Introduction to WFIRST H4RG-10 Detector Arrays

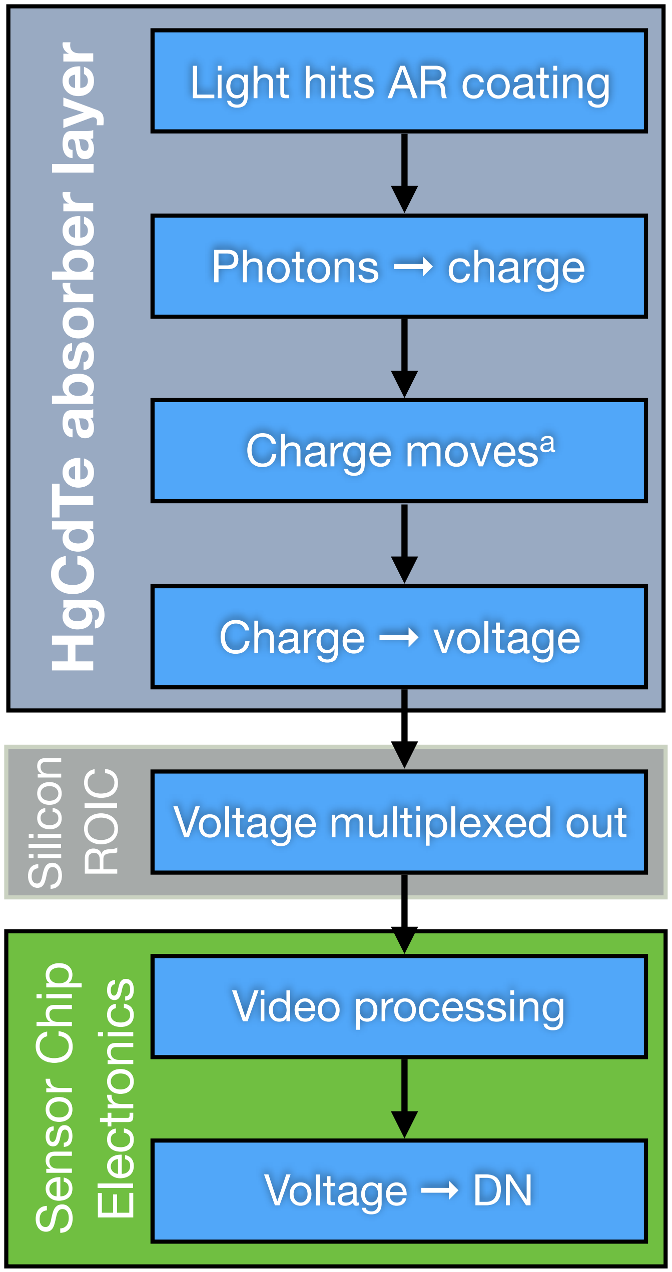
Bernard J. Rauscher
for the Goddard WFIRST Study Team

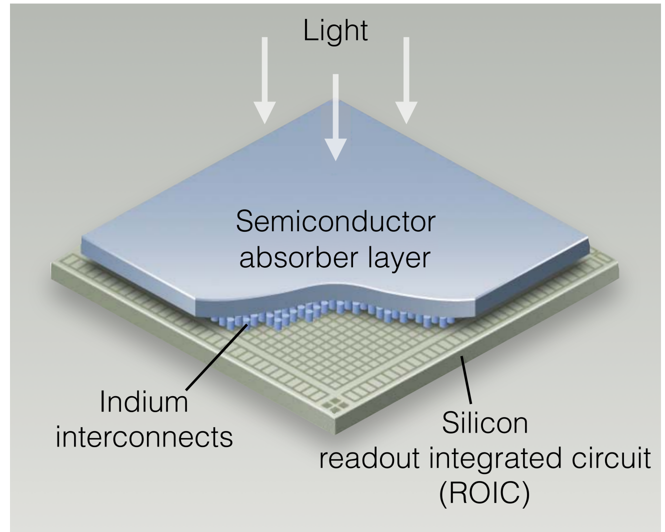
NASA Goddard Space Flight Center, Greenbelt, MD, USA

(Bernard.J.Rauscher@nasa.gov)

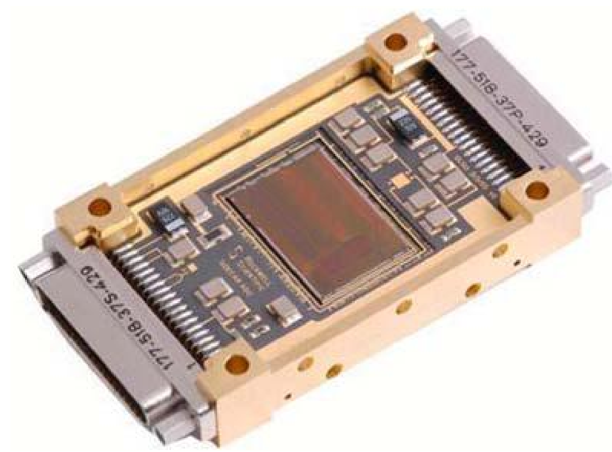
Presented at WFIRST Formulation Science Working Group Meeting #1, 2-5 February 2016, Maritime Institute - 692 Maritime Blvd, Linthicum Heights, MD 21090

