# High Performance Infrared Focal Plane Arrays

## Good Attributes and Bad Attributes


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Presented by
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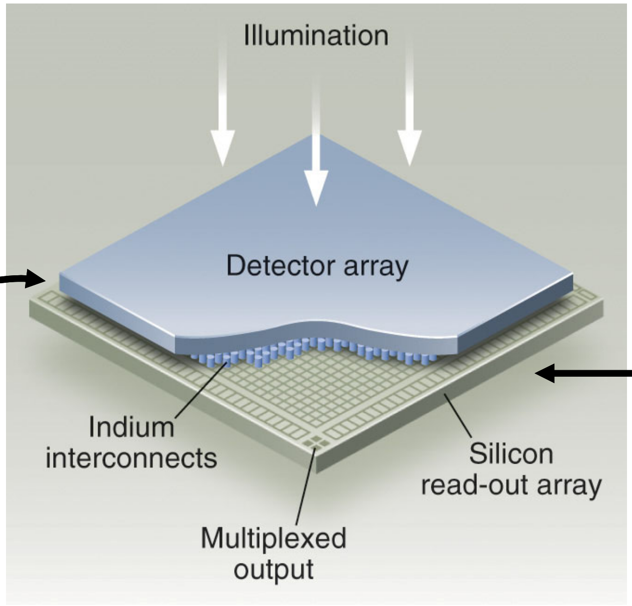
Image Sensors for Precision Astronomy
ISPA 2024
Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) at SLAC
12 March 2024

# Hybrid CMOS Imaging Sensor




## Readout Integrated Circuit (ROIC)

Input signal

- Flux – object and background

Operating Mode

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

Interface

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

Environment

- Temperature
- Radiation

Other Requirements

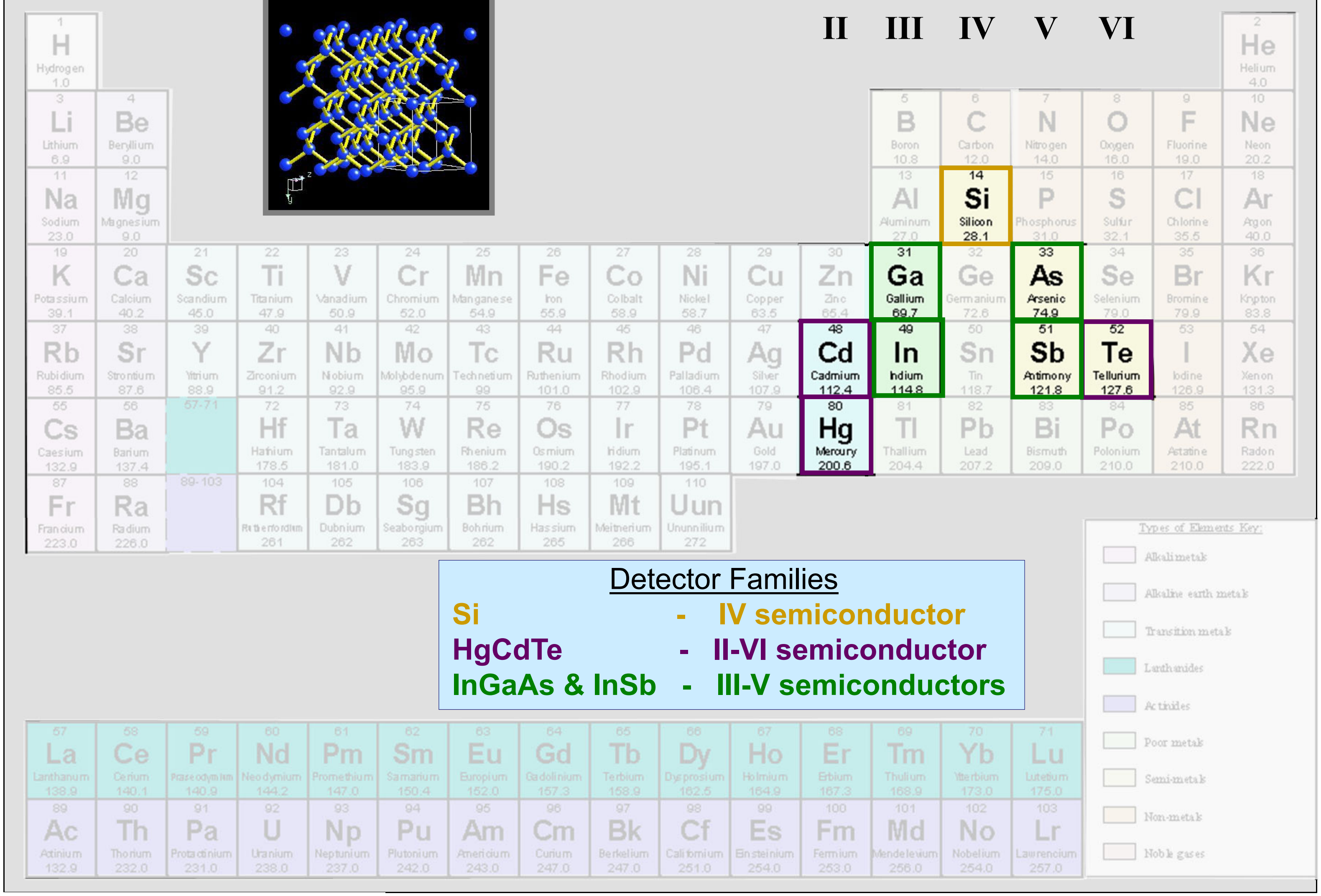
- Linearity
- Anti-blooming

## Detector

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

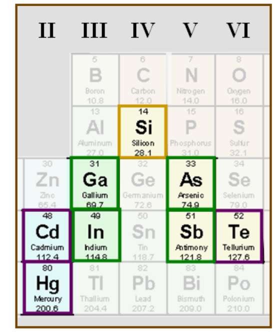
The functionality ("the brains") of a CMOS-based sensor is provided by the readout circuit

# Periodic Table

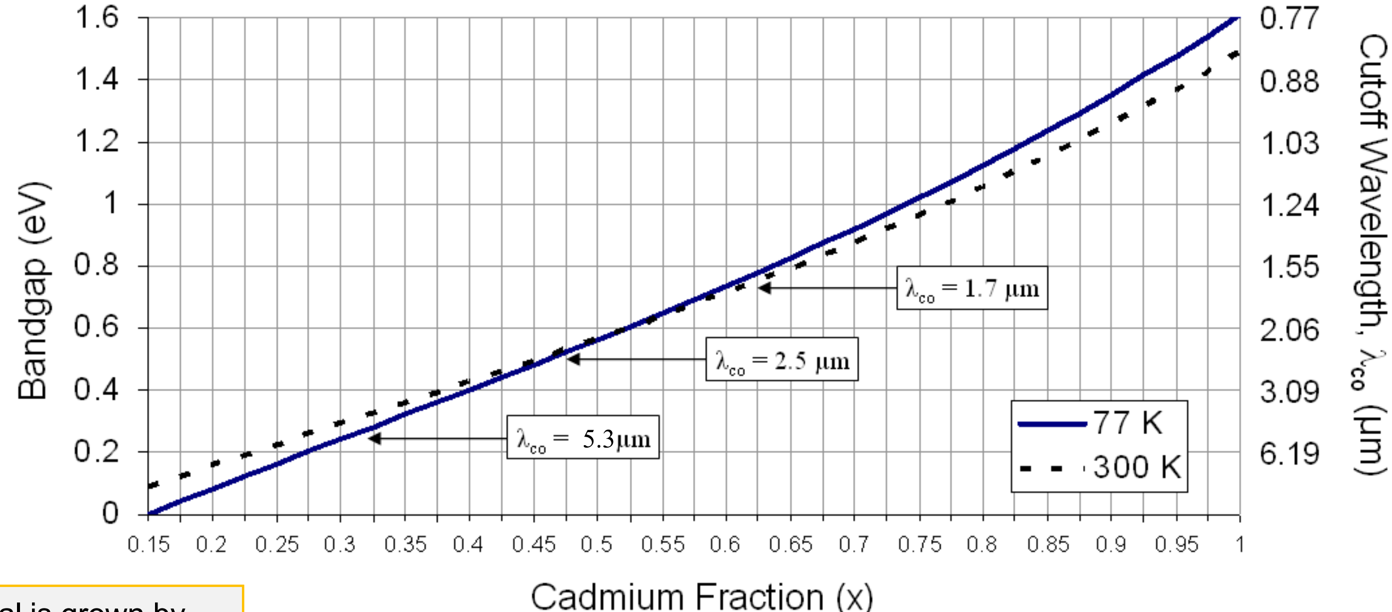


# Tunable Wavelength: Unique property of HgCdTe

**$Hg_{1-x}Cd_xTe$** 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 Molecular Beam Epitaxy (MBE) on CdZnTe Substrates

