High Performance Infrared Detectors

For Extreme Precision Radial Velocity Measurement

Presented by
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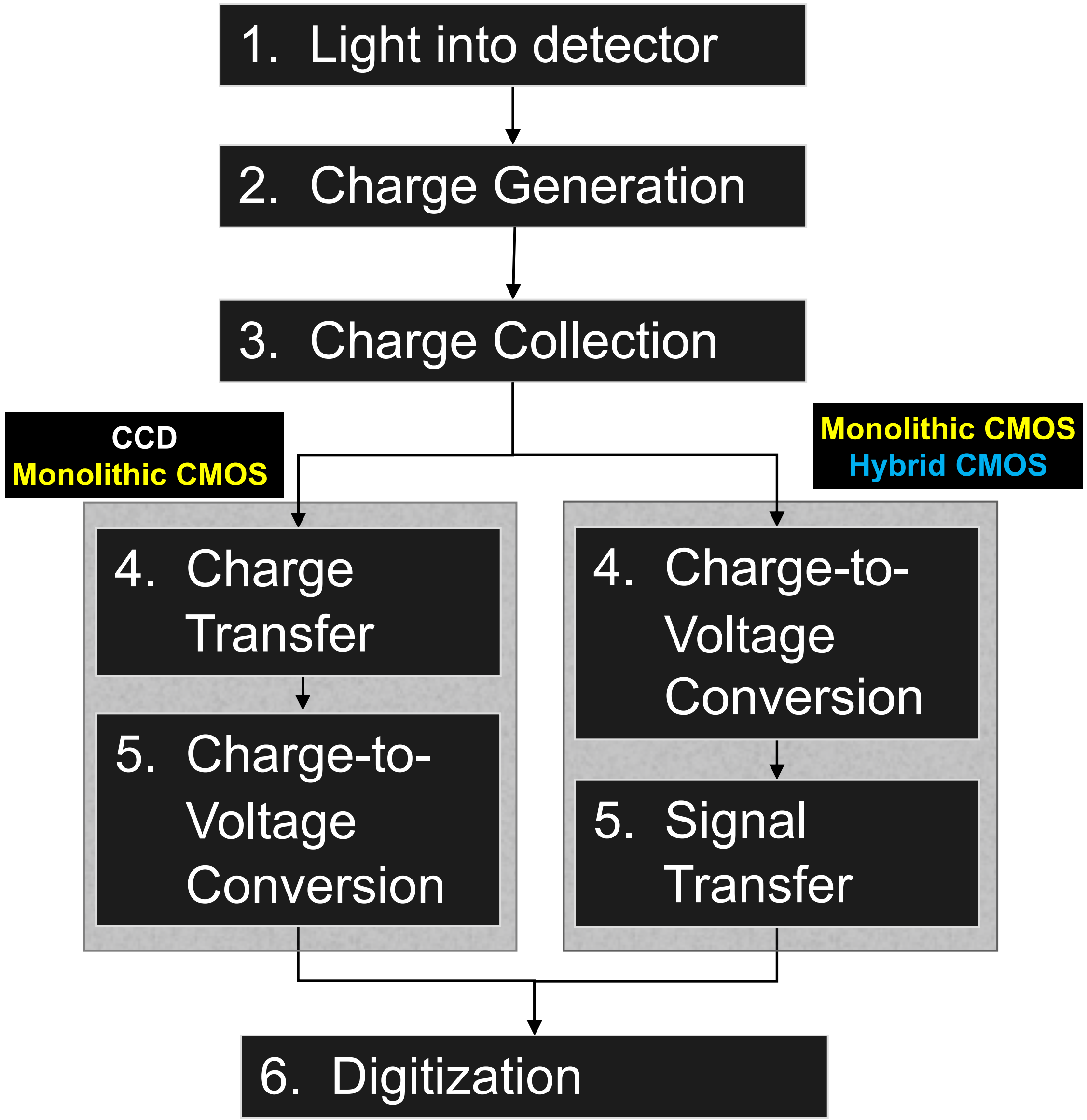
Camarillo, California

Presented at
Extreme Precision for Radial Velocity IV
Grindelwald, Switzerland
19 March 2019

6 steps of optical / IR photon detection



TELEDYNE IMAGING SENSORS
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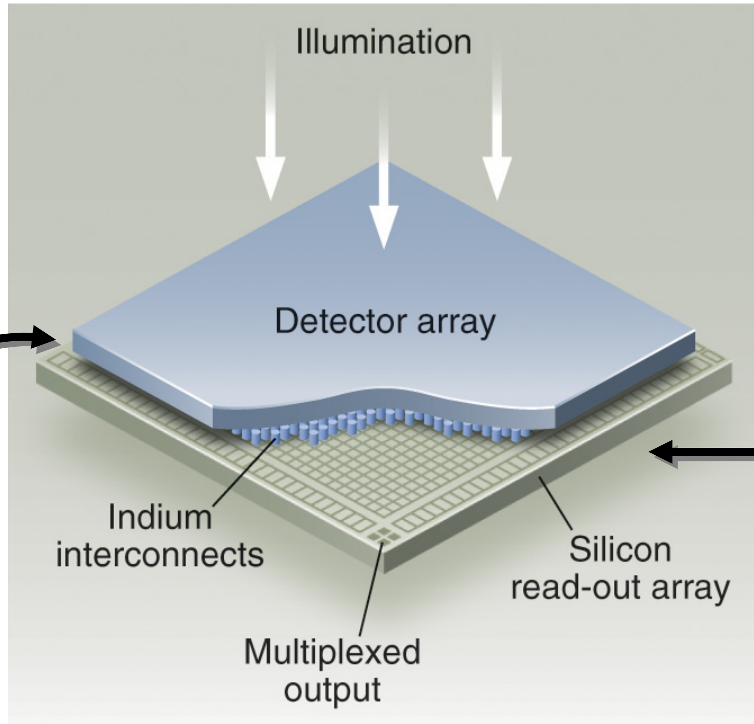
Hybrid CMOS Imaging Sensor



Readout Integrated Circuit (ROIC)

<u>Input signal</u>

- Flux – object and background

<u>Operating Mode</u>

- Integration time
- Frame readout time
- Shutter (rolling, snapshot)
- Multiple storage cells per pixel
- Windows
- Reset (pixel, line, global)
- Event driven

<u>Interface</u>

- Input (analog, digital)
- Output (analog, digital)
- # of readout ports

<u>Environment</u>

- Temperature
- Radiation

<u>Other Requirements</u>

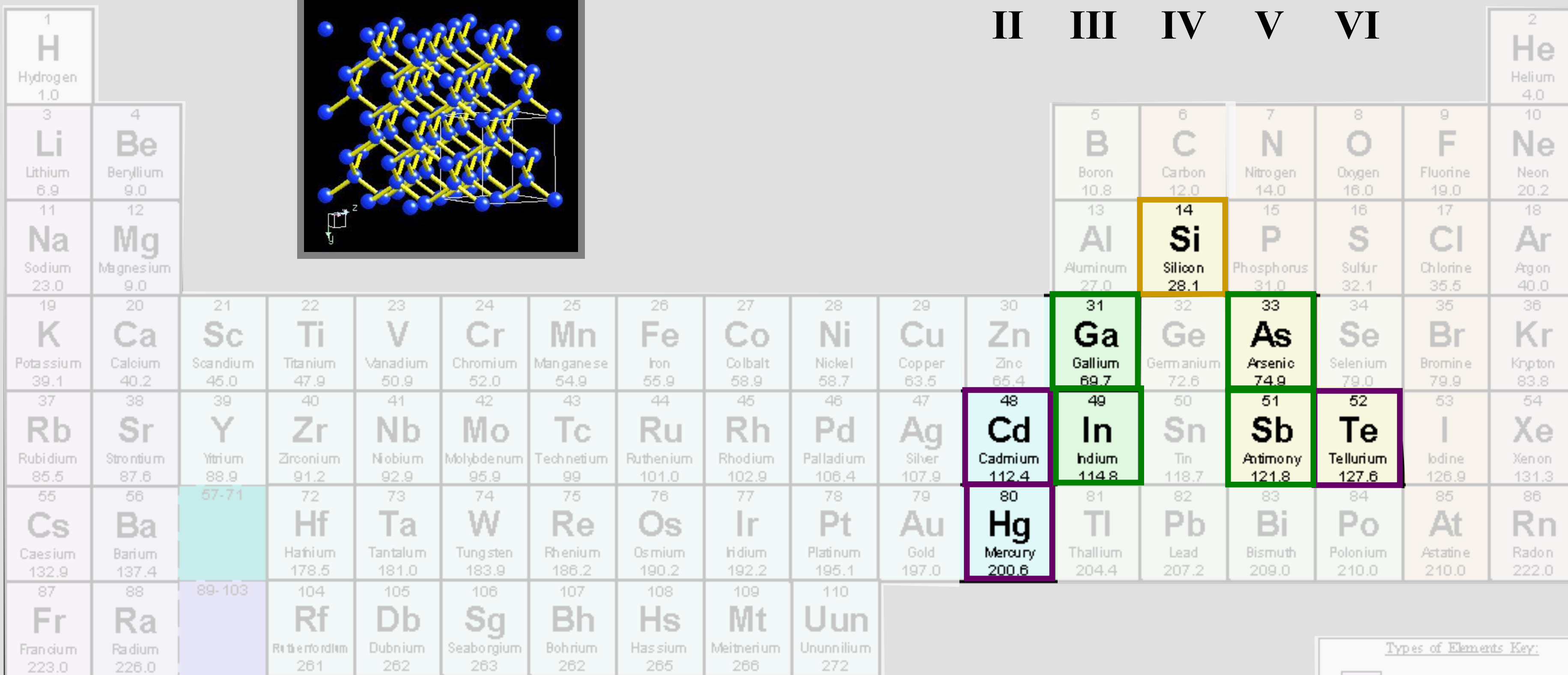
- Linearity
- Anti-blooming

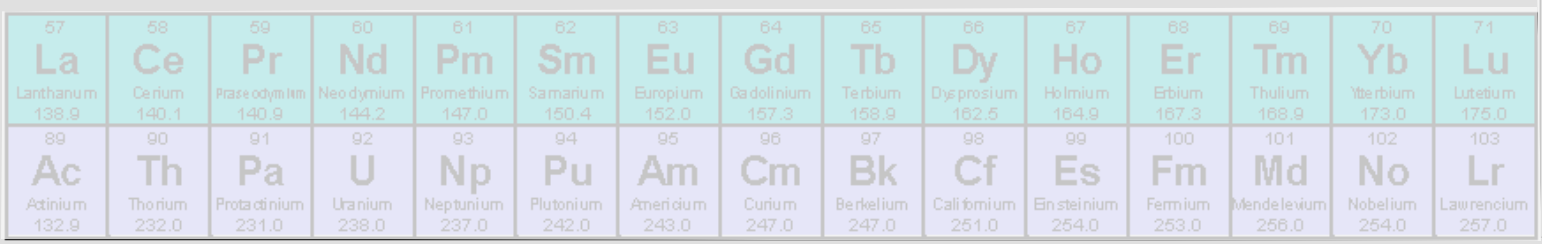
Detector

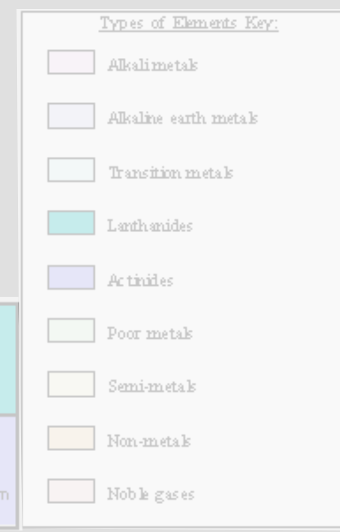
- Wavelength (λ)
- Quantum Efficiency
- Dark current & Noise
- Radiation environment
- Persistence

The functionality ("the brains") of a CMOS-based sensor is provided by the readout circuit

Periodic Table





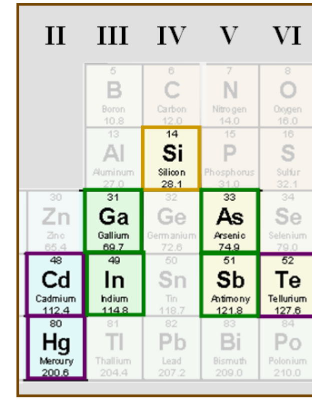


Detector Families

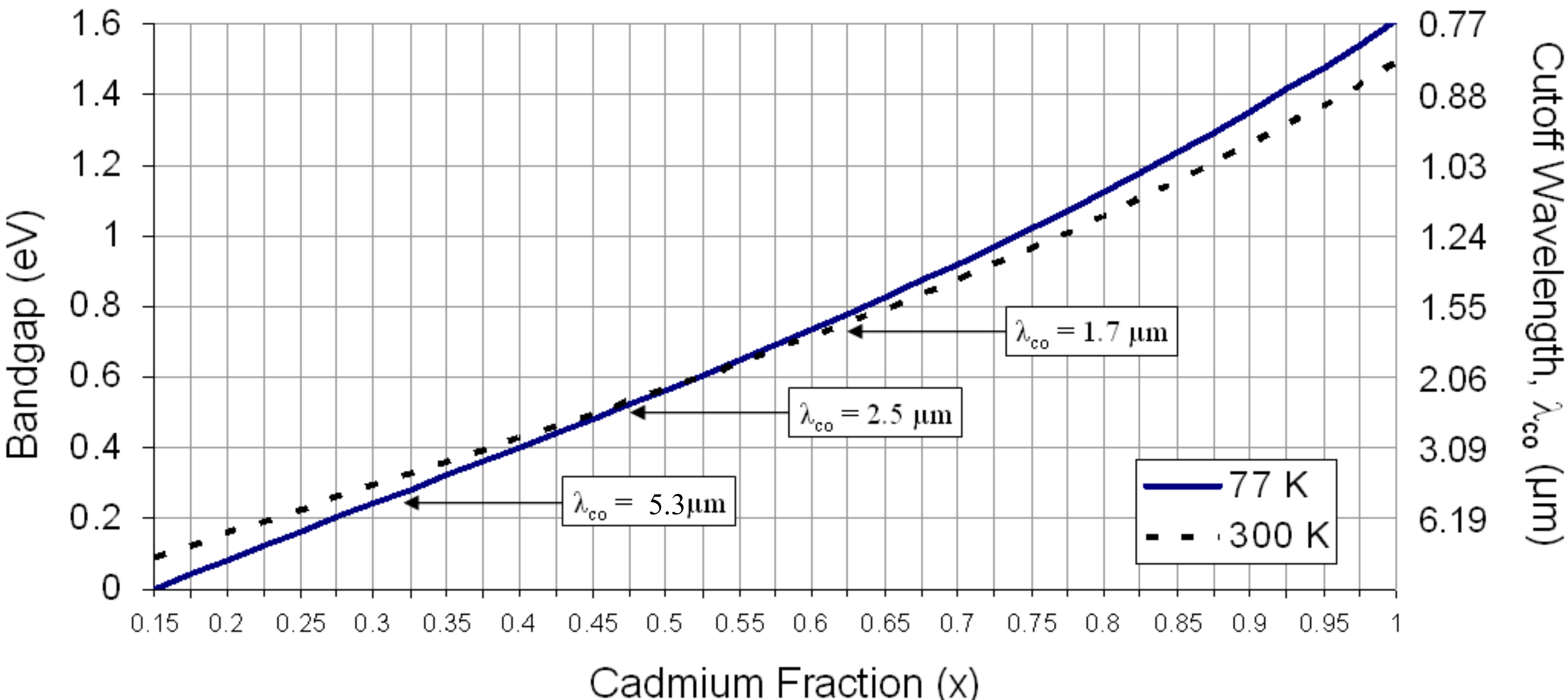
Si	-	IV semiconductor
HgCdTe	-	II-VI semiconductor
InGaAs & InSb	-	III-V semiconductors

