Near Infrared Detectors

AST 542 Claire Lackner April 6, 2011

Quick History

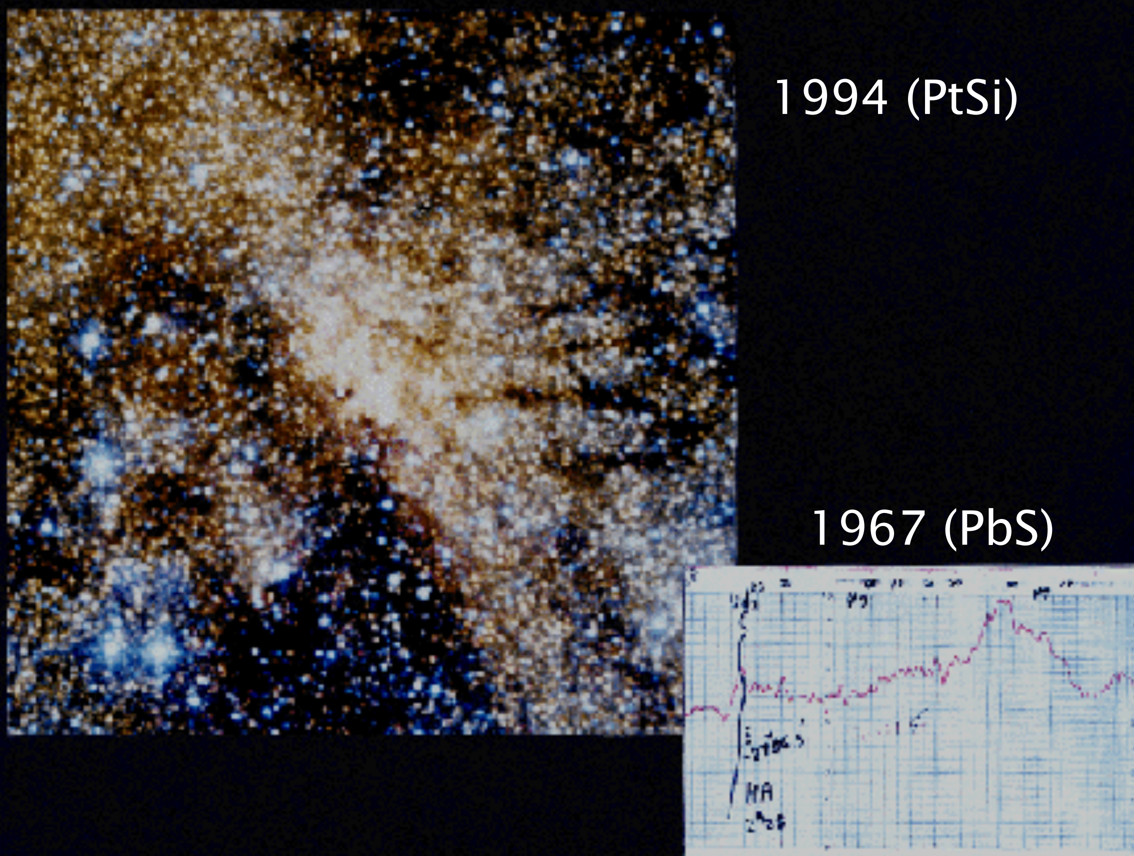
- William Herschel—discovered IR (1800)
- 1950s–PbS detectors invented
- Invention of Ge:Ga bolometer (Low, 1961)—Chelsea's talk
- PbS cell used for TMSS (Leighton and Neugebauer, 1969)—4' resolution, 20,000 sources
- IRAS—1983
- 1980's—first detector arrays
- most major telescopes have IR cameras

Improvements in IR

The Galactic center

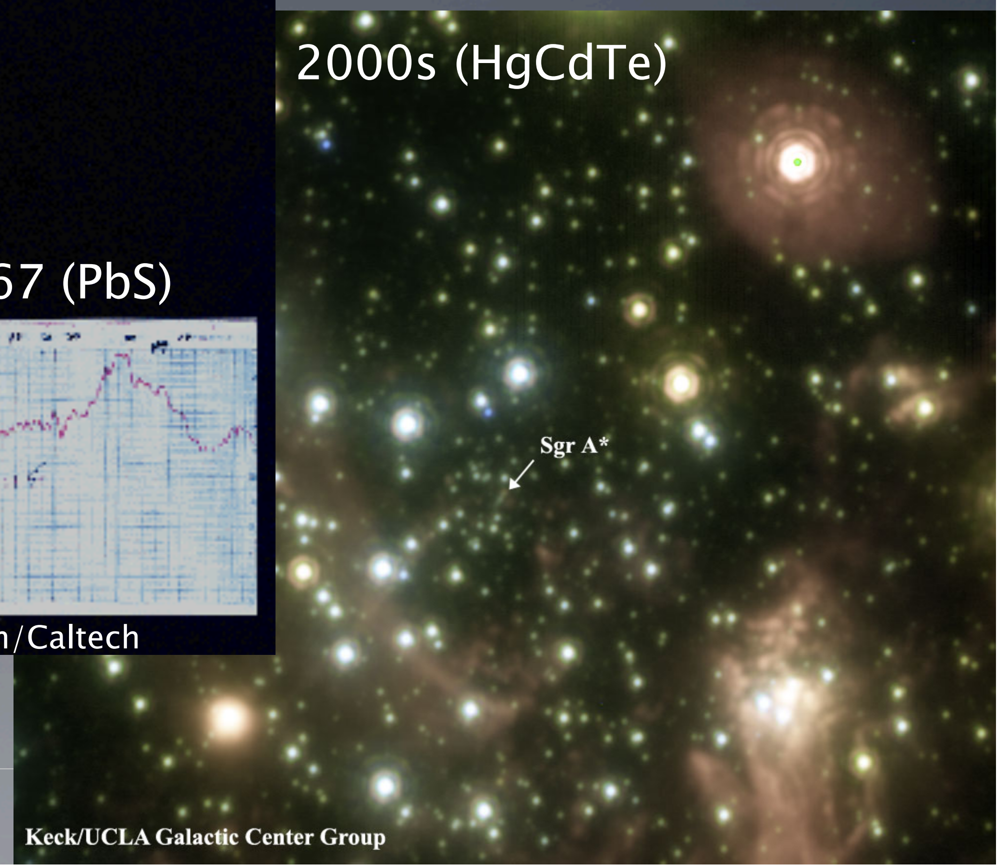
1994 (PtSi)

