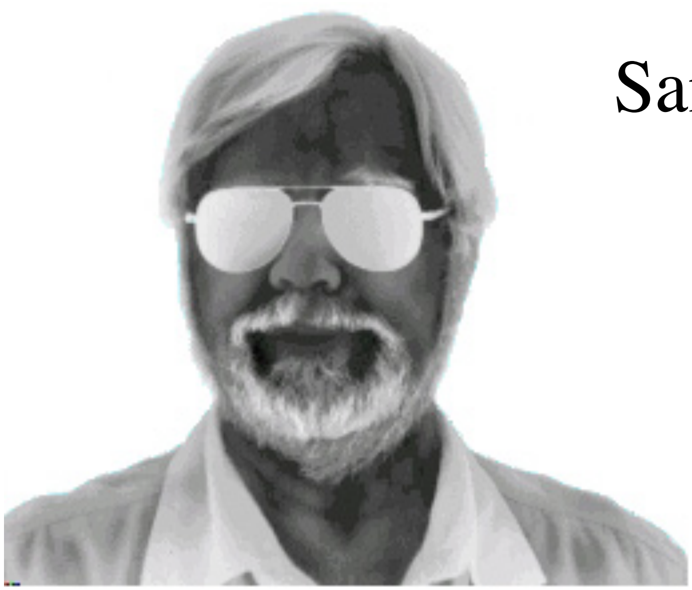
Infrared detectors

Paul Norton
Santa Barbara, CA



Outline

- Norton's Law of infrared detectors
- Brief status of cooled infrared detectors and current issues
  - HgCdTe
  - Type II strained-layer superlattices
  - MWIR detectors
  - SWIR detectors
- The origin of 1/f noise
- NEΔT for dummies

Norton's Law and the Project Uncertainty Principle

"All physical phenomena in the range of 0.1-1 eV will be proposed as an infrared detector"

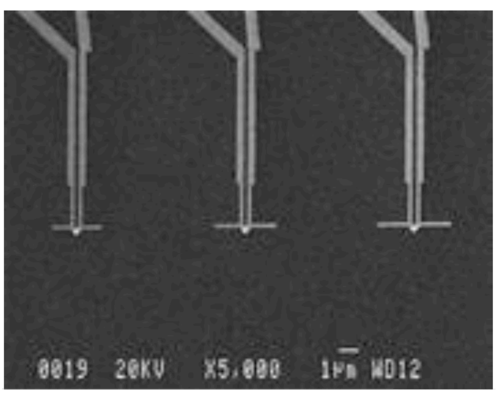
Corollary to Norton's Law—

"No phenomena proposed as an infrared detector will fail to find a sponsor"

project uncertainty principle

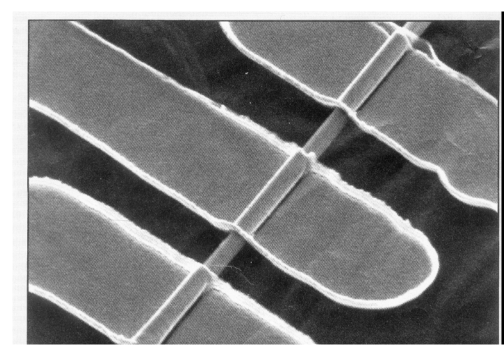
Norton’s Law data (*predictions)

- Thermocouples
- Golay cells
- Photon drag effect
- Quantum wells
- Superlattices
- Josephson junctions
- SQUIDs
- Ballistic electron transistors
- Quantum dots
- Protein microbolometers
- Giant magnetoresistance*√
- Quantum entanglement*
- Polyvinylidene flouride
- Ferro- and pyro-electrics
- Antenna-coupled Shottky diodes
- Metal-semiconductor-metal junctions
- Resonant tunneling diodes
- Thallium-indium-phosphide/arsenide
- Bimaterial cantilevers
- Nanowires
- Organic semiconductors*√
- Nanotubes*√
- Bose-Einstein condensates*



