Innovative Long Wavelength Infrared Detector Workshop

PROCEEDINGS

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1990

Center for Space Microelectronics Technology
Jet Propulsion Laboratory
Pasadena, California
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# INNOVATIVE LONG WAVELENGTH INFRARED DETECTOR WORKSHOP

## CONFERENCE CHAIRS
F. Allario, LaRC  
C.A. Kukkonen, JPL

## ORGANIZATION COMMITTEE
- R.W. Capps, JPL
- R. De Paula, NASA Headquarters
- D. Duston, SDIO/IST
- F.J. Grunthaner, JPL
- D. Jackson, Army/ASTRO
- R.A. Lemons, Los Alamos
- J. Maserjian, Chair, JPL
- C.R. McCreight, ARC
- P.B. McLane, JPL
- R.R. Nelms, LaRC
- A. Pavel, DARPA
- V. Sarohia, JPL
- B.D. Seery, GSFC
- J.R. Swenson, SDIO/SIT

## PROGRAM COMMITTEE
- K.A. Forrest, GSFC
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- G.S. Hubbard, ARC
- S.A. Lyon, Princeton
- T.C. McGill, Caltech
- R.E. McMurray, ARC
- J.L. Merz, UCSB
- W.E. Miller, LaRC
- P.S. Peercy, Sandia
- D.L. Smith, Los Alamos
- D. Spears, MIT/Lincoln
- B.A. Wilson, Chair, JPL
- M. Wigdor, Nicholas
- A. Yariv, Caltech
ABSTRACT

The focus of the workshop was on innovative long wavelength ($\lambda < 17\mu m$) infrared (LWIR) detectors with the potential of meeting future NASA and DoD long-duration space application needs. Requirements are for focal plane arrays which operate near 65K using active refrigeration with mission lifetimes of five to ten years. The workshop addressed innovative concepts, new material systems, novel device physics, and current progress in relation to benchmark technology. It also provided a forum for discussion of performance characterization, producibility, reliability, and fundamental limitations of device physics.

The workshop was attended by a broad cross section of industry, government laboratories and offices, and universities. There were over 170 registered attendees. It covered the status of the incumbent HgCdTe technology, which shows encouraging progress towards LWIR arrays, and provided a snapshot of research and development in several new contender technologies. These contenders span quantum well, heterojunctions, and superlattices in column II-VI, III-V and IV semiconductor materials and promise producible LWIR arrays with the required performance. The workshop also included a session on new innovations for high performance thermal detectors.
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1 - 2 SDIO Long Wavelength Infrared Detector Requirements  
*D. Duston, Strategic Defense Initiative Organization*

1 - 3 LWIR Detector Requirements for Low-Background Space Applications  
*F. De Luccia, The Aerospace Corporation*
SENSOR REQUIREMENTS FOR EARTH AND PLANETARY OBSERVATIONS

Moustafa T. Chahine

Chief Scientist
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

ABSTRACT

Future generations of Earth and planetary remote sensing instruments will require extensive developments of new long-wave and very long-wave infrared detectors. The upcoming NASA Earth Observing System (EOS) will carry a suite of instruments to monitor a wide range of atmospheric and surface parameters with an unprecedented degree of accuracy for a period of 10 to 15 years. These instruments will observe Earth over a wide spectral range extending from the visible to nearly 17 micrometers with a moderate to high spectral and spatial resolution. In addition to expected improvements in communication bandwidth and both ground and on-board computing power, these new sensor systems will need large two-dimensional detector arrays. Such arrays exist for visible wavelengths and, to a lesser extent, for short wavelength infrared systems. The most dramatic need is for new LWIR and VLWIR detector technologies that are compatible with area array readout devices and can operate in the temperature range supported by long life, low power refrigerators. A scientific need for radiometric and calibration accuracies approaching 1% translates into a requirement for detectors with excellent linearity, stability and insensitivity to operating conditions and space radiation. Current examples of the kind of scientific missions these new thermal IR detectors would enhance in the future include instruments for Earth science such as AIRS, MODIS, SAFIRE and OVO. Planetary exploration missions such as Cassini also provide examples of instrument concepts that could be enhanced by new IR detector technologies.
SENSOR REQUIREMENTS FOR
EARTH AND PLANETARY EXPLORATION

Moustafa T. Chahine

DETECTOR REQUIREMENTS —
GENERAL REMARKS

• PERFORMANCE OF PROPOSED INSTRUMENTS DEPENDS
  ALMOST ENTIRELY ON DETECTOR PERFORMANCE

• INSTRUMENT PERFORMANCE REQUIREMENTS OFTEN
  DICTATED BY EXISTING DETECTOR PERFORMANCE DATA
  • NASA FUNDING PROCESS ENSURES THAT PROPOSED
    DETECTOR PERFORMANCE MUST:
      a, EXIST
      b, BE READILY AVAILABLE, WITH FLIGHT HERITAGE
      c, BE BELIEVED TO SATISFY a, AND b, BY THE COMMUNITY

• PROPOSED INSTRUMENTS REQUIRING DETECTOR DEVELOPMENT
  PROGRAMS FARE POORLY AGAINST THOSE THAT DO NOT

• FOR THESE REASONS, REAL DETECTOR REQUIREMENTS
  ARE OFTEN NOT COMMUNICATED TO THOSE ABLE TO
  ADDRESS THEM

• THE PRIMARY PURPOSE OF THIS MEETING IS TO ACHIEVE
  THIS COMMUNICATION.

EARTH OBSERVING SYSTEM (EOS) PAYLOAD

<table>
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<th>Eos-A</th>
<th>Eos-B</th>
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<tr>
<td>AIRS (JPL) 3-15.4μm</td>
<td>ALT/RA</td>
</tr>
<tr>
<td>AMSU</td>
<td>GGI</td>
</tr>
<tr>
<td>CERES (LaRC) 0.2-100μm</td>
<td>GLRS</td>
</tr>
<tr>
<td>HIRDLS (NCAR/OXFORD) 6-18μm</td>
<td>IPEI</td>
</tr>
<tr>
<td>EOSP</td>
<td>LIS</td>
</tr>
<tr>
<td>GGI</td>
<td>MLS</td>
</tr>
<tr>
<td>HIMSS/MIMR/AMSR</td>
<td>SAFIRE (LaRC) 6.4-125μm</td>
</tr>
<tr>
<td>HIRIS</td>
<td>SAGE III</td>
</tr>
<tr>
<td>IPEI</td>
<td>SCANSAT/STIKSCAT</td>
</tr>
<tr>
<td>ITIR (JAP) 0.52-11.65μm</td>
<td>SOLSTICE</td>
</tr>
<tr>
<td>MISR</td>
<td>SWIRLS (JPL) 7.6-17.2μm</td>
</tr>
<tr>
<td>MODIS-N (GSFC) 0.4-14.24μm</td>
<td>TES (JPL) 2.9-17μm</td>
</tr>
<tr>
<td>MODIS-T/MERIS</td>
<td>XIE</td>
</tr>
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# CRAFT PAYLOAD

<table>
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<tr>
<th>Acronym</th>
<th>Investigation</th>
<th>PI/Team Leader</th>
</tr>
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<td>ISS</td>
<td>Imaging (Facility)</td>
<td>J. Veverka/Cornell</td>
</tr>
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<td>VIMS</td>
<td>Visual/Infrared Mapping Spectrometer (Facility)</td>
<td>T. McCord/U of Hawaii</td>
</tr>
<tr>
<td>0.35-5.1 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIREX</td>
<td>Thermal Infrared Radiometer Experiment</td>
<td>F. P.J. Valero/NASA Ames</td>
</tr>
<tr>
<td>PEN</td>
<td>Penetrator</td>
<td>W. Boynton/U of Arizona</td>
</tr>
<tr>
<td>COMA</td>
<td>Cometary Matter Analyzer</td>
<td>J. Kissel/Max Planck Institut</td>
</tr>
<tr>
<td>CIDEX</td>
<td>Comet Ice/Dust Experiment</td>
<td>G. Carle/NASA Ames</td>
</tr>
<tr>
<td>SEMPA</td>
<td>Scanning Electron Microscope and Particle Analyzer</td>
<td>A. Albee/CIT</td>
</tr>
<tr>
<td>CODEM</td>
<td>Comet Dust Environment Monitor</td>
<td>W.M. Alexander/Baylor Univ</td>
</tr>
<tr>
<td>NGIMS</td>
<td>Neutral Gas and Ion Mass Spectrometer</td>
<td>H. Niemann/NASA GSFC</td>
</tr>
<tr>
<td>MAG</td>
<td>Magnetometer</td>
<td>B. Tsurutani/JPL</td>
</tr>
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<td>CREWE</td>
<td>Coordinated Radio, Electrons, and Waves Experiment</td>
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<td>Radio Science (Facility)</td>
<td>D. K. Yeomans/JPL</td>
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# CASSINI PAYLOAD

<table>
<thead>
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<th>Acronym</th>
<th>Investigation</th>
<th>Wavelength/Freq Range</th>
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<tr>
<td>CIRS (GSFC)</td>
<td>Mid &amp; Far IR Spectrometer</td>
<td>7.5-1000 μm</td>
</tr>
<tr>
<td>HSP</td>
<td>High Speed Photometer</td>
<td>117-180 nm</td>
</tr>
<tr>
<td>ISS</td>
<td>Solid State Imaging</td>
<td>0.2-1.1 μm</td>
</tr>
<tr>
<td>MSAR</td>
<td>Microwave Spectrometer/Radiometer</td>
<td>15-230 GHz</td>
</tr>
<tr>
<td>PRWS</td>
<td>Plasma/Radio Wave Spectrometer</td>
<td>5 Hz - 20 MHz</td>
</tr>
<tr>
<td>RADR</td>
<td>Radar</td>
<td>14, 30 GHz</td>
</tr>
<tr>
<td>RS</td>
<td>Radio Science</td>
<td>3.6-13 cm</td>
</tr>
<tr>
<td>UVSI</td>
<td>UV Spectrometer</td>
<td>500-3200 Å</td>
</tr>
</tbody>
</table>

| VIMS (JPL) | Visual/Infrared Mapping Spectrometer | 0.4-5.2 μm |

5
AIRS is a high spectral-resolution sounder covering the range between 3 and 17 μm with more than 4000 spectral measurements, having a resolving power $\Delta \lambda / \lambda = 1/1200$. AIRS permits simultaneous determination of a large number of atmospheric and surface parameters including temperature and humidity profiles, ocean and land surface temperature, clouds, O₃, CH₄, and other minor gases. This is accomplished in part through multispectral, narrow bandpass channels which can be selected away from unwanted absorption lines, while taking advantage of the unique spectral properties of several regions such as the high J-lines in the R-branch of the 4.3 μm CO₂ band and the clear super-windows near 3.6 μm.
AIRS (used with AMSU) provides simultaneous determination of a large number of atmospheric and surface parameters under both day and night conditions:

1. Atmospheric temperature profiles with an average accuracy of 1°C and in 1 km thick layers.
2. Relative humidity profiles and total precipitable water vapor.
3. Sea surface temperature.
4. Land surface temperature and infrared spectral emissivity.
5. Fractional cloud cover, cloud infrared emissivity, and cloud-top pressure and temperature.
6. Total ozone burden of the atmosphere.
7. Mapping of the distribution of minor atmospheric gases such as methane, carbon monoxide and nitrous oxide.
8. Surface albedo.
9. Snow and ice cover.
10. Outgoing long wave radiation.
11. Precipitation index.

**AIRS Atmospheric Temperature Profile**

Atmospheric temperature profiles $T(p)$ will be derived with an average accuracy of 1°C in 1 km thick layers. Clear-column temperature profiles will be derived in the presence of multiple cloud layers without requiring any field-of-view (FOV) to be necessarily completely clear. Observations over adjacent FOVs will be used to filter out the effects of clouds on all channels. Improvements in the $T(p)$ are a result of:

- AIRS narrow contribution functions
- Number of available sounding channels
- Minimizing contamination by $O_3$, $H_2O$, ...
- Simultaneous determination of the surface temperature, emissivity and reflectivity
- Use of AMSU lower atmosphere sounding channels to filter out the effects of clouds

**ORIGINAL PAGE IS OF POOR QUALITY**
Humidity profiles will be derived from channels selected in the 6.3 μm water vapor band and the 11 μm windows which are sensitive to water vapor continuum. The radiance measured in these channels depends on atmosphere and surface temperature and the distribution of humidity in the atmosphere. The 6.3 μm channels are more sensitive to humidity in the middle and upper troposphere, while the narrow bandpass channels in the 11 μm continuum are more sensitive to humidity in the lower troposphere. Determination of surface temperature and spectral emissivity is essential for obtaining accurate low level water vapor distribution.

**TABLE 1**

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<thead>
<tr>
<th>AIRS FUNCTIONAL PARAMETERS</th>
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<tr>
<td><strong>Design Altitude</strong></td>
<td>705 km</td>
</tr>
<tr>
<td><strong>IFOV</strong></td>
<td>1.1°</td>
</tr>
<tr>
<td><strong>Cross-track Scan Motion</strong></td>
<td>± 48.95°</td>
</tr>
<tr>
<td><strong>Infrared</strong></td>
<td></td>
</tr>
<tr>
<td>Spectral Coverage</td>
<td>3.4 - 17.0 μm</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>1200</td>
</tr>
<tr>
<td>NEΔT Channels</td>
<td>0.2 K</td>
</tr>
<tr>
<td>Channels</td>
<td>115 (minimum)</td>
</tr>
<tr>
<td></td>
<td>3638 Spectral elements</td>
</tr>
<tr>
<td><strong>Visible Light</strong></td>
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<tr>
<td>Spectral coverage</td>
<td>0.4 - 1.1 μm</td>
</tr>
<tr>
<td>Channel wavelengths (tentative)</td>
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</tr>
<tr>
<td></td>
<td>0.40 - 0.50 μm</td>
</tr>
<tr>
<td></td>
<td>0.67 - 0.71 μm</td>
</tr>
<tr>
<td></td>
<td>0.70 - 0.80 μm</td>
</tr>
<tr>
<td></td>
<td>0.9 - 1.0 μm</td>
</tr>
<tr>
<td></td>
<td>0.4 - 1.0 μm</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>SNR = 100 at albedo = 0.4 (daytime only)</td>
</tr>
<tr>
<td><strong>Data Encoding</strong></td>
<td>12 bits/sample</td>
</tr>
<tr>
<td><strong>Number of Samples/Cross-track Scan</strong></td>
<td>89</td>
</tr>
<tr>
<td><strong>Mean Data Rate</strong></td>
<td>1.8 Mb/s</td>
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<tr>
<td><strong>Maximum Data Rate</strong></td>
<td>1.8 Mb/s</td>
</tr>
</tbody>
</table>
### TABLE 2
OPTICAL SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>IFOV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>± 0.52°</td>
</tr>
</tbody>
</table>

#### Visible/near IR system:

<table>
<thead>
<tr>
<th></th>
<th>Fore optics:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>full aperture</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>10.0</td>
</tr>
<tr>
<td>EFL (mm)</td>
<td>50</td>
</tr>
<tr>
<td>Focal Ratio</td>
<td>F/5</td>
</tr>
</tbody>
</table>

#### Relay:

<table>
<thead>
<tr>
<th></th>
<th>Magnification</th>
<th>Final Focal Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4:1</td>
<td>F/13.7</td>
</tr>
</tbody>
</table>

#### Detector Diam. (mm)

|                      | 0.5           |

#### IR systems:

<table>
<thead>
<tr>
<th></th>
<th>Fore optics:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>full aperture</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>121.0 x 5.5</td>
</tr>
<tr>
<td>EFL (mm)</td>
<td>500</td>
</tr>
<tr>
<td>Focal Ratio</td>
<td>F/4.1 x F/90.9</td>
</tr>
</tbody>
</table>