1967 (PbS)

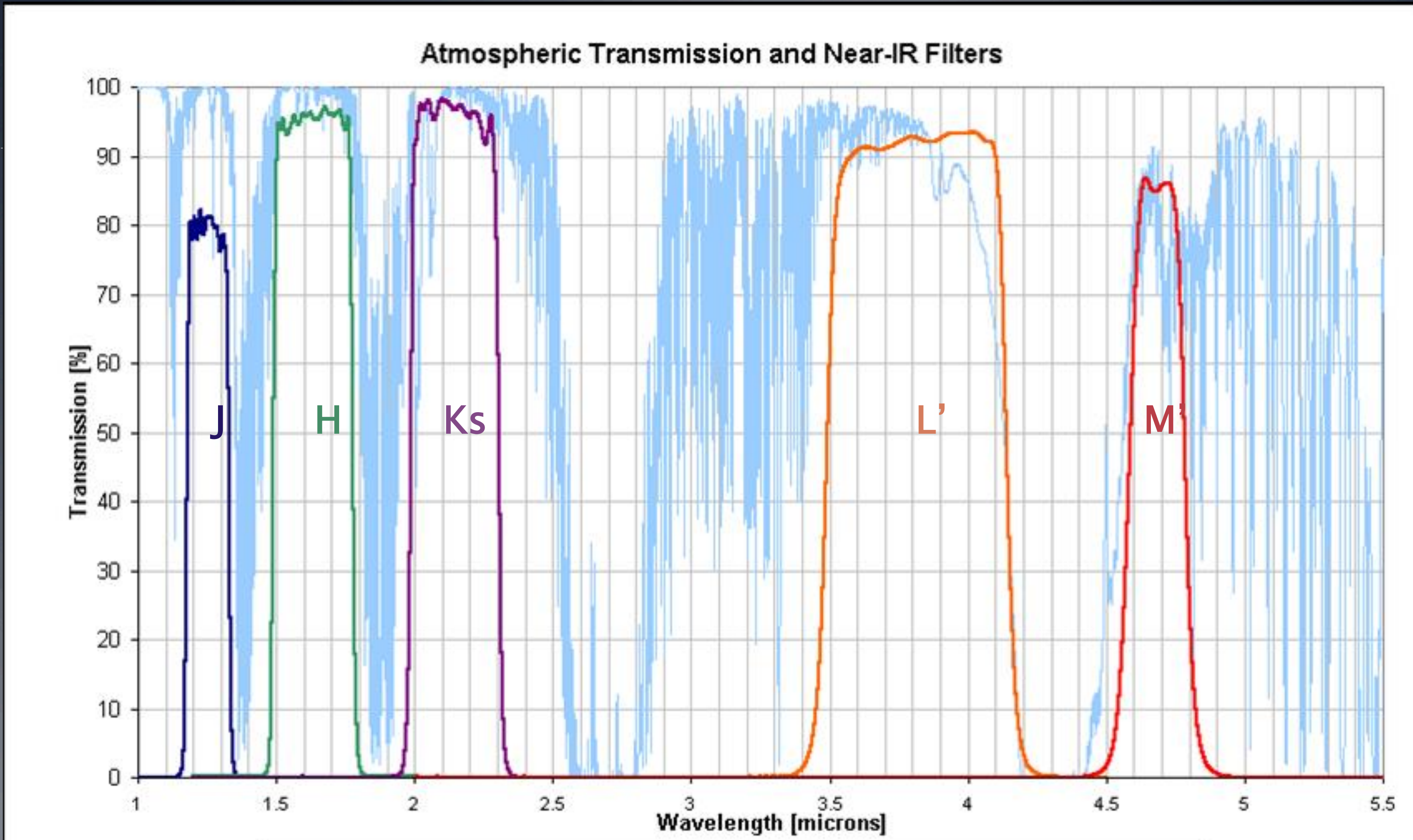


I. Gatley/NOAO/KPNO, (inset) G. Neugebauer & E. E. Becklin/Caltech

2000s (HgCdTe)



