SOFIA
Possible Mid-IR Photodetector Array Technologies

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Mid-IR Photodetector Arrays: Current/Near-Future Status

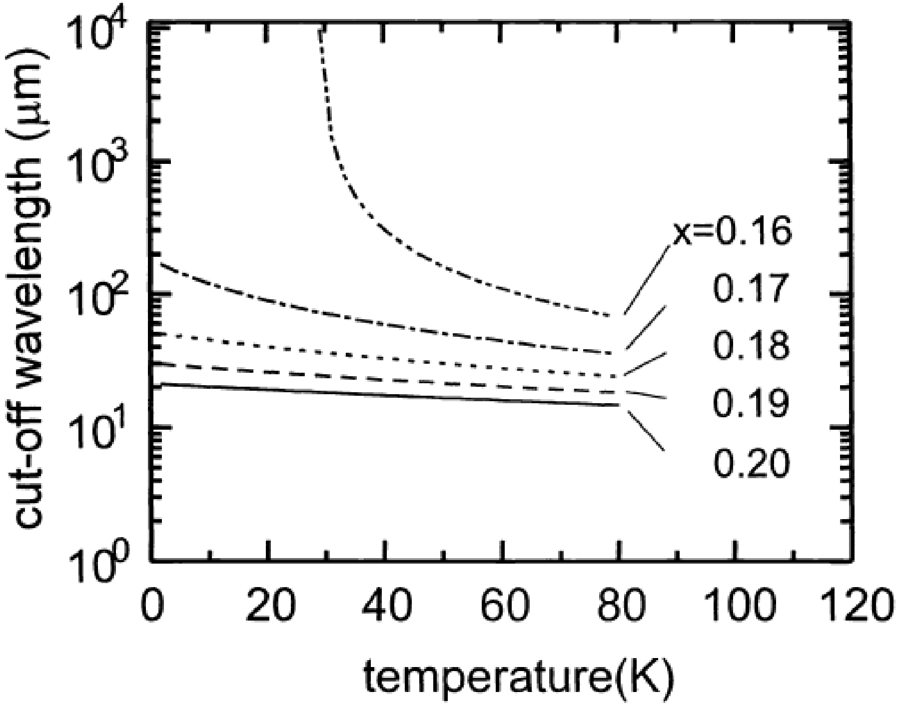
(For purpose of this discussion, Mid-IR refers to ~20-40 μm; MWIR 5 μm cutoff; LWIR 14 μm cutoff and VLWIR >14 μm cutoff)

- 5-15 (30?) μm HgCdTe photovoltaic 1024 x 1024 arrays
  - Teledyne Imaging Sensors (~11 μm cutoff 2k x 2k arrays NEOSM; 13 μm cutoff arrays with GEOSnap CTIA multiplexer readout for high background ground-based astronomy 1k x 1k demo.); 15+ μm cutoff arrays – U. Rochester lab demo
  - Extension to 30 μm? –Teledyne has never produced; early papers suggest the possibility
- 1-30+ μm Type 2 superlattice (T2SL) detector arrays. Have not yet realized their promise.
- 5-28 μm Si:As BIB and IBC arrays

  DRS (FORCAST 256 x 256; Spitzer IRS & MIPS 128 x 128) and Raytheon (Spitzer IRAC 256 x 256; MIMIZUKU on TAO 6.5-m 1024 x 1024; JWST 1024 x 1024) – mature, well-developed technology
- 28-40 μm Si:Sb BIB arrays
  - DRS (FORCAST 256 x 256; Spitzer IRS 128 x 128; MIMIZUKU on TAO 6.5-m 128 x 128);
  - **1024 x 1024 desired for SPICA – need investment**
- 50-120 μm Ge:Ga PC array, and stressed Ge:Ga array to 200 μm, FIFI-LS (very small arrays)