#### Spectrometers:

<table>
<thead>
<tr>
<th></th>
<th>Short-Wave</th>
<th>Long-Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture (mm)</td>
<td>69.3 x 138.6</td>
<td>69.3 x 138.6</td>
</tr>
<tr>
<td>Grating Incidence Angle</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>Grating Diffraction Angle</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>Grating Spacing (mm)</td>
<td>0.057</td>
<td>0.127</td>
</tr>
<tr>
<td>EFL (mm)</td>
<td>138.6</td>
<td>138.6</td>
</tr>
<tr>
<td>Focal Ratio</td>
<td>F/2.0 x F/1.0</td>
<td>F/2.0 x F/1.0</td>
</tr>
<tr>
<td>Pixel size (mm)</td>
<td>0.2 x 0.1</td>
<td>0.2 x 0.1</td>
</tr>
</tbody>
</table>

---

**Figure 2**

SCHEMATIC MULTI-APERTURE SPECTROMETER DIAGRAM

In the multi-aperture spectrometer, several sub-apertures (1) in a line across the telescope aperture are relayed to the spectrometer slit (5), then dispersed (7) and re-imaged onto a series of linear arrays (9).
### AIRS INSTRUMENT DIAGRAM WITH X-RAY VIEW OF THE TWO SPECTROMETERS

### AIRS DETECTOR TECHNOLOGY REQUIREMENTS / CHALLENGES

<table>
<thead>
<tr>
<th>ISSUE</th>
<th>REQUIREMENT</th>
<th>CHALLENGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Flux Range</td>
<td>$10^7 - 10^{12}$ photons/sec/pix</td>
<td>Large dynamic range, low readout noise, storage and speed</td>
</tr>
<tr>
<td>Radiometric Performance</td>
<td>BLIP at all flux levels, 1% linearity and calibration accuracy</td>
<td>Low noise detectors, high QE, feedback in cell, radiation tolerance</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>To 15.4 $\mu$m extendable to 17 $\mu$m</td>
<td>Only single pixels demonstrated in MCT, linear arrays required</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>Compatible with long life coolers, $T \geq 60$ K</td>
<td>Not demonstrated, new options needed</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>10 - 50 $\mu$W per pixel with readout 0.1 - 0.2 W for full focal plane</td>
<td>Cooler power limitation</td>
</tr>
</tbody>
</table>
MODERATE RESOLUTION IMAGING SPECTROMETER
(MODIS-N)

[Team Leader: Vince Salomonson, GSFC]

MODERATE RESOLUTION IMAGING SPECTROMETER
SCIENCE OBJECTIVES

- STUDIES OF SPATIAL AND TEMPORAL VARIABILITY OF OCEANIC SURFACE PROPERTIES WITH SPECIAL EMPHASIS ON OCEAN PRIMARY PRODUCTIVITY

- STUDIES OF THE SPATIAL AND TEMPORAL VARIABILITY IN LAND SURFACE PROPERTIES WITH EMPHASIS ON PROBLEMS SUCH AS DESERTIFICATION, REGIONAL VEGETATION STRESS DUE TO ACID RAIN OR DROUGHT, AND SUCCESSION OR CHANGE IN VEGETATION SPECIES DUE TO DEFORESTATION AND ANTHROPOGENIC EFFECTS

- STUDIES OF TROPOSPHERIC DYNAMICS, CLIMATOLOGY AND CHEMISTRY AS OBTAINED THROUGH OBSERVATIONS OF CLOUD CHARACTERISTICS, AEROSOLS, WATER VAPOR, AND TEMPERATURE (INCLUDING SURFACE TEMPERATURE)
MODERATE RESOLUTION IMAGING SPECTROMETER
INSTRUMENT DESCRIPTION

• SCANNING IMAGING SPECTROMETER
• PIXEL SIZES OF 214 M, 428 M, AND 856 M
• SWATH WIDTH OF 2300 KM
• SPECTRAL RANGE 0.6-15 MICRONS, 36 BANDS
• 200 KG, 8.3 MBPS, 250 W

MODIS-N
SPECTRAL CHANNEL CHARACTERISTICS

<table>
<thead>
<tr>
<th>No. CHANNELS</th>
<th>λ (µm)</th>
<th>Δλ (nm)</th>
<th>IFOV (meters)</th>
<th>S/N (AT 70° SZA)</th>
<th>NEDT (TYPICAL)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.6 - 0.9</td>
<td>40 - 50</td>
<td>214</td>
<td>100 - 200</td>
<td></td>
<td>EDGE DETECTION</td>
</tr>
<tr>
<td>5</td>
<td>0.4 - 2.1</td>
<td>20 - 50</td>
<td>428</td>
<td>100 - 300</td>
<td></td>
<td>LAND PROCESSES AND CLOUD CHARACTERISTICS</td>
</tr>
<tr>
<td>7</td>
<td>0.4 - 0.9</td>
<td>10 - 15</td>
<td>856</td>
<td>500 - 900</td>
<td></td>
<td>OCEAN COLOR</td>
</tr>
<tr>
<td>2</td>
<td>0.6 - 0.7</td>
<td>10 - 15</td>
<td>856</td>
<td>1100</td>
<td></td>
<td>FLUORESCENCE</td>
</tr>
<tr>
<td>3</td>
<td>0.9 - 1.0</td>
<td>10 - 50</td>
<td>856</td>
<td>60 - 250</td>
<td></td>
<td>WATER VAPOR</td>
</tr>
<tr>
<td>10</td>
<td>3.7 - 8.6</td>
<td>50 - 300</td>
<td>856</td>
<td>0.05K AT 300K</td>
<td></td>
<td>ATMOS. PARAMETERS AND SURFACE TEMPERATURE</td>
</tr>
<tr>
<td>7</td>
<td>9.7 - 14.2</td>
<td>300 - 500</td>
<td>856</td>
<td>0.25K AT 250K</td>
<td></td>
<td>CLOUD AND SURFACE TEMPERATURE</td>
</tr>
</tbody>
</table>

36
## MODIS-N INSTRUMENT SUMMARY

<table>
<thead>
<tr>
<th>PLATFORM ALTITUDE</th>
<th>705 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFOV (NO. OF BANDS AT IFOV)</td>
<td>29 AT 1.21 mrad (656 m)</td>
</tr>
<tr>
<td></td>
<td>5 AT 0.607 mrad (428 m)</td>
</tr>
<tr>
<td></td>
<td>2 AT 0.303 mrad (214 m)</td>
</tr>
<tr>
<td>SWATH</td>
<td>110 deg/2330 km</td>
</tr>
<tr>
<td>SPECTRAL BANDS</td>
<td>36 BANDS TOTAL</td>
</tr>
<tr>
<td></td>
<td>(19/0.4-3.0 μm;</td>
</tr>
<tr>
<td></td>
<td>17/3-15 μm)</td>
</tr>
<tr>
<td>RADIOMETRIC ACCURACY</td>
<td>5% ABSOLUTE, &lt; 3 μm</td>
</tr>
<tr>
<td></td>
<td>1% ABSOLUTE, &gt; 3 μm</td>
</tr>
<tr>
<td></td>
<td>2% REFLECTANCE</td>
</tr>
<tr>
<td>QUANTIZATION</td>
<td>12 bit</td>
</tr>
<tr>
<td>POLARIZATION SENSITIVITY</td>
<td>2% MAX, ≤ 2.2 μm</td>
</tr>
<tr>
<td>MODULATION TRANSFER FUNCTION</td>
<td>0.3 AT NYQUIST</td>
</tr>
<tr>
<td>S/N PERFORMANCE</td>
<td>630:1 (443 nm)</td>
</tr>
<tr>
<td></td>
<td>745:1 (520 nm)</td>
</tr>
<tr>
<td></td>
<td>503:1 (865 nm)</td>
</tr>
<tr>
<td>NEDT PERFORMANCE (THERMAL BANDS)</td>
<td>LESS THAN 0.05</td>
</tr>
<tr>
<td>AT 300 deg K/WINDOW BANDS</td>
<td></td>
</tr>
<tr>
<td>SCAN EFFICIENCY</td>
<td>(TO BE DETERMINED)</td>
</tr>
<tr>
<td>INTEGRATION TIME</td>
<td>(TO BE DETERMINED)</td>
</tr>
<tr>
<td>SIZE (APPROX)</td>
<td>1 x 1.6 x 1 m</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>APPROX 200 kg</td>
</tr>
<tr>
<td>POWER</td>
<td>250 W</td>
</tr>
<tr>
<td>PEAK DATA RATE</td>
<td>15 MBS (DAYTIME)</td>
</tr>
<tr>
<td>DUTY CYCLE</td>
<td>100%</td>
</tr>
</tbody>
</table>

## MODIS-N LWIR PARAMETERS

<table>
<thead>
<tr>
<th>BAND NUMBER</th>
<th>CENTER WVLNGTH (μm)</th>
<th>DELTA WVLNGTH (nm)</th>
<th>TYP. SCENE TEMP (K)</th>
<th>TYP. SPECTRAL RADIANCE (+)</th>
<th>NOISE EQUIV. SPECTRAL RADIANCE (+)</th>
<th>REQ. SIGNAL/NOISE RATIO</th>
<th>NOMINAL NEP (W)**</th>
<th>CALCULATED D*</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>9.73</td>
<td>300</td>
<td>250</td>
<td>3.6</td>
<td>0.25</td>
<td>2.19E-02</td>
<td>168</td>
<td>6.04E-11</td>
</tr>
<tr>
<td>31</td>
<td>11.03</td>
<td>500</td>
<td>300</td>
<td>9.55</td>
<td>0.05</td>
<td>7.01E-03</td>
<td>1362</td>
<td>3.22E-11</td>
</tr>
<tr>
<td>32</td>
<td>12.02</td>
<td>300</td>
<td>300</td>
<td>8.94</td>
<td>0.05</td>
<td>6.06E-03</td>
<td>1475</td>
<td>2.79E-11</td>
</tr>
<tr>
<td>33</td>
<td>13.34</td>
<td>300</td>
<td>260</td>
<td>4.52</td>
<td>0.25</td>
<td>1.83E-02</td>
<td>247</td>
<td>5.05E-11</td>
</tr>
<tr>
<td>34</td>
<td>13.64</td>
<td>300</td>
<td>250</td>
<td>3.76</td>
<td>0.25</td>
<td>1.61E-02</td>
<td>234</td>
<td>4.44E-11</td>
</tr>
<tr>
<td>35</td>
<td>13.94</td>
<td>300</td>
<td>240</td>
<td>3.11</td>
<td>0.25</td>
<td>1.41E-02</td>
<td>221</td>
<td>3.89E-11</td>
</tr>
<tr>
<td>36</td>
<td>14.24</td>
<td>300</td>
<td>220</td>
<td>2.08</td>
<td>0.35</td>
<td>1.54E-02</td>
<td>135</td>
<td>4.25E-11</td>
</tr>
</tbody>
</table>

**NOTE:**

THE COLUMNS UP TO REQUIRED SIGNAL-TO-NOISE RATIO ARE SPECIFICATION VALUES FROM THE SEP. 19, 1989 SPECIFICATION CIRCULATED TO INDUSTRY FOR REVIEW. THE CALCULATED D* VALUES DEPEND ON SYSTEM ASSUMPTIONS AND MUST BE ACHIEVED AT FOCAL PLANE TEMPERATURES WARMER THAN 85K.

SYSTEM ASSUMPTIONS ANTICIPATE THE USE OF SHORT LINEAR WHISKERBROOM ARRAYS OF LESS THAN 20 DETECTORS.

**ASSUME:**

<table>
<thead>
<tr>
<th>APERTURE (cm)</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-NUMBER</td>
<td>2.00</td>
</tr>
<tr>
<td>TRANSMISSION</td>
<td>0.20</td>
</tr>
<tr>
<td>IFOV</td>
<td>1.21E-03</td>
</tr>
<tr>
<td>DET. SIZE (μm)</td>
<td>4.8E+02</td>
</tr>
<tr>
<td>NOISE BW (Hz)</td>
<td>3000</td>
</tr>
</tbody>
</table>

*WATTS/(cm²-sr-μm)

**ASSUME:**

ORIGINAL PAGE IS OF POOR QUALITY
TROPOSPHERIC EMISSION SPECTROMETER (TES)

[P.I.: Reinhard Beer, JPL]

TROPOSPHERIC EMISSION SPECTROMETER
SCIENCE OBJECTIVES

- GENERATE VERTICAL CONCENTRATION PROFILES ON A GLOBAL BASIS OF THE FOLLOWING SPECIES WITH SUB-SCALE-HEIGHT RESOLUTION AND 5° LATITUDE SPACING:

<table>
<thead>
<tr>
<th>Misc.</th>
<th>HO₂</th>
<th>NO₂</th>
<th>NO₃</th>
<th>Hydrocarbons</th>
<th>SO₂</th>
<th>CFCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>H₂O</td>
<td>NO</td>
<td>CH₄</td>
<td>SO₂</td>
<td>CF₃Cl</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>H₂O₂</td>
<td>NO₂</td>
<td>C₂H₆</td>
<td>COS</td>
<td>CF₂Cl₂</td>
<td></td>
</tr>
<tr>
<td>(CO₂)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td></td>
<td></td>
<td></td>
<td>H₂O₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TES: SPECIES DETECTABILITY MATRIX

<table>
<thead>
<tr>
<th>SPECIES</th>
<th>LOWER STRATOSPHERE (15 - 30 km)</th>
<th>FREE TROPOSHERE (2 - 15 km)</th>
<th>BOUNDARY LAYER (0 - 2 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MEASURABILITY KEY:

- ACCURACY 1 - 10%
- FACTOR OF 2 OR BETTER
- TBD
- UNLIKELY TO BE MEASURABLE

VALUE ASSUMED FOR TEMPERATURE SOUNDING
TROPOSPHERIC EMISSION SPECTROMETER
INSTRUMENT DESCRIPTION

- HIGH SPECTRAL RESOLUTION INFRARED IMAGING FOURIER TRANSFORM SPECTROMETER
- 491 KG, 660 W PEAK POWER
- SPECTRAL COVERAGE 600 TO 3200 CM\(^{-1}\) (2.9 TO 16.6 MICRONS)
- FOUR LINEAR ARRAYS OF 32 DETECTORS, EACH WITH ITS OWN SIGNAL CHAIN, IN CONJUGATE FOCAL PLANES
- ALL DETECTOR ELEMENTS ARE 0.1 MM BY 1.0 MM
- DETECTOR FOV 0.75 X 7.5 MRAD. NADIR PIXEL SUBTENDS 0.5 X 5 KM
- ON-BOARD SOURCES ARE PROVIDED FOR RADIOMETRIC CALIBRATION AND DETECTOR ALIGNMENT