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

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

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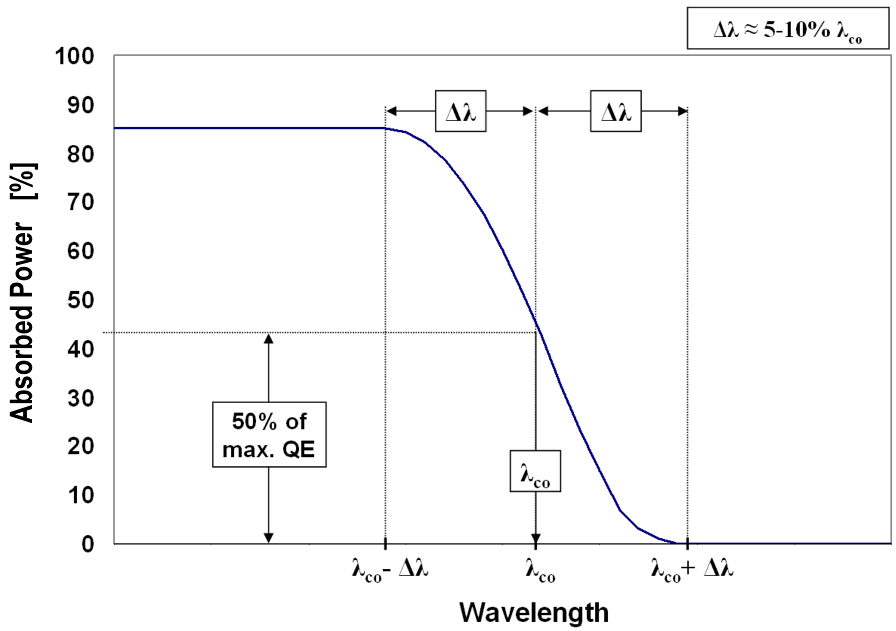
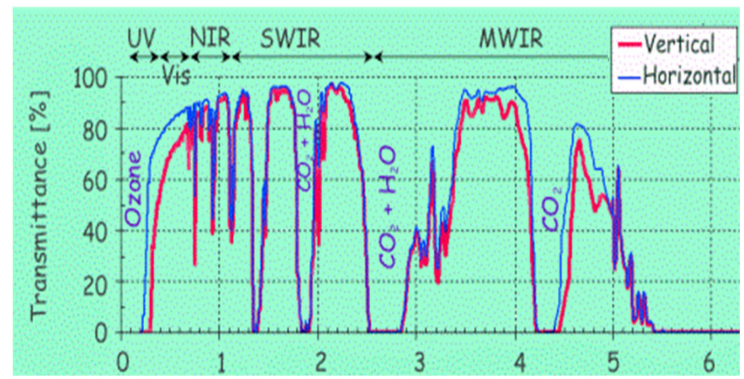
# HgCdTe Cutoff Wavelength




Atmospheric Transmission



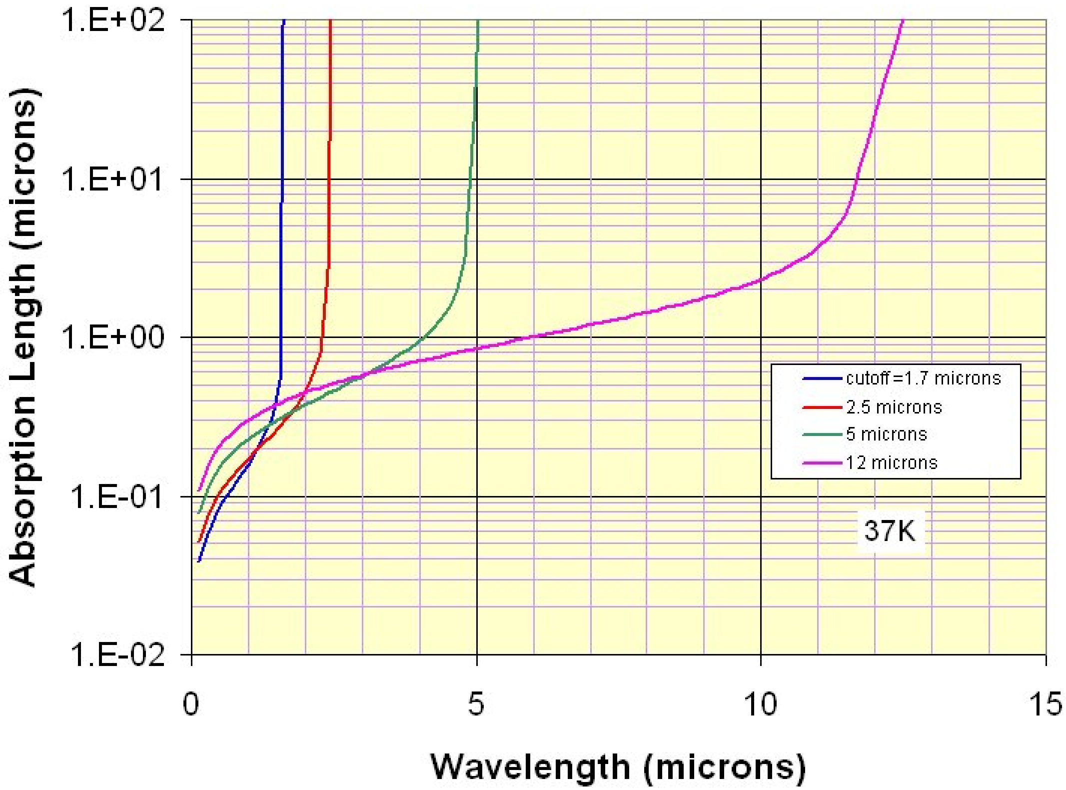

Wavelength (microns)

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

<u>Ground-based astronomy cutoff wavelengths based on atmospheric windows</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 |

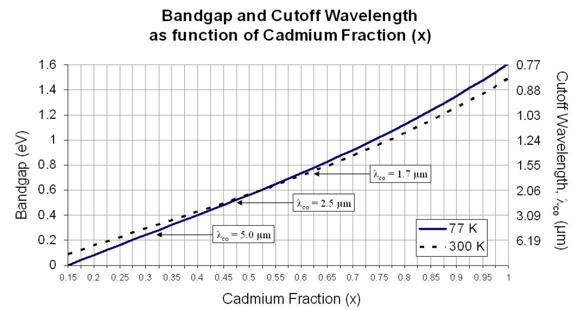
# Absorption Depth of HgCdTe




**Rule of Thumb**
Thickness of HgCdTe layer needs to be about equal to the cutoff wavelength
(wavelength in a vacuum)

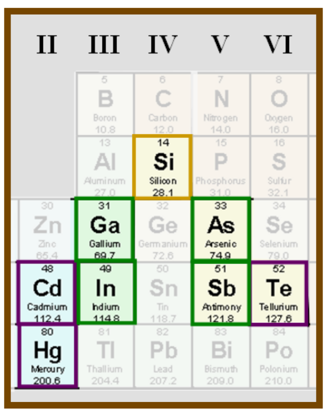
- HgCdTe is a direct bandgap material.
- HgCdTe is extremely efficient at converting electromagnetic energy into free electrons.
- The electromagnetic energy can come from photons or electrons accelerated through the material.

# Growth Structure
# of p-on-n HgCdTe arrays



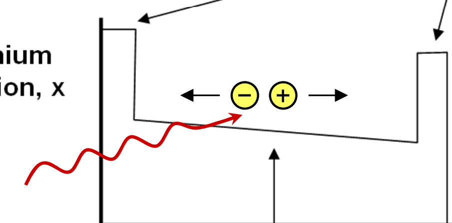


**P-n junction that collects charge and is connected to the readout circuit**




**Cap layers with higher cadmium fraction keeps holes away from surfaces of the HgCdTe detector layer**

**Cadmium Fraction, x**



**Gradient in x pushes photocharge (holes) to the readout circuit connection**

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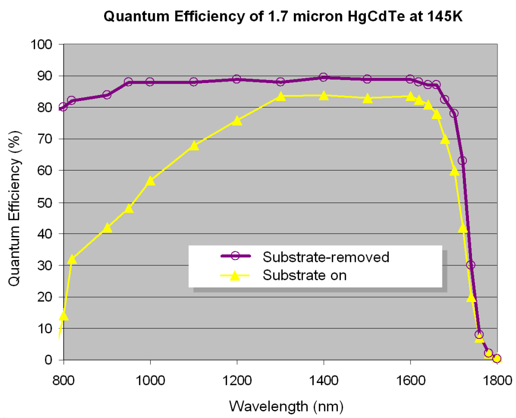
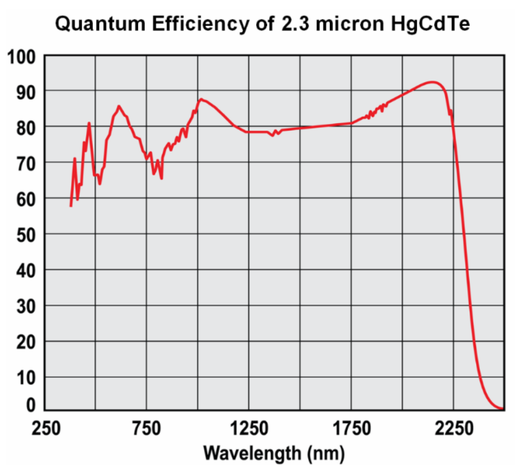
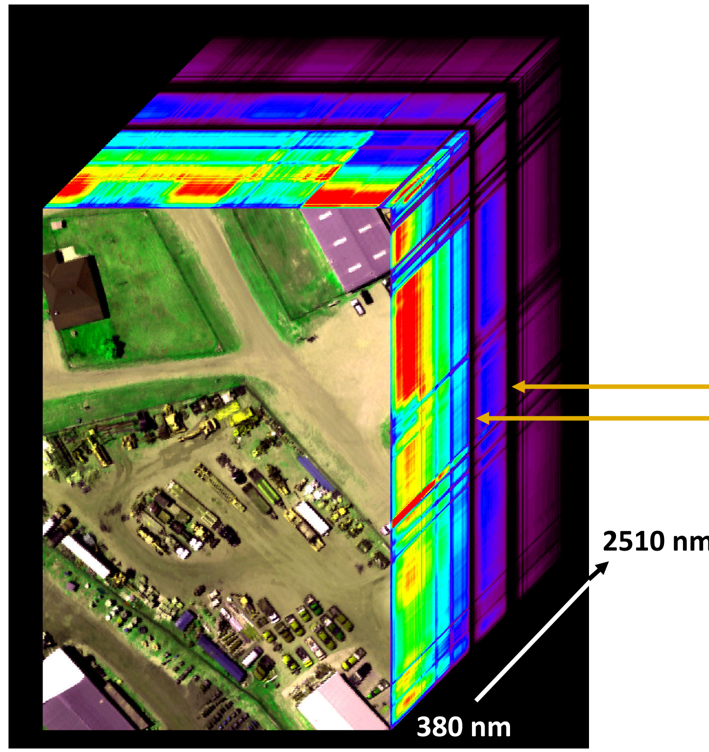
# Substrate Removed HgCdTe Provides Simultaneous UV-Vis-IR Light Detection