http://legacy.spitzer.caltech.edu/about/techdev.shtml



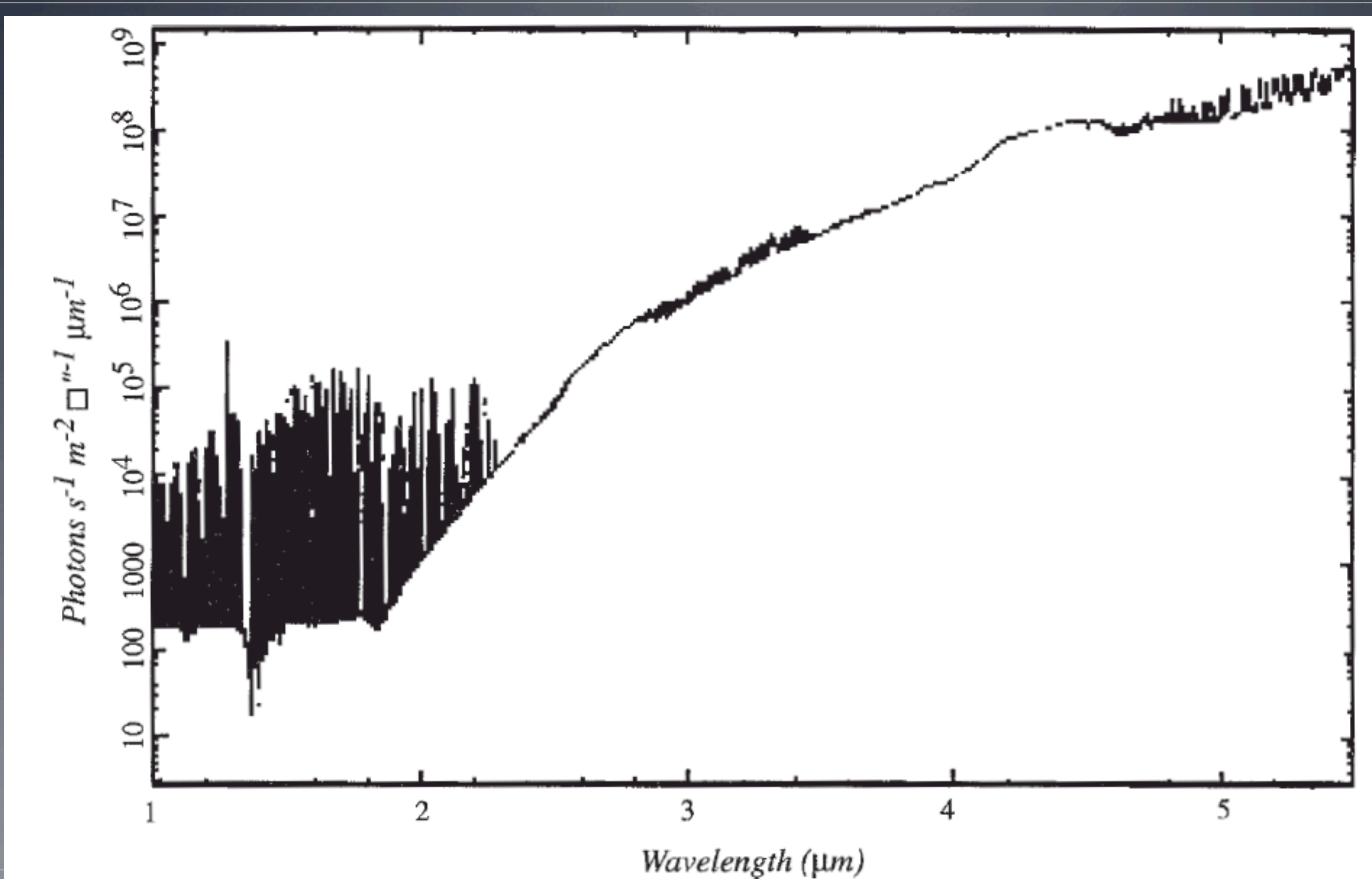
http://people.bu.edu/clemens/mimir/atmospheric_transmission.htm

Also: N~10.6 μm and Q~21μm

IR from the ground

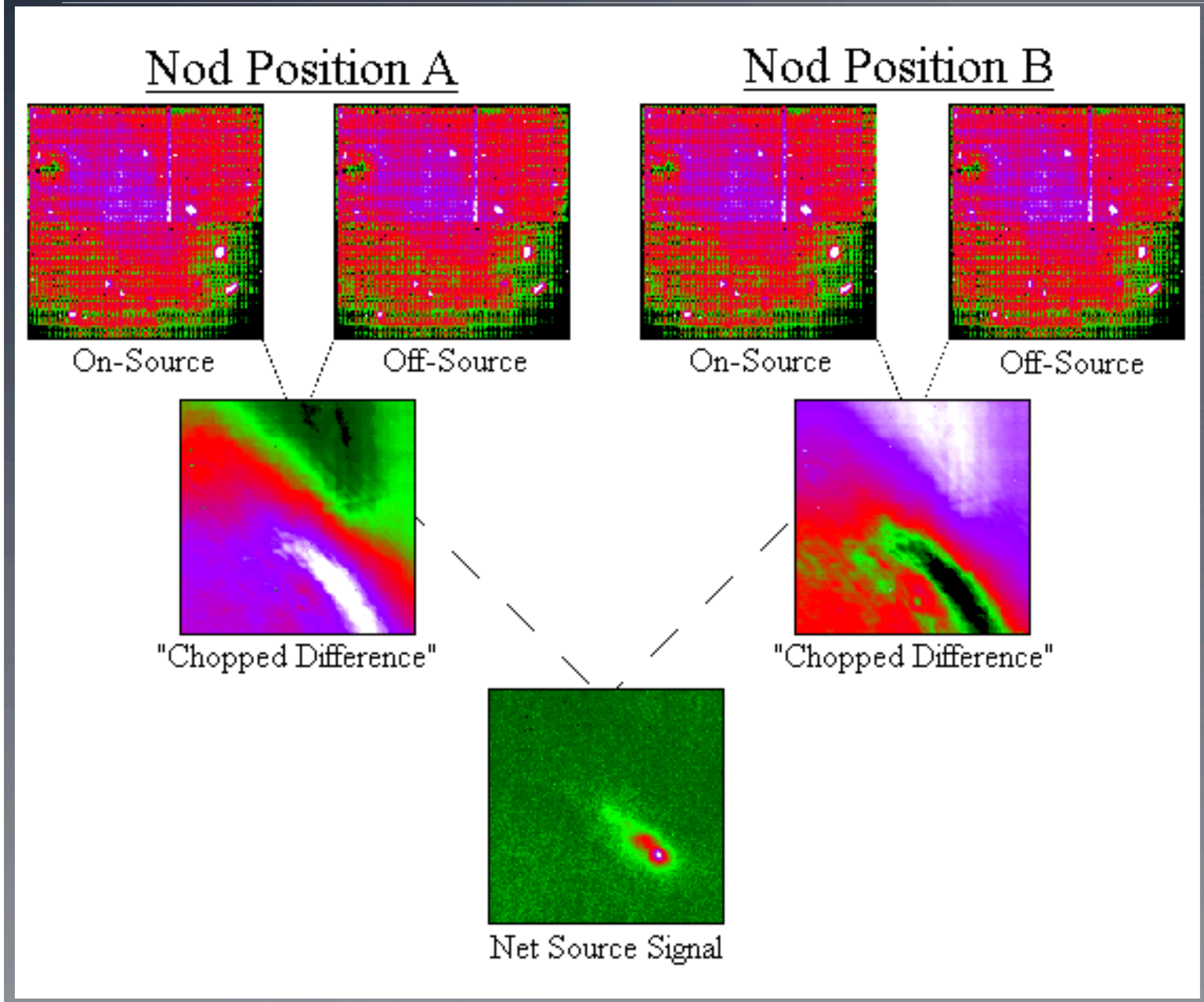
- windows between H_2O and CO_2 absorption lines
- transmission better at high altitude
- Atmospheric emission (Tim's talk):
  - airglow from OH bands, significant at JHK (1–2 μm)
  - thermal emission from telescope, optics, and atmosphere
- Sky brightness, u: m≈24 (no Moon), 2.2 μm: m≈13.5, 10 μm: m≈−3