TROPOSPHERIC EMISSION SPECTROMETER
CONCEPTUAL DESIGN

ORIGINAL PAGE IS OF POOR QUALITY
TROPOSPHERIC EMISSION SPECTROMETER
FOCAL PLANE ARRAY - TECHNICAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>MATERIAL:</th>
<th>InSb (PV)</th>
<th>HgCdTe (PV)</th>
<th>HgCdTe (PV)</th>
<th>HgCdTe (PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAVEBAND (μm)</td>
<td>2.9 - 5.6</td>
<td>8.3 - 12.5</td>
<td>5.3 - 9.1</td>
<td>11.1 - 16.7</td>
</tr>
<tr>
<td>CUTOFF FREQ (cm⁻¹)</td>
<td>1800 - 3400</td>
<td>800 - 1200</td>
<td>1100 - 1900</td>
<td>600 - 900</td>
</tr>
<tr>
<td>QUANTUM EFFICIENCY</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>IMPEDANCE (OHMS)</td>
<td>100 M</td>
<td>10 K</td>
<td>100 K</td>
<td>100</td>
</tr>
<tr>
<td>BGKRD FLUX DENSITY (Ps⁻¹ cm⁻¹)</td>
<td>2.9E11 - 2.6E14</td>
<td>1.3E14 - 3.0E15</td>
<td>8.9E12 - 1.1E15</td>
<td>1.2E15 - 3.9E15</td>
</tr>
<tr>
<td>D* (cm Hz⁻¹/² W⁻¹)</td>
<td>&gt;7.0E11</td>
<td>&gt;5.0E11</td>
<td>&gt;6.0E11</td>
<td>&gt;2.0E11</td>
</tr>
</tbody>
</table>

THESE DETECTOR REQUIREMENTS ARE COMPATIBLE WITH DETECTOR MATERIAL CURRENTLY BEING PRODUCED

TROPOSPHERIC EMISSION SPECTROMETER
PERFORMANCE ESTIMATES

<table>
<thead>
<tr>
<th>FREQ. RANGE (cm⁻¹)</th>
<th>WAVELENGTH (microns)</th>
<th>NADIR SNR (2 sec scan)</th>
<th>LIMB SNR (8 sec scan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 - 900</td>
<td>11.1 - 16.7</td>
<td>500 - 600</td>
<td>200 - 300</td>
</tr>
<tr>
<td>800 - 1200</td>
<td>8.3 - 12.5</td>
<td>400 - 500</td>
<td>100 - 200</td>
</tr>
<tr>
<td>1100 - 1900</td>
<td>5.3 - 9.1</td>
<td>100 - 600</td>
<td>40 - 300</td>
</tr>
<tr>
<td>1800 - 3450(N)</td>
<td>2.9 - 5.6</td>
<td>30 - 150</td>
<td>na</td>
</tr>
<tr>
<td>1800 - 2450(L)</td>
<td>4.1 - 5.6</td>
<td>na</td>
<td>20 - 40</td>
</tr>
</tbody>
</table>
SPECTROSCOPY OF THE ATMOSPHERE USING FAR INFRARED EMISSION (SAFIRE)

[P.I.: Jim Russell, LaRC]

• SCIENTIFIC GOAL
  - To improve understanding of the middle atmosphere ozone distribution by conducting and analyzing global-scale measurements of important chemical, radiative, and dynamical processes, including coupling among processes and atmospheric regions.

• SCIENTIFIC OBJECTIVES
  - Study key processes in the Oy, HOy, NOy, ClOy, and BrOy chemical families
  - Study polar night chemistry
  - Conduct non-LTE investigations
  - Investigate diurnal change processes (OH, HO2, NO2, N2O5, O3)
  - Conduct dynamics studies and study coupling between chemistry and dynamics
  - Investigate lower stratosphere phenomena (e.g. polar night O3 depletion)
TROPOSPHERIC EMISSION SPECTROMETER
CONCEPTUAL DESIGN

Payload Assembly
Plate Interface 1.35 x 1.0 m

Standard Integrated Connector

Electronics Bay (Warm)

Cube Corner Actuator
Calibration Sources
Lasers
Cube Corner Reflector
Star Tracker
2 Axis Pointing Mirror
Service Access

Optics Housing (150 K)
Beam Recombiner
Beam Splitter
8 Point Suspension Mount (Partial)
Imaging Parabola

Reflective Silt
Dichroic beamsplitter
Collimating Parabola
Filter Wheel
Array Detector
Flexible Cold Strap
Cooler Compressors

Dove Mirror Assembly

Cooler Regenerator

18
TROPOSPHERIC EMISSION SPECTROMETER
FOCAL PLANE ARRAY - TECHNICAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>MATERIAL:</th>
<th>InSb (PV)</th>
<th>HgCdTe (PV)</th>
<th>HgCdTe (PV)</th>
<th>HgCdTe (PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAVEBAND (μm)</td>
<td>2.9-5.6</td>
<td>8.3-12.5</td>
<td>5.3-9.1</td>
<td>11.1-16.7</td>
</tr>
<tr>
<td>CUT-OFF FREQ (cm⁻¹)</td>
<td>1800-3400</td>
<td>800-1200</td>
<td>1100-1900</td>
<td>600-900</td>
</tr>
<tr>
<td>QUANTUM EFFICIENCY</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>IMPEDANCE (OHMS)</td>
<td>100 M</td>
<td>10 K</td>
<td>100 K</td>
<td>100</td>
</tr>
<tr>
<td>BKGRD FLUX DENSITY (Ps⁻¹cm⁻¹)</td>
<td>2.9E11-</td>
<td>1.3E14-</td>
<td>8.9E12-</td>
<td>1.2E15-</td>
</tr>
<tr>
<td></td>
<td>2.6E14</td>
<td>3.0E15</td>
<td>1.1E15</td>
<td>3.9E15</td>
</tr>
<tr>
<td>D* (cm Hz⁻¹/² W⁻¹)</td>
<td>&gt;7.0E11</td>
<td>&gt;5.0E11</td>
<td>&gt;6.0E11</td>
<td>&gt;2.0E11</td>
</tr>
<tr>
<td>ELECTRICAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BANDWIDTH (kHz)</td>
<td>27</td>
<td>12</td>
<td>14</td>
<td>8.5</td>
</tr>
<tr>
<td>OPERATING TEMP (K)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
</tbody>
</table>

THESE DETECTOR REQUIREMENTS ARE COMPATIBLE
WITH DETECTOR MATERIAL CURRENTLY BEING PRODUCED

TROPOSPHERIC EMISSION SPECTROMETER
PERFORMANCE ESTIMATES

<table>
<thead>
<tr>
<th>FREQ. RANGE cm⁻¹</th>
<th>WAVELENGTH microns</th>
<th>NADIR SNR (2 sec scan)</th>
<th>LIMB SNR (8 sec scan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 - 900</td>
<td>11.1 - 16.7</td>
<td>500 - 600</td>
<td>200 - 300</td>
</tr>
<tr>
<td>800 - 1200</td>
<td>8.3 - 12.5</td>
<td>400 - 500</td>
<td>100 - 200</td>
</tr>
<tr>
<td>1100 - 1900</td>
<td>5.3 - 9.1</td>
<td>100 - 600</td>
<td>40 - 300</td>
</tr>
<tr>
<td>1800 - 3450(N)</td>
<td>2.9 - 5.6</td>
<td>30 - 150</td>
<td>na</td>
</tr>
<tr>
<td>1800 - 2450(L)</td>
<td>4.1 - 5.6</td>
<td>na</td>
<td>20 - 40</td>
</tr>
</tbody>
</table>

19
ORBITAL VOLCANOLOGICAL OBSERVATIONS
(OVO)

[P.I.: Dave Pieri, JPL]

ORBITAL VOLCANOLOGICAL OBSERVATIONS
SCIENCE GOALS

• IMPROVED UNDERSTANDING OF ERUPTION MECHANISMS

• IMPROVED DETERMINATION OF THE NATURE AND AMOUNT OF VOLCANIC CONTRIBUTIONS TO THE GLOBAL ENVIRONMENT

• IMPROVED UNDERSTANDING OF HOW THE PRODUCTS OF VOLCANIC ERUPTIONS INTERACT WITH THE ENVIRONMENT TO PRODUCE SIGNIFICANT GLOBAL CHANGES

ORBITAL VOLCANOLOGICAL OBSERVATIONS
MEASUREMENT OBJECTIVES

• MULTISPECTRAL THERMAL IR MAPPING OF VOLCANIC LITHOLOGIES

• BRIGHTNESS TEMPERATURE AND HEAT SOURCE DISTRIBUTION MAPS OF ACTIVE VOLCANIC FEATURES (E.G. LAVA FLOWS, SUMMIT CRATERS, LAVA TUBE SYSTEMS, FUMAROLES, HOT WATER LAKES, HOT WATER OCEANIC PLUMES)

• BRIGHTNESS TEMPERATURE MAPS OF ERUPTION COLUMNS AND DISPERSED VOLCANIC PLUMES

• MULTISPECTRAL DETECTION AND MAPPING OF AIRBORNE ASH PLUMES IN THE PRESENCE OF METEOROLOGICAL CLOUDS

• DETERMINATION OF COMPOSITION AND VOLUME OF SUBAERIAL GLOBAL VOLCANIC GAS BUDGET OVER TIME
ORBITAL VOLCANOLOGICAL OBSERVATIONS
DATA PRODUCTS

- THERMAL MAPS OF SOLID PRODUCTS OF VOLCANIC ERUPTIONS ON THE GROUND
- MULTISPECTRAL MAPPING IMAGES OF THE SURFACE OF VOLCANOES
- 2-D THERMAL MAPS OF AIRBORNE PLUMES
- 3-D THERMAL PROFILES OF ERUPTION PLUMES

ORBITAL VOLCANOLOGICAL OBSERVATIONS
INFRARED DETECTOR REQUIREMENTS

- 1.0-2.5 \( \mu \text{m} \), 5-10 CHANNELS FOR HIGH TEMPERATURE THERMAL RADIOMETRY, GAS AND AEROSOL MEASUREMENTS
- 2.5-5.0 \( \mu \text{m} \), 5 CHANNELS FOR LOWER TEMPERATURE RADIOMETRY, GEOLOGICAL MAPPING, GAS AND AEROSOL MEASUREMENTS
- 8-12 \( \mu \text{m} \), 10+ CHANNELS FOR MULTISPECTRAL MAPPING, LOWEST TEMPERATURE THERMAL RADIOMETRY, ATMOSPHERIC MEASUREMENTS AND CORRECTIONS
- IMAGING CAPABILITY REQUIRED, \( \geq 25 \) km SWATH, \( \leq 100 \) m SPATIAL SAMPLING
- LOW TEMP RADIOMETRY REQUIRES \(-0.3K\) NedT MEASUREMENT CAPABILITY
- MASS CONSIDERATIONS ARGUE FOR DEVELOPMENT OF DETECTORS WITH REDUCED COOLING REQUIREMENTS
MULTISPECTRAL THERMAL IMAGER
(MSTI)

[P.I.: Tim Schofield, JPL]

MULTISPECTRAL THERMAL IMAGER
SCIENCE OBJECTIVES AND KEY MEASUREMENTS

- UNDERSTAND THE INTERPLAY BETWEEN RADIATIVE, DYNAMICAL AND
  PHOTOCHEMICAL PROCESSES IN THE ATMOSPHERES OF SATURN, TITAN
  AND JUPITER

- OBTAIN MEASUREMENTS OF THE 3-D DISTRIBUTION OF
  TEMPERATURE, DYNAMICAL FIELDS, KEY SPECIES CONCENTRATIONS
  AND AEROSOL EXTINCTION IN THESE ATMOSPHERES WITH
  COMPREHENSIVE COVERAGE AND RESOLUTION, BOTH SPATIALLY
  AND TEMPORALLY

- DEVELOP A DESCRIPTION OF THE PHYSICAL AND COMPOSITIONAL UNITS
  OF THE SATELLITES AND RINGS

  OBTAIN COMPREHENSIVE MULTISPECTRAL MEASUREMENTS OF
  BRIGHTNESS TEMPERATURE AND ALBEDO

MULTI-SPECTRAL THERMAL IMAGER (MSTI)
CONCEPTUAL INSTRUMENT SPECIFICATIONS

<table>
<thead>
<tr>
<th>INSTRUMENT PARAMETER</th>
<th>VALUE/COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSTRUMENT TYPE</td>
<td>MULTI-SPECTRAL THERMAL IMAGER</td>
</tr>
<tr>
<td>MEASUREMENT TECHNIQUES</td>
<td>GAS CORRELATION AND FILTER RADIOMETRY</td>
</tr>
<tr>
<td>SPECTRAL CHANNELS AND RANGE</td>
<td>8 CHANNELS, 8-14 μm</td>
</tr>
<tr>
<td></td>
<td>7 CHANNELS, 15-100 μm</td>
</tr>
<tr>
<td></td>
<td>1 CHANNEL, 0.3-3.0 μm</td>
</tr>
<tr>
<td>TELESCOPE APERTURE</td>
<td>NARROW ANGLE, 15 cm</td>
</tr>
<tr>
<td></td>
<td>WIDE ANGLE, 4 cm</td>
</tr>
<tr>
<td>NARROW ANGLE FOV</td>
<td>ARRAY, 1.15&quot; x 1.15&quot;</td>
</tr>
<tr>
<td>WIDE ANGLE FOV</td>
<td>ARRAY, 4.58&quot; x 4.58&quot;</td>
</tr>
<tr>
<td>MID-IR DETECTOR</td>
<td>64 x 64 PV HgCdTe ARRAY, 70K</td>
</tr>
<tr>
<td>FAR-IR AND SOLAR DETECTOR</td>
<td>64 x 64 BOLOMETER ARRAY, 180K</td>
</tr>
<tr>
<td>DATA RATE</td>
<td>1.5 kbps, APOCHRONE</td>
</tr>
<tr>
<td></td>
<td>3.0 kbps, FAR ENCOUNTER</td>
</tr>
<tr>
<td></td>
<td>6.0 kbps, NEAR ENCOUNTER</td>
</tr>
<tr>
<td>INSTRUMENT DATA BUFFER</td>
<td>2 MBytes</td>
</tr>
<tr>
<td>SPACECRAFT POINTING</td>
<td>CONTROL, 2 mrad</td>
</tr>
<tr>
<td>PITCH, ROLL, AND YAW</td>
<td>KNOWLEDGE, 1 mrad</td>
</tr>
<tr>
<td></td>
<td>STABILITY, 100 μrad - 2 seconds</td>
</tr>
<tr>
<td></td>
<td>STABILITY, 300 μrad - 30 seconds</td>
</tr>
<tr>
<td>MASS GOAL</td>
<td>23 kg</td>
</tr>
<tr>
<td>POWER GOAL</td>
<td>19 WATTS (AVERAGE)</td>
</tr>
</tbody>
</table>
## Multi-Spectral Thermal Imager (MSTI)

### Channel Spectral Characteristics and Measurement Functions

<table>
<thead>
<tr>
<th>CHANNEL (1)</th>
<th>BANDPASS CENTER, cm⁻¹</th>
<th>BANDPASS FILTER TYPE (2)</th>
<th>MEASUREMENT FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1240 - 1290</td>
<td>7.9</td>
<td>STRATOSPHERIC TEMPERATURE</td>
</tr>
<tr>
<td>A2</td>
<td>1240 - 1290</td>
<td>7.9</td>
<td>ETHANE CONCENTRATION</td>
</tr>
<tr>
<td>A3</td>
<td>805 - 845</td>
<td>12.1</td>
<td>ACETYLENE CONCENTRATION</td>
</tr>
<tr>
<td>A4</td>
<td>805 - 845</td>
<td>12.1</td>
<td>PHOSPHINE</td>
</tr>
<tr>
<td>A5</td>
<td>730 - 760</td>
<td>13.4</td>
<td>AMMONIA ICE</td>
</tr>
<tr>
<td>A6</td>
<td>730 - 760</td>
<td>13.4</td>
<td>TROPOSPHERIC TEMPERATURE</td>
</tr>
<tr>
<td>A7</td>
<td>920 - 1050</td>
<td>10.2</td>
<td>ORTHO-PARA HYDROGEN RATIO</td>
</tr>
<tr>
<td>A8</td>
<td>1120 - 1180</td>
<td>8.7</td>
<td>AEROSOL DISTRIBUTION</td>
</tr>
</tbody>
</table>

**FILTER WHEEL A - MID INFRARED, 70K HgCdTe DETECTOR ARRAY, 64 x 64 PIXELS**

<table>
<thead>
<tr>
<th>CHANNEL (1)</th>
<th>BANDPASS CENTER, cm⁻¹</th>
<th>BANDPASS FILTER TYPE (2)</th>
<th>MEASUREMENT FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>570 - 630</td>
<td>16.7</td>
<td>TROPOSPHERIC TEMPERATURE</td>
</tr>
<tr>
<td>B2</td>
<td>470 - 510</td>
<td>20.4</td>
<td>ORTHO-PARA HYDROGEN RATIO</td>
</tr>
<tr>
<td>B3</td>
<td>350 - 390</td>
<td>27.0</td>
<td>AEROSOL DISTRIBUTION</td>
</tr>
<tr>
<td>B4</td>
<td>210 - 250</td>
<td>43.5</td>
<td>ENERGY BALANCE</td>
</tr>
<tr>
<td>B5</td>
<td>170 - 210</td>
<td>52.6</td>
<td></td>
</tr>
<tr>
<td>B6</td>
<td>80 - 140</td>
<td>90.1</td>
<td></td>
</tr>
<tr>
<td>B7</td>
<td>OPEN</td>
<td>OPEN</td>
<td></td>
</tr>
<tr>
<td>B8</td>
<td>3333 - 3333</td>
<td>0.54</td>
<td></td>
</tr>
</tbody>
</table>

**FILTER WHEEL B - FAR INFRARED, 180K BOLOMETRIC DETECTOR ARRAY, 64 x 64 PIXELS**

(1). Imaging is performed in all spectral channels.

