Advanced Infrared Detector Development for Space Lidar

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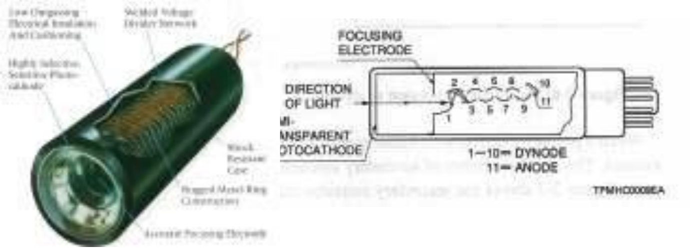
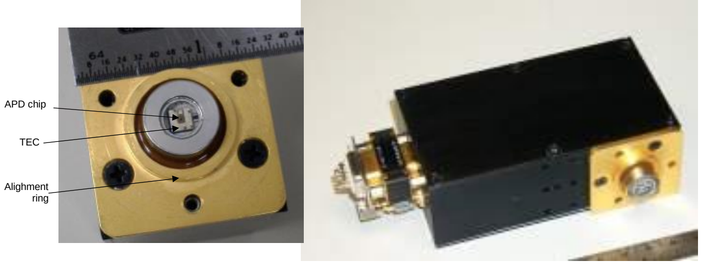
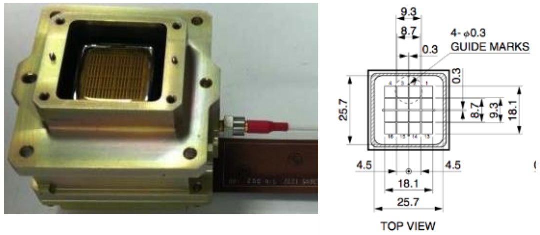
Detectors used in Space Lidar to Date

- **PMT with Multialkali photocathodes:**
  - LITE, CALIPSO
- **Si avalanche photodiodes (APD), linear mode, IR-enhanced (1064 nm):**
  - Clemetine lidar, NEAR/LR, MOLA, GLAS/ICESat-1, CALIPSO, MLA, LOLA, GEDI, BELA
- **Geiger mode Si APD photon counters:**
  - GLAS/ICESat-1, CATS/ISS
- **PMT with Multialkali photocathodes and segmented anodes:**
  - ATLAS/ICESat-2





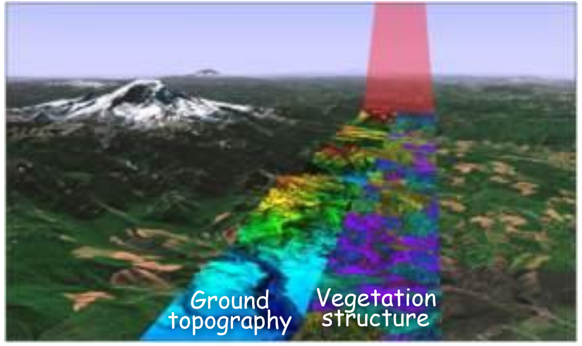


New Trends in Space Lidar

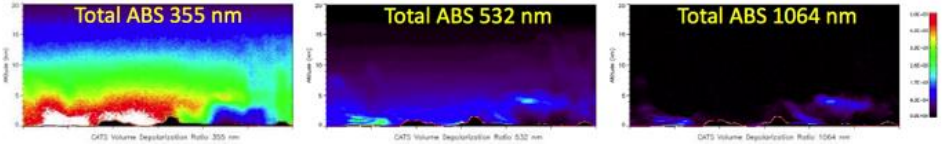
- Multi-beam swath-mapping surface and vegetation lidar
- Atmosphere backscatter profiling lidar at different wavelengths and polarizations
- Integrated Path Differential Absorption (IPDA) lidar for greenhouse gases, CO_2 CH_4, etc.
- Laser absorption spectrometer for surface composition studies (e.g., ice) for the moon, Mercury, comets, etc.

Multi-pixel lidar detector sensitive in short to mid infrared wavelengths

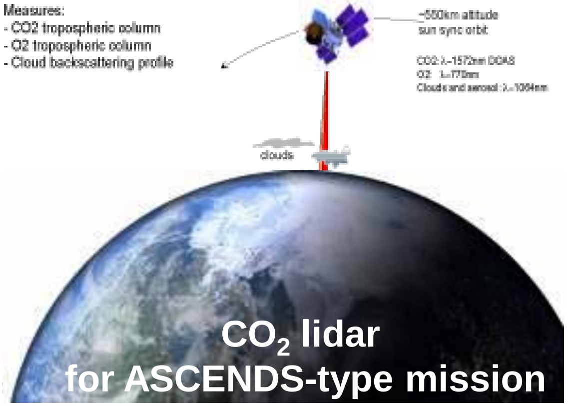
Surface topography and vegetation coverage



Atmosphere backscatter profiles

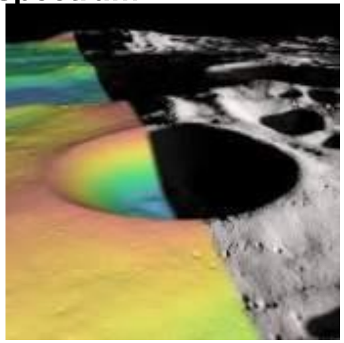


IPDA lidar - measures column absorption of target gases



CO_2 lidar for ASCENDS-type mission

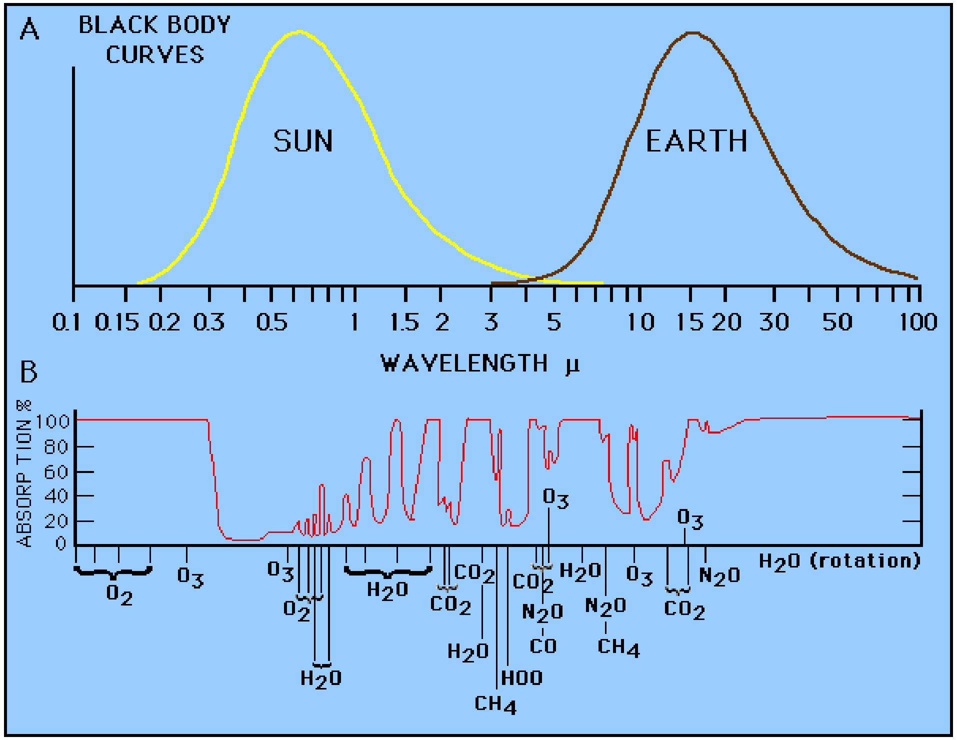
Lidar sampling of surface reflection/absorption spectrum



Why lidar in Short to Mid-IR Wavelengths ?