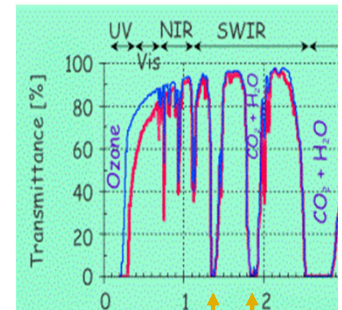


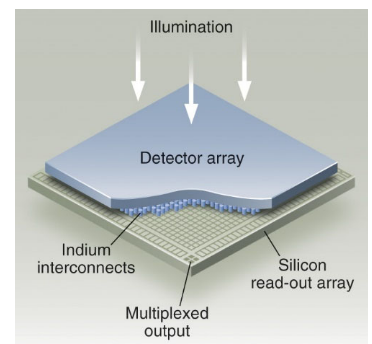




**JPL AVIRIS-NG**
**Imaging Spectrometer**

JPL
Jet Propulsion Laboratory




Atmospheric water vapor absorption bands at 1400 and 1900 nm

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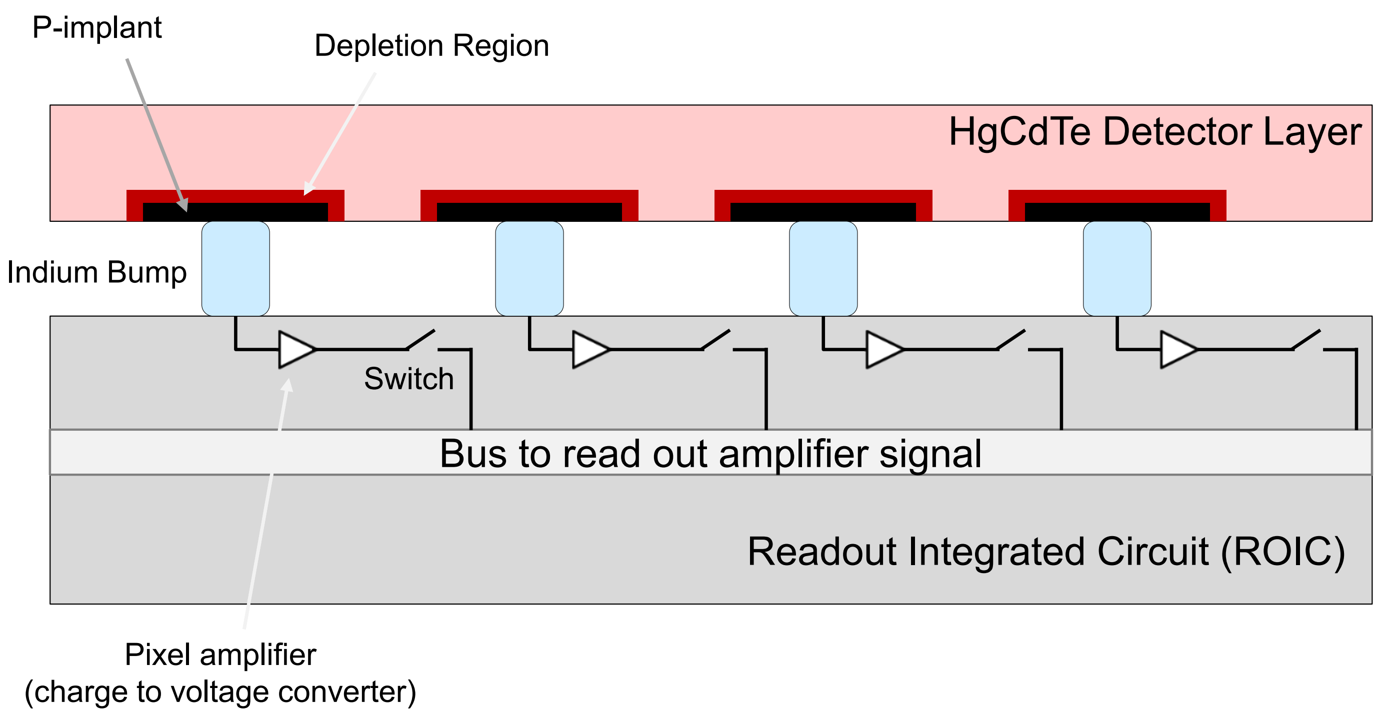
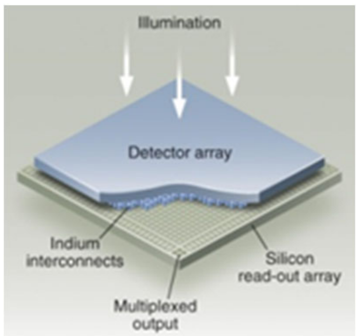
# Hybrid Imager Cross Section

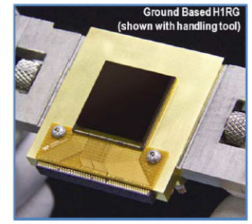


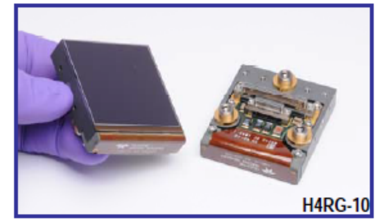
# HxRG Family of Hybrid Imaging Sensors

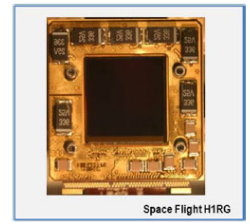


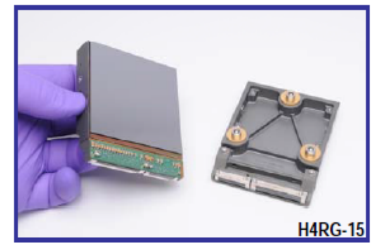

**H**: **HAWAII**: **H**gCdTe **A**stronomical **W**ide **A**rea **I**nfrared **I**mager
*x*: Number of 1024 (or 1K) pixel blocks in x and y-dimensions
**R**: **R**eference pixels
**G**: **G**uide window capability

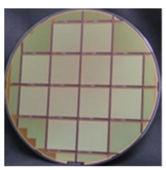
- Substrate-removed HgCdTe for simultaneous visible & IR
- Hybrid Visible Silicon Imager; Si-PIN (HyViSI)



