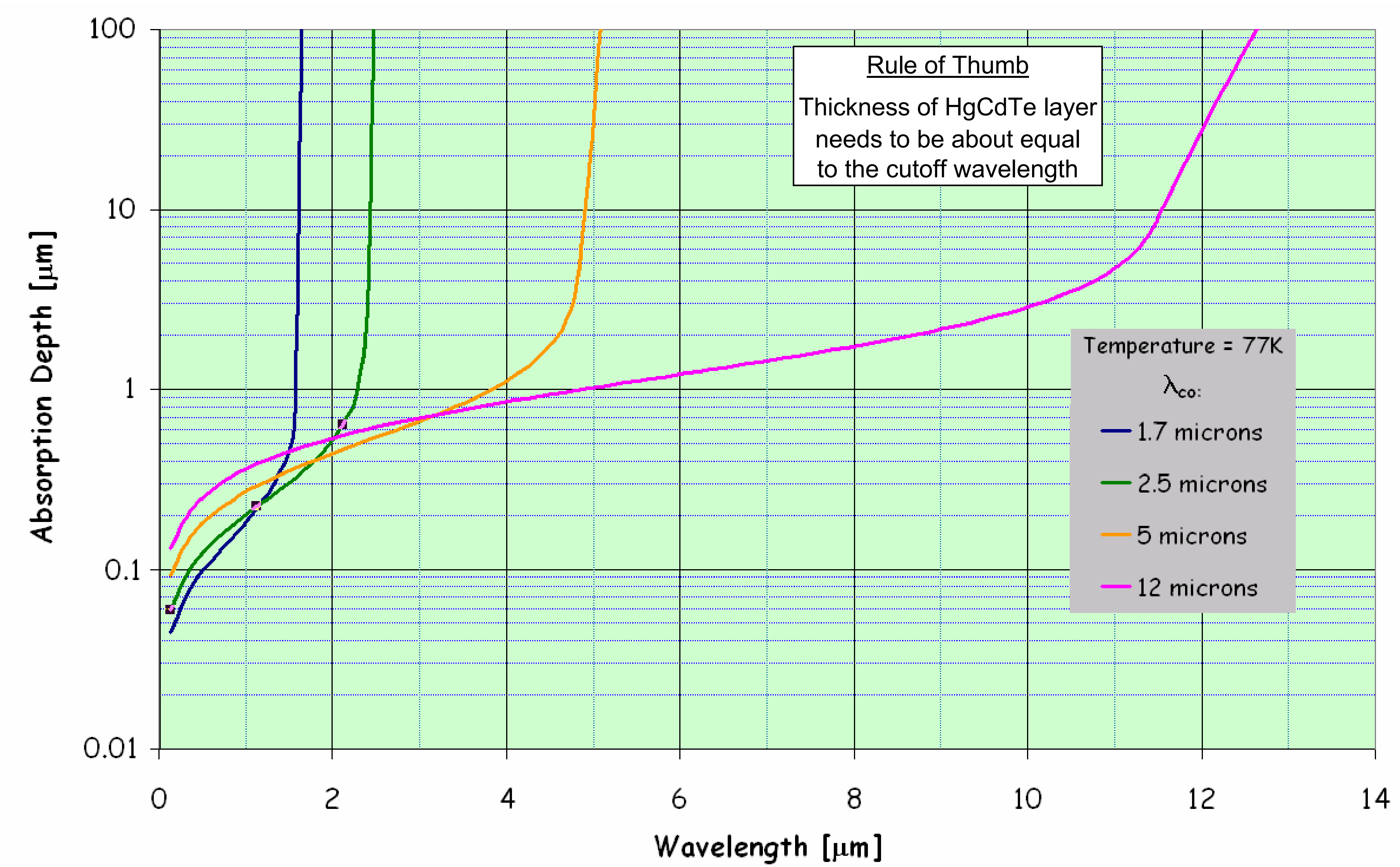
1	absorption depth(s)	63.2% of light absorbed
2		86.5%
3		95.0%
4		98.2%

For high Quantum Efficiency,
the thickness of detector material should be ≥ 3 absorption depths

Absorption Depth of Silicon



Absorption Depth of Photons in HgCdTe



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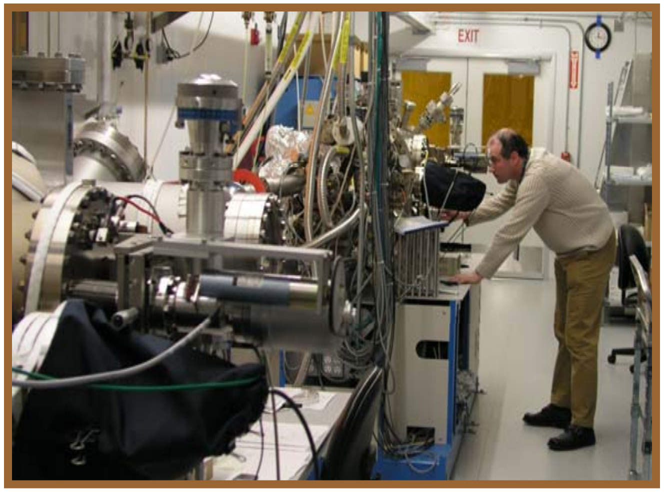
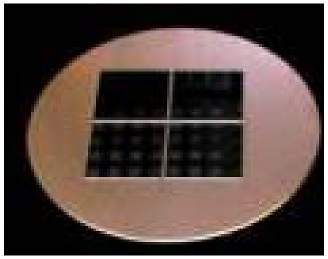
Molecular Beam Epitaxy (MBE) Growth of HgCdTe



RIBER 3-in MBE Systems

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

RIBER 10-in MBE 49 System



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

More than 7500 HgCdTe wafers grown to date

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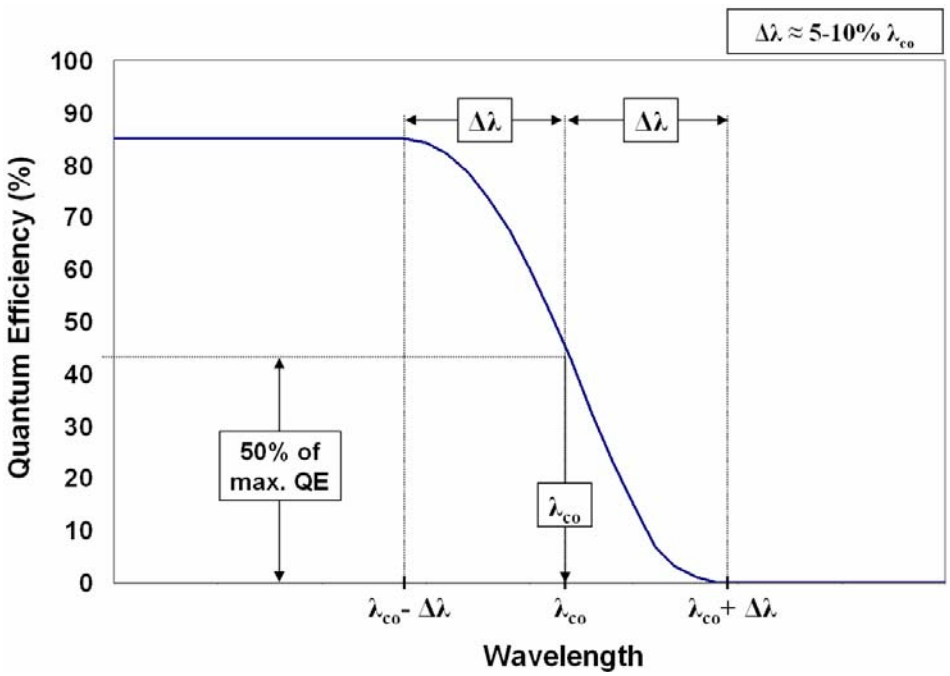
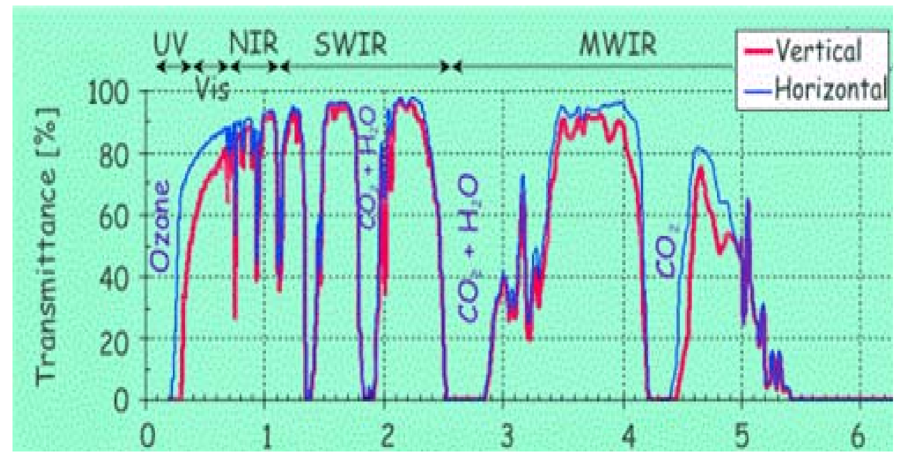
HgCdTe Cutoff Wavelength



Atmospheric Transmission

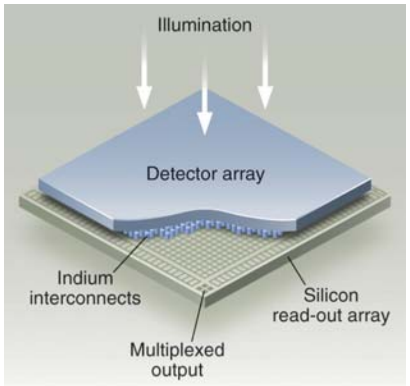


Wavelength (microns)

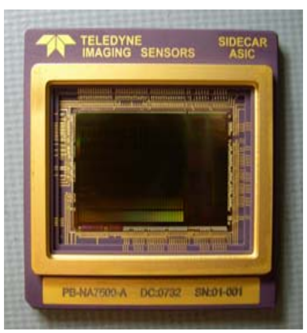
<u>“Standard” Ground-based astronomy cutoff wavelengths</u>

Near infrared (NIR)	1.75 µm	J,H
Short-wave infrared (SWIR)	2.5 µm	J,H,K
Mid-wave infrared (MWIR)	5.3 µm	J,H,K,L,M

6 Steps of CMOS-based Optical / IR Photon Detection



HYBRID SENSOR
CHIP ASSEMBLY (SCA)



SIDECAR ASIC

Anti-reflection coating Substrate removal	**1. Light into detector**
Detector Materials HgCdTe, Si	**2. Charge Generation**
Electric Fields in detector collect electrical charge p-n junction	**3. Charge Collection**
Source follower	**4. Charge-to-Voltage Conversion**
Random access or full frame read	**5. Signal Transfer**
SIDECAR ASIC	**6. Digitization**

Steps 1–2: Quantum Efficiency

Step 3: Point Spread Function

Sensitivity

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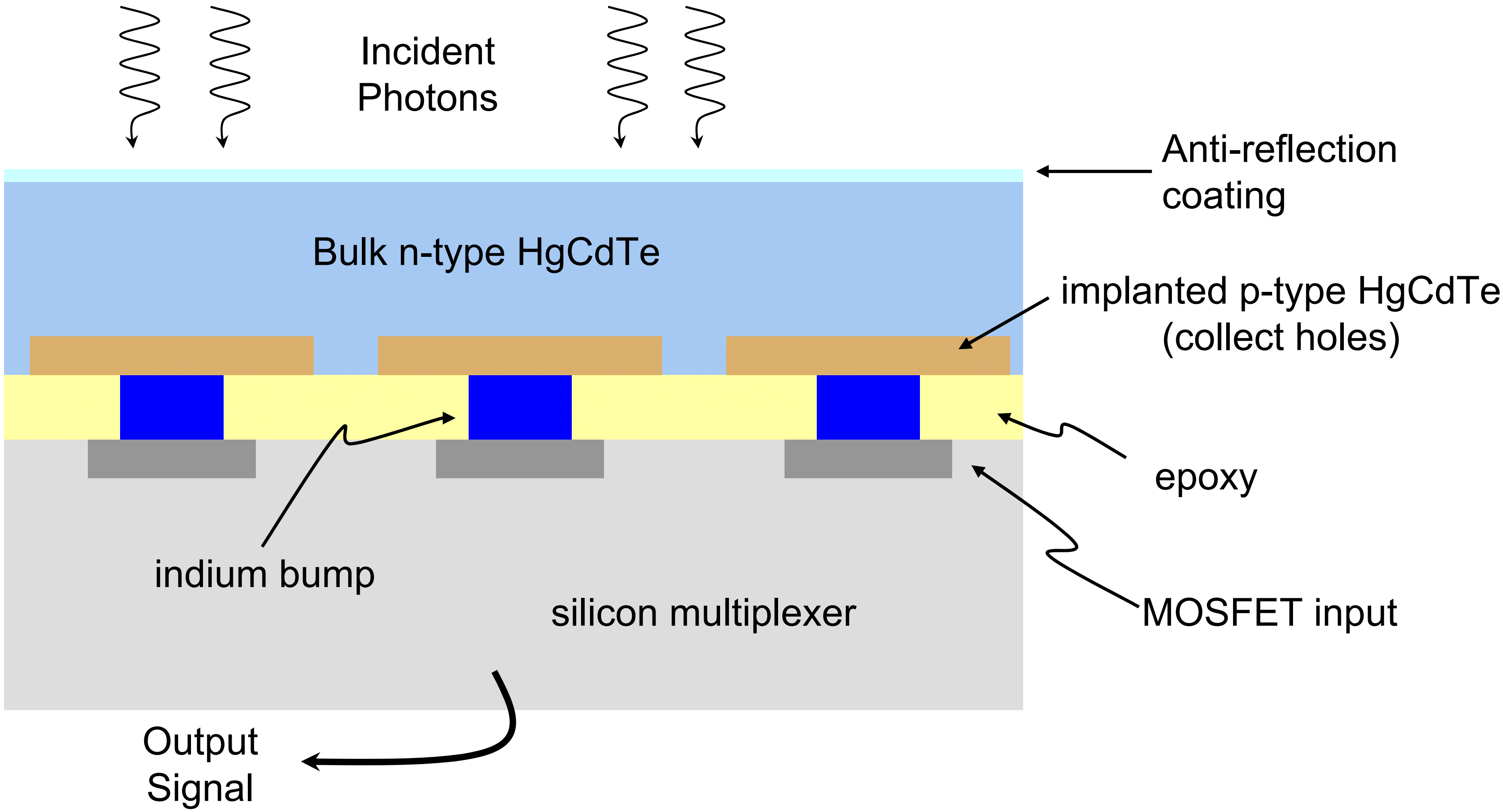
HgCdTe hybrid FPA cross-section (substrate removed)