- Low background from sunlight & low thermal emission from surface
- Rich in spectral absorption lines of interesting species
  - in atmosphere and on surface

e.g. for Earth



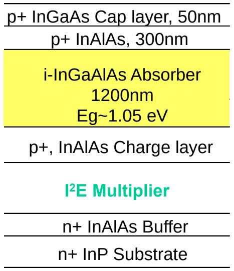
http://objectivistindividualist.blogspot.com/2013/02/infrared-absorbing-gases-and-earths.html

Some candidate laser wavelengths for sensing gases on Mars of high interest

Molecule	Wavelength (nm)
H_2O	3146.5
HDO	3613.5
CH_4	3260.2
C_2H_6	3360.9
N_2O	3884.5
SO_2	3985.1
H_2S	3753.6
H_2CO	3595.8
NH_3	3051.7
O_3	3298.3

Candidate IR Lidar Detectors

- **InGaAs APDs**
  - High noise
  - Space radiation damage
- **InGaAs PMTs**
  - Low quantum efficiency
  - Not available beyond 1.7 µm
- **HgCdTe photodiode array**
  - Imaging sensors with too low frame rate for lidar application
  - Lack of pulse shape information
- **HgCdTe avalanche photodiodes**
  - Quantum limited performance and wide linear dynamic range from visible to 5 µm
  - Need cryo-cooler and radiation damage testing