UKIRT IRCAM sky bright



Leinert, 1998 & Beckwith, 1994

Chopping and Nodding



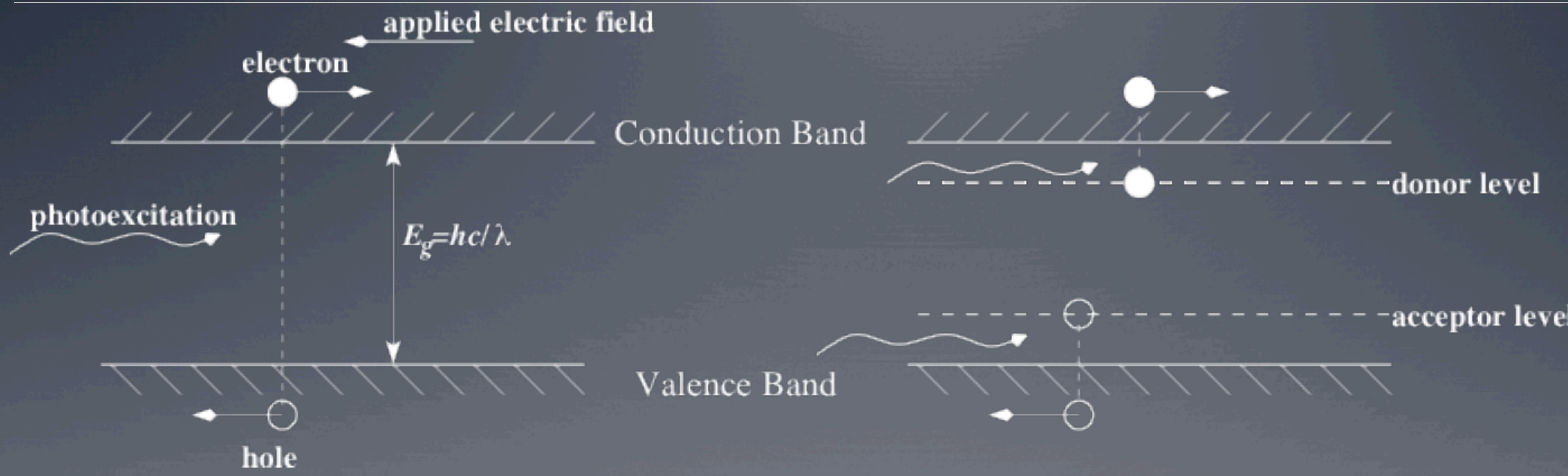
- Chopping—secondary mirror wobbled (few Hz)
- Nodding—move entire telescope to 'switch' chop positions (1-2 /min)
- Essential for λ>3.5μm
- IR telescopes have small (gold-coated) secondaries, slow f/ ratio

http://www.gemini.edu/sciops/instruments/michelle/imaging

5 detector steps (Beletic)

1. Get the light in
2. Generate charge—absorb photon
3. Collect charge (photodiodes—p-n junctions, Schottky barriers—metal-semiconductor junctions)
4. Charge to voltage conversion (source follower)
5. Signal Transfer

Intrinsic vs. Extrinsic



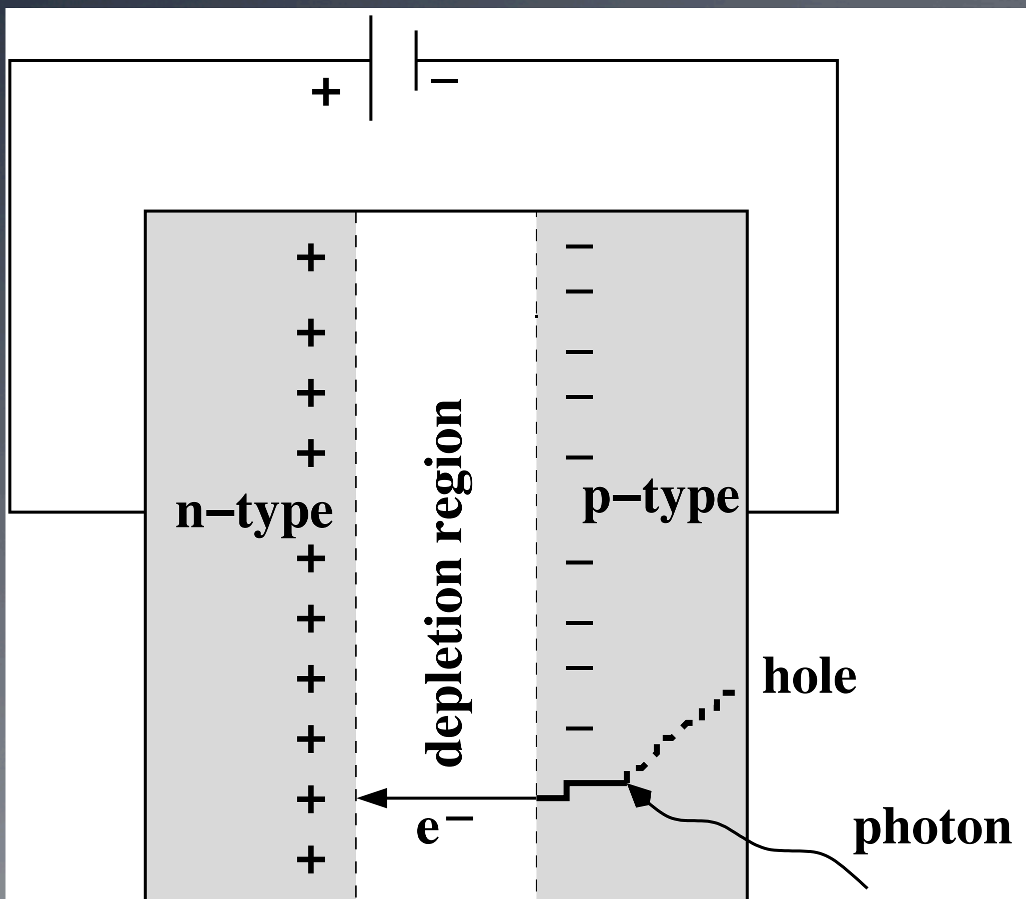
Pure semiconductor absorbs photons with $E > E_g$

