# How well do we understand NIR detectors?

(focus on hybrid HgCdTe)

Roger Smith

**Caltech**

2018-12-03

# Photodiodes, with low bandgap

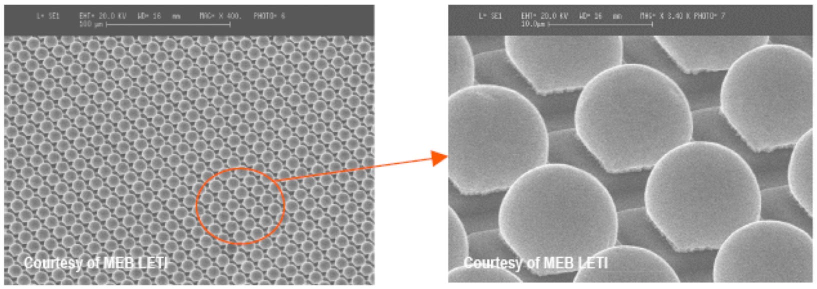
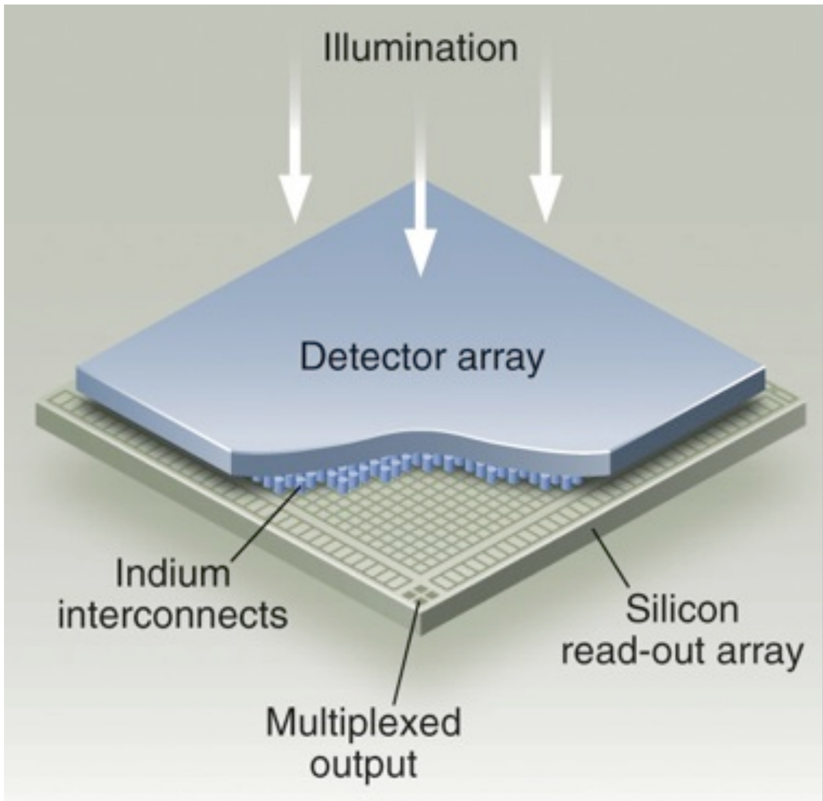
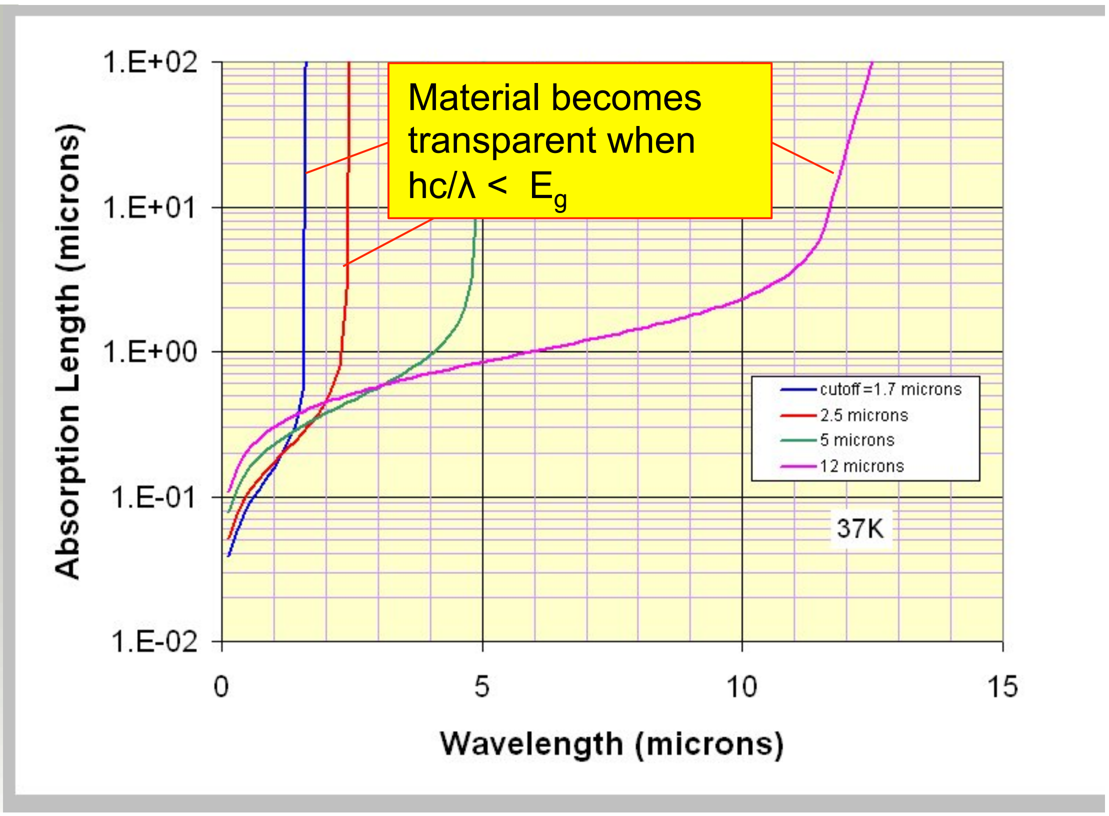



Figure 2: View of a field of indium micro-bumps with a pitch of 15 µm

- Bump bond low bandgap material to silicon readout IC.
- Integrate charge on diode capacitance.

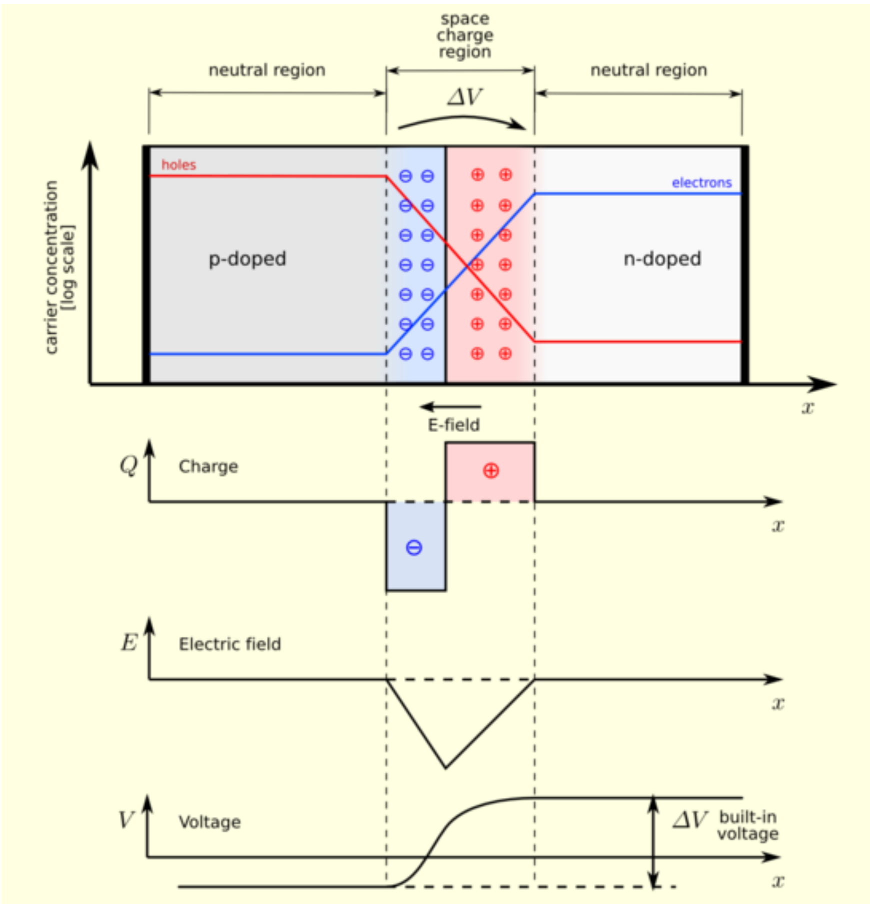


# Basic theory of PN junction

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24




http://en.wikipedia.org/wiki/P-n_junction

When majority carriers diffuse across PN junction they recombine leaving a charged but carrier free region. The charge on the donor atoms produces an E field which opposes further diffusion.

For given donor density profile, Q(x) at equilibrium, within space-charge region:

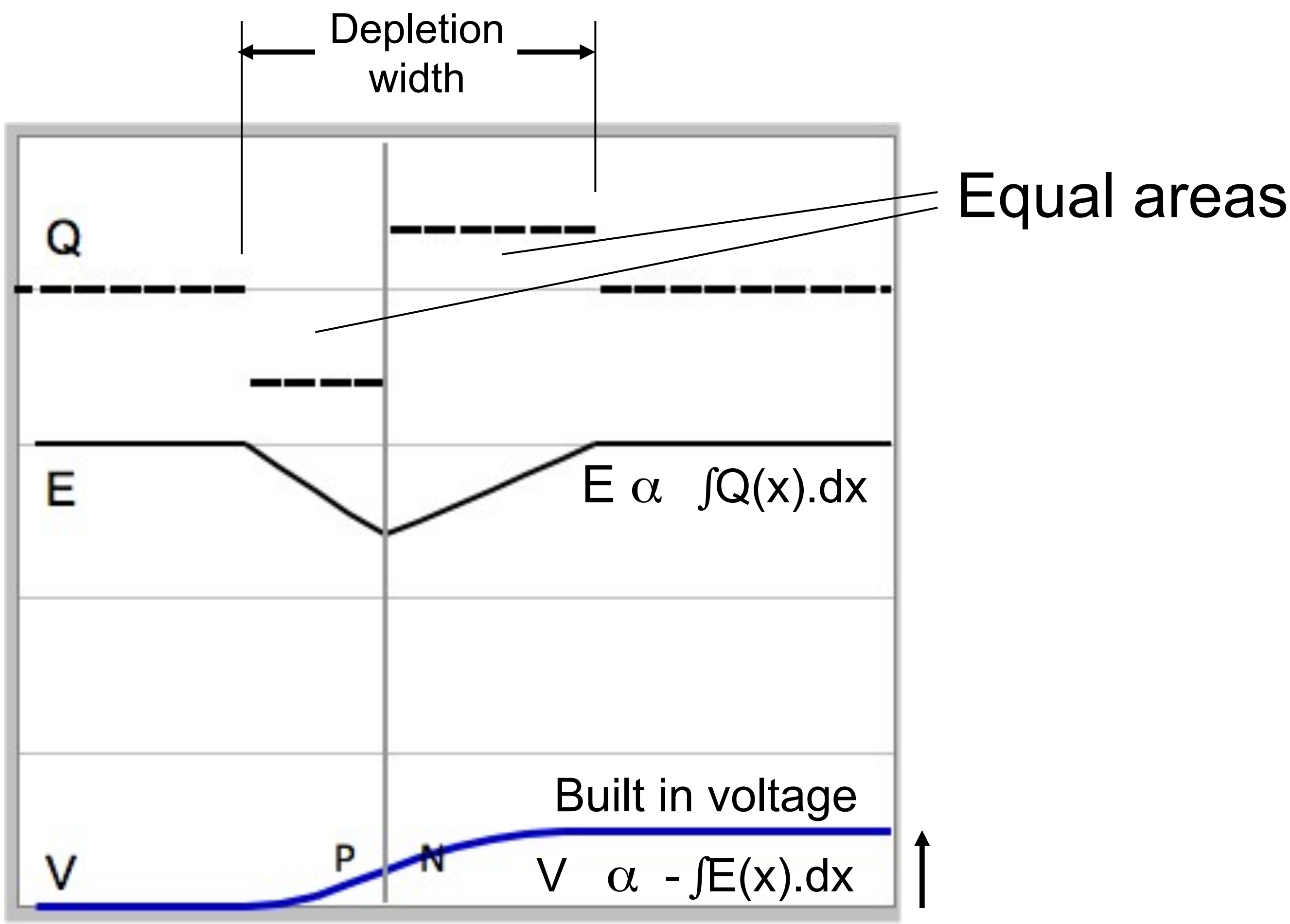
$$E \quad \alpha \quad \int Q(x).dx$$

$$V \quad \alpha \quad -\int E(x).dx$$

# Built in voltage

Roger Smith et al., Caltech

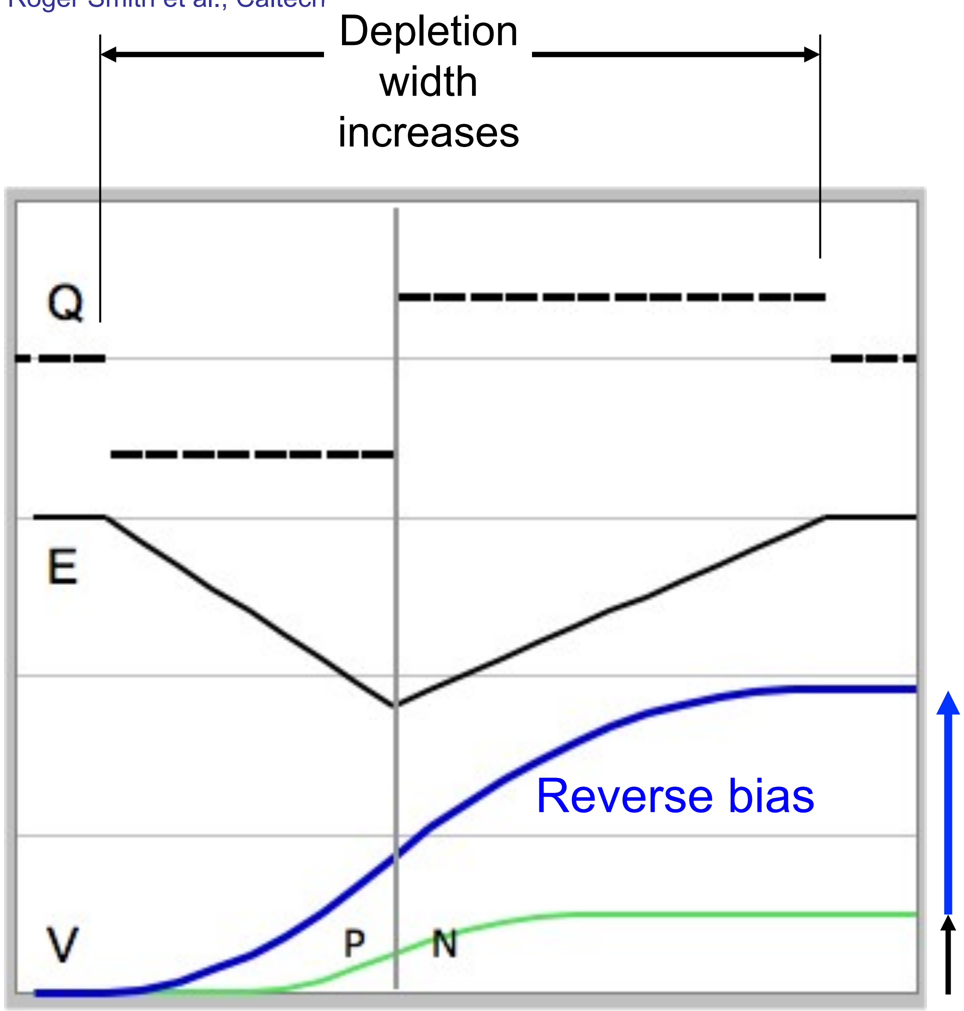
SPIE 7021-22, Marseille
2008-06-24



# Reverse bias

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24

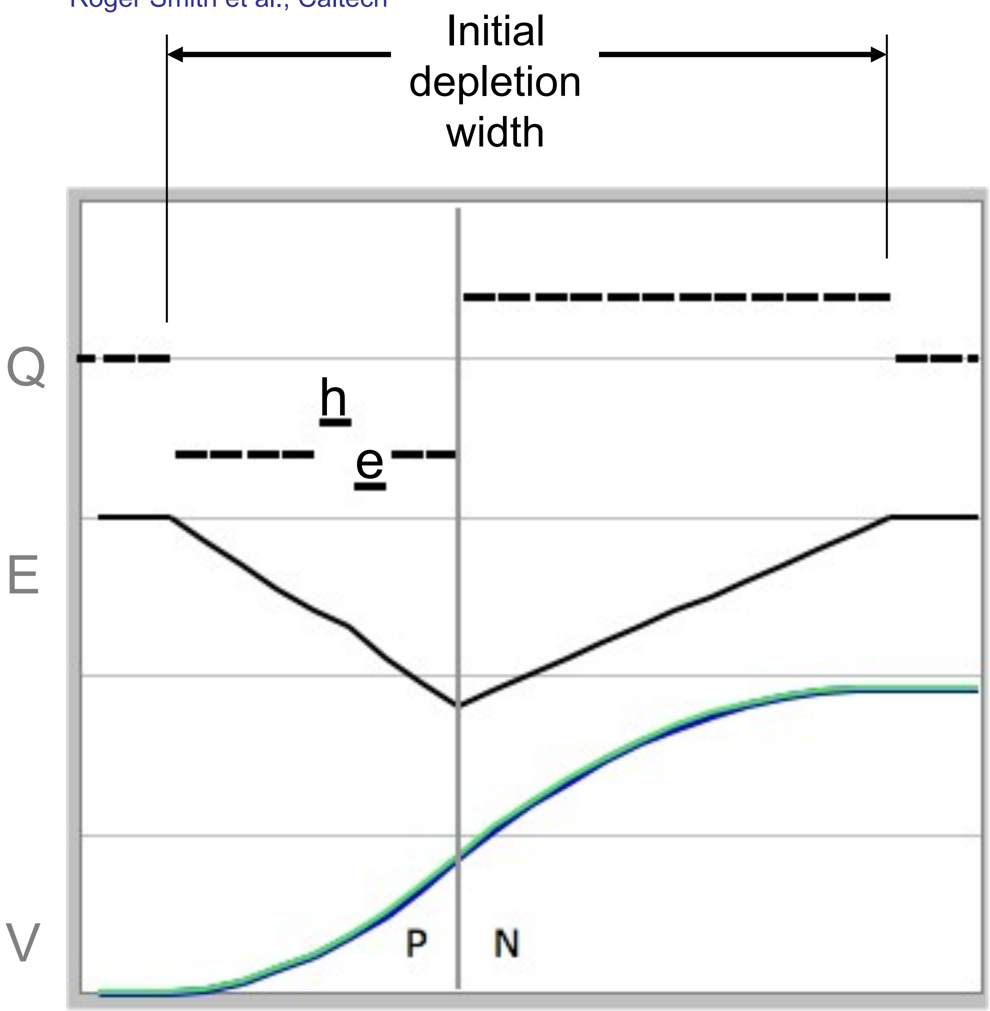



At “reset”, a reverse bias is applied : charge is removed, increasing depletion width.

# Photon makes electron hole pair



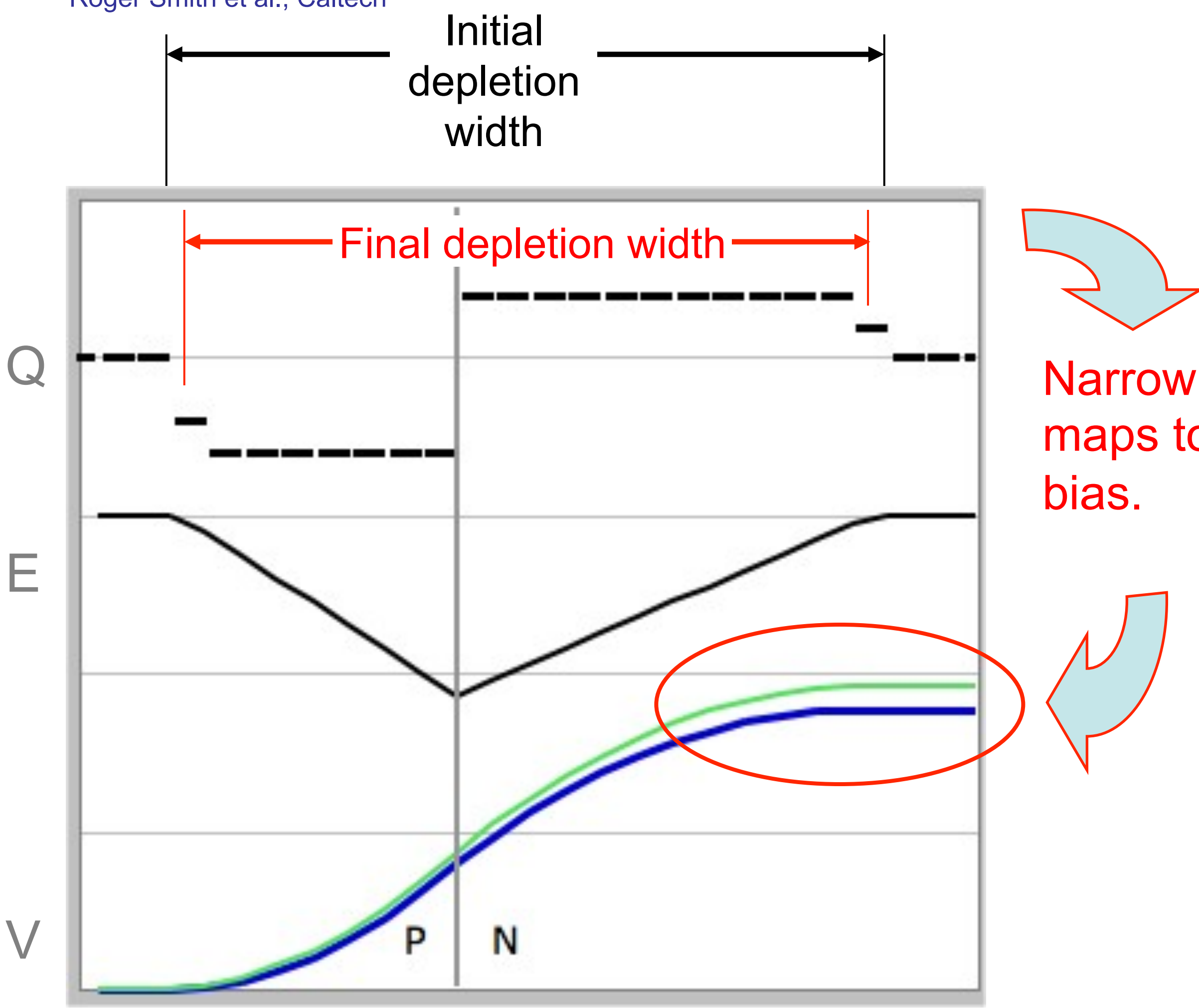




# E field separates e-h ⇒ voltage drops

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24

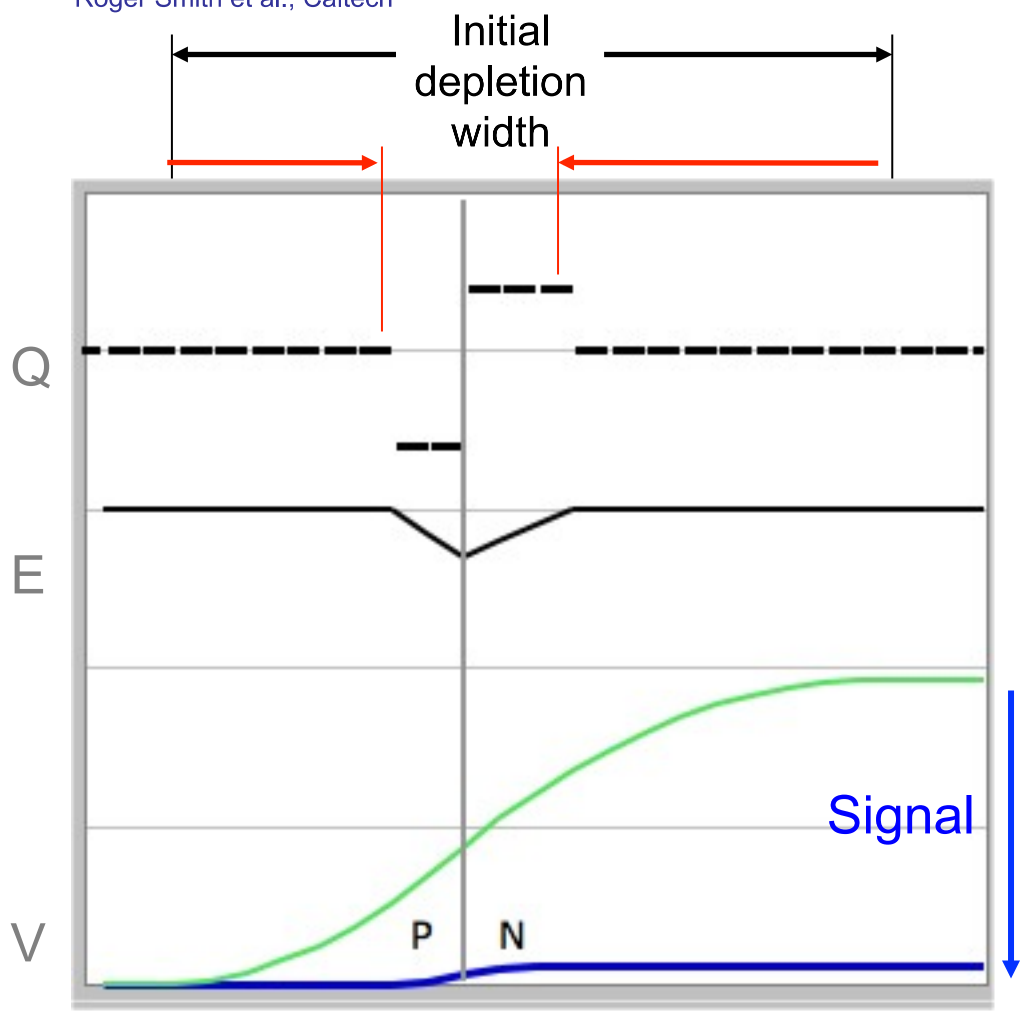



Narrowing of depletion region maps to a drop in the reverse bias.