p+ InGaAs Cap layer, 50nm

p+ InAlAs, 300nm

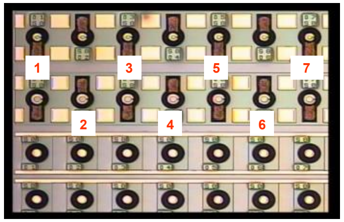
i-InGaAlAs Absorber
1200nm
Eg~1.05 eV

p+, InAlAs Charge layer

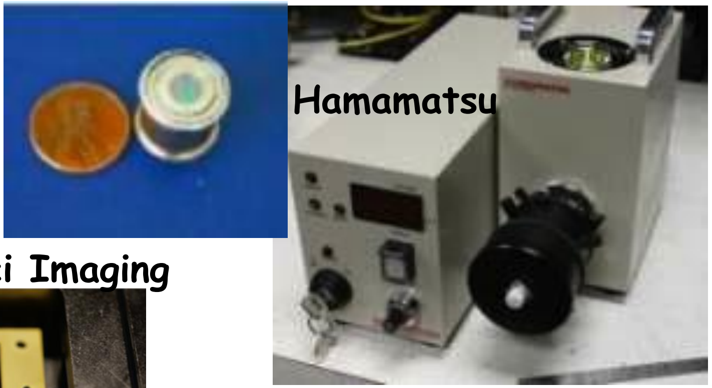
I²E Multiplier

n+ InAlAs Buffer

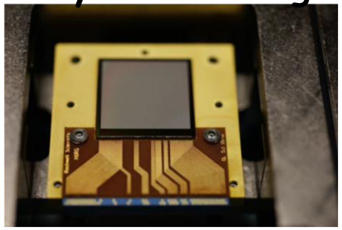
n+ InP Substrate

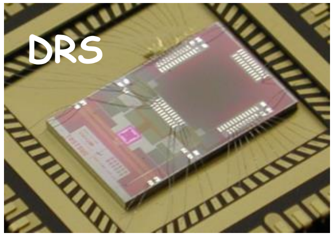


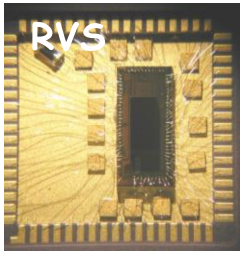
Many suppliers and low cost

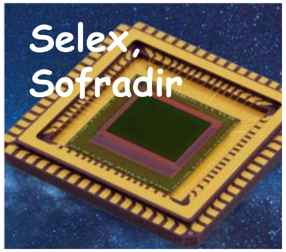


Teledyne Sci Imaging



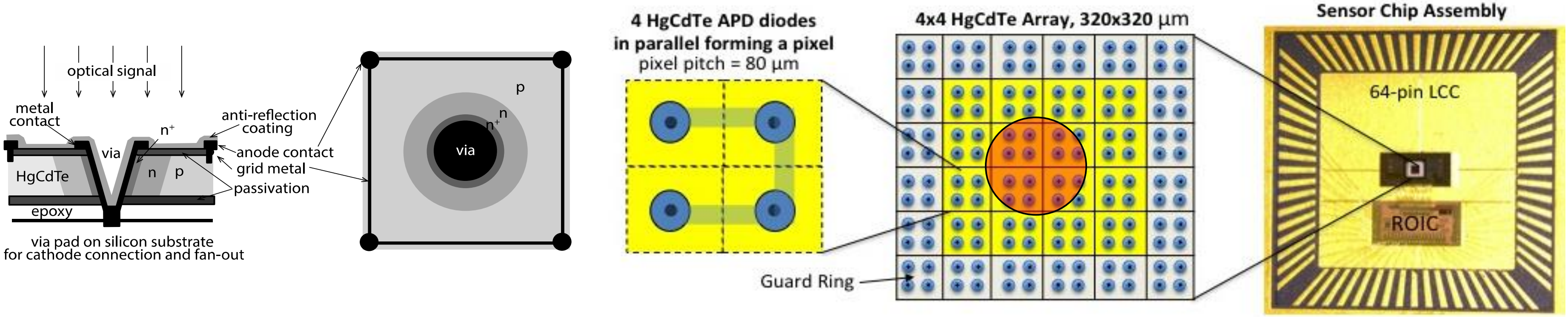






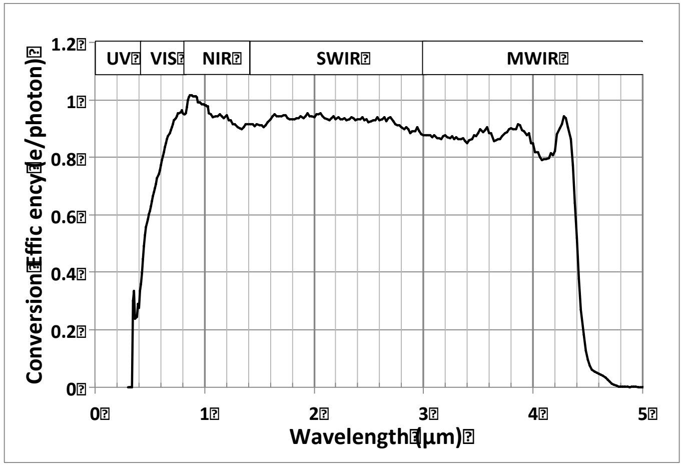
HgCdTe APD Arrays for Trace Gas Lidar

HDVIP^{TM} HgCdTe APD by Leonardo DRS under ESTO IIP-10

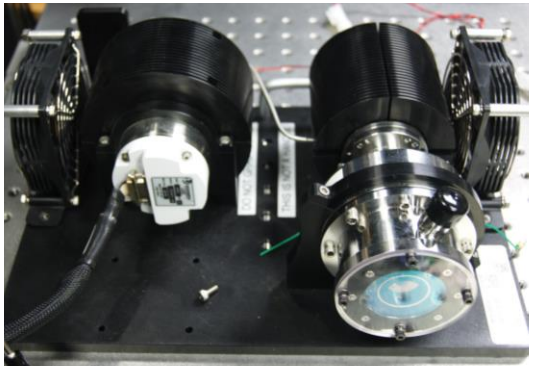


HgCdTe APD for GSFC CO_2 lidar
80x80 µm pixel and 4x4 pixels

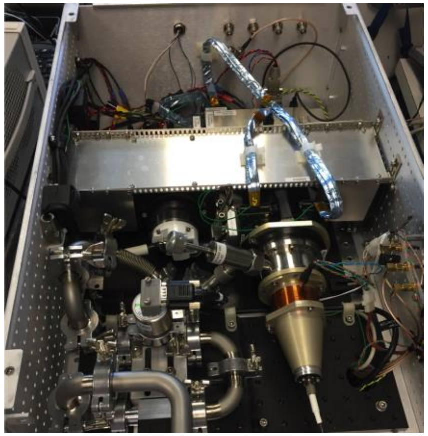
~90% Quantum efficiency from 0.7 to 4.3 µm



Closed-cycle cryocooler used for lab tests and aircraft



Packaged detector system for airborne lidar

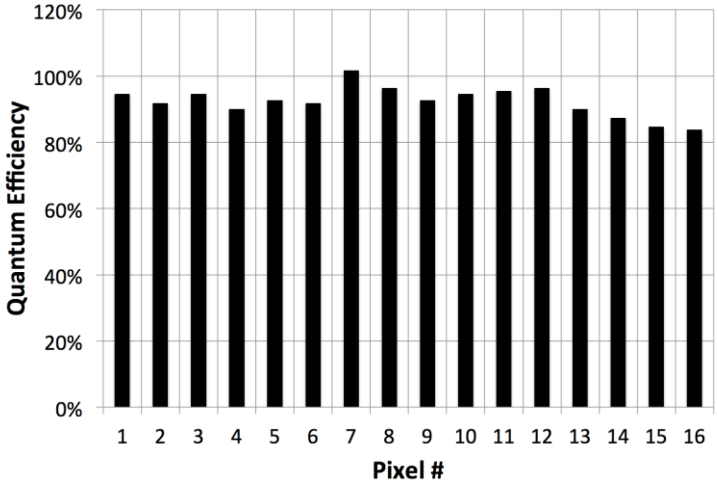


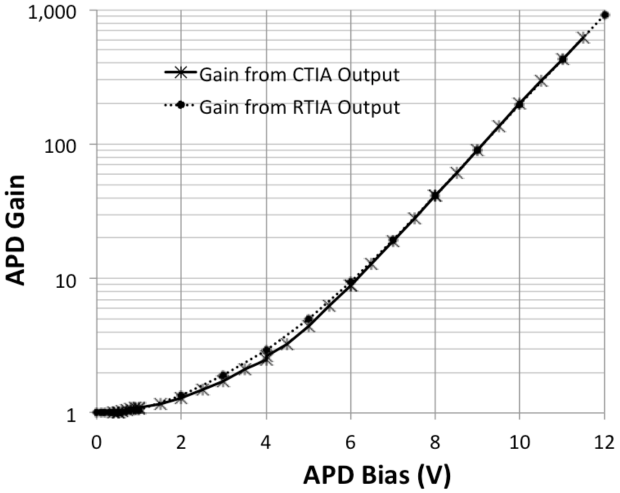
More details can be found in Beck et al., *J. Electron Materials*, 2014; *Sun et al. SPIE 9114*, 2014; Sun et al., *Optics Express*, 2017

NASA GSFC Measurements of the DRS 4x4 HgCdTe APD Arrays

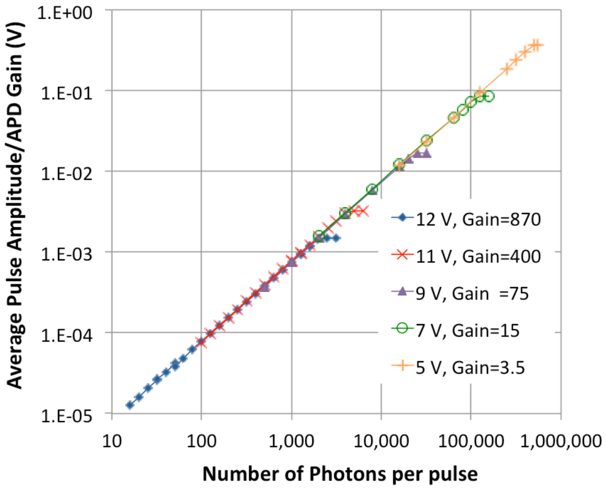
GSFC

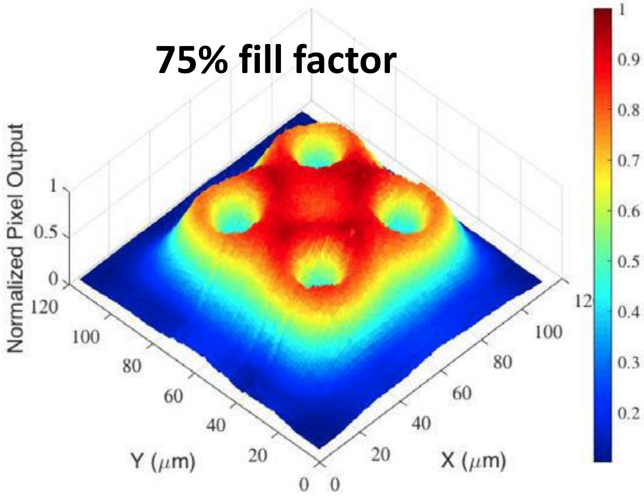
High quantum efficiency and high APD gain to override circuit noise