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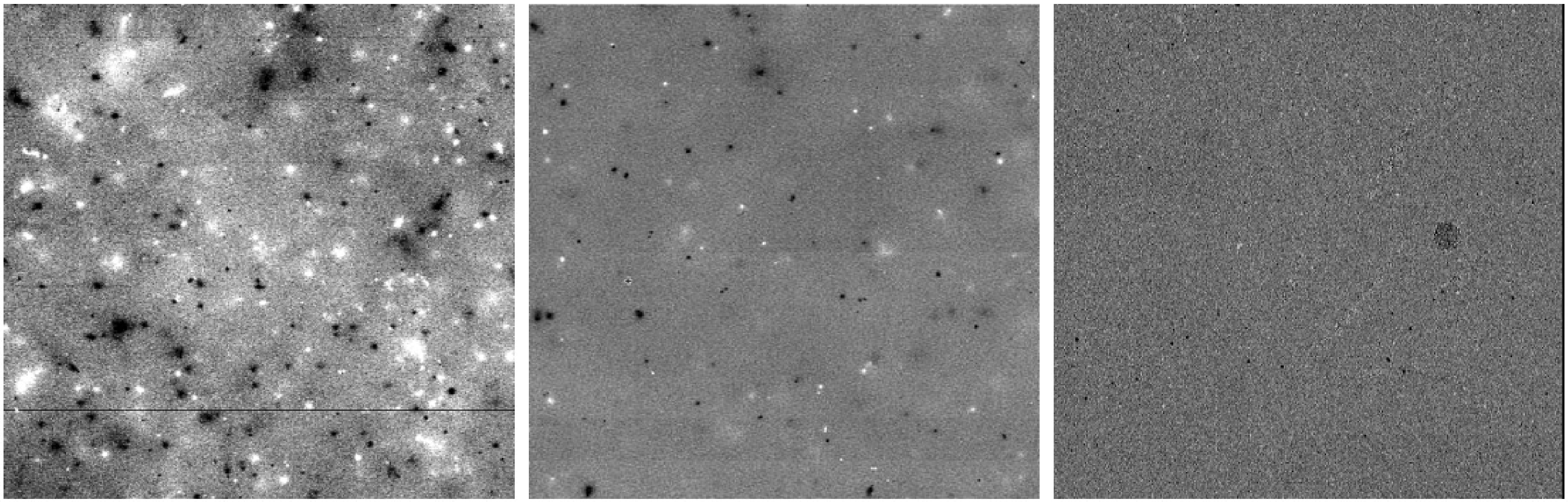
Cosmic Rays and Substrate Removal

- 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**

Substrate Removal Positive Attributes

1. **Higher QE in the near infrared**
2. **Visible light response**
3. **Eliminates cosmic ray fluorescence**
4. **Eliminates fringing in the substrate material**
5. **Eliminates CTE mismatch with silicon ROIC**

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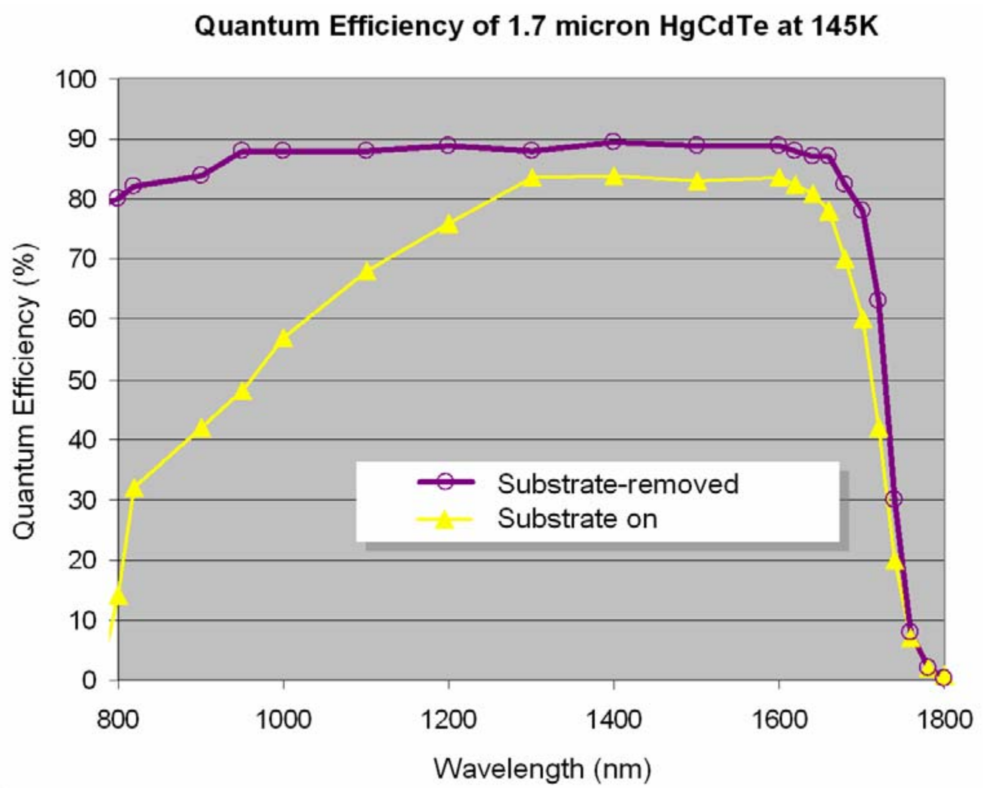
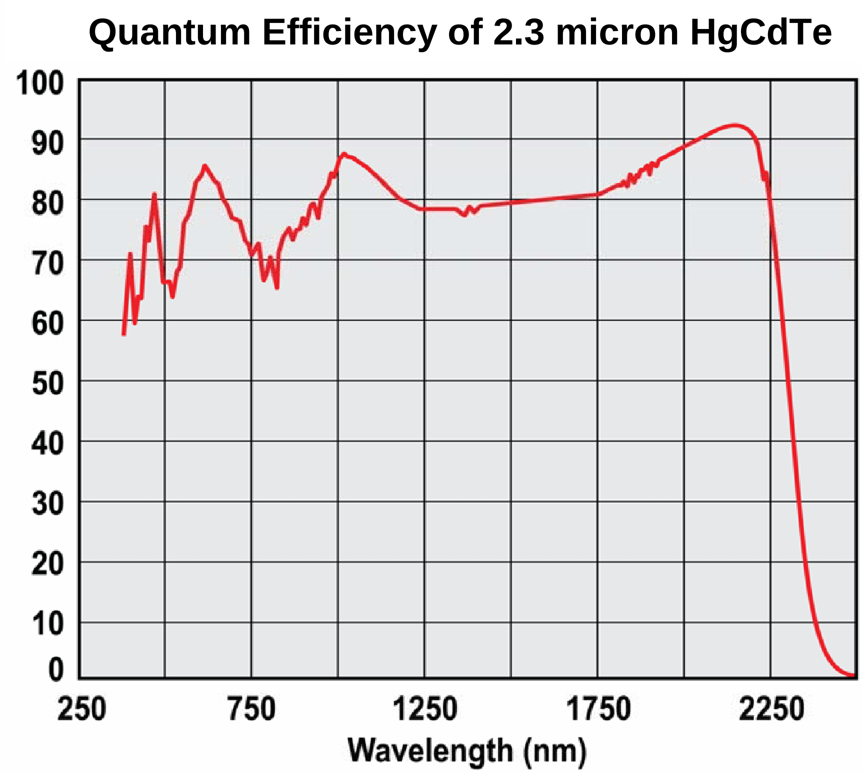
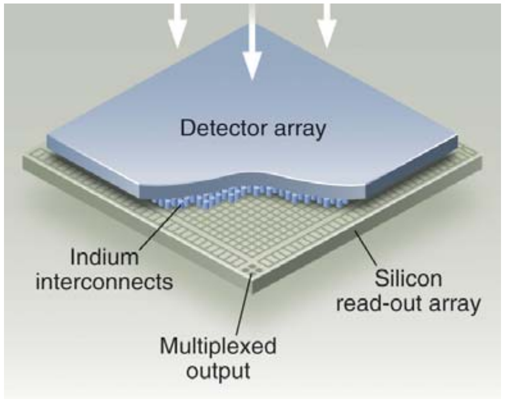
Images courtesy of Roger Smith

Quantum Efficiency of substrate-removed HgCdTe







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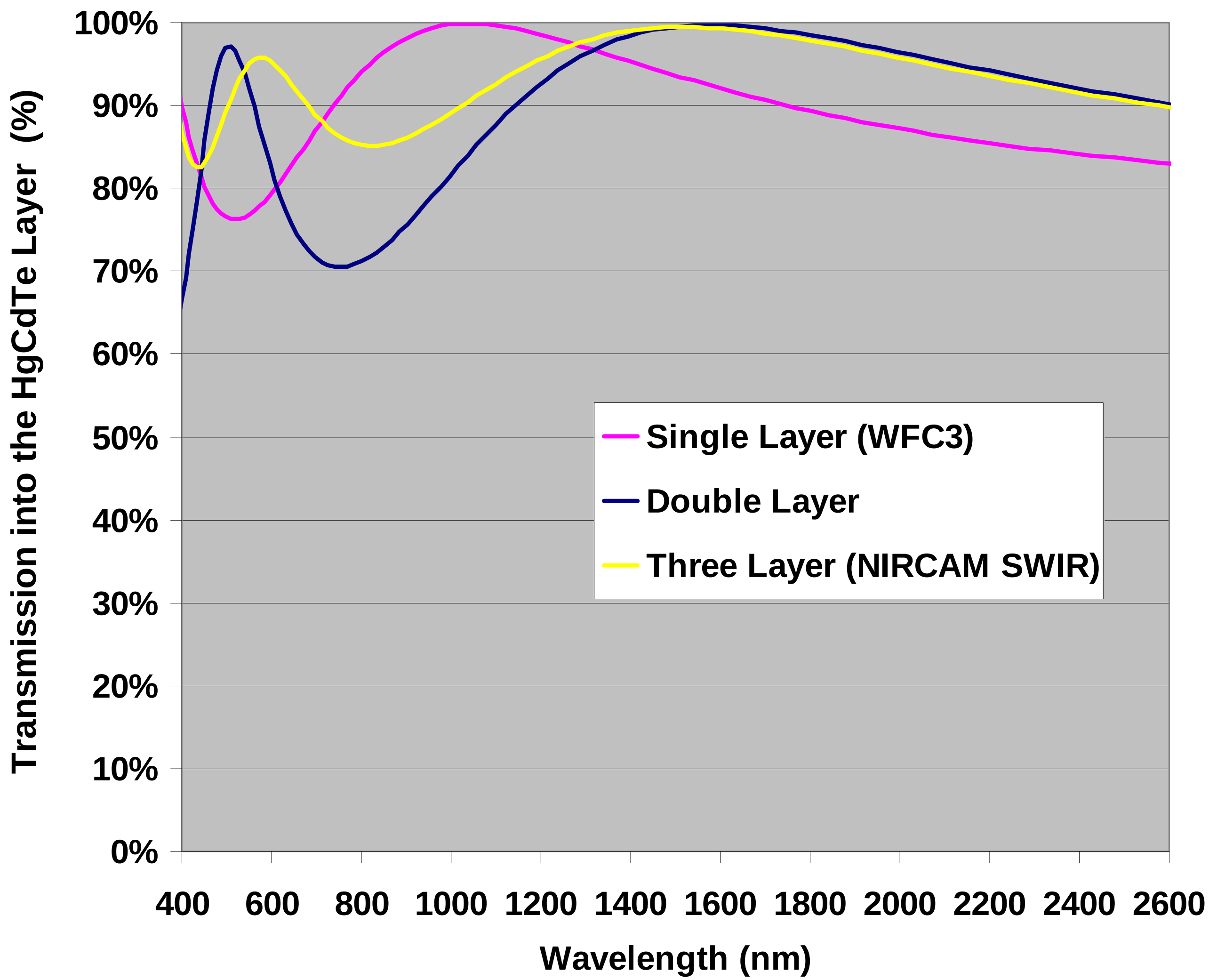
Example Anti-reflection coatings for HgCdTe



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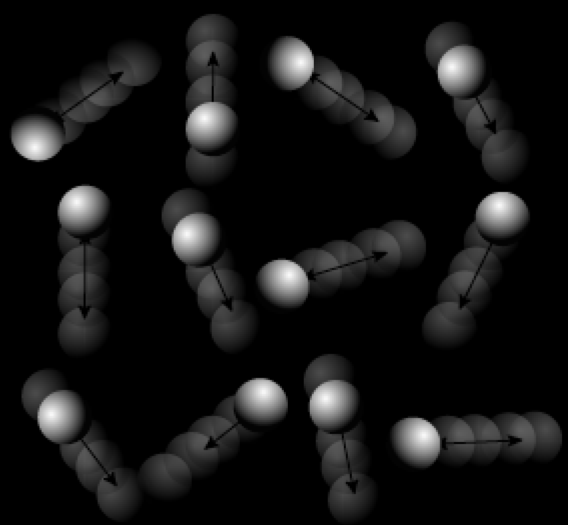
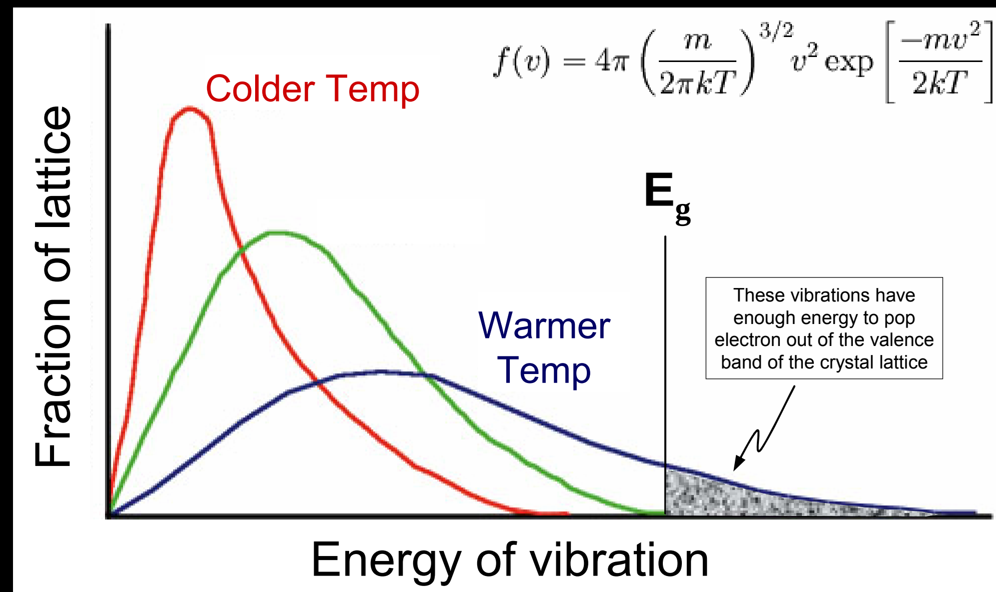
Dark Current