# Charge accumulates during exposure

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24

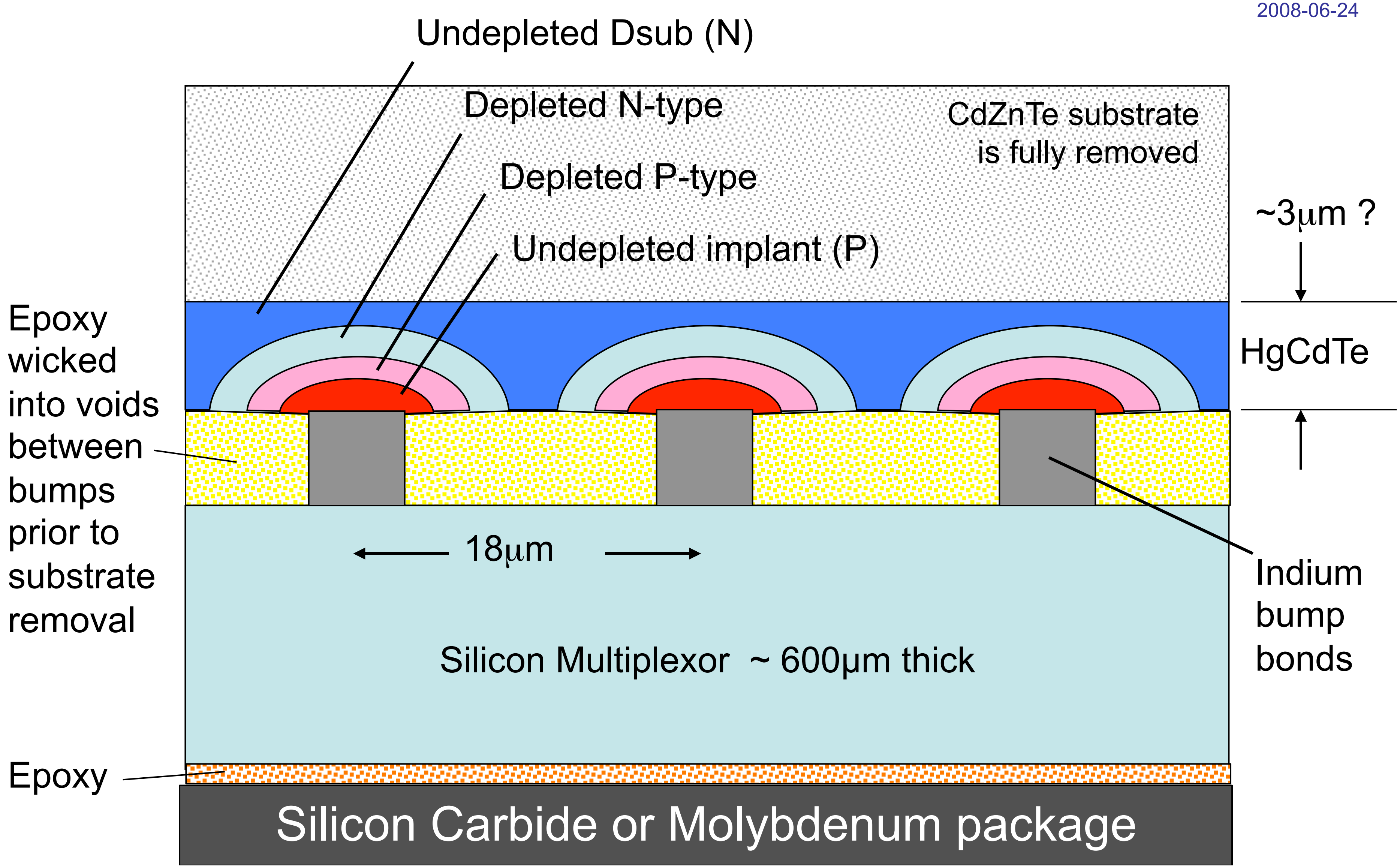



- Saturation = forward bias occurs when depletion region collapses

# PN junctions on common substrate

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24



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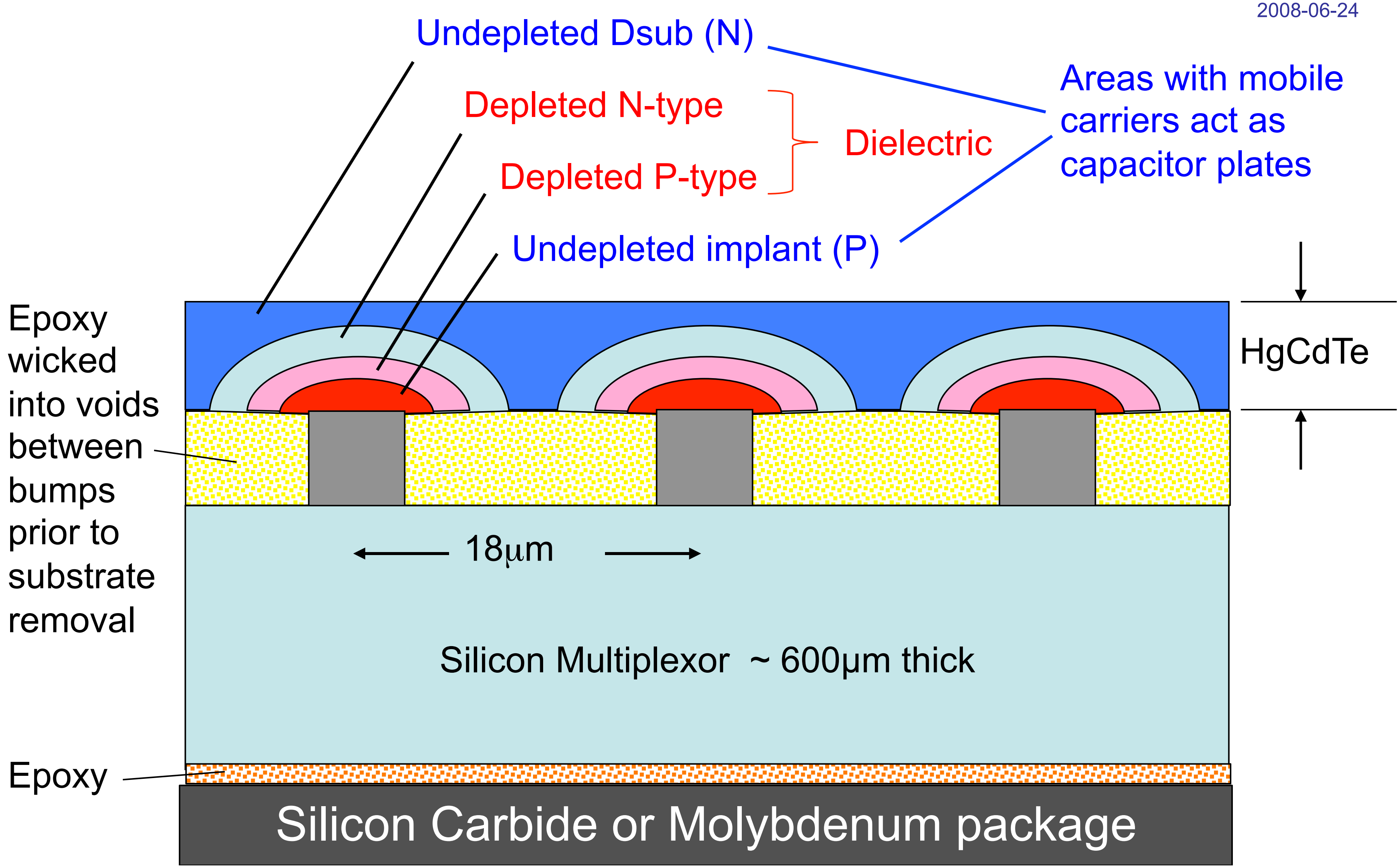
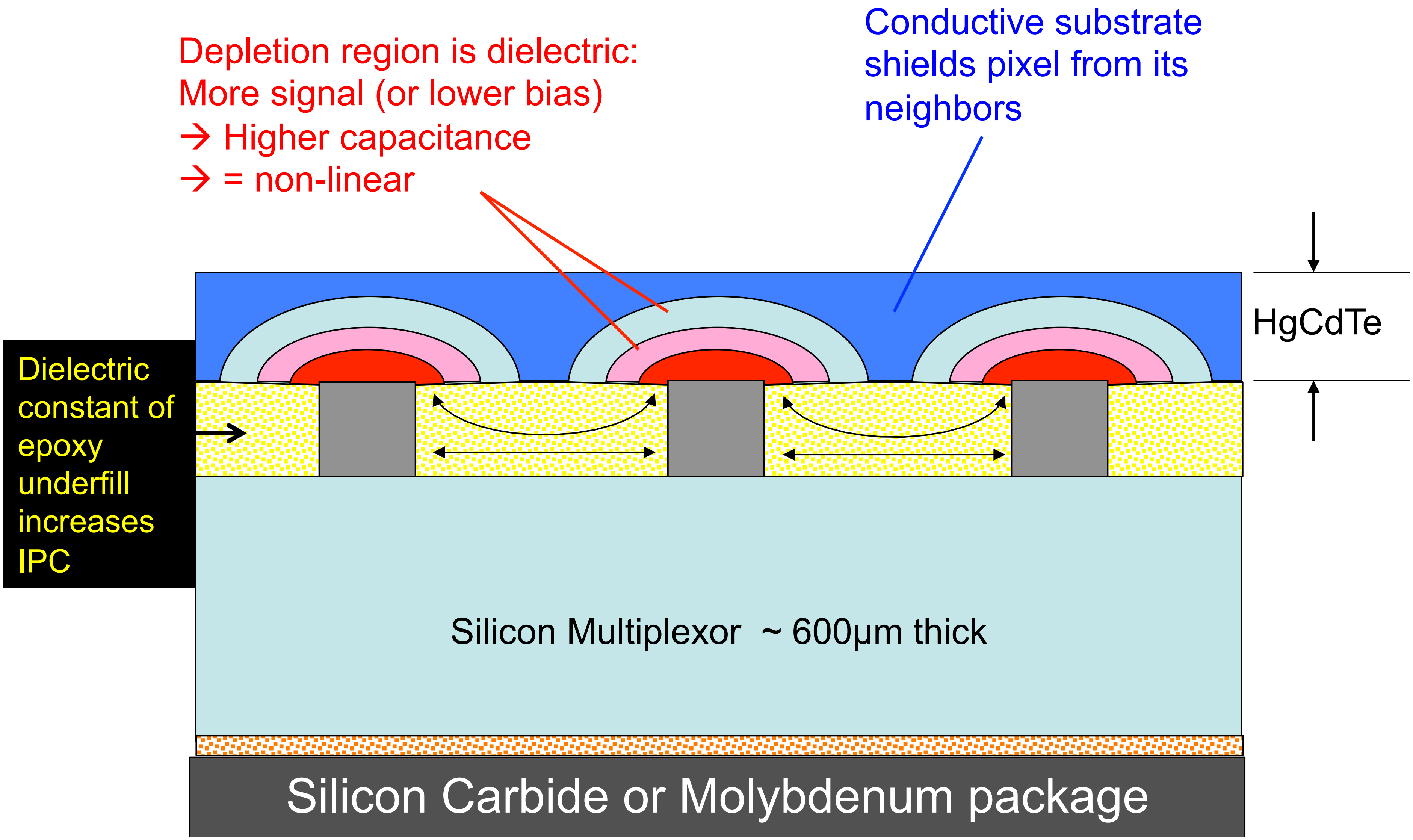


# Inter-Pixel Capacitance

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24



See Kevan Donlon's talk



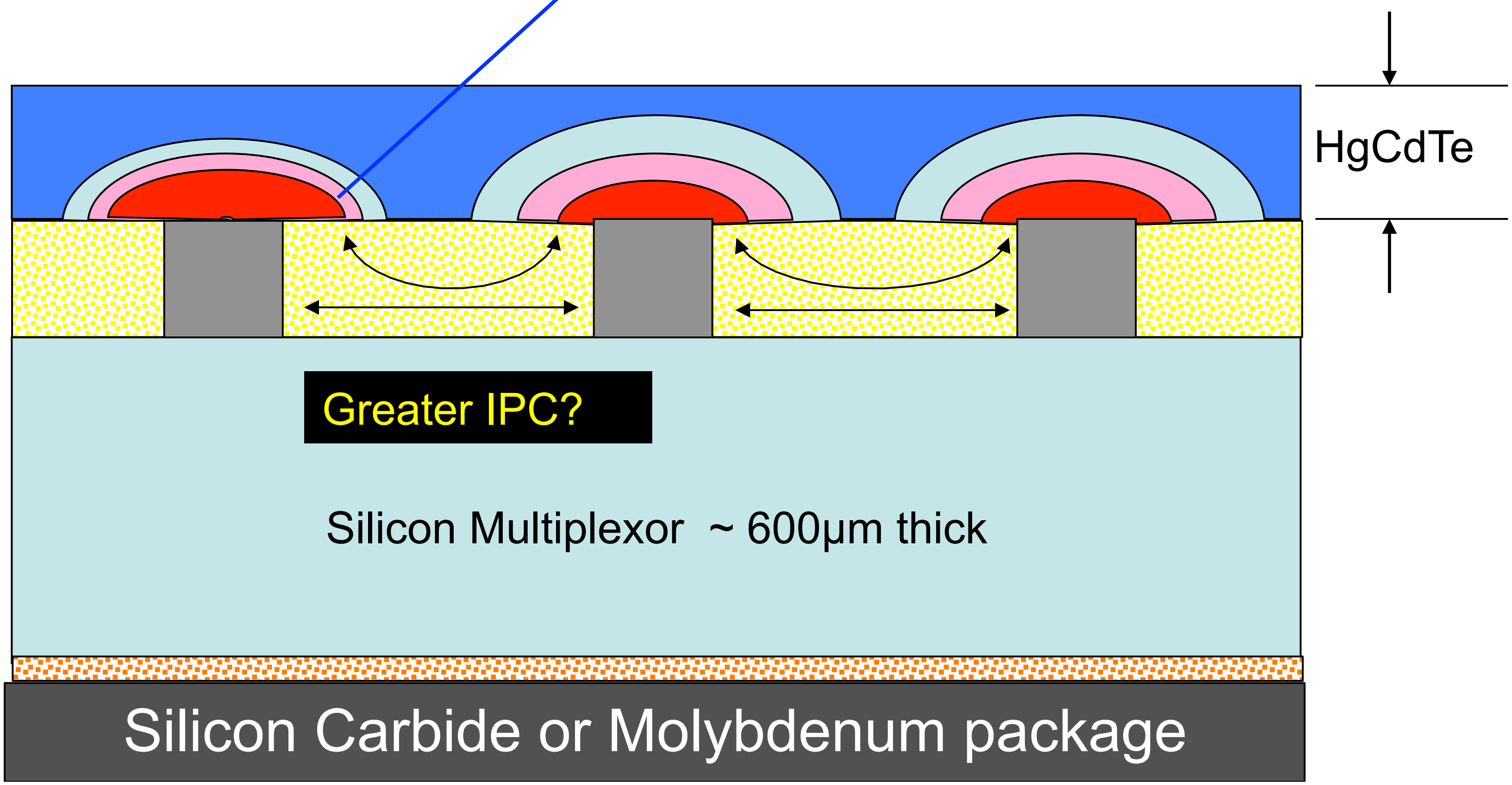
# IPC non-linearity

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24

Carriers in implant with high signal get closer → increased IPC expected.