(2). Channels A1 - A6 perform gas correlation radiometry using bandpass filters and cells containing the gas indicated to obtain high energy grasp, spectral discrimination, and species selectivity. Channels A7, A8, and B1 - B8 bandpass filters only.

## Multispectral Thermal Imager (MSTI)

### LWIR Focal Plane Array Requirements

- **D* (cm hz¹/² w⁻¹)**

  **GOAL:**  \( \geq 2.0 \times 10^{11} \) (8μm),  \( \geq 2.0 \times 10^{10} \) (13.5μm),  \( \geq 1.0 \times 10^{9} \) (100μm)

  **REQ:**  \( \geq 1.0 \times 10^{11} \) (8μm),  \( \geq 1.0 \times 10^{10} \) (13.5μm),  \( \geq 1.0 \times 10^{10} \) (100μm).

- **CURRENT PV-HgCdTe TECHNOLOGY CAN MEET THE D* REQUIREMENTS, BUT CANNOT MEET THE GOALS AT BOTH 8 AND 13.5 μm SIMULTANEOUSLY**
COMPOSITE INFRARED SPECTROMETER
(CIRS)

[P.I.: Virgil Kunde, GSFC]

COMPOSITE INFRARED SPECTROMETER
SCIENCE OBJECTIVES

- DETERMINE THE TROPOSHERIC AND STRATOSPHERIC TEMPERATURE AND AEROSOL STRUCTURE OF SATURN AND TITAN

- DETERMINE THE MIXING RATIOS AND SPATIAL DISTRIBUTIONS OF TRACE GASES IN BOTH ATMOSPHERES
  - MANY ORGANIC MOLECULES FOR TITAN
  - PH$_3$ AND NH$_3$ FOR SATURN

- CONSTRAIN THE PROPERTIES OF NH$_3$ ICE CLOUDS IN SATURN’S ATMOSPHERE

- DETERMINE THE BULK COMPOSITION OF SATURN’S ATMOSPHERE

- DETERMINE SURFACE TEMPERATURE PROPERTIES OF THE SMALLER ICY SATELLITES AND THE EMISSIVITY OF THE RINGS
Figure B6  CIRS sensitivity for Saturn.

Figure B7  CIRS sensitivity for Titan.
COMPOSITE INFRARED SPECTROMETER
INSTRUMENT CHARACTERISTICS

- DUAL INTERFEROMETER CONFIGURATION SHARING A 50 CM CASSEGRAIN TELESCOPE
- SPECTRAL RANGE 7.5-1000 μm
- SPECTRAL RESOLUTION 0.25 cm⁻¹ UNAPODIZED
- INDIVIDUAL DETECTOR FIELD-OF-VIEW .25° (FAR-IR), .0057° (MID-IR)
- FAR-IR INTERFEROMETER EMPLOYS A 1x5 ARRAY USING EITHER THERMOPILES OR PYROELECTRICS
- MID-IR INTERFEROMETER EMPLOYS TWO 1 x 43 HgCdTe ARRAYS, COOLED TO 70-90K

POLARIZING FTS (CIRS)

Figure B8 Optical schematic for CIRS.
COMPOSITE INFRARED SPECTROMETER
FOCAL PLANE PARAMETERS

<table>
<thead>
<tr>
<th>SPECTRAL RANGE (cm⁻¹)</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-700</td>
<td>700-1200</td>
<td>1200-1400</td>
</tr>
<tr>
<td>DETECTORS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERMOPILE</td>
<td></td>
<td>HgCdTe</td>
<td>HgCdTe</td>
</tr>
<tr>
<td>(1x5)</td>
<td></td>
<td>(1x43)</td>
<td>(1x43)</td>
</tr>
<tr>
<td>PIXEL FOV (mrad)</td>
<td>4.3x12.9</td>
<td>0.1x0.3</td>
<td>0.1x0.3</td>
</tr>
<tr>
<td>PIXEL Ω (cm²-sr)</td>
<td>1.1x10⁻¹</td>
<td>6.1x10⁻⁵</td>
<td>6.1x10⁻⁵</td>
</tr>
<tr>
<td>NEP (W Hz⁻¹/²)</td>
<td>2x10⁻¹¹</td>
<td>8x10⁻¹⁴</td>
<td>2x10⁻¹⁴</td>
</tr>
<tr>
<td>NESR (W cm⁻²sr⁻¹/cm⁻¹)</td>
<td>7x10⁻¹⁰</td>
<td>5x10⁻⁹</td>
<td>1x10⁻⁹</td>
</tr>
<tr>
<td>TEMPERATURE (K)</td>
<td>170</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

GENERAL AREAS FOR EXPERIMENT ENHANCEMENT

- ALL THE PROPOSED EXPERIMENTS WOULD BE ENHANCED BY ONE OR MORE OF THE FOLLOWING IMPROVEMENTS.
  - IMPROVED DETECTOR PERFORMANCE, GIVING:
    - SAME INSTRUMENT PERFORMANCE AT HIGHER DETECTOR TEMPERATURES.
    - IMPROVED PERFORMANCE AT THE SAME DETECTOR TEMPERATURE
  - LOWER INSTRUMENT AND DETECTOR OPERATING TEMPERATURES, GIVING:
    - IMPROVED PERFORMANCE WITH EXISTING DETECTORS
    - IMPROVED DETECTOR PERFORMANCE PLUS LOWER OPERATING TEMPERATURES
  - IMPROVED COOLING IS EXPENSIVE IN MASS AND POWER
  - IMPROVED DETECTOR PERFORMANCE IS EXPENSIVE IN UP FRONT DEVELOPMENT COSTS
SAFIRE MEASUREMENT OBJECTIVES

- Conduct global-scale, simultaneous, vertical profile measurements of temperature and key Oy, HOy, NOy, ClOy, and BrOy constituents, including the following:

\[
\begin{align*}
&\text{O}_3 \text{ O}^{50}_3 \text{ O}^{(3P)}; \quad \text{OH, HO}_2, \text{H}_2\text{O}, \text{HDO, CH}_4; \quad \text{NO}_2, \text{HNO}_3, \text{N}_2\text{O}_5; \quad \text{HCl, HOCl; HBr and HF}
\end{align*}
\]

- Conduct measurements (e.g. T, O3, CH4, and H2O) that can be used to derive and study dynamical quantities such as geopotential height, potential vorticity, winds, and Eliassen Palm flux

- Employ a 3 km IFOV in the far IR and 1.5 km in the mid IR

- Provide scan mode flexibility to enhance science return
  - Chemistry mode, 10-110 km vertical scan, 1.5 km sampling interval, 5° of latitude
  - Polar chemistry mode, 10-106 km, 3 km, 2.5°
  - Dynamics mode, 10-100 km, 0.75 km, 1.25°
  - Thermospheric mode, 84-180 km, 3 km, 5°

SAFIRE Experiment Measurement Objectives

<table>
<thead>
<tr>
<th>Parameters Measured</th>
<th>Spectral Range (cm⁻¹)</th>
<th>Alt. Range (km)</th>
<th>IFOV² (km)</th>
<th>Horizontal Resolution²</th>
<th>Temporal Resolution (sec)²</th>
<th>Lat. Cov. (deg.)</th>
<th>Vertical Range (km)</th>
<th>Estimated Precision²</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>82 - 84.4; 926 - 1141</td>
<td>10 - 100</td>
<td>1.5 - 3</td>
<td>1.5 - 5</td>
<td>25</td>
<td>18 - 72</td>
<td>86°S-86°N</td>
<td>5</td>
</tr>
<tr>
<td>O(3P)</td>
<td>157 - 159</td>
<td>90 - 180</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>OH</td>
<td>82 - 84.4; 117.8 - 119.6</td>
<td>20 - 90</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
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<tr>
<td>HO₂</td>
<td>93.8 - 96; 110.0 - 112.6</td>
<td>20 - 75</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
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<td>15</td>
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<tr>
<td>H₂O₂</td>
<td>93.8 - 96</td>
<td>20 - 50</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>H₂O</td>
<td>157 - 159</td>
<td>10 - 100</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>CH₄</td>
<td>1335 - 1365</td>
<td>10 - 65</td>
<td>1.5</td>
<td>1 - 5</td>
<td>36 - 72</td>
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<td>15</td>
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<tr>
<td>NO₂</td>
<td>1560 - 1630</td>
<td>15 - 60</td>
<td>1.5</td>
<td>1 - 5</td>
<td>36 - 72</td>
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<td>15</td>
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<td>HNO₃</td>
<td>850 - 929</td>
<td>10 - 45</td>
<td>1.5</td>
<td>1 - 5</td>
<td>36 - 72</td>
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<td>15</td>
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<tr>
<td>N₂O₅</td>
<td>310 - 390; 1230 - 1250</td>
<td>10 - 45</td>
<td>1.5 - 3</td>
<td>1 - 5</td>
<td>36 - 72</td>
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<td>15</td>
</tr>
<tr>
<td>HCl</td>
<td>82 - 84.4</td>
<td>10 - 65</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>HOCl</td>
<td>98.5 - 100; 117.8 - 119.6</td>
<td>20 - 45</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>HBr</td>
<td>98.5 - 100</td>
<td>15 - 40</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>HF</td>
<td>82 - 84.4</td>
<td>40 - 60</td>
<td>3</td>
<td>2.5 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Temp.</td>
<td>630 - 670; 580 - 760</td>
<td>10 - 110</td>
<td>1.5</td>
<td>1 - 5</td>
<td>18 - 72</td>
<td></td>
<td></td>
<td>&lt;0.5K</td>
</tr>
<tr>
<td>Pressure</td>
<td>630 - 670; 580 - 760</td>
<td>10 - 110</td>
<td>1.5</td>
<td>1 - 5</td>
<td>18 - 72</td>
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<td>&lt;2</td>
</tr>
<tr>
<td>O₂</td>
<td>82 - 120</td>
<td>10 - 80</td>
<td>3</td>
<td>1 - 5</td>
<td>36 - 72</td>
<td></td>
<td></td>
<td>&lt;2</td>
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<tr>
<td>O₂(v2)</td>
<td>82-84.4</td>
<td>20-50</td>
<td>2.5-5</td>
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<td></td>
<td></td>
<td></td>
<td>10*</td>
</tr>
<tr>
<td>O₂(v1,3)</td>
<td>82-84.4</td>
<td>20-35</td>
<td>2.5-5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15*</td>
</tr>
<tr>
<td>H₂O₂O</td>
<td>82-84.4</td>
<td>20-40</td>
<td>2.5-5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15*</td>
</tr>
</tbody>
</table>
## SAFIRE Experiment Measurement Objectives (Con't)

<table>
<thead>
<tr>
<th>Parameters Measured¹</th>
<th>Spectral Range (cm⁻¹)</th>
<th>Alt. Range (km)</th>
<th>IFOV² (km)</th>
<th>Horizontal Resolution³</th>
<th>Temporal Resolution (sec)⁴</th>
<th>Lat. Cov. (deg.)</th>
<th>Estimated Precision⁵</th>
<th>% (1σ)</th>
<th>Vertical Range (km)</th>
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<tbody>
<tr>
<td>O³¹8O⁶</td>
<td>82-84.4</td>
<td>20-35</td>
<td>3</td>
<td>2.5-5</td>
<td>36-72</td>
<td>86°S - 86°N</td>
<td>15*</td>
<td>20-30</td>
<td></td>
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<tr>
<td>O³¹7O⁶</td>
<td>117.8-119.8</td>
<td>20-40</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td>15*</td>
<td>20-35</td>
<td></td>
</tr>
<tr>
<td>O¹7O⁶</td>
<td>82-84.4</td>
<td>20-35</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
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<td>10*</td>
<td>20-30</td>
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<tr>
<td>H₂18O</td>
<td>93.8-96, 117.8-119.8</td>
<td>20-60</td>
<td>1.5</td>
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<td>10*</td>
<td>20-30</td>
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<tr>
<td>H₂17O</td>
<td>99.2-101.4, 117.8-119.8</td>
<td>20-50</td>
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<td>1.5</td>
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<td>10*</td>
<td>20-30</td>
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<tr>
<td>HCN</td>
<td>82-84</td>
<td>25-35</td>
<td>1.5</td>
<td>1.5</td>
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<td>10*</td>
<td>20-30</td>
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<tr>
<td>N₂O</td>
<td>1230-1260</td>
<td>20-40</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td>15*</td>
<td>20-30</td>
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</tr>
</tbody>
</table>

¹These are estimated precisions based on spectral features and absorption strengths. Retrieval simulations have not been performed.

²Does not include derived quantities such as winds, potential vorticity, and others.

³Spectral range is estimated to be 4 km.

⁴Latitudinal resolution is determined by vertical profile skew or ground-track motion during the measurement time. Longitudinal resolution is determined by the orbital spacing. The horizontal FOV width is ≈ 0.1°.

⁵Observations are made continuously with a vertical profile scan time of 72 sec in the chemistry and thermospheric modes, 36 sec in the polar chemistry mode, and 18 sec in the dynamics mode.

⁶Precision is the 1σ uncertainty determined from simulation set of 5 retrievals, except for HDO which is for a single retrieval only.