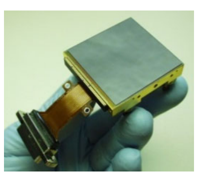



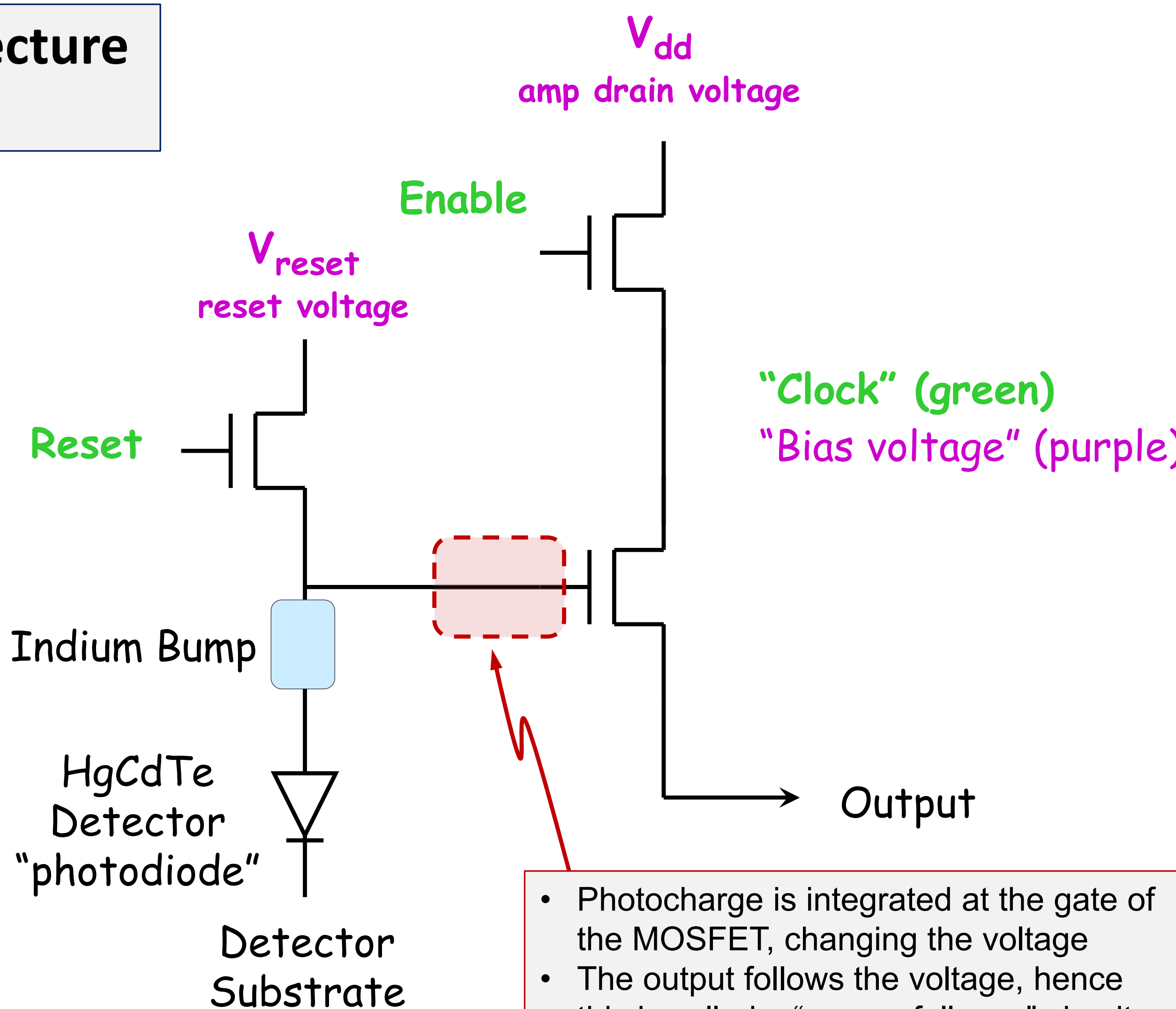



H2RG



| Name | Format (# of pixels) | Pixel Pitch (microns) | # of Outputs | NASA TRL | Institutions, Observatories, & Programs using HxRG Arrays<br>**Missions / Instruments discussed at ISPA 2024 shown in bold blue** |
|---|---|---|---|---|---|
| **H1RG** | 1024 x 1024 | 18 | 1, 2, 16 | 9 | Wide Field Survey Explorer (WISE) Orbiting Carbon Observatory (OCO), OSIRIS-REx, Ground-based Astronomy, **HST (H1R)**, ESA MAJIS, ESA ARIEL |
| **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, **Dominion Astrophysics Observatory**, **SPHEREx**. |
| **H4RG-10** | 4096 x 4096 | 10 | 1, 4, 16, 32, 64 | 8 | Joint Miliarcsecond Pathfinder Survey (JMAPS), **Roman Space Telescope** |
| **H4RG-15** | 4096 x 4096 | 15 | 1, 4, 16, 32, 64 | 9 | U. Hawai'i, Gemini Observatory, Subaru, CFHT, **ESO (MOONS)**, PIANO (Aerospace instrument on the International Space Station) |

## HxRG Pixel Architecture
"Source follower"



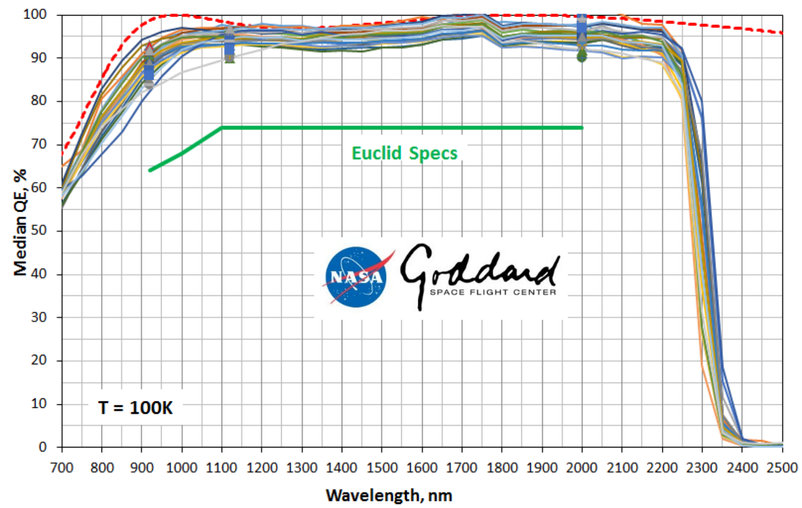

- Photocharge is integrated at the gate of the MOSFET, changing the voltage
- The output follows the voltage, hence this is called a "source follower" circuit

# Good Attributes of HxRG arrays

- **High Quantum Efficiency**
- **Low Dark Current**
- **Low Readout Noise**
- **Very low power**
- **Many pixels**:
  - 1, 4, or 16 million pixels per array (H1RG / H2RG / H4RG)
  - Mosaics up to 300 million pixels (Roman Space Telescope)

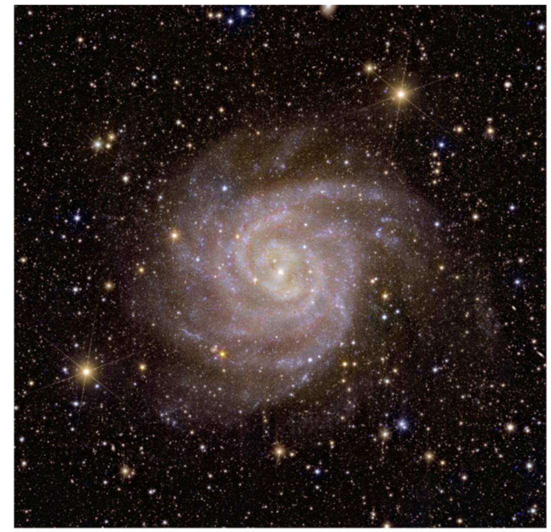
# Teledyne Visible and IR Detectors for Euclid

- Euclid is the ESA's flagship astronomy mission.
- Launched on July 1, 2023.
- 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 launched into space
- **24 flight candidate H2RGs delivered to NASA**
- **NASA tested and delivered 20 flight grade H2RG arrays to ESA, all of which greatly exceed requirements**



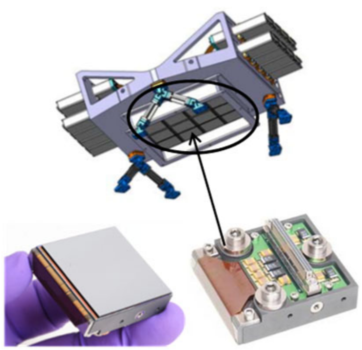

## Quantum Efficiency of 24 flight candidate H2RGs

**Measured by Goddard SFC Detector Characterization Laboratory**



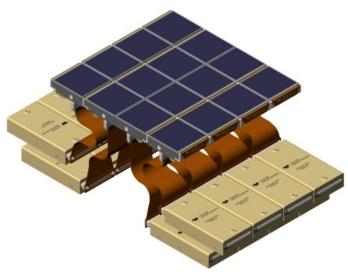
The "Hidden Galaxy" (IC 342)

- One hour observation
- 8800 x 8800 pixels
- Four bands of VIS and NISP data observed
- Three bands displayed:
  - 0.7 µm → blue
  - 1.1 µm → green
  - 1.7 µm → red



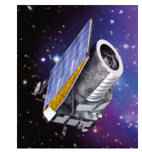
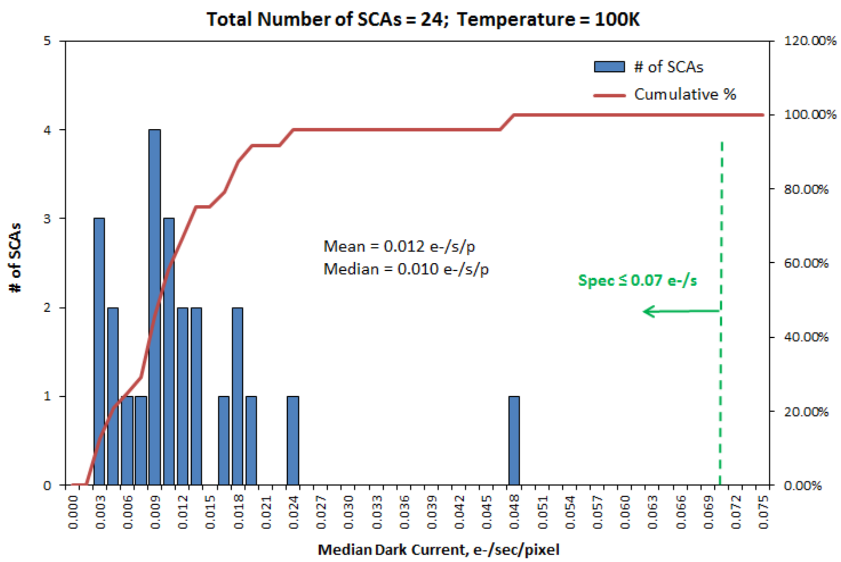
H2RG SCA (top view)

H2RG SCA (bottom view)