At higher fluence, depletion region narrows

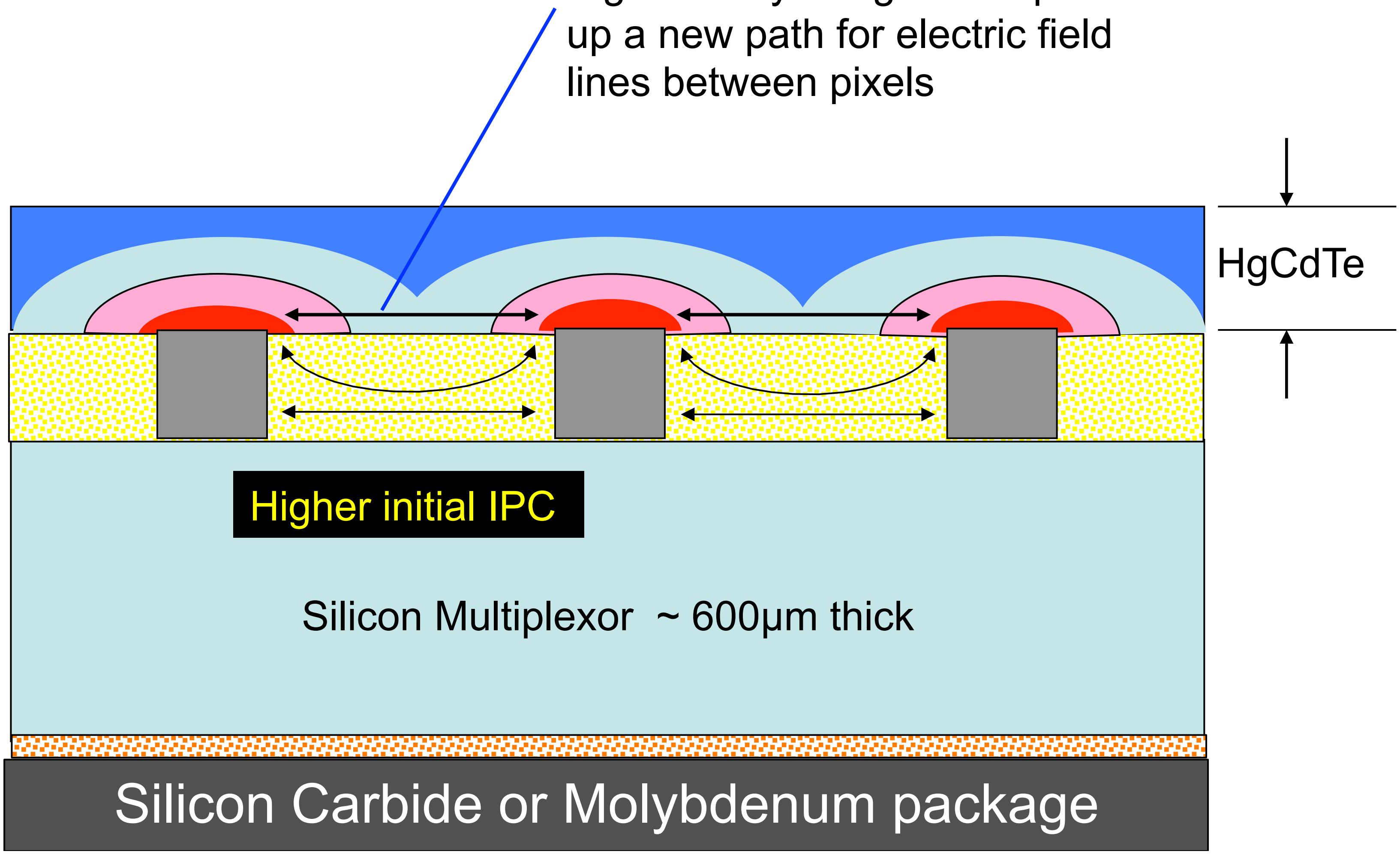


# IPC dependent on detector bias ??



SPECULATION:

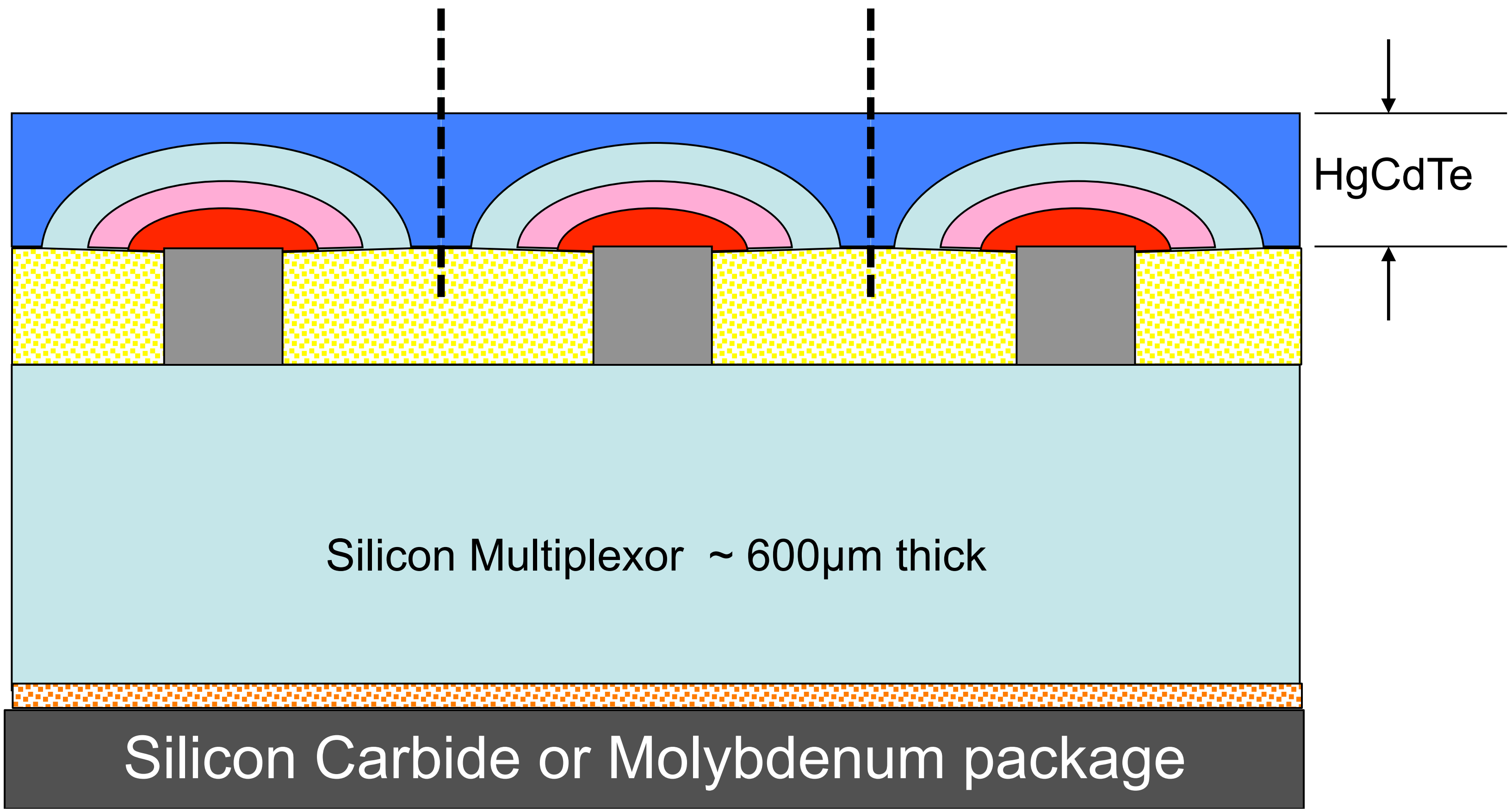
At high reverse bias depletion regions may merge and open up a new path for electric field lines between pixels



# Pixel boundaries after reset

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24



Brighter-fatter paper by Andres Plazas; see Eric Huff's talk

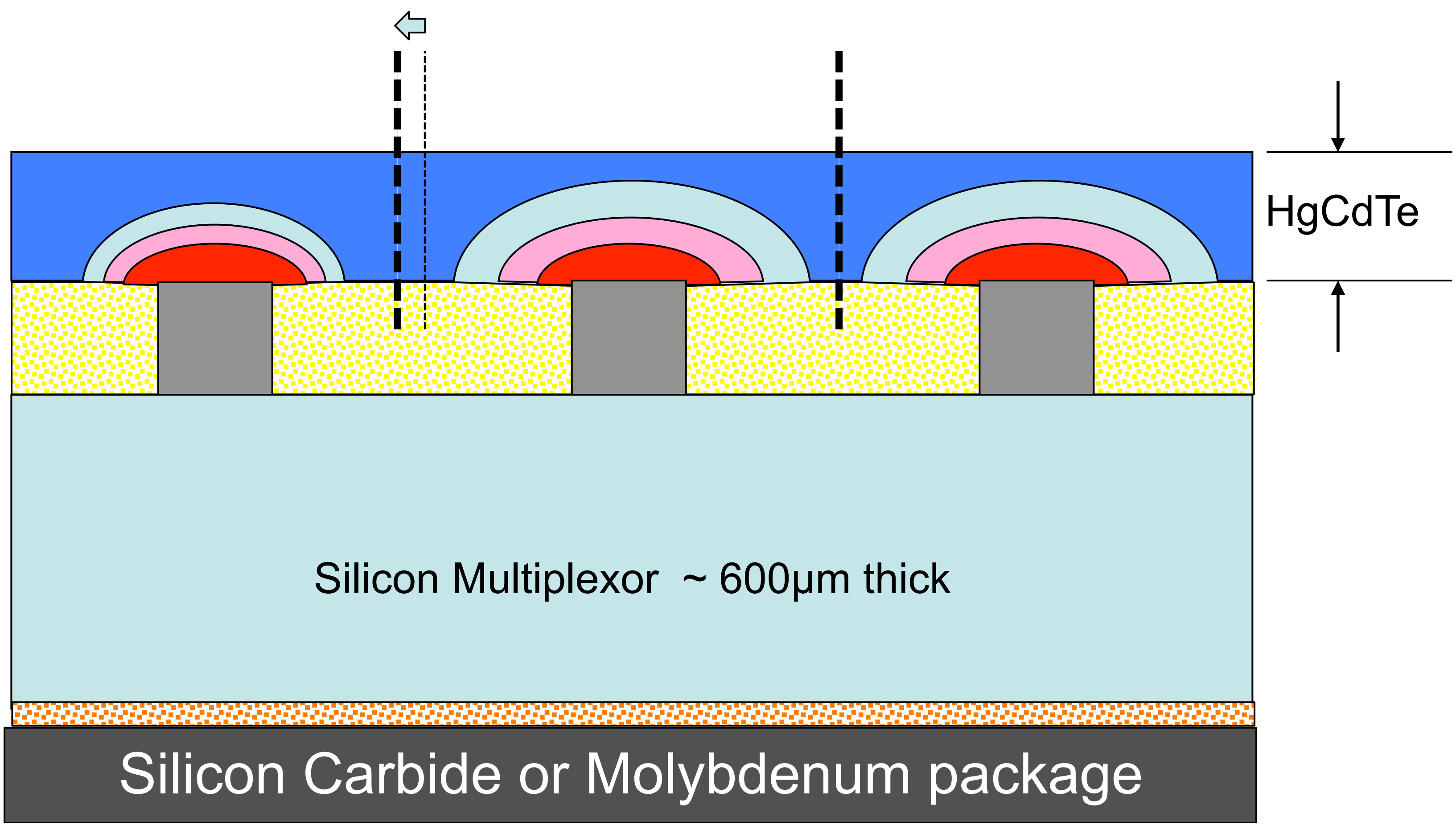


# Signal contrast moves boundary

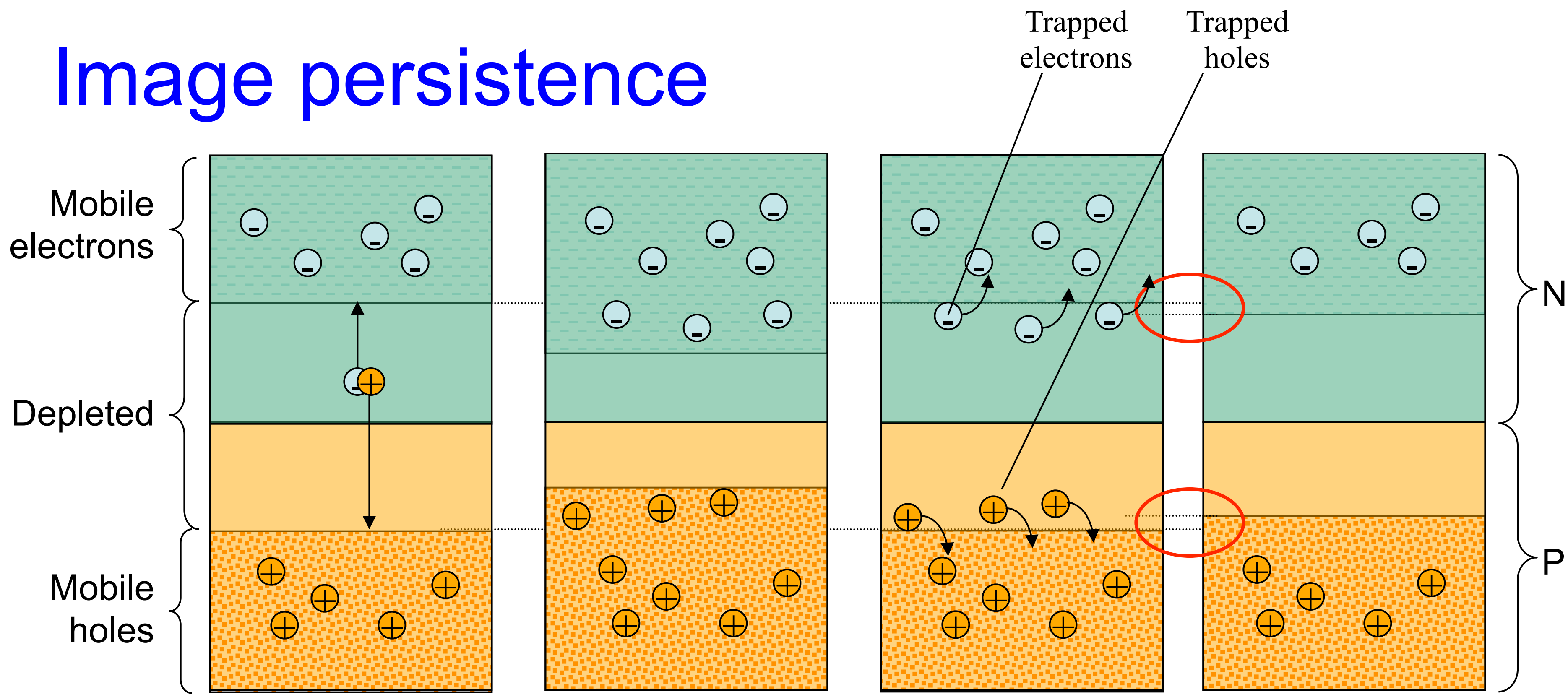
Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24

Pixel shrinks as charge accumulates so PSF seems to grow.



# Image persistence




### Idle / Reset
### (initial reverse bias)

Charge diffusing across the PN junction recombines leaving behind charge donor sites that produce an E field opposing the diffusion. When traps in depleted area release charge, it is swept towards depleted areas by this E field, and cannot be recaptured: **eventually only undepleted area has populated traps.**

### Signal
### (lower bias)

As signal accumulates the depletion width is reduced. Traps newly exposed to charge can capture some mobile carriers.