Tunable Wavelength: Unique property of HgCdTe

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



Bandgap and Cutoff Wavelength as function of Cadmium Fraction (x)



HgCdTe crystal is grown by MBE on CdZnTe Substrates

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

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

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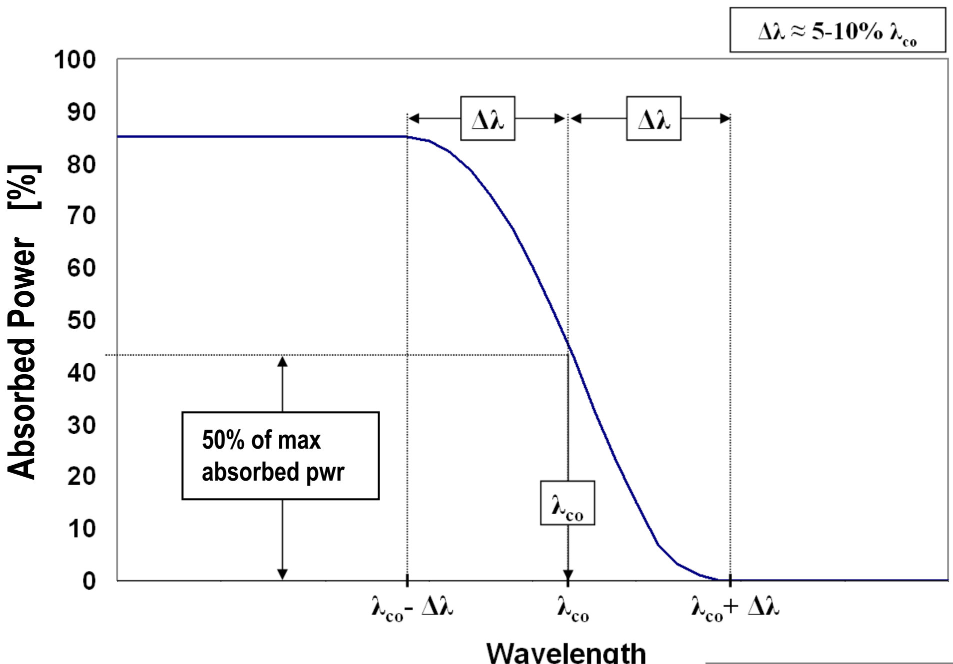
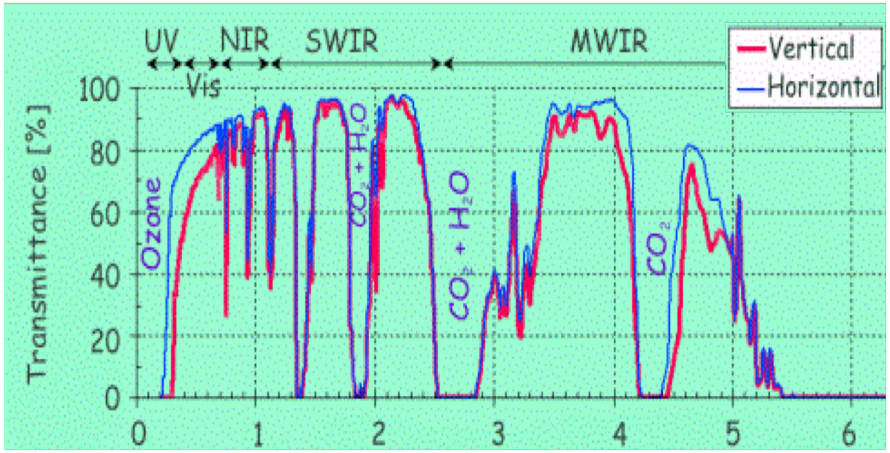
HgCdTe Cutoff Wavelength



Atmospheric Transmission



Wavelength (microns)

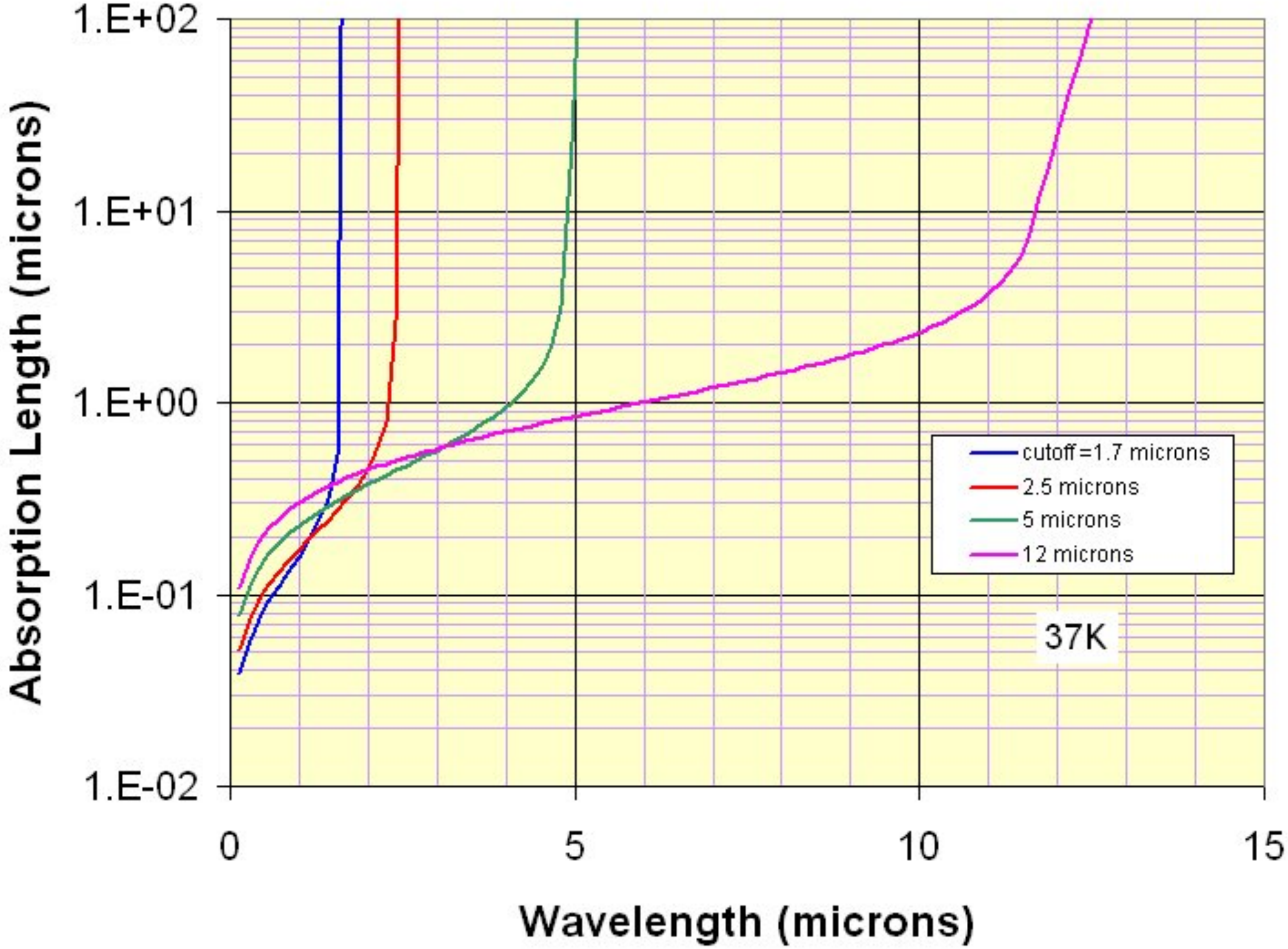
The cutoff wavelength, λ_{CO}, is defined as the wavelength at which the absorbed optical power falls to half of the maximum value.

Cutoff wavelengths are based on standard atmospheric windows

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

Absorption Depth of HgCdTe

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



- HgCdTe is a direct bandgap material.
- HgCdTe is <u>extremely</u> efficient at converting electromagnetic energy into free electrons.
- The electromagnetic energy can come from photons or electrons accelerated through the material.

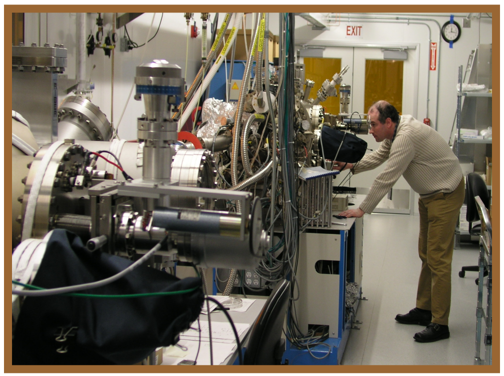
MBE produces the highest performance HgCdTe

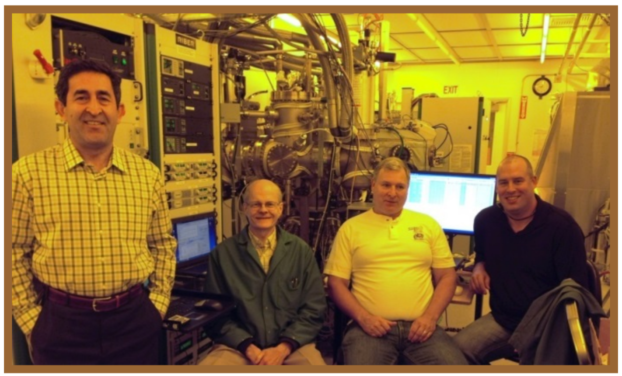
Molecular Beam Epitaxy (MBE)

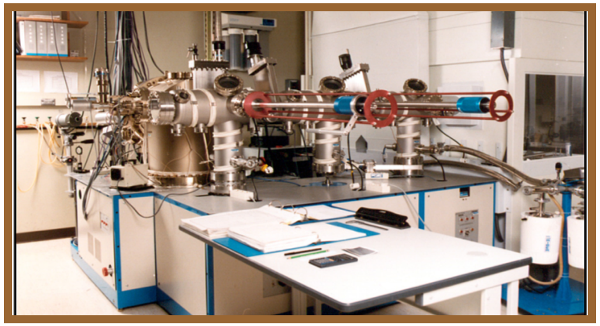
- Enables very accurate deposition ⇒ "bandgap engineering"
- Teledyne has 4 MBE machines for detector growth

- Background pressure is 10^{-8} Torr
- Beam pressure: 10^{-6} Torr for CdTe & Te and 10^{-4} Torr for Hg

Degree of Vacuum	Pressure (Torr)	Gas Density (molecules m^{-3})	Mean Free Path (m)	Time / ML (s)
Atmospheric	760	2×10^{25}	7×10^{-8}	10^{-9}
Low	1	3×10^{22}	5×10^{-5}	10^{-6}
Medium	10^{-3}	3×10^{19}	5×10^{-2}	10^{-3}
High	10^{-6}	3×10^{16}	50	1
UltraHigh	10^{-10}	3×10^{12}	5×10^{5}	10^{4}





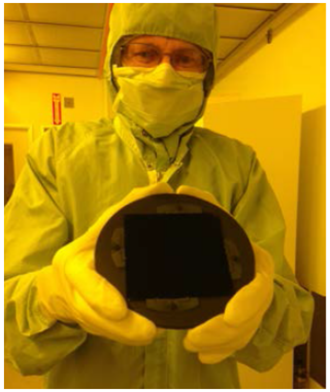


RIBER 3-in MBE Systems

RIBER 5-in MBE System

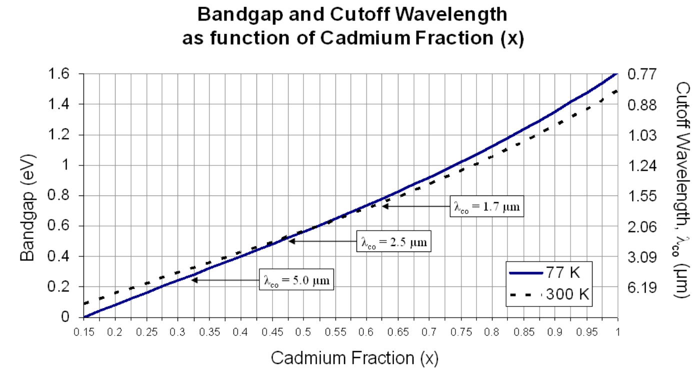
3 inch diameter platen allows growth on one 6x6 cm substrate

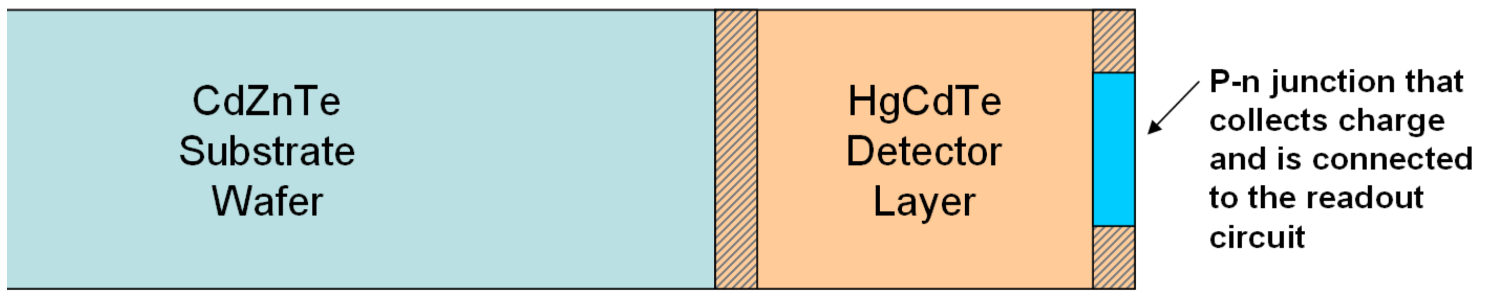
More than 9000 HgCdTe wafers grown to date