Antenna-coupled
MOM detectors

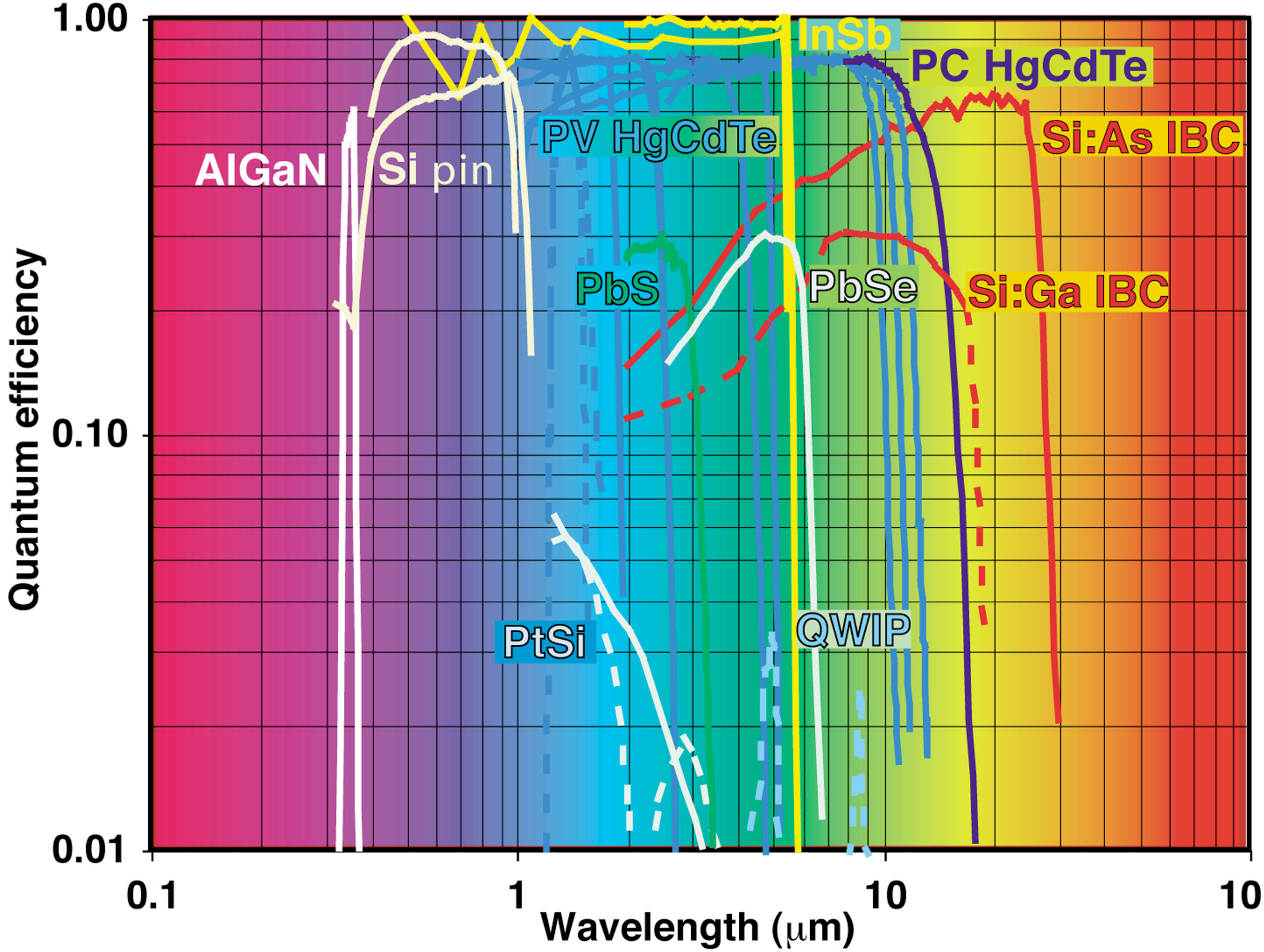
ZnO nanowires



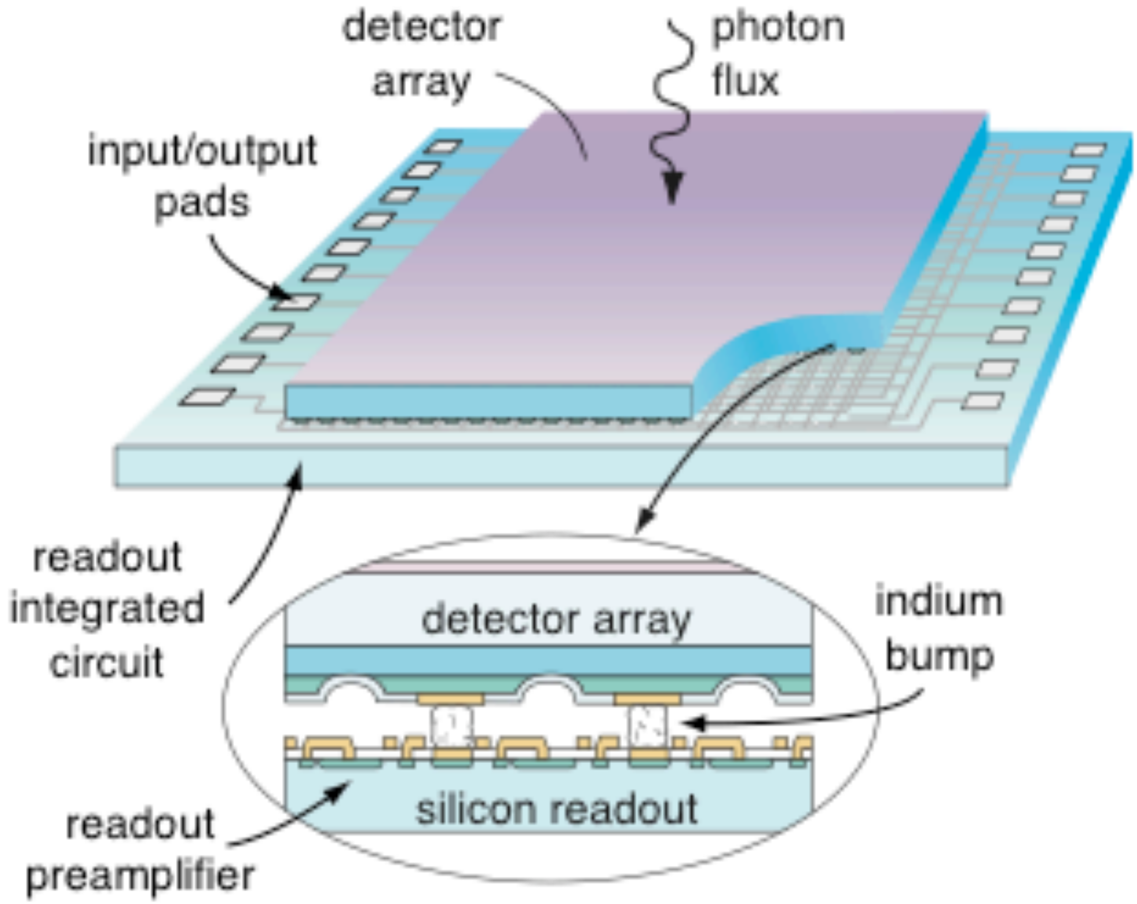
Requirements for a good detector

- Large $\alpha\tau$ product
  - where α is the absorbtion coefficient and τ is the minority carrier lifetime