### Reset
### (increased bias)

At "reset" the reverse bias and wider the depletion region ware restored,**but trapped charge stays behind**. When this is later released, it is swept by the E field out of the depletion region to rejoin carriers of the same type.

### Next Exp.
### (bias relapses)

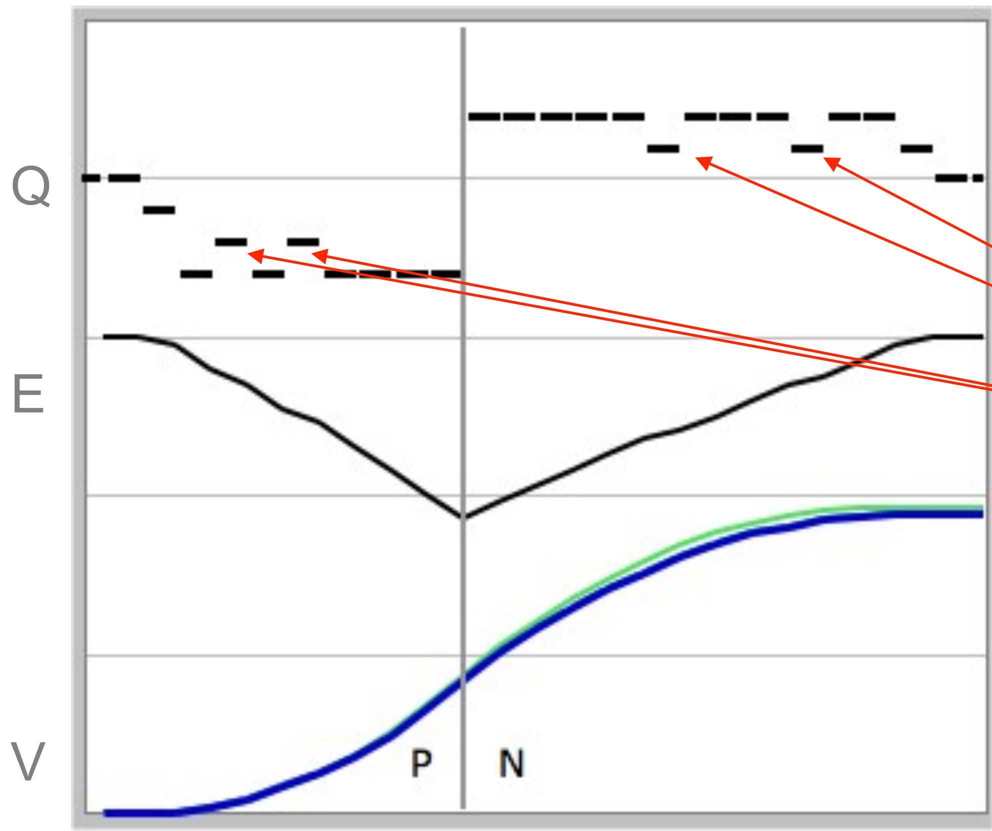
The motion of the released charge reduces the E field: the reverse bias and depletion width tend to towards the previous values. The voltage change has the same polarity as signal and is"persistence".

# Reset

Roger Smith et al., Caltech

SPIE 7021-22, Marseille
2008-06-24

Actual reset



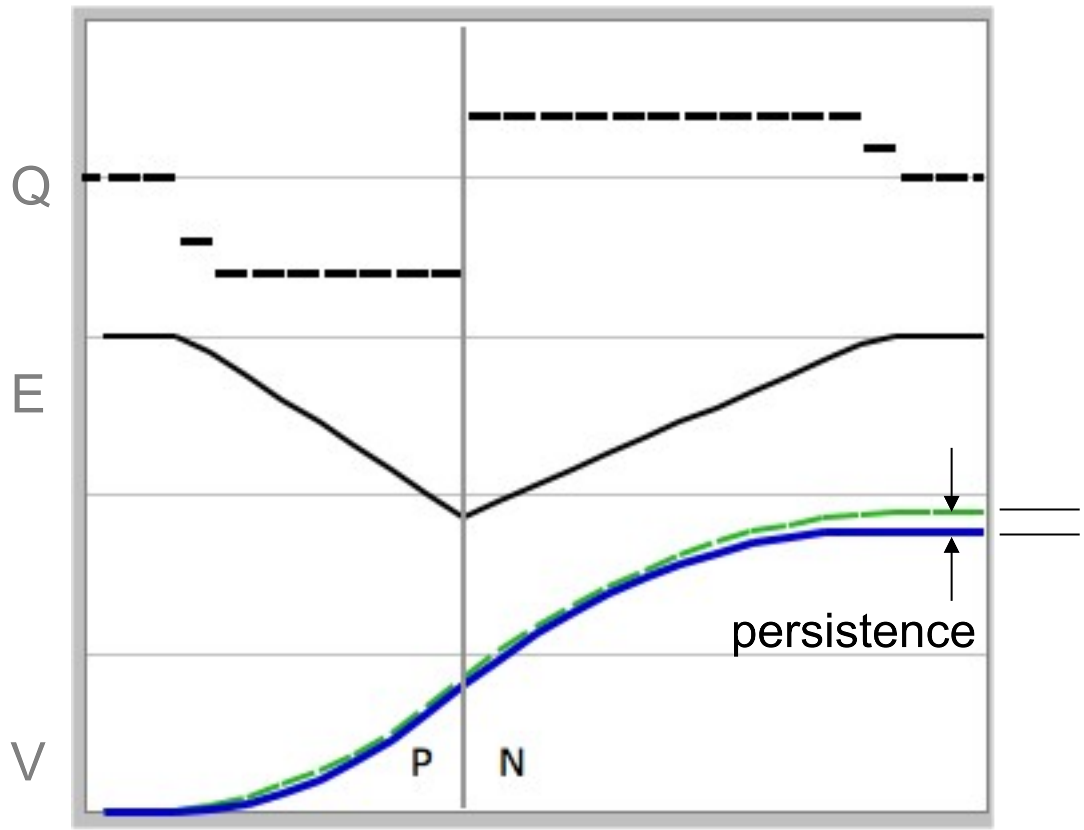

Reverse bias is reapplied at reset.

- Ideally this would reestablish the initial depletion width, but..
- some charge remains behind in traps.

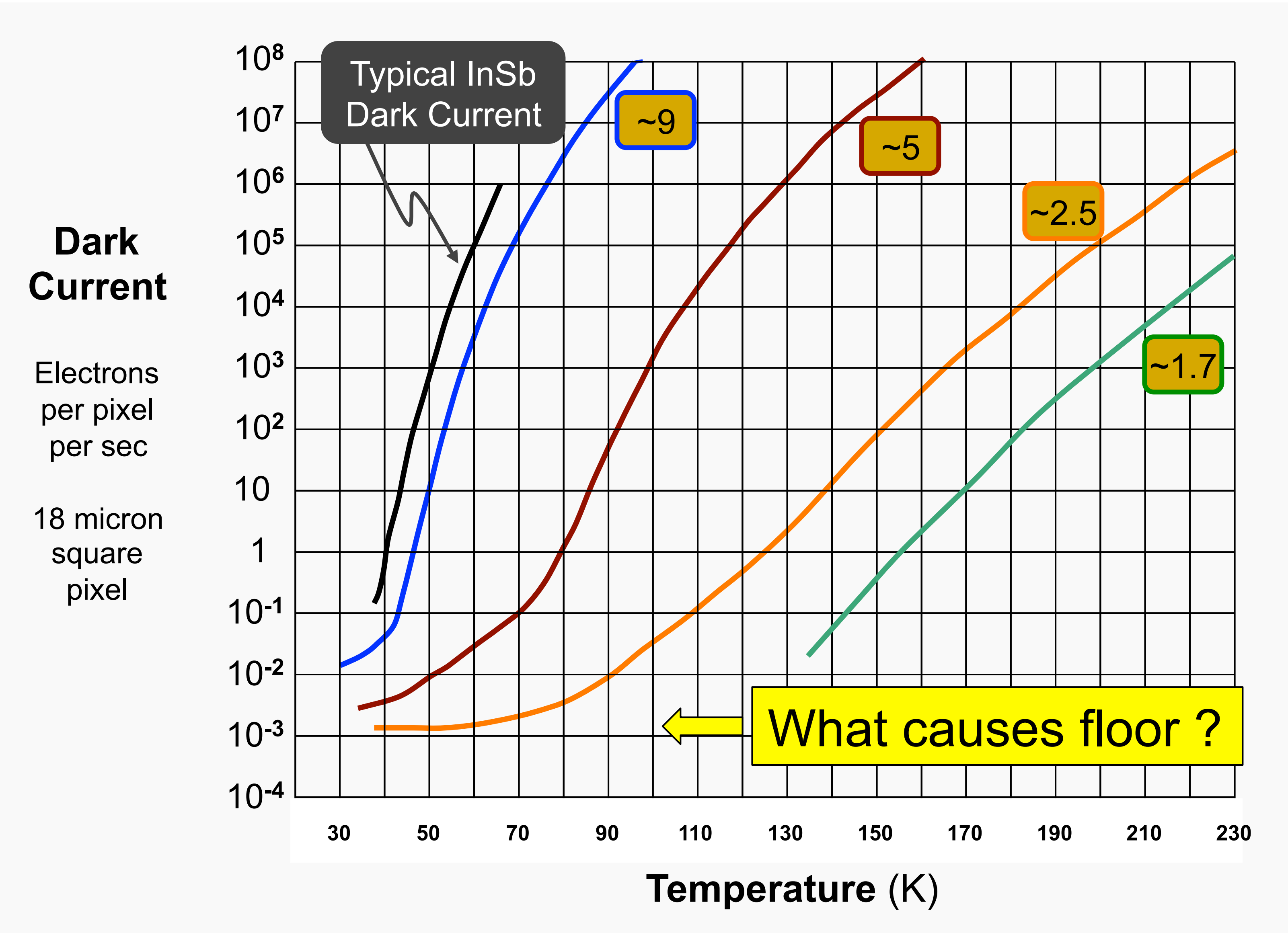
# Charge release ⇒ Signal in later frames



Persistence

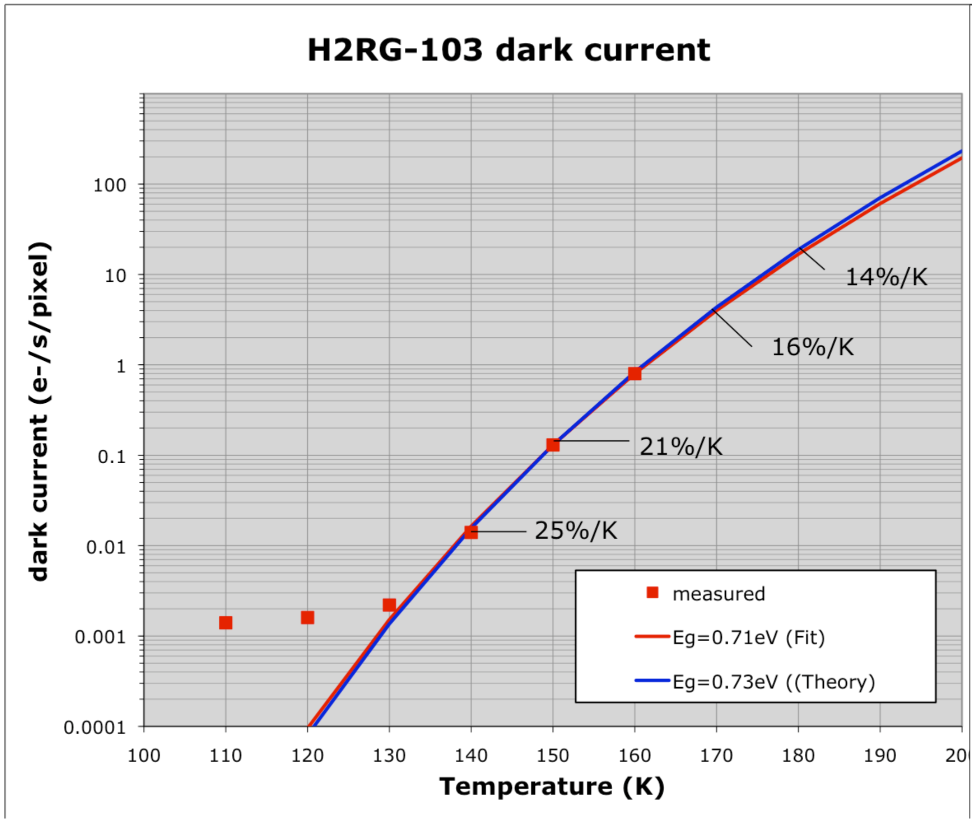


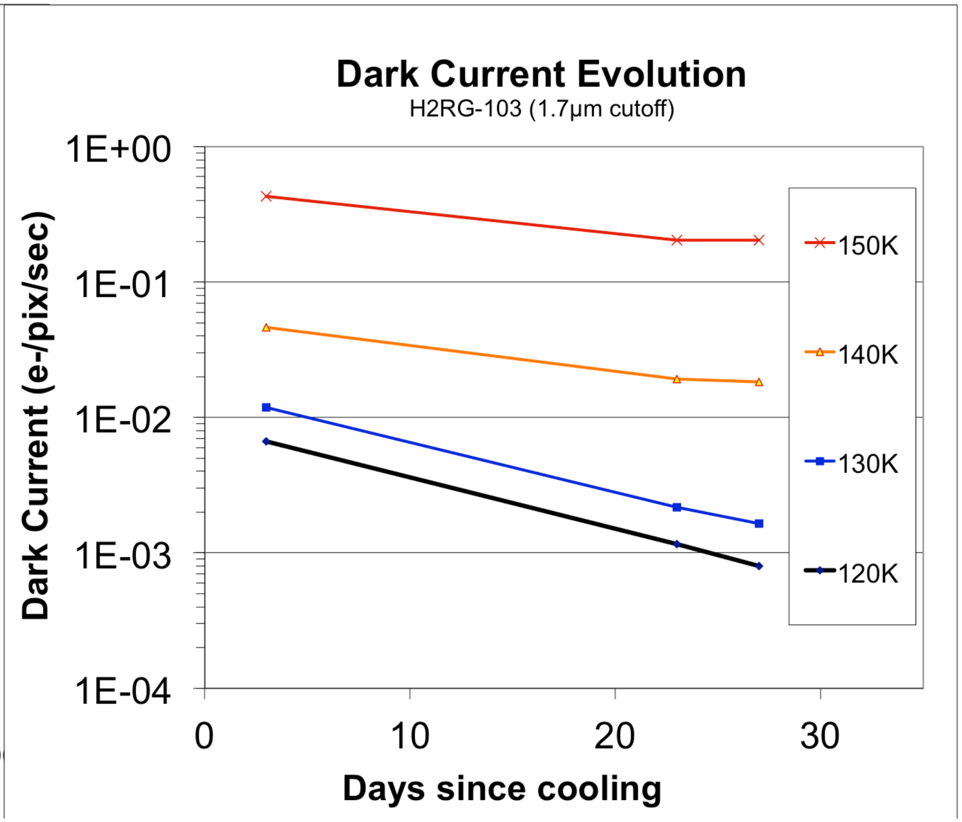
# MBE HgCdTe Dark current



# Dark current floor

- Dark current is high after turn-on due to de-trapping.
- Floor continues to drop for weeks if dark and stable.
- De-trapping is less noisy than equivalent photo-generated signal → **our noise model may be wrong** at low enough temperatures for de-trapping to dominate dark current.