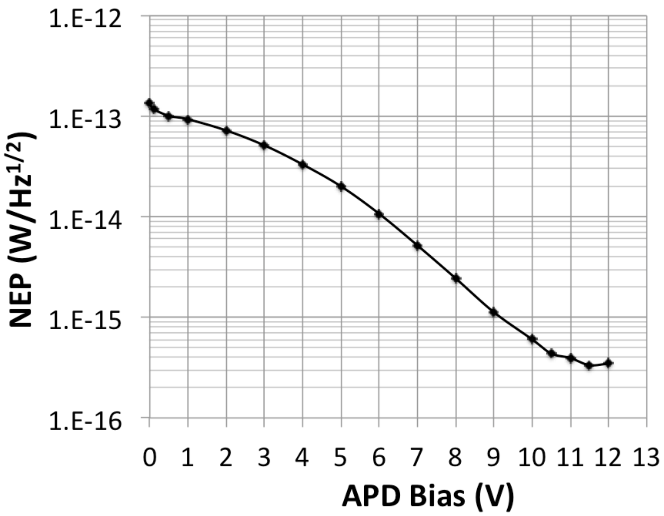
Wide linear dynamic range to accommodate signals from various ground surface and airplane altitude

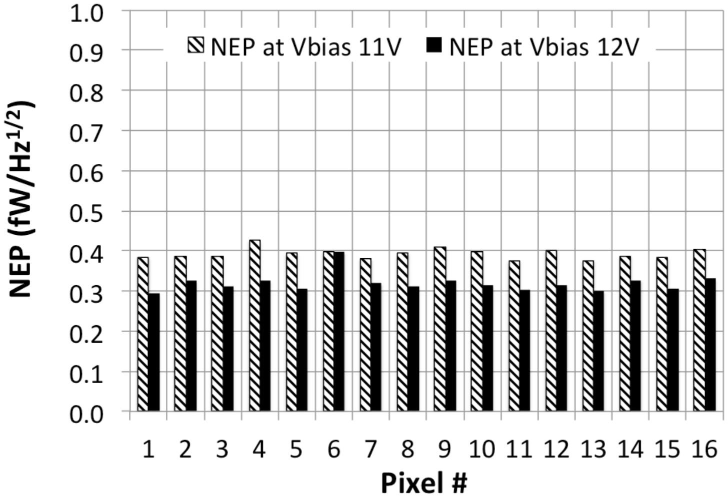



75% fill factor

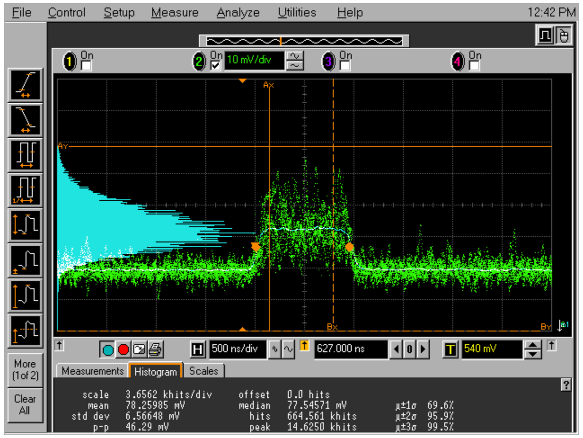
NASA GSFC Measurements of the DRS 4x4 HgCdTe APD Arrays (cont’d)

Lowest noise equivalent power

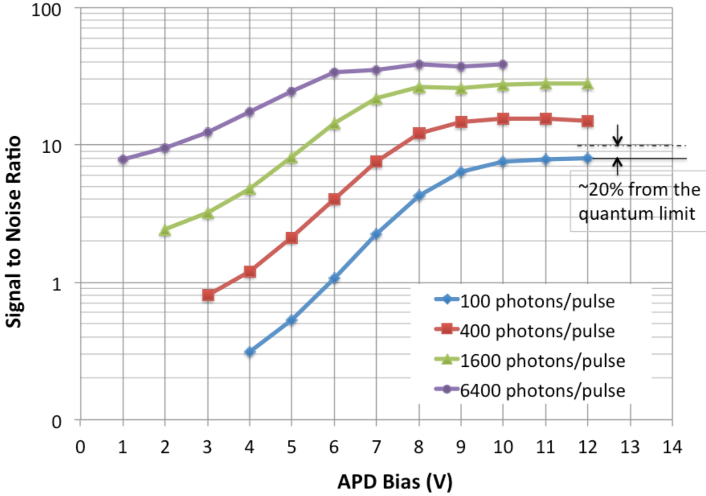




Analog waveform (100 photons/pulse



```
   scale   3.6562 khits/div    offset   0.0 hits
    mean   78.25985 mV         median   77.54571 mV       µ±1σ  69.6%
 std dev   6.56648 mV            hits   664.561 khits     µ±2σ  95.9%
     p-p   46.29 mV              peak   14.6250 khits     µ±3σ  99.5%
```



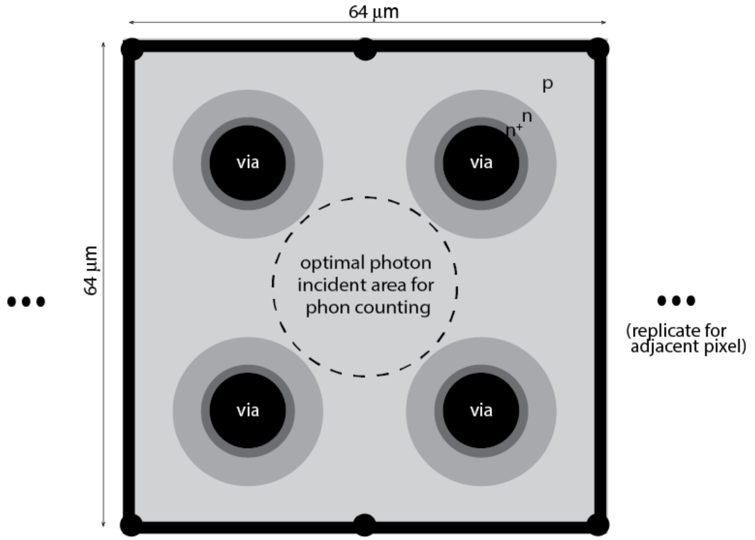
- Near quantum limited receiver performance in the GSFC 1.57 µm CO_2 Sounder lidar
- One unit is used in GSFC 1.65 µm CH_4 lidar
- One unit is now used in NASA LaRC 2-µm CO_2 Lidar
- Also used in GSFC’s development of:
  - a Mars 1.064 µm climate lidar
  - a 3-µm lunar surface volatile lidar

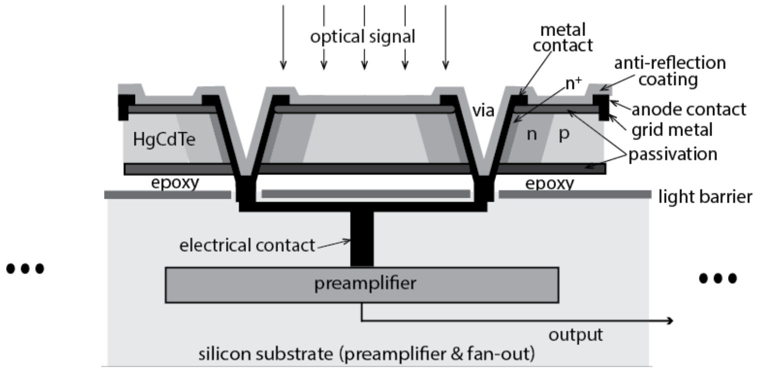
***Sun et al. SPIE 9114*, 2014; *Sun et al.*, *Optics Express*, 2017**