### SAFIRE INSTRUMENT PARAMETERS

- **Mass**: 304 kg
- **Power (watts)**: Average--304, Peak--350, Standby--175
- **Data Rate**: 9 mbs (FTS), 9 kbs (Radiometer)
- **Envelope**: 1.5m(L) x 1.5m(W) x 1.5m(H)
- **Limb View Direction**: Elevation 14° to 27° depression angle
  Azimuth + 10° Forward
  - 170° Aft
### SAFIRE MID-IR DETECTOR REQUIREMENTS

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>FREQUENCY (cm(^{-1}))</th>
<th>DYNAMIC RANGE (E+03)</th>
<th>D(^*) REQUIRED (E+10 cm (Hz/W)(^{1/2}))</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>630-670</td>
<td>7</td>
<td>1.4</td>
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<tr>
<td>2</td>
<td>580-760</td>
<td>28</td>
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<td>3</td>
<td>850-920</td>
<td>7</td>
<td>1.5</td>
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<tr>
<td>4</td>
<td>1335-1365</td>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>1560-1630</td>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>926-1141</td>
<td>15</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>1230-1260</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

CONFIGURATION: 15 x 7 Array  
ELEMENT SIZE: 0.2 x 0.3 mm

### SAFIRE FAR-IR REQUIREMENTS

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>FREQUENCY (cm(^{-1}))</th>
<th>NO. OF DETECTORS</th>
<th>TYPE</th>
<th>NEP (W Hz(^{-1/2})) x E-15</th>
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<tbody>
<tr>
<td>1</td>
<td>82-85</td>
<td>8</td>
<td>Ge:Ga</td>
<td>1</td>
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<tr>
<td>2</td>
<td>94-96</td>
<td>8</td>
<td>Ge:Ga</td>
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<tr>
<td>3</td>
<td>98-100</td>
<td>8</td>
<td>Ge:Ga</td>
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<td>4</td>
<td>111-113</td>
<td>8</td>
<td>Ge:Ga</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>118-120</td>
<td>8</td>
<td>Ge:Ga</td>
<td>1</td>
</tr>
<tr>
<td>6A</td>
<td>157-160</td>
<td>4</td>
<td>Ge:Ga</td>
<td>1</td>
</tr>
<tr>
<td>6B</td>
<td>310-390</td>
<td>4</td>
<td>Ge:Be</td>
<td>10</td>
</tr>
</tbody>
</table>

CONFIGURATION: (3) 2 x 8 ARRAYS  
ELECTRONICS: TIA-JFET 10 kHz BANDWIDTH  
BLIP-LIMITED PERFORMANCE (10\(^9\) ph/sec-typical)  
DETECTORS TO BE PROVIDED BY FRANCE
1990 REFERENCE HANDBOOK

Goddard Space Flight Center

NASA

Earth Observing System
The Strategic Defense Initiative Organization has a significant requirement for infrared sensors for surveillance, tracking and discrimination of objects in space. Projected SDIO needs cover the range from short wavelengths out to 30 μm. Large arrays are required, and producibility and cost are major factors. The SDIO is pursuing several approaches including innovative concepts based on semiconductors and superconductors.
SDIO INFRARED TECHNOLOGY EFFORTS

LT COL HILMER SWENSON
SENSORS AND INTERCEPTORS DIRECTORATE

MARCH 13, 1990

AGENDA (U)

- SCOPE OF SDIO IR SENSOR TECHNOLOGY DEVELOPMENT
- TECHNOLOGY THRUSTS
  - OPTICS TECHNOLOGY
  - FOCAL PLANE TECHNOLOGY
  - CRYO COOLERS
  - SIGNAL PROCESSORS
  - INTEGRATED SENSORS
- SUMMARY
SCOPE OF SDIO IR SENSOR TECHNOLOGY (U) (U)

SDI MISSION AREAS

PROJECT 5 MISSION
- Develop IR technology necessary to support SDI surveillance and weapon system sensors for Phase I
- Advance the state of art for IR sensors

AGENTS
SAT 9.1 USAFDC DONALD PARKER (205)895-2758
SAT 18 AFSTC CAPT MICHAEL DEVINE (505)846-8964
SAT 19 AFSTC LT. JEFF BRUNING (505)846-4964

PROJECT PHILOSOPHY

CRYOCOOLERS (U)

UNCLASSIFIED

CRITICAL PATH TECHNOLOGIES DESIGN EFFORT DESIGN SPECIFICATION PROTOTYPE DEVELOPMENT PROTOTYPE TESTING PRODUCTION PRODUCTION SPECIFICATION

- Proof of Principle
- Parts to a Goal
- Viable Production Documentation
- Parts to Spec
- Low Rate Production
- Mid Rate Production
- Production Spec

DRIVERS
- High reliability
- Extend on-orbit lifetime
- High efficiency
- Low weight
- Accrue operating history
- Reduce cost

CURRENT APPROACH
- Turbo-Brayton (3-stage)
- Rotary Reciprocating Refrigerator (R-3 Stage)
- 2-stage life testing
- Develop thermal integration technologies
  (Heat Pipe, Thermal Switch)

NEW TECHNOLOGY
- Magnetic cooling
- Sorption compression
- Mixed gas quick cooldown J-T
- Pulse tubes
- Acoustic drivers

NEEDS
- Hardened flight control electronics
- Reduced weight high effectiveness heat exchangers
- Modular/scaleable cryocoolers
- Solid state concepts
CRYOGENIC TECHNOLOGY PARAMETERS

ASSUME COOLING TEMPERATURE 65-80K

THERMAL RADIATORS

MEchanical Coolers

TACTICAL STIRLING

STORED CRYOGENS (LN2)
(CH4/NH3)

Sorption
Pulse Tube
Flexure
Stirling
TADOPTR
Standard Spacecraft Cooler
Turbo Cooler

CRYOGENIC SYSTEM WEIGHT

TEMPERATURE 65-80K

WEIGHT (kg)

COOLING LOAD (WATTS)
FOCAL PLANE ARRAY TECHNOLOGY (U)

DRIVERS       DRIVING SYSTEM

+ YIELD/COST/KEW, GSTS
  PRODUCIBILITY
+ RADIATION HARDNESS KEW, SSTS
+ OPERATING TEMPERATURE SSTS
+ HYBRID PERFORMANCE SPIRIT III, SSTS, GSTS
+ D* SSTS, GSTS
+ CUTOFF WAVELENGTH SSTS, GSTS
+ UNIFORMITY SPIRIT III, GSTS
+ CROSSTALK SPIRIT III, SSTS, GSTS

CURRENT APPROACH

+ MANTECH
  - MWIR PILOT LINE DEMO FOR BOOST PHASE
    APPLICATION
+ HYWAYS
  - IBC HYBRID DEVELOPMENT FOR SSTS, GSTS
  - ADVANCED HYBRID DEVELOPMENT
  - PILOT LINE DEMO
+ SLIM
  - LWIR HgCdTe FOR KEW & SSTS BACKUP
+ HARDENED INSB TECHNOLOGY
  FOR SCANNERS

NEW TECHNOLOGY

+ INTRINSIC EVENT DISCRIMINATOR
+ SOLID STATE PHOTOMULTIPLIER
+ Ge CTIA
+ GaAs MUX FOR HgCdTe
+ HIGH OPERATING TEMPERATURE
  DETECTORS
+ HIGH TEMPERATURE SUPERCONDUCTORS
+ STRAINED LAYER SUPERLATTICE
+ VLWIR HgCdTe — HIT DETECTORS, SOFADIR
+ LWIR HgCdTe TECHNOLOGY
+ HgCdTe PASSIVATION TECHNOLOGY

NEEDS

+ MODULES
+ NOISE MODELS FOR HYBRID INTEGRATION
+ LARGER SUBSTRATES
+ AUTOMATED TESTING FACILITY
+ TRAINING FOR TEST FACILITY PERSONNEL
+ INTEGRATED FOCAL PLANE TECHNOLOGY

IRFPA DESIGN DRIVERS (U)

+ LOW TEMPERATURE TARGETS
+ LOW BACKGROUNDS
+ HIGH TOTAL DOSE ENVIRONMENT
+ 3 COLORS REQUIRED FOR DISCRIMINATION
+ LARGE FOV — HIGH SCAN RATES
  - SHORT INTEGRATION TIMES
  - HIGH DATA RATES FOR ANALOG SIGNAL PROCESSOR
+ LARGE NUMBERS OF TARGETS/DECOYS
+ HIGH THROUGHPUT REQUIREMENTS FOR OBJECT DEPENDENT PROCESSORS
RELATIVE HARDNESS

MATERIALS/APPLICATIONS MATCH-UPS (U)
80% COST REDUCTION DEMONSTRATED WITH INTERMEDIATE RUN

MANTECH STATUS (U)

<table>
<thead>
<tr>
<th>ORIGINAL</th>
<th>CONFIGURATION</th>
<th>YIELD</th>
<th>YIELD GOAL</th>
<th>COST/HYBRID</th>
<th>COST GOAL</th>
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<tbody>
<tr>
<td>ROCKWELL (HYBRIDS)</td>
<td>32x8</td>
<td>0.2</td>
<td>—</td>
<td>$100 K</td>
<td>—</td>
</tr>
<tr>
<td>SBRC (DETECTOR ARRAYS)</td>
<td>32x8</td>
<td>0.2</td>
<td>—</td>
<td>$200 K</td>
<td>—</td>
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</tbody>
</table>

| BASELINE RESULTS | | | | | |
| ROCKWELL (HYBRIDS) | 32x64 | 1.35% | 0.4% | $34 K (100% TEST) | $20/CHANNEL |
| SBRC (DETECTOR ARRAYS) | 128x128 | 3.5% | 0.4% | $15 K (SAMPLE TEST) | $20/CHANNEL |

| INTERMEDIATE RESULTS | | | | | |
| ROCKWELL | 32x64 | 10.3% | 1.5% | $6.5 K | $5/CHANNEL ($3.18 ACHIEVED) |
| SBRC | 128x128 | 35% | 1.5% | $4.6 K (SAMPLE TEST) | $5/CHANNEL ($0.28 PROJECTED WITH SAMPLE TESTING) |

| CdTe PASSIVATION |

# OF PIXELS WORKING MADE UNDER MANTECH = >3M
# OF PIXELS REQUIRED BY END OF CONTRACT = ~2M
## ISSUES REMAINING AFTER MWIR HgCdTe MANTECH (U)

<table>
<thead>
<tr>
<th>ISSUE</th>
<th>NEED TO BE ADDRESSED BY</th>
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<tr>
<td>HARDNESS</td>
<td>TECHNOLOGY PROGRAM MANTECH REVISITED</td>
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<tr>
<td>PRODUCIBILITY OF NUCLEAR HARD ARRAYS</td>
<td>TECHNOLOGY OR PRIMES</td>
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<tr>
<td>INTERGRATION OF ARRAYS</td>
<td>TECHNOLOGY DEVELOPMENT</td>
</tr>
<tr>
<td>UNIFORMITY</td>
<td>TACTICAL?</td>
</tr>
<tr>
<td>SUSTAINING MARKET PLACE</td>
<td>DPESO/DSTAR</td>
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<tr>
<td>TRUE HANDOFF TO PRODUCTION WITH LESS TOUCH LABOR</td>
<td>TECHNOLOGY MATERIALS/DSTAR LABOR</td>
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<tr>
<td>THIRST FOR HIGHER PERFORMANCE AT LOWER COST</td>
<td>TECHNOLOGY</td>
</tr>
<tr>
<td>RADIOMETRY PERFORMANCE</td>
<td>TECHNOLOGY</td>
</tr>
<tr>
<td>READOUTS</td>
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</tr>
</tbody>
</table>

## BENEFITS OF IBC DETECTORS (U)

- RADIATION HARDNESS
- RESPONSE LINEARITY
- FREQUENCY OF RESPONSE
- UNIFORMITY OF RESPONSE
- PREDICTABLE BEHAVIOR
- HIGH RESPONSIVITY
- RELATIVELY HIGH PIXEL YIELD
VLWIR TECHNOLOGY NEARS PILOT PRODUCTION (U)
IR SENSOR COMPONENTS STATUS ON TECHNOLOGY CYCLE MODEL (U)

<table>
<thead>
<tr>
<th></th>
<th>TECHNOLOGY DEVELOPMENT</th>
<th>TECHNOLOGY DEMONSTRATION</th>
<th>TECHNOLOGY TRANSFER</th>
<th>PRODUCIBILITY ENGINEERING</th>
<th>PILOT PRODUCTION</th>
<th>PRODUCIBILITY IMPROVEMENTS</th>
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<td>PARTS TO A GOAL</td>
<td>VERIFIED PROCESS DOCUMENTATION</td>
<td>PRODUCT SPEC</td>
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<tr>
<td>SI2/A3</td>
<td>BORON FREE SI, SEER, PATH</td>
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<td>SUBSTRATE FAB</td>
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<tr>
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</tbody>
</table>

FUTURE PLANS (U)

- NEAR TERM
  HYWAYS - ADVANCED HYBRIDS FOR ENHANCED RADIATION TOLERANCE,
  HIGHER SENSITIVITY, LOWER NOISE
  HYWAYS - ENHANCED PRODUCTION RATES
  DECISION ON CONTINUATION OF Si:Ga

- MID-TERM
  IED PERFORMANCE IMPROVEMENTS
  EXTENDED WAVELENGTH RESPONSE
  MICROLENSSES
  APPLICATION OF IBC TECHNOLOGY TO INTERCEPTOR REQUIREMENTS
  HIGHER OPERATING TEMPERATURE

- FAR TERM
  EXPLORE IBC CONCEPT IN OTHER MATERIALS AND DEVICES
  ADDRESS IED/SSPM PRODUCIBILITY

ORIGINAL PAGE IS OF POOR QUALITY
CONCLUSION

• TECHNOLOGY PROGRAMS ARE PLANNED TO ENCOMPASS
  SYSTEM NEEDS FOR DETECTOR/READOUT PERFORMANCE
  AND AVAILABILITY

• TECHNOLOGY PROGRAMS OR SYSTEM PROGRAMS MUST
  ADDRESS FPA INTEGRATION ISSUES

• HARDNESS IS THE LAGGING TECHNOLOGY

• HARDNESS IS SUFFICIENT FOR SPACE DEMO PROGRAM
Detection of "cold" bodies (200 - 300 K) against space backgrounds has many important applications, both military and non-military. The detector performance and design characteristics required to support low-background applications are discussed, with particular emphasis on those characteristics required for space surveillance. The status of existing detector technologies under active development for these applications is also discussed. In order to play a role in future systems, new, potentially competing detector technologies such as multiple quantum well detectors must not only meet system-derived requirements, but also offer distinct performance or other advantages over these incumbent technologies.
TOPICS

■ APPLICATIONS OVERVIEW
  - OBJECTS OF INTEREST
  - BACKGROUNDS
  - RADIATION ENVIRONMENT
  - SENSORS

■ DETECTOR REQUIREMENTS

■ APPLICABLE DETECTOR TECHNOLOGIES
  - STATE OF THE ART
  - TECHNOLOGY DEVELOPMENT DIRECTIONS

■ REQUIREMENTS FOR NEW, COMPETING DETECTOR TECHNOLOGIES
LOW-BACKGROUND LWIR APPLICATIONS

- STRATEGIC DEFENSE
  - SURVEILLANCE, ACQUISITION, TRACKING, DISCRIMINATION, AND KILL ASSESSMENT ("SATKA")
  - WEAPON SYSTEM SUPPORT (FIRE CONTROL, HOMING, ETC.)