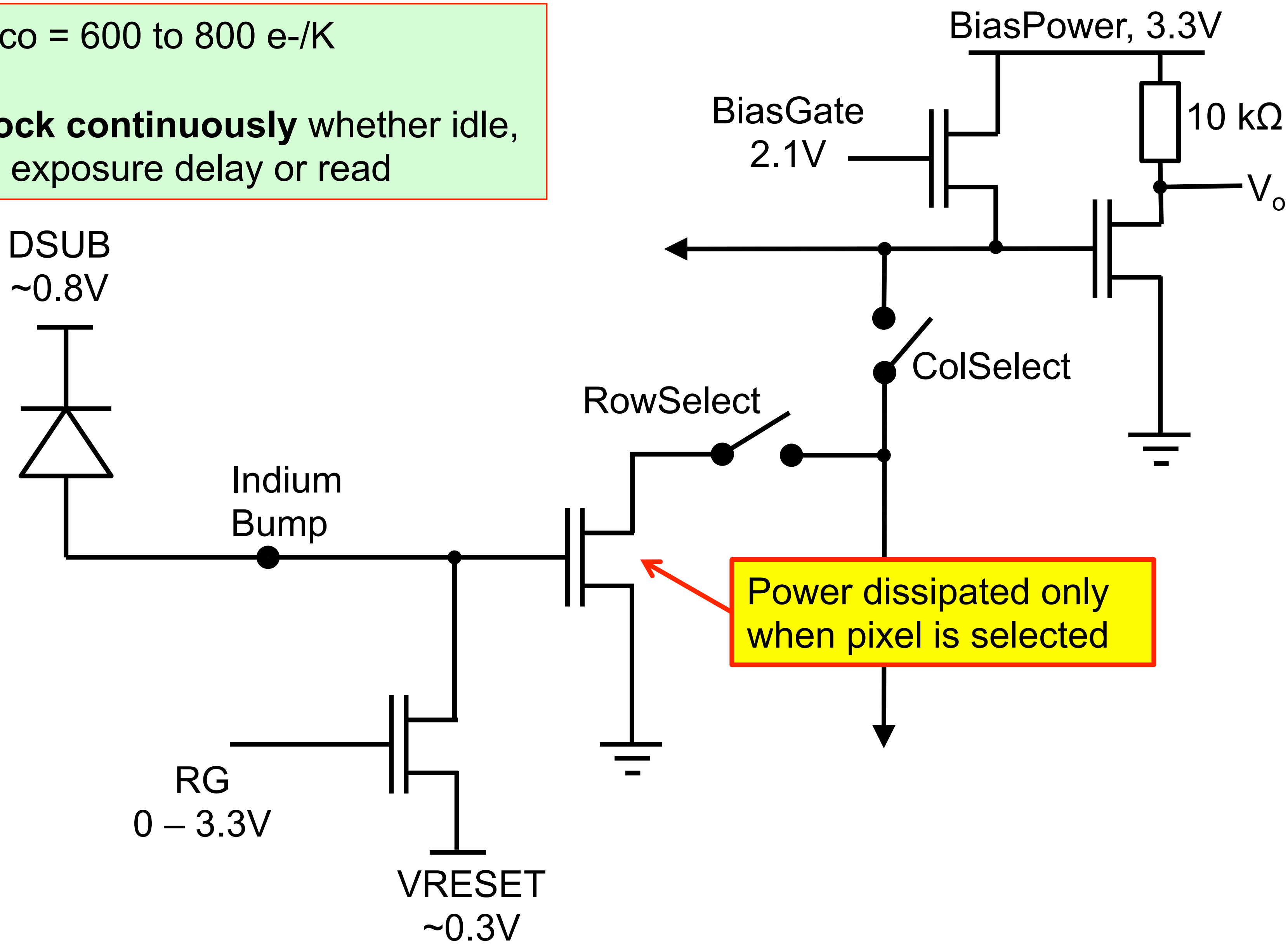


# Pixel circuit

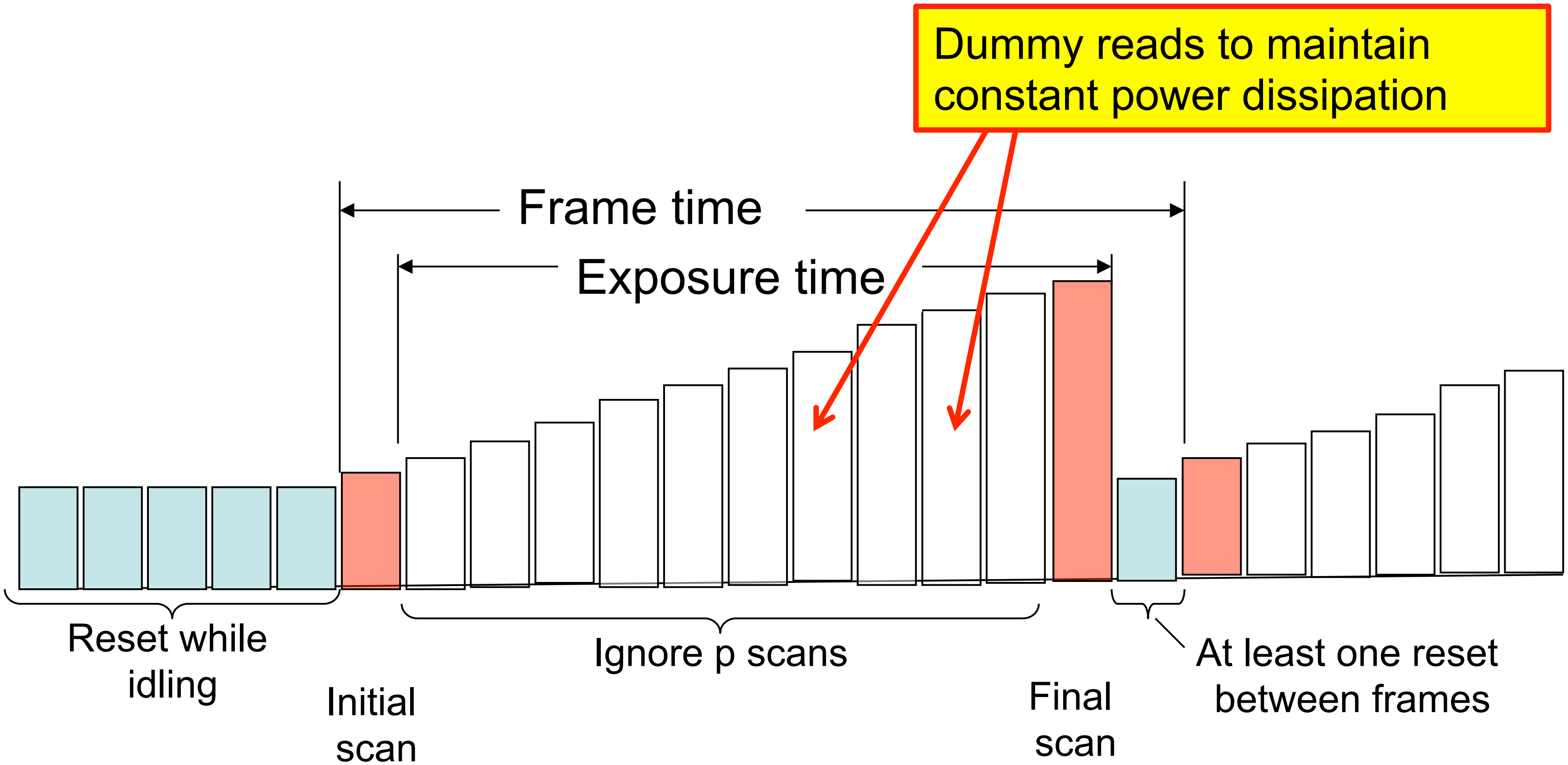
Tempco = 600 to 800 e-/K

→ **Clock continuously** whether idle, reset, exposure delay or read



# Correlated Double Sampling



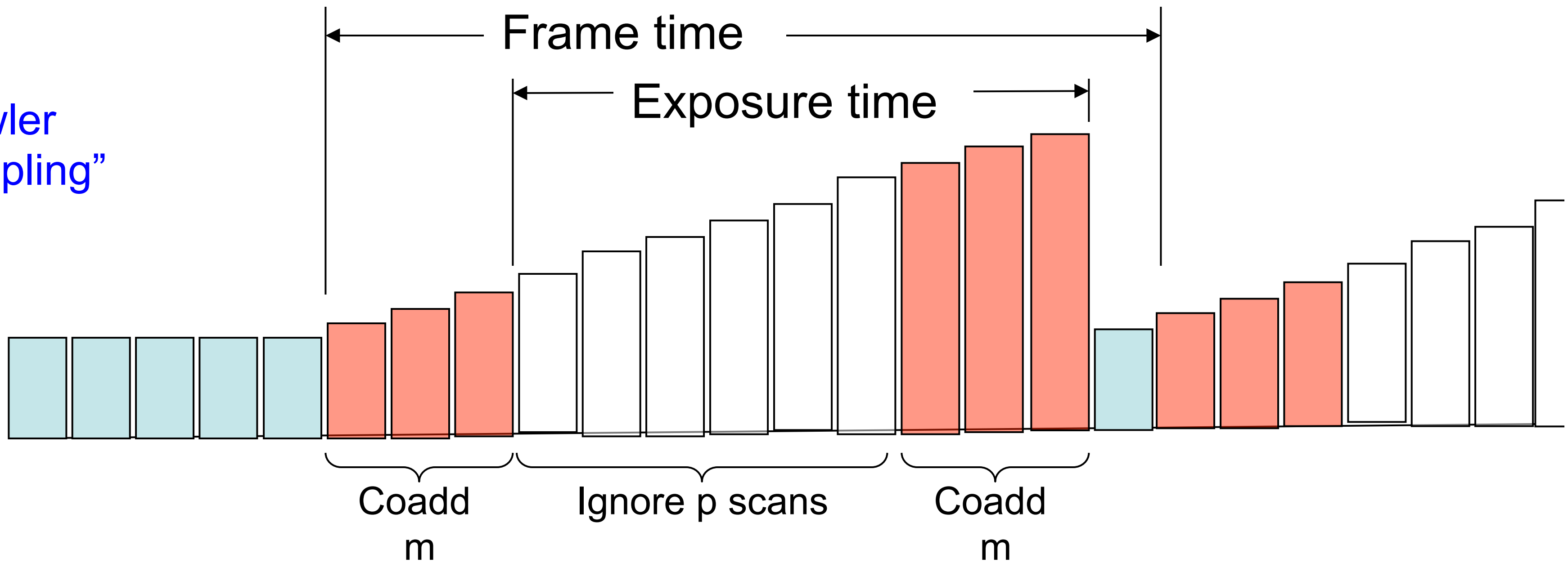



- Exposure delay = p dummy reads for constant self heating
- Subtract first frame from last frame
- Equivalent to Fowler sampling with m = 1

# Fowler sampling, … same dissipation



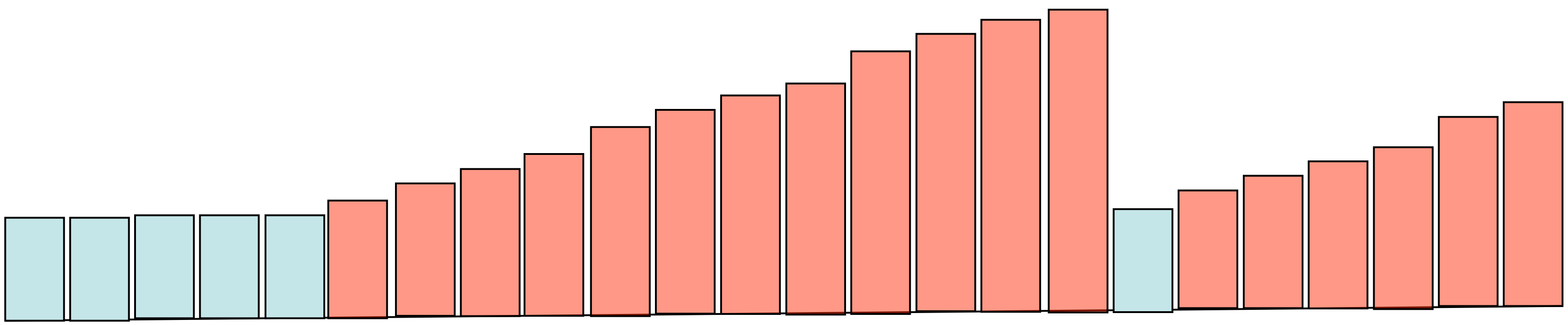
"Fowler Sampling"




- Exposure delay is in units of full scan ties but need not be multiple of m.
- Subtract mean of first group from mean of last group.