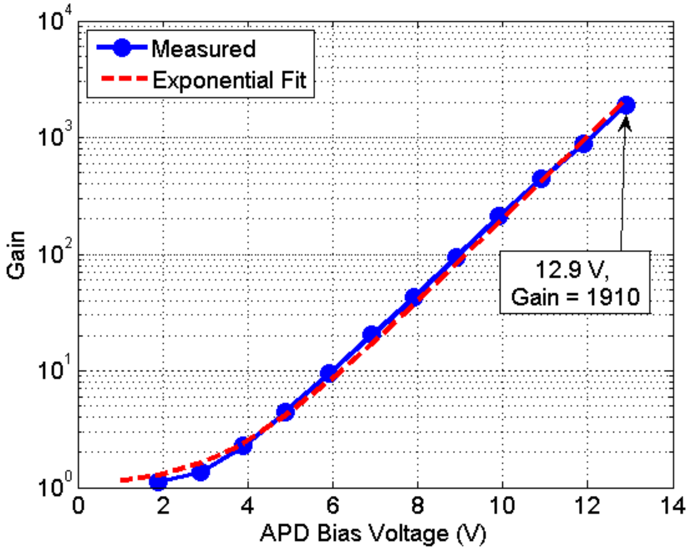
Advanced HgCdTe APD Arrays (DRS) - Single photon sensitivity

GSFC

Similar to earlier HgCdTe APDs but with higher electrical bandwidth, lower preamplifier noise and high APD gain to make it possible to detect single photons







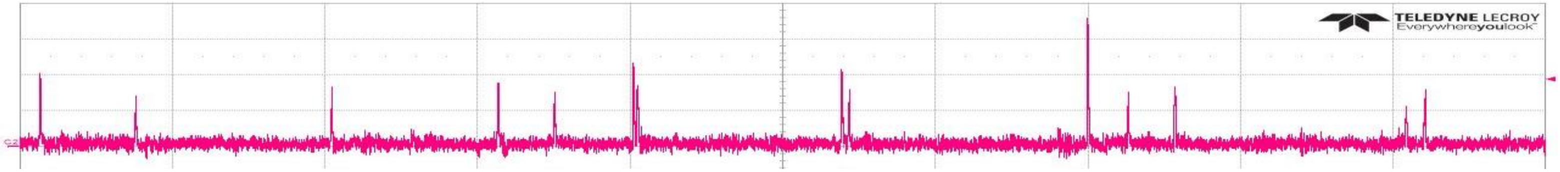
One batch of 2x8 pixel prototype devices were successfully developed

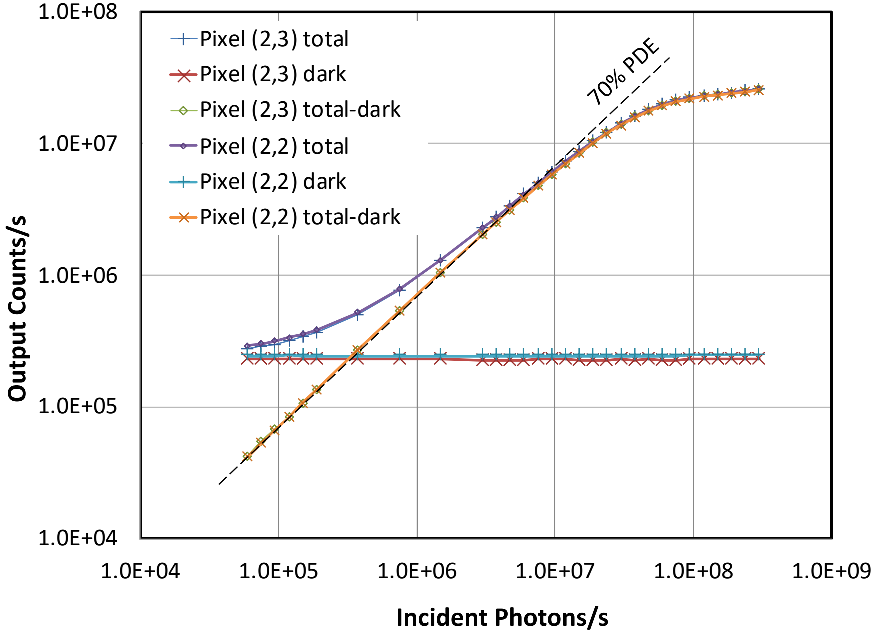
Supported by the ESTO ACT program

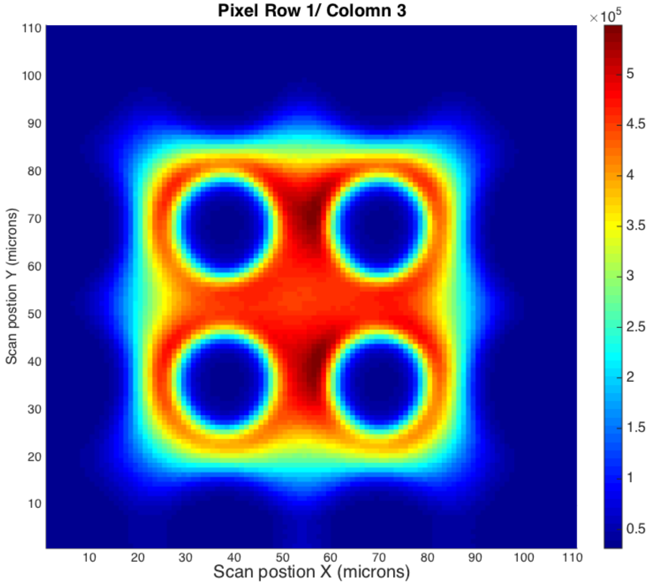
More details in Beck et al., Optical Engineering 2014; Sullivan et al., J. Electron Materials 2015;

Advanced HgCdTe APD Arrays
- Performance Verification at NASA GSFC

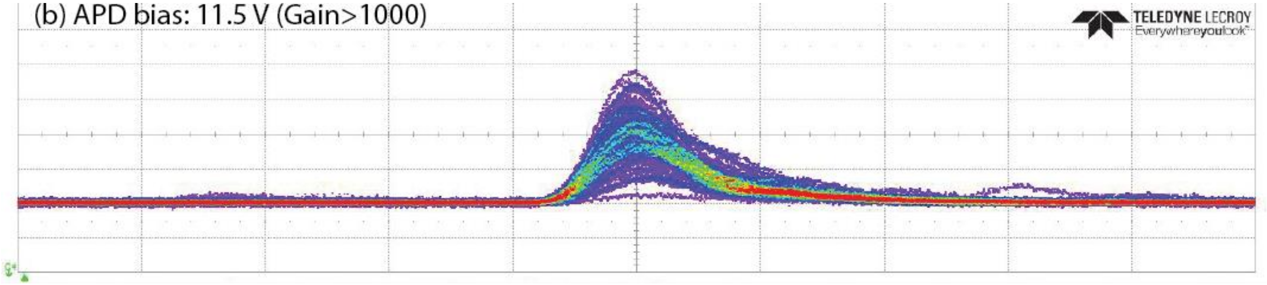
Pulse waveforms from single photon detection under cw illumination.