- OTHER MILITARY APPLICATIONS
  - RESIDENT SPACE OBJECT SURVEILLANCE
  - DETECTION OF NEWLY LAUNCHED OBJECTS
  - TREATY MONITORING

- NON-MILITARY APPLICATIONS
  - INFRARED ASTRONOMY
  - NEAR-EARTH PHENOMENOLOGY
  - SPACE "JUNK" DETECTION AND TRACKING

TARGET/SENSOR/EARTH GEOMETRY

TARGET ORBIT

<CAD CROSS-SCAN FOV

BC MINIMUM TANGENT HEIGHT

SENSOR
OBJECTS OF INTEREST

- EMISSIVITY-AREA PRODUCTS:
  
  0.1 - 10 m²

- TEMPERATURE:

  200 - 300 K

- RANGES:

  1000 - 8000 km
PERCENTAGE OF TOTAL RADIANCE Emitted
AT SHORTER WAVELENGTHS

IR BACKGROUNDS

- SPACE BACKGROUNDS
  - EARTH LIMB ('ELR')
  - ZODIACAL
  - CELESTIAL
  - NON-REJECTED EARTH RADIANCE ('NRER')
  - ENHANCED (NATURAL AND NUCLEAR)

- FOR TANGENT HEIGHTS > 100 KM AND REALISTIC ASSUMPTIONS
  ABOUT THE LEVEL OF LIKELY OPTICS CONTAMINATION, NRER
  WILL BE THE DOMINANT NON-ENHANCED BACKGROUND FOR
  NEAR-EARTH LINES OF SIGHT
BACKGROUND RADIANCE VS TANGENT HEIGHT

17-26 nm BAND

Zodiacal Radiance, 17-24 μm Band

RADIANCE (W/cm²-sr)

TANGENT HEIGHT (KM)

NRER  ELR

RADIANCE, Watts cm⁻² ster⁻¹

ELONGATION, deg

1977 MODEL
1983 MODEL

50
RADIATION ENVIRONMENT

- NATURAL ENVIRONMENT
  - Worst case dose rate at FPA, assuming 0.5 inch aluminum shielding:
    0.02 rad(Si)/sec \( (5 \times 10^7 \text{ gammas/cm}^2\text{-sec}) \)
  - Worst case total dose after 5 years on orbit:
    \( 3 \times 10^6 \text{ rad(Si)} \)

- ENHANCED NUCLEAR ENVIRONMENT
  - Transient dose rate due to nuclear detonations can be orders of magnitude higher
  - Sustained dose rate due to saturated belt condition can be 1 rad(Si)/sec, worst case
  - Worst case total dose due to saturated belts:
    \( > 10^7 \) accumulated over 10–300 days

EARTH'S VAN ALLEN BELTS VERSUS ALTITUDE AT 0°

[Diagram showing dose rate (rad(Si))/day versus altitude (1,000 nmi and km)]

ORIGINAL PAGE IS OF POOR QUALITY
SENSOR SYSTEM OPERATION

- Baffles reject off-axis radiation
- Optics focus target and background energy
- Gimbal scans scene across detectors
- Detectors convert photon scene to electrical signal

SAMPLE FPA DESIGN CONFIGURATION
THREE TDI STAGES, TWO STAGGERED SUBARRAYS
SIGNAL PROCESSING CHAIN

- Detector Bias/ Photocurrent Integration
- Charge-to-Voltage Conversion/ Buffer Amplifier
- First Stage Multiplexing
- Analog-to-Digital Conversion
- Gain & Offset Correction
- TDI
- BG Subtraction/ Clutter Suppression
- Matched Filtering/ Centroiding/ Track Formation...

FPA Requirements Flowdown
SENSOR PERFORMANCE LIMITED BY NOISE

- DETECTOR NOISE
  - MAY BE REDUCED BY COOLING

- READOUT NOISE
  - DEPENDS STRONGLY ON COUPLING CIRCUIT DESIGN AND DEVICE CHARACTERISTICS

- IR BACKGROUND NOISE
  - RANDOM FLUCTUATIONS OF IN-FOV SOURCES
    - FUNDAMENTAL LIMIT ON SENSOR PERFORMANCE DUE TO NEAR EARTH, ZODIACAL RADIANCE VIEWING AWAY FROM EARTH
  - SPATIAL STRUCTURE ('CLUTTER')
  - OPTICS THERMAL EMISSION
    - CAN BE RENDERED NEGLIGIBLE BY COOLING

NOISE-EQUIVALENT TARGET VS DETECTOR D*

<table>
<thead>
<tr>
<th>NET (W/SR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.85</td>
</tr>
<tr>
<td>12.59</td>
</tr>
<tr>
<td>10.00</td>
</tr>
<tr>
<td>7.94</td>
</tr>
<tr>
<td>6.31</td>
</tr>
<tr>
<td>5.01</td>
</tr>
<tr>
<td>3.98</td>
</tr>
<tr>
<td>3.16</td>
</tr>
<tr>
<td>2.51</td>
</tr>
<tr>
<td>2.00</td>
</tr>
<tr>
<td>1.58</td>
</tr>
<tr>
<td>1.26</td>
</tr>
<tr>
<td>1.00</td>
</tr>
<tr>
<td>0.79</td>
</tr>
<tr>
<td>0.63</td>
</tr>
<tr>
<td>0.50</td>
</tr>
<tr>
<td>0.40</td>
</tr>
</tbody>
</table>

DETECTOR D*

RANGE = 5000 KM
ATHE = 5 DEG.
BAND = 17–26 UM
READOUT NOISE = 100 EL.

T1: SMALL, WARM
T2: SMALL, COLD

BKGD NOISE = 50 EL.
BKGD NOISE = 30 EL.
BKGD NOISE = 20 EL.

54
NOISE-EQUIVALENT TARGET VS DET. D*

NET (W/SR)

31.62
25.12
19.95
15.85
12.59
10.00
7.94
6.31
5.01
3.98
3.16
2.51
2.00
1.58
1.26
1.00
0.79
0.63

T3: 25 CM APERTURE

T2: SMALL, COLD (0.43 W/SR)

T1: SMALL, WARM

T3: MEDIUM, WARM

RANGE = 5000 KM
ATHE = 5 DEG.
BAND = 6–10 UM
READOUT NOISE = 100 EL.

BKGD NOISE = 40 EL.

BKGD NOISE = 30 EL.

BKGD NOISE = 20 EL.

2.0E+12 5.0E+12 1.3E+13 3.2E+13 7.9E+13 2.0E+14

DETECTOR D*

KEY DETECTOR REQUIREMENTS FOR LOW-BACKGROUND SPACE APPLICATIONS

- SPECTRAL COVERAGE:
  SIGNIFICANT BROAD-BAND RESPONSE WITHIN 6–30 UM REGION, E.G., QUANTUM EFFICIENCY > 40% OVER A 5 UM SUB-BAND

- SENSITIVITY:
  \( D* > 1E14 \text{ CM-HZ} \text{ /W AT 20 UM} \)
  \( D* > 5E13 \text{ CM-HZ} \text{ /W AT 10 UM} \)

- FREQUENCY RESPONSE:
  BANDPASS > 10 KHZ, NO ANOMALIES

- DYNAMIC RANGE:
  LINEAR RESPONSE FROM NOISE LEVEL TO 1E4 TIMES THE NOISE LEVEL
KEY DETECTOR REQUIREMENTS FOR LOW-BACKGROUND SPACE APPLICATIONS (CONT.)

- **POWER DISSIPATION:**
  
  POWER DISSIPATED ON FPA < 10 UW/DETECTOR

- **RADIATION HARDNESS:**
  
  TOTAL DOSE HARDNESS < 1E6 RAD(Si)
  
  EFFECTIVE GAMMA AREA < 1E-6 CM (100 UM DET.)

- **PIXEL SIZE:**
  
  50-150 UM (SQUARE)

- **CONFIGURATION:**
  
  TWO-DIMENSIONAL MOSAIC ARRAYS, E.G., 10-20 X 50 DETECTORS PER CHIP

APPLICABLE TECHNOLOGIES

- **DETECTORS**

<table>
<thead>
<tr>
<th>DETECTOR</th>
<th>SPECTRAL CUTOFF (UM)</th>
<th>OPERATING TEMPERATURE (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiAs IBC</td>
<td>26</td>
<td>12</td>
</tr>
<tr>
<td>SiGe IBC</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>PV HgCdTe</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>

- **READOUTS**

  - MATERIALS: SILICON, GERMANIUM, GaAs
  
  - VERY LOW NOISE, RADIATION HARD DEVICES ARE UNDER DEVELOPMENT
TECHNOLOGY ASSESSMENT

- Si/As IBC
  - MEETS PERFORMANCE REQUIREMENTS
  - LOW OPERATING TEMPERATURE REQUIRES ADVANCED 3-STAGE CRYOCOOLERS FOR SPACE-BASED SYSTEMS
  - PRODUCIBILITY DEMONSTRATION PLANNED

- SiGe IBC
  - REQUIRES DEVELOPMENT
  - OPERATING TEMPERATURE NOT HIGH ENOUGH TO ALLEVIATE CRYOCOOLER PROBLEM (3 STAGES STILL REQUIRED)

- LWIR PV HgCdTe
  - INDIVIDUAL DETECTORS WITHIN ARRAYS MEET REQUIREMENTS
  - OPERATING TEMPERATURE COULD BE SUPPORTED BY A 2-STAGE COOLER
  - SEVERE NON-UNIFORMITY PROBLEM
  - UNSUITABLE FOR SOME STRATEGIC DEFENSE SURVEILLANCE MISSIONS
    - TRACKING COLD TARGETS
    - DISCRIMINATION

TECHNOLOGY DEVELOPMENT DIRECTIONS

- GREATER SENSITIVITY
  - ULTRA-LOW NOISE READOUTS
  - IMPROVED RoA UNIFORMITY OF HgCdTe DETECTORS

- GREATER TOTAL DOSE HARDNESS
  - ULTRA-RAD HARD READOUTS
  - IMPROVED HARDNESS OF HgCdTe DETECTORS

- GREATER OPERABILITY IN GAMMA ENVIRONMENTS
  - DEVELOPMENT OF "INTRINSIC EVENT DISCRIMINATION" (IED) CONCEPTS

- GREATER PRODUCIBILITY
  - PILOT LINE DEMONSTRATION FOR Si/As IBC HYBRIDS IS PLANNED
REQUIREMENTS FOR NEW, COMPETING TECHNOLOGIES

Assumption: New technology has performance equivalent to or superior to that of the incumbent technology with which it competes.

Operating Temperature

<table>
<thead>
<tr>
<th>Spectral Band: 6 - N μm</th>
<th>&lt;25 K</th>
<th>&gt;25 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>N = 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>G</td>
</tr>
<tr>
<td>Not competitive with either HgCdTe or SiAs.</td>
<td>Competitive with HgCdTe, especially if harder or more uniform.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>B</td>
</tr>
<tr>
<td>Competitive with SiAs, especially if operability in a gamma environment is superior.</td>
<td>Could displace SiAs - only a 2-stage cooler required.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Could displace SiAs in applications requiring very cold body detection.</td>
<td>Could displace SiAs. Additional spectral coverage may be useful.</td>
<td></td>
</tr>
</tbody>
</table>

≤little or no utility = Moderate utility = Great utility

Summary

- Detector sensitivity requirements for low background space applications are stringent and are driven by:
  - Stressing missions, e.g., dim targets, long ranges
  - Low background noise limit
  - Availability of low noise readouts

- Detector radiation hardness requirements are also stringent:
  - Space basing makes high total dose hardness essential
  - Strategic defense survival and operability requirements are extremely stressing

- New technologies such as MQW detectors can compete with the better developed existing technologies only if they:
  - Meet performance requirements
  - Offer a substantial advantage over an existing technology
    - Higher operating temperatures (>25 K) with spectral coverage to 25-30 μm
    - Higher performance or producibility than HgCdTe with comparable spectral coverage at a comparable operating temperature
SESSION II: Benchmark Technology Status

II - 1 Status of LWIR HgCdTe Infrared Detector Technology
M.B. Reine, Loral Infrared & Imaging Systems

II - 2 LWIR HgCdTe - Innovative Detectors in an Incumbent Technology
W.E. Tennant, Rockwell International Science Center

II - 3 HgCdTe for NASA Eos Missions and Detector Uniformity Benchmarks
P.R. Norton, Santa Barbara Research Center
Since its first synthesis in 1959, the HgCdTe semiconductor alloy system has proven to be a remarkably versatile intrinsic infrared detector material. A wide variety of high performance HgCdTe infrared detectors have been demonstrated and developed, including photoconductors, homojunction and heterojunction photodiodes, and metal-insulator-semiconductor photovoltaic devices. Controlled variations in HgCdTe alloy composition have enabled cutoff wavelengths to be tailored over the 2-25 μm wavelength region.

The success that HgCdTe has achieved is rooted in a unique set of semiconductor properties that make it a nearly ideal infrared detector material. Its large optical absorption coefficient enables (internal) quantum efficiencies approaching 100% to be achieved in devices that are 12-15 μm thick. Long carrier lifetimes allow the highest operating temperatures for achieving a given detectivity at a given cutoff wavelength.

This paper will review the status of LWIR HgCdTe detector technology for wavelengths between 8 and 17 μm, for application in NASA and DoD focal plane arrays (FPAs) operating at temperatures near 65 K with mission lifetimes of 5 to 10 years.

Linear arrays of LWIR HgCdTe photoconductors have been in production for the past ten years for DoD applications such as scanning thermal imaging systems and missile seekers. These arrays contain as many as 180 elements, operate at 77 K and cover the 8 to 12 μm wavelength region, which corresponds to a Hg_{1-x}Cd_xTe alloy composition of x=0.21. These arrays are usually fabricated from bulk-grown n-type HgCdTe crystals having donor concentrations of 2-5 E14 cm^{-3}. Detector sensitivity is typically background limited, with detectivities of 0.6-1.5E11 cm-Hz^{1/2}/W. Device resistances are typically 40 ohms per square at 77 K, with dc power dissipations of 0.1-0.5 mW. The total U.S. industry capacity for these units is about 2500-3000 deliveries per month.

LWIR HgCdTe photoconductors represent a mature established technology that will continue to play an important role in NASA and DoD applications that require relatively small numbers of elements (less than several hundred) which do not require a multiplexer on the focal plane. For example, Loral provided a large-area HgCdTe photoconductor with a detectivity of 3E10 cm-Hz^{1/2}/W at 16 μm for the ATMOS interferometer.

Advanced DoD and NASA applications require orders of magnitude more detectors in a focal plane array. For these applications, HgCdTe photovoltaic (PV) devices are the detectors of choice because their higher impedance enables them to match into low-noise silicon CMOS input amplifiers. NxM arrays of HgCdTe photovoltaic detectors on IR-transparent substrates are bump interconnected to matching NxM arrays of input circuits on silicon CMOS multiplexer chips to form large focal
plane arrays. LWIR FPAs for scanning applications are typically 128 to 256 elements long, with 4, 8 or 16 elements in the scan direction for signal-to-noise enhancement, and have pixel sizes on the order of 50 μm x 50 μm. LWIR staring FPAs typically have 64x64 or 128x128 formats, with unit cells usually less than 50 μm x 50μm.

These advanced LWIR FPAs place stringent performance requirements on the HgCdTe photovoltaic detector arrays in terms of zero-bias impedance, reverse-bias impedance and leakage current, quantum efficiency, fill factor, crosstalk, 1/f noise, uniformity of response and reliability.

Initial LWIR HgCdTe photovoltaic detectors were planar n-on-p devices made by mercury-diffusion and ion implantation. More recently, substantial improvements in device performance have been achieved with the use of a double-layer P-on-n LPE heterojunction photodiodes grown onto CdTe substrates. These LPE heterojunctions have demonstrated performance which approaches the theoretical limit set by n-side diffusion current at temperatures of 80 to 70 K over the 10-19 μm range.

Major improvements have been made over the years in HgCdTe materials technology. At Loral, uniformity of alloy composition in both bulk-grown and LPE HgCdTe is such that variations in detector cutoff wavelength are less than ±1% over the 2-12 μm range.