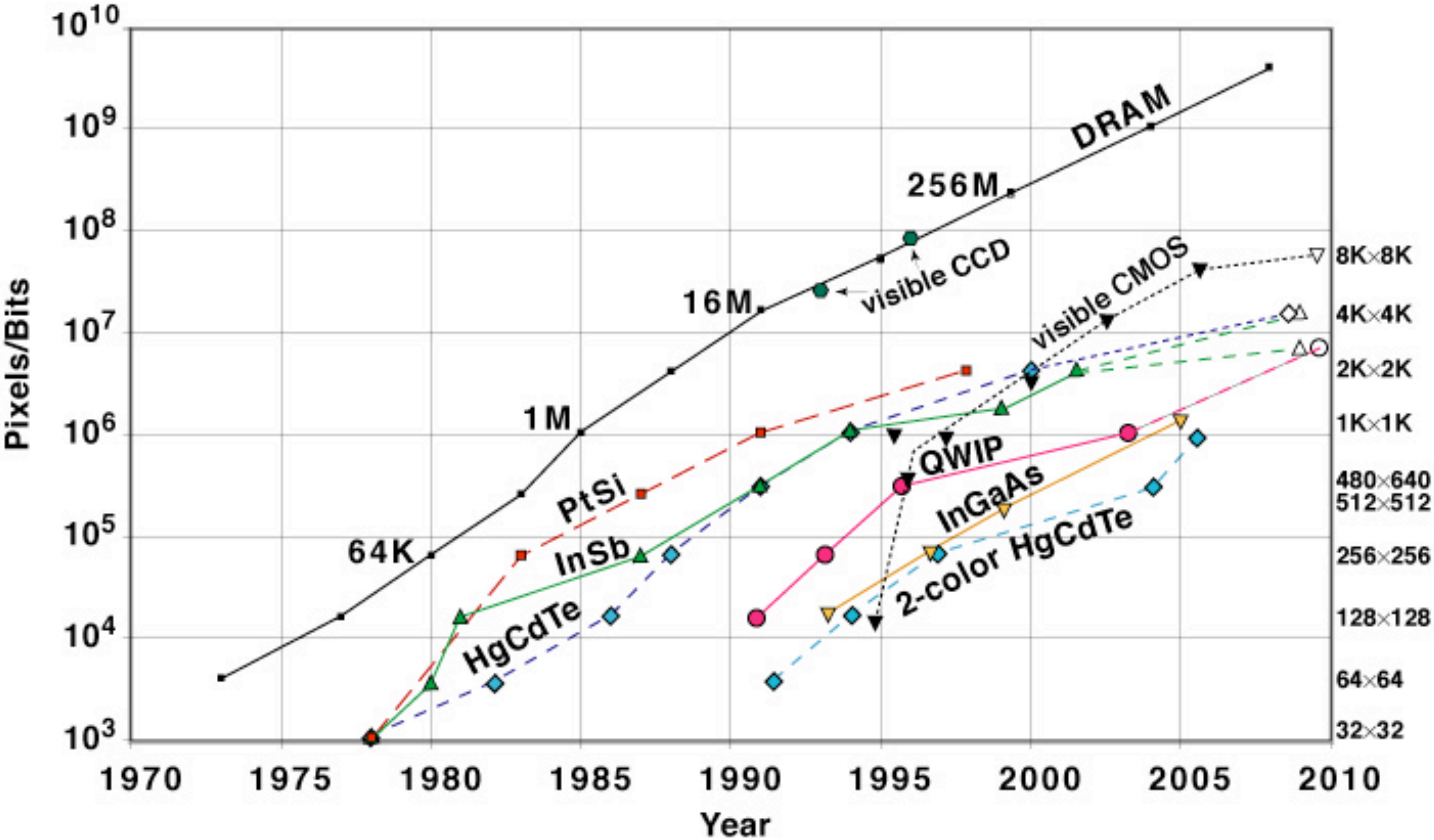
Photon detectors



Hybrid detector structure

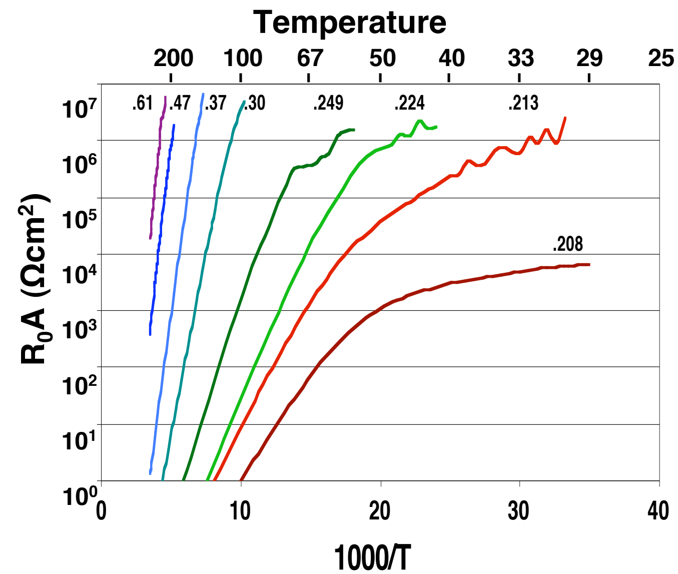


Detector size progression

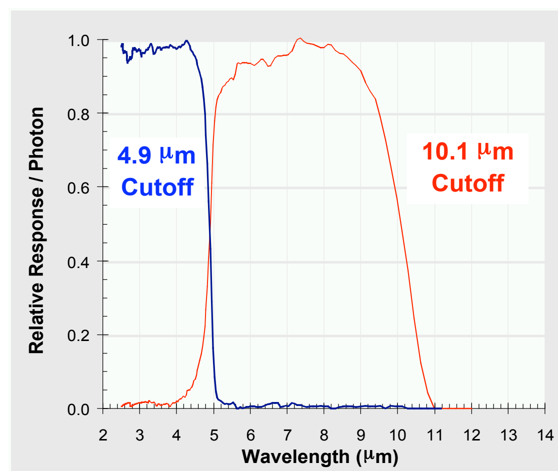


Status of HgCdTe

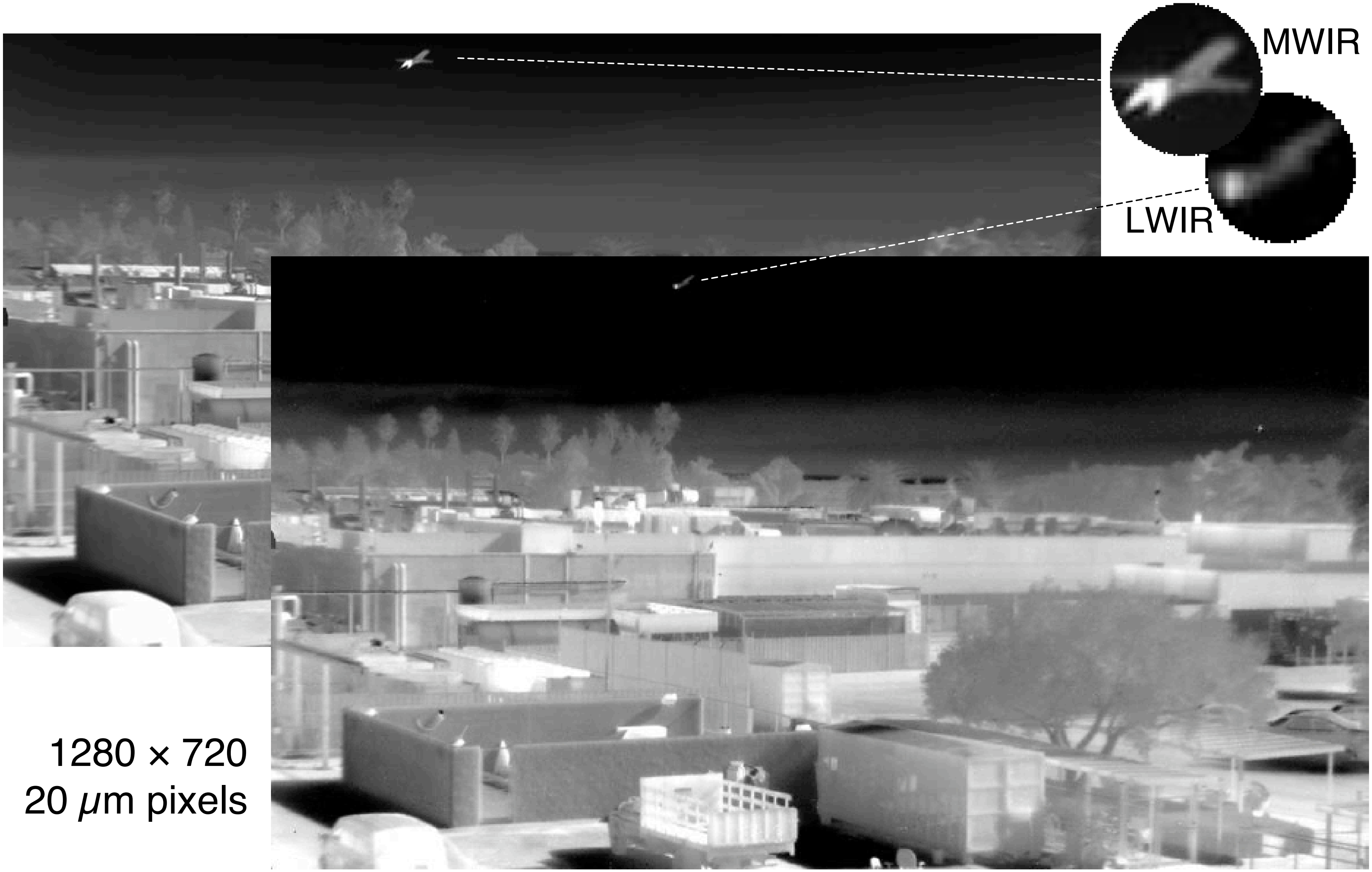
- Most versatile and widely used detector
  - 0.8 to >20 μm coverage
  - Approaches theoretical limits for many situations
  - Maturing dual-band capabilities
    - MWIR/MWIR and MWIR/LWIR
  - Growth on Si and GaAs substrates has made very large arrays possible
    - 4K × 4K