Steps of WFIRST IR detection





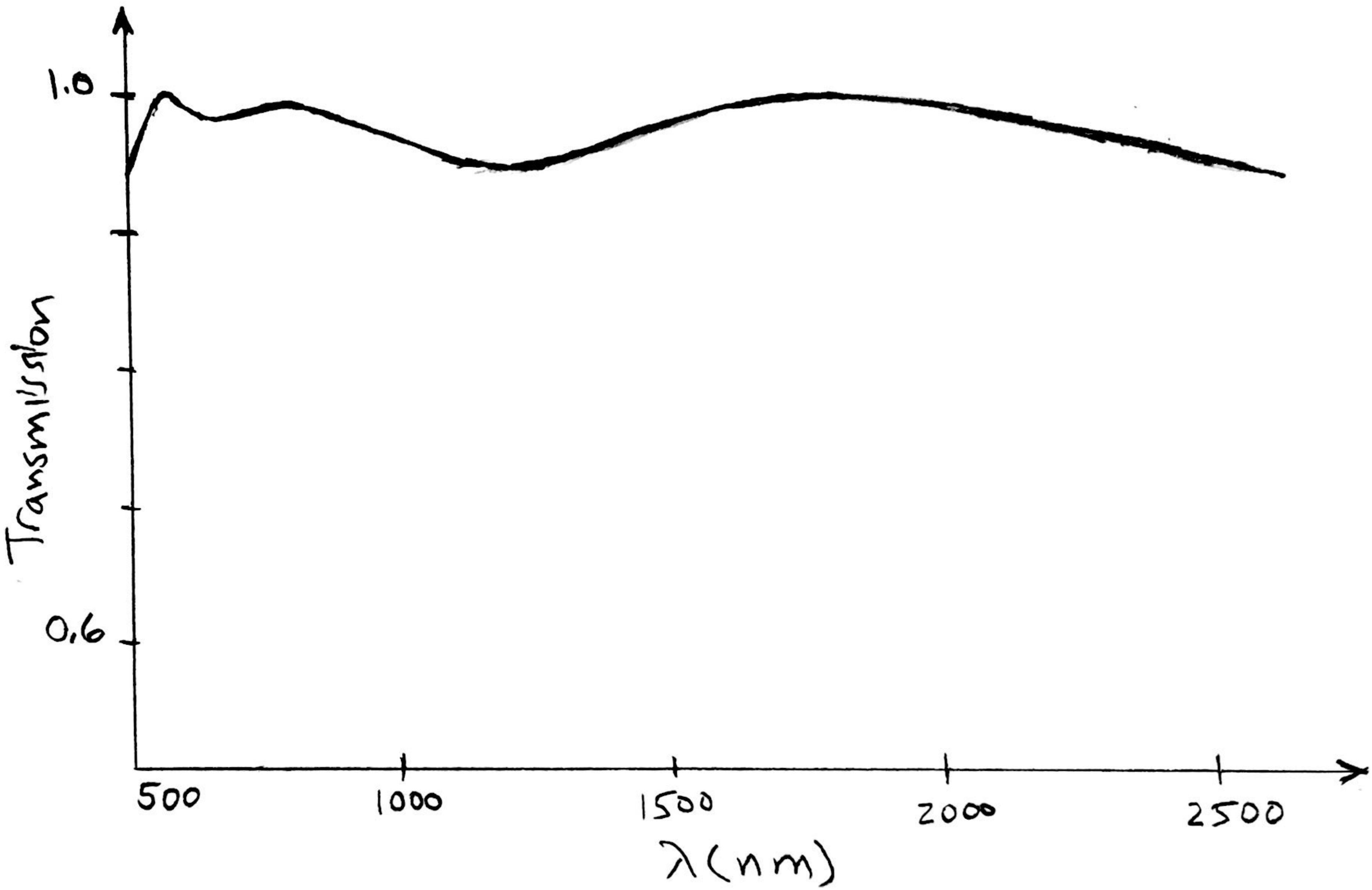
WFIRST's H4RG-10s are hybrid near-IR detector arrays. Light is collected in an HgCdTe absorber layer. The absorber layer is "hybridized" to the silicon readout integrated circuit (ROIC) using indium bonds to establish electrical contact. There is one indium bond per pixel. The absorber layer and ROIC are fabricated separately using processes that are optimized for each material. *Credit: Based upon a similar figure by Jim Beletic of Teledyne Imaging Sensors.*



JWST's SIDECAR ASIC is one example of sensor chip electronics (SCE). *Figure credit: Rauscher, B.J. et al. 2007, Proc SPIE, 6690, 19–66900M–10*

[a]Charge moves, but completely unlike in a CCD. See following charts.