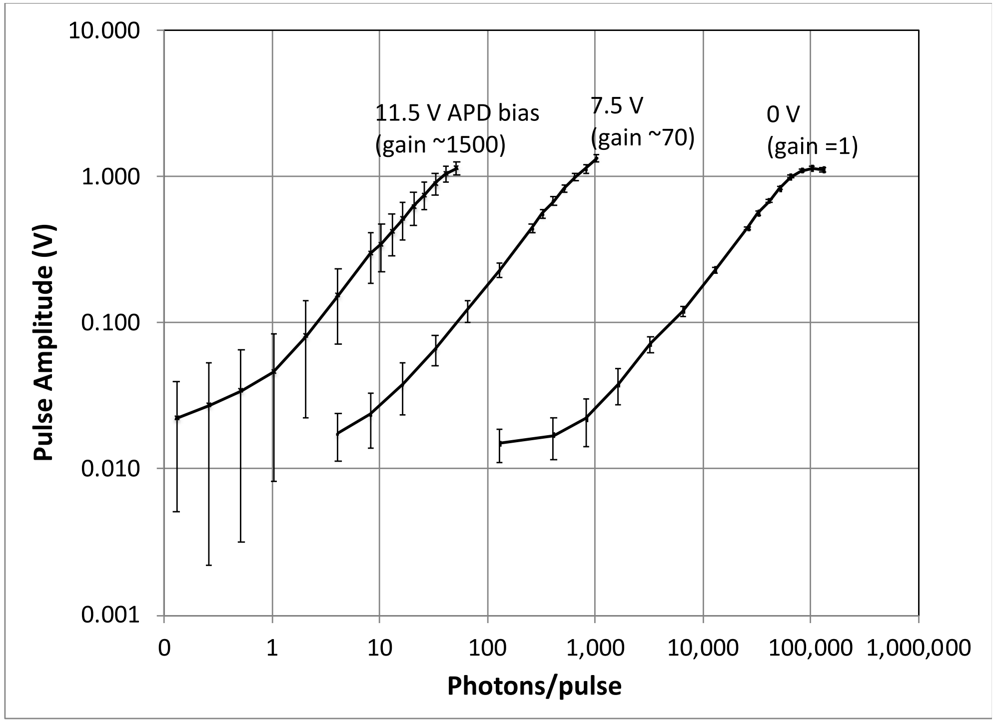




Advanced HgCdTe APD Arrays
- Linear mode operation



Pulse waveforms from multiple (~15) photons/pulse

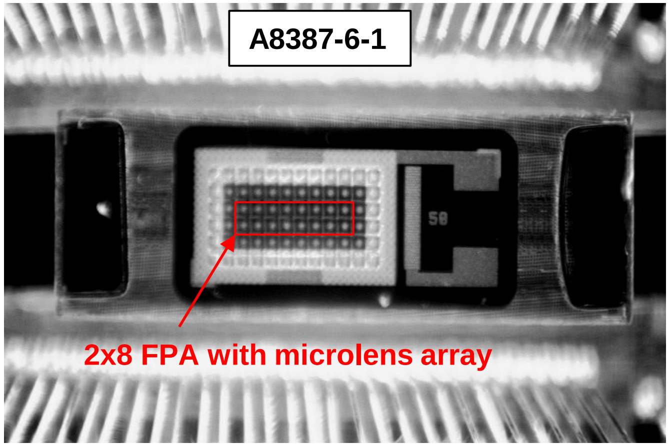


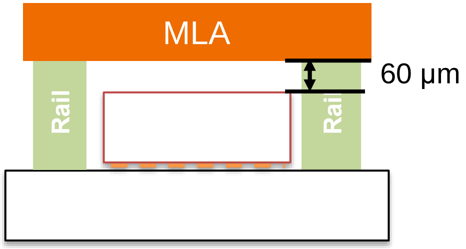
- Output pulse amplitude can be used to estimate the received number of photons/pulse
- Estimated APD excess noise factor <1.3

More details in Sun *et al.*, SPIE 10659, 2018

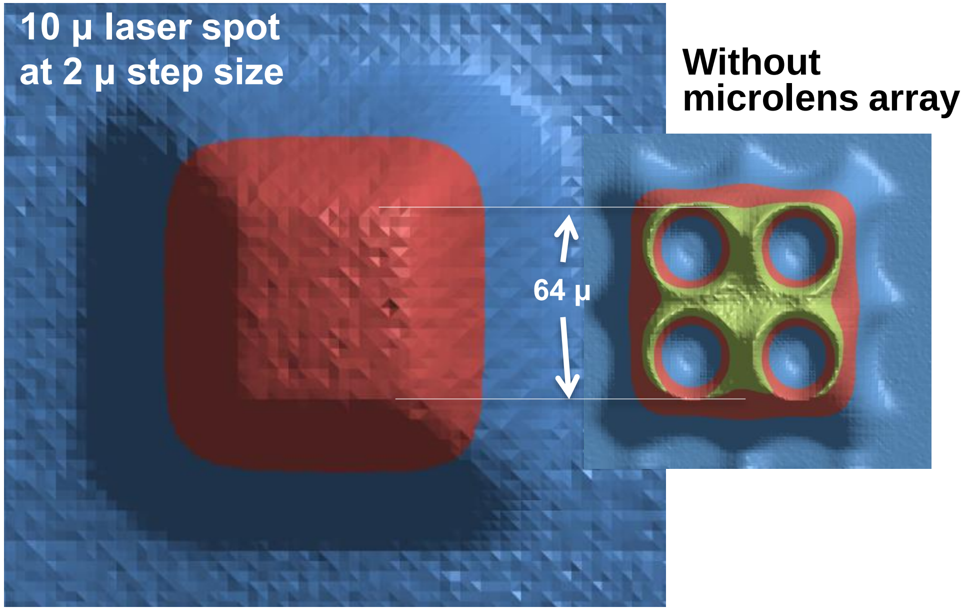
Advanced HgCdTe APD Arrays
- Adding a Microlens Arrays for ~100% fill factor

Microlens array on HgCdTe APD array





Surface map shows the microlens array concentrated light on the center of the pixel and achieved ~100% fill factor at f/7.