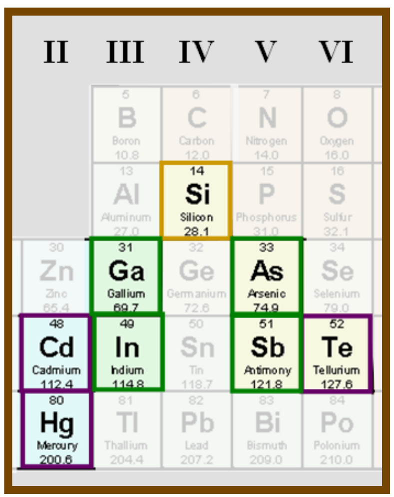


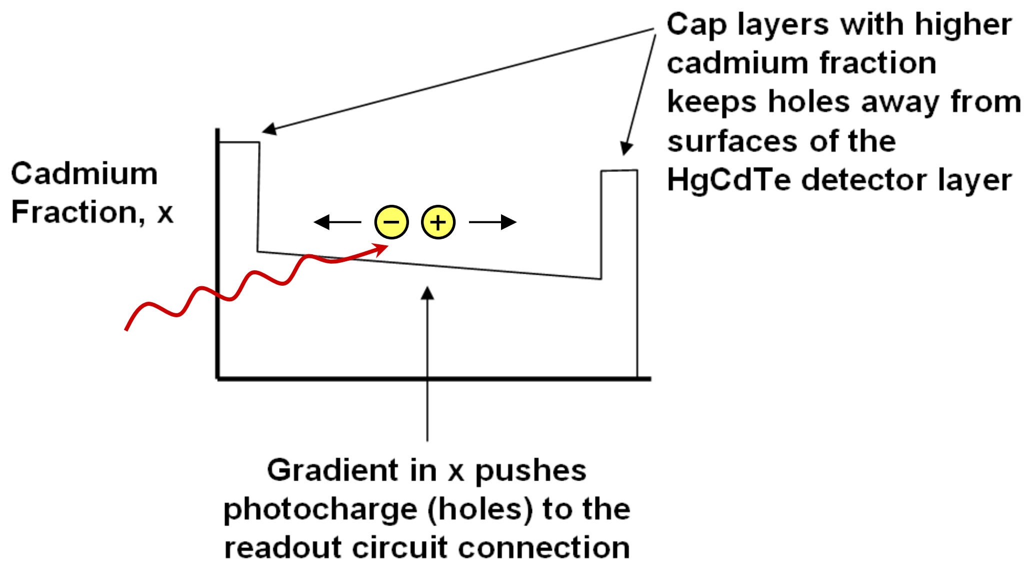
5 inch diameter platen enables growth of 7x7 cm and 9x9.5 cm substrates
(8 × 8 cm shown in photo)

Growth Structure of p-on-n HgCdTe arrays

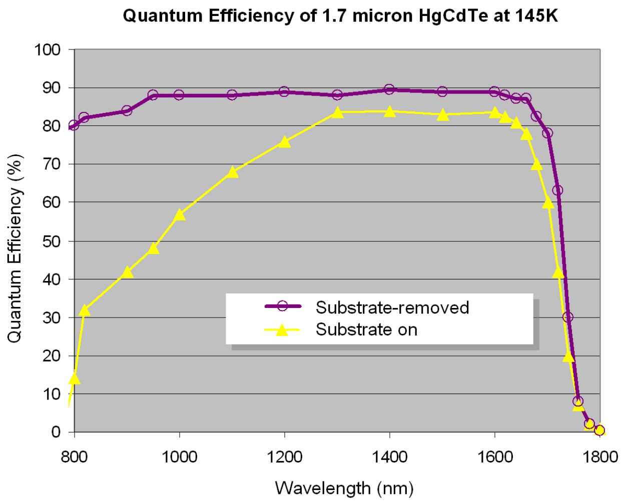


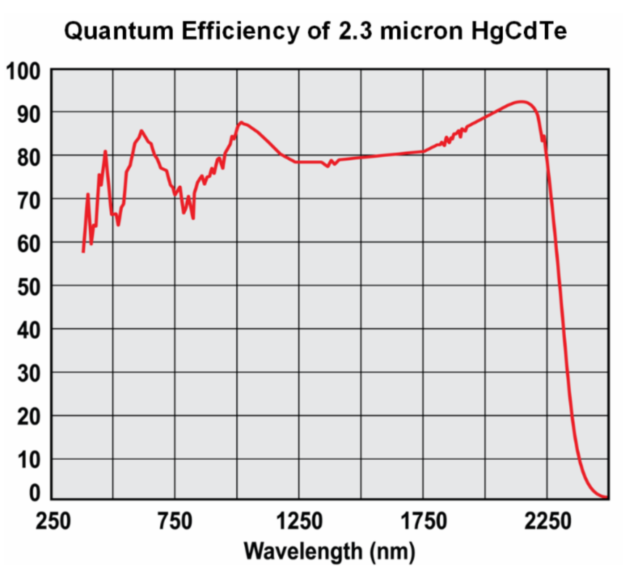


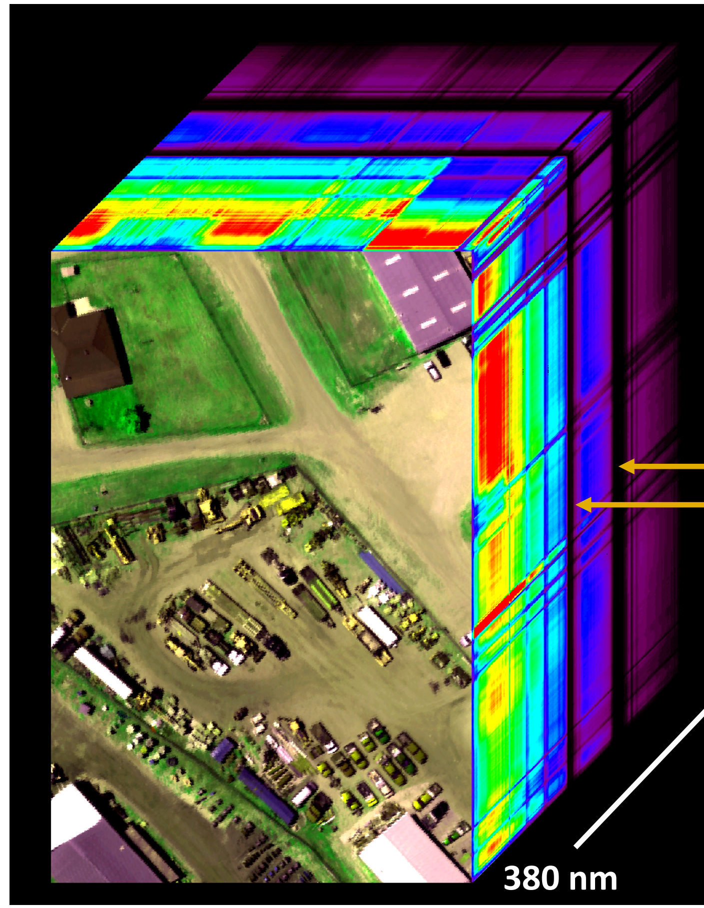




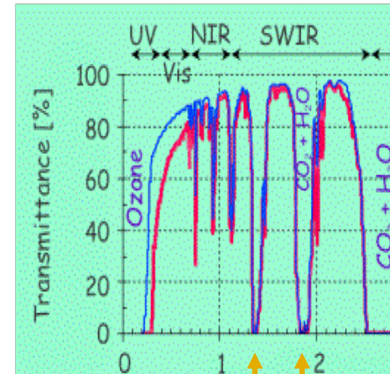
Substrate Removed HgCdTe Provides Simultaneous UV-Vis-IR Light Detection







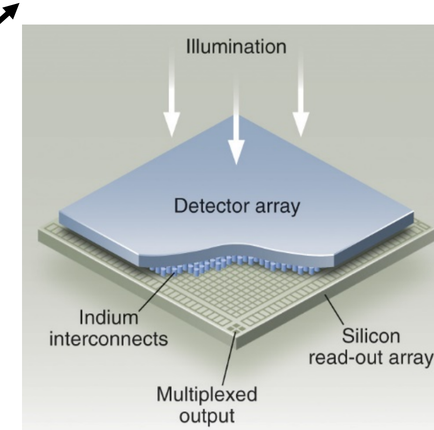
2510 nm



Atmospheric water vapor absorption bands at 1400 and 1900 nm

JPL AVIRIS-NG Imaging Spectrometer

JPL Jet Propulsion Laboratory



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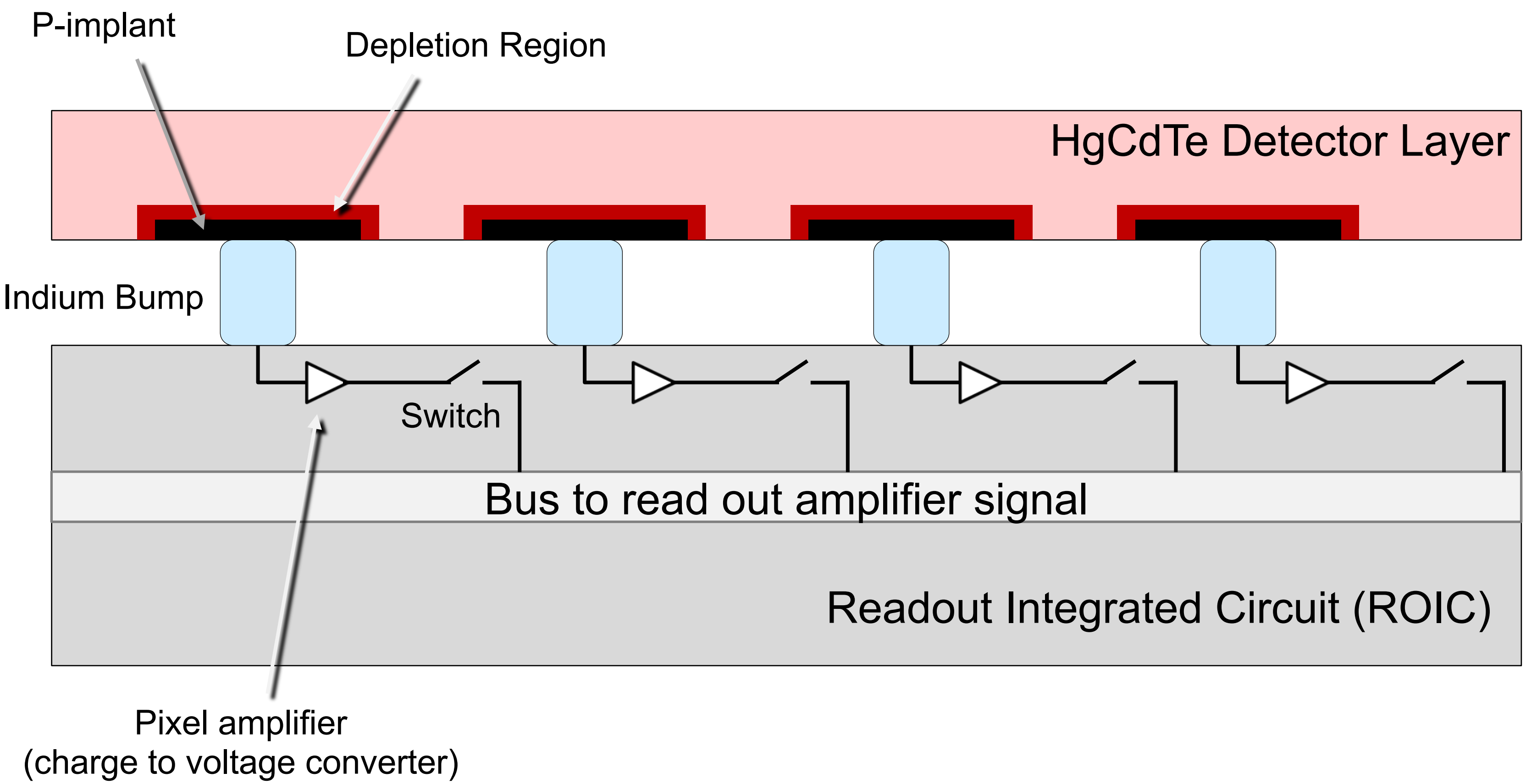
Hybrid Imager Cross Section



HxRG Family of Hybrid Imaging Sensors

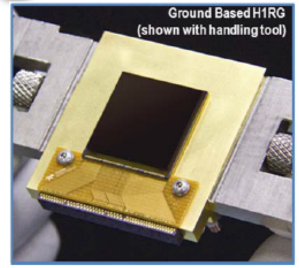
H: HAWAII: **H**gCdTe **A**stronomical **W**ide **A**rea **I**nfrared **I**mager

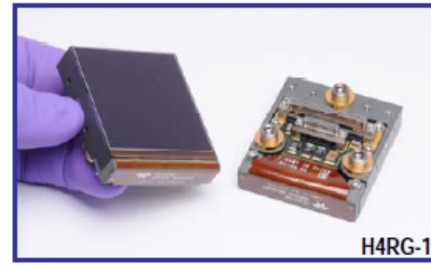
x: Number of 1024 (or 1K) pixel blocks in x and y-dimensions

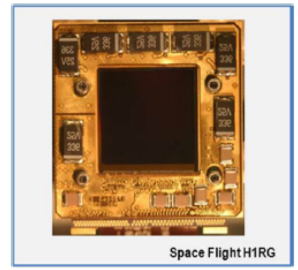
R: **R**eference pixels

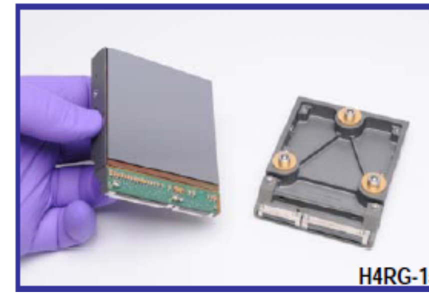
G: **G**uide window capability

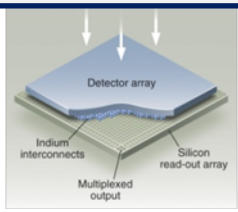
- Substrate-removed HgCdTe for simultaneous visible & IR
- Hybrid Visible Silicon Imager; Si-PIN (HyViSI)