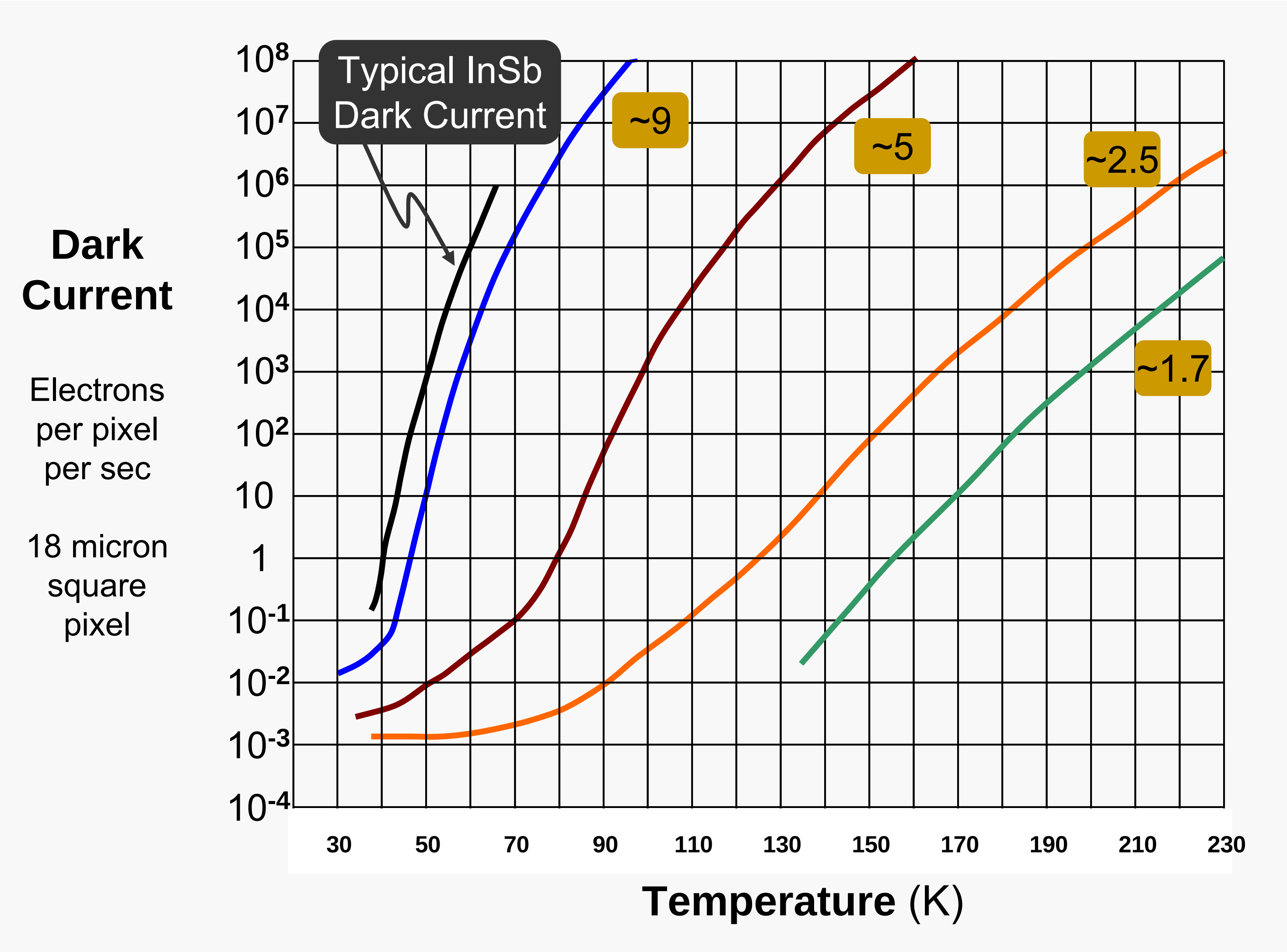
Undesirable byproduct of light detecting materials





- 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 MBE HgCdTe



HgCdTe cutoff wavelength (microns)

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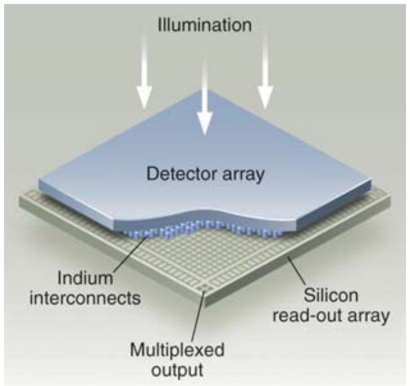
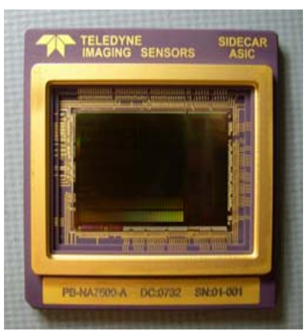
6 Steps of CMOS-based Optical / IR Photon Detection



HYBRID SENSOR
CHIP ASSEMBLY (SCA)



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SIDECAR ASIC	**6. Digitization**

Quantum Efficiency (steps 1–2)

Point Spread Function

Sensitivity

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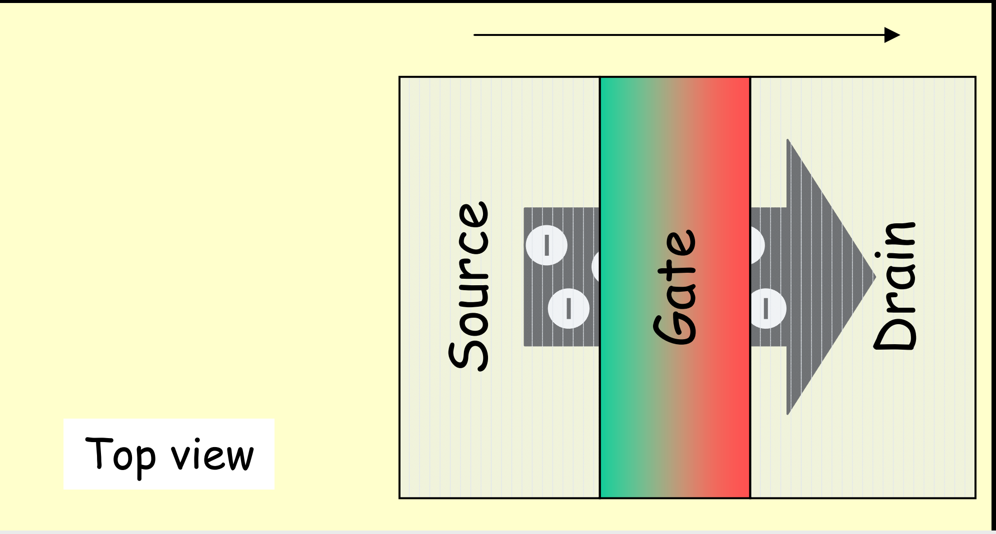
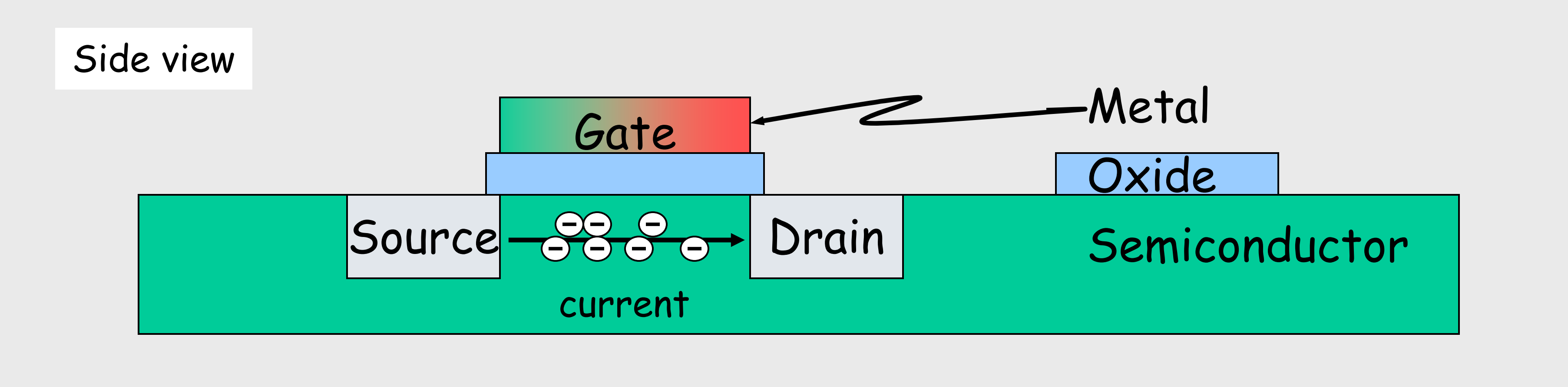
MOSFET Principles

MOSFET = metal oxide semiconductor field effect transistor



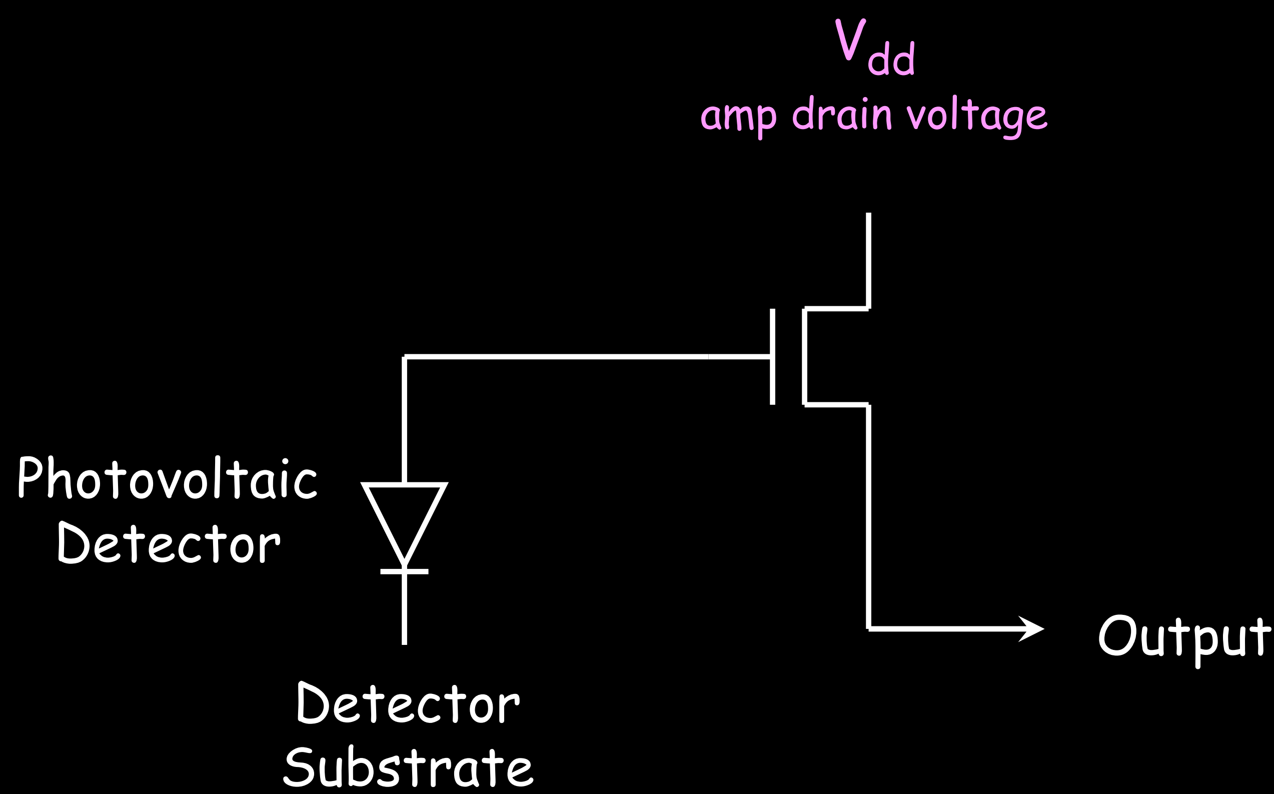
Turn on the MOSFET and current flows from source to drain

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

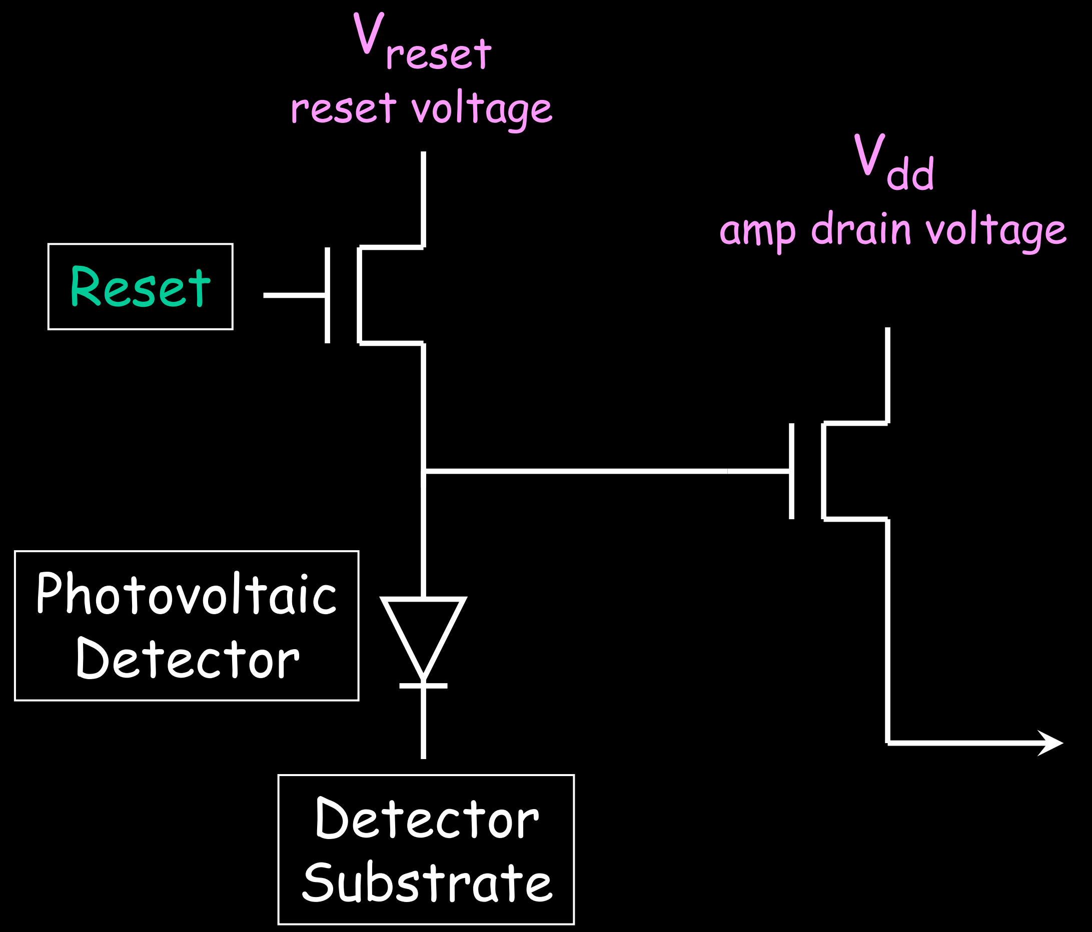


Fluctuations in current flow produce "readout noise"
Fluctuations in reset level on gate produces "reset noise"