**H2RG**
**2K×2K pixels**
**18µm pitch**

# H2RG IR Detectors for Euclid

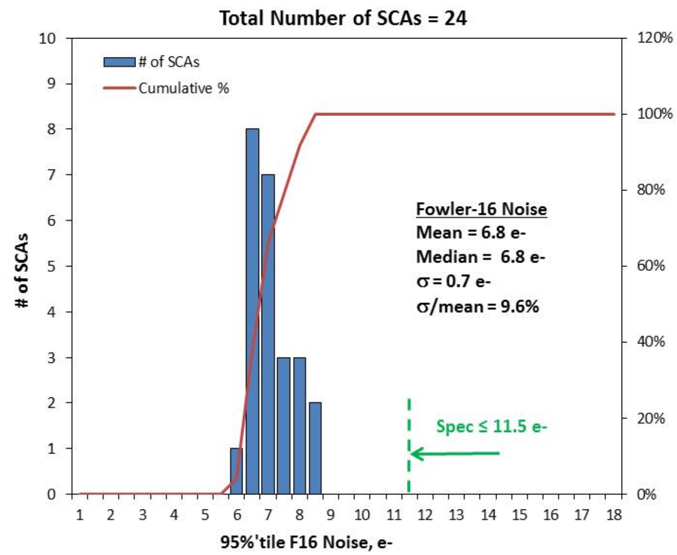




**Dark Current at 100K**

**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-**

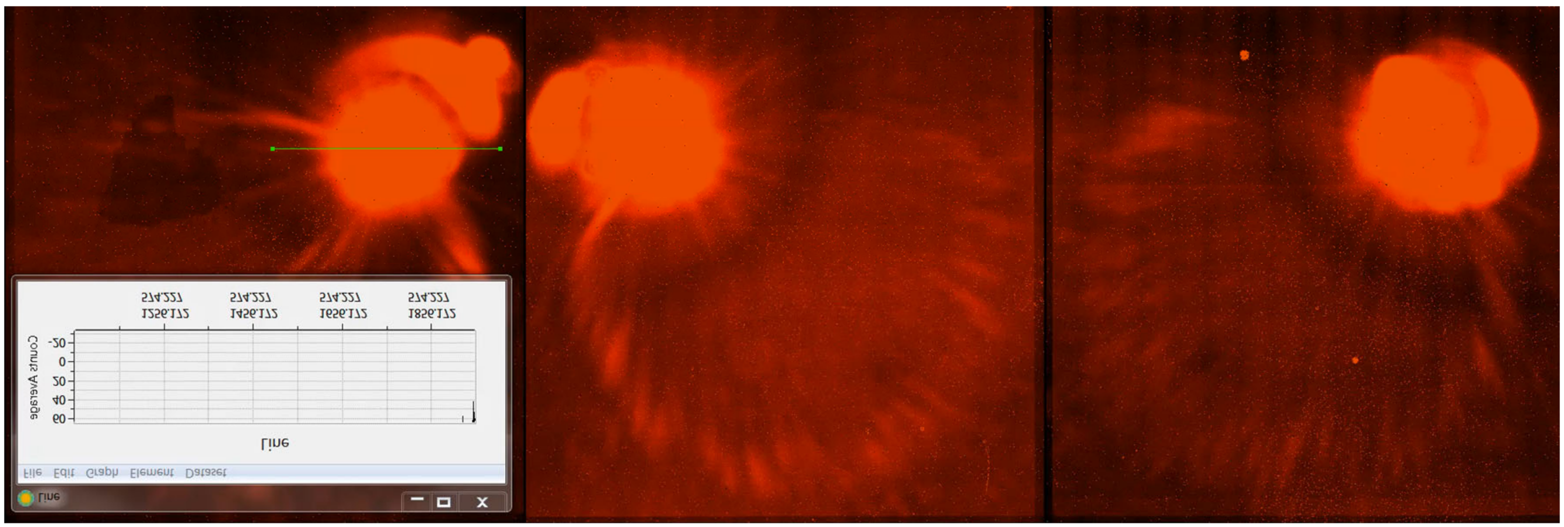
**40% better than specification (11.5 e-)**

# Imperfections of HxRG arrays

| | |
|---|---|
| **1. Persistence** | Memory (afterglow) of previous image<br>Bright calibration frames can cause big problems |
| **2. Inter-Pixel Capacitance** | Electrical crosstalk |
| **3. Brighter-fatter effect** | Intensity-dependent Point Spread Function (PSF) |
| **4. Non-linearity** | For highest precision, must correct each pixel |
| **5. Charge diffusion** | Pixel PSF is not ideal top-hat function |
| **6. Cross Hatching** | Intra-pixel QE variation |
| **7. Bad pixels / cosmetics** | Can dither to “fill in” bad pixels |
| **8. Epoxy voids** | Slight responsivity difference corrected by flat fielding |

# HxRG Imperfections: #1 Persistence

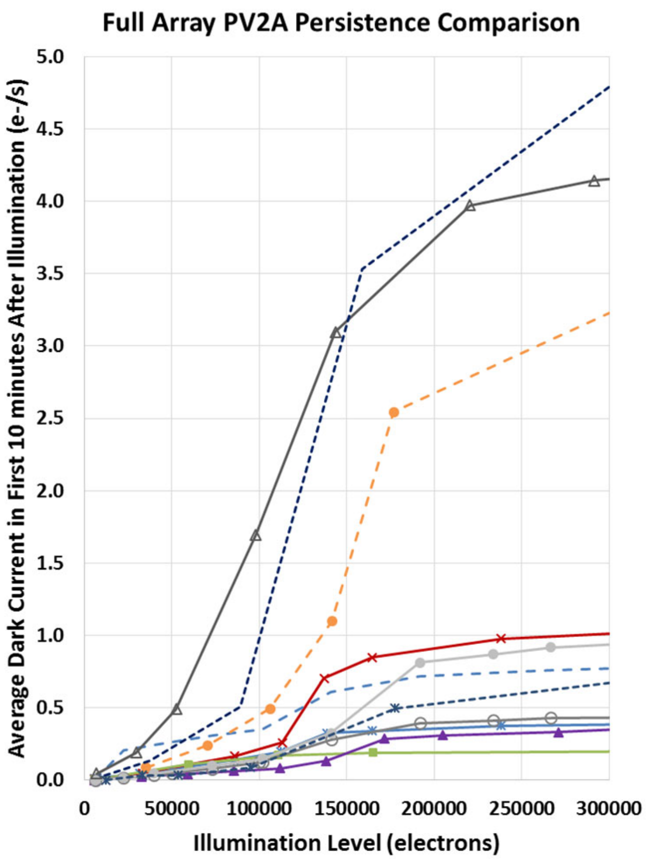
- European Southern Observatory CRIRES+ instrument has 3 MWIR H2RG arrays
- To demonstrate persistence:
  - CRIRES+ detectors exposed to an LED flash for a few milliseconds.
  - LED switched off and the detectors are read out with reset-read every 30 sec for a few minutes

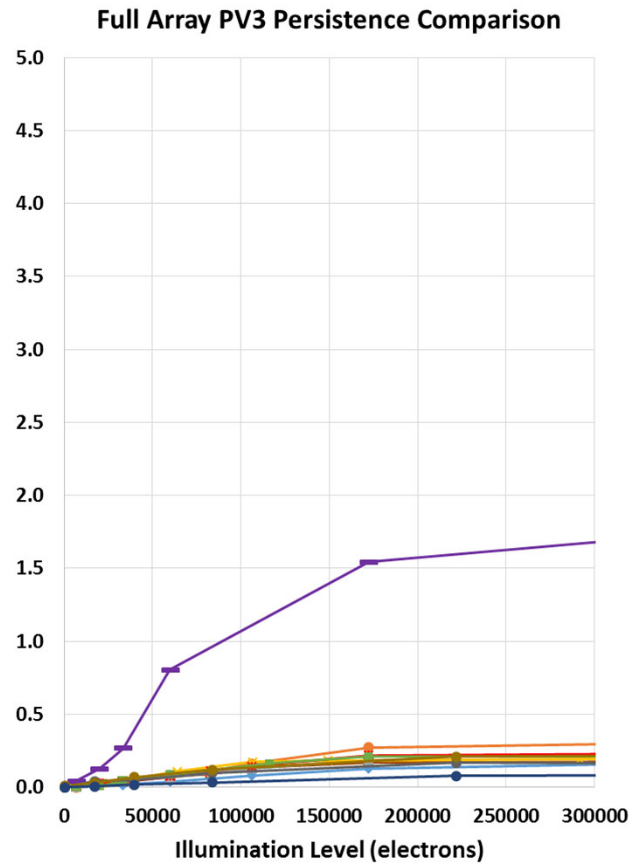


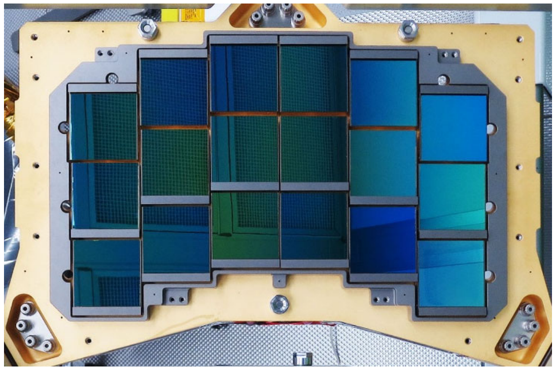
Courtesy of Derek Ives, European Southern Observatory

# HxRG Imperfections: #1 Persistence

**The Roman Space Telescope (RST) worked closely with Teledyne during 2014-2018 to develop a new passivation process (PV3) that has shown near zero persistence.**



- The low persistence process works
  - But has low yield, higher cost
- PV3 is not Teledyne's baseline process
  - Customers can request PV3 (the RST process) for custom production

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

# 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*

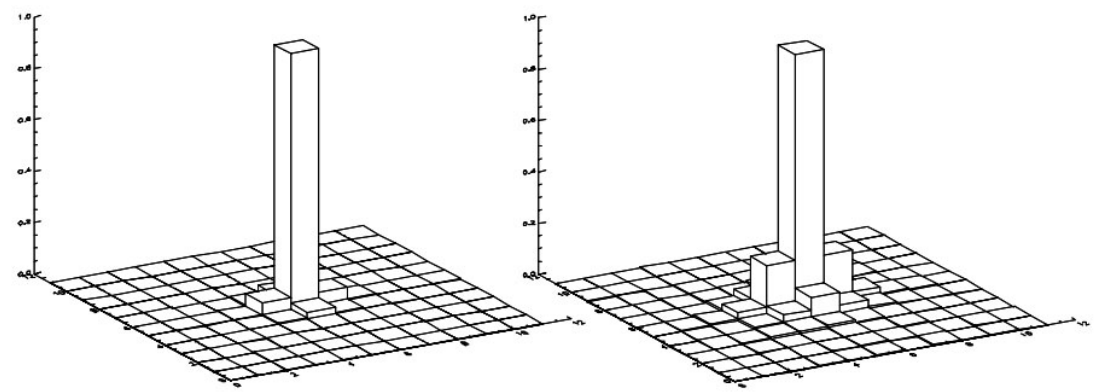
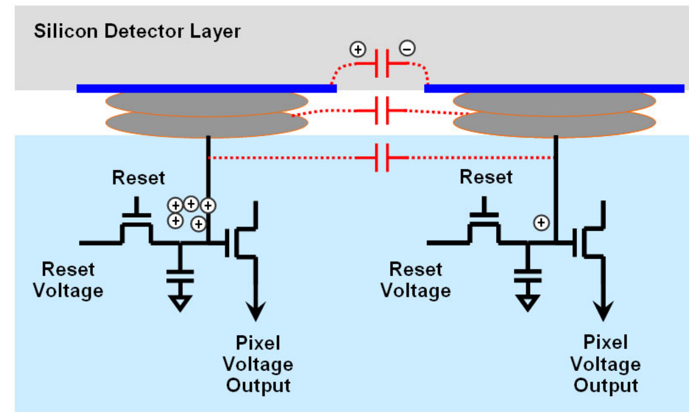


*Figure 10.* Autocorrelation of CMOS Hawaii-2RG hybrid arrays. Left: $\lambda_c$=2.5 µm HgCdTe array, φ=1.23. Right: Si-PIN HyViSI array, φ=2.03.