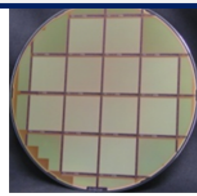




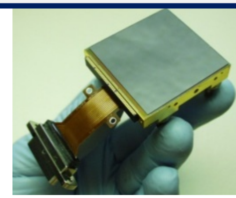








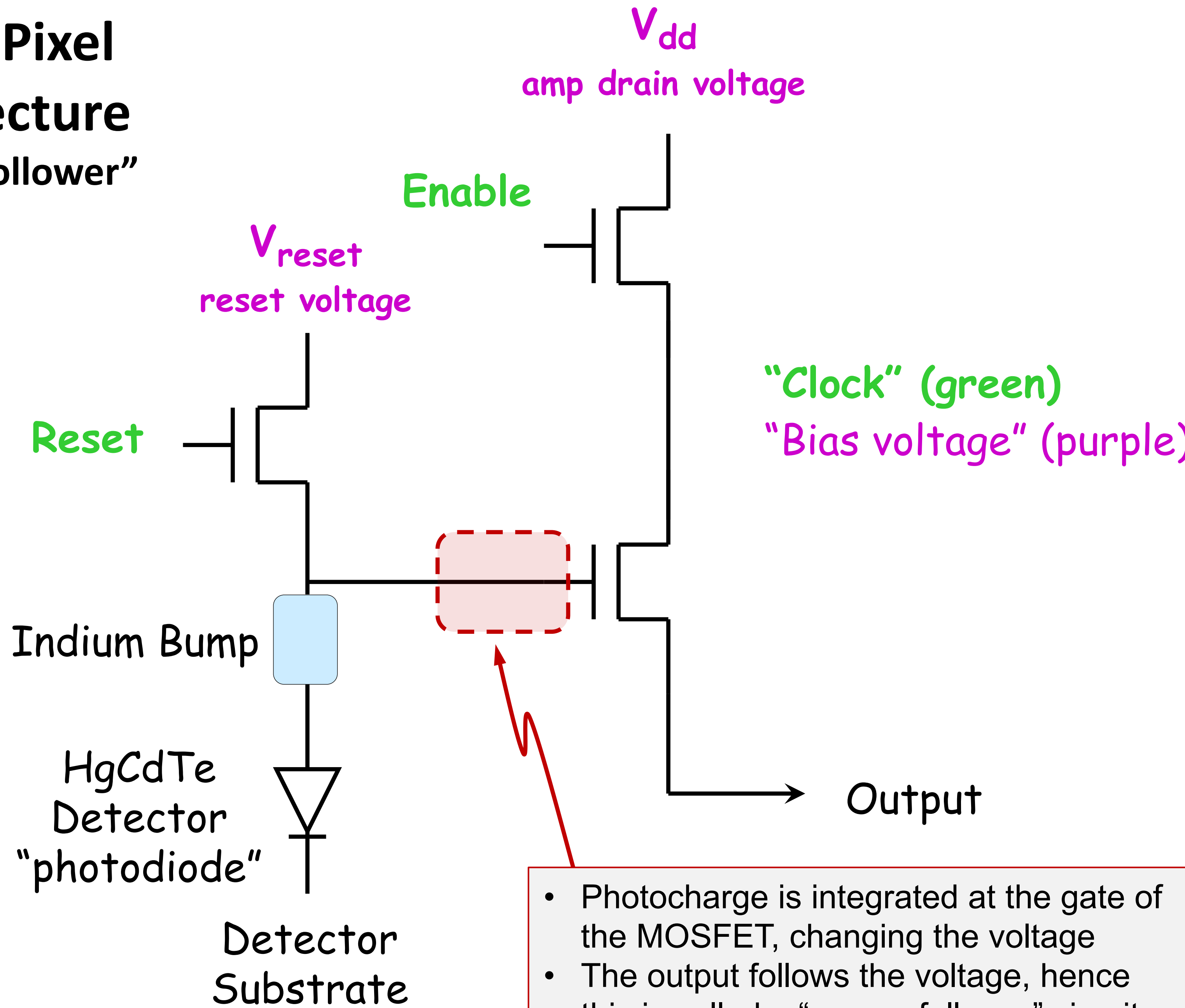
H2RG



Name	Format (# of pixels)	Pixel Pitch (microns)	# of Outputs	NASA TRL	Institutions, Observatories, & Programs using HxRG Arrays
H1RG	1024 x 1024	18	1, 2, 16	9	Wide Field Survey Explorer (WISE) Orbiting Carbon Observatory (OCO), OSIRIS-REx, Ground-based Astronomy, Dev. Programs, ESA MAJIS, GeoCarb
H2RG	2048 x 2048	18	1, 4, 32	9	Calar Alto, Caltech, CFHT, ESO, ESA (EUCLID), ESTEC, IRTF, ISRO, IUCAA, JHU-APL, Keck, Kyoto Sangyo Univ., LBNL, LMU, MIT, MPIA, MPS, NASA (James Webb Space Telescope (JWST), Joint Dark Energy Mission (JDEM(), OCIW, PSU, RIT, SALT, SAO, Subaru, TAT, U. Arizona, UCLA, UC Berkeley, U. Hawaii, U. Rochester, U. Tokyo, U. Toronto, U. Wisconsin, Space Surveillance Applications, Development Programs in Astronomy and Earth Science, etc.
H4RG-10	4096 x 4096	10	1, 4, 16, 32, 64	6	Joint Miliarcsecond Pathfinder Survey (JMAPS), WFIRST
H4RG-15	4096 x 4096	15	1, 4, 16, 32, 64	4	U. Hawai'i, Gemini Observatory, Subaru, CFHT, ESO

HxRG Pixel architecture

“Source follower”

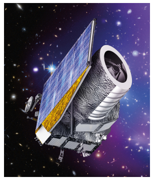


- Photocharge is integrated at the gate of the MOSFET, changing the voltage
- The output follows the voltage, hence this is called a “source follower” circuit

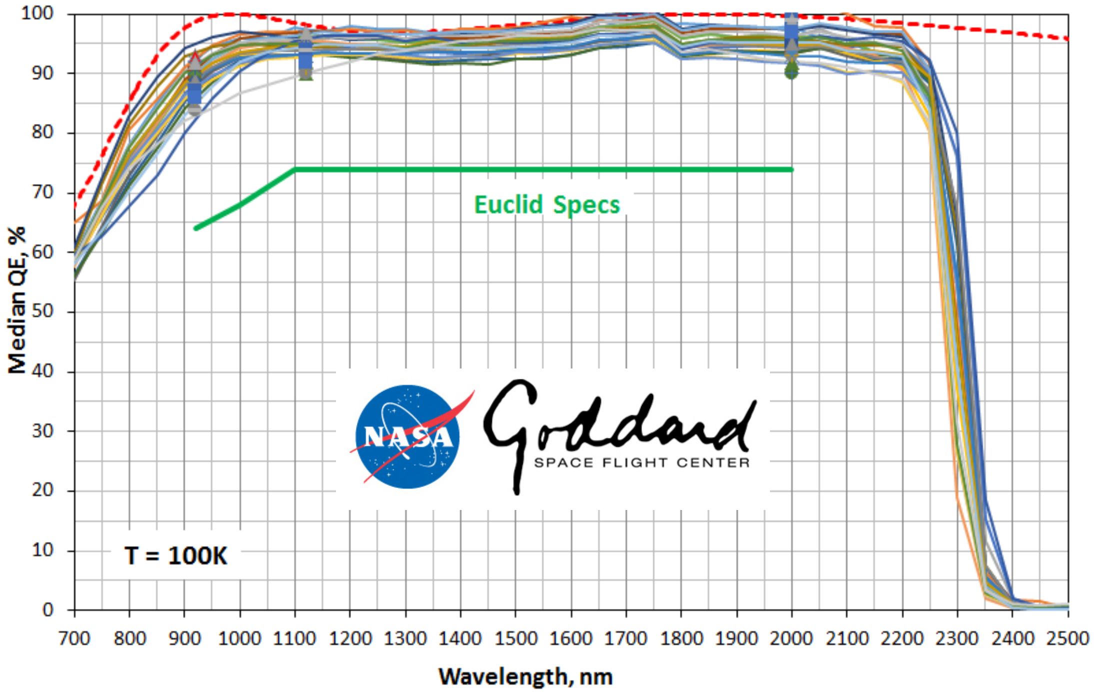
Good Attributes of HxRG arrays

- **High Quantum Efficiency**
- **Low Dark Current**
- **Low Readout Noise**
- **Very low power**
- **Lots of pixels**: 1, 4, or 16 Mpixel per array
  - Mosaics up to 300 million pixels (WFIRST)

Teledyne Visible and IR Detectors for Euclid

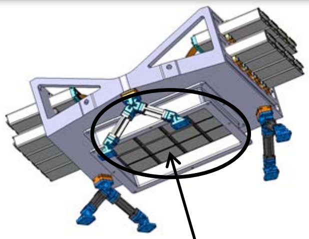


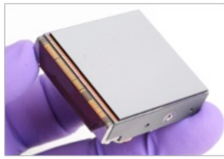
- Euclid is the European Space Agency's next flagship astronomy mission.
- Target launch date is 2021.
- Euclid has a 1.2-m diameter large field of view telescope with visible and infrared arrays produced by Teledyne:
  - 600 million visible pixels
    - 36 4K×4K (16 Mpix) CCDs
  - 64 million infrared pixels
    - 16 H2RG (4 Mpix) SWIR arrays
    - 16 SIDECAR ASIC modules
- Largest IR focal plane array when it launches
- **24 flight candidate H2RGs delivered to NASA**
- **NASA tested and delivered 20 flight grade H2RG arrays to ESA, all of which greatly exceed requirements**



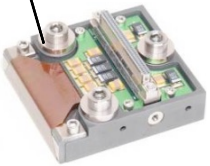
Quantum Efficiency of 24 flight candidate H2RGs

Measured by Goddard SFC Detector Characterization Laboratory

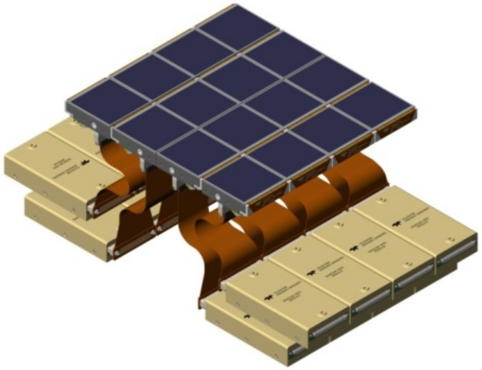




H2RG SCA (top view)

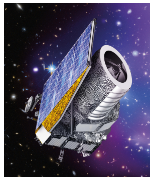


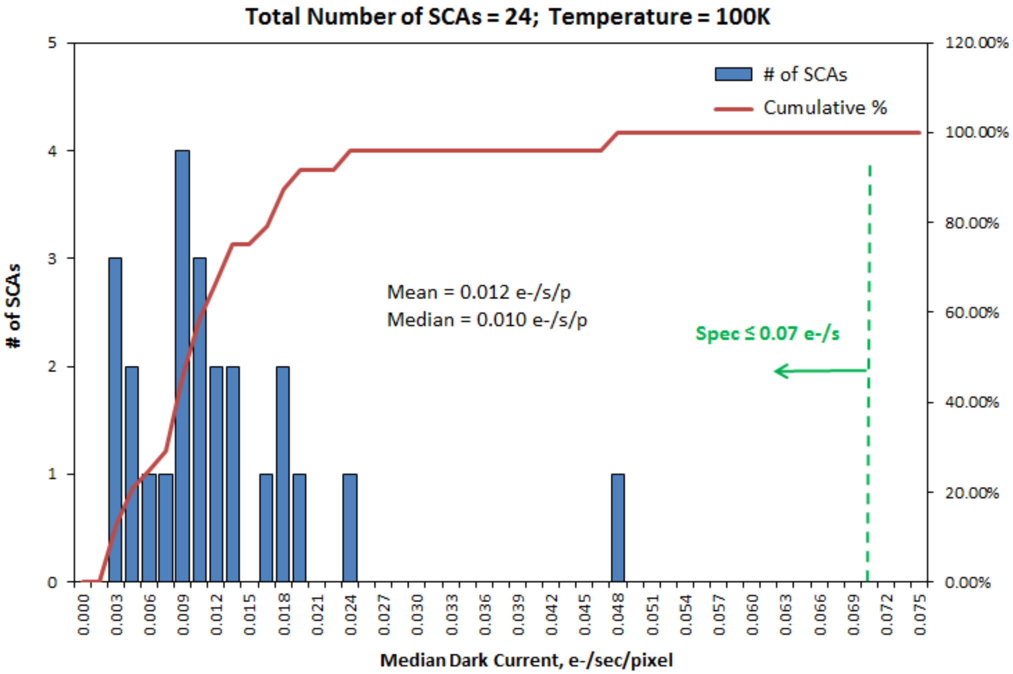
H2RG SCA (bottom view)

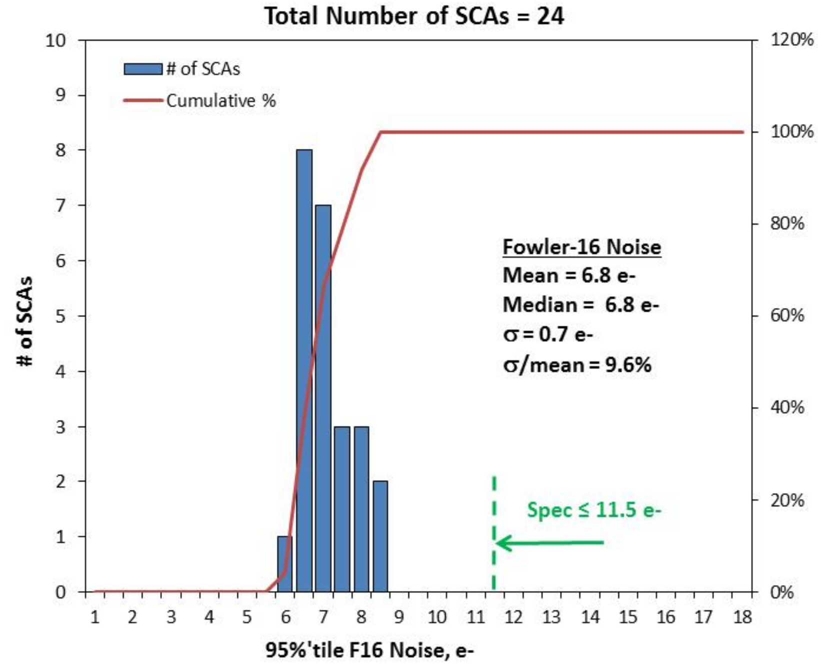


Teledyne Imaging Sensors H2RG
2K×2K pixels, 18µm pitch

H2RG IR Detectors for Euclid







Dark Current at 100K

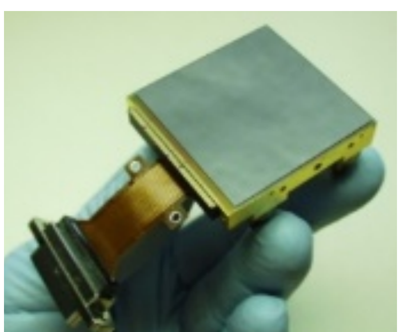
Median = 0.012 e-/pix/sec
More than 5X better
than specification (0.07 e-/pix/sec)
2.3 µm cutoff wavelength