MWIR/LWIR

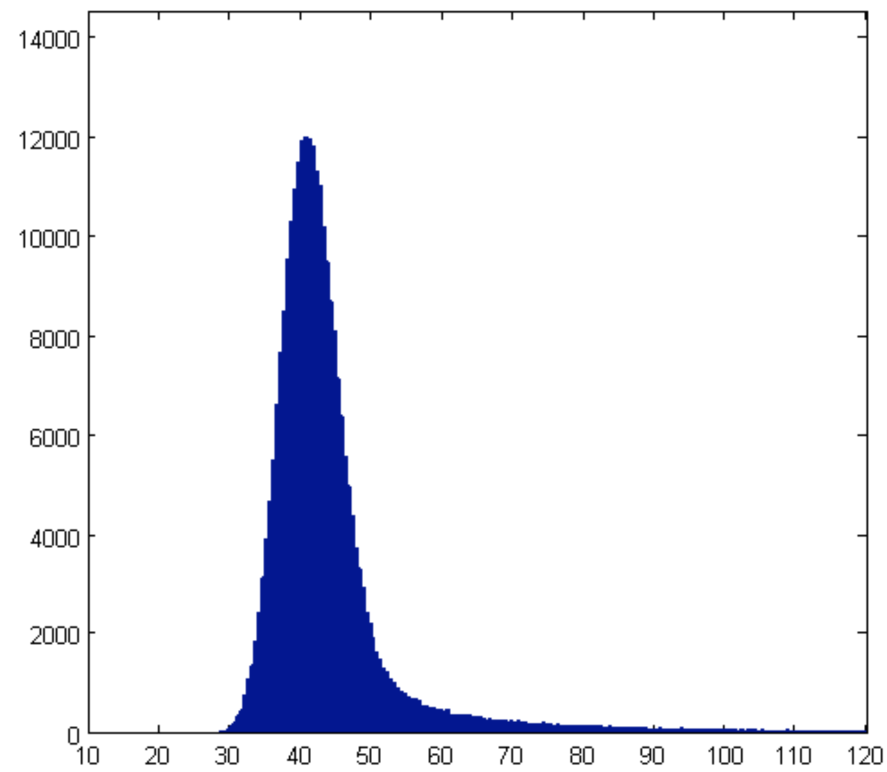


Two-color images in 1280 × 720 format



HgCdTe issues

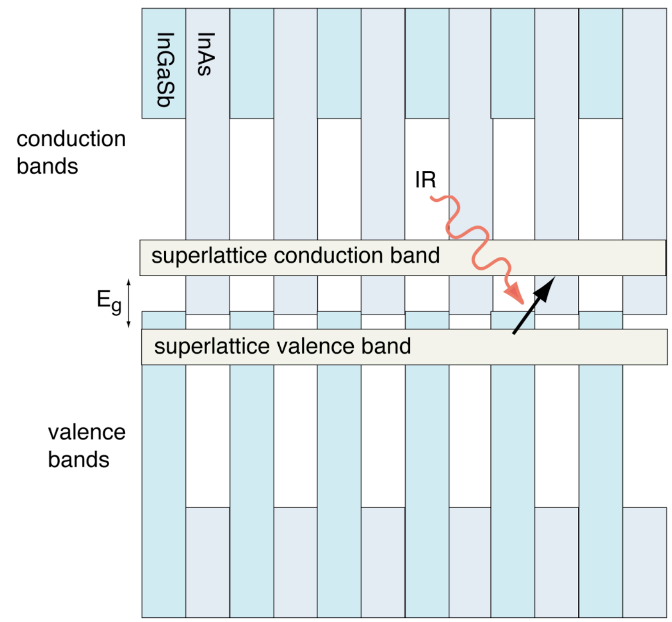
- Cost is high on CdZnTe substrates
  - But very competitive on Si or GaAs substrates
- LWIR on Si and GaAs has significant high noise tail
- VLWIR yield is low for the most demanding applications

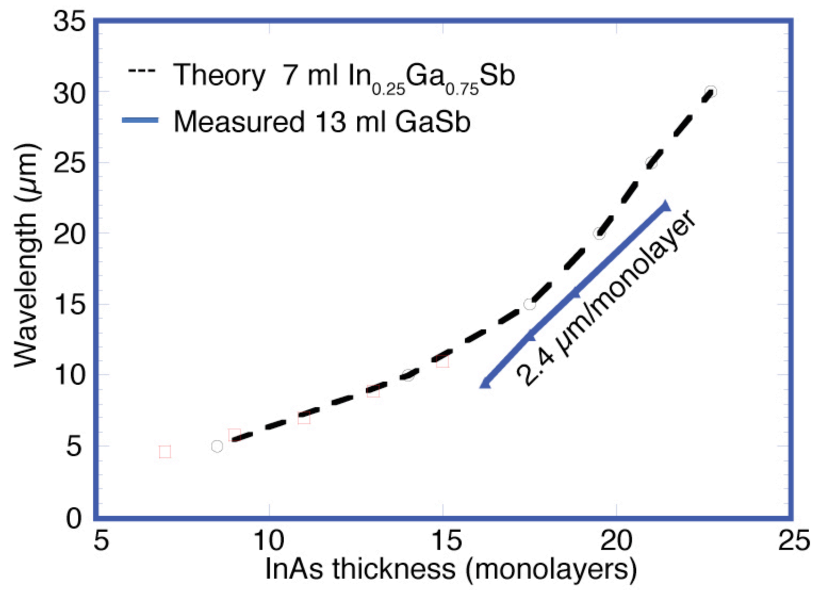


NEΔT of MCT on GaAs at f/6

Type II strained-layer superlattices

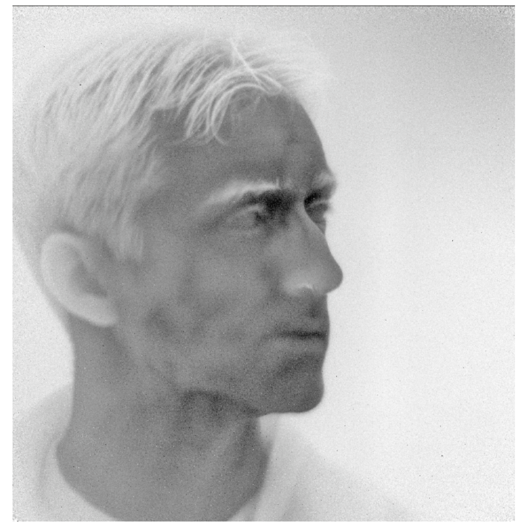
- Potential replacement for HgCdTe
  - Theoretically longer lifetime—but LWIR lifetimes are currently <100 nsec which MCT is >1 μsec
- Flexible spectral range—artificial bandgap made by varying the thicknesses of InAs/(In)GaSb layers
- AIM (Germany) has begun production of a dual-band MWIR/MWIR detector array for the European A400 transport plane