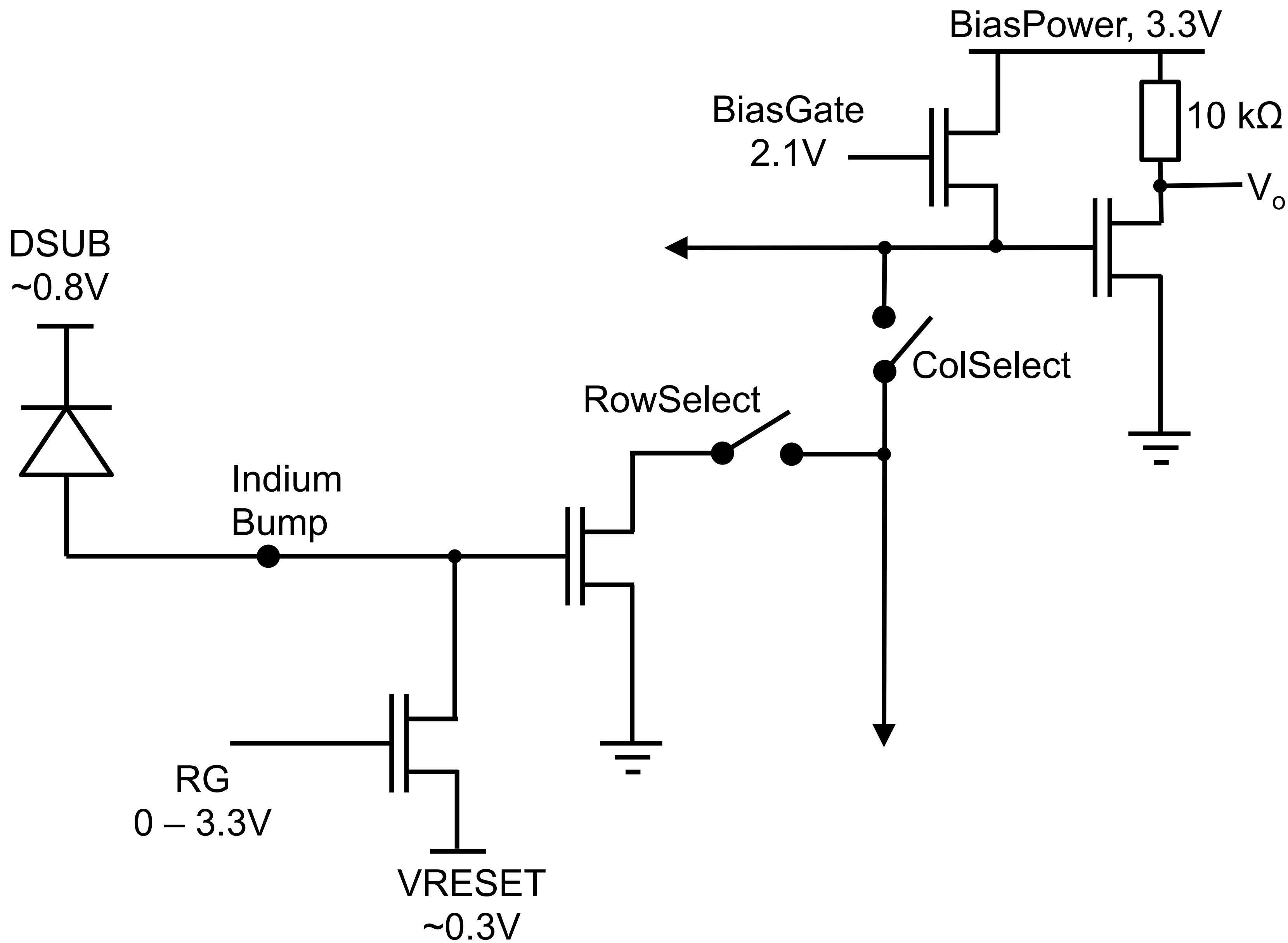
# Sample Up The Ramp ... same dissipation





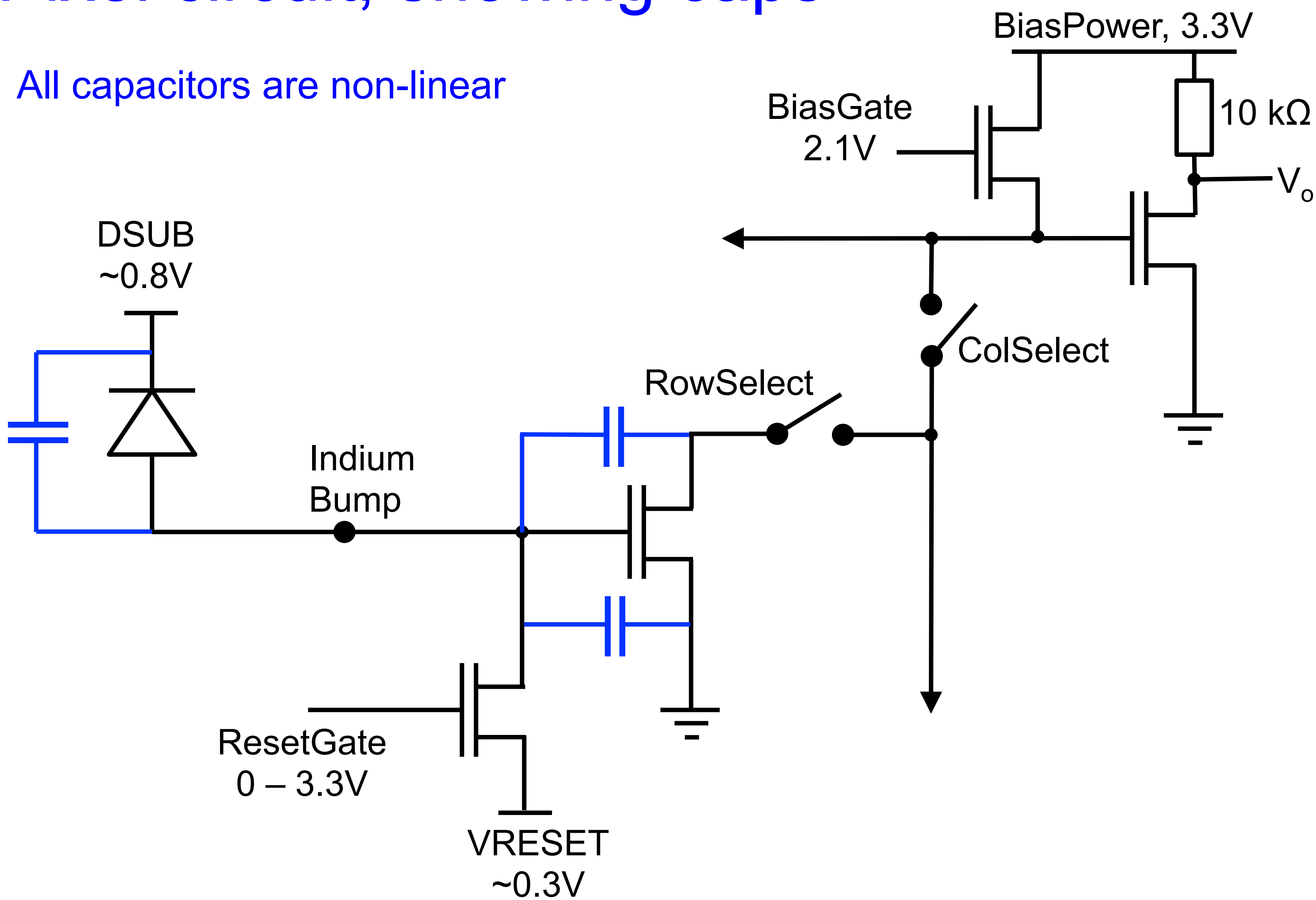
- Store every scan (no real time coadd)
- Use post facto least squares fit to measure slope with best S/N;
- Effective exposure duty cycle due to weighting of shot noise by least squares ~ 90%; reduce this to include effect of the reset overhead.
- Equivalent MultiAccumulate with m=1.

# Pixel circuit



# Pixel circuit, showing caps

All capacitors are non-linear



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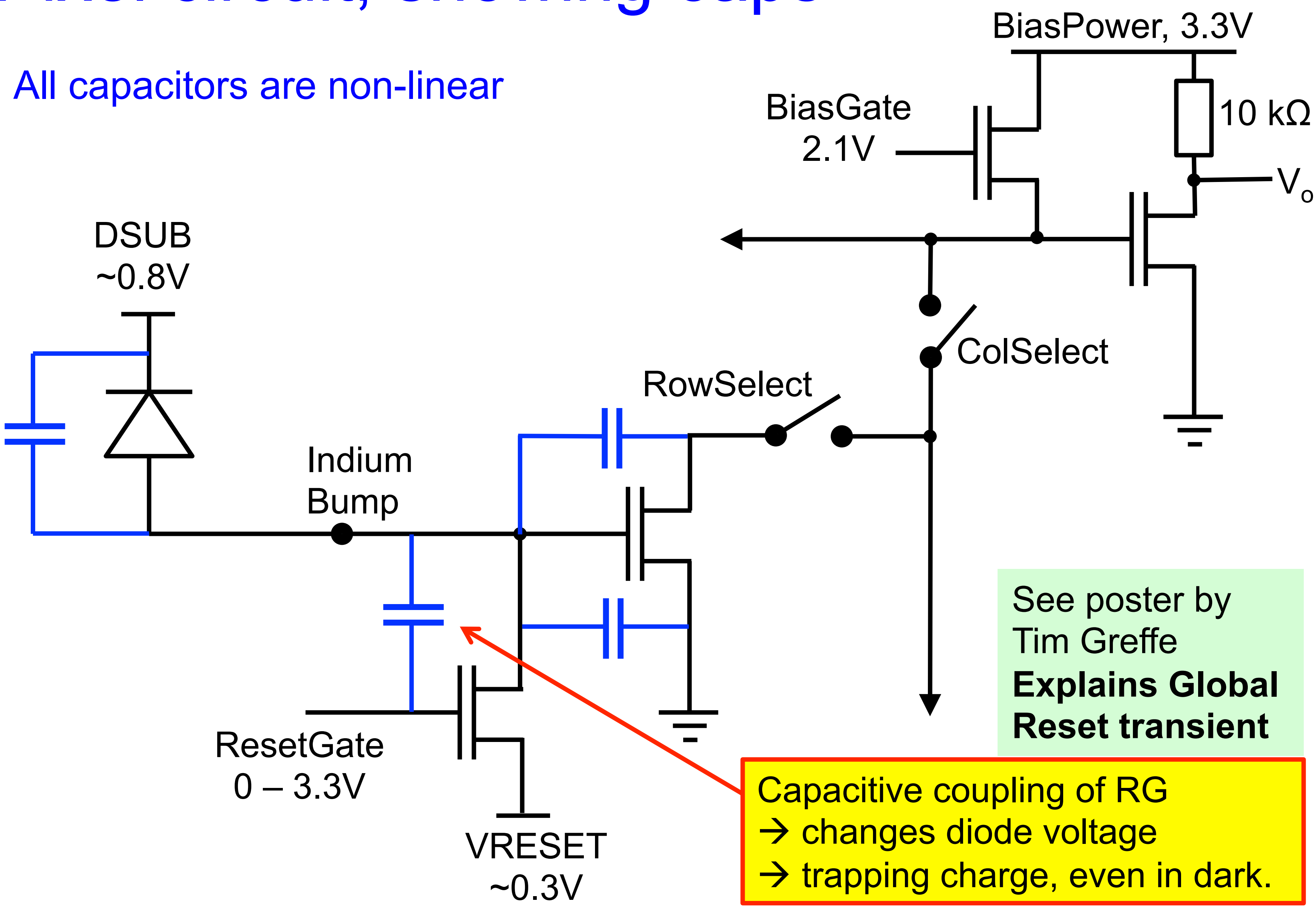
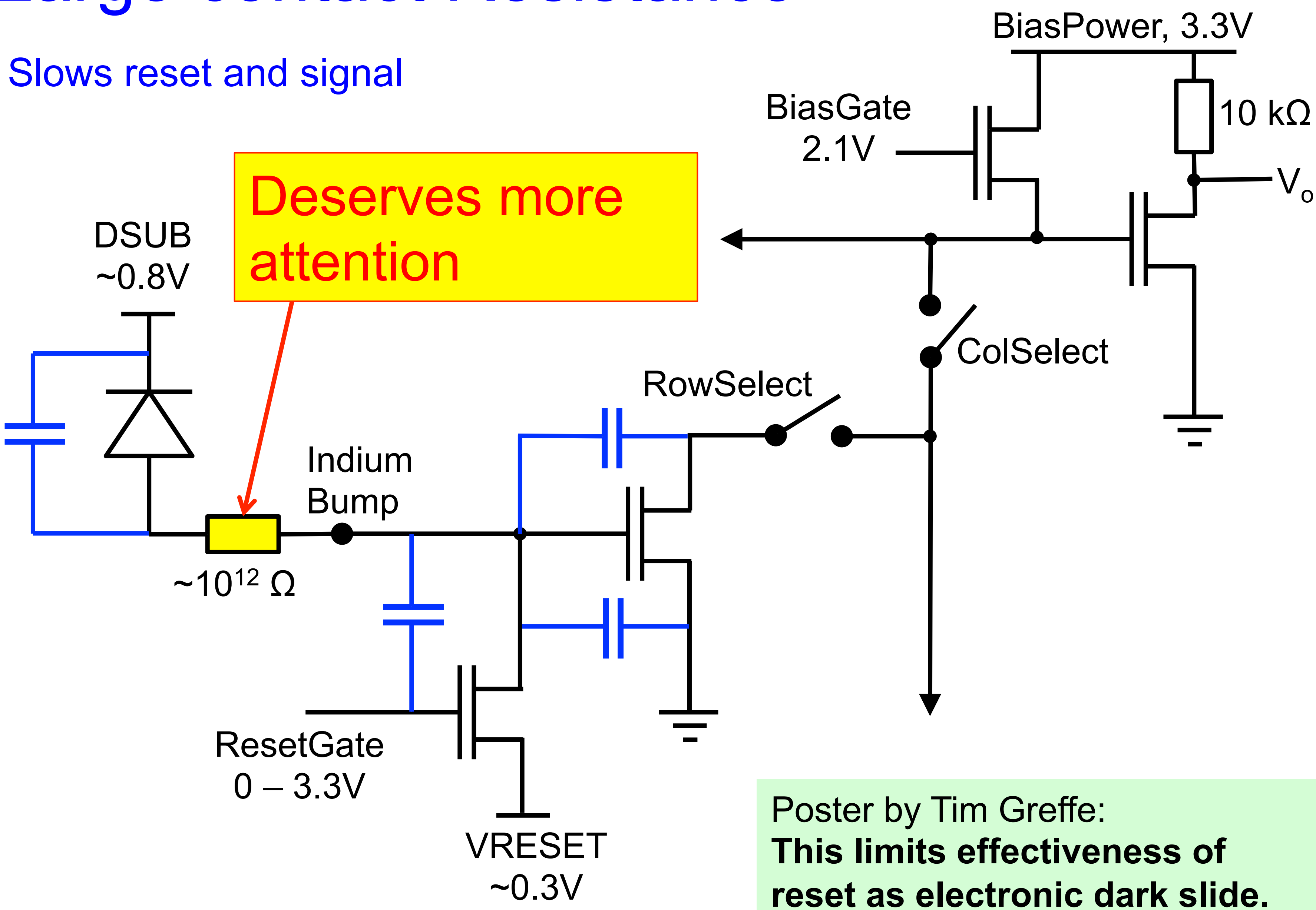



See poster by
Tim Greffe
**Explains Global Reset transient**

Capacitive coupling of RG
→ changes diode voltage
→ trapping charge, even in dark.