IR multiplexer pixel architecture



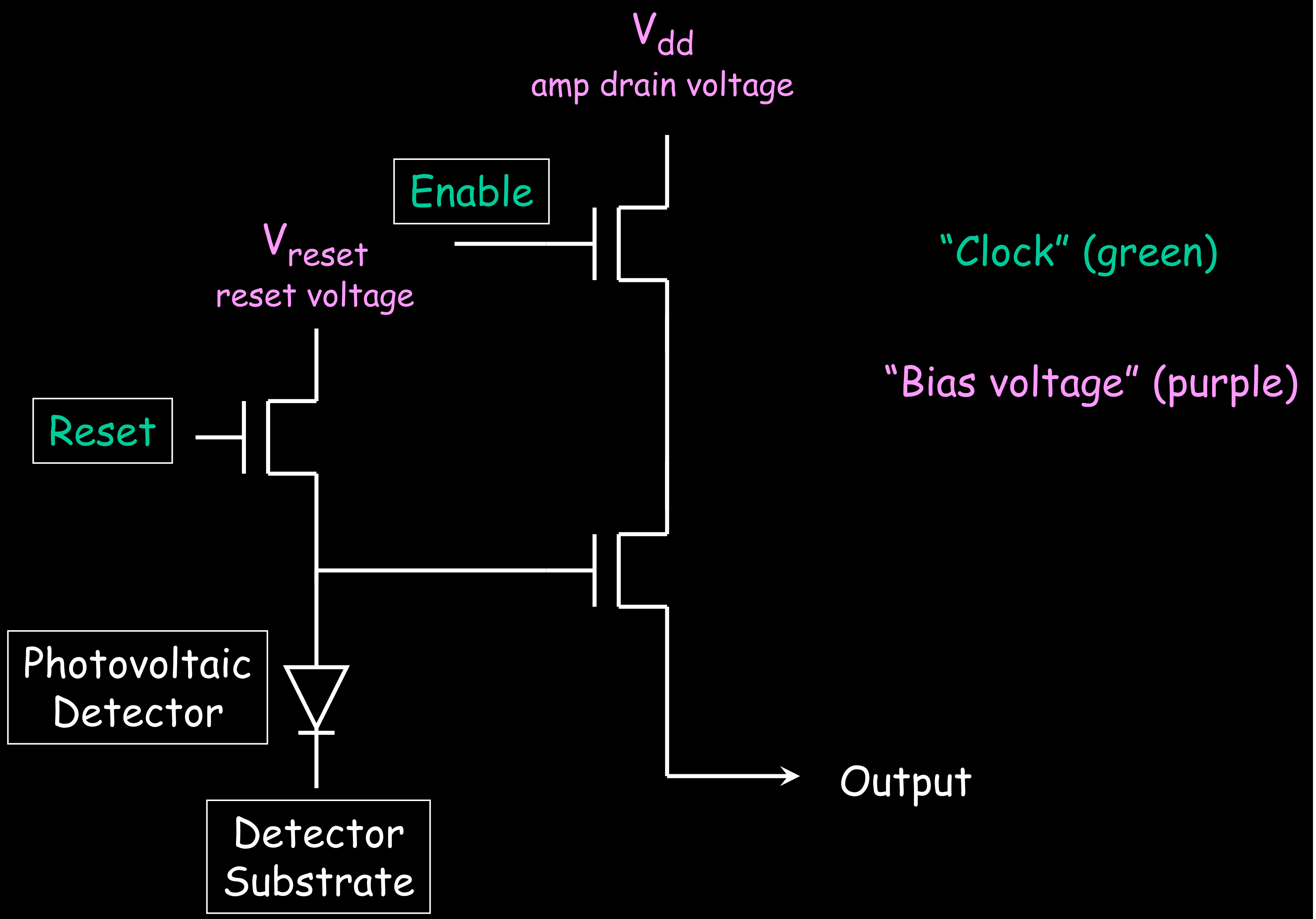
IR multiplexer pixel architecture



"Clock" (green)

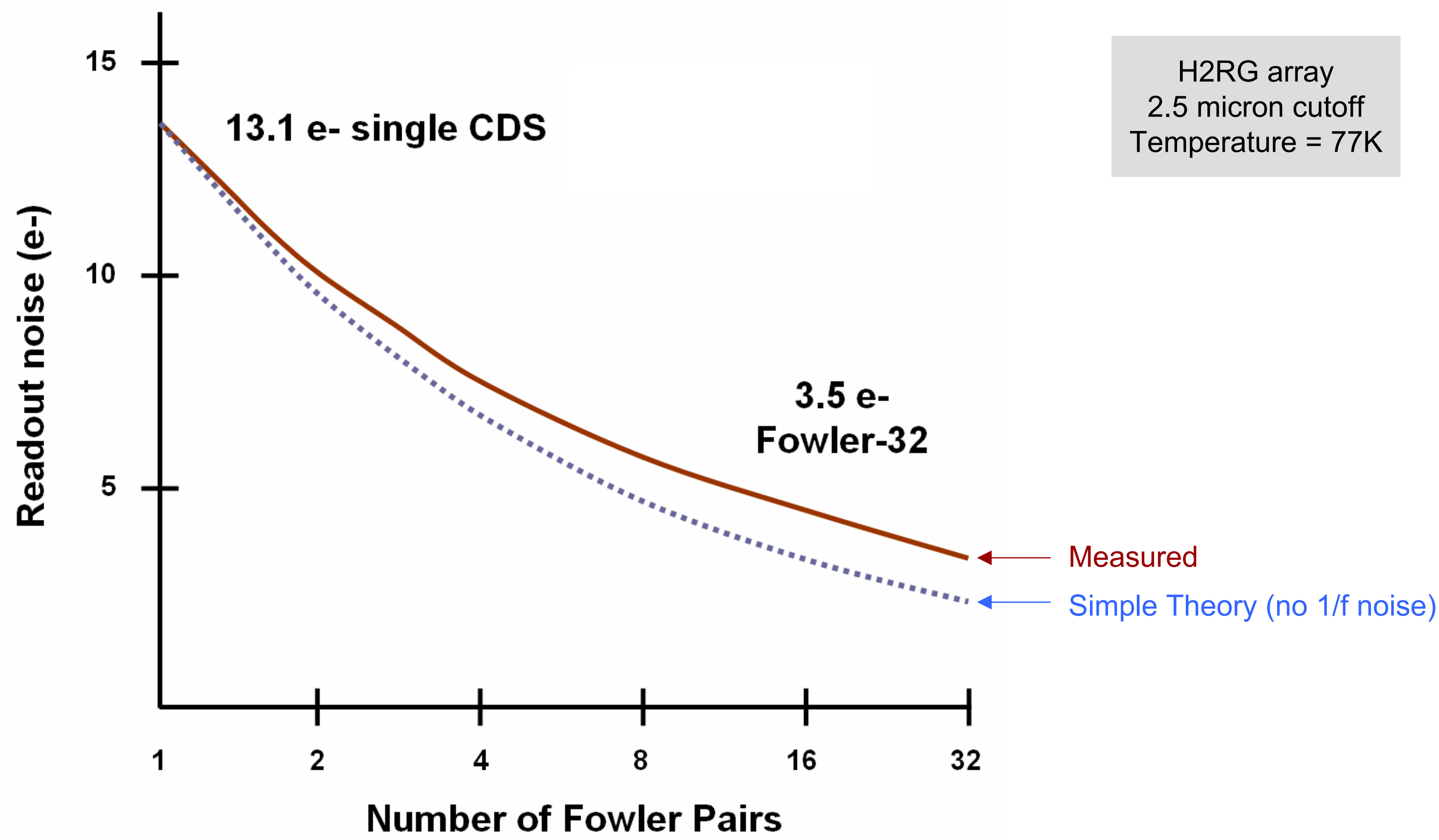
"Bias voltage" (purple)

IR multiplexer pixel architecture



Reduction of noise from multiple samples

Non-destructive readout enables reduction of noise from multiple samples



H2RG array
2.5 micron cutoff
Temperature = 77K

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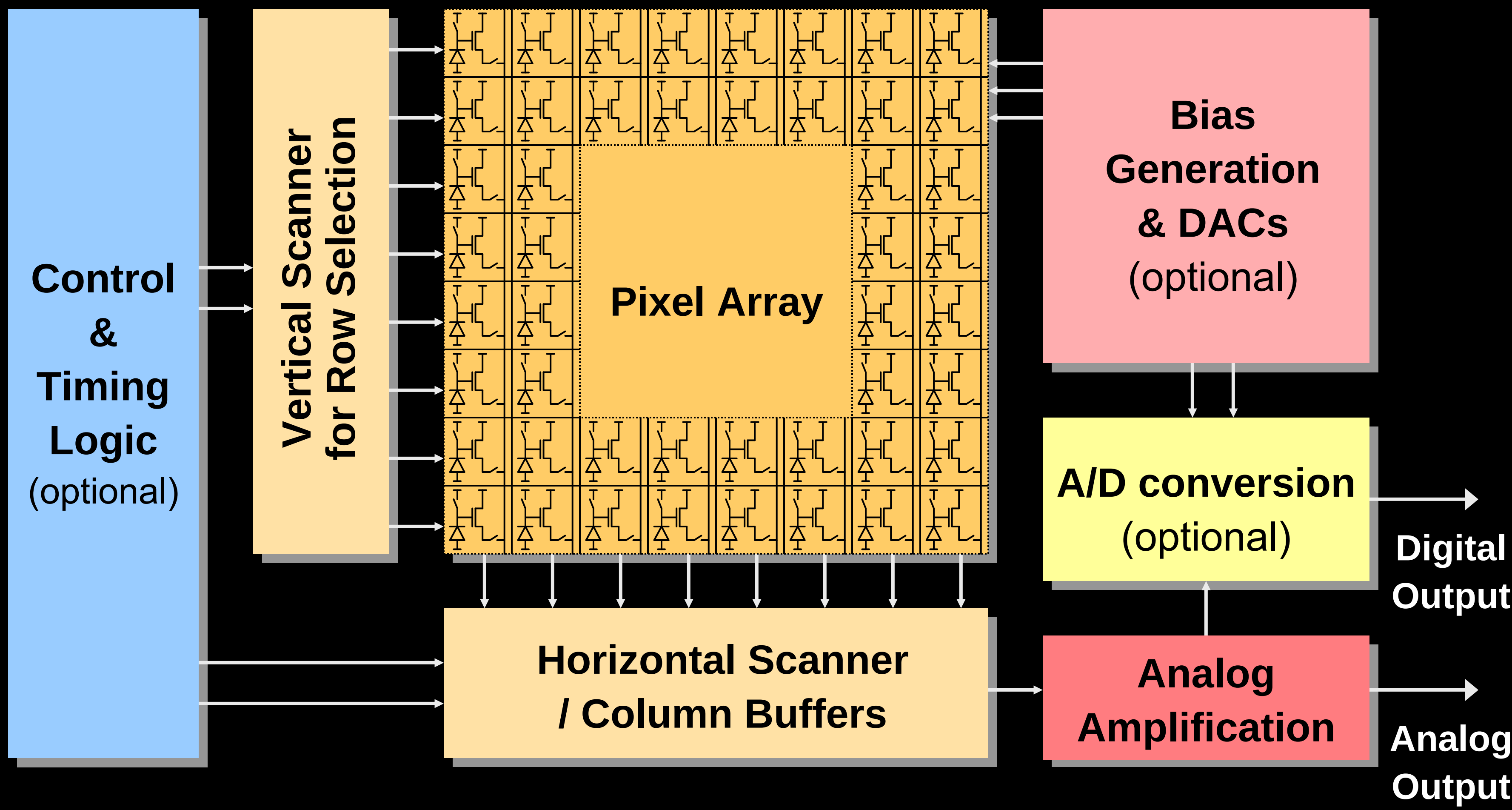
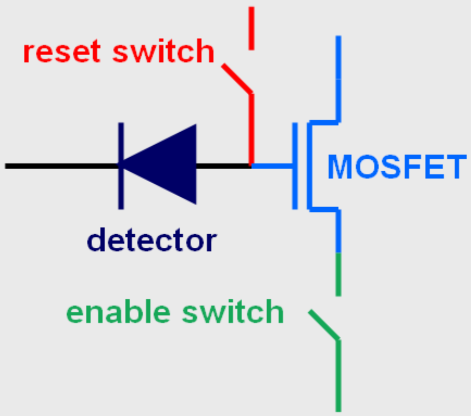
CDS = correlated double sample

General Architecture of CMOS-Based Image Sensors



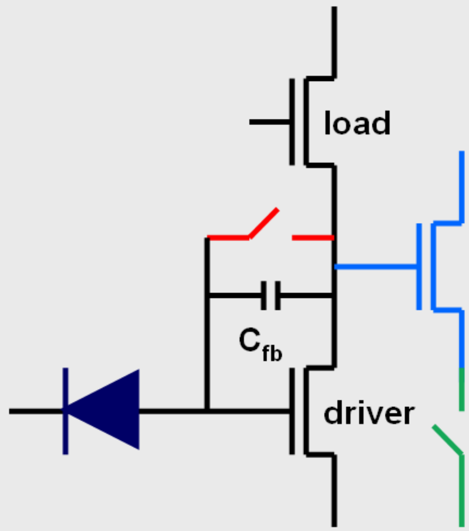
Pixel Amplifier Options



Source follower
(SF)

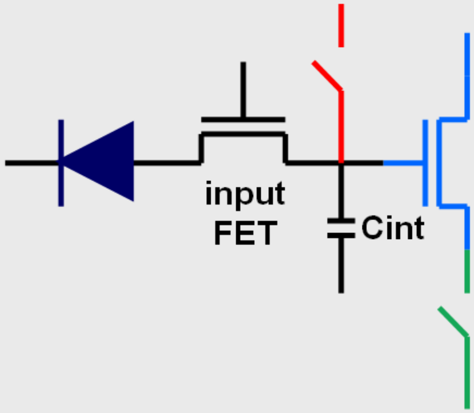
- Integration on detector node
- Low power & compact
  (3 FETs / pixel)
- Ideal for small pixels & low flux
- Poor performance for high flux

- Full Well: ~100,000 electrons
- Readout Noise: <15 e-



Capactive TransImpedance Amplifier (CTIA)

- Versatile circuit suitable for all backgrounds and detectors
- High linearity
- High power, higher noise and larger circuit than SF for low flux
- Worse performance than DI for high flux
- Full Well: ~1 to 10 million e-
- Readout Noise: <50 e-



Direct Injection
(DI)

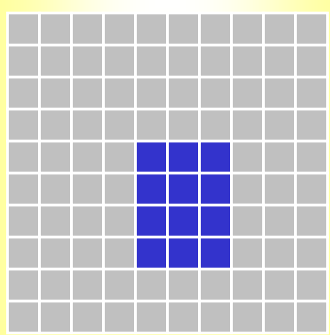
- Extremely small circuit
- Large integration density in pixel
- High well capacity for high flux applications
- Ultra low power
- Poor injection efficiency for low flux applications
- Full Well: tens of millions of e-
- Readout Noise: <1000 e-

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**

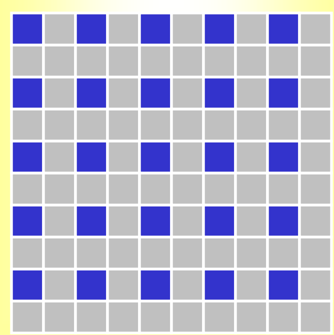
Windowing

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



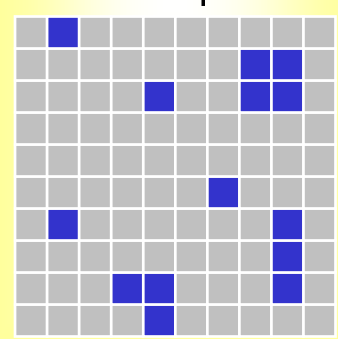
Subsampling

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



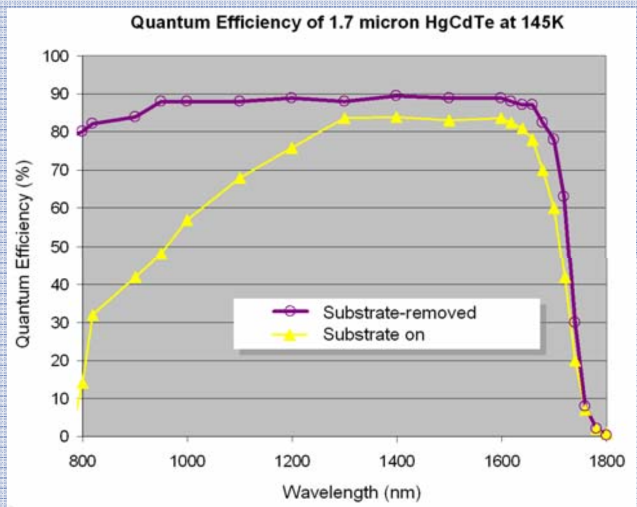
Random Read

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



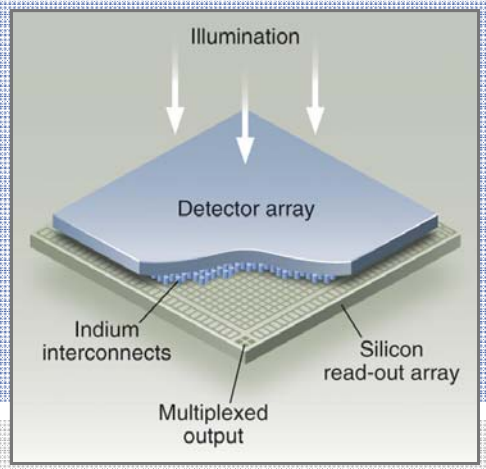
High Performance Hybrid CMOS Visible-Infrared Arrays