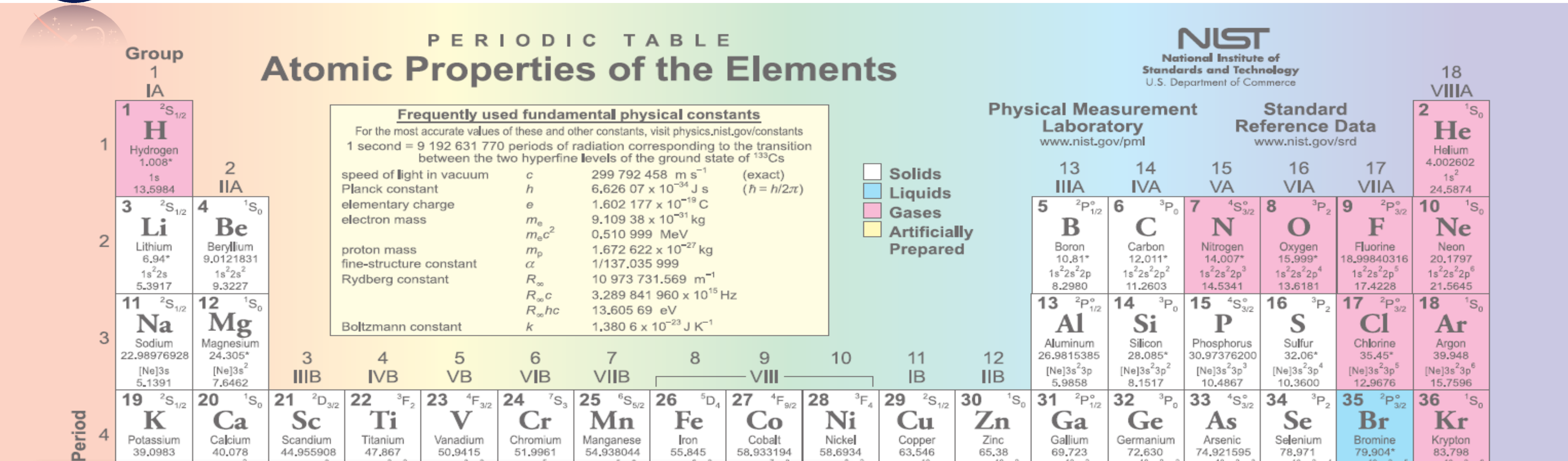
The AR coating has bumps and wiggles



Cartoon AR coating for 2.5 µm cutoff HgCdTe

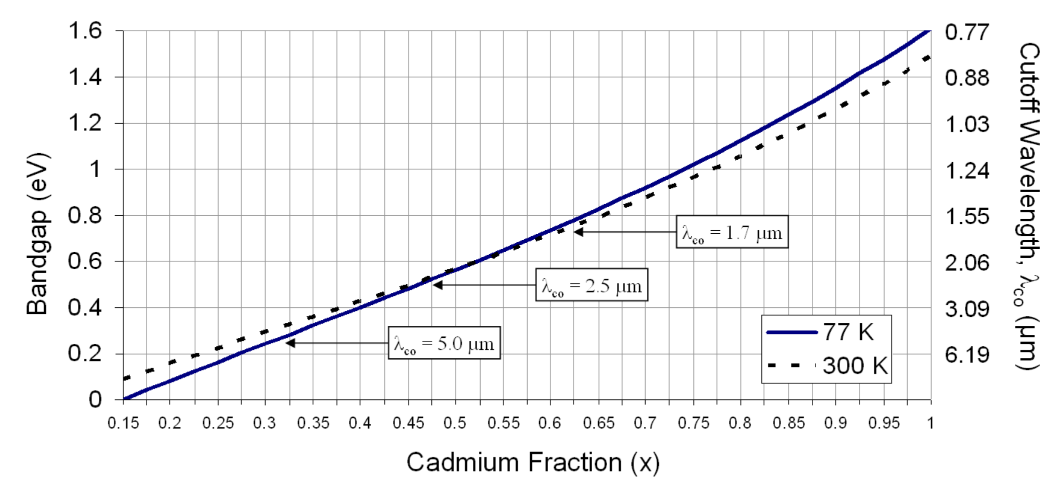
HgCdTe absorber layer has tunable bandgap

Used to set cutoff, but also to grow in electric fields via grading the mole fraction of cadmium vs position



Tunable Cutoff Wavelength

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



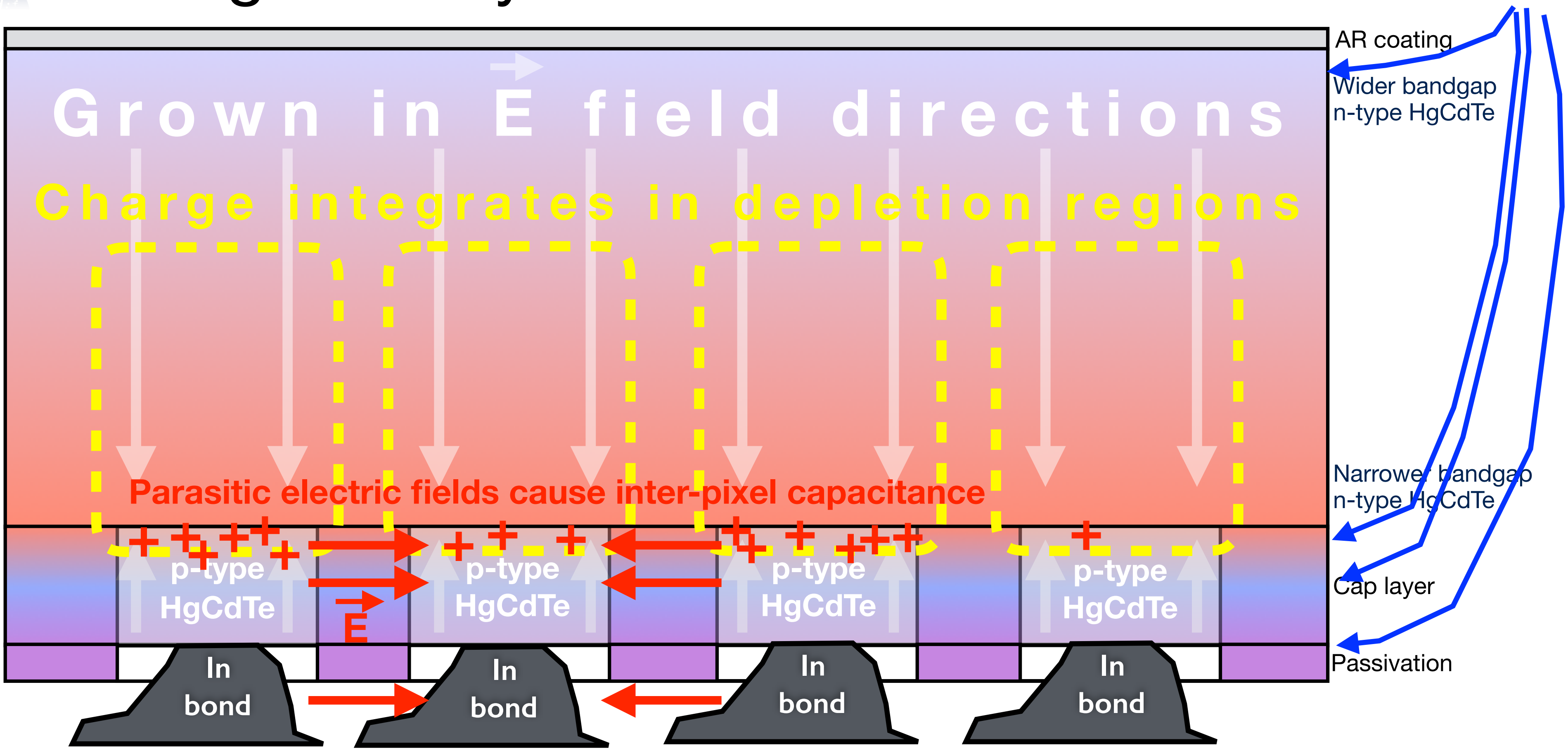
Bandgap and cutoff wavelength of $Hg_{1-x}Cd_xTe$ as a function of cadmium fraction, *x*. *Credit: Beletic, J. et al. 2008, Proc SPIE, 7021, 70210H–70210H–14.*