- Si (λ_{co}=1.1 μm)
- HgCdTe (λ_{co}=1.24- 14 μm)
- InSb (λ_{co}=5.5 μm)
- PbS (λ_{co}=3.6μm)

Donor (acceptor) impurity atoms have electrons (holes) closer to conduction (valence) band

- Si:As (λ_{co}=23.1 μm)
- Ge:Ga (λ_{co}=115μm)

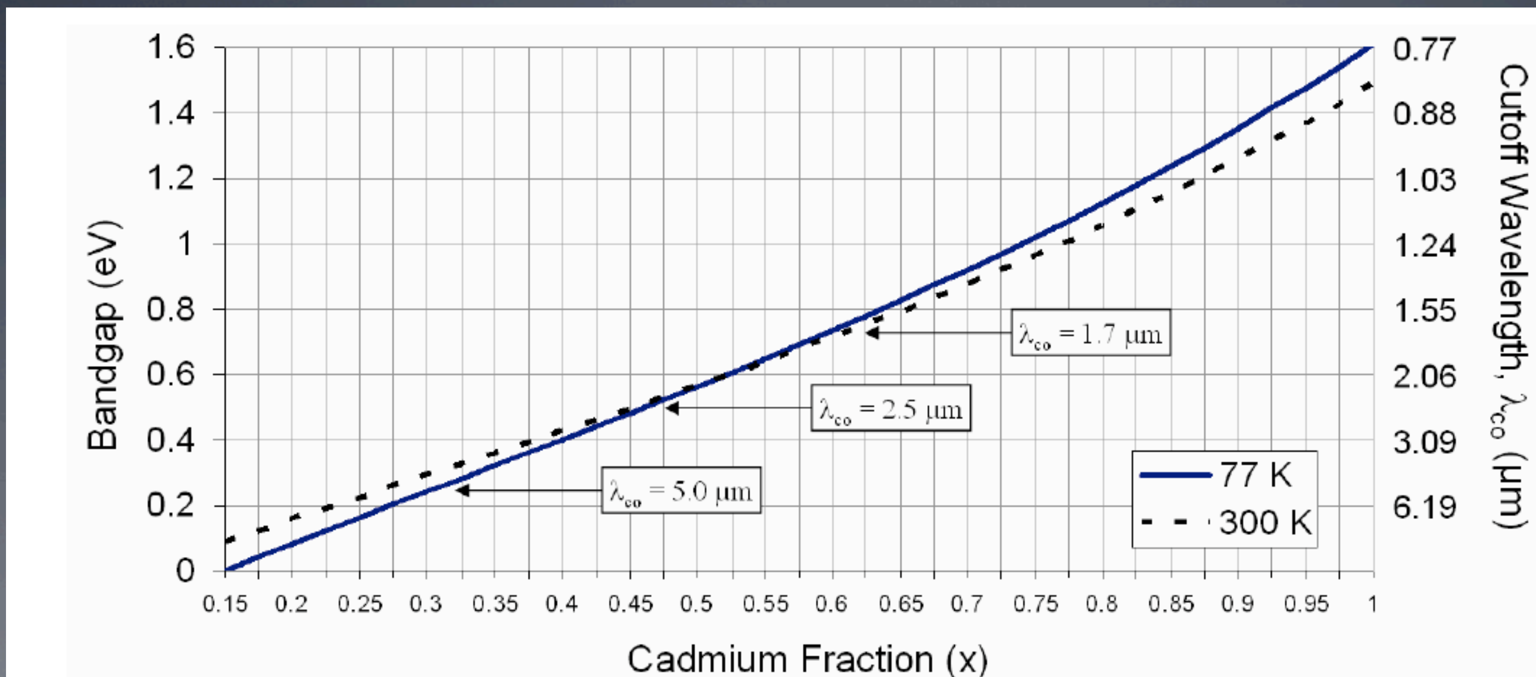
Photodiodes in IR



- reverse-biased p-n junctions act like capacitors
- photon generated electrons are captured in the n-type region, discharging the capacitor
- saturation occurs when junction is fully de-biased
- well depth ~ 100,000 e^-
    - Fills fast! (exposure times in milliseconds to seconds)

HgCdTe

- Mer-Cad-Tel has tunable bandgap, $Hg_{1-x}Cd_xTe$



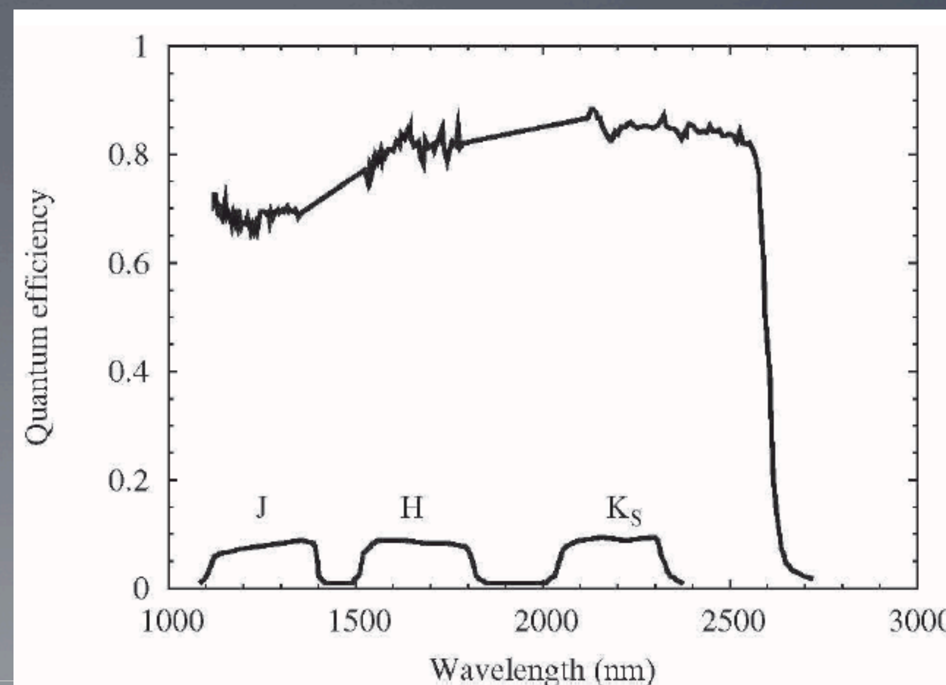
- Can cover NIR(IY), SWIR (JHK) and MWIR (LM)