Readout Noise

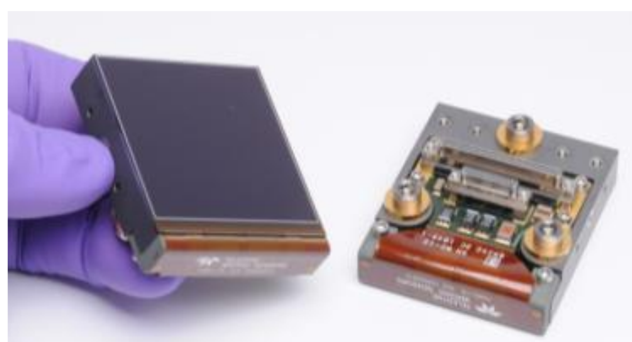
Median = 6.8 e-
40% better than specification (11.5 e-)

EPRV is moving into the Infrared

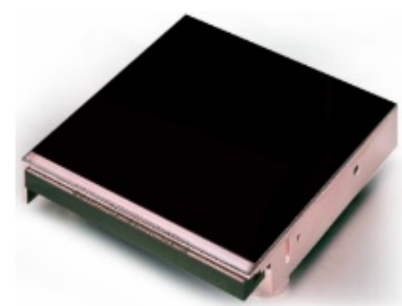
	Instrument	Wavelength (µm)	Spectral Resolution	Telescope	IR Detector	
Operational	iSHELL	1.1 - 5.3	75,000	NASA IRTF 3.0-m	H2RG	SWIR
Operational	CARMENES	0.52-0.96 & 0.96-1.71	94,600 (Vis), 80,400 (IR)	Calar Alto 3.5-m	H2RG (2)	SWIR
Operational	GIAno	0.9 - 2.5	50,000	TNG 3.6-m	H2RG	SWIR
Operational	HPF	0.9 - 1.65	50,000	Hobby-Eberly 10-m	H2RG	NIR
Operational	NIRSPEC	0.95 - 5.2	37,500	Keck II 10-m	H2RG	MWIR
Operational	SPIRou	0.955 - 2.515	70,000	CFHT 3.6-m	H4RG-15	SWIR
In Dev.	CRIRES+	0.95 - 5.2	100,000	ESO VLT 8.2-m	H2RG (3)	MWIR
In Dev.	NIRPS	0.955 - 2.515	>80,000	La Silla 3.6-m	H4RG-15	SWIR
In Dev.	iLocater	0.97 - 1.27	170,000	LBT both 8.4-m	H4RG-10	SWIR
In Dev.	IRD	0.97 - 1.75	70,000	Subaru 8.2-m	H2RG (2)	NIR



H2RG



H4RG-10

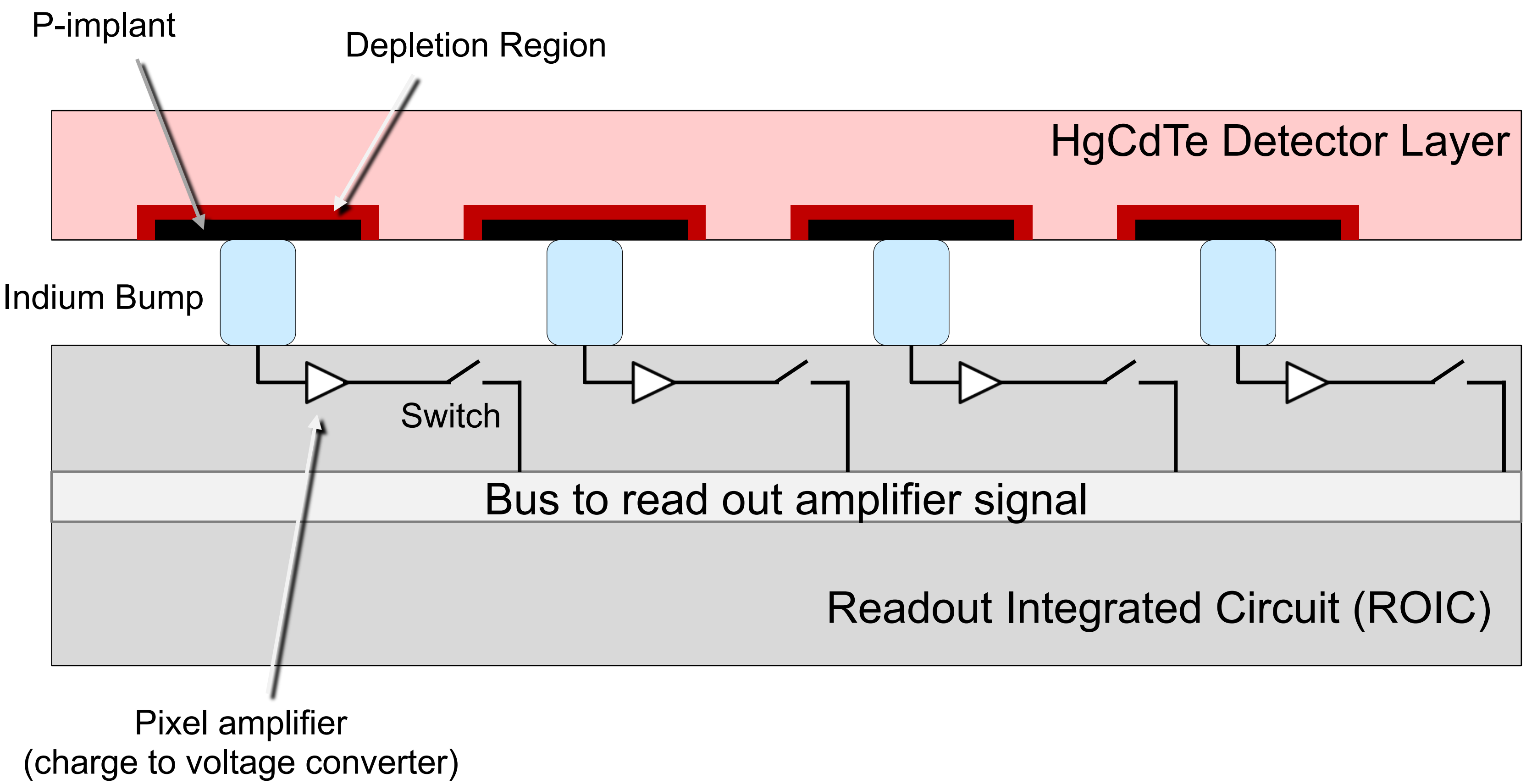


H4RG-15

Imperfections of HxRG arrays

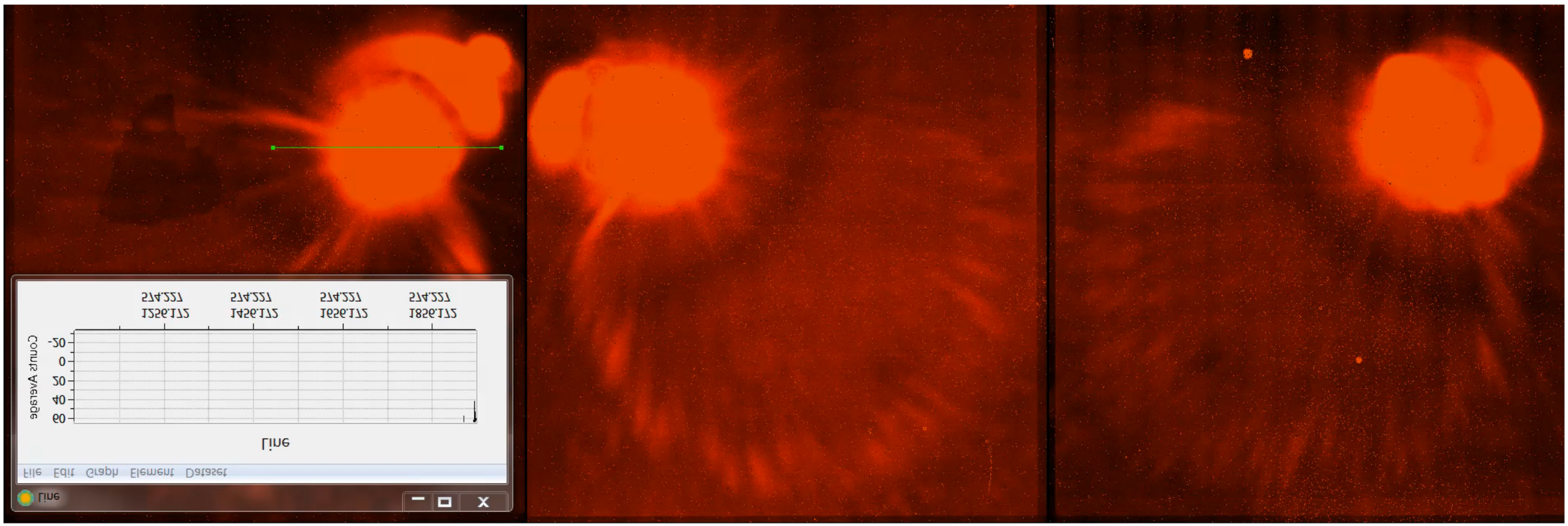
1. Persistence	Memory (afterglow) of previous image
	Bright calibration frames can cause big problems
2. Inter-Pixel Capacitance	Electrical crosstalk (time/flux dependent?)
3. Cross Hatching	Intra-pixel QE variation
4. Brighter-fatter effect	Intensity-dependent Point Spread Function (PSF)
5. Non-linearity	For high precision, must correct each pixel

Hybrid Imager Cross Section



HxRG Imperfections: #1 Persistence

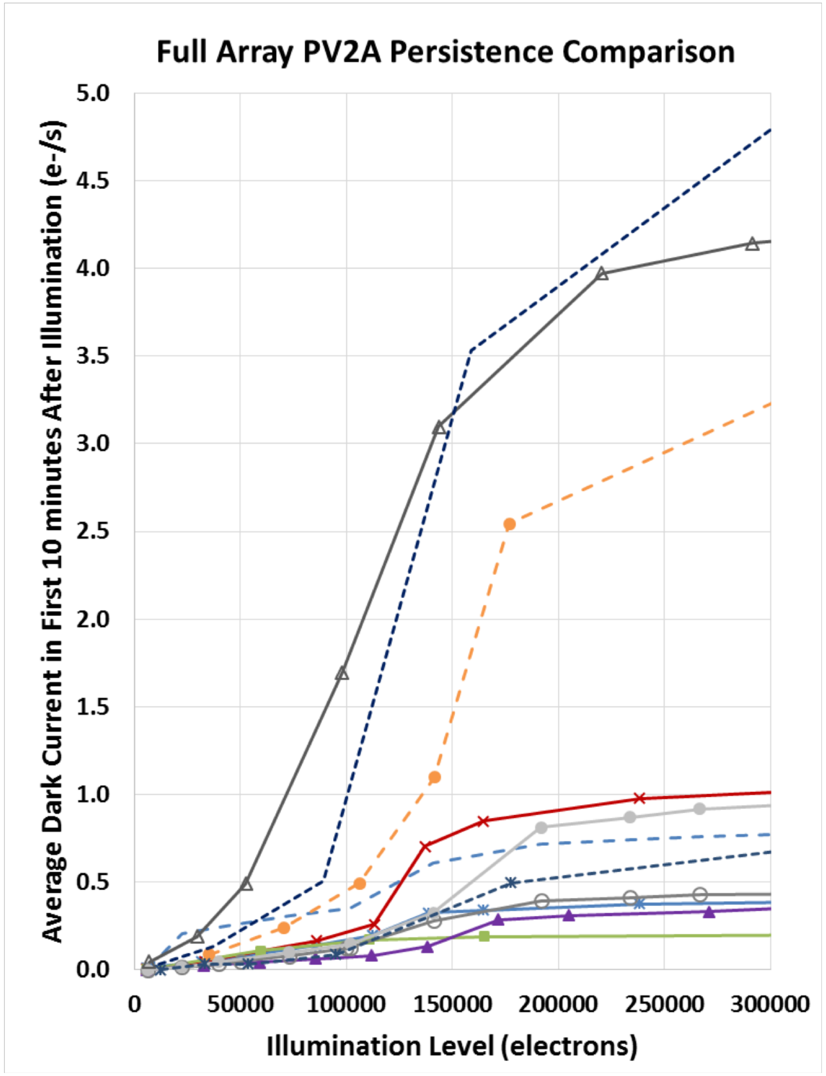
- CRIRES+ has 3 MWIR H2RG arrays
- To demonstrate persistence:
  - CRIRES+ detectors exposed to an LED flash for a few milliseconds.
  - LED switched off and the detectors are read out with reset-read every 30 sec for a few minutes

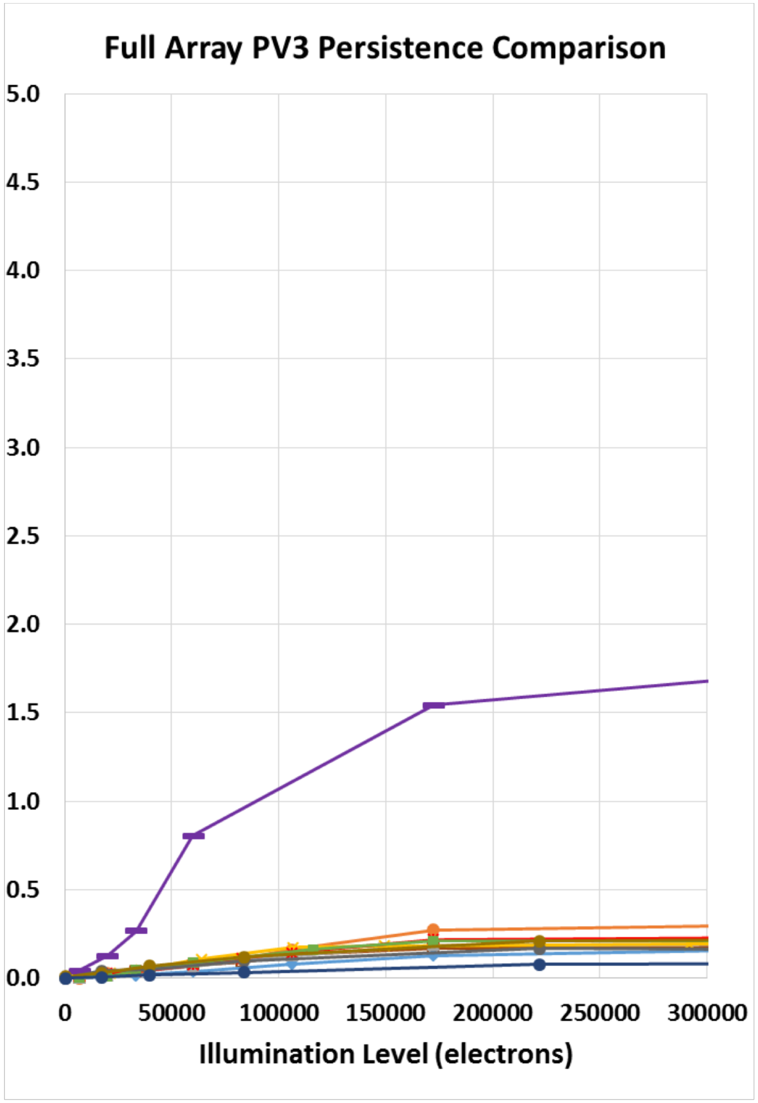


Courtesy of Derek Ives, European Southern Observatory

HxRG Imperfections: #1 Persistence

WFIRST worked closely with Teledyne during 2014-2018 to develop a new passivation process (PV3) that has shown near zero persistence.