Lattice spacing depends upon *x*. Grading bandgap builds in stress. Stress relieves creating dislocation defects. Some dislocation defects become charge traps (more later).

HgCdTe is a II-VI semiconductor

Idealized composition of the HgCdTe layer

Comparatively high defect density where:
(1) near surfaces and/or
(2) HgCdTe composition graded strongly

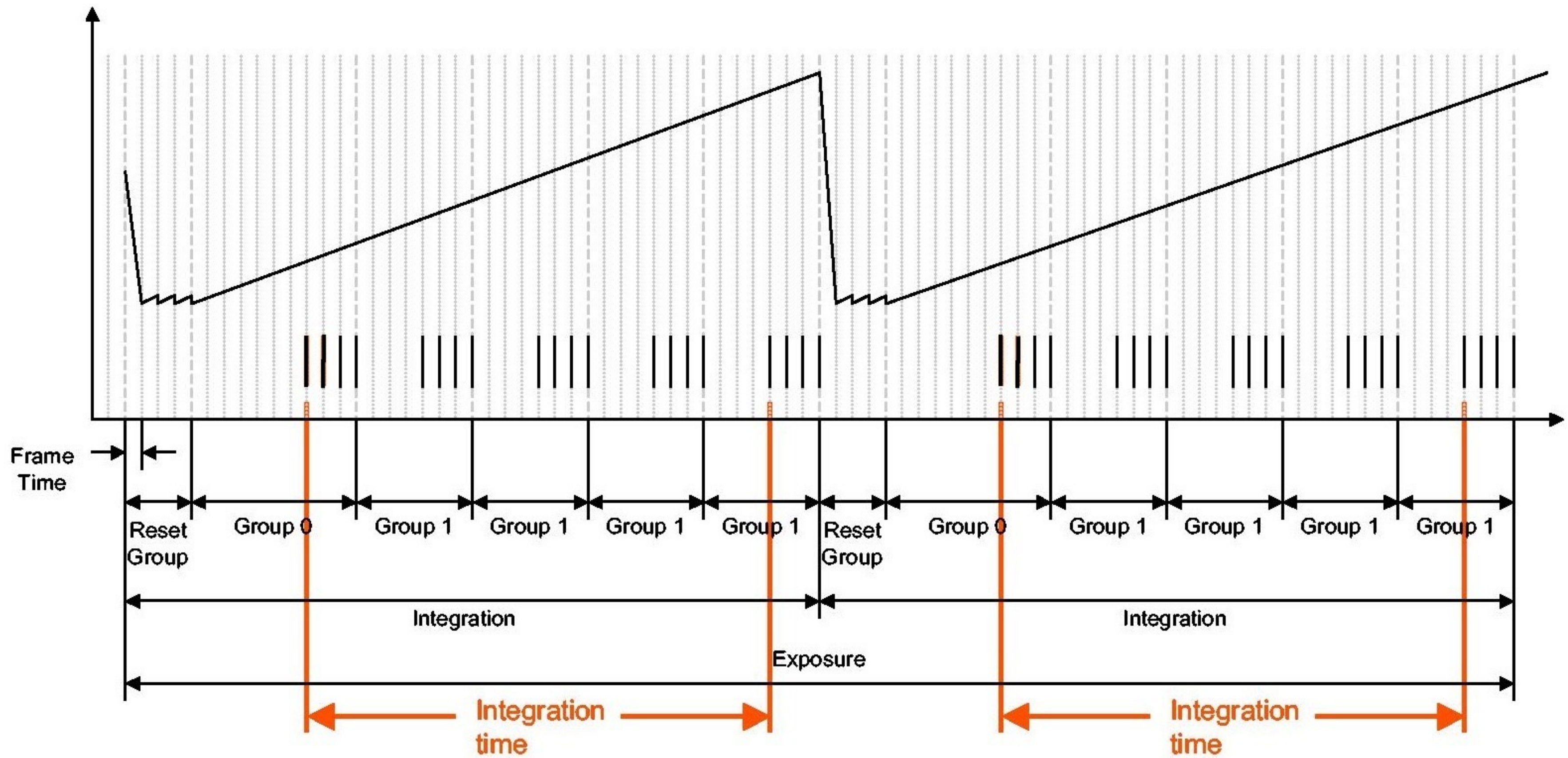


- Unlike in a CCD, charge is never deliberately moved between pixels
- Charge integrates in each pixel, where it is read out. Possible to read many times before resetting. Has important benefits for read noise and cosmic ray mitigation

Not all pixel structure is shown. This cartoon has been simplified to show the most salient features

Example of multiple non-destructive reads

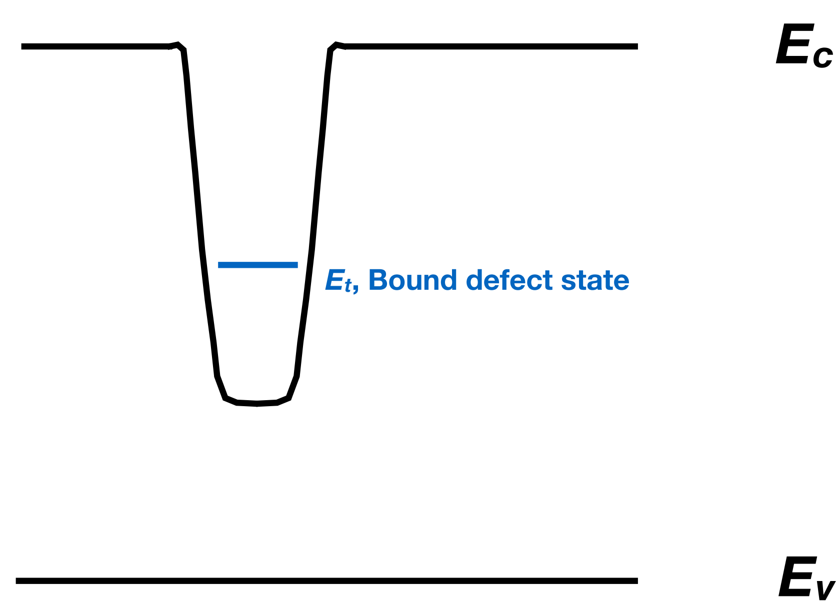
JWST Implementation of Multiple Non-Destructive Reads



- Frame Time
  - Tframe : Time to digitize all pixels in a rectangular area (full frame or subarray)
- Reset Group
  - Nreset : 0 or more Reset Frames (4 in this example)
- Group 0
  - Nidle0 : 0 or more Idle Frames (8 in this example)
  - Noutput0 : 0 or more Output Frames (4 in this example)
- Group 1
  - Nidle1 : 0 or more Idle Frames (3 in this example)
  - Noutputs1 : 0 or more Output Frames (4 in this example)
- 0 or more Groups per Integration (6 in this example)
  - 0 or 1 Reset Group cycles (1 in this example)
  - 0 or 1 Group 0 cycles (1 in this example)