- Dominant IR detector

Beletic, 2008

Quantum Efficiency

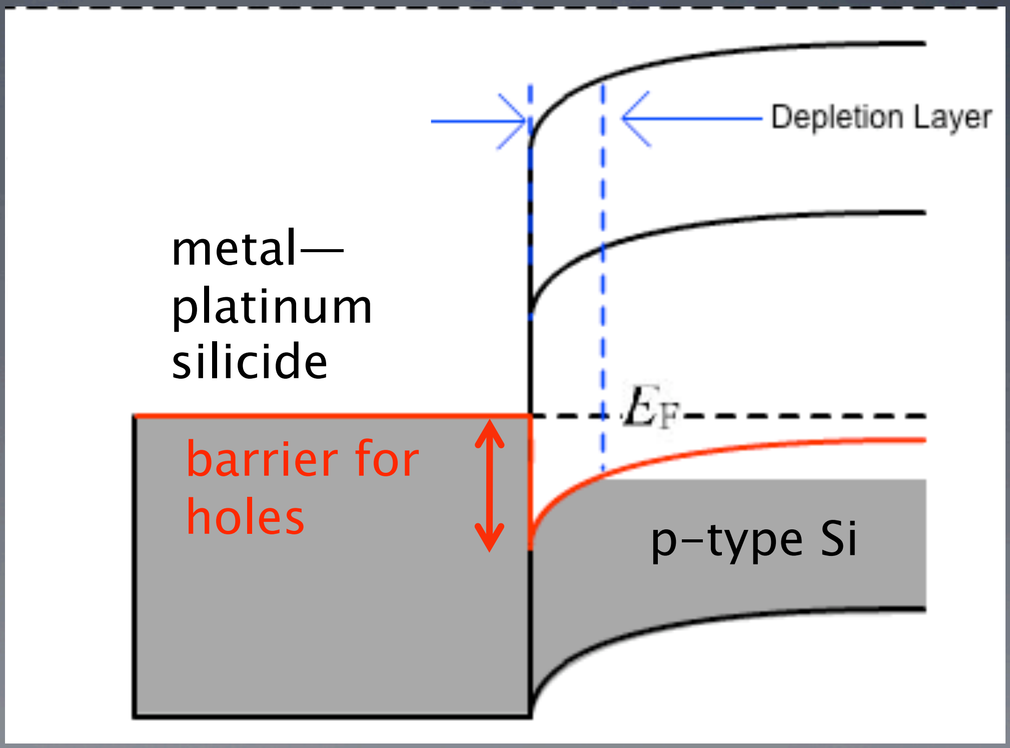
- Reflected energy =
- anti-reflective coatings of SZn introduced in 2G IR detectors, QE ~ 80%-90%
- removal of substrate (CdZnTe) allows sensitivity in visible
- HgCdTe is a direct bandgap material, absorption depth ~ µm over entire band pass



2Kx2K HAWAII array Beletic, 2005

Schottky barrier diode—PtSi

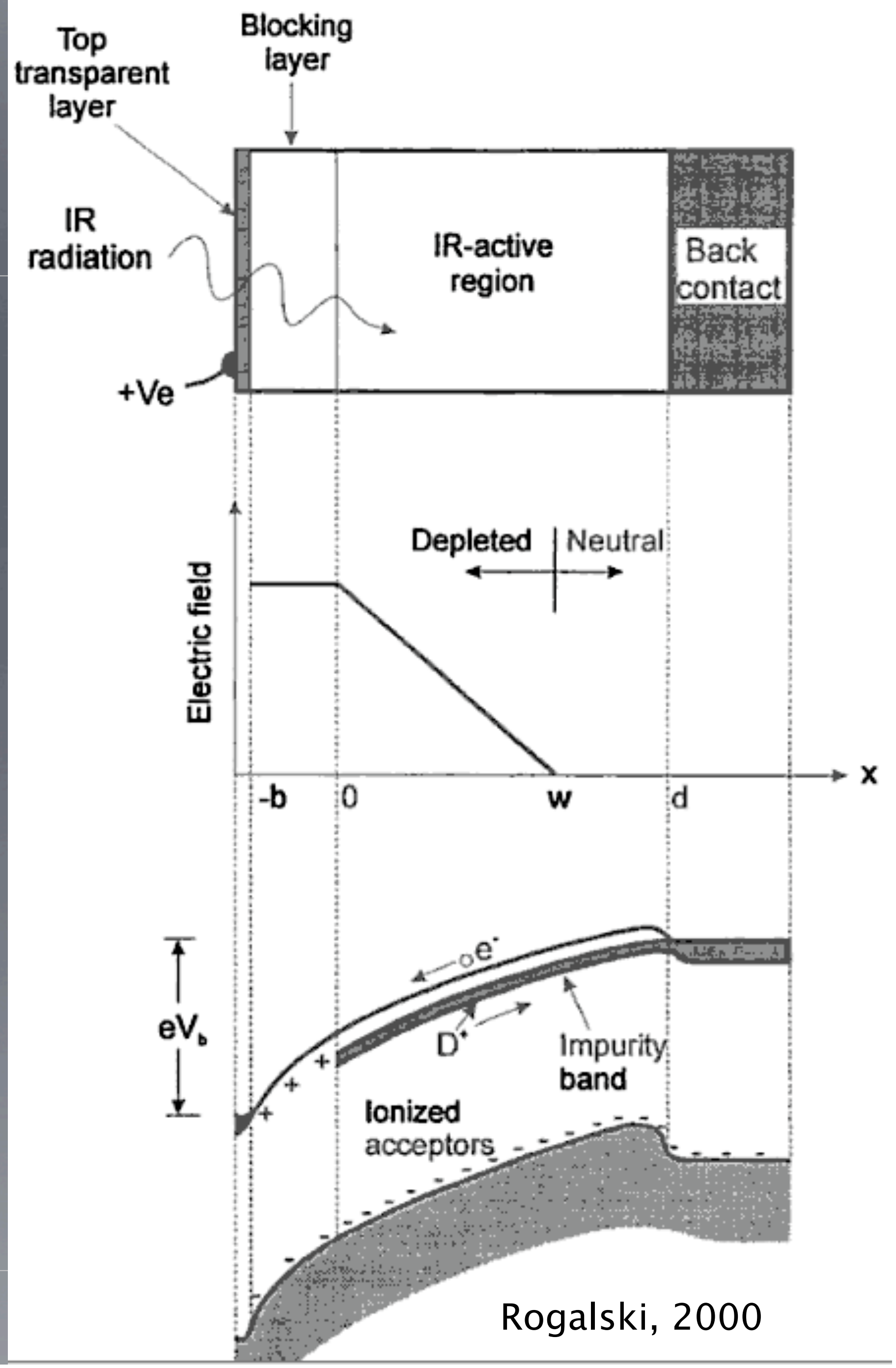
- metal– (p–type) doped semiconductor boundary replaces p–n junction
- λ_{co} = 5.6 µm
- QE ~ 1–2%, but easy to manufacture in large formats (McLean, 1996)