Data and figures courtesy of Bob Hill, Goddard Spaceflight Center Detector Characterization Laboratory, and WFIRST Program Office

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HxRG Imperfections: #2 Inter-pixel capacitance (IPC)

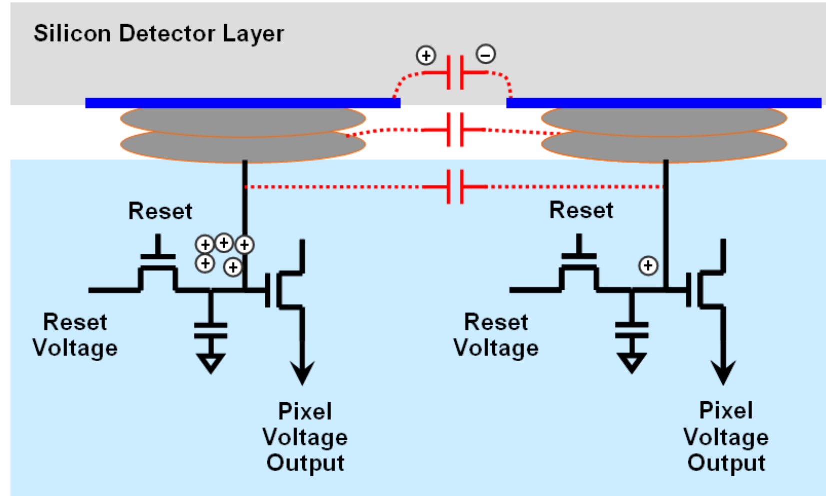
First identified in a 2005 paper

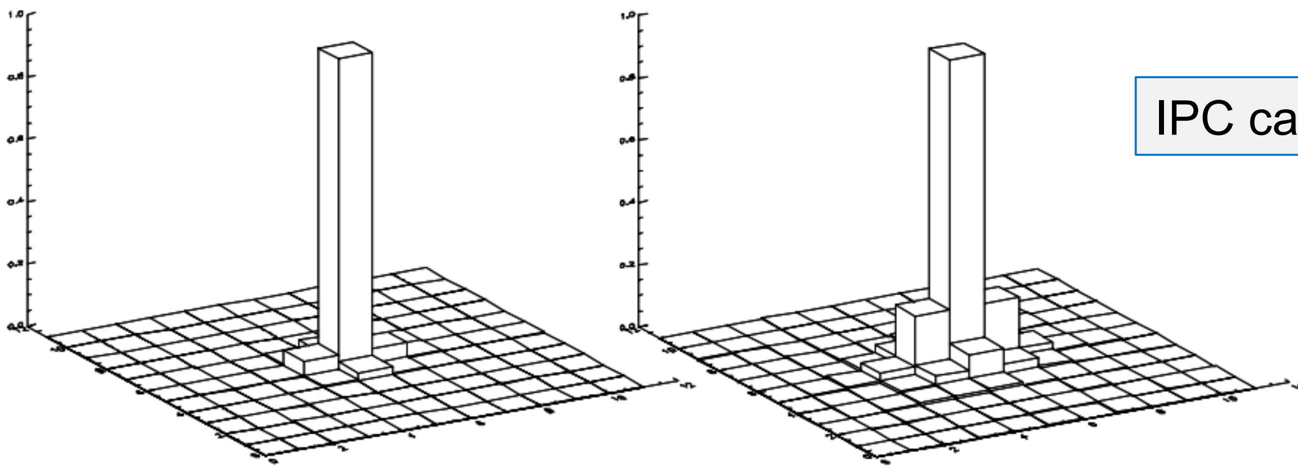
CONVERSION GAIN AND INTERPIXEL CAPACITANCE OF CMOS HYBRID FOCAL PLANE ARRAYS

Nodal capacitance measurement by a capacitance comparison technique

G. Finger[1], J. Beletic[2], R. Dorn[1], M. Meyer[1], L. Mehrgan[1], A.F.M. Moorwood[1], J. Stegmeier[1]

[1]*European Southern Observatory,* [2]*Rockwell Scientific Company*

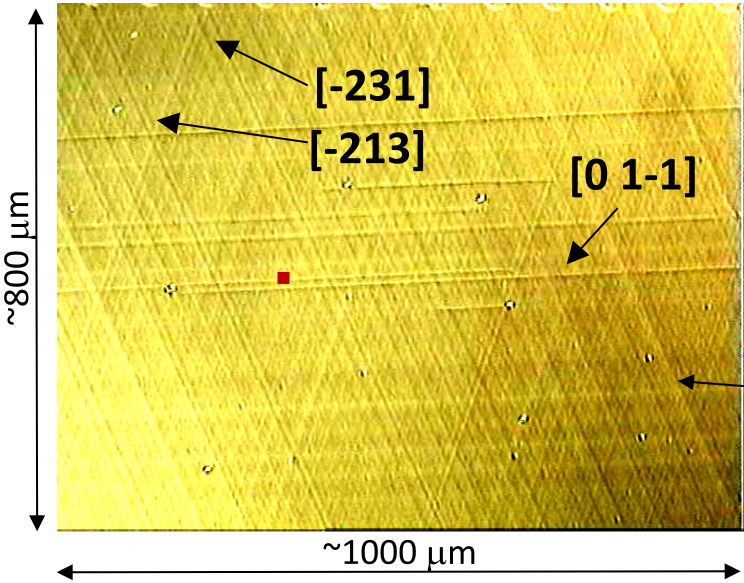


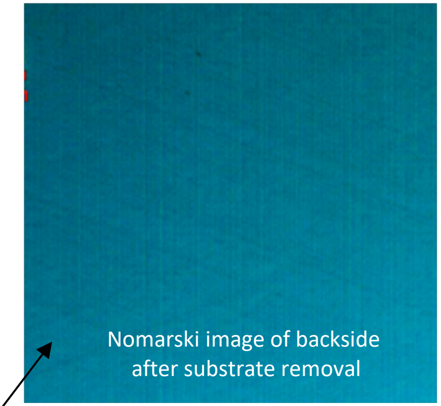


IPC can be de-convolved

Figure 10. Autocorrelation of CMOS Hawaii-2RG hybrid arrays. Left: λ_c=2.5 µm HgCdTe array, φ=1.23. Right: Si-PIN HyViSI array, φ=2.03.

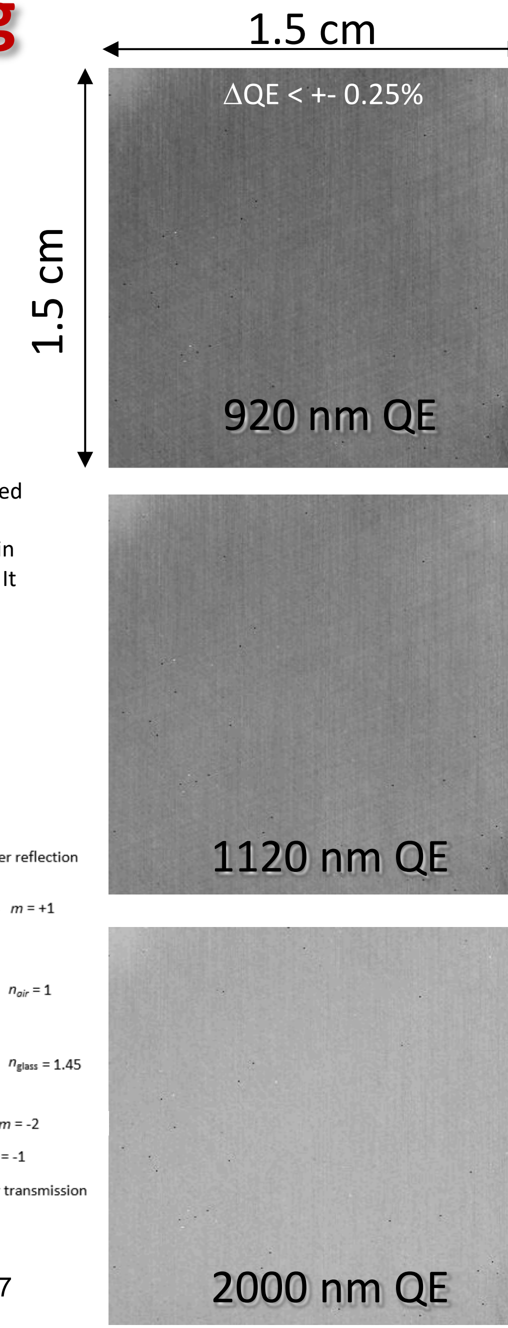
HxRG Imperfections: #3 Cross Hatching



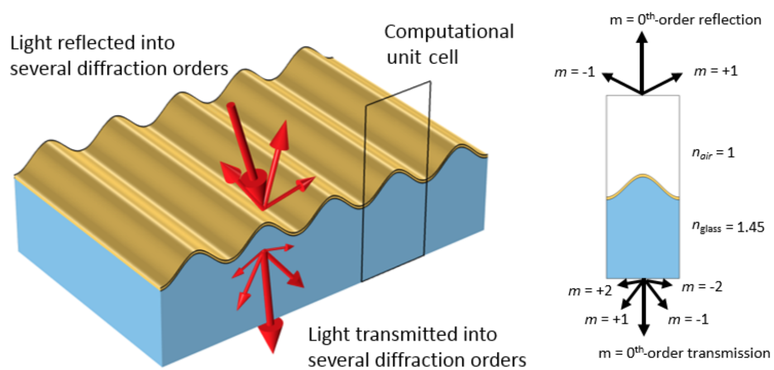


Cross hatch develops on the surface of low-misfit strained layers which undergo relaxation by the introduction of cross hatch growth morphology and misfit dislocations in the interface between the strained layer and substrate. It can be reduced or eliminated with lattice matching.

Nomarski image of as-grown layer (side by ROIC)
■ H2RG (18 µm) size shown as red square



- Light from one pixel is diffracted to neighboring pixels
- Effect is 0.2% to 0.5% QE variation of flat field illumination
- Less QE variation due to cross hatching for longer wavelengths



Figures courtesy of Walter Frei, COMSOL Blog, 6 June 2017

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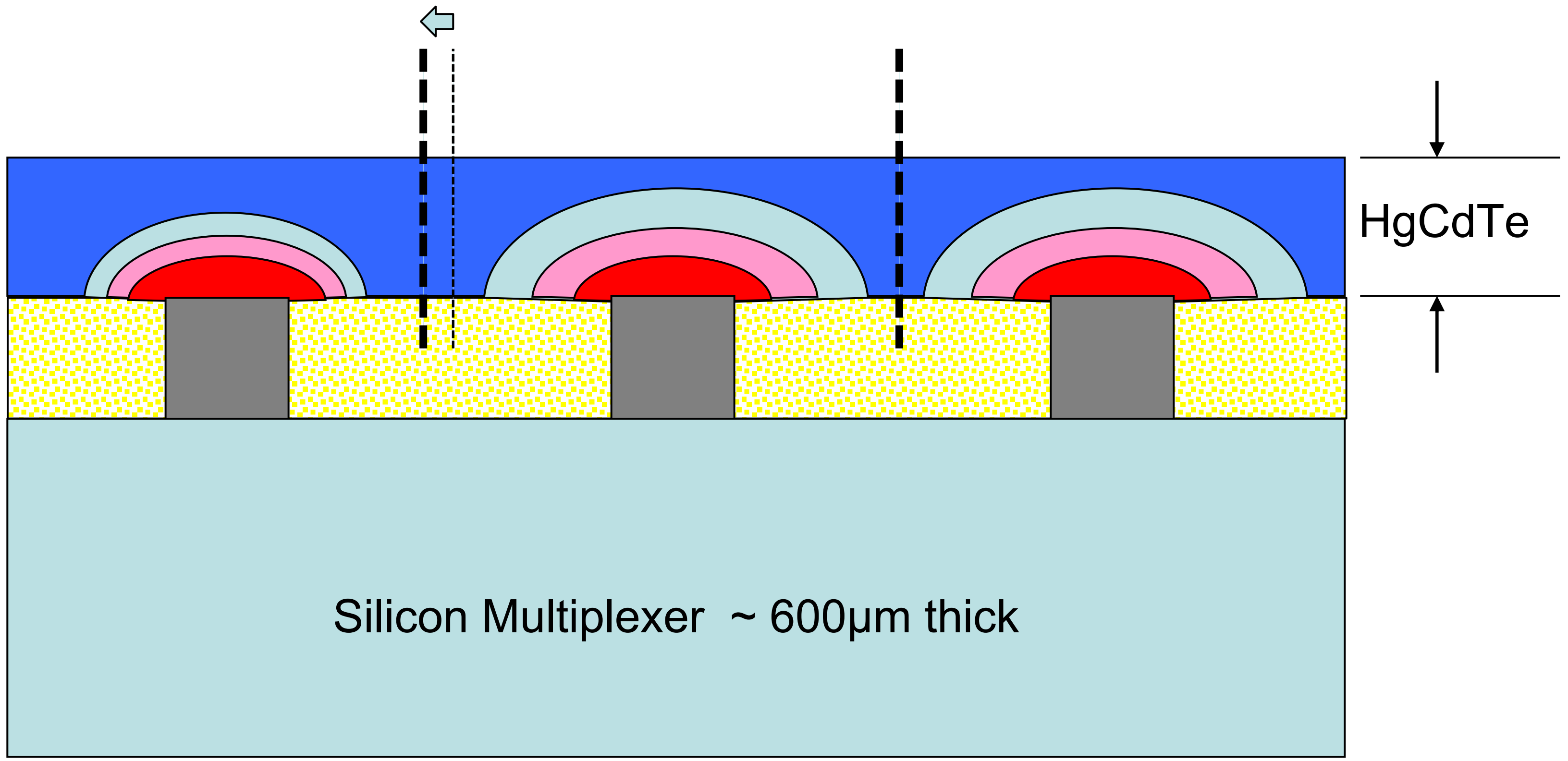
HxRG Imperfections: #4 “Brighter-fatter” effect