  - Ngroup1 : 0 or more Group 1 cycles (4 in this example)
- 1 or more Integrations per Exposure (2 in this example)
  - Nint

Charge traps

- Electrically active defect states (AKA “traps”) can cause many things we don’t like!
  - Dark current
  - QE loss
  - Persistence
  - Reciprocity failure
- Expect high trap density near surfaces, implant sites, and where HgCdTe composition is strongly graded, *i.e.*
  - Cap layer and under frontside passivation
  - Backside passivation under AR coating
  - Contacts



- **Expect to hear a lot about charge traps when discussing persistence and reciprocity failure!**
- **Process/design maturity matters! Might expect lower defect density than in HST/WFC3. About the same as in JWST and Euclid**
- **Temperature matters! Traps will be thermally activated vs JWST. Likely similar to WFC3**

Image spreading in H4RG-10

- Charge can move from one pixel to another after charge generation but before being collected
  - Known as **charge diffusion**
- Parasitic capacitance can cause charge to appear in a neighbor, although the charge never actually moves
  - Known as **inter pixel capacitance (IPC)**
- Other mechanisms exist. For example, "open pixels" are the result of a missing indium bond

Charge diffusion[a]

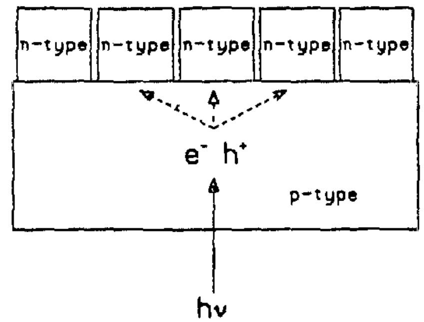
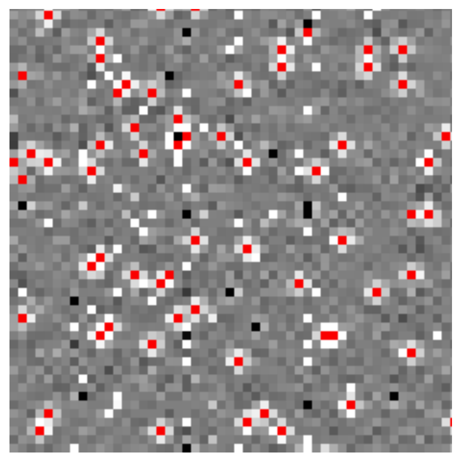


FIG. 1. Schematic cross section of a closely spaced photodiode array showing diffusional spread of photo-generated electron-hole pairs.