http://cleanroom.byu.edu/schottky_animation.phtml

Extrinsic and IBC(BIB) detectors

- Impurity band conduction (IBC) uses higher doping than extrinsic detectors
- photo-electrons from IR-active region can pass blocked layer, but impurity band electrons can't
- Si:As, λ_{co}= 23 µm, QE~10-50%
- Ge:XX used at larger λ



Rogalski, 2000

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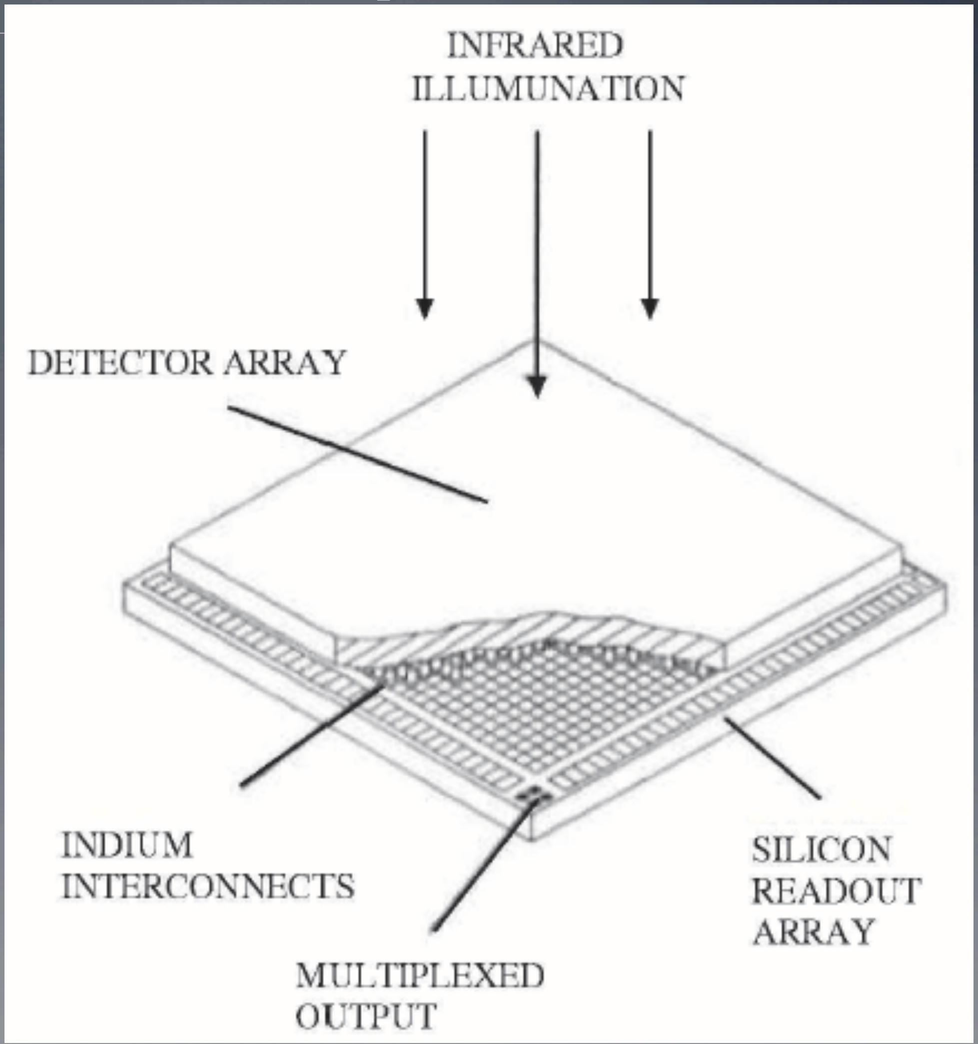
Hybrid Arrays

- Takes advantage of Si-based integrated circuit technology
- Indium bumps bond when pressed together, epoxy filled
- Important to control for different thermal properties of detector/multiplexer



Beletic, 2005

Amplification and Read Out

- Each pixel has it's own charge storage and amplifier (unit cell)

1. photo-generated charge discharges reverse-biased p-n junction in IR detector (capacitor) (pixel saturated when diode de-biased)