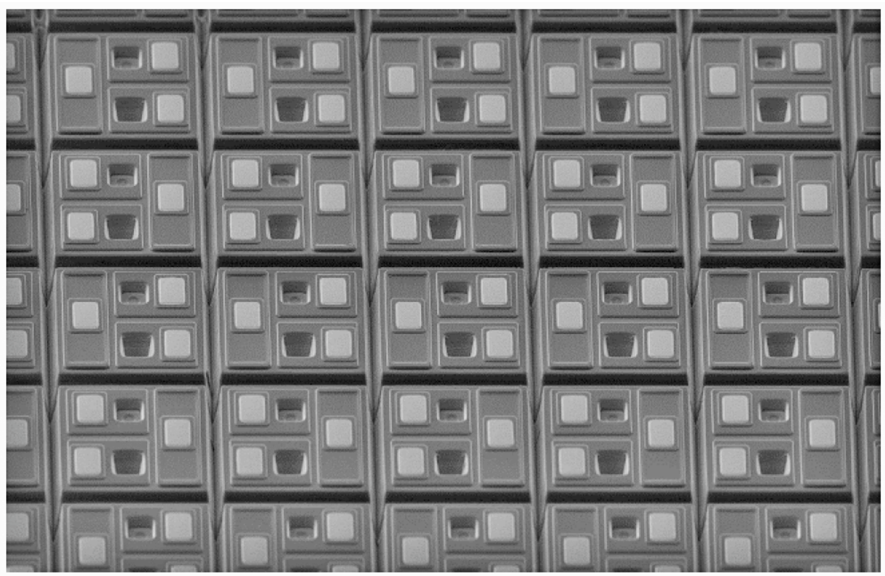


Type II SLS issues

- The short lifetime gives large dark currents
  - The origin is has not been determined yet
  - Developers have been incorporating majority-carrier barriers to limit the dark current
- GaSb substrates only developed to 4-inch



1024^2 SLS MWIR image with 19 μm pixels —JPL/RVS

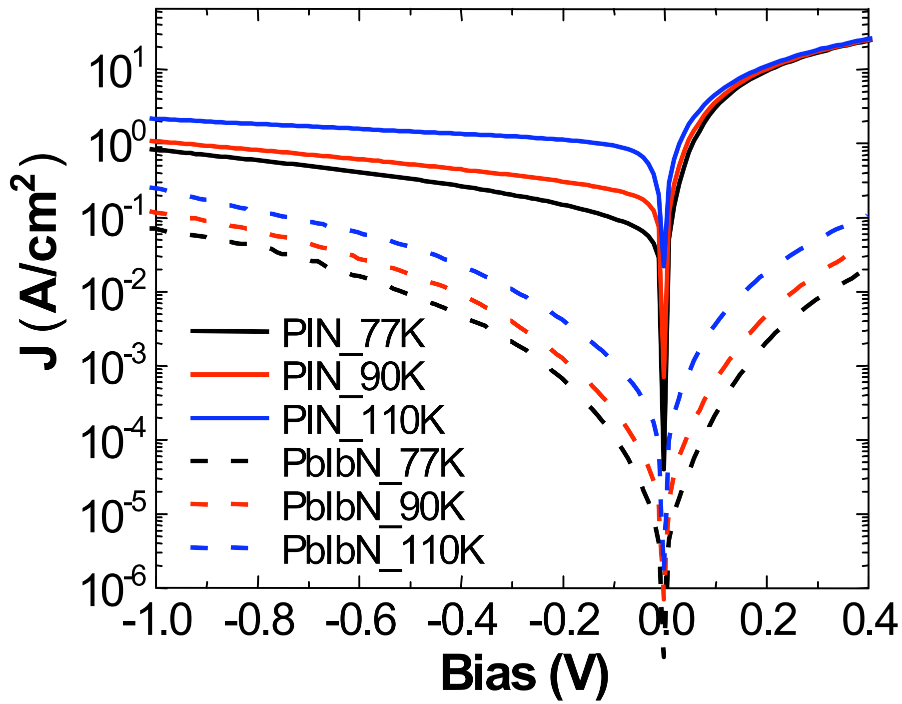


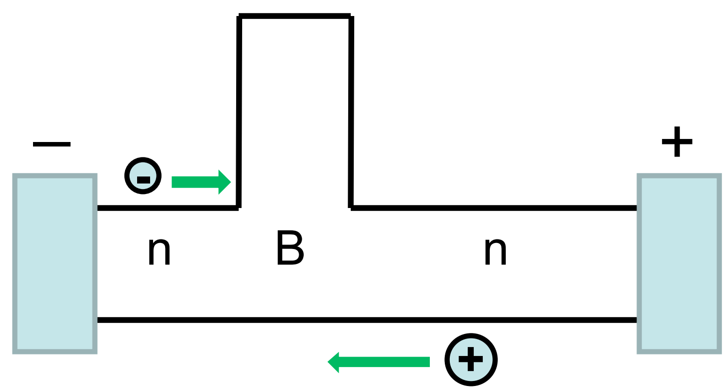
Dual band Type II SLS MWIR/MWIR array pixels —AIM

MWIR detectors

Contenders—InSb, HgCdTe, Type II SLS, and xBy

- InSb is very mature but needs to be cooled to <90 K
- MCT on Si can be cost competitive
  - Operating temperature to >150 K (maybe >200 k)
  - Long lifetime— >10 μsec
- Type II SLS going into dual band production
- xBy (e.g. nBn or pBn) provides blocking to compensate for short lifetime and provides quasi-passivation





Barriers

- Being deployed in both Type II SLS and xBy structures
  - Localize wave function to increase overlap in Type II SLS
  - Block majority carrier currents
  - Provide quasi-passivation
    - Blocks majority carriers from free surfaces, but does not block minority carriers

SWIR detectors—potential replacement for night vision goggles

Contenders—InGaAs, HgCdTe, and Ge

- InGaAs grown on InP is currently highly developed out to 1.7 μm
  - Performance degrades for $\lambda > 1{,}7$ μm due to InP lattice mismatch
  - Limited InP substrate size
- HgCdTe
  - R_0A products lower than InGaAs with 1.7 μm cutoff
  - Performance does not drop going to longer λ
- Ge
  - Indirect bandgap limits absorbtion near bandgap
  - Can be integrated with Si circuits at some foundries
    - Wafers up to 12 inches grown on Si