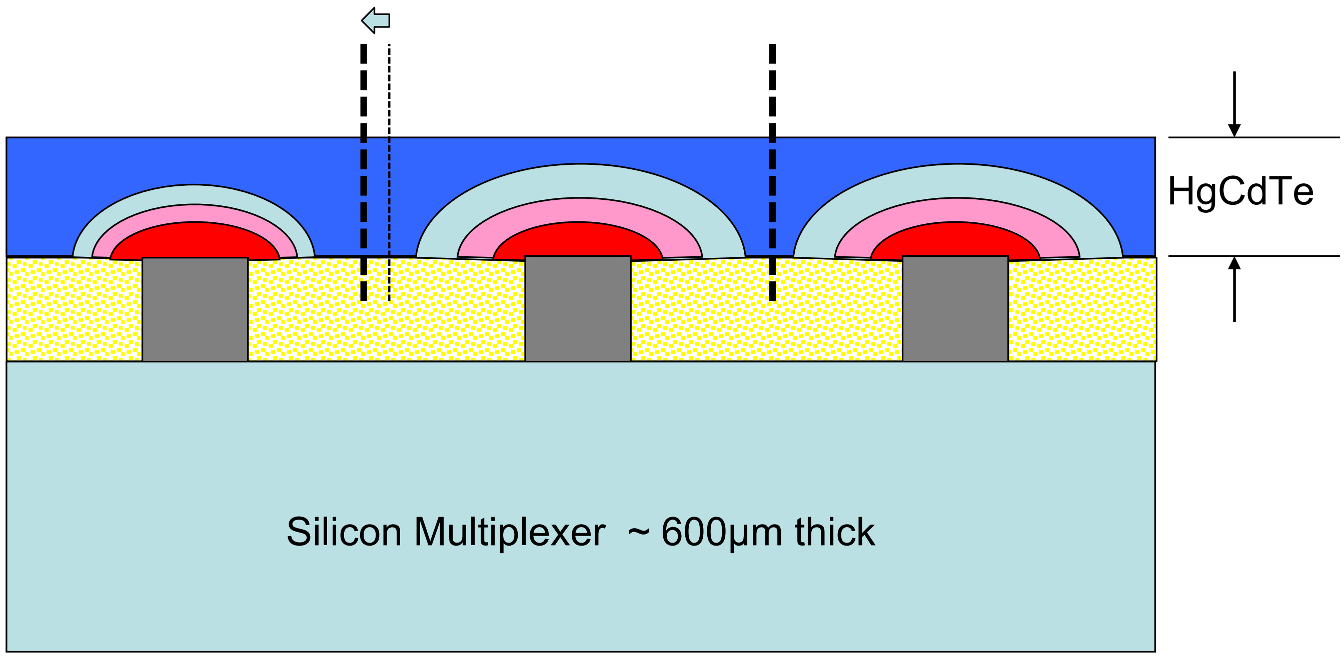



IPC can be de-convolved

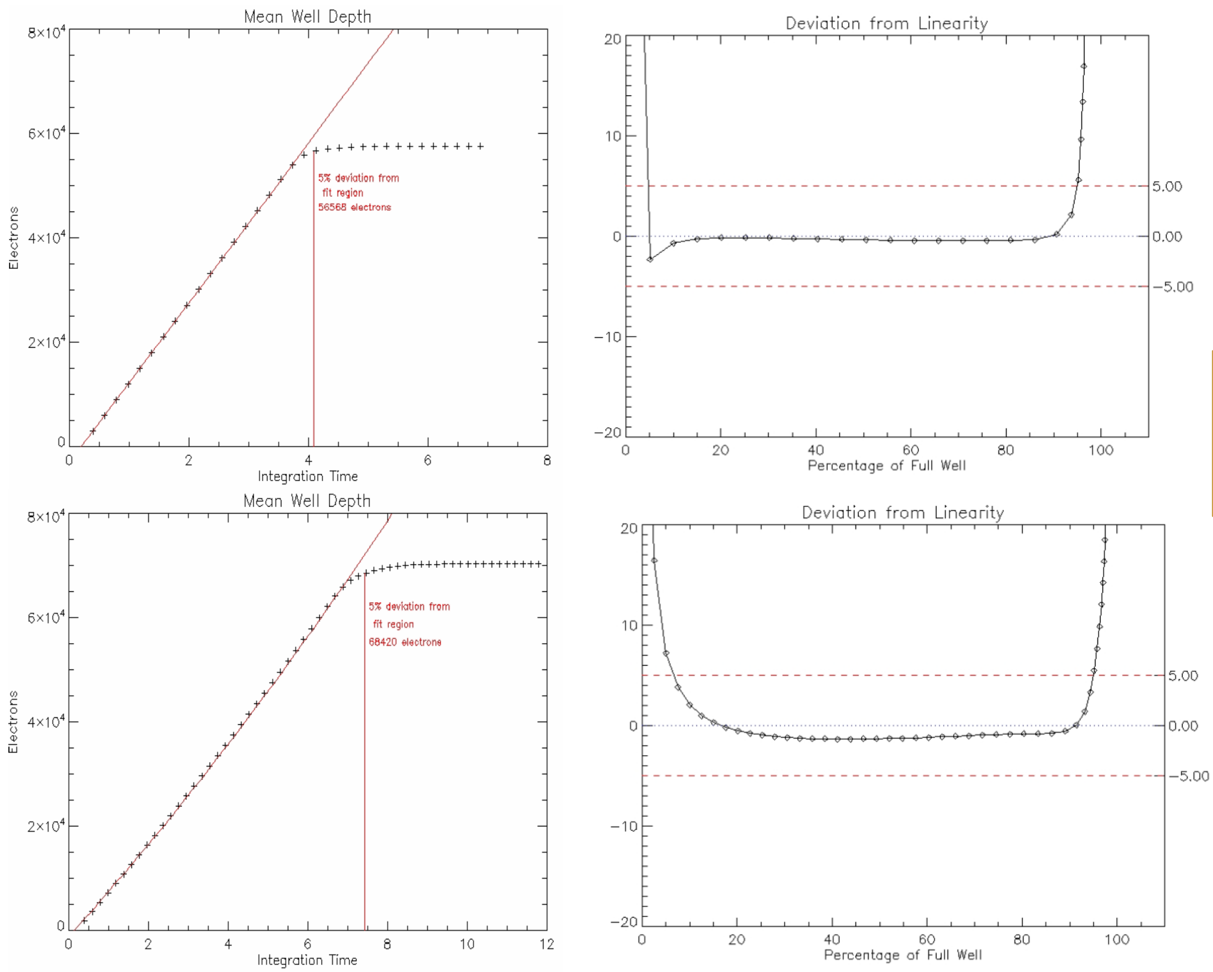
# HxRG Imperfections: #3 “Brighter-fatter” effect

Figure courtesy of Roger Smith, Caltech

Pixel grows as charge accumulates so the point spread function (PSF) may be flux dependent



# HxRG Imperfections: #4 Non-linearity (of source follower pixel)

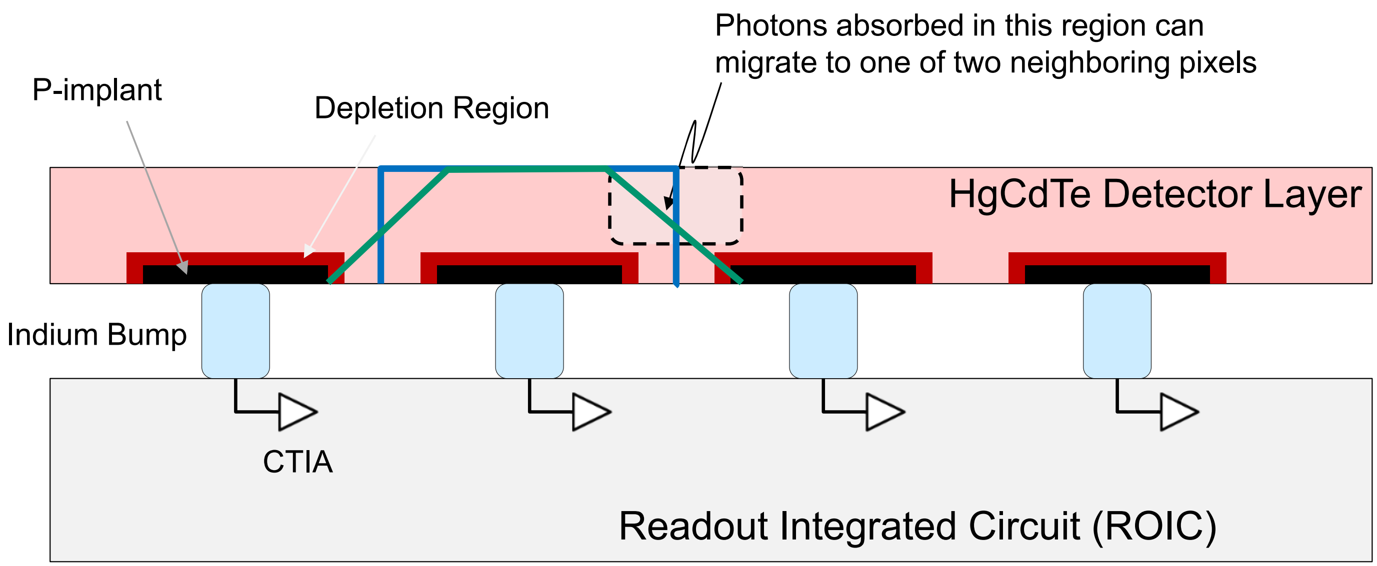



Full well defined as 5% variation from linear response

- Can correct for non-linearity at the pixel level.
- “Computationally intensive but required”