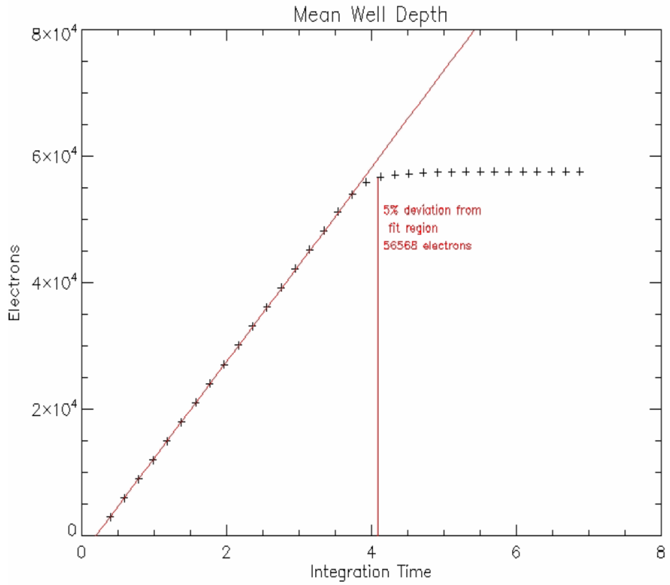
Figure courtesy of Roger Smith, Caltech

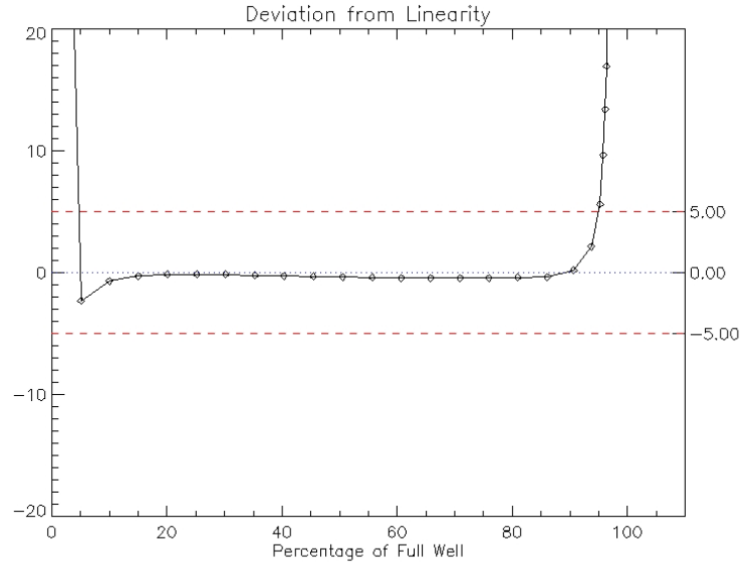
Pixel shrinks as charge accumulates so PSF may be flux dependent

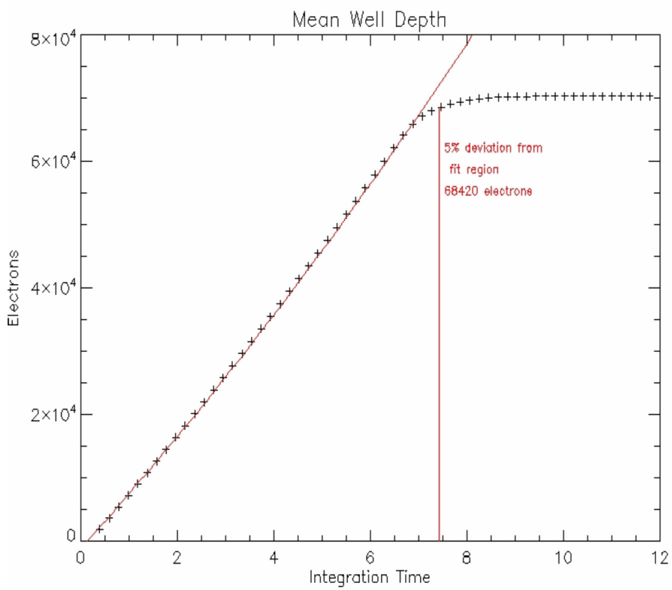


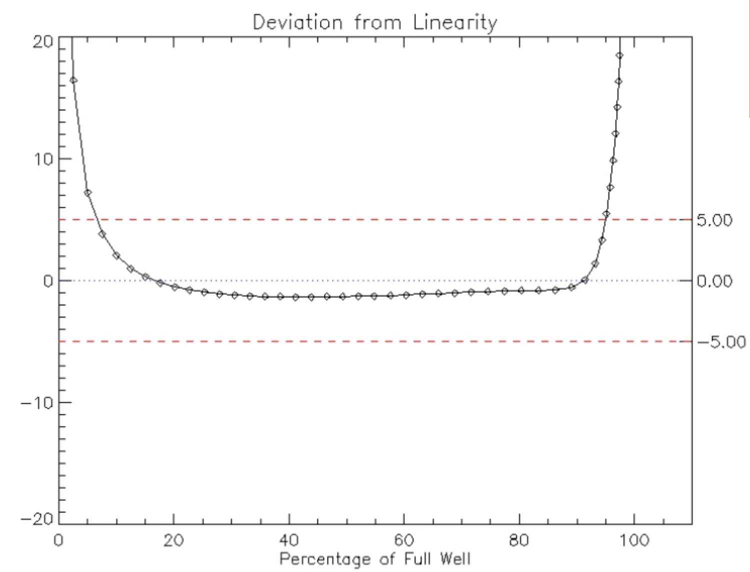
HxRG Imperfections: #5 Non-linearity

Full well defined as 5% variation from linear response









HPF corrects for non-linearity at the pixel level. “Computationally intensive but required”

Examples from recent H1RG MWIR testing

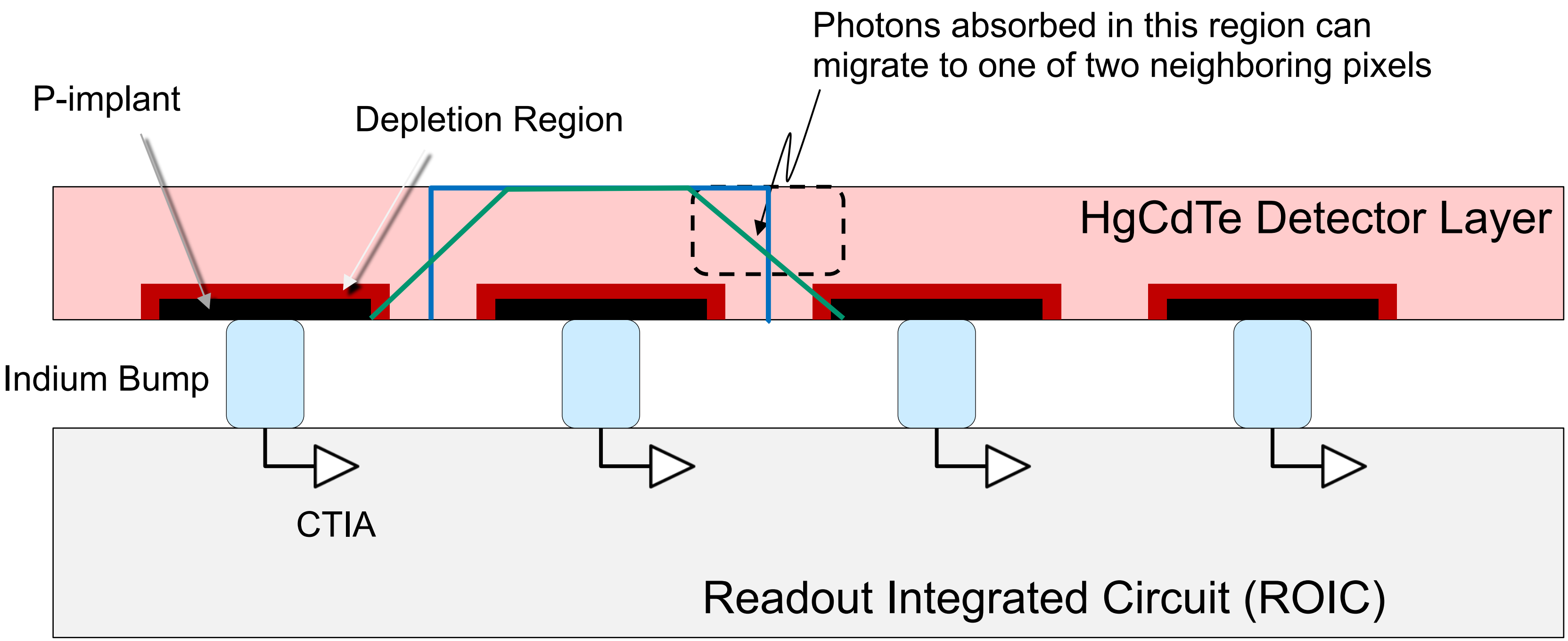
Imperfections of HxRG arrays

1. **Persistence**	Memory (afterglow) of previous image
	Bright calibration frames cause big problems
2. **Inter-Pixel Capacitance**	Electrical crosstalk (time/flux dependent?)
3. **Cross Hatching**	Intra-pixel QE variation
4. **Brighter-fatter effect**	Intensity-dependent Point Spread Function (PSF)
5. **Non-linearity**	For high precision, must correct each pixel

Let's keep piling up the issues!

6. **Bad pixels / cosmetics**	Fixed format used for stability, can't dither
7. **Windowing artifacts**	Limits operation modes to overcome issues
8. **Epoxy voids**	Variation of QE with time? 1st time heard of this
9. **Charge diffusion**	Pixel PSF is not ideal top-hat function
10. **Add your issue here!**	

HxRG Imperfections: #9 Charge Diffusion



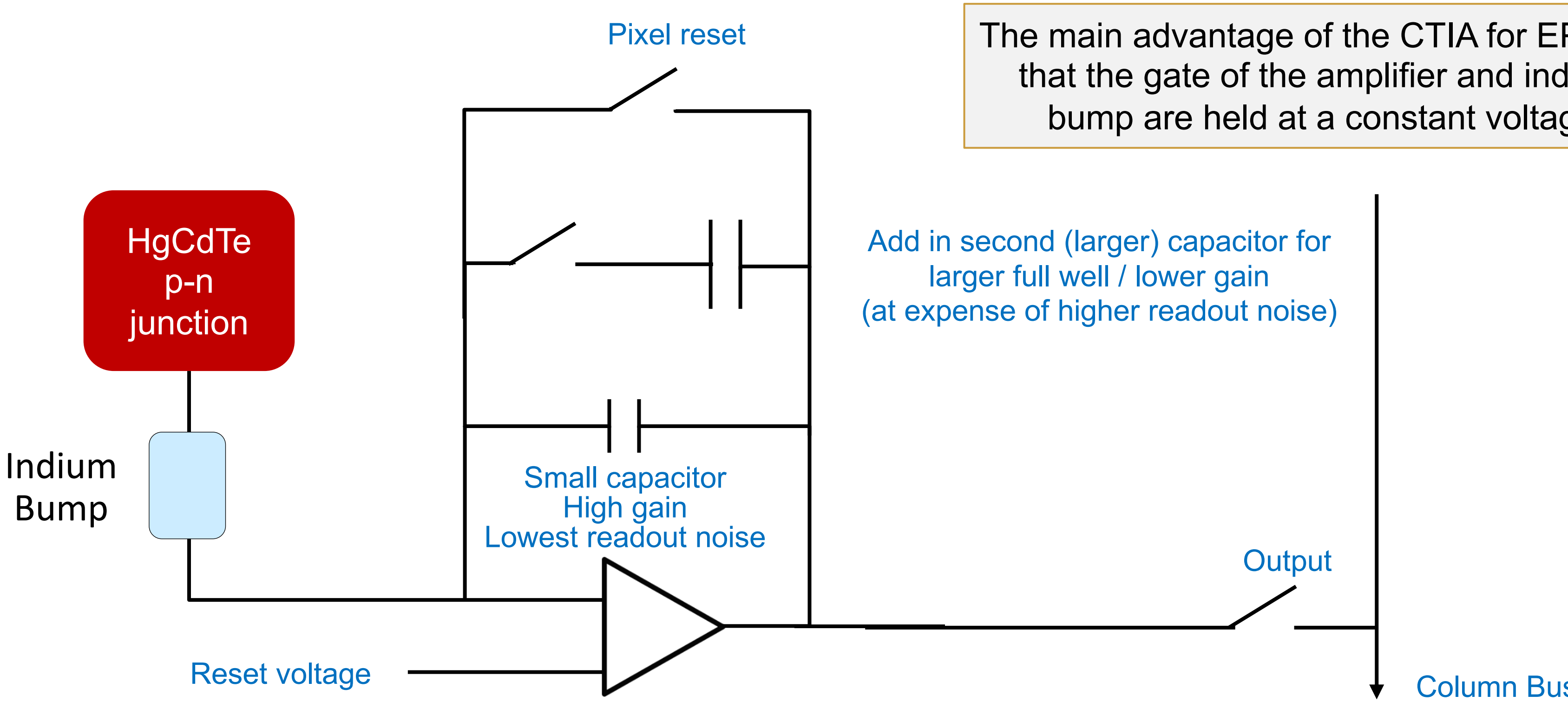
Ideal pixel response (“top-hat” function)

Charge diffusion function

Making a Better EPRV detector starts with the Pixel

Better to use a Capacitive TransImpedance Amplifier (CTIA)

The main advantage of the CTIA for EPRV is that the gate of the amplifier and indium bump are held at a constant voltage



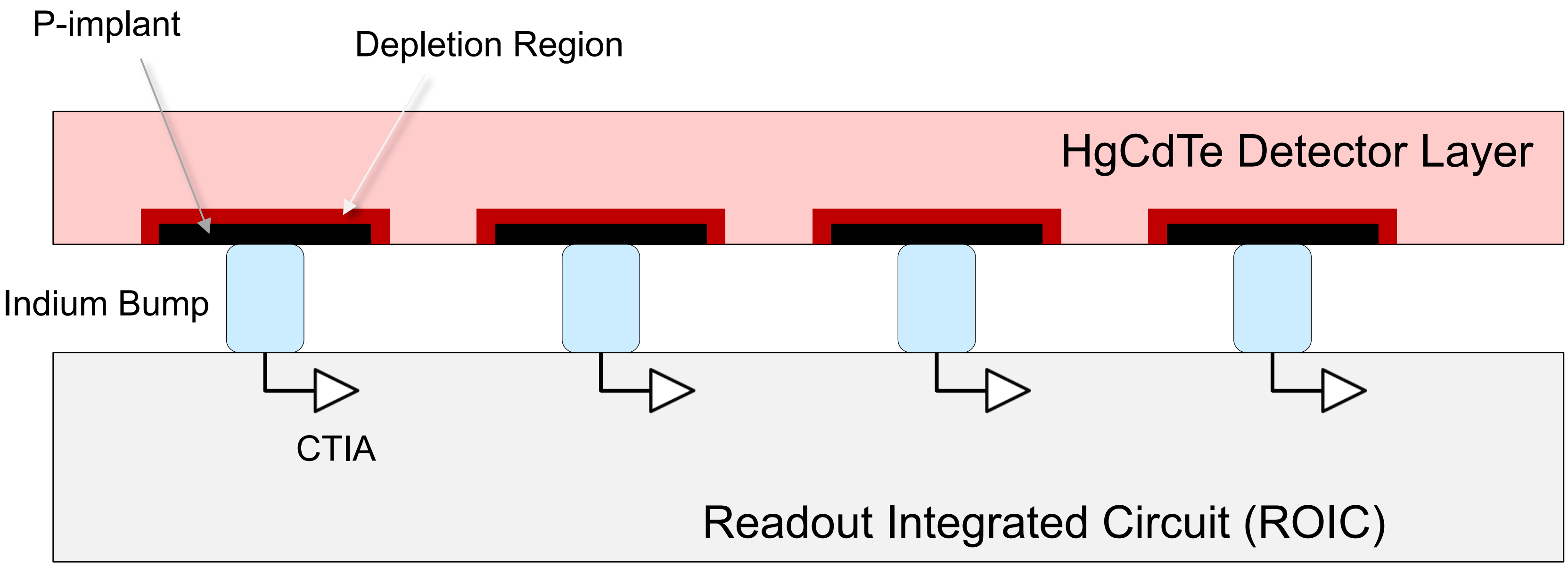
No correlated double sampling (CDS) in this circuit

- For high frame rate operation, such as Earth Observation, CDS is usually included in the pixel.
- But since in-pixel CDS adds circuitry and increases noise, should probably not be used for astronomy CTIA array.
- The circuit shown allows "sample up the ramp" for lowest noise and detection of cosmic ray hits.