In this paper, the performance requirements that today's advanced LWIR focal plane arrays place on the HgCdTe photovoltaic detector array will be summarized. The theoretical performance limits for intrinsic LWIR HgCdTe detectors will be reviewed as functions of cutoff wavelength and operating temperature. The status of LWIR HgCdTe photovoltaic detectors will be reviewed and compared to the FPA requirements and to the theoretical limits. Emphasis will be placed on recent data for two-layer HgCdTe LPE heterojunction photodiodes grown at Loral with cutoff wavelengths ranging between 10 and 19 μm at temperatures of 70 - 80 K. Development trends in LWIR HgCdTe detector technology will be outlined, and conclusions will be drawn about the ability for photovoltaic HgCdTe detector arrays to satisfy a wide variety of advanced focal plane array applications.
Status of LWIR HgCdTe Infrared Detector Technology

M.B. Reine
Loral Infrared & Imaging Systems
Lexington, Massachusetts 02173-7393

Innovative Long Wavelength Infrared Detector Workshop
April 24 - 26, 1990
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

Status of LWIR HgCdTe Detector Technology

EMPHASIS
• Wavelength: 10 to 17 \( \mu \)m
• Operating temperature: 60 K to 65 K
• Future NASA and DoD long-duration space applications

TOPICS:
1. HgCdTe material properties for infrared detectors
   • Uniformity of Hg\textsubscript{n-1}Cd\textsubscript{n}Te alloy composition
2. Theoretical limits to HgCdTe detector performance and operating temperature
   • Thermal g-r noise
   • Background g-r noise
3. Detector requirements for advanced focal plane arrays
4. Status of HgCdTe infrared detectors:
   • Photoconductors
   • Photodiodes
5. Development trends in HgCdTe materials and devices
Success of HgCdTe as an Infrared Detector Material Is Due to Its Energy Band Structure

- Adjustable energy band gap covers the 1-25 μm IR region
- Direct interband transitions give quantum efficiencies approaching 100% for 15 μm thick devices
- Intrinsic recombination mechanisms give long carrier lifetimes and high operating temperatures

The Hg_{1-x}Cd_xTe Semiconductor Alloy System Possesses Many Desirable Properties for an Infrared Detector Material

- Continuously adjustable energy gap from -0.3 eV to 1.6 eV
- Large absorption coefficient for high quantum efficiency
- Small lattice mismatch: 0.3% between HgTe and CdTe
- Amphoteric (can be made n-type or p-type):
  - Foreign atom donors and acceptors
  - Native defect acceptors
- Large electron-to-hole mobility ratio (400 for x = 0.2 at 77K)
- Electrical purity levels of less than 1E14 cm⁻³
- Surfaces are compatible with many passivation approaches:
  - ZnS, SiO₂
  - Native (anodic) oxide, sulphide or fluoride
  - Wide-gap HgCdTe
The Hg$_{1-x}$Cd$_x$Te Semiconductor Alloy System Possesses Many Desirable Properties for an Infrared Detector Material (continued)

- Long minority carrier lifetimes:
  - p-type: Shockley-Read, Auger 7
  - n-type: Auger 1, Shockley-Read

- Favorable thermal expansion coefficient:
  - Good match to silicon
  - Excellent match to GaAs, sapphire

- Low dielectric constant for low junction capacitance

- Compatible with many advanced crystal growth techniques:
  - Bulk: Honeywell's DME; THM
  - LPE: from Hg-rich and Te-rich solutions
  - VPE: MOCVD, MBE

Detector Cutoff Wavelength for Hg$_{1-x}$Cd$_x$Te Devices

$$\lambda_{\infty} (\mu m) = \frac{1.24}{E_g (eV)}$$

$E_g(x,T)$ from:

Hansen, Schmit, Casselman
Today's Hg$_{1-x}$Cd$_x$Te has Excellent Uniformity of Alloy Composition

![Graph showing the relationship between alloy composition and cutoff wavelength.]

HgCdTe Device Technology

**PHOTOCONDUCTORS**
- n-type and p-type
- Signal Processing In The Element (SPRITE)
- Photo-JFET structures with gain enhancement

**PHOTODIODES**
- Homojunctions: n-on-p and p-on-n
- Heterojunctions: N-on-p and P-on-n
- Avalanche photodiode for 1.3 to 1.6 μm

**PHOTOCAPACITORS**
- n-channel and p-channel Charge Coupled Devices
- Charge Imaging Matrix

**OTHER**
- n-channel Insulated-Gate Field Effect Transistors
- Spin-flip Raman laser
Noise in A Two-Level Detector

\[ n(t) = n_0 + n_B + \delta n(t) \]

\[ p(t) = p_s + p_a + \delta p(t) \]

\[ G_s \]

\[ g_m \]

\[ r \]

\[ E_s \]

C.B.

V.B.

\[ n_s = p_s = G_s \tau \]

\[ \frac{1}{\tau} = \frac{\delta}{\delta n} \text{(r-g)} \]

\[ \delta n(t) = \delta p(t) \]

\[ p(t) = p_s + p_a + \delta p(t) \]

\[ n(t) = n_0 + n_B + \delta n(t) \]

\[ \frac{1}{\tau} = \frac{\delta}{\delta n} \text{(r-g)} \]

\[ \delta n(t) = \delta p(t) \]

\[ n_s p_s = n_s' (E.g,T) \]

for \( n_s > p_s \)

---

LWIR PC HgCdTe Sensitivity vs Temperature

**LWIR HgCdTe PC**

- \( t = 800 \mu m \)
- \( w = 50 \mu m \)
- \( f_p = 400 \Omega \)
- \( S_{P_x} = 500 \text{ cm}^2/\text{s} \)
- \( S_{P_y} = 2000 \text{ cm}^2/\text{s} \)
- \( \eta = 0.7 \)
- \( Q_B = 2 \times 10^{10} \text{ ph/cm}^2-\text{s} \)
- \( 1/f \) noise
- \( P_{\text{BAMM}} = 0.2 \text{ mW} \)

\( V_{\text{AMP}} = 0.5 \times 10^4 \text{ V}/\text{Hz} \)
LWIR PC HgCdTe Status

- Transit-limited response times of 0.5 μsec
- Photoconductive gain = 200
- DC bias power = 0.1-0.3 mW
- 60-180 element linear arrays in full production (capacity: 600 units/month):
  - T = 77 K
  - λ_{peak} = 11.8 μm
  - λ_{eq} = 13.0 μm
  - D^* = 6 x 10^{10} - 1.4 x 10^{11} cm-Hz^{1/2}/W (BLIP for Q_e = 0.3 - 1 x 10^{17} ph/cm^2-s)
  - 1/f noise knee frequencies less than 50 - 100 Hz
  - Area = 50 μm x 50 μm
- DME bulk-grown Hg_{1-x}Cd_xTe material:
  - x - uniformity: Δx = ± 0.0005 → Δλ_{eq} (77 K, 12.5 μm) = ± 0.1 μm
  - Electrical purity: 1 x 10^{14} cm^3
- Passivation by anodic oxide surface accumulation:
  - Surface recombination velocity < 500 cm/s
  - Shunt resistance = 70 Ω/□

Generalized Backside-Illuminated HgCdTe Focal Plane Array
The Photon Detection Process in LWIR Focal Plane Arrays

1. Photoexcitation of electrons or electron-hole pairs
2. Transport and recombination of photoexcited carriers: drift, diffusion, charge separation
3. Interaction with the external "input" circuit
4. Signal conditioning within each unit cell: amplification, integration, filtering, sampling
5. Multiplexing
6. Signal processing with uncooled electronics off the focal plane: nonuniformity compensation, sub-frame integration

Detector Requirements for LWIR Focal Plane Arrays

1. Cutoff Wavelength: Today: 10.5 - 12.0 μm
   Desired: out to 19 μm (e.g., AIRS)
2. Operating Temperature: 60-80 K (always as high as possible)
3. Detectivity: Usually BLIP: 1E11 cm-Hz^{1/2}/W
4. Impedance: High; 10 to 20 times larger than for BLIP
5. Quantum Efficiency: > 70%
6. Active Area: 35 μm x 35 μm to 100 μm x 100 μm
7. 1/f Noise: Critical for staring FPAs (BW=0.1 - 10 Hz)
8. Uniformity:
   - cutoff wavelength: ± 0.1 - 0.2 μm
   - quantum efficiency: ± 10%
   - impedance: depends on input circuit design
Detector Requirements for LWIR Focal Plane Arrays (Continued)

9. Bias Voltage: -10 mV to -40 mV for direct injection
   0 ± 0.5 mV with active offset control
10. Crosstalk: < 2 - 3%
11. Fill Factor: > 80% for staring FPAs
12. Linearity: ± 2%
13. Dynamic Range: 1E4-1E5
14. Frequency Response: Not an issue
15. Environmental Stability: Thermal cycling; shock; vibration
16. Radiation Hardness: Total dose; various particles

Simplified Input Coupling Model for Hybrid FPA

\[
D^* = \frac{q n \lambda}{hc} \sqrt{\frac{A}{\eta \phi A}} \left( 2q^2 \frac{4kT}{R} + \frac{e_s^2}{R^2} \right)^{-1/2}
\]

- \(e_s\) = amplifier (or input gate) noise voltage
- \(A\) = detector area
- \(R\) = detector zero bias resistance

(Assumes coupling efficiency \(\approx 1.0\))
Key Focal Plane
Requirements for AIRS Instrument

FPA SENSITIVITY REQUIREMENTS

- Configuration
  - Multiple linear arrays
  - 8 SWIR Bands: 3.4 to 8.0 \( \mu m \)
  - 8 LWIR Bands: 8.0 to 15.4 \( \mu m \) (17.0 \( \mu m \) Goal)
- Pixel Size: 200 \( \mu m \) x 100 \( \mu m \)
- Total Pixel Count: 3950
- Background Flux Density: \( \leq 2E15 \) ph/cm\(^2\)-s (LWIR)
- Minimum Operating Temp: 60 K
- Thermal Heat Load \( \leq 500 \) mW
- Outages \( \leq 2\% \)
- Reliability \( \geq 0.99 \) at 5 years
- Total Dose \( \leq 2E4 \) rads (Si)
- Technology Cutoff: 1992 1st instrument

REQUIRED \( R_{\rho A} \) PRODUCTS
FOR AIRS PV DETECTORS
P-N Junction Formation in HgCdTe

1968  Hg-Diffused n⁺-on-p
   • Hg-vacancy acceptors

1975  Ion-implanted n⁺-on-p (n⁺-n⁻-on-p)
   • implant damage
   • native & foreign acceptors

1982  LPE grown heterojunctions
   • N-on-p
   • P-on-n

1987  Acceptor-diffused p-on-n
   • diffusion sources:
     ion implant
     Hg-solution

1990  MOCVD grown heterojunctions

BACKSIDE-ILLUMINATED P-on-n LPE HgCdTe
HETEROJUNCTION PHOTODIODES
VLWIR P-on-n LPE HgCdTe Heterojunction
Film Grown at Loral

HONEYWELL P-on-n
LPE HETEROJUNCTION
T = 80 K

VLWIR P-on-n LPE HgCdTe Heterojunction
Film Grown at Loral

LD 026FB
T = 80 K
\( \lambda_{\text{cut}} = 18.8 \, \mu\text{m} \)
I. INTRINSIC MECHANISMS
- Diffusion Current (Thermally Generated Current)
  - n-side
  - p-side
- Band-to-Band Tunneling current (Zener Tunneling)
  - Can be eliminated near zero bias by low doping

II. DEFECT-MEDIATED MECHANISMS
- Generation-Recombination (g-r) current
- Trap-Assisted Tunneling Current
- Defects may be at surface or within bulk

---

**DIFFUSION CURRENT:**
\[
\frac{1}{R_A} = \frac{e \eta^* d}{kT_n^2}
\]

**G-R CURRENT:**
\[
\frac{1}{R_A} = \frac{\eta}{V_n \tau_n} W
\]
LWIR LPE P-on-n HgCdTe Photodiodes Grown at Loral

N-SIDE DIFFUSION CURRENT AUGER-1 LIFETIME
\(N_0 = 2 \times 10^{15} \text{ cm}^{-3}\)

\(D^*_{\lambda} = 1 \times 10^{12} \text{ cm-Hz}^{1/2}/\text{W}\)
\(T = 80 \text{ K}\)

\(D^*_{\lambda} = 1 \times 10^{11} \text{ cm-Hz}^{1/2}/\text{W}\)
\(T = 80 \text{ K}\)

LORAL P-on-n PV HgCdTe
\(\odot T = 70 \text{ K}\)
\(\odot T = 80 \text{ K}\)

\(D^*_{\lambda} \text{ Limited by thermal noise:}\)
\[D^*_{\lambda} = \frac{\lambda}{hc} \eta e \sqrt{\frac{R_{oA}}{4kT}}\]

Bilinear Array ER02C2
10.58 \(\mu\)m at 72 K

Ave Rbb = 2.71 Amp/Watt
Std Dev = 4.9%
1 open in 83 elements accessed

RoA at 72K
RoA at 80K
Rbb at 72K
Bilinear Array ER02D4
10.68 μm at 72 K

Ave Rbb = 2.75 Amp/Watt
Std Dev = 5.1%
83 elements accessed

LWIR P-on-n HgCdTe PV Array

T = 70 K
λ_{co} = 11.6 μm
-40 mV reverse bias
0 zero bias voltage
Trends in HgCdTe Materials Growth

1. LOWER GROWTH TEMPERATURE AND LAYERED GROWTH:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 °C</td>
<td>Bulk crystal growth:</td>
</tr>
<tr>
<td></td>
<td>• Solid state recrystallization</td>
</tr>
<tr>
<td></td>
<td>• Honeywell's DME</td>
</tr>
</tbody>
</table>
|               | • Traveling heater method        | { PC}
| 400 °C - 500 °C| Liquid Phase Epitaxy            | { PV}
|               | • Te-Rich                        |
|               | • Hg-Rich                        |
| 150 °C - 300 °C| MOCVD                            |
| 120 °C - 195 °C| MBE                              |

2. FOREIGN SUBSTRATES:
   CdTe → CdTeSe → Sapphire → GaAs → GaAs on Si
   CdZnTe

Conclusions

1. HgCdTe has nearly ideal semiconductor properties for LWIR detection
2. Alloy composition uniformity of today's bulk-grown and LPE HgCdTe is more than adequate
3. LWIR HgCdTe P-on-n LPE heterojunction photodiode performance is at the limit set by n-side diffusion current for Auger-1 lifetime for T > 70 K
4. Continued development of HgCdTe material and device technology will:
   a. Improve performance:
      • Reduced leakage current and 1/f noise
      • Longer cutoff wavelengths
   b. Increase producibility:
      • Low-cost large-area substrates
      • Improved screening techniques for material and arrays
   c. Enable in situ VPE growth of advanced device structures:
      • p-n homojunctions and heterojunctions
      • Wide-gap passivation
      • Low-resistivity contact layers
HgCdTe is the current material of choice for high performance imagers operating at relatively high temperatures. Its lack of technological maturity compared with silicon and wide-band gap III-V compounds is more than offset by its outstanding IR sensitivity and by the relatively benign effect of its materials defects. This latter property has allowed non-equilibrium growth techniques (MOCVD and MBE) to produce device quality LWIR HgCdTe even on common substrates like GaAs and GaAs/Si. Detector performance in these exotic materials structures is comparable in many ways with devices in equilibrium-grown material. Lifetimes are similar. RoA values at 77K as high as several hundred have been seen in HgCdTe/GaAs/Si with 9.5 μm cut-off wavelength. HgCdTe/GaAs layers with ~15 μm cut-off wavelengths have given average 77K RoAs of >2. Hybrid focal plane arrays have been evaluated with excellent operability.
OVERVIEW

- Pace Background and Materials
- Test Diode Performance and Technology Limits
- Preliminary LWIR Array Data
- Directions and Conclusions
DEFINITIONS