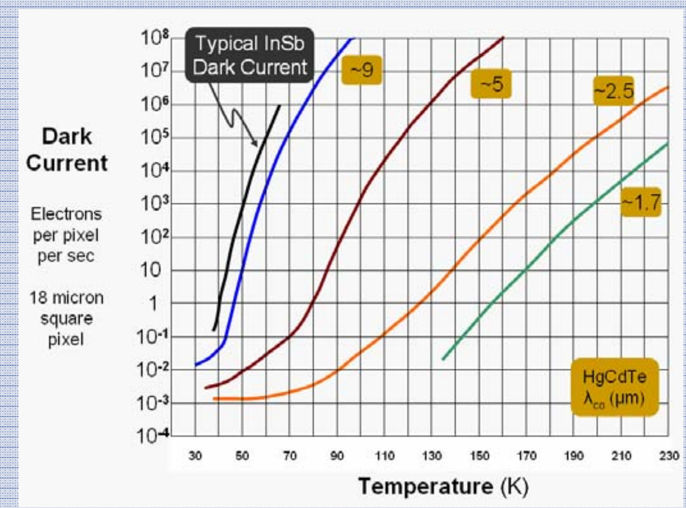
High Quality MBE HgCdTe + High Performance CMOS Design + Large Area Hybridization



High Quantum Efficiency

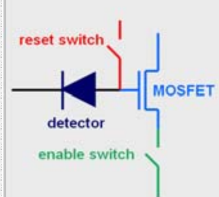
High Quality Detectors





Low Dark Current

High Performance Amplifiers



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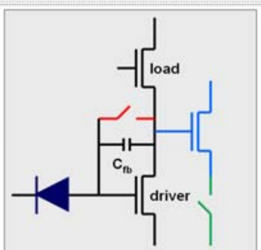

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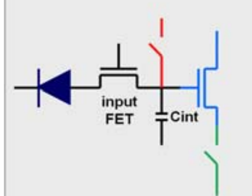

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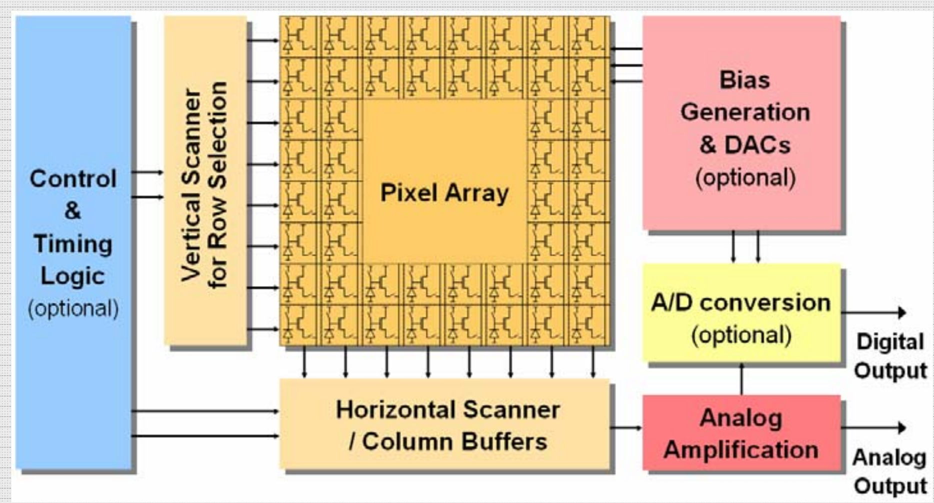
Imaging System on Chip Architecture



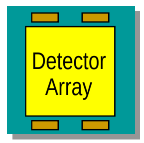
High Performance Readout Circuits

H2RG Production - Standard SCA Build Cycle

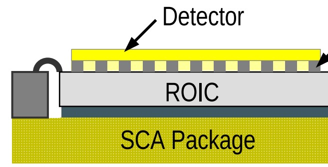
Detector Fabrication → SCA Fabrication → Test

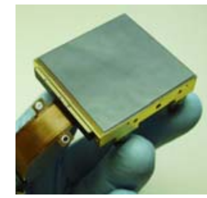
CdZnTe

HgCdTe



Process Evaluation Chip

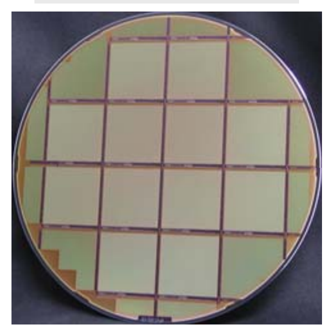




HgCdTe Growth | Array Processing | Dicing | Electrical & Optical Characterization | SCA Hybridization & Packaging | Test

Molecular Beam Expitaxy (MBE) Machine

- Hybridization
- Substrate Removal
- Passivation
- Anti-reflection coating
- Mounting
- Wirebonding



SCA Test Station

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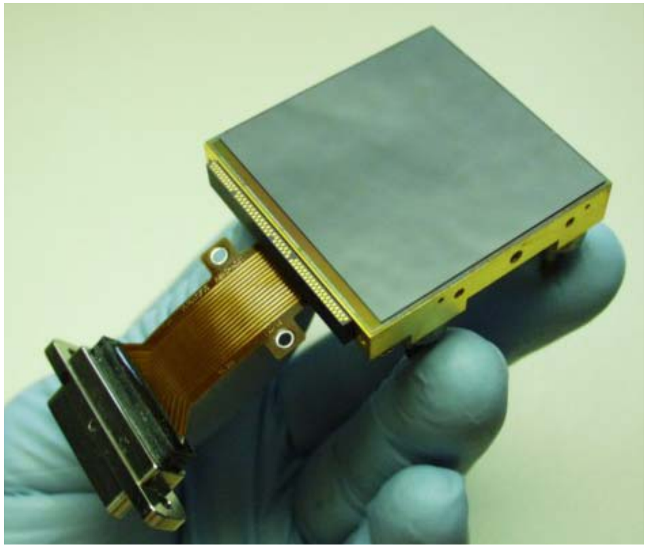
SCA = Sensor Chip Assembly

HAWAII-2RG 2048×2048 pixels



4Kx4K mosaic of 4 H2RGs

HAWAII-2RG (H2RG)

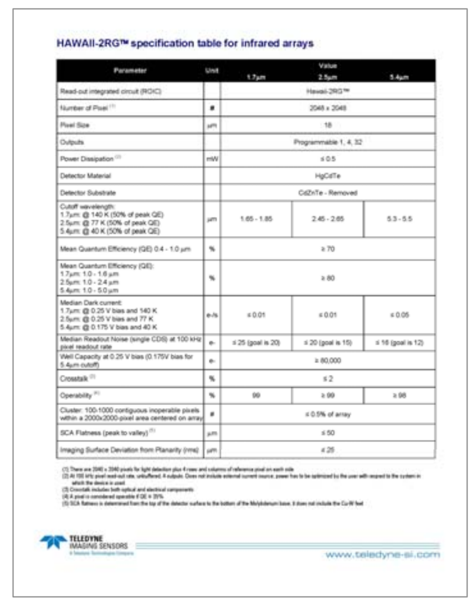
- 2048×2048 pixels, 18 micron pitch
- 1, 2, 4, 32 ports
- “R” = reference pixels (4 rows/cols at edge)
- “G” = guide window
- Low power: <1 mW (4 port, 100 kHz rate)
- Detector material: HgCdTe or Si
- Interfaces directly to the SIDECAR ASIC
- **Qualified to NASA TRL-6**
  - Vibration, radiation, thermal cycling
  - Radiation hard to ~100 krad

Teledyne Imaging Sensors
HAWAII-2RG™
Visible & Infrared Focal Plane Array

The 2048×2048 pixel HAWAII-2RG™ (H2RG) is the state-of-the-art readout integrated circuit for visible and infrared astronomy in ground-based and space telescope applications.

- Large (2048×2048 pixel) array with 18 µm pixel pitch.
- Compatible with Teledyne Imaging Sensors (TIS) HgCdTe infrared (IR) and silicon PIN HyViSI™ visible detectors, providing sensing of any spectral band from soft X-ray to 5.5 µm.
- Substrate-removed HgCdTe enhances the J-band QE, enables response into the visible spectrum (70% QE down to 400nm) and eliminates fluorescence from cosmic radiation absorbed in the substrate.
- Reference rows and columns for common-mode noise rejection.
- Guide window output – windowing with simultaneous science date acquisition of full array. Programmable window which may be read out at up to 5 MHz pixel rate for guiding. Readout is designed to allow interleaved readout of the guide window and the full frame science data.
- Selectable number of outputs (1, 4, or 32) and user-selectable scan directions provide complete flexibility in data acquisition.
- Built with modularity in mind – the array is 4-side-buttable to allow assembly of large mosaics of 2048×2048 H2RG modules, such as TIS' 4096×4096 mosaic FPA and larger mosaics.
- Fully compatible with the TIS SIDECAR™ ASIC Focal Plane Electronics.

www.teledyne-si.com



HAWAII-2RG™ specification table for infrared arrays

Parameter	Unit	1.7µm	2.5µm	5.4µm
Read-out integrated circuit (ROIC)		Hawaii-2RG™		
Number of Pixel [1]	#	2048 x 2048		
Pixel Size	µm	18		
Outputs		Programmable 1, 4, 32		
Power Dissipation [2]	mW	≤ 0.5		
Detector Material		HgCdTe		
Detector Substrate		CdZnTe - Removed		
Cutoff wavelength: 1.7µm: @ 140 K (50% of peak QE) 2.5µm: @ 77 K (50% of peak QE) 5.4µm: @ 40 K (50% of peak QE)	µm	1.65 - 1.85	2.45 - 2.65	5.3 - 5.5
Mean Quantum Efficiency (QE) 0.4 - 1.0 µm	%	≥ 70		
Mean Quantum Efficiency (QE): 1.7µm: 1.0 - 1.6 µm 2.5µm: 1.0 - 2.4 µm 5.4µm: 1.0 - 5.0 µm	%	≥ 80		
Median Dark current: 1.7µm: @ 0.25 V bias and 140 K 2.5µm: @ 0.25 V bias and 77 K 5.4µm: @ 0.175 V bias and 40 K	e-/s	≤ 0.01	≤ 0.01	≤ 0.05
Median Readout Noise (single CDS) at 100 kHz pixel readout rate	e-	≤ 25 (goal is 20)	≤ 20 (goal is 15)	≤ 18 (goal is 12)
Well Capacity at 0.25 V bias (0.175V bias for 5.4µm cutoff)	e-	≥ 80,000		
Crosstalk [3]	%	≤ 2		
Operability [4]	%	99	≥ 99	≥ 98
Cluster: 100-1000 contiguous inoperable pixels within a 2000x2000-pixel area centered on array	#	≤ 0.5% of array		
SCA Flatness (peak to valley) [5]	µm	≤ 50		
Imaging Surface Deviation from Planarity (rms)	µm	≤ 25		

(1) There are 2040 x 2040 pixels for light detection plus 4 rows and columns of reference pixel on each side
(2) At 100 kHz pixel read-out rate, unbuffered, 4 outputs. Does not include external current source, power has to be optimized by the user with respect to the system in which the device is used
(3) Crosstalk includes both optical and electrical components
(4) A pixel is considered operable if QE > [illegible]
(5) SCA flatness is determined from the top of the detector surface to the bottom of the Molybdenum base. It does not include the CuW feet

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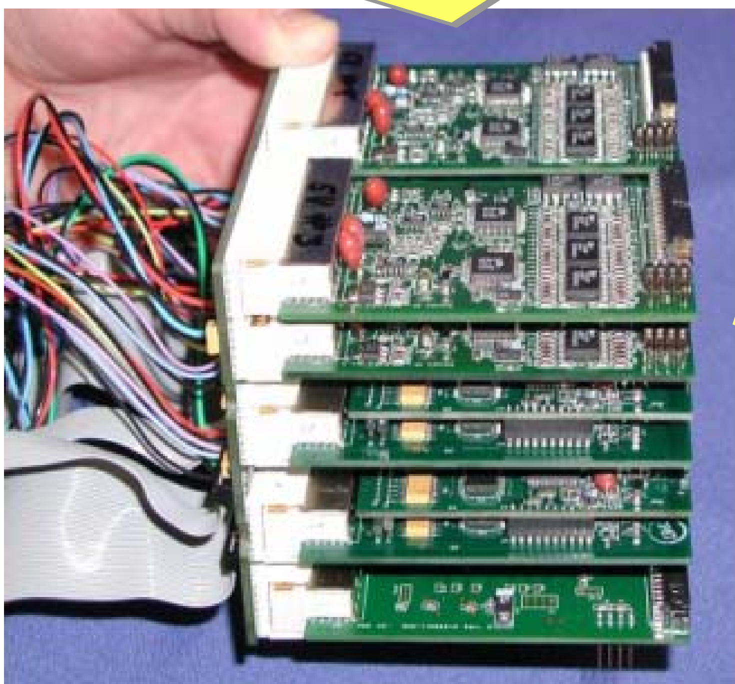
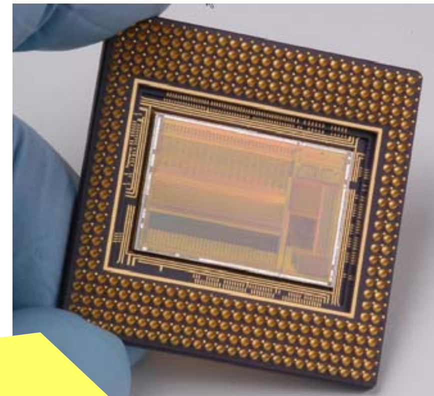
The SIDECAR ASIC – Focal Plane Electronics on a Chip

Replace this



with this!