The challenges for using a CTIA are:

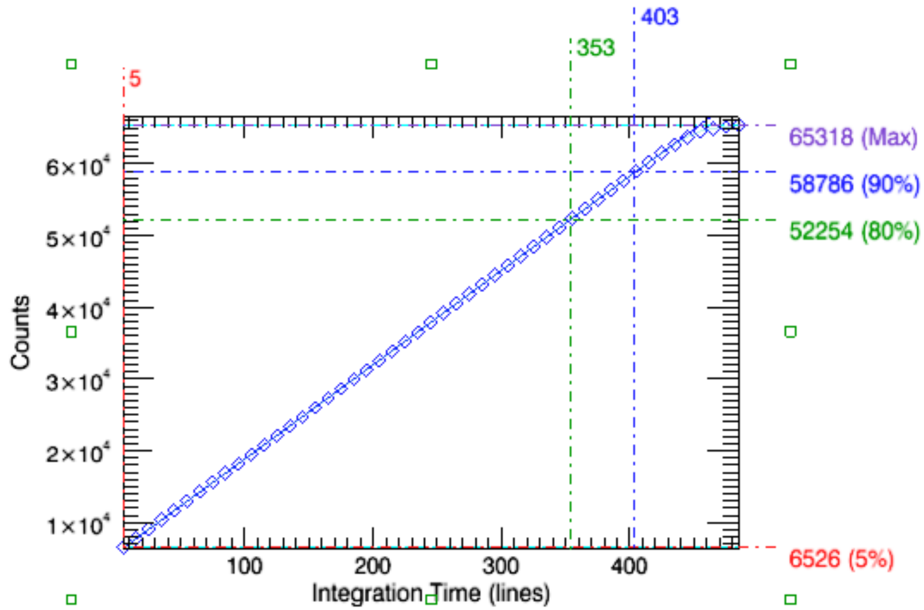
- Must always stay on, so higher power
- Ensuring no ROIC glow
- Achieving low noise

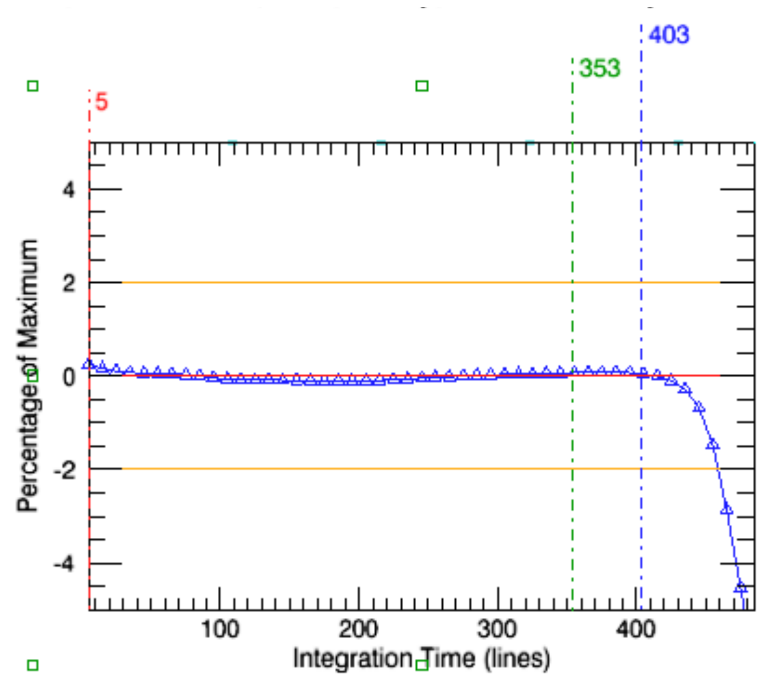
CTIA addresses Persistence, IPC, Brighter-fatter effect



- The input gate to all CTIAs are held at the reset voltage during operation.
- The depletion region stays constant, with no de-biasing and biasing of trap states
  - This may **eliminate persistence.** Need data to confirm.
- **No inter-pixel capacitance** since all pixel gates at same voltage.
- **No brighter-fatter effect** since the voltage fields in the HgCdTe stay constant during exposure.

CTIA is highly linear – better than 99.9%

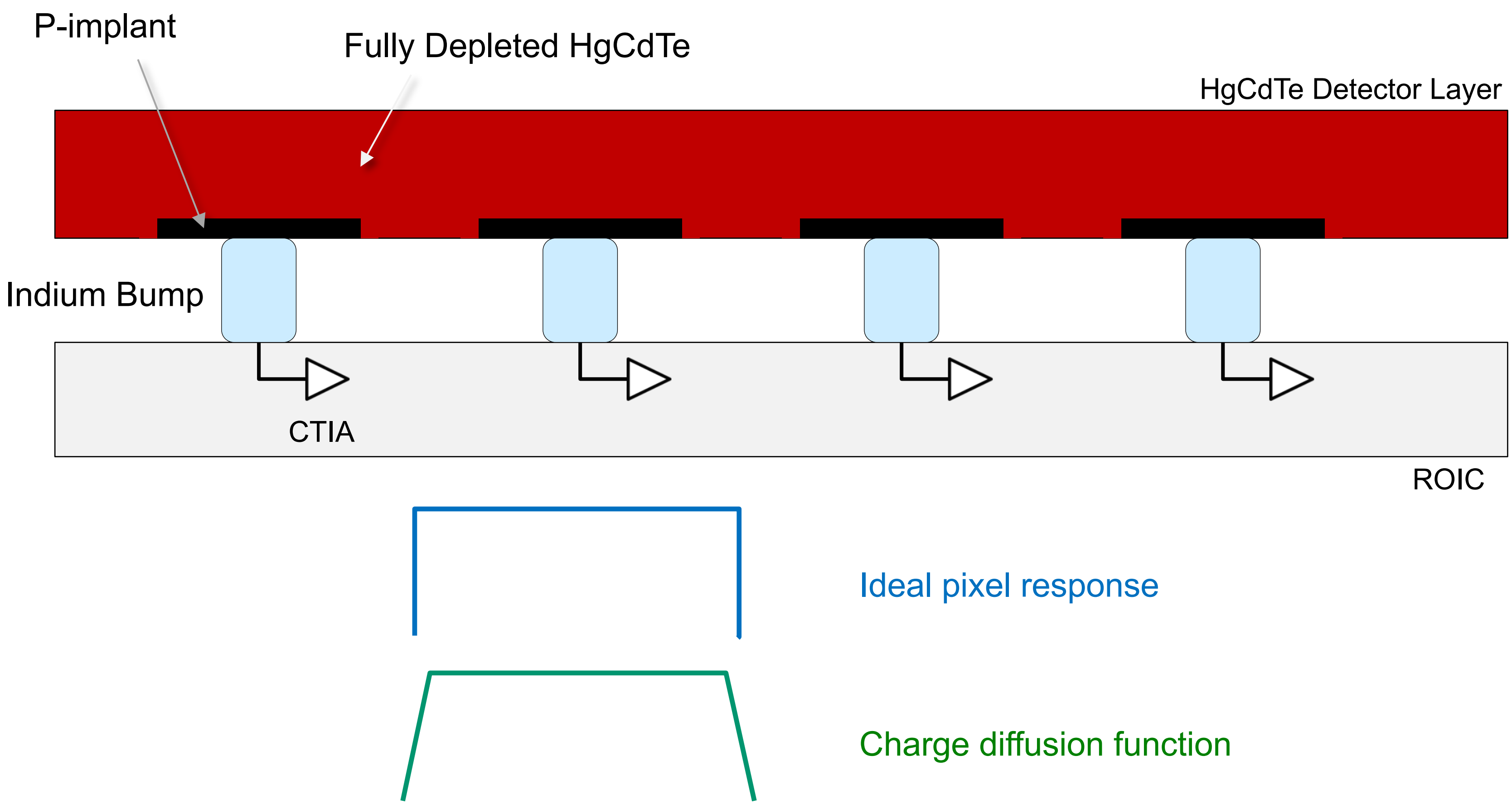




Example from recent testing of a CHROMA-A CTIA pixel

Optimizing the HgCdTe detector layer for EPRV

- **Eliminate cross hatching** with improved growth / processing
- Use low trap process developed for WFIRST to reduce persistence
- **Minimize charge diffusion** by fully depleting detector layer
- Charge diffusion function becomes close to an ideal top-hat function



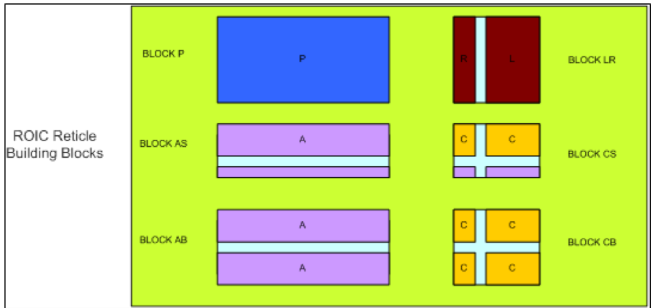
An optimized CTIA + better HgCdTe detector could be a nearly ideal EPRV detector

- **Use Capacitive TransImpedance Amplifier pixel**
  - Will reduce persistence
  - Eliminates inter-pixel capacitance (and any potential time/flux variation)
  - Eliminates intensity dependent PSF (no more “fatter-bigger” effect)
  - Produces very linear response
- **Utilize the latest advances in HgCdTe growth and processing**
  - Eliminate cross hatching
  - Use WFIRST low trap process to reduce persistence
- **Operate the HgCdTe in fully depleted mode**
  - Sweep charge to p-n junction to minimize charge diffusion
  - Full depletion will also keep traps empty, reducing persistence

Three ways to reduce / eliminate persistence

1. Reduced trap passivation process developed for WFIRST
2. Fully depleted HgCdTe to avoid any charge going into few remaining traps
3. CTIA pixel will keep the HgCdTe biasing constant throughout operation

GeoSnap-18 (stitchable to 3Kx3K)

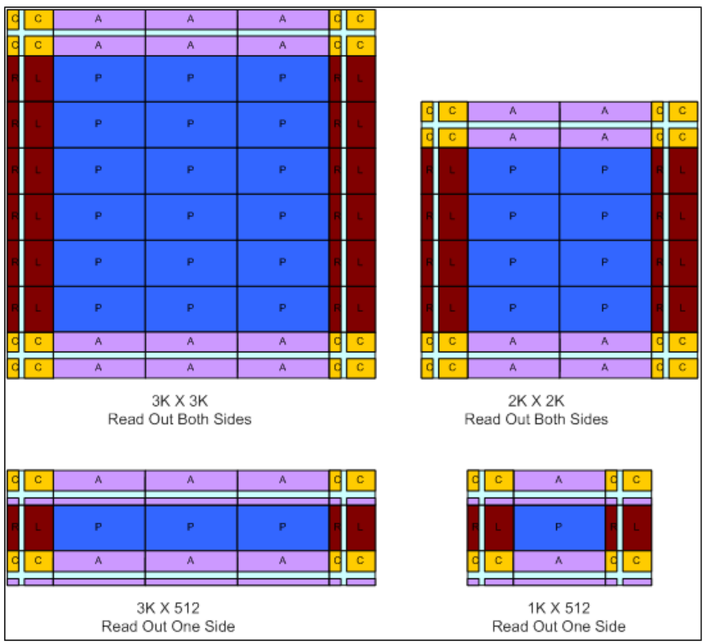


GeoSnap / CHROMA-D Design

- 18 micron pitch pixel
- CTIA unit cell with 2 gains / full well
  - 100 ke- and 1 Me- or 180 ke- and 2.7 Me-
- Stitchable design, up to 3K × 3K pixels
- Snapshot, integrate while read
- Fully digital chip, 14 bit ADCs
- Full frame rate: 120 Hz for 2K × 2K, 250 Hz for 3K × 512
- ROIC formats fabricated: 2K × 2K, 2K × 512, 3K × 512
- Focal plane arrays made and tested with several types of detectors:
  - Visible (Silicon), MWIR (5.3 μm HgCdTe), VLWIR (14.5 μm HgCdTe)

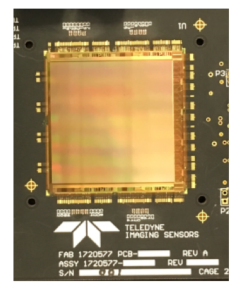
GeoSnap 3K × 3K

CHROMA-D 3K × 512

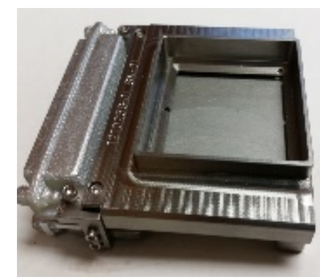


CHROMA-D 1K × 512

GeoSnap 2K × 2K



ROIC



Focal Plane Module

- ROIC passed radiation tests (no latchup)
- GeoSnap 2K×2K space flight package developed
- GeoSnap 2K×2K in production
- Being used for Visible, MWIR, VLWIR
- CHROMA-D 2K×512 and 3K×512 being developed for Earth Science applications

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Next Steps

- Test existing CTIA arrays:
    - Measure persistence
    - Measure potential glow of the ROIC
- Learn more about EPRV IR detector range of operations to optimize design
    - Exposure times / Flux levels / Flux variation across the array
    - Need / desire for window readout (integration monitoring)?
- Define detector requirements
    - Rolling shutter?
    - Correlated double sampling (CDS) off-chip?
    - Full well requirement
    - Enable multiple-sampling
- Assess design feasibility – can low noise requirement be achieved?
- Form partnership(s) for detector development and demonstration in an instrument

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