Credit: Holloway. 1986, J Appl Phys, 60, 1091–1096

Open Pixels



When an indium bond is either not present or fails, charge integrates in neighboring pixels. Something similar can be expected when a pixel hard saturates.

IPC

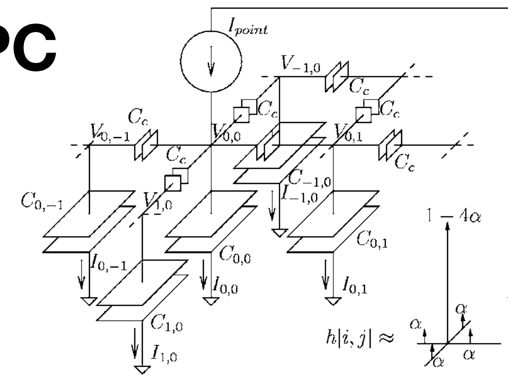


Fig. 1 Photocurrent physically entering a detector node may leave the node as displacement current through small coupling capacitors (labeled C_c) and appear on adjacent nodes instead. Even if all quanta are captured by the central C_{00}, the signal still appears on neighboring nodes that have captured no quanta.

Credit: Moore, Ninkov & Forrest. 2006, Optical Engineering, 45, 076402

[a]Holloway's model is for a n-on-p HgCdTe design. WFIRST uses p-on-n. The equations are similar either way.

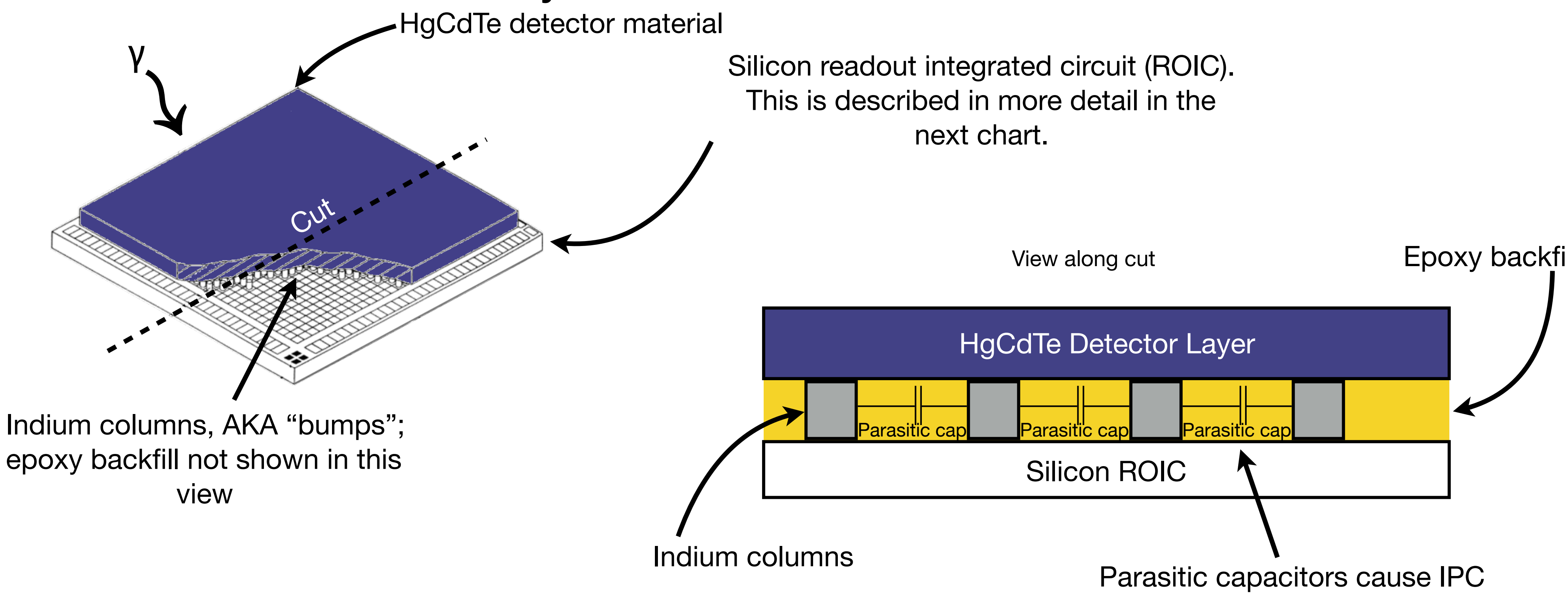
Compare and Contrast

	HST/WFC3	JWST NIRCam (short wave)	WFIRST
Teledyne Detector type	H1R	H2RG	H4RG-10
Format	1024x1024	2048x2048	4096x4096
Pixel Size	18 µm	18 µm	10 µm
Cutoff wavelength	1.7 µm	2.5 µm	2.4 µm (TBC)
Operating temperature	145 K	~40 K	~100 K

Backup charts

What is IPC?