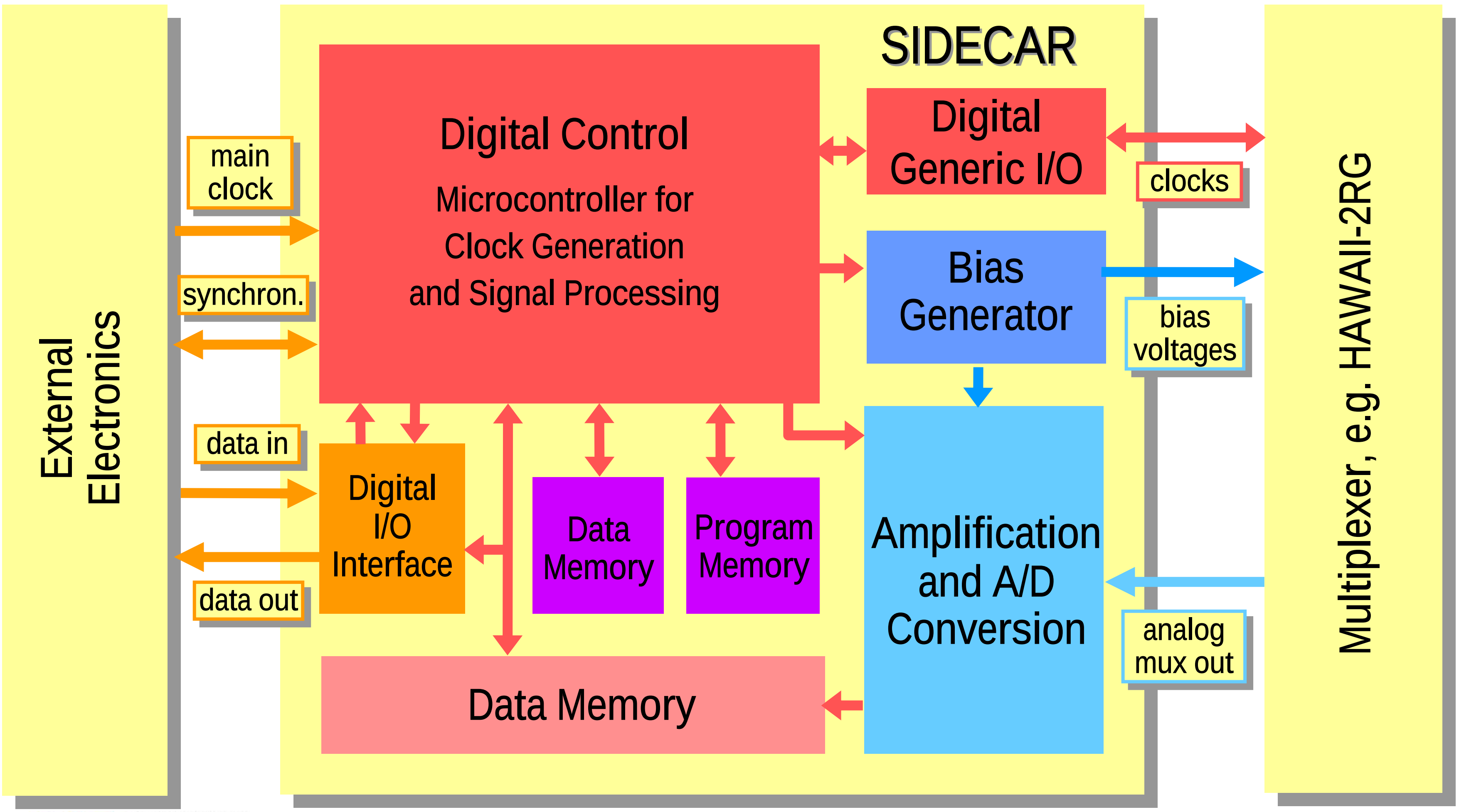


1% volume
1% power
1% hassle

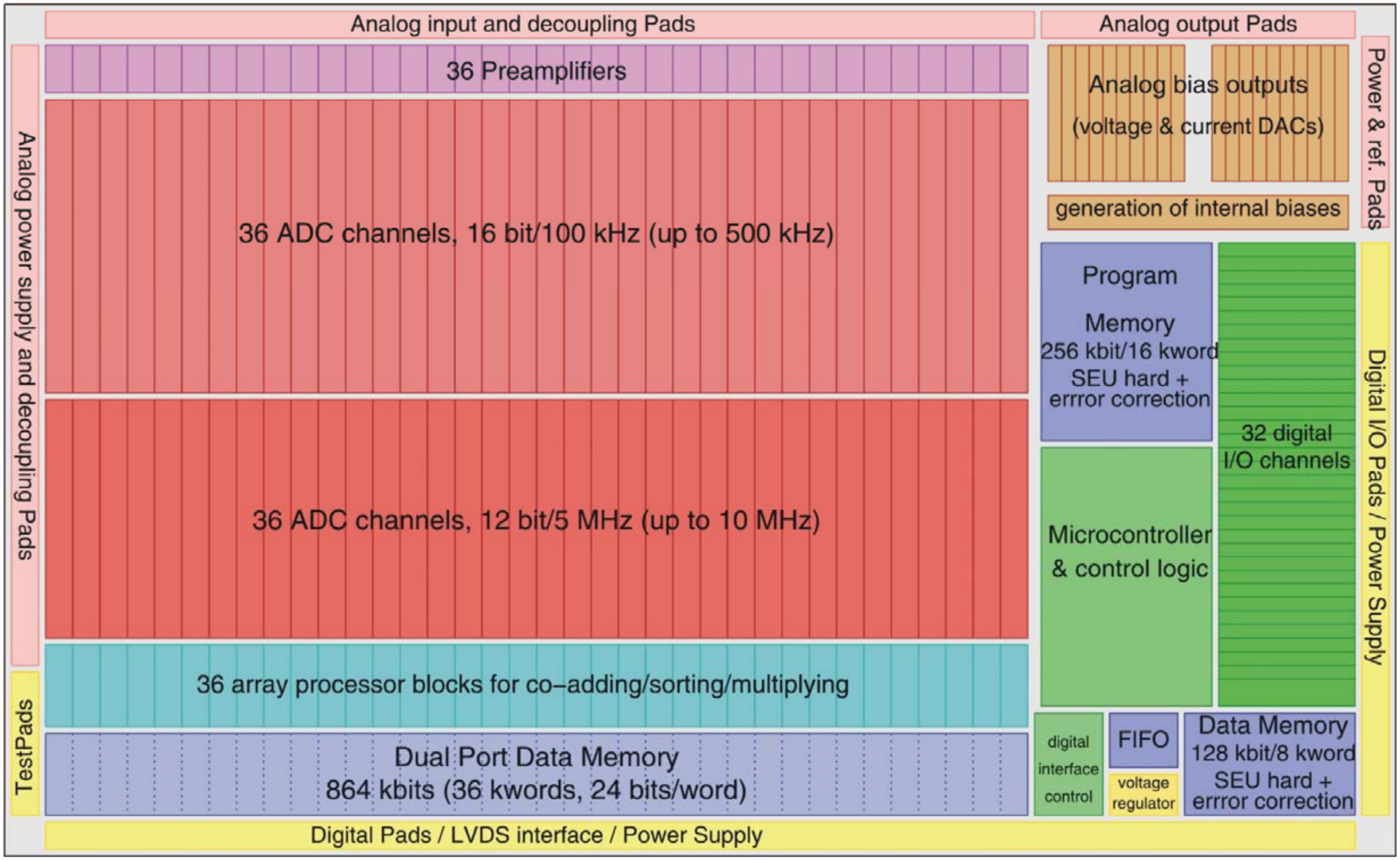
SIDECAR: System for Image Digitization, Enhancement, Control And Retrieval

The SIDECAR ASIC - Complete FPA Electronics on a Chip

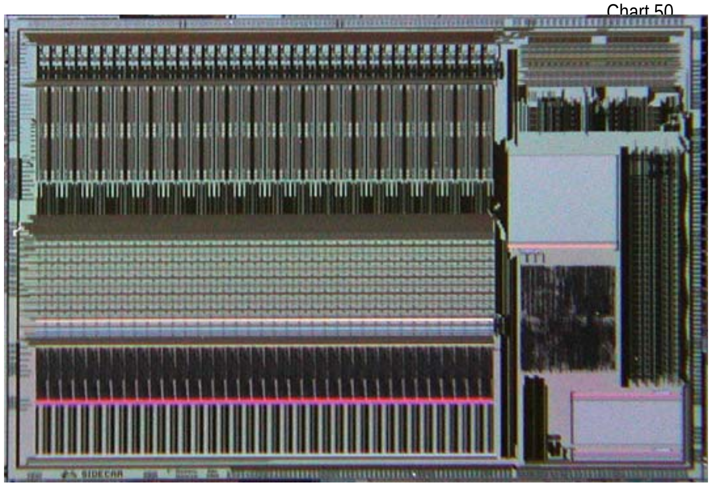
SIDECAR: System for Image Digitization, Enhancement, Control And Retrieval



ASIC Floorplan

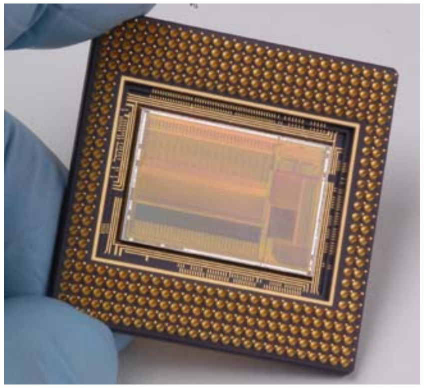


SIDECAR Feature List

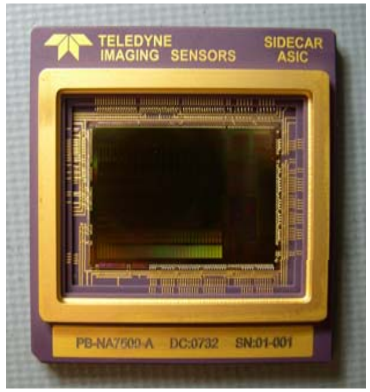


- 36 analog input channels, each channel provides:
  - 500 kHz A/D conversion with 16 bit resolution
  - 10 MHz A/D conversion with 12 bit resolution
  - gain = 0 dB …. 27 dB in steps of 3 dB
  - optional low-pass filter with programmable cutoff
  - optional internal current source (as source follower load)
- 20 analog output channels, each channel provides:
  - programmable output voltage and driver strength
  - programmable current source or current sink
  - internal reference generation (bandgap or vdd)
- 32 digital I/O channels to generate clock patterns, each channel provides:
  - input / output / highohmic
  - selectable output driver strength and polarity
  - pattern generator (16 bit pattern) independent of microcontroller
  - programmable delay (1ns - 250µs)
- 16 bit low-power microprocessor core (single event upset proof)
  - responsible for timing generation and data processing
  - 16 kwords program memory (32 kByte) and 8 kwords data memory (16 kByte)
  - 36 kwords ADC data memory, 24 bit per word (108 kByte)
  - additional array processor for adding, shifting and multiplying on all 36 data channels in parallel (e.g. on-chip CDS, leaky memory or other data processing tasks)

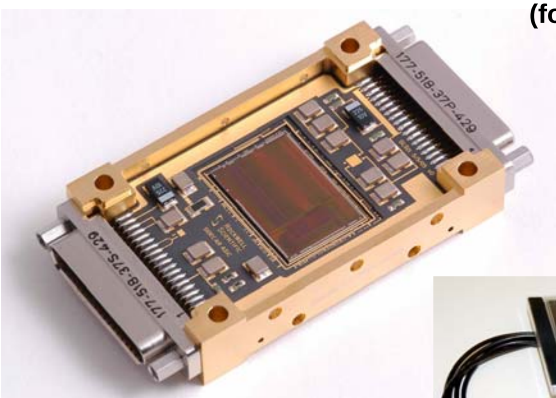
SIDECAR ASIC – Focal Plane Electronics on a Chip



SIDECAR ASIC
Ground-based package



Hubble Space Telescope
SIDECAR ASIC package
(for ACS Repair)



JWST SIDECAR ASIC package

SIDECAR ASIC development kit

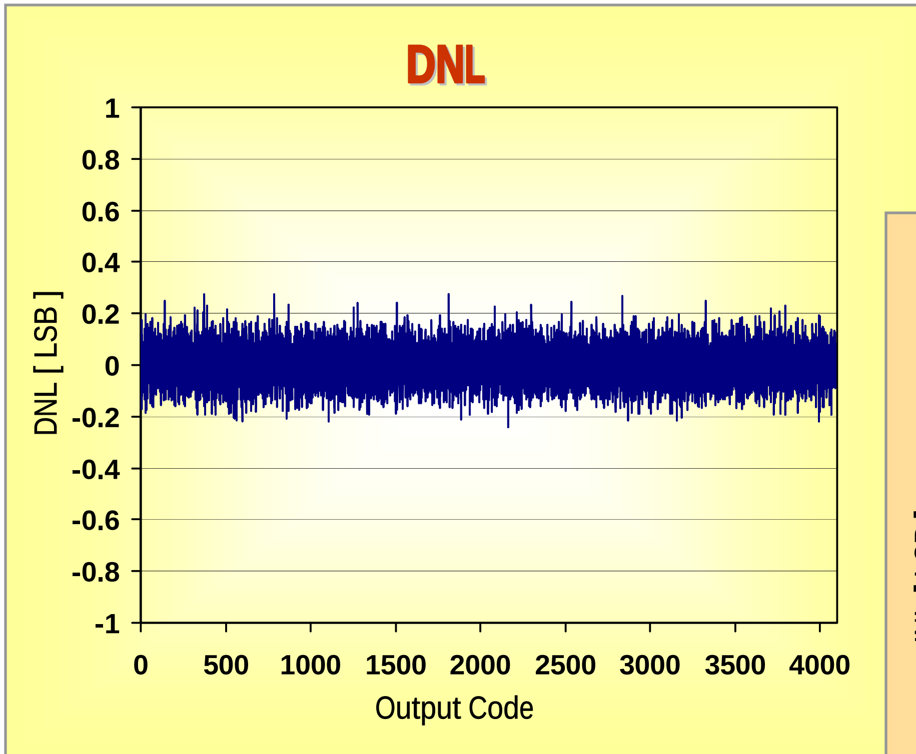
SIDECAR ASIC

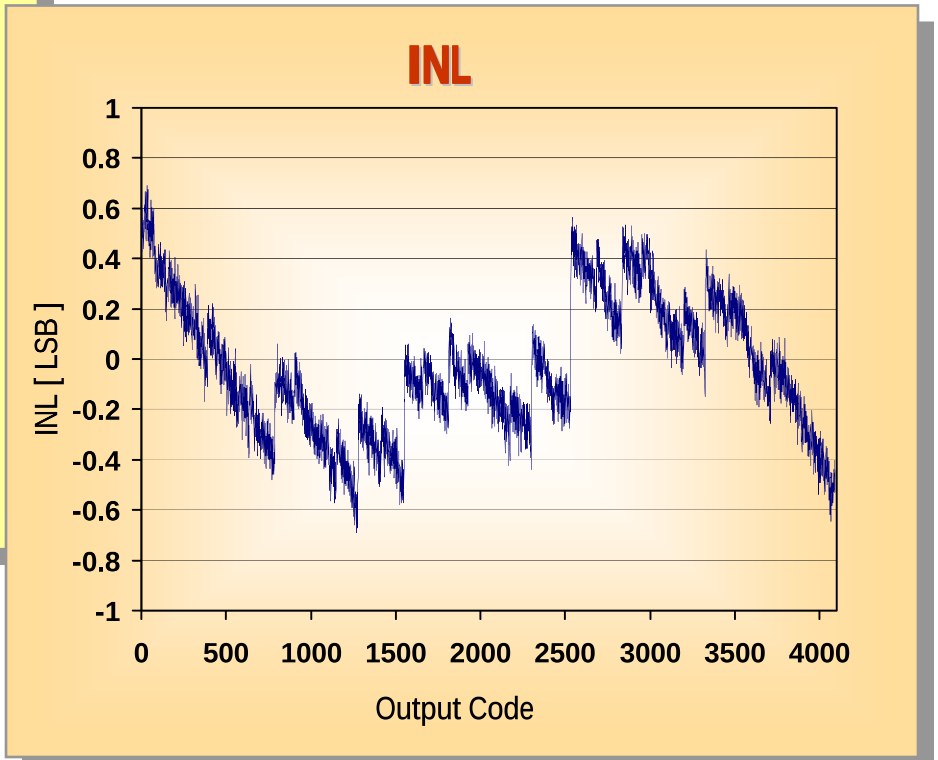
- 36 analog input channels
- 36 16-bit ADCs: up to 500 kHz
- 36 12-bit ADCs: up to 10 MHz
- 20 output bias channels
- 32 digital I/O channels
- Microcontroller (low power)
- LVDS or CMOS interface
- Low power:
  - <15 mW, 4 channels, 100 kHz, 16-bit ADC
  - <150 mW, 32 channels, 100 kHz, 16-bit ADC
- Operating temperature: 30K to 300K
- Interfaces directly to H1RG, H2RG, H4RG
- **Qualified to NASA TRL-6**
  - Vibration, radiation, thermal cycling
  - Radiation hard to ~100 krad