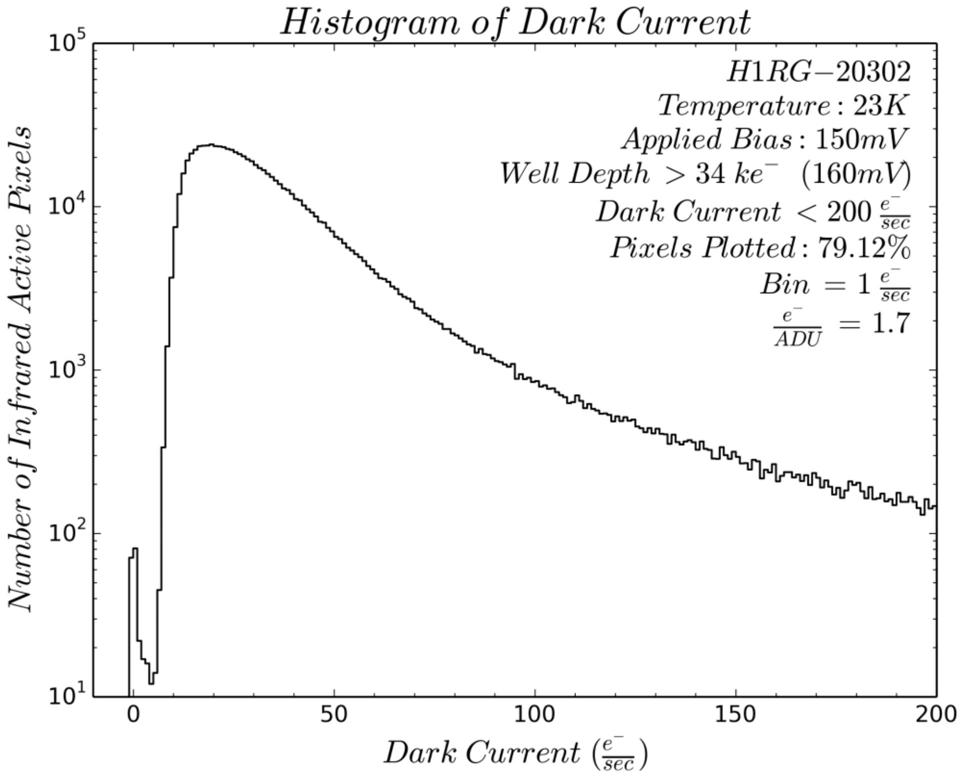
HgCdTe – can it be extended to longer wavelengths?