- Inter-pixel capacitance (IPC) is the small, parasitic capacitance, that is found between pixels in an infrared array detector



<u>A few handy references</u>

1. Moore, A. C., Ninkov, Z. & Forrest, W. J. 2006, Optical Engineering, 45, 076402 describes the statistics in detail from a Fourier perspective

2. Fox, O., Waczynski, A., Wen, Y., et al. 2009, PASP, 121, 743 arrives at many of the same results working in the pixel domain

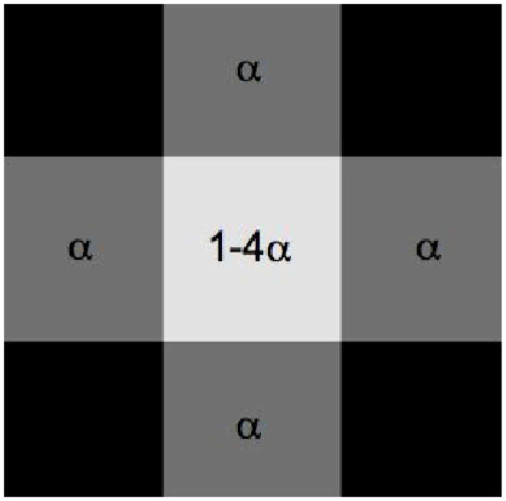
What does the ROIC do?

- Readout is completely different from a CCD
- Charge never leaves the pixel that it is collected in. The ROIC senses voltage in place, and multiplexes the small signals from several million pixels to a few analog outputs for further processing by separate readout electronics
  - The ROIC is just a silicon integrated circuit, albeit one that can operate at cryogenic temperatures
  - The ROIC is fabricated on a standard silicon wafer and uses CMOS components like field effect transistors to buffer and multiplex signals from pixels. The ROIC is also responsible for resetting pixels. The ROIC has no "smarts", these are provided by a separate "controller", of which the SIDECAR ASIC is one example
- In astronomy near-IR arrays like Teledyne's H2RG and H4RG, each pixel has a simple, dedicated, first amplifier in the ROIC[b]
  - Voltages created before this first pixel amplifier in the ROIC can cause IPC

[a]In jargon, this is a "source follower per detector" architecture

How does IPC affect images?

- Most obvious effect is blurring of collected light and hot pixels by a small kernel (more sophisticated kernels are possible, see Ref. 2)



(a) Symmetric PSF

"IPC-alpha" is typically of order 1% in an H2RG detector array. IPC-alpha be an adjustable parameter because its value is detector specific.

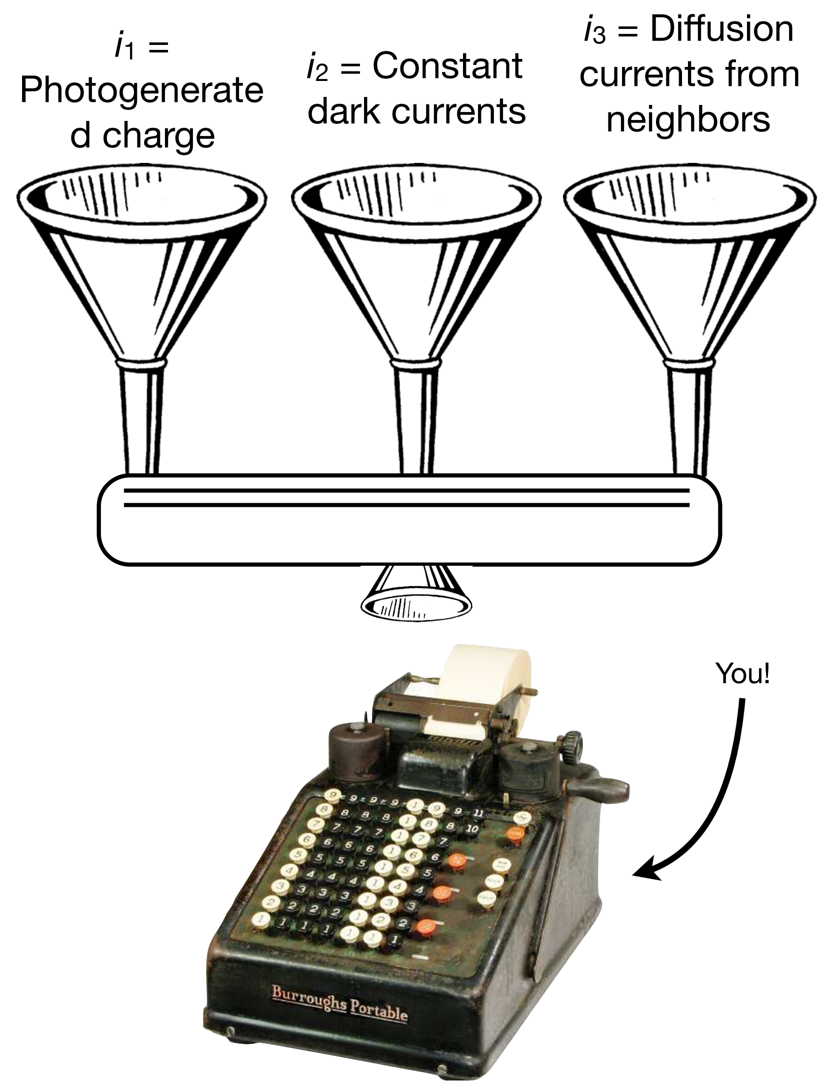
- Only signals that appear before the first amplifier in the ROIC get blurred
  - Collected light gets blurred
  - Hot pixels get blurred
- Read noise, some of which enters later in the detection process, is more complicated
  - Only some of the read noise gets blurred by IPC

How does IPC differ from charge diffusion?