2. Detector connected through indium bump to Si source-follower amplifier (MOSFET) $V_{out} \sim V_{in}$

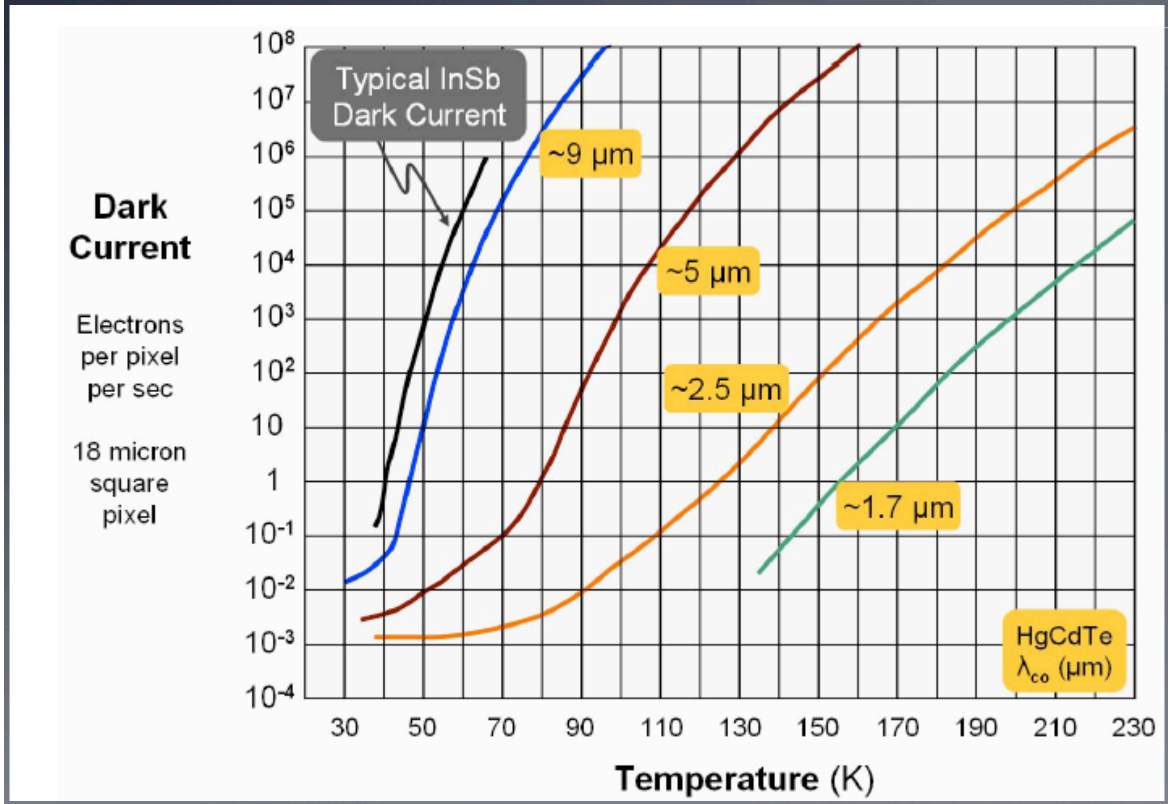
3. output V of source follower read out for each pixel (address a pixel) along rows and columns (CMOS device)

Unit cell is linear to few percent for unsaturated pixels

Different from Optical (CCDS)

- Smaller band gap -> higher dark current -> more stringent cooling requirements
- Direct bandgap materials (HgCdTe), more efficient absorbers than Si
- Detection done in IR-sensitive material, read out, multiplexing done in silicon (hybrid array)
- No charge transfer
  - no drift scanning, on-chip binning, column bleeds
  - non-destructive read out

Dark Current



Beletic, 2008

Must cool detectors

HgCdTe~50 K

15 e⁻/pix/hr

InSb ~ 30 K

Si CCDs ~ 160 K

< 2 e⁻/pix/hr

Si:As ~ 4 K

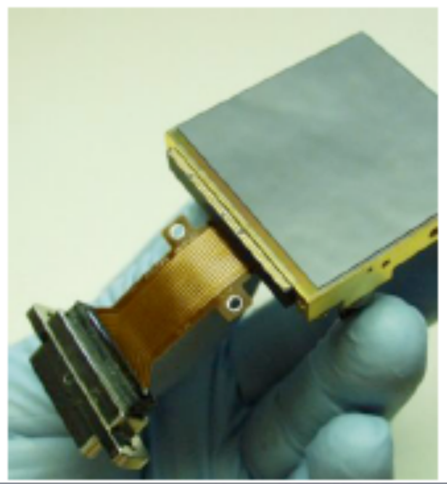
Readout and Reset Noise

- Noise in FET amplifier, since each pixel has 1 amplifier, space constraints don't allow for lower-noise amplifiers used on CCDS
- Non-destructive readout allows averaging of multiple readouts (limited to a factor 4-5 improvement)
- Teledyne 2Kx2K readout noise of $< 15\ e^-$ for 1 read and $3-5e^-$ for many samples (Beletic, 2005)

- Reset (kTC) noise from resetting bias voltage: rms $Q_N \sim \sqrt{(kTC)}$
- Eliminate with correlated double sampling, reset-read-read (Fowler sampling) reads can be repeated

State of the art

- NIR HgCdTe (InSb) detectors are on virtually all major telescopes
- few major manufacturers today: Teledyne, Raytheon
- Teledyne state-of-the-art (JWST)
  - HgCdTe 2kx2k substrate removed
  - 10-15 μm thick
  - 18 μm pixels
  - λ_{co}=2.5-6μm
  - read noise ~ 6-9 e^- (multiple reads)
  - well depth ~ 100,000 e^-
  - linear to few percent



Summary

- 40 years of development have taken near-mid IR from photometers to million pixel image arrays
- HgCdTe can reach QE~95%, detector of choice (Si:As IBC for longer wavelengths)
- IR detector bump bonded to Si CMOS read out circuitry—hybrid arrays
- noise properties of detectors are becoming comparable to CCDs
- Sky noise and thermal background make observing hard
- Future: cheaper, bigger detectors?

IR cameras

- 2MASS (1997) –3x 256x256 HgCdTe in JHK
- UKIDSS (2005)–4x 2Kx2K HgCdTe in JHK
- HiCiao (Subaru)–2Kx2k HgCdTe
- OSIRIS (Keck) –2Kx2K HgCdTe array, NIRC2 (Keck) 1024x1024 InSb array
- Spitzer IRAC (3.6,4.5,5.8,8 μm) –2 256x256 InSb + 2 Si:As IBC
- Hubble—WFC3–1024x1024 HgCdTe, NICMOS 256x256 HgCdTe

References

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- Infrared image sensors, Paul R. Norton, Opt. Eng. 30, 1649 (1991)