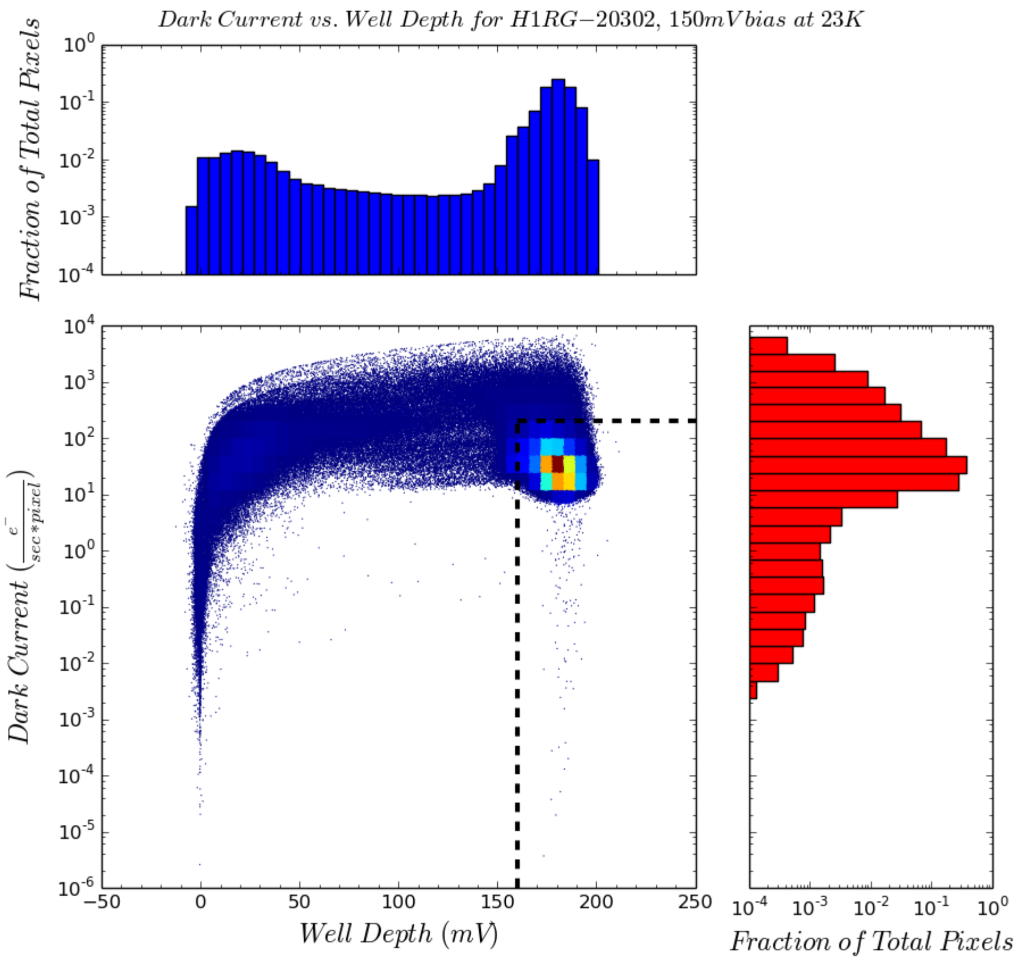
- $Hg_{1-x}Cd_xTe$ photovoltaic detectors can be tailored to different wavelengths by modifying the Cd molar fraction; MWIR HgCdTe arrays operate at relatively high temperatures c.f. bolometers
- D. L. Spears (1988) reported developing longer wavelength photoconductors from LPE p-type $Hg_{0.812}Cd_{0.188}Te$ but never followed up (too difficult to control alloy with LPE; very modest performance)
- Teledyne near-IR and now MWIR HgCdTe arrays are common in astronomy - HST, JWST, WISE etc. and ground-based observatories – 2k x 2k and 4k x 4k
- Longer wave arrays (10, 13 and 15+ μm cutoff wavelengths) have been developed and tested in our lab - the smaller x value, and the larger the compositional gradient, the longer the cutoff wavelength for a given T
  - Phillips, Edwall and Lee (2002) cite difficulty in maintaining $\Delta x \leq \pm 0.002$ as required at λ_{co} =14 μm, much less at 20+ μm



- Increasing Hg concentration produces softer and softer arrays; defects more likely – hard to keep dark currents down: excellent 2k x 2k 10 μm arrays developed for NEOSM (e.g. McMurtry et al. 2013; Dorn et al. 2019)
- Longer wave HgCdTe devices so far 1k x 1k (Cabrera et al. 2019, 2020) to **16.7 μm** cutoff λ

Performance of λ_{co} = 16.7 µm 1k x 1k array

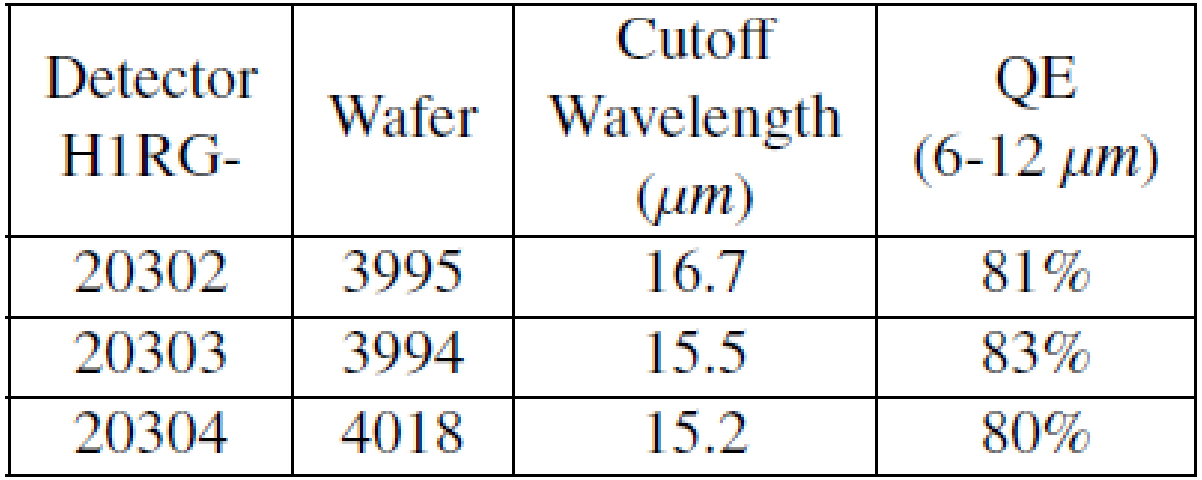




Using astronomy readout H1RG, 150 mV applied bias at T=23K the median dark current is 32 e-/s, and 38 ke- well depth for H1RG-20302 (M. Cabrera, PhD thesis, UR 2019 and Cabrera et al. 2020)