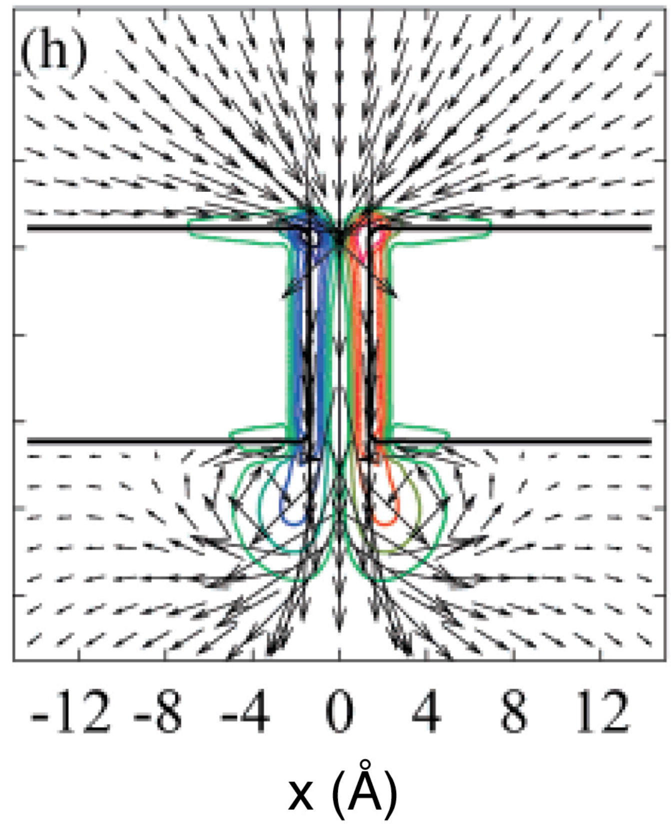
SWIR imagery

- Achieving absolute minimum dark current and low readout noise

InGaAs SWIR image from a 640 × 512 array (with help from Photoshop shaddows/highlights adjustment) under “minimal street lighting” conditions with f/1.4 and t_{int} = 30 ms —Aerius

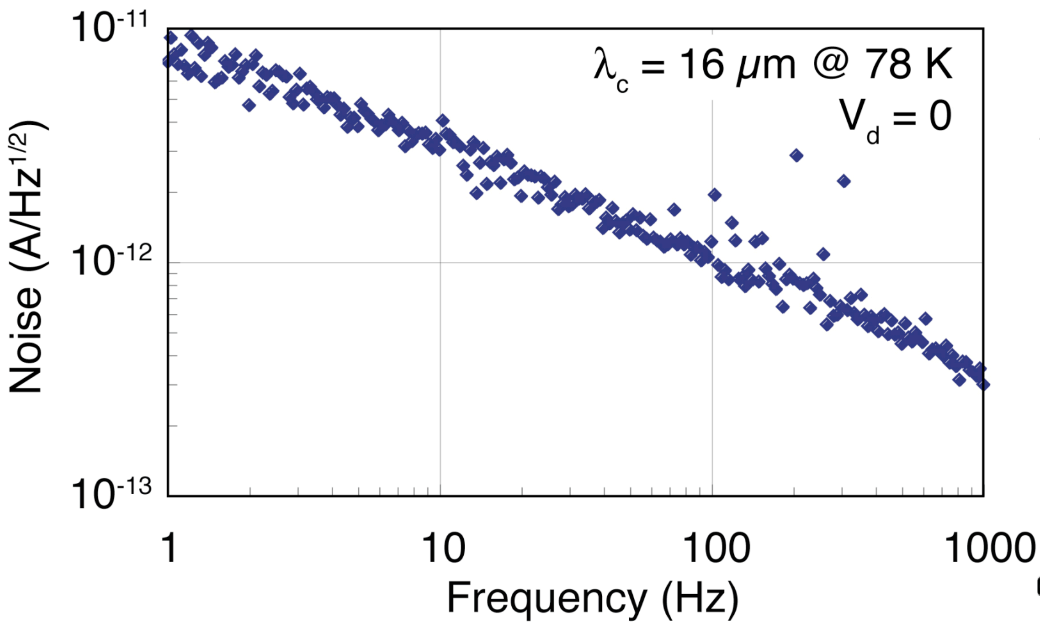
The origin of 1/f noise

Recent mathematical modeling of electron transport using the Navier-Stokes equation has shown that for certain geometrical flows, the onset of turbulence occurs at very low Reynolds numbers