- In IPC, the charge stays in the pixel where the photon was absorbed. It only appears to be in a neighbor because voltage, not charge, is sensed and voltages can suffer crosstalk
- In charge diffusion, the charge physically moves and is collected in a neighboring pixel; it is one component of the overall photonic current that gets integrated
- Importantly, the covariance matrices are different
  - For charge diffusion, the covariance matrix is diagonal
  - For IPC, the covariance matrix is not diagonal

Why doesn't charge diffusion create off-diagonal covariance?

- Charge diffusion happens in the charge domain
- Imagine that you are a pixel, and that you are doing a classical counting experiment (see right)
- For our counting experiment, we know that the variance in the counts is equal to the number of counts
- All of the variance is therefore accounted for by the diagonal (variance) elements, and no off-diagonal covariance is needed
- Can I still simulate this by blurring with a kernel?
  - Yes, but it has to be done at the right time…
  - OK to blur theoretical input image, or
  - OK to drop photons in one-by-one and model diffusion of individual charges, but
  - NOT OK to integrate a scene in the detector and blur the result as this introduces unrealistic covariance for the charge diffusion process (the resulting covariance looks like IPC, not charge diffusion)



$$\text{Signal} = (i_1 + i_2 + i_3)\, t$$

$$\text{Noise} = \sqrt{(i_1 + i_2 + i_3)\, t}$$

Why does IPC create off diagonal covariance?

- Consider an idealized 3x3 pixel detector that has some IPC that is parameterized by α as before

$$\text{Ideal } 3\times 3 \text{ Pixel Detector} = \begin{pmatrix} s_1 & s_2 & s_3 \\ s_4 & s_5 & s_6 \\ s_7 & s_8 & s_9 \end{pmatrix}$$

- Imagine that you drop photons into pixel s_5 while keeping all other pixels blanked off. The integrated charge, S, and variance, V, are as follows (where $v_{i\,j}$ is the covariance matrix).

$$S = s_2 + s_4 + s_5 + s_6 + s_8$$

$$V = \sum_i \sum_j v_{i\,j} \frac{\partial S}{\partial s_i} \frac{\partial S}{\partial s_j}$$

- Because of IPC, we know that s_5 does not reflect all of the signal; what appears to be missing from s_5 appears in the neighbors. The same is true of the variance. This is the off-diagonal covariance. If we measure the value s_5 in the central pixel, then from Chart 4 we know that the charge that is really there is,

$$s_5' = \frac{s_5}{(1 - 4\,\alpha)}.$$

- Moreover, the variance that appears to be missing from s_5 appears in each of the four nearest neighbors as a consequence of the off diagonal covariance

Diagonal covariance: $v_{5\,5} = s_5$ Off diagonal covariance (to nearest neighbors): $v_{i\,j} = \dfrac{\alpha}{1 - 4\,\alpha} s_5.$

Does IPC go away if I work in DN instead of electrons?

- No
  - However, IPC does complicate the conversion between DN and electrons
  - IPC first noticed for this reason
- Because IPC causes off-diagonal covariance (chart 5), statistics that consider only the diagonal elements under-estimate the noise
- "Conversion gain", g_c (e^-/DN), is conventionally measured by taking a series of exposures to increasingly higher signal levels, plotting variance in DN^2 versus signal in DN, and fitting a straight line, $y = a + b\,x$
- In the absence of IPC, g_c in units of e^-/DN is equal to the reciprocal of the fitted slope, $g_c = b^{-1}$

$$g_c' = (1 - 8\,\alpha)\,g_c$$

If I want to use convolution for the implementation, when should I apply the charge diffusion and IPC kernels?

1. Generate a noiseless, theoretical image
    a. Include any blurring by the optics
    b. Including any blurring from the charge diffusion kernel
2. Simulate the integration of charge up to (but not including) the first amplifier in the ROIC. There is now shot noise on the integrated charge and some read noise from the pixel interconnects, but the covariance matrix will still be diagonal.
3. Blur the integrated image by the IPC kernel. This will smooth out the image structure, smooth out the noise, and introduce off diagonal covariance.
4. Add in read noise from amplifiers and components that come

In practice, read noise is a tricky topic because it is seldom white (more on this later)

How can I add more realistic read noise?

- In real IR detector systems, the read noise is seldom white. Here is a short list of the kinds of correlated noise that are commonly seen
  - Variable alternating column noise
  - 1/*f* noise
  - Bars and bands
  - and probably many more if one looks hard enough…
- There are likely many interdependencies between these things
- One way to concisely capture the correlations and interdependencies is to specify the covariance matrix and to use that when generating read noise

Since first preparing these charts, we have written an HxRG correlated noise generator. The python language source code is freely available for download.

Source Code Download: http://jwst.nasa.gov/resources/nghxrg.tar.gz.

See Rauscher, B.J. 2015, *Teledyne H1RG, H2RG, and H4RG Noise Generator*, Publications of the Astronomical Society of the Pacific, Vol. 127, pp. 1144 - 1151

Caveats and limitations

- We did not allow for the detector system to inject correlated noise before the first pixel amplifier. In practice, this can and does happen. To capture these effects, one would modify the steps shown on Chart 9.