Any potential for ≥20 μm HgCdTe for SOFIA ?

Betz et al. (2002) at Far-IR, Submm and mm Detector Technology Workshop sponsored by NASA Ames and USRA/SOFIA suggested $Hg_{1-x}Cd_xTe$ wavelengths out to 100 μm were possible either by extending the photovoltaic technology or utilizing a super-lattice approach with alternating layers of CdTe and HgTe.



Detector H1RG-	Wafer	Cutoff Wavelength (μm)	QE (6-12 μm)
20302	3995	16.7	81%
20303	3994	15.5	83%
20304	4018	15.2	80%

- **16.7 μm array longest wavelength Teledyne has produced**
  - **BUT operability is limited 79%** – thermal and tunneling dark currents limit percent of pixels to DC < 200 e-/s and well depth > 34 ke- (determined by applied reverse bias of 150 mV)
- Could λ_{co} be increased further?
  - Yes, although maintaining control of Δx across the wafer, and concern of pixel defects (need better lattice matched CdZnTe substrate; less force bonding) and careful temperature trade to address resultant dark current-based operability

→Impractical without substantial investment into new territory for Teledyne. Would need low reverse bias and CTIA multiplexer readout to achieve.

Yes, there is potential for longer wave HgCdTe – not 100 μm

Superlattice approach to VLWIR with II-VI materials

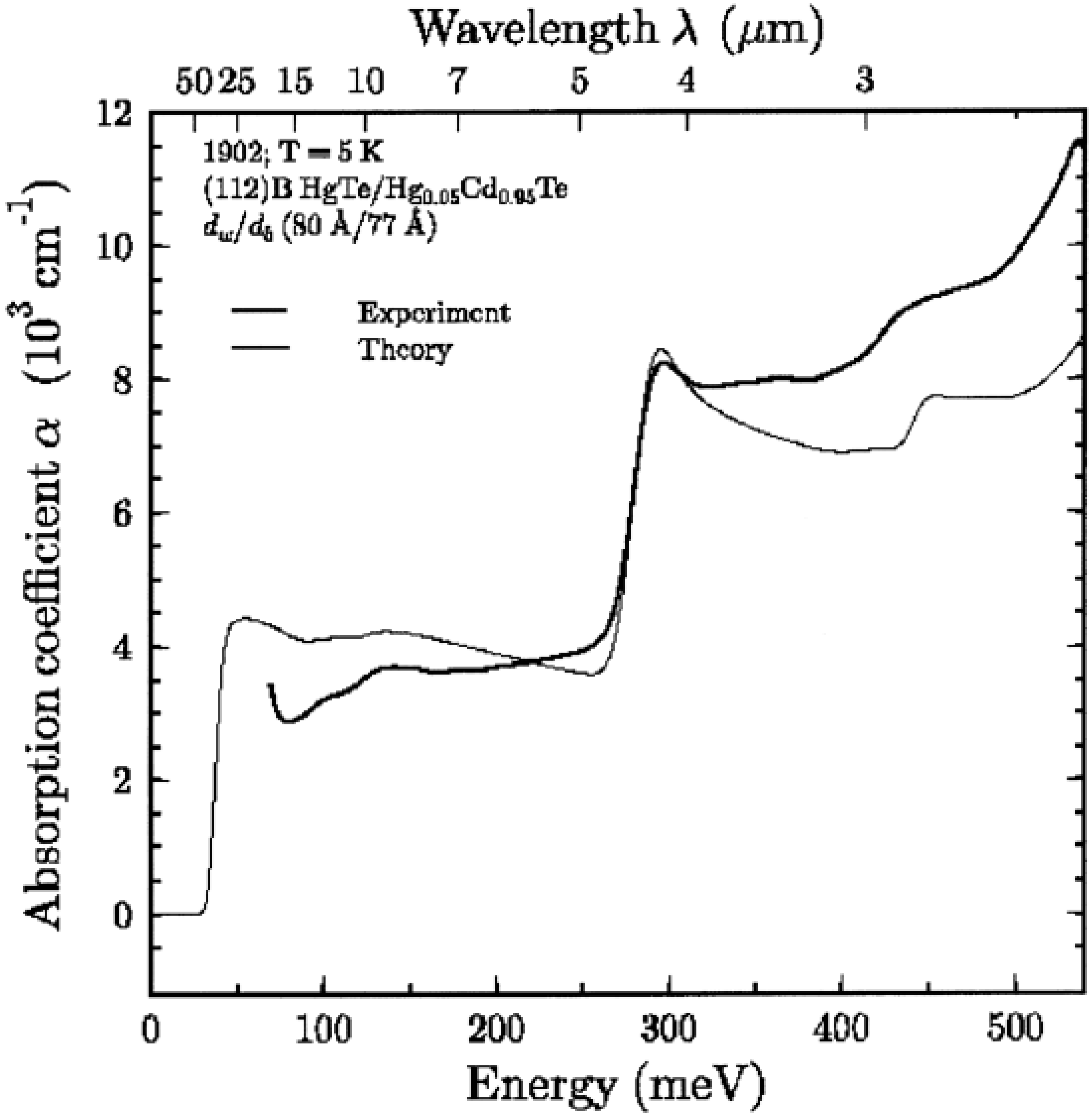
Zhou et al. (2003) report

HgTe/$Hg_{0.05}Cd_{0.95}Te$ MBE superlattice

growth on CdZnTe substrate

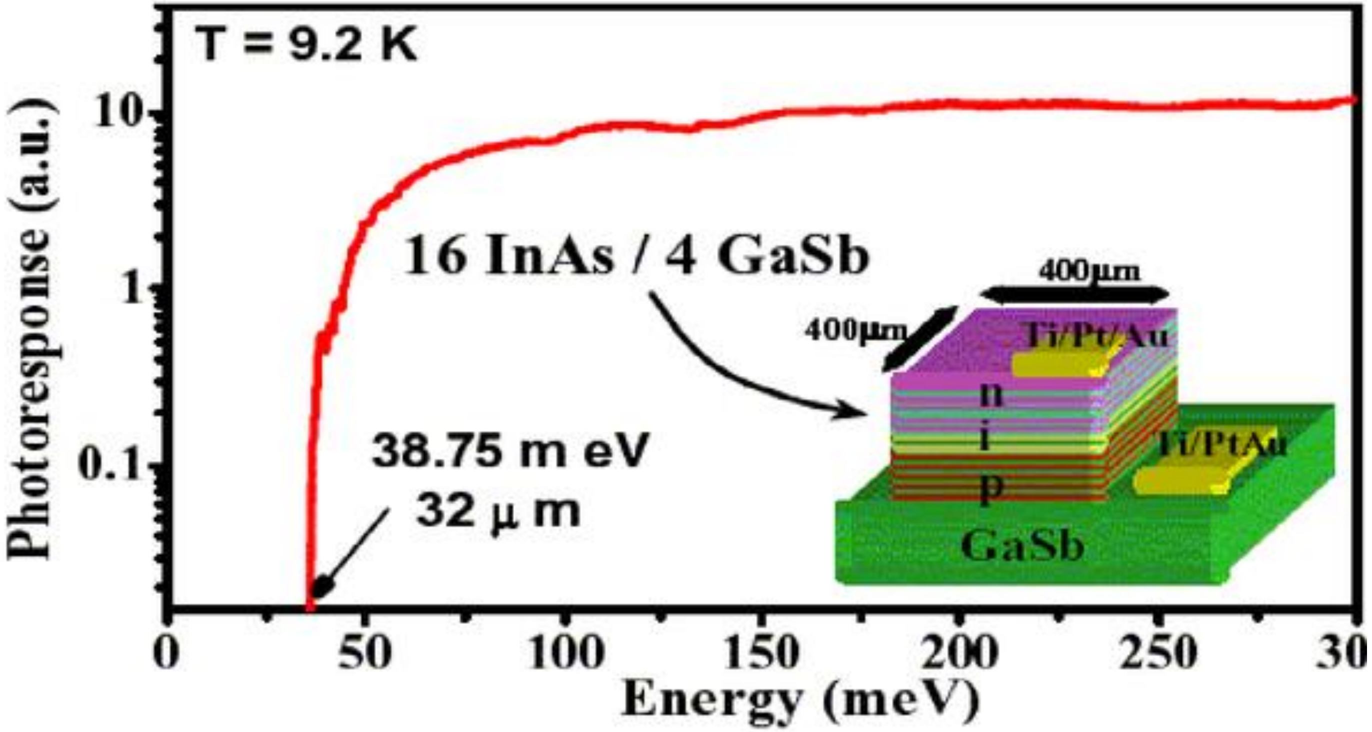
- Predicted cutoff wavelength 30 μm at 4K
- Need p-type layer; typically anneal an arsenic layer – but resulting interdiffusion leads to absorption edges at higher energies.
  - Single element prototype had 20 μm cutoff wavelength