12-bit ADC Results

Measured at 7.5 MHz Sample Rate

Chart 52

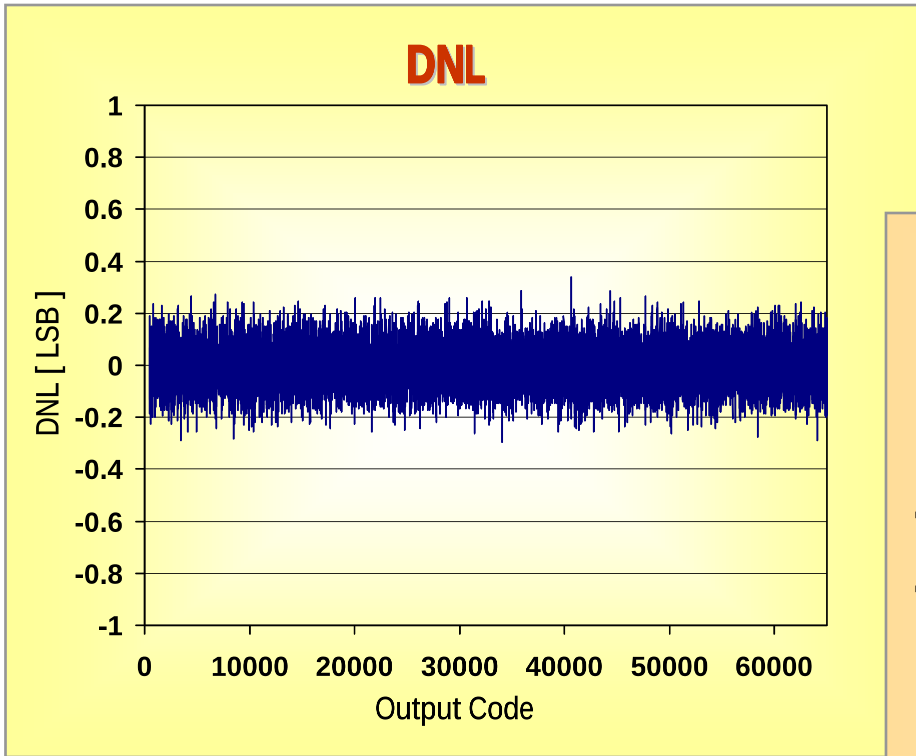


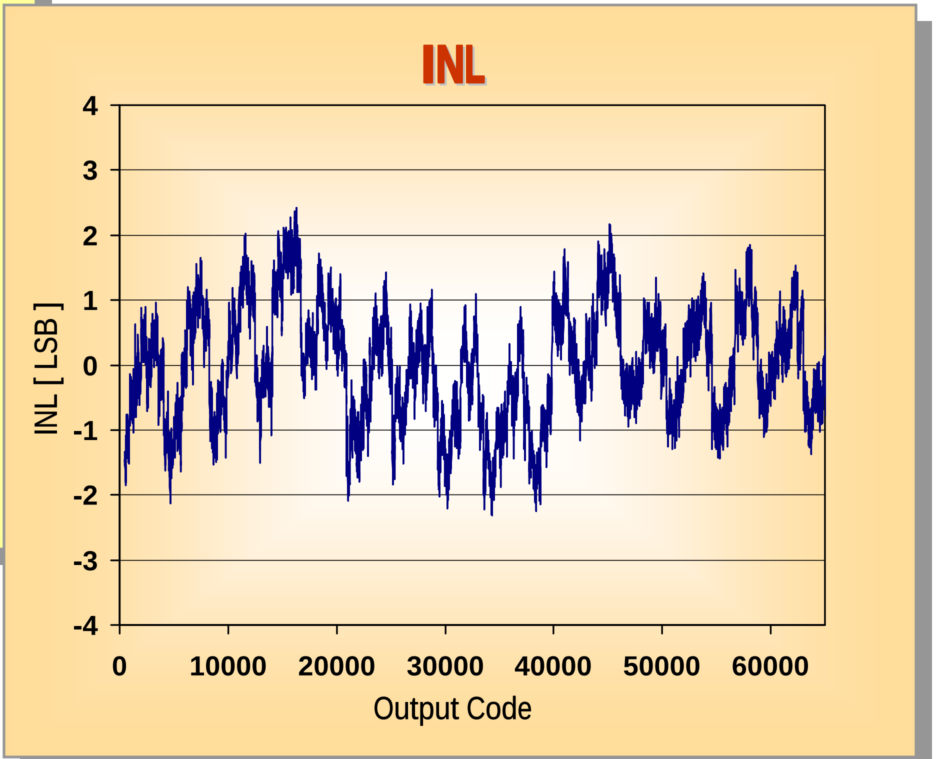


- Differential Non-Linearity: < ± 0.3 LSB
- Integral Non-Linearity: < ± 0.7 LSB
- Temporal Noise at 300 K < 0.4 LSB

16-bit ADC Results

Measured at 125 kHz Sample Rate





- Differential Non-Linearity: < ± 0.3 LSB
- Integral Non-Linearity: < ± 0.2 LSB
- Temporal Noise: < 3 LSB

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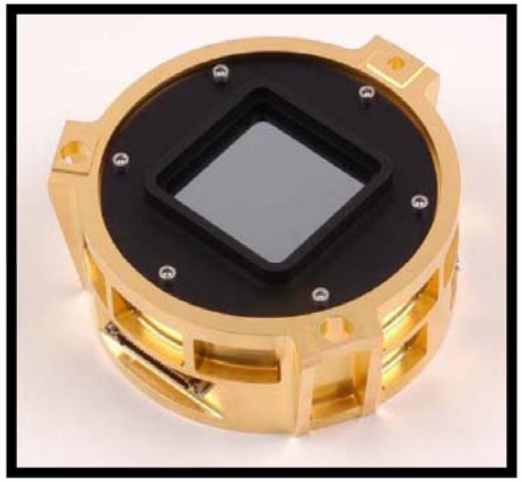
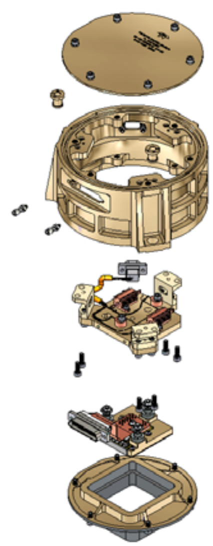
Spaceflight packaging: JWST Fine Guidance Sensor

FPA - Backside - Cover Removed



Light Facing Side - Scene

- Package for H2RG 2048x2048 pixel array
- TRL-6 spaceflight qualified
- Interfaces directly to the SIDECAR ASIC
- Robust, versatile package



- **Thermally isolated FPA can be stabilized to 1 mK when cold finger fluctuates several deg K**

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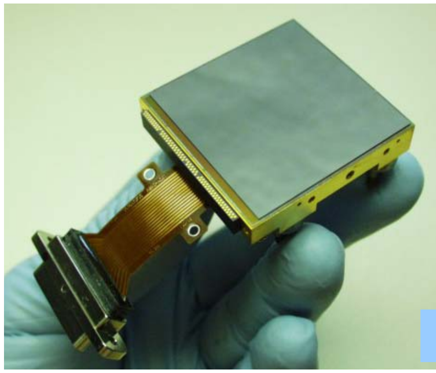
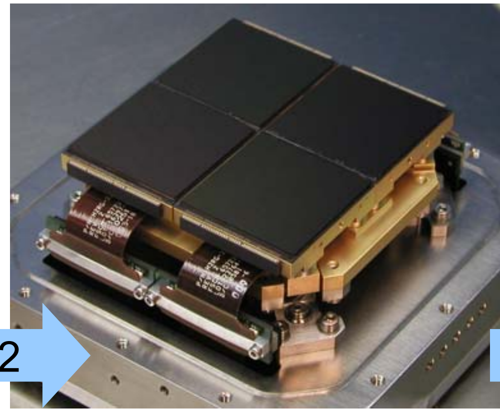
SIDECAR ASIC & large mosaic focal plane arrays

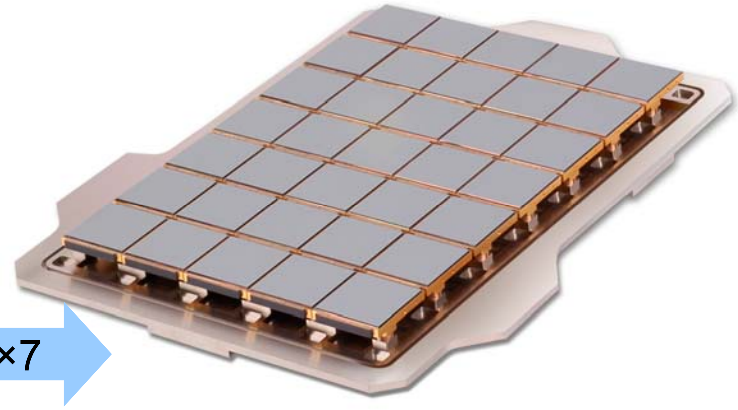


H2RG 2K×2K

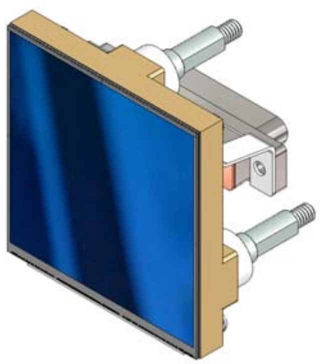
2×2



5×7

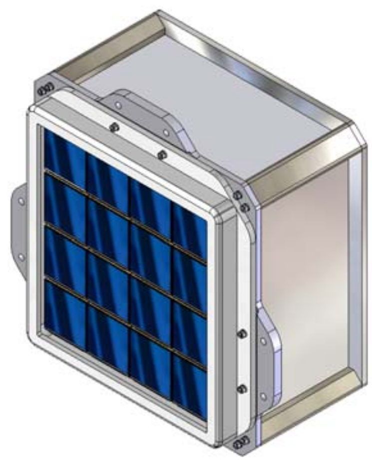


Mechanical Prototype



H2RG

4×4



**4x4 Mosaic
for Space Mission**

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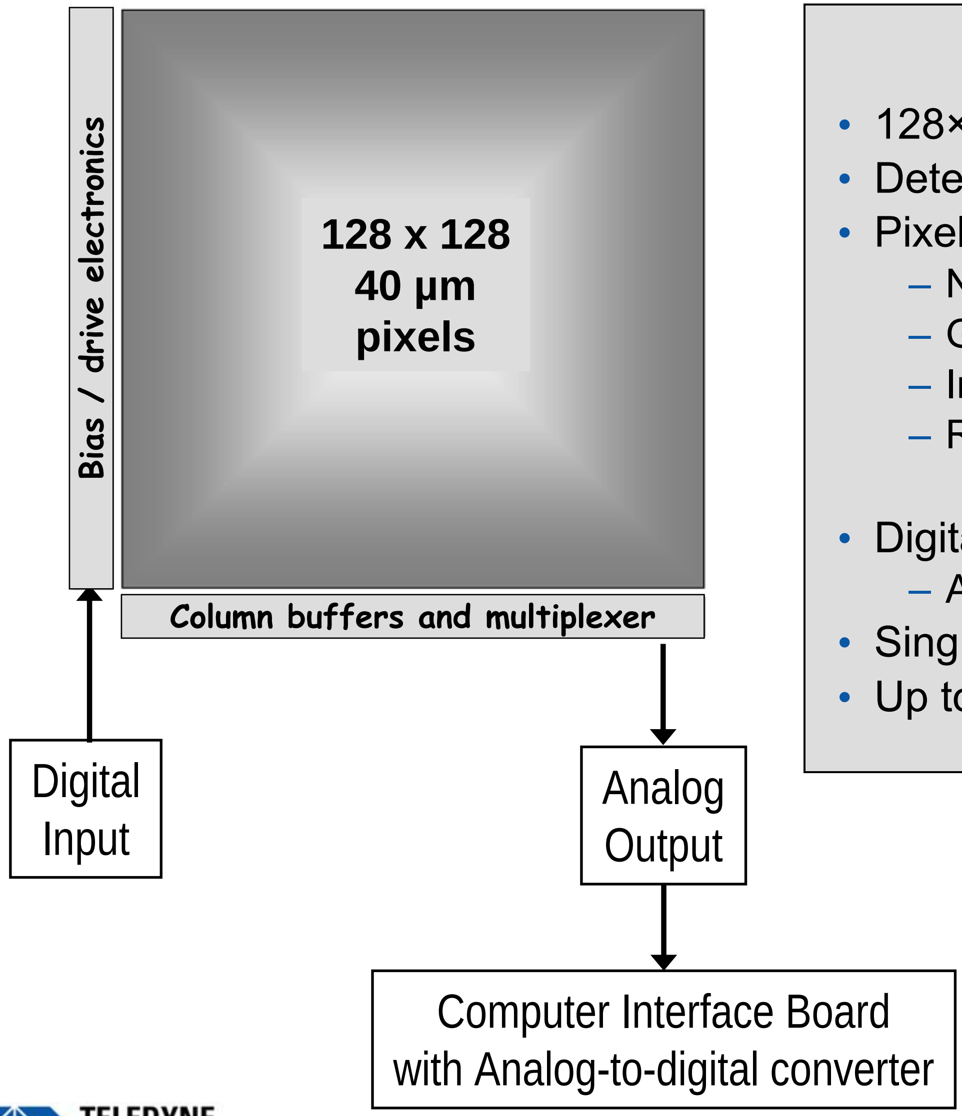
High Speed, Low Noise, Event Driven Readout



Speedster128

- 128×128 pixels, 40 micron pitch
- Detector material: HgCdTe or Si
- Pixel design
  - Next generation CTIA pixel amplifier
  - Global snapshot, integrate while read
  - In-pixel CDS (correlated double sampling)
  - Readout noise: < 5 e- for HgCdTe
    < 4 e- for Si
- Digital input
  - All clocking produced on-chip
- Single analog output
- Up to 900 Hz frame rate

2008/9: Fabricate and demonstrate Speedster128 arrays

2009: Modify design for event driven readout

Designed for IR AO and interferometry

High speed, low noise, event driven HyViSI is optimal detector for soft x-ray astronomy