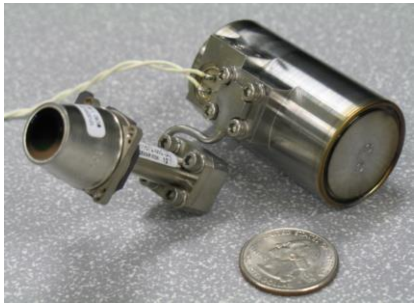


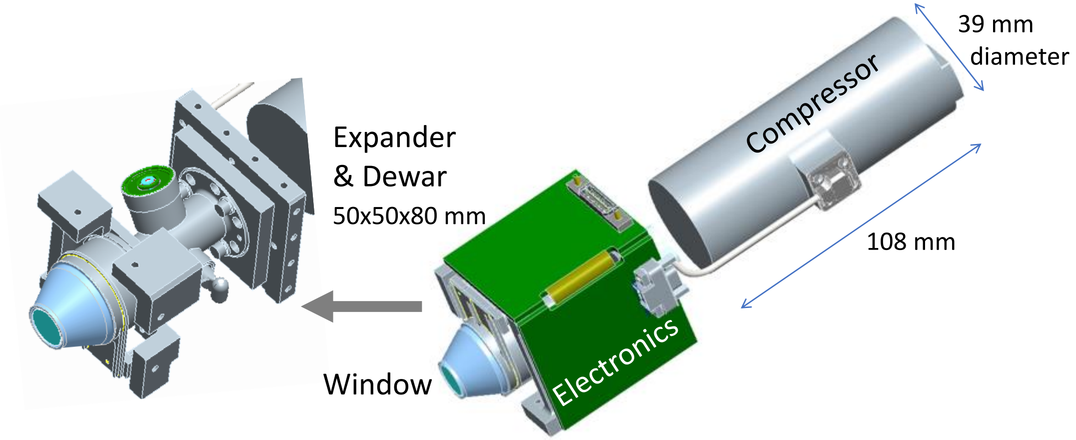
Supported by ESTO InVEST program

More details in Sun et al., SPIE 10659, 2018

Integrated Detector Cooler Assembly*

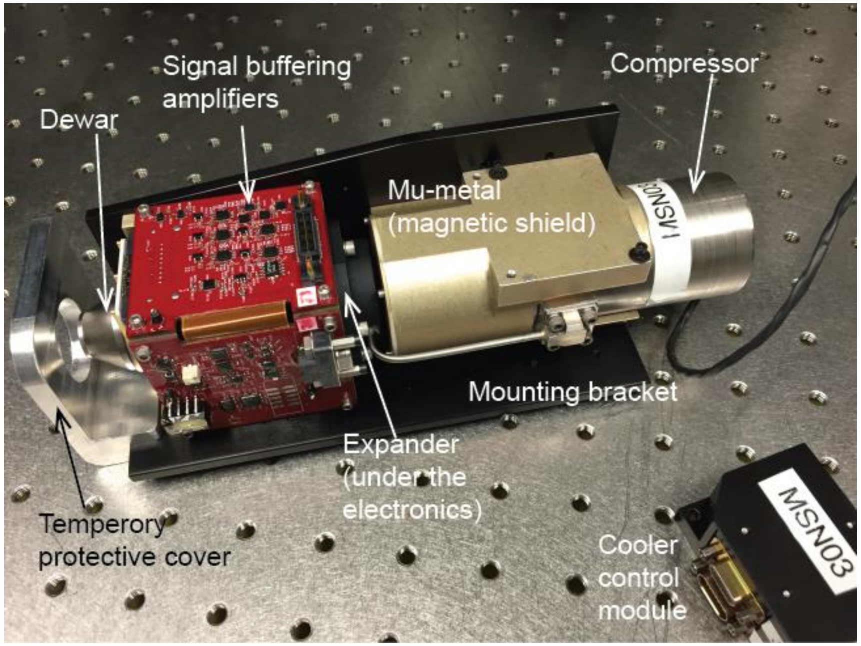
DRS 1/5W Mini-Stirling Cooler





- **Miniature Stirling cryo-cooler from DRS**
  - multi-year life time
- **Detector temperature : 80K or 110K**
- **Mass: ~0.8 kg cooler only and 1.4 kg with mounting bracket and Mu-metal magnetic shield for CubeSat**
- **Electrical power: 6-8 W with heat sink at 30˚C**

*** Supported by ESTO InVEST-12 program**



Integrated Detector Cooler Assembly
- Passed Environmental Tests

Thermal cycle test:

-34 to 71°C storage and -24 to 60°C operation, 1 cycle at DRS,
5 cycles at GSFC

Thermal shock test:

-34°C soak for 4 hours and then transfer to a 71°C oven in <1 minute

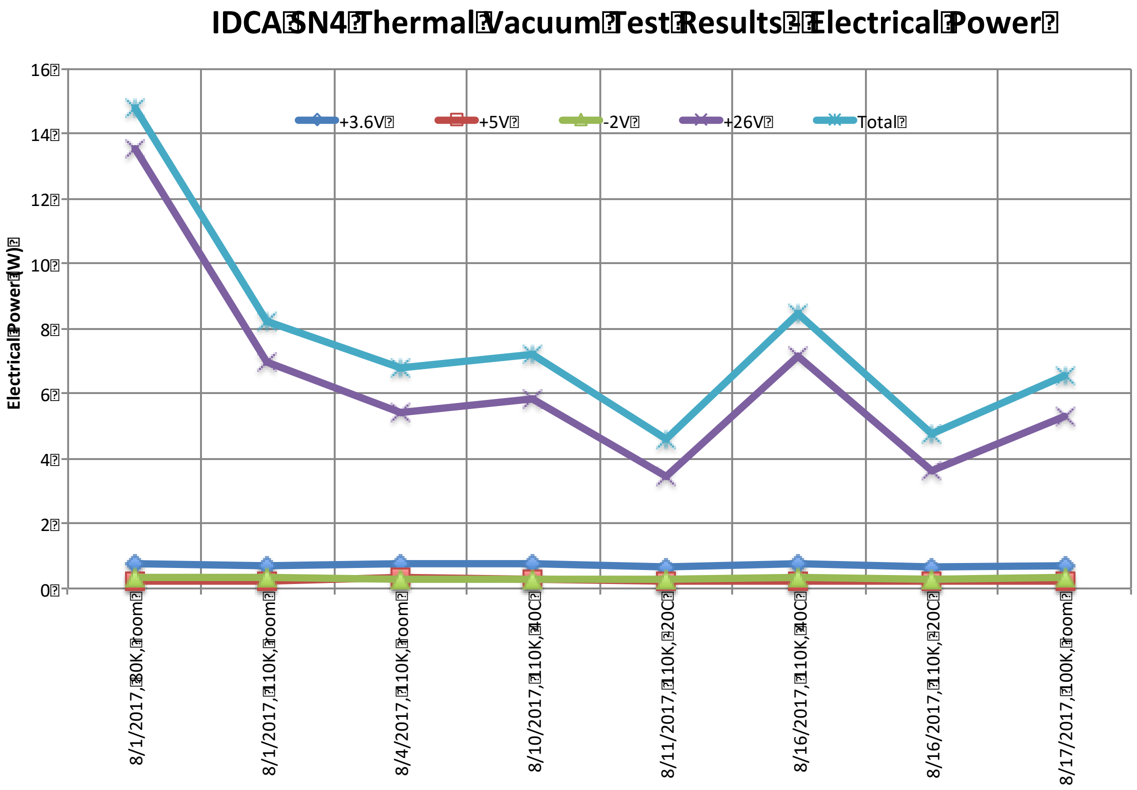
Vibration test:

Cold finger and shield assembly: 14 g rms

Entire IDCA:10 g rms

Thermal vacuum test

-20 to 40°C, 4 cycles

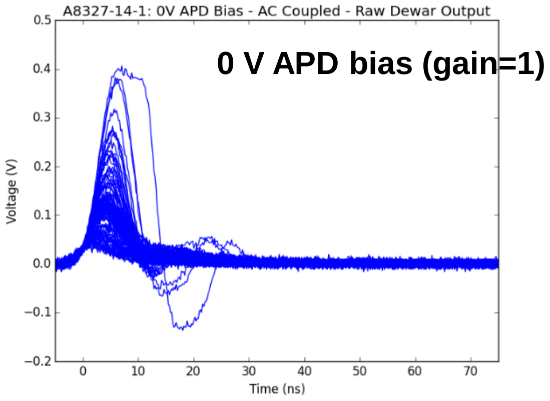


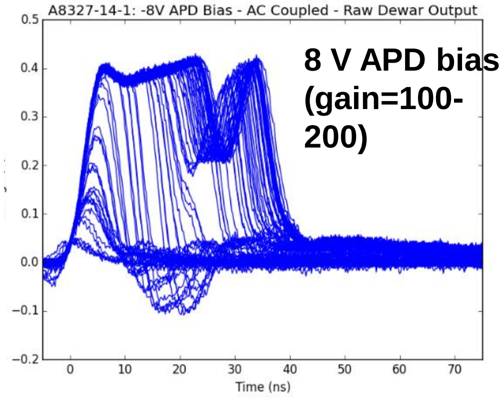
More details in Sun et al., SPIE 10659, 2018

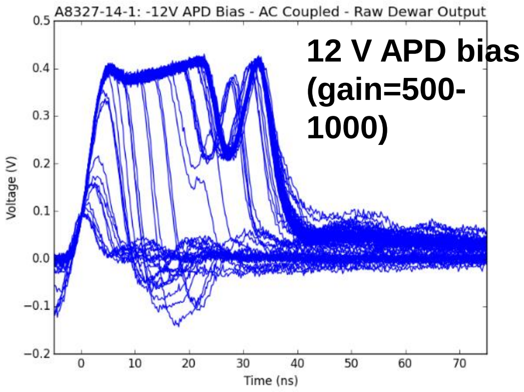
Radiation Damage Tests*

Transient effects, from proton hits:

- large output pulses, saturating electronics (no latch-up), recovered within 1 µs







Accumulated radiation effects, tested with protons up to 100 krad(Si):

- Slight decrease in quantum efficiency, 7% at 100 krad(Si)
- Slight change in the APD gain, but recovered after annealing
- Linear increase in dark currents with proton dose
- ~100x increase in dark current after warming detector to 25C & cooling down again
- Complete annealing of radiation effects by heating detector to 85ºC for 3 hours

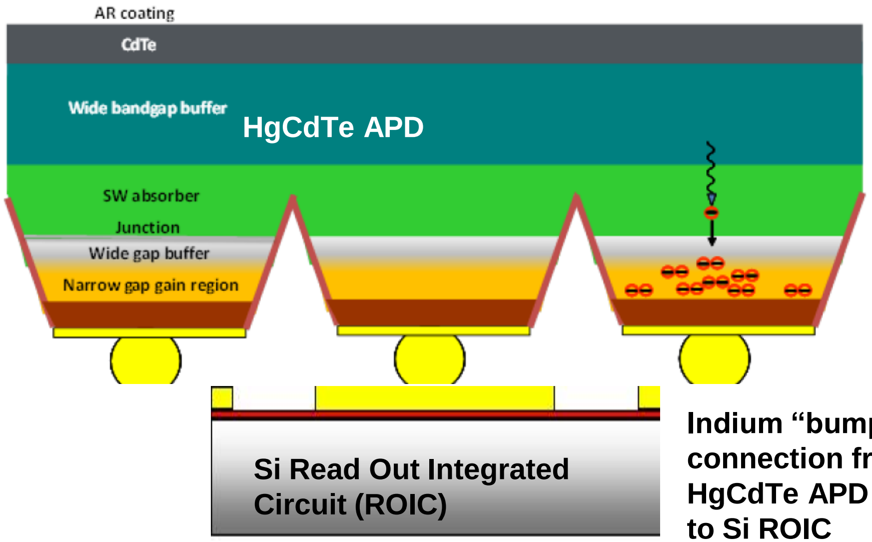
*Tests supported by ESTO QRS programs

More details in Sun *et al.*, SPIE 10624, 2018

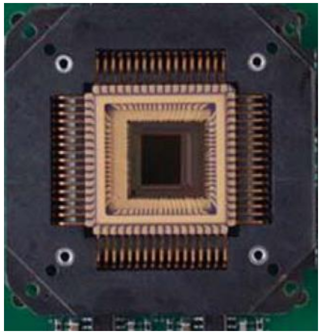
Another HgCdTe APD Array* - Leonardo UK

- Developed under ESA SAPHIRA program for fast frame imaging in astronomy.
- Planar Metal-organic vapor phase epitaxy (MOVPE) multi-anodes mesa avalanche photodiode array (100% fill factor)
- Indium ‘bump’ connection to Si ROIC as in the H1RG in HST and H2RG in JWST
- 24 µm pixel size, 320x256 pixels
- Extremely low dark current
- Nominal APD gain = 80 at 12 V bias and up to 580 at 20 V.
- Spectral response 0.8-2.5 µm

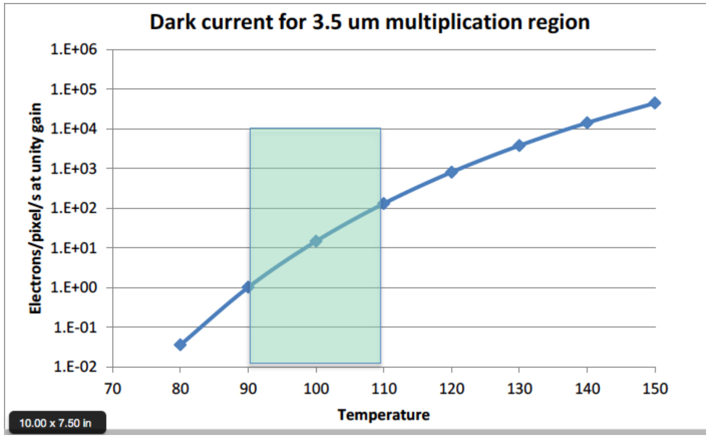
* To be evaluated under ESTO QRS-17



Indium “bump” connection from HgCdTe APD to Si ROIC



HgCdTe APD FPA operate from for high frame rate IR imaging for astronomy



Dark Count Rate vs. Temperature

Baker *et al.*, SPIE 9915, 2016

Summary

- For the past 30 years, all space lidar have used similar detectors
- But for the future, new capabilities are needed:
  - Higher quantum efficiency from visible to mid-wave IR
  - Linear mode photon counting with wide dynamic range
  - Continuous operation, no dead-time, after pulsing, or other nonlinear effects
- Recently developed HgCdTe APD arrays have filled this need
- NASA collaborated with Leonardo DRS (support from IIP, ACT, InVEST programs)
  - Successfully developed several prototype HgCdTe APD arrays and an integrated detector cooler assembly for next generation of space lidar
  - The new detectors have enabled new lidar and passive spectrometer approaches for Earth and planetary science investigation
- NASA is continuing to develop HgCdTe APDs for space and is looking for new technologies from other developers