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**
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**

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

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>3146.5</td>
</tr>
<tr>
<td>HDO</td>
<td>3613.5</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>3260.2</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>3360.9</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>3884.5</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>3985.1</td>
</tr>
<tr>
<td>H$_2$S</td>
<td>3753.6</td>
</tr>
<tr>
<td>H$_2$CO</td>
<td>3595.8</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>3051.7</td>
</tr>
<tr>
<td>O$_3$</td>
<td>3298.3</td>
</tr>
</tbody>
</table>

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

Many suppliers and low cost

Hamamatsu
Teledyne Sci Imaging

DRS
RYV
Selex, Sofradir

InGaAsP Graded layer

i-InGaAs
p+ InAlAs, 300nm

p+ InGaAs Cap layer, 50nm

p+, InAlAs Charge layer

IPE Multiplier

n+ InAlAs Buffer

n+ InP Substrate

Eg~1.05 eV
HgCdTe APD Arrays for Trace Gas Lidar

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

HgCdTe APD for GSFC CO₂ lidar
80x80 µm pixel and 4x4 pixels
~90% Quantum efficiency from 0.7 to 4.3 µm

Conversion Efficiency (e/photon) vs Wavelength (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

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

- Near quantum limited receiver performance in the GSFC 1.57 μm CO₂ Sounder lidar
- One unit is used in GSFC 1.65 μm CH₄ lidar
- One unit is now used in NASA LaRC 2-μm CO₂ 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

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.

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
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.

10 µ laser spot at 2 µ step size

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 25°C & cooling down again
- Complete annealing of radiation effects by heating detector to 85°C 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
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