# Large contact Resistance

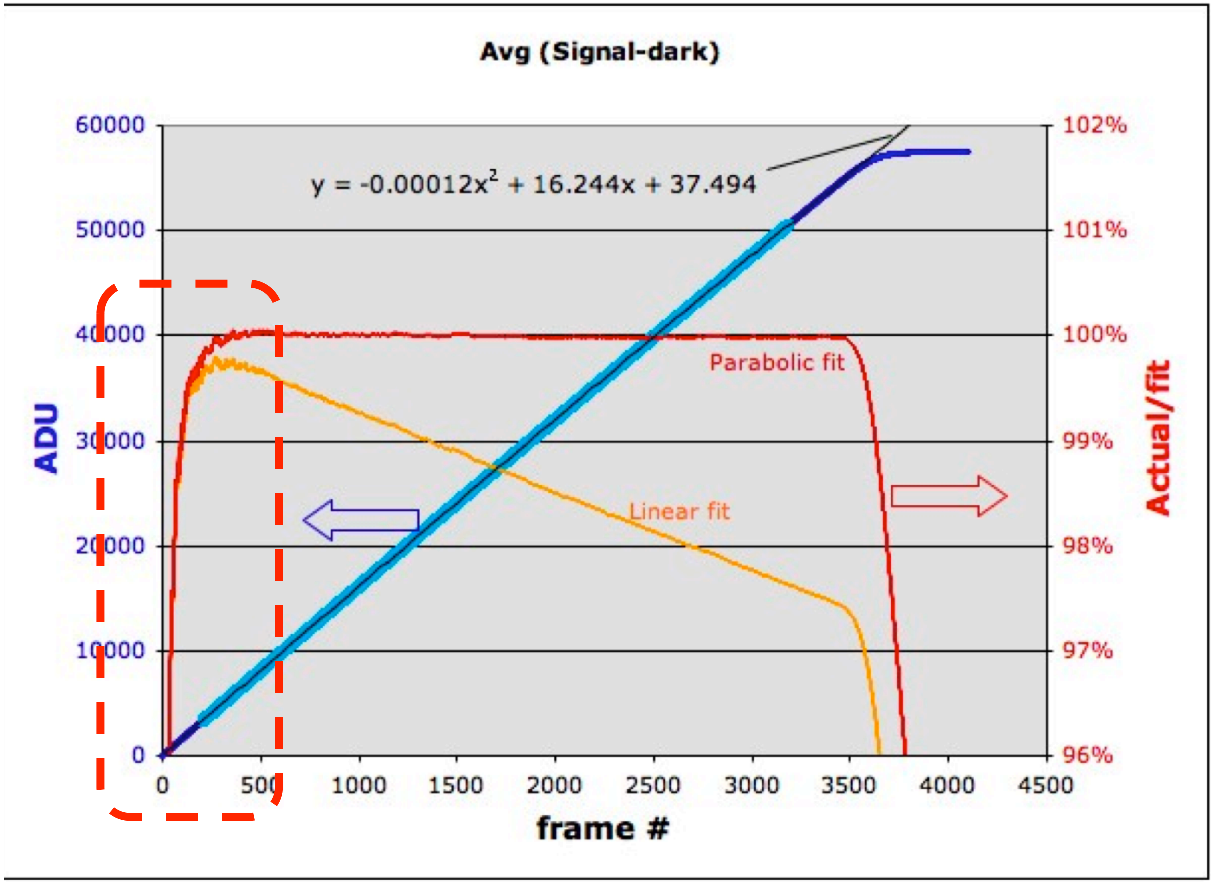
Slows reset and signal




Poster by Tim Greffe:
**This limits effectiveness of reset as electronic dark slide.**

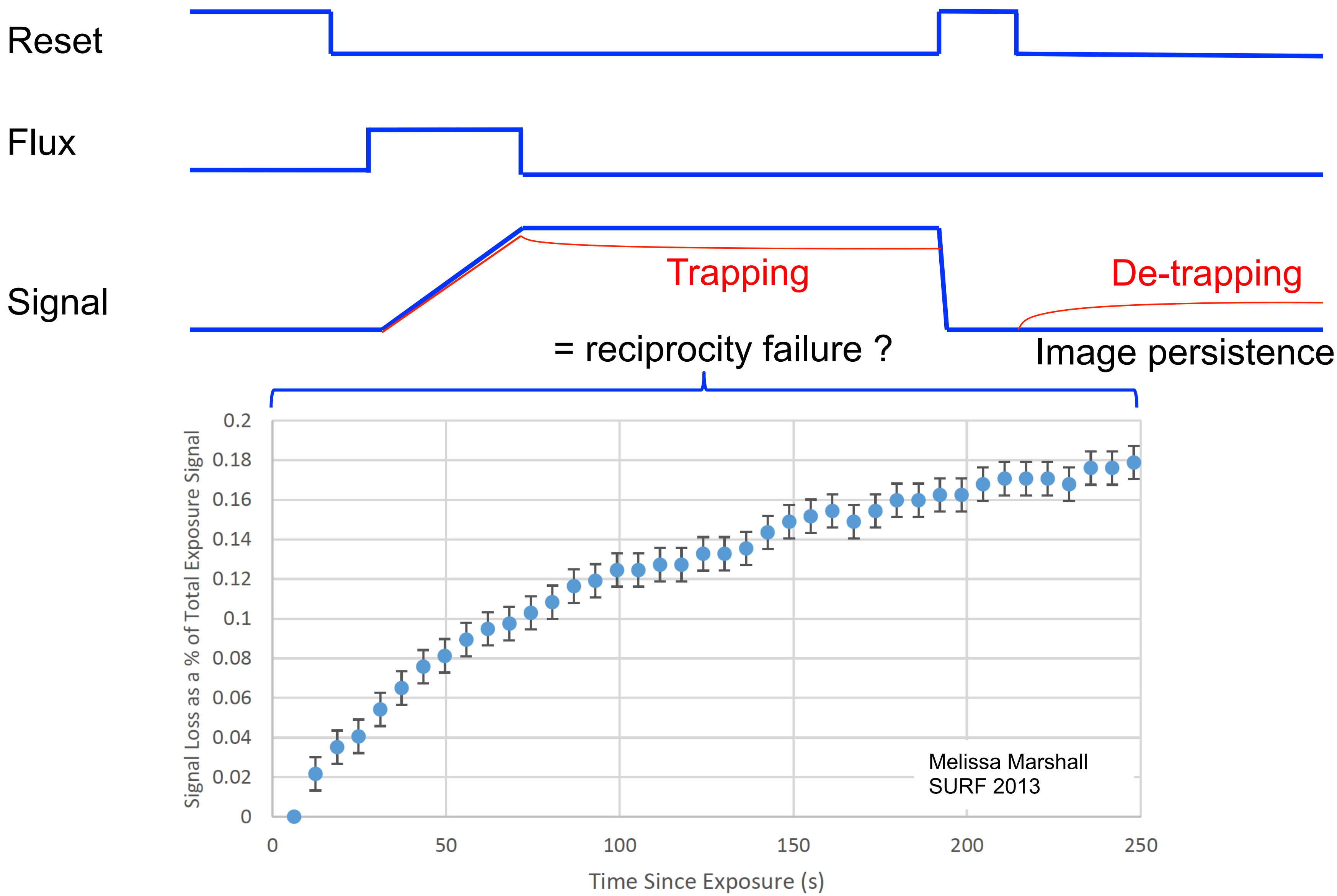
# Initial signal deficit

## Pixel contact resistance ? …. much larger effect and faster settling than charge trapping




- SUTR data acquired at 100 Hz through a single channel. Several illuminated frames were averaged as were several *matched* darks which have been subtracted.
- The fit was derived using the points marked in cyan to eliminate the area affected by the initial signal deficit.
- The quadratic fit is extremely good except for the large deviation in the first 3s (300 frames).

# Signal loss due to charge trapping



# Initial signal deficit (AKA burn in)

Engineering grade H2RG (2.3 μm cutoff from Euclid)

1st frame / 4th frame -1

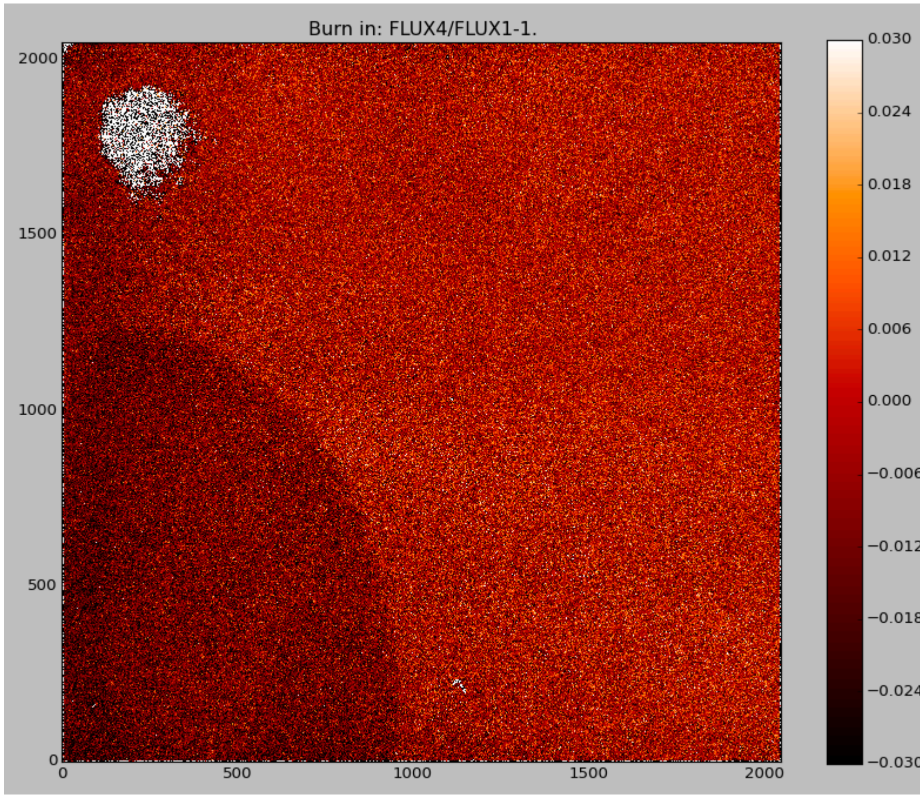
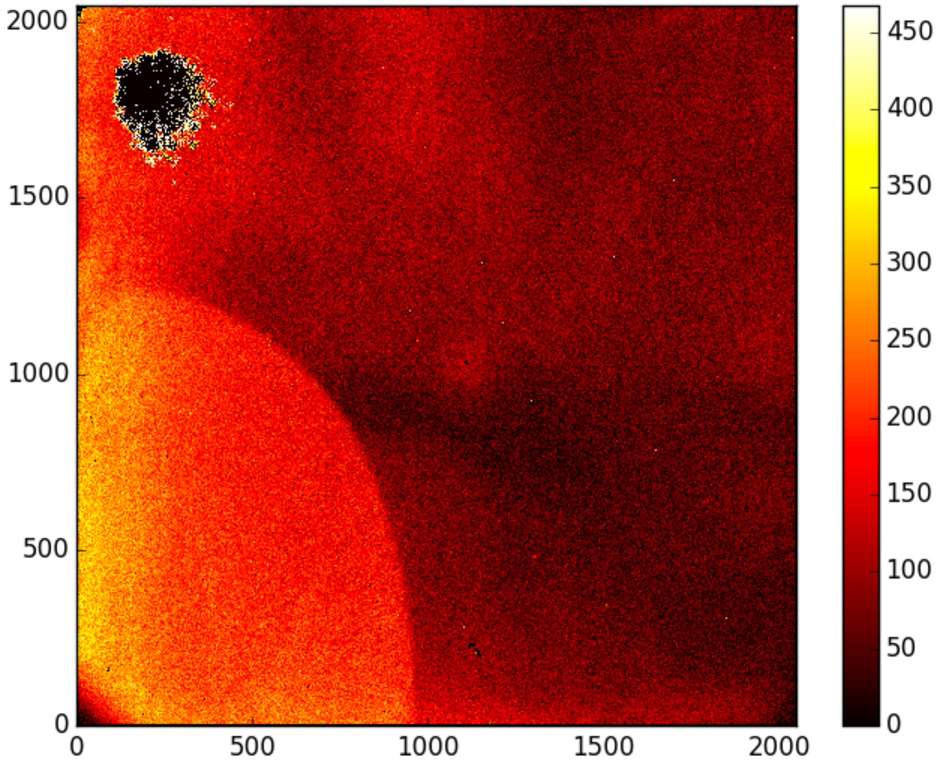



Image persistence




This suggests that charge trapping is dominant cause of initial signal deficit in some areas of this device.

# Read noise

- The *photodiodes* generate more read noise than the ROIC and have much stronger 1/f component, as demonstrated by much lower noise and better reduction by multiple sampling for
  → Permanent reset (shorting out detector noise)
  → Reference pixels
- Is this due to trapping/detrapping?
- Contact resistance is about the correct magnitude to produce about this much Johnson noise.
  - This is worth investigating since lower contact resistance could improve both dynamics (linearity) and noise.

See Bernie Rauscher's talk

# Linearity

Rarely is this well characterized and corrected

- First, subtract *time-dependent* offsets
  - Self heating (minimize by Constant Cadence Clocking)
  - Electronic drifts (reference pixels help)
  - Reset induced (de)trapping
- Correct for dependence of capacitance on voltage
- Correct for trapping of charge (complicated)
- Correct for photodiode time-constant (contact resistance)

Everything is spatially variable.

# To do list

- Characterize contact resistance and its consequences
- Study burn-in and reciprocity failure to see how much comes from contact resistance an how much from trapping.
- Evaluate noise produced by dark current at floor.  Hot pixels may be noisier.
- Improve linearity calibration methods and/or fix these odd behaviors which make linearity correction so difficult.