<u>Discontinued work on this project</u>



Superlattice approach to VLWIR with III-V materials

- Center for Quantum Devices –CQD- at Northwestern used III-V materials (stronger covalent bonds, greater uniformity) – demonstrated >30 μm material. SLs with cutoff wavelengths of 32 μm grown to produce InAs/GaSb photodiodes (Wei et al. 2002, 2004)



T2SL Current Status

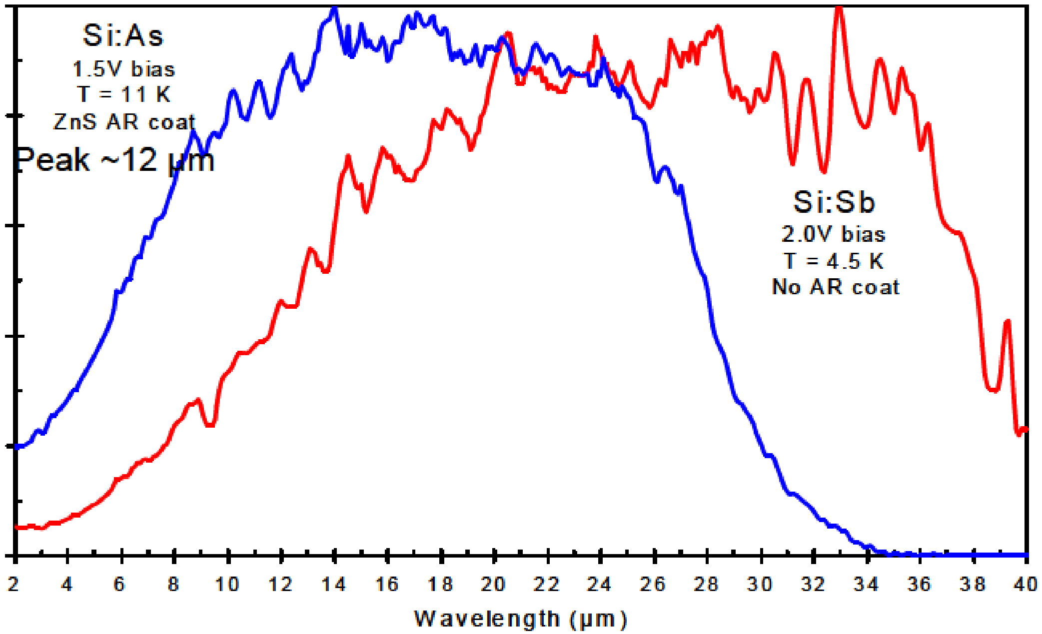
- Optimistic view (Daumer et al. 2019)
  - "Type-II superlattices (T2SLs) are currently recognized as the sole material system offering comparable (?) performance to HgCdTe, yet providing higher operability, stability over time, spatial uniformity, scalability to larger formats, producibility and affordability. Hence, T2SL technology is very promising for space applications."
  - Raghezi et al. (2006) – part of CQD - began looking at FPA implementation, but at 5 μm!