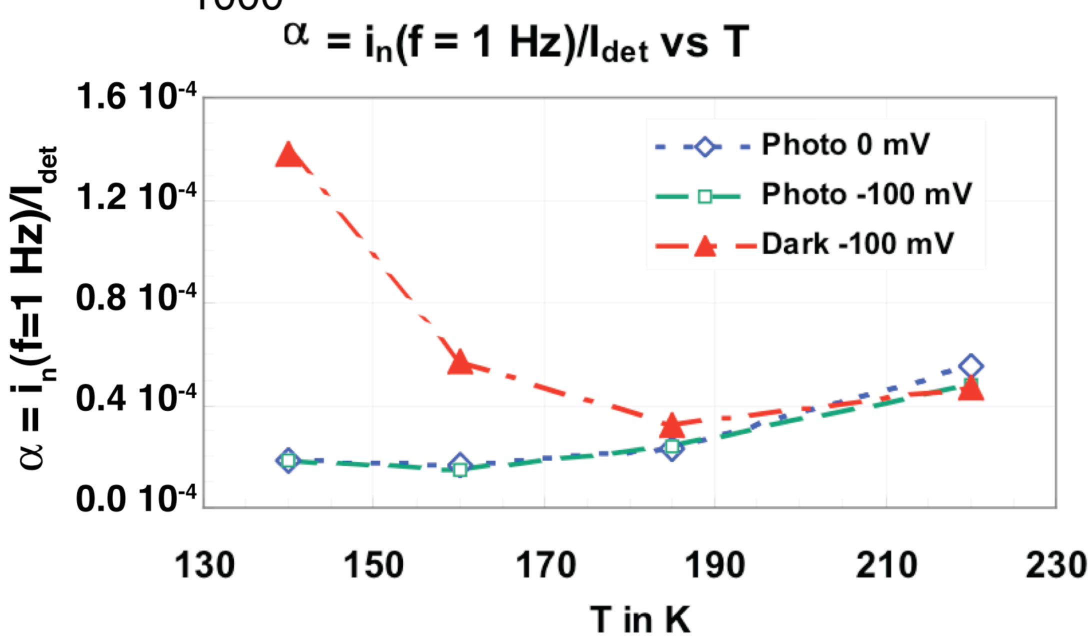


R_e was 32.5 for this case

Recent data from D'Sousa



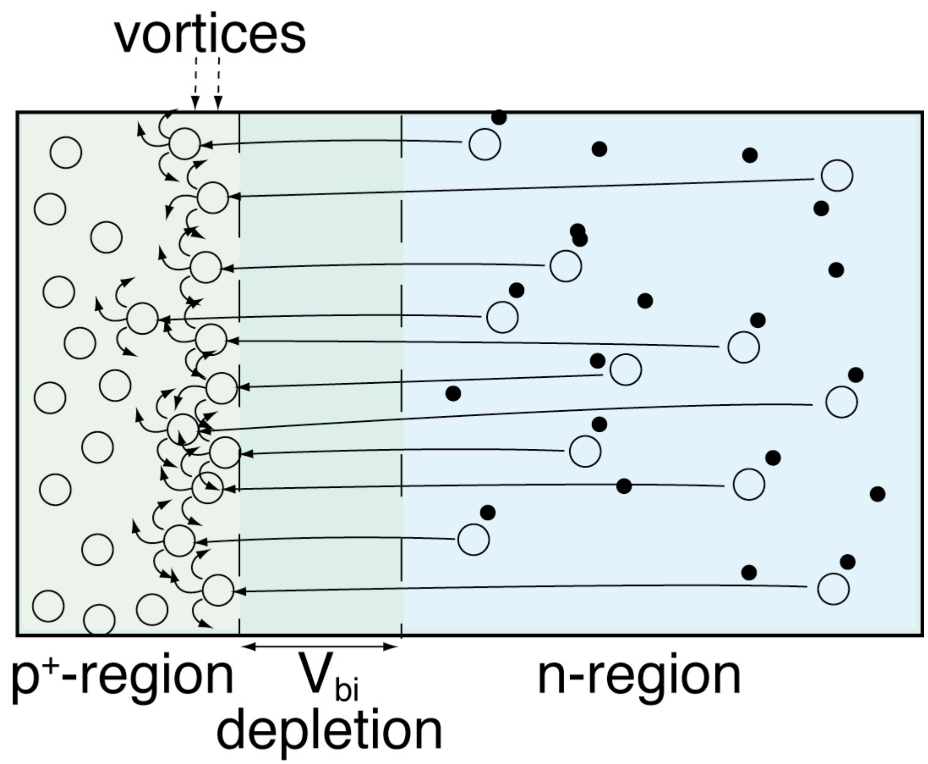
1/f noise from photocurrent at zero bias



Strength of g-r currents in producing 1/f noise is much greater than that of photo- or diffusion currents —higher α value

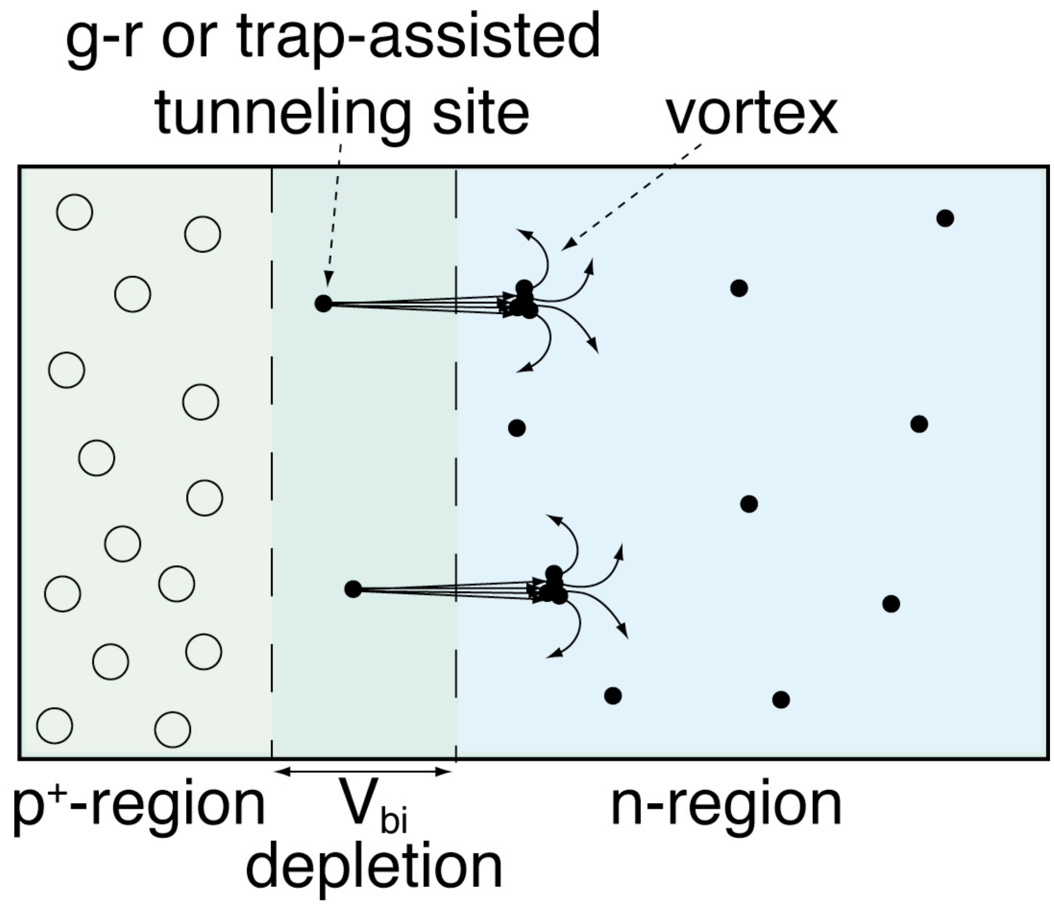
Consider flow from diffusion- or photo-curent

- Flow is uniformly-distributed across junction
- Turbulence from adjacent regions will screen (damp) each other
- Reynolds number may be several thousand



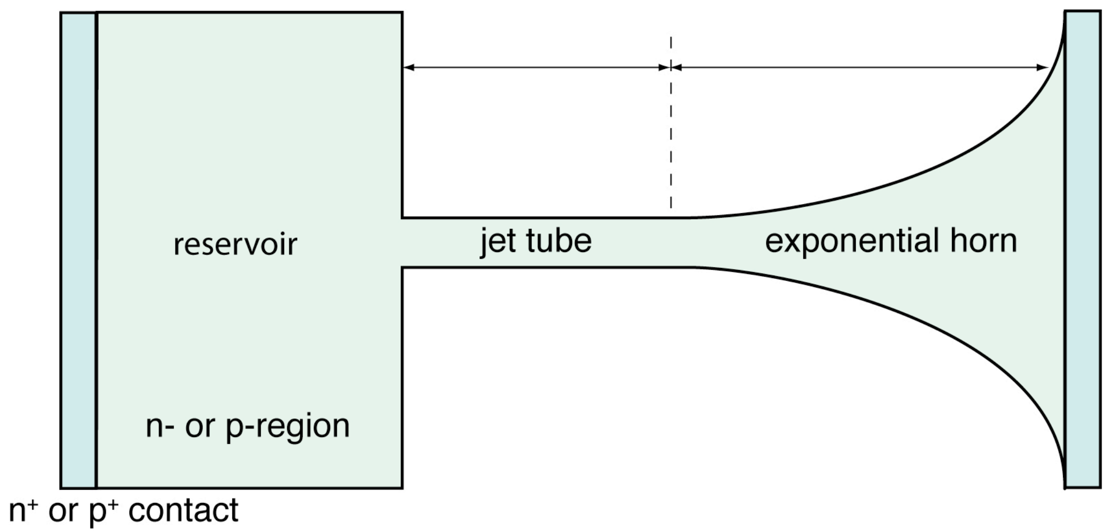
Consider flow from g-r or trap-assisted tunneling (TAT) centers