Examples from H1RG MWIR testing

# HxRG Imperfections: #5 Charge Diffusion




**Ideal pixel response ("top-hat" function)**

**Charge diffusion function**

# HxRG Imperfections: #6 Cross Hatching

- Cross hatching is an intra-pixel effect and very hard (impossible?) to correct with post-detection image processing.
- Need to find and fix the root cause.

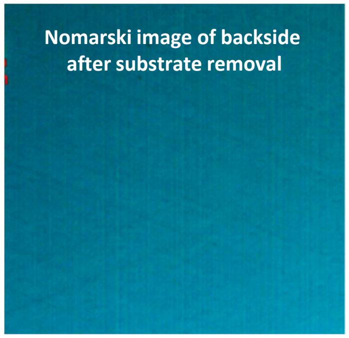
- Light from one pixel is diffracted to neighboring pixels
  - 0.2% to 0.5% QE variation of flat field illumination
- Less QE variation for longer wavelengths

- Cross hatching observed in QE map is believed to be correlated with detector material morphology
- We believe we understand the physical mechanisms governing the morphology and can control it to an impactful degree
- Process developments are underway, full focal plane array testing has not yet started

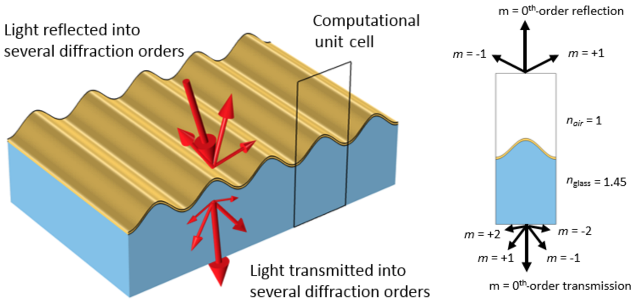
Demonstration of detector material morphology control (as-grown surface)



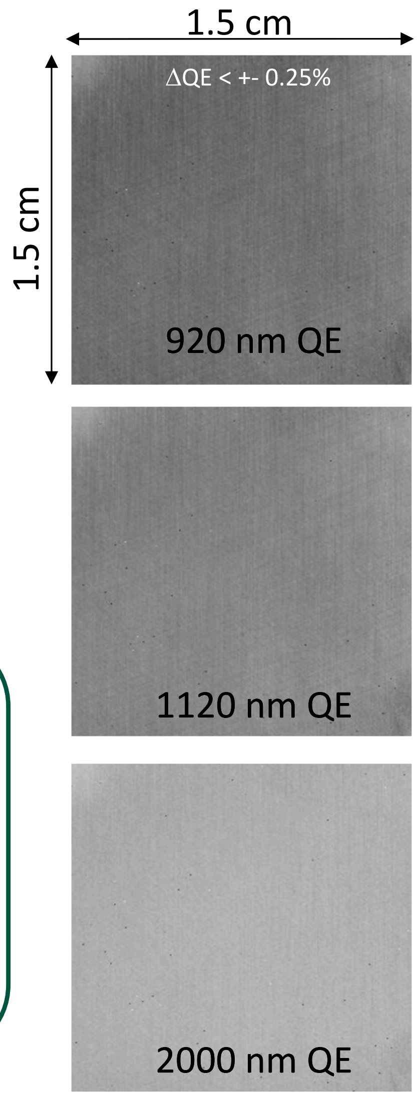
- Optical microscopy images are presented in false color and with increased saturation to help the viewer distinguish surface cross hatch.




Cross hatching features are smaller than pixel dimension




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

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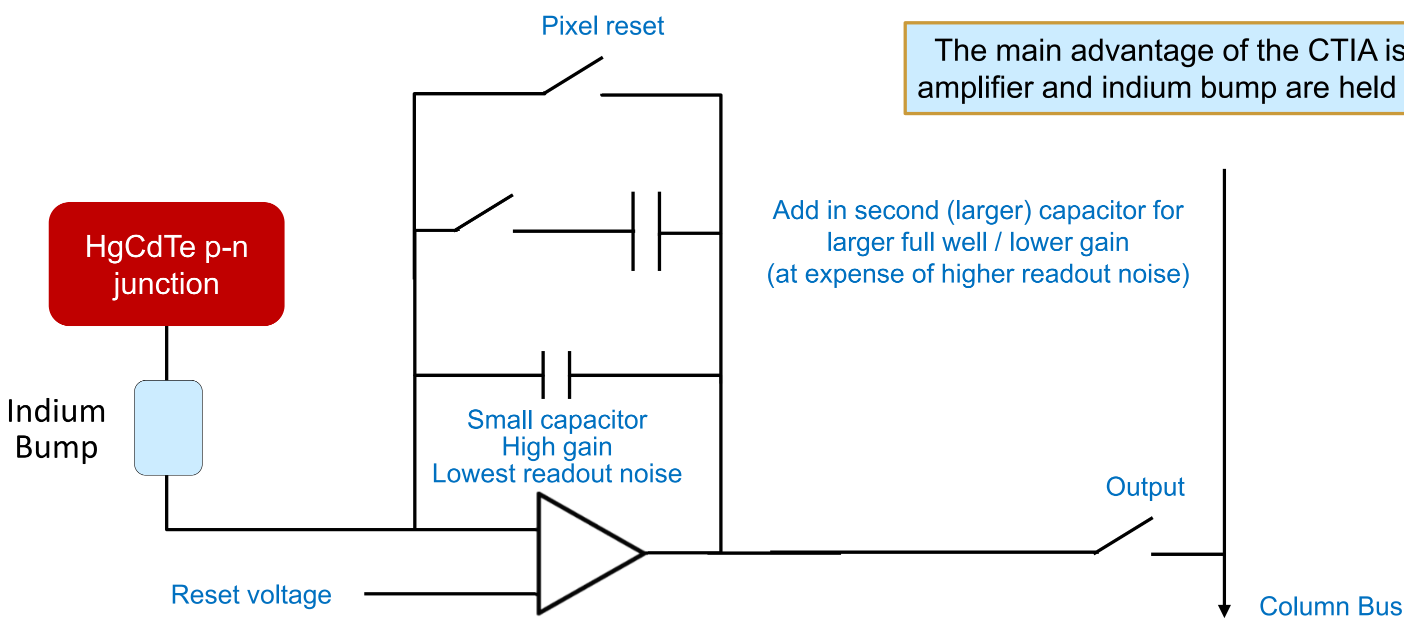
# Making a higher precision focal plane array (FPA) starts with the Pixel

## Better to use a Capacitive TransImpedance Amplifier (CTIA)




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

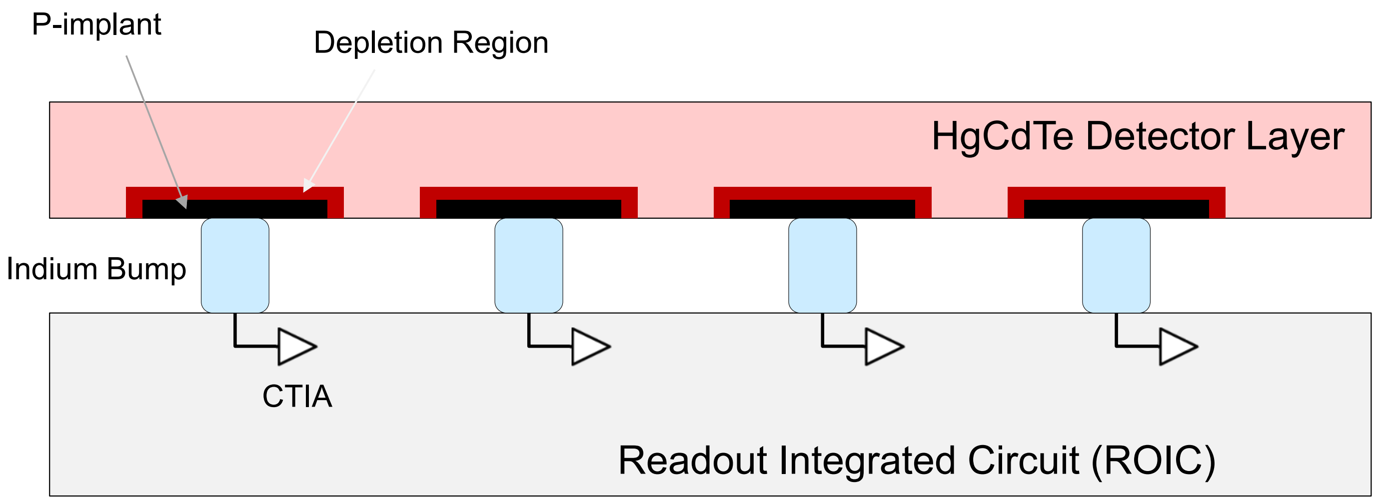
No correlated double sampling (CDS) in this circuit

- For high frame rate operation, such as Earth Observation, CDS is usually included in the pixel.
- Since in-pixel CDS adds circuitry and increases noise, in-pixel CDS not be optimal for an 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:

- CTIA must always stay on, so higher power
- Ensuring no ROIC glow
- Achieving low readout noise

# CTIA addresses Persistence, IPC, Brighter-fatter effect




- The input gate to all CTIAs are held at the reset voltage during operation (image integration).
- The depletion region stays constant, with no de-biasing and biasing of trap states.
  - This will **eliminate persistence.**
- **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.