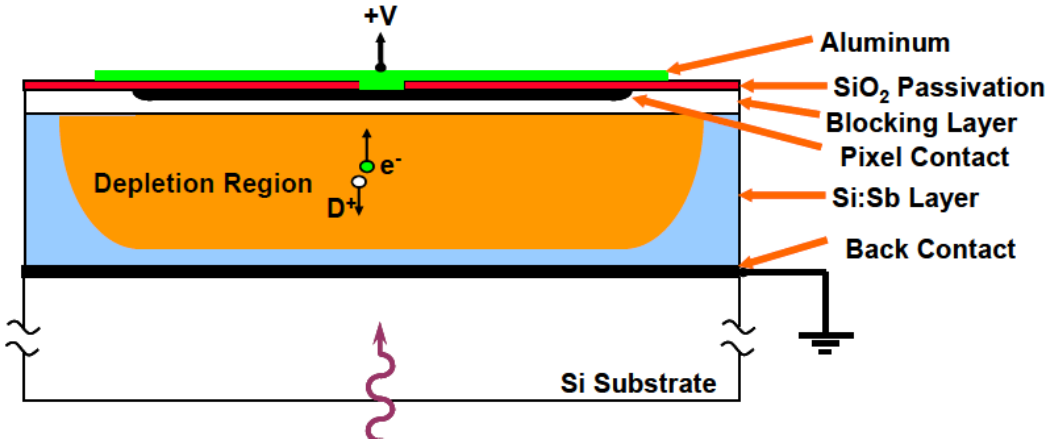
- Reality check: (Rogalski et al. 2019)
  - They consider III-V T2SL, e.g. InAs/GaSb or InAs/InAsSb SLs for MWIR (0-5 μm) and LWIR (5-14 μm)
  - "In comparison with HgCdTe, fundamental properties of T2SLs are inferior. On the other hand, T2SL and barrier detectors have several theoretical advantages including lower tunneling and surface leakage currents, as well as suppressed generation-recombination dark current. To date the superior promise of these detectors has not been realized."

Conclude T2SL arrays (and other barrier arrays) will not be useful for mid-IR λ > 20 μm arrays in foreseeable future, until the far easier, shorter wavelength FPA technologies have proved competitive

Si:As and Si:Sb Blocked Impurity Band Arrays

- Si:As IBC arrays from both Raytheon Vision Systems (RVS) and DRS BIB arrays flown on Spitzer, DRS arrays on WISE and SOFIA FORCAST, and RVS arrays planned for JWST and SPICA
  - Cutoff wavelength 28 μm; 1k x 1k; well-developed mature technology
- Si:Sb arrays from DRS flown on Spitzer; FORCAST; demonstrated in TAO 6.5-m
  - Cutoff wavelength 38 μm (figures from Khalap and Hogue 2012 for SPICA)
  - A more highly doped IR active layer would increase 40 μm response at expense of increased dark current





Si:Sb arrays in 2020 - 2023?

- Past attempt to replace the Si:Sb arrays in FORCAST led to failure to produce equal or better quality arrays with larger format at DRS
  - The prime developers of the technology are no longer at DRS (Guptil deceased; Hogue retired)
  - *"We have made little progress maturing/reinstituting a capability to fabricate Si:Sb detectors again. Our only customer for this technology has been JAXA. They have provided small intermittent funds over the last 8 years making very slow progress. They have recently started to ramp up interest and funding." (Felicia Campbell DRS July 2020)*
  - Originally Hirokazu Kataza (JAXA) led the Si:Sb development for the SPICA Mid-IR camera and Spectrometer (Kataza et al. 2015), but Takehiko Wada (JAXA) has taken over.
  - SPICA in Phase A development: May use Si:Sb wafers developed earlier (Khalap and Hogue 2012) and 1k x 1k multiplexer heritage developed for WISE (if tests show mux works properly at 8K!)
  - Wada July 2020: *"If SPICA project passes the final selection in ESA CV M5 in 2021, we will fabricate 1Kx1K Si:Sb SCA hybridizing them."*

Cost to restart the program at DRS: $6-8M over 2-3 years.

Still the best bet for 20-40 μm photodetector arrays! Perhaps SOFIA could partner with the JAXA SPICA investigators, although the backgrounds are different,