- Originates from a few points in the depletion region—probably close to the plane of maximum electric field
- Flow jets are isolated from each other
- Note—all the current comes streaming from a very few locations
- Reynolds number may be quite low



Proposed test structure

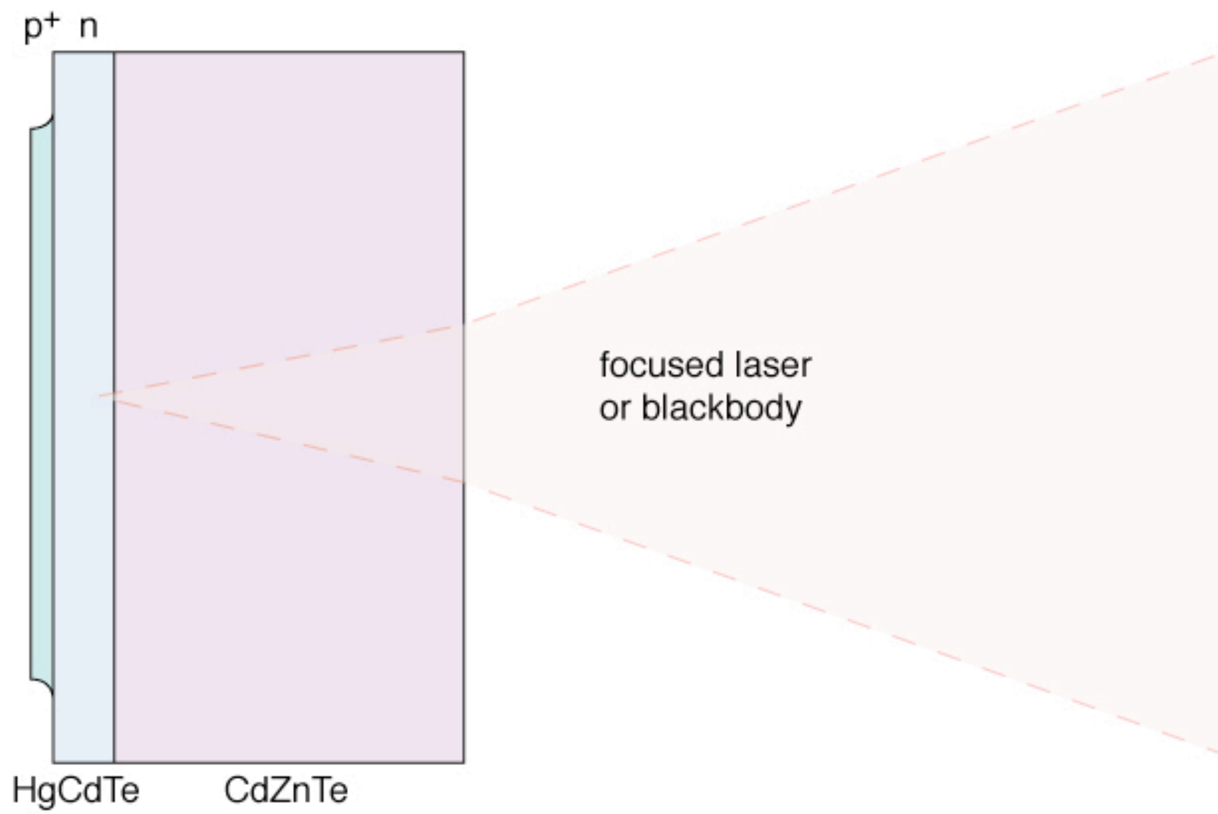
- Measure 1/f noise vs bias direction in a test structure with asymmetrical design
  - Flow into reservoir should be much more turbulent than into an exponential horn



Alternative test

- Mimics point source generation
- Compare with flood illumination from the same source

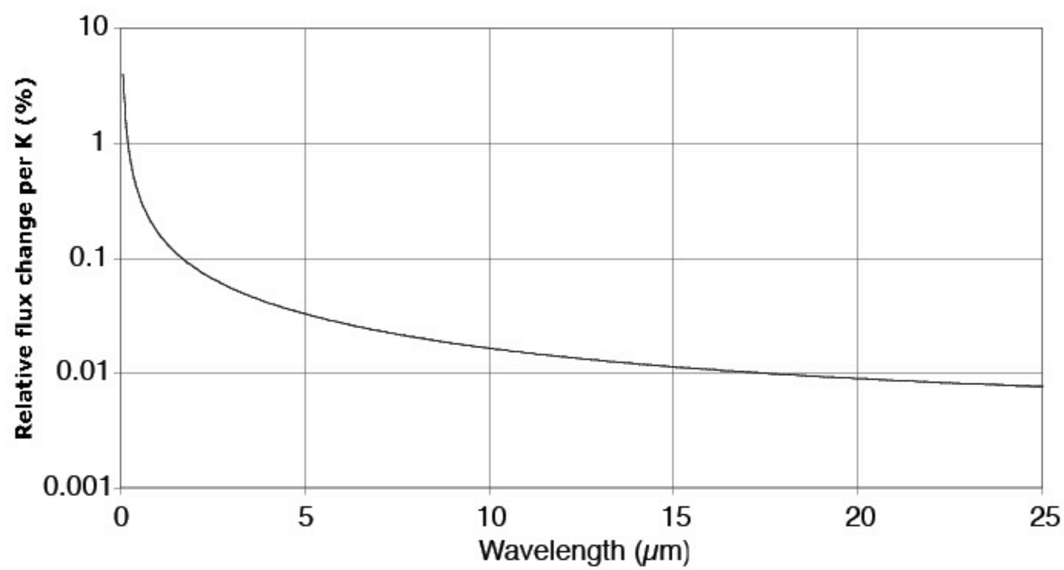
  - suggested by W. Tennant



NEΔT for dummies (like me)

- First consider the flux change for a change of 1 K at 300 K
  - This case is for 300 K with an f/2 field of view
- Note that rows 5 and 6 are independent of f/#

Quantity	Value
LWIR photon flux at 301 K	1.20345×10^{16}
LWIR photon flux at 300 K	1.18210×10^{16}
Δ flux	2.13532×10^{14}
Contrast = Δ flux/300 K flux	1.8 %
S/N = 300 K flux/Δ flux	55



Counting statistics for a Poisson distribution

- $S/N = \eta^{1/2}N/N^{1/2} = (\eta N)^{1/2}$
- Consider a detector with high quantum efficiency coupled to a readout having a well capacity of Q electrons
  - It is common practice to half-fill the well during an integration to maintain room for signal
  - So $S/N = (\eta N)^{1/2} = (\eta Q/2)^{1/2}$
  - We also need to add another factor of $1/2^{1/2}$ to adjust for bandwidth

An example

- Consider a readout with 2×10^7 capacity
- If we half fill it, we get a S/N of 3162 or a sensitivity of $3162^{-1} = .031\%$
  - Referring back to the table, we see that we need a sensitivity of 1.8% to detect 1 K
- $NE\Delta T = (2\eta)^{1/2} \times .03/1.8 = 24$ mK for $\eta = 1$

NEΔT for dummies