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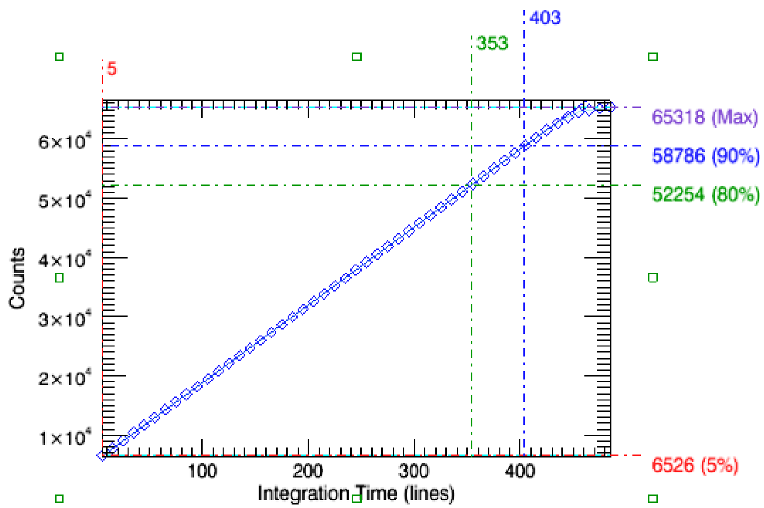
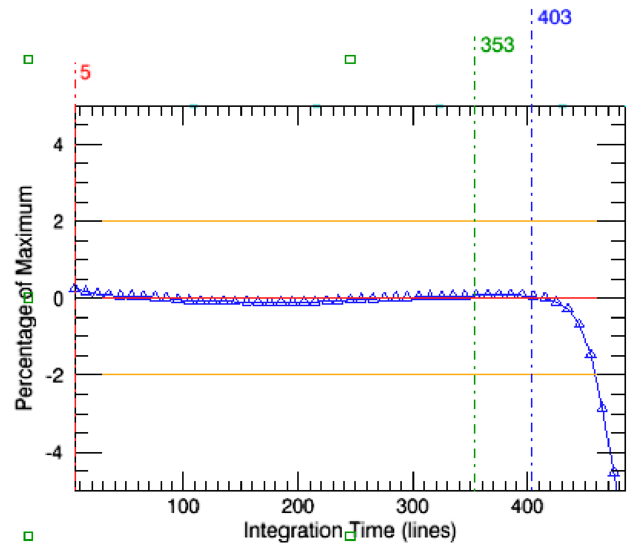
# CTIA is highly linear – better than 99.9%

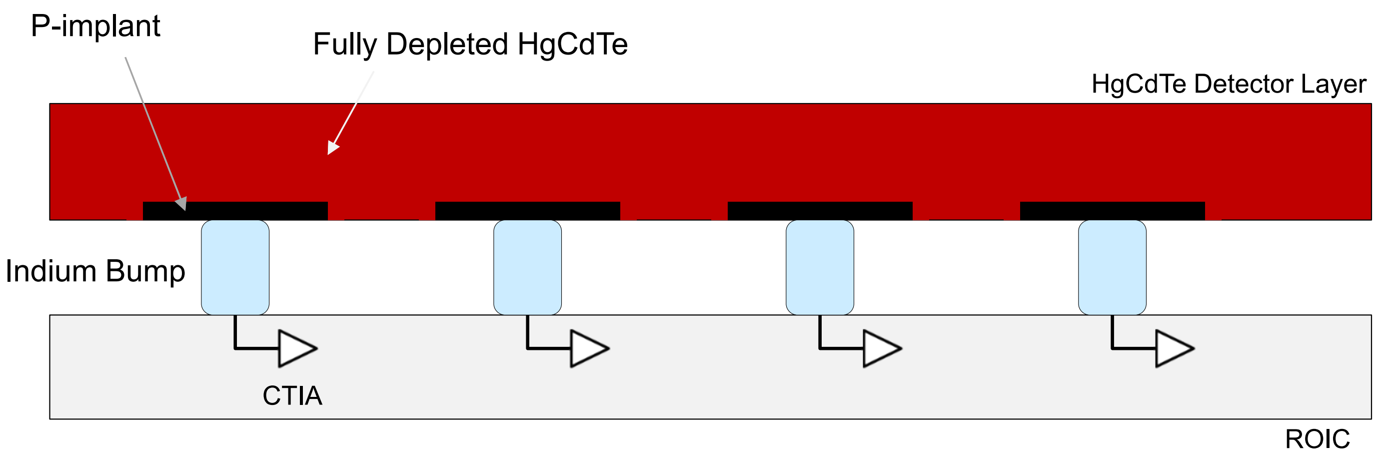


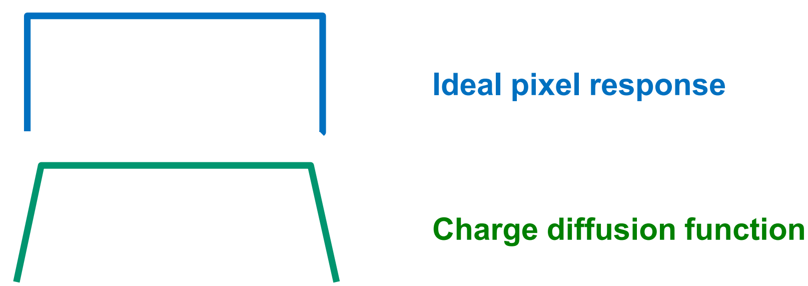




Example from testing of a CHROMA-A CTIA pixel

# Optimizing the HgCdTe detector layer

- **Eliminate / minimize cross hatching** with improved growth / processing
- Use low trap passivation process (PV3) developed for RST to reduce persistence (if using HxRG)
- **Minimize charge diffusion** by fully depleting detector layer
  - Charge diffusion function becomes close to an ideal top-hat function

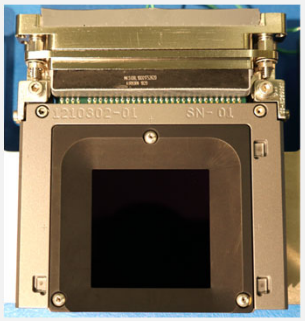


# An optimized CTIA + better HgCdTe detector can be a nearly ideal focal plane array

- **Use Capacitive TransImpedance Amplifier (CTIA) pixel**
  - Eliminates:
    - Persistence
    - Inter-pixel capacitance
    - 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 low trap process (PV3) to reduce persistence (if using an HxRG readout circuit)
- **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 (for HxRG arrays)

# GeoSnap Focal Plane Arrays Use the CTIA Pixel



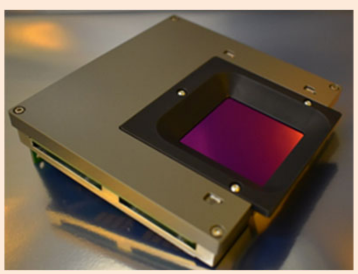
**GeoSnap-18 2K × 2K**
**Focal Plane Module**

## GeoSnap-18

**2K×2K is TRL-9**
Operating in Space

- 18-micron pixel pitch
- **CTIA unit cell** with 2 gains / full well (180 ke- and 2.7 Me-)
- 1K × 512-pixel stitch block, can fabricate up to 3K × 3K pixels
- Snapshot, integrate while read
- Fully digital chip, 14-bit ADCs
- Full frame rate: 100 Hz for 2K × 2K, 250 Hz for 3K × 512
- ROIC formats fabricated: 1K × 512, 2K × 512, 2K × 2K, 3K × 512
- Focal plane arrays made and tested with several types of detectors:
  - Silicon (VNIR) & HgCdTe for SWIR (2.5 µm), MWIR (5.3 µm), VLWIR (14.5 µm)

VLWIR GeoSnap-18 2K×2K FPM delivered to the European Southern Observatory for the ELT METIS instrument



**GeoSnap-10 4K × 4K**
**Focal Plane Module**

## GeoSnap-10

**4K×4K is TRL-9**
Operating in Space

- 10-micron pixel pitch
- **CTIA unit cell** with 2 gains / full well (120 ke- and 1.2 Me-)
- 2K × 1K-pixel stitch block
- Snapshot, integrate while read or integrate then read
- Fully digital chip, 14-bit ADCs
- Full frame rate: 60 Hz for 4K × 4K
- Focal plane arrays made and tested with HgCdTe detectors:
  - SWIR (2.5 µm), S/MWIR (3.8 µm), MWIR (5.3 µm)

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# Reserve your calendars!
# Scientific Detector Workshop 2025 (SDW2025)
## 6 – 10 October 2025
### Canberra, Australia

**A workshop for the scientists and engineers who develop, produce, implement, and operate the most advanced imaging sensors used in scientific instrumentation:**

- **Talks from leading experts in science, instrumentation, and imaging sensors**
- **Extensive time for discussions & interactive roundtables**
- **Group activities include numerous social and cultural events**

**Hosted by the Australian National University (ANU)**


**Activities include tour and dinner at Mt. Stromlo Observatory**

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