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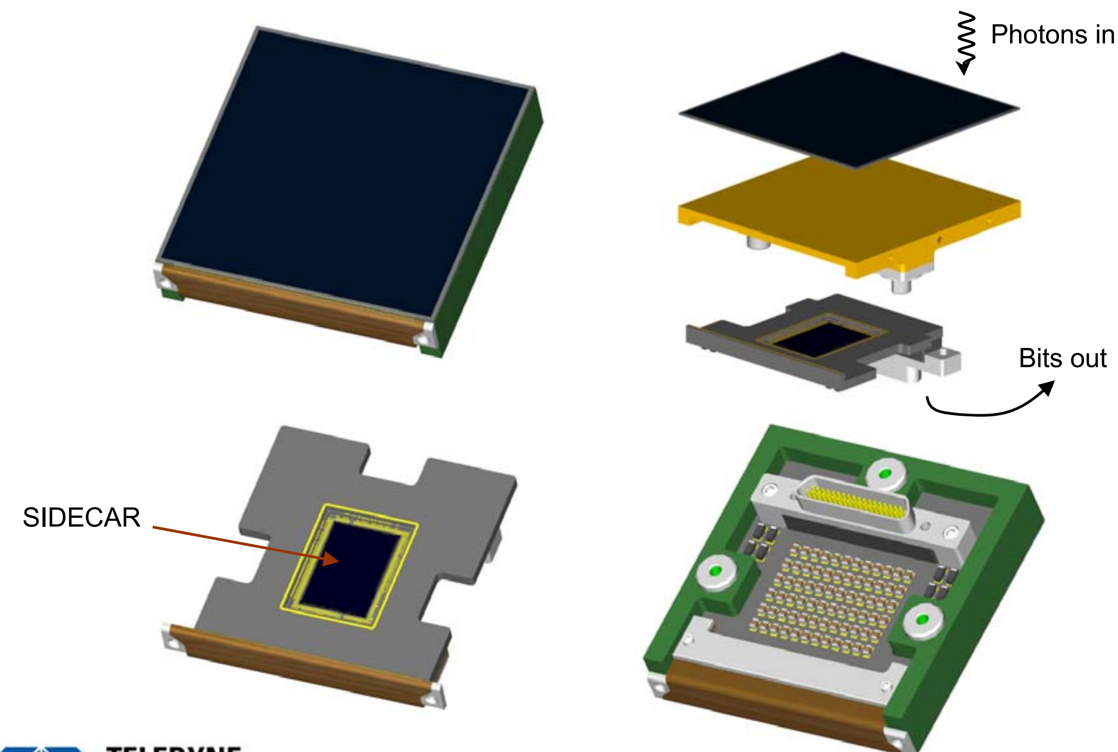
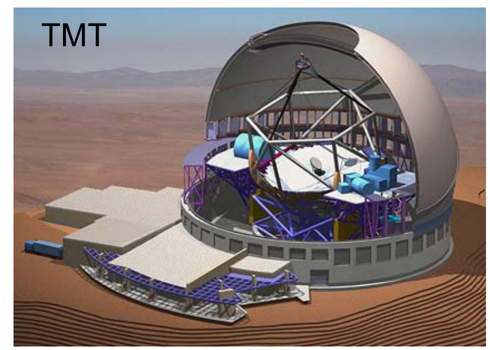
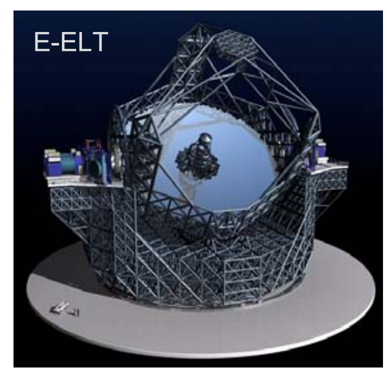
Large IR Astronomy Focal Plane Development
The Next Step: 4096×4096 pixels

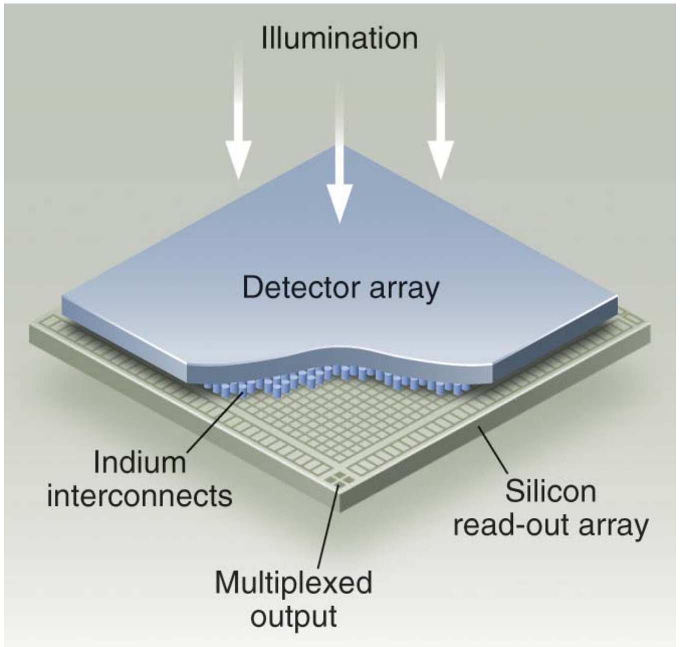
- 4096×4096 pixels, 15 µm pitch with embedded SIDECAR ASIC
- Design readout circuit for high yield (4 ROICs per 8-inch wafer)
    - New design process
- Minimize detector cost by growing HgCdTe on silicon substrate
- 4-side buttable for large mosaics
- Option: SIDECAR ASIC integrated into SCA package

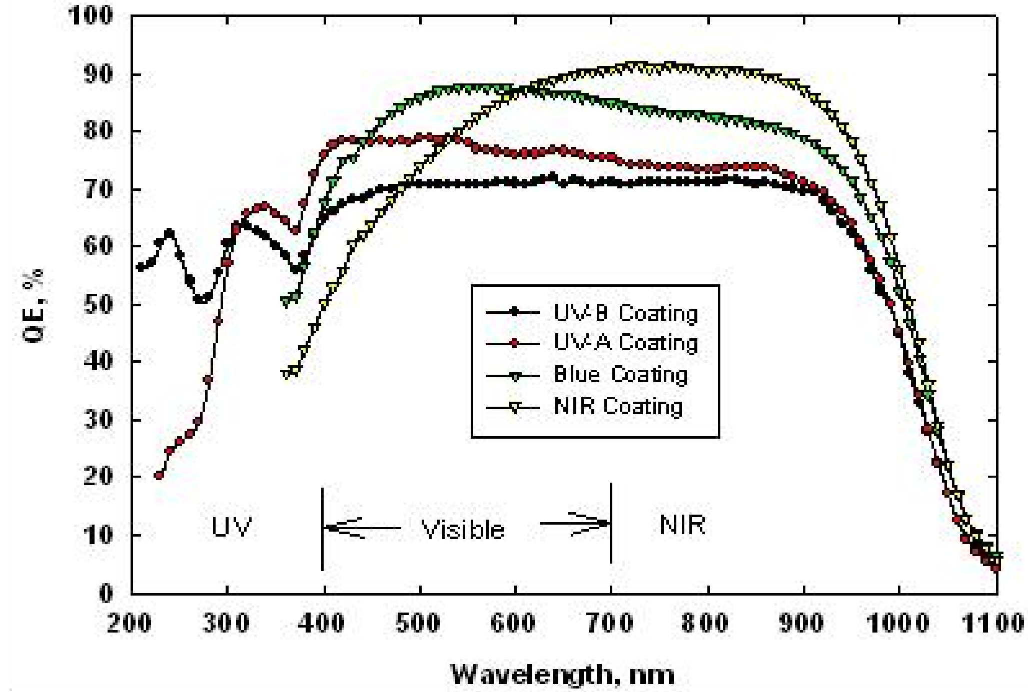






HyViSI™ – Hybrid Visible Silicon Imager





Focal plane array performance independently verified by:

- Rochester Institute of Technology
- European Southern Observatory
- US Naval Observatory & Goddard Space Flight Center

Readout noise, at 100 kHz pixel rate

- 7 e- single CDS, with reduction by multiple sampling

Pixel operability > 99.99%

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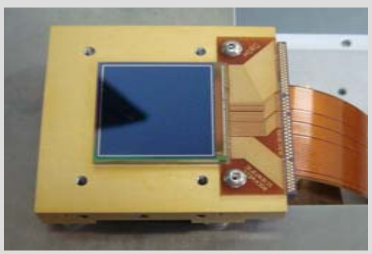
HyViSI Array Formats

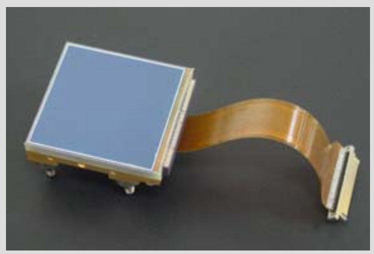
Ground-based Astronomy (Rochester Institute of Technology)

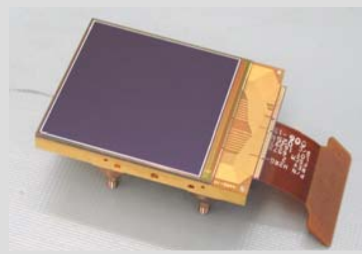

Crab Nebula (M1)


NGC2683 Spiral Galaxy

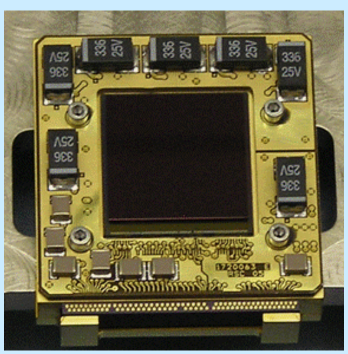

Hercules Cluster (M13)


1K×1K H1RG-18


2K×2K H2RG-18


4K×4K H4RG-10

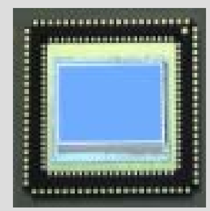
Orbiting Carbon Observatory



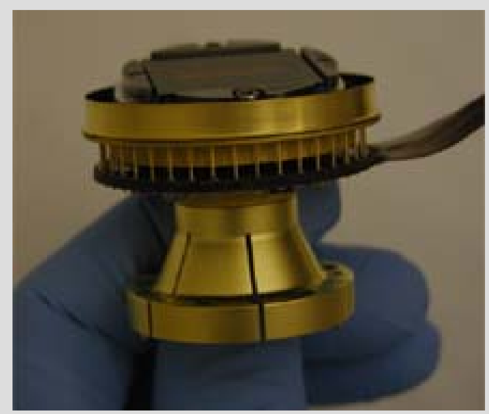
1K×1K
H1RG-18
(same used by IR)

Launch: Feb 2009

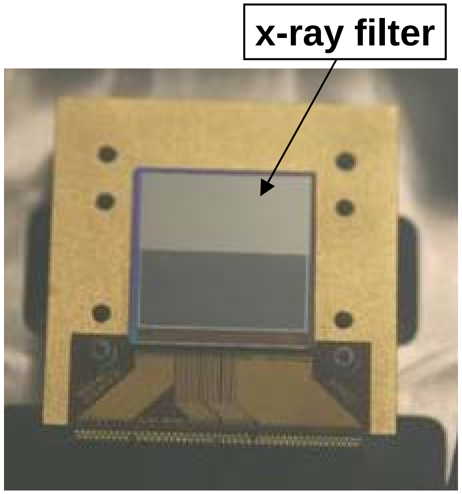
Mars Reconnaissance Orbiter (MRO)



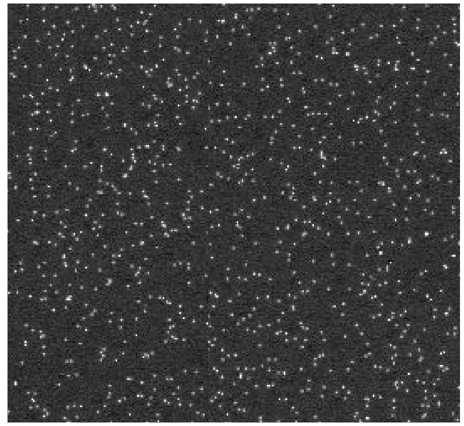
TCM 6604A
640×480 pixels
27 µm pitch
CTIA


TEC Package by Judson

HyViSI™ – Soft X-ray Imager



1Kx1K HyViSI array



Fe^{55} x-ray response

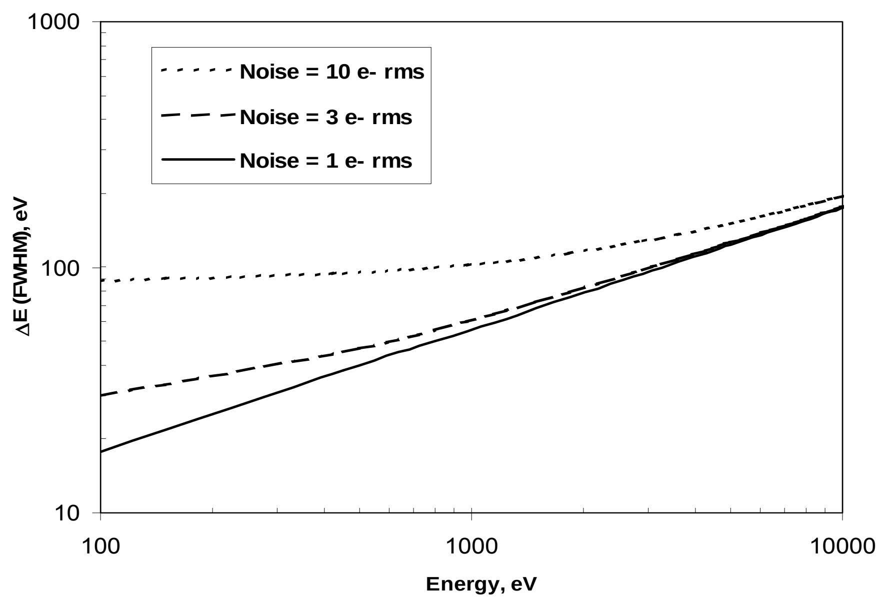
700 nm optical response

Fig. 15: Energy resolution of silicon detector as a function of x-ray energy and detector read noise.

If readout noise is low enough, the energy of each x-ray can be measured. Assuming the FPA is cooled so that detector dark current is negligible, the non-dispersive energy resolution of the detector can be expressed as:

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

where f is the Fano factor (0.12 for silicon), ω is charge conversion factor (3.65 eV/e- for silicon), E is the energy of the x-ray and σ is the detector read noise (e-). This formula produces the plot at right, showing that <3 e- noise is desired for soft x-ray spectroscopy.



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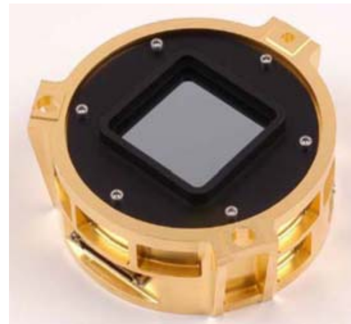
Teledyne – Your Imaging Partner for Astronomy & Civil Space

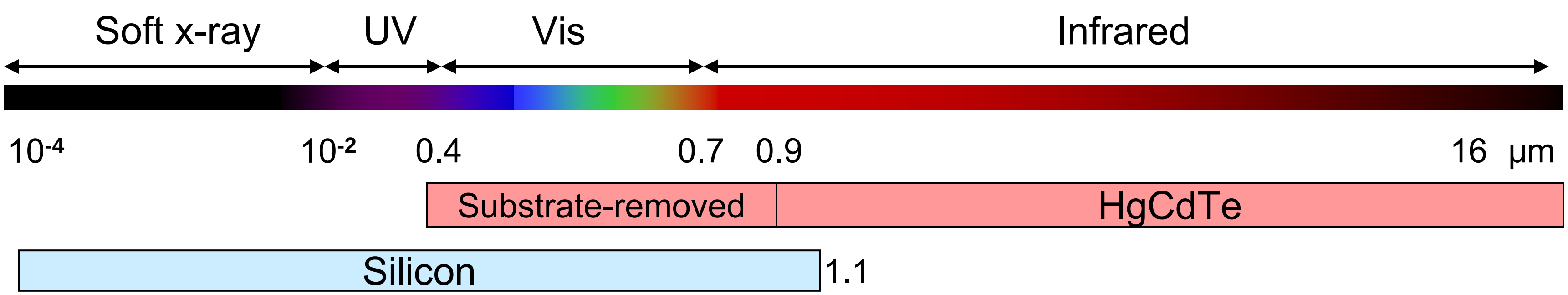
State-of-the-art & high TRL

- CMOS Design
- Detector Materials
- Packaging
- Electronics
- Systems Engineering



Packaging

Electronics



CMOS Design Expertise

- Pixel amplifiers – lowest noise to highest flux
- High level of pixel functionality (LADAR, event driven)
- Large 2-D arrays, pushbroom, redundant pixel design
- Hybrids made with HgCdTe, Si, or InGaAs
- Monolithic CMOS
- Analog-to-digital converters
- Imaging system on a chip
- Specialized ASICs
- Radiation hard
- Very low power