- CONVENTIONAL TECHNOLOGY
  - MCT GROWN BY LIQUID PHASE EPITAXY ON CdTe OR SIMILAR COMPOUND

- PACE (PRODUCIBLE ALTERNATIVE TO CdTe FOR EPITAXY)
  - ROCKWELL APPROACH TO OVERCOME MCT PRODUCIBILITY ISSUES
  - PACE-1: MCT GROWN BY LIQUID PHASE EPITAXY ON VAPOR PHASE EPITAXIAL CdTe/SAPPHIRE -- SUITABLE FOR SWIR (1-3 MICRONS) AND MWIR (3-5+) MICRONS
  - PACE-2: MCT GROWN BY VAPOR PHASE EPITAXY ON GaAs (OR EVENTUALLY Si) -- SUITABLE FOR ALL IR WAVELENGTHS

PACE-2 HAS BETTER COMPOSITIONAL UNIFORMITY THAN LPE

LEGEND
* — COMPOSITION, X VALUE
— THICKNESS, \( \mu m \)
— CRYSTALLINITY, ARC-SEC
LWIR TACTICAL MCT DETECTOR PERFORMANCE

\[ D^* (\text{cm}^2 \text{Hz}^{1/2} / \text{W}) \]

\[ R_0 A (\Omega \cdot \text{cm}^2) \]

\[ \lambda_c (\mu\text{m}) \]

RADIATIVE LIMIT (10\(\mu\text{m} \) THICK DETECTOR)

RANGE OF BEST MCT DETECTORS AND SMALL ARRAYS

MCT ION IMPLANTED (LETI) PHOTODIODES

MCT S.A.T. DIFFUSED HOMOJ (BULK)

MCT DIFFUSION LIMITED TREND LINES

PACE-2

\( n/P \)

\( P/m \)

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n⁺/p TEST DIODES IN HgCdTe/GaAs (PACE-2)

MTD DATA FOR 3-623 BASELINE LAYER
n ON p DEVICES, ION IMPLANTED
LWIR HgCdTe/Pace-2 p/n Devices Show Higher Performance Than LPE Devices

- ARSENIC IMPLANATATION
- OMVPE HgCdTe ON GaAs

**RECENT p ON n MTD PERFORMANCE CONFIRM EARLIER RESULTS**

ARSENIC IMPLANT/DIFFUSION IN DOUBLE LAYER HETEROSTRUCTURE

- n ON p DIODES HAVE BETTER UNIFORMITY
EXCELLENT DIODE PERFORMANCE IN VLWIR MOCVD MCT/GaAs p ON n DIODES

Minority Carrier Lifetime

4-334, N-Type, Undoped, x=0.235, Nd=1.1 x 10^{15} cm^{-3}

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LIFETIMES IN SOME VACANCY DOPED PACE-2 APPROXIMATE THEORY

BEST IMPURITY DOPED PACE-2 SAMPLES SHOW THEORETICAL LIFETIMES

Layer 3-581
P-Type, Vacancy Doped
x = 0.226
Na = 3.7E16 cm⁻³

Layer 1-1316
P-Type, Arsenic Doped
x = 0.25
Na = 4E15 cm⁻³

Layer 1-1281
N-Type, In Doped
x = 0.23
Nd = 2.7E15 cm⁻³

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Performance of an LWIR MCT/GaAs Array at 50K

\[ R_0A = 3.4 \times 10^3 \]
\[ R_0A_{\text{MED}} = 1.2 \times 10^3 \]
\[ \text{TOT CT} = 14 \]
\[ \text{SHORT} = 4 \]

\[ T = 50K \]
\[ \lambda_c = 10.8 \]

LWIR MOCVD HgCdTe/GaAs DIODES
BEST PERFORMANCE IS AT TOP LPE LEVELS FOR 77 AND 40K

---

Original page is of poor quality
VLWIR I-V Characteristics for MOCVD Grown MCT/GaAs Detector

\[ T = 30K \]
\[ R_0A = 30 \Omega \text{ cm}^2 \]
\[ \lambda_c(30K) = 15.8 \mu m \]

-1 0 0.5 1
-Va (V)

10^{-3} 10^{-4} 10^{5} 10^{6}
-R (d)

-1 0 0.5 1
-Va (V)

R_0A vs 1/T
Layer 3-581, L-134, Planar Ion Implanted

\[ x = 0.226 \] (Ic = 9.22 \mu m at 77K)
\[ Na = 3.7 \times 10^{16} \text{ cm}^{-3}, d = 13 \mu m \]
Temperature Dependence of the $R_0A$ Product of a P/N Diode Fabricated from PACE-2 Material

![Graph showing temperature dependence of $R_0A$ product]

STRATEGIC APPLICATIONS REQUIRE CONTROL OF DISLOCATION DENSITY

**Etch Pit Density MCT/GaAs**

- MADE GOOD DIODES IN DIFFUSION REGIME
- CURRENT TYPICAL
- POTENTIAL

**Low Temperature Operation**

- EPD > $5 \times 10^5$ cm$^{-2}$
- EPD < $5 \times 10^5$ cm$^{-2}$

$\lambda_c > 9.1 - 9.3 \mu$m AT 40K FOR 38 LAYERS

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SAMPLE DIODES FROM PACE II 128 x 128 WAFER (ROCKWELL IR&D)

FULL PLANAR PROCESS: n/p, B-IMPLANTED, ZnS/SiO_2 PASSIVATED

Pace-2 Shows D* Uniformity and Operability of LWIR Hybrid
CONCLUSIONS

- MCT HAS DEMONSTRATED THE HIGHEST PERFORMANCE OF ANY INTRINSIC AT ALL IR WAVELENGTHS

- NOVEL, ALTERNATIVE-SUBSTRATE, VPE APPROACHES CAN MEET PROGRAM GOALS WHILE ENHANCING PRODUCIBILITY AND MAKING POSSIBLE ADVANCED ARCHITECTURES

- THE PRESENT LIMITATIONS OF THE TECHNOLOGY ARE NOT FUNDAMENTAL BUT DUE TO IMMATURITY

- WE EXPECT LWIR/PACE-2 (GaAs) OR 3 (Si) TO FOLLOW A SIMILAR PATH TO PRODUCIBILITY AS THAT OF MWIR PACE-1 WHICH HAS RESULTED IN THE LARGEST (256X256) INTRINSIC IR FPA TO DATE
HgCdTe for NASA Eos Missions and Detector Uniformity Benchmarks

Paul R. Norton  
Santa Barbara Research Center  
Goleta, CA 93117

Important NASA Eos missions (AIRS and MODIS-N) which require detector spectral response in the range of 14 to 17 μm at medium background flux levels and operation in the range of temperatures between 65 to 95 K will be flown beginning in the next few years. Currently, a prime candidate detector technology for these missions is trapping-mode photoconductive HgCdTe devices. These devices can be tailored to the exact cutoff wavelengths required by those missions, and thus offer the performance advantages of an intrinsic detector which is ideally matched to the mission wavelength.

Under the long wavelength-background-temperature conditions of these Eos missions, any detector will at best be thermal generation-recombination noise limited. Photoconductive devices are generally preferred under these circumstances, since at elevated temperatures their performance degrades with $n_i$ while for photovoltaic detectors performance degrades as $n_i^2$ ($n_i$ is the intrinsic carrier concentration which is a function of alloy composition and temperature, but not doping).

Very high performance trapping-mode photoconductive HgCdTe detectors have been developed which can be reproducibly fabricated. Detectivity ($D^*$) at 80K and 16 μm cutoff wavelength in excess of $10^{11}$ Jones has been measured for these devices. Power dissipation is at least two orders of magnitude less than conventional HgCdTe photoconductors - on the order of 0.12 W/cm$^2$ compared with 12 W/cm$^2$.

Eos missions define thermal noise limited conditions for the long wavelength operating bands. Trapping-mode photoconductive HgCdTe detectors are linear under such conditions and responsivity is independent of background flux. At lower temperatures or high flux conditions in which background flux limits detector performance, trapping-mode detectors have a responsivity which varies with background flux. Internal
calibration must be provided for radiometric measurements under the latter conditions (not an Eos mission concern).

Liquid phase epitaxy is used to grow these HgCdTe device structures. This technique has been shown to give control of the cutoff wavelength on the order of 16±1 μm or less, both from run to run and across wafer dimensions of several centimeters on a side. Responsivity uniformity of linear arrays (300 elements with areas of -2.5x10^{-5} cm^2 and 100 μm center-to-center spacings) of trapping-mode detectors with 12 μm cutoff have shown typical uniformities of 5-10% one-sigma standard deviation measured at 80 K and 5x10^{16} photons/cm^2/sec background flux. Measurements of PV detector responsivity uniformity shows that uniformity scales as 1/√A and can be attributed to ±1mm variations in detector area. Thus, larger area HgCdTe detectors are anticipated to be more uniform.
Hard copies of visuals not available for publication due to ITAR restrictions.
SESSION III: Device Design and Evaluation Issues

III - 1 Detector Array Evaluation and Figures of Merit
   E.L. Dereniak, University of Arizona

III - 2 Issues and Directions in IR Detector Readout Electronics
   E.R. Fossum, Columbia University

III - 3 Radiation Response Issues for Infrared Detectors
   A.H. Kalma, Mission Research Corporation
This presentation will review the commonly used methods to evaluate the performance of a two-dimensional focal-plane array using charge transfer devices. Two figures of merit that attempt to combine quantum efficiency, read noise and dark-current generation into a single parameter are discussed. The figures of merit are suggested as possible alternatives to the D*.
DETECTOR ARRAY EVALUATION AND FIGURES OF MERIT

STATE OF CONFUSION

- WHAT WE GET FROM MANUFACTURER
- WHAT WE WANT
- WHAT WE TEST FOR

EUSTACE L. DERENIAK

OPTICAL SCIENCES CENTER
UNIVERSITY OF ARIZONA

(602) 621-1019

GENERIC PARAMETERS QUOTED FROM MANUFACTURER

- SIZE AND # OF PIXELS
- D*
- D* HISTOGRAM
- READ NOISE HISTOGRAM
- DARK CURRENT HISTOGRAM
- SATURATION LEVEL
- RESPONSIVITY MAP
D* PROBLEMS

- SMALL AREA DETECTORS (D* = CONSTANT)
- SPATIAL VARIATIONS ACROSS ARRAY
- RADIANT "POWER" DEPENDENT FOR PHOTODETECTOR
- D*(f) - NO 1/f CHARACTERISTIC (i.e., 0.5 Hz)

  SPECIFICATION OF CHOPPER FREQ.

- WAVELENGTH SPECIFICATION

PARAMETERS WANTED BY USER

- SPATIAL AVERAGED QUANTUM EFF. vs WAVELENGTH
- CONVERSION GAIN
- SPATIAL AVERAGED DARK CURRENT vs INTEGRATION TIME FOR OPERATING TEMPERATURE
- READ NOISE
- DEFECTIVE PIXEL MAP
- DYNAMIC RANGE
- CROSSTALK
- FILL FACTOR (DETECTOR AREA)
- SATURATION LEVEL
TEST/DATA COLLECTED

- MEAN VARIANCE CURVE - $\sigma_r$
- DARK CURRENT GENERATION - $D_g$
- SIGNAL MEASURE FOR Q.E. OVER SPECTRAL BAND - $\eta$
- EFFECTIVE DETECTOR AREA - $A_d$

PLOT SPATIAL MAPS OF:

- DARK CURRENT
- QUANTUM EFFICIENCY
- DEAD PIXELS

MEAN - VARIANCE CURVE

PLOT OF VARIANCE (NOISE²) VERSUS THE MEAN IRRADIANCE (FLAT FIELD) ACROSS ARRAY

$$\sigma^2 = \sigma_r^2 + E_p \eta A_d \tau \text{ (electrons)}$$

COMPUTER PROCESSING

$E_p \propto \text{ADU} \text{ (ANALOG - DIGITAL UNITS IN COMPUTER)}$
SO UNITS CAN BE RELATED BETWEEN ADU'S AND FLAT FIELD IRRADIANCE.
MEAN - VARIANCE IN PRACTICE

- TWO WAYS TO CHANGE MEAN IRRADIANCE ON ARRAY
  - VARY INTEGRATION TIME
  - VARY BLACKBODY TEMPERATURE, OR RANGE

[NOT NECESSARILY EQUIVALENT]

IMPORTANCE OF DARK CURRENT

WILL PHOTONS BE DETECTED IN INTEGRATION TIME, OR WILL DARK GENERATED ELECTRONS DOMINATE FOR PARTICULAR APPLICATION?
DARK CURRENT TESTS

FOR VARIOUS INTEGRATION TIMES; ONE TAKES SEVERAL (i.e. 25) FRAMES OF DATA;

A. $\tau \approx 1$ ms (SHORTEST POSSIBLE)

$$\overline{P}_{ij} = \frac{1}{25} \sum_{K=1}^{25} P_{ij}(K) ; \text{K is Time Index}$$

$F_\tau = \{\overline{P}_{11}, \overline{P}_{12}, \overline{P}_{13}, ..., \overline{P}_{ij}\}$ Average Dark Frame

B. $\tau \gg 1$ ms

(REPEAT)

FIND THE DARK FRAME VALUE FOR SEVERAL INTEGRATION TIMES
DARK FRAME ANALYSIS

- LOCATE A WELL BEHAVED REGION
- READ NOISE VALUE IS FOUND
  @ SHORT INTEGRATION TIMES

DARK CURRENT GENERATION RATE
$D_g \text{ (# of } e^-/\text{sec-pixel})$

INCLUDES OTHER SOURCES

- LIGHT LEAKS
- "SELF-EMISSION" OF ELECTRICAL COMPONENTS
FIGURES OF MERIT

IR SENSOR

SCANNER SYSTEM

STARING

NETD (LLoyd)
MRT (LLoyd)

HI BACKGROUND

LOw BACKGROUND

*NETD
MRT
M (Birtley)
*CSNR (Mooney)

NEI (Kohn)

SINGLE DETECTOR

ARRAY

ARRAY

D*
D**

*2-D*

DQE
(Nudelman/Shaw)

σr = read
D* = dark
η = QE
U = nonuniformity

ARRAY TESTING AND FIGURE OF MERIT ARE APPLICATION DEPENDENT

* RELATED
NON-UNIFORMITY DEFINITION

\[ U(\text{Ep}) = \frac{\text{r.m.s. SPATIAL VARIATION IN ARRAY OUTPUT}}{\text{SPATIALLY AVERAGED ARRAY OUTPUT}} \]

\[ = \frac{\sigma_{p_{ij}}}{\langle P \rangle} \]

SPATIAL AVERAGE

\[ \langle P \rangle = \frac{1}{NM} \sum_{i} \sum_{j} P_{ij} \]

SPATIAL VARIANCE

\[ \sigma_{p_{ij}}^2 = \frac{1}{NM} \sum_{i} \sum_{j} (P_{ij} - \langle P \rangle)^2 \]

\( U(\text{Ep}) \) CAN BE IMPROVED THROUGH USE OF A NON-UNIFORMITY CORRECTOR

\( U(\text{Ep}) \) IS TYPICALLY REDUCED TO ZERO AT SYSTEM CALIBRATION POINTS.

ARRAY FIGURE OF MERIT

\( 2-D^* \) IS A \( D^* \) PLUS THE RANDOM CONTRIBUTION OF NON-UNIFORMITY, READ NOISE, AND DARK CURRENT

A MODIFIED \( D^* \) CALLED 2-D* MAY BE USED IN LLOYDS NETD EXPRESSION TO YIELD CSNR

\[ 2 - D^* = \frac{\lambda}{hc} \sqrt{\frac{\eta}{2 \left( E_p + \frac{\sigma_r^2}{A_d} + E_p^2 A_d \eta \mu + \frac{D_g}{A_d} \eta \right) \eta}} \]

PHOTON SHOT NOISE - Ep

READ NOISE - \( \sigma_r \)

SPATIAL PATTERN - \( u \)

DARK CURRENT GENERATION (ZERO) - \( D_g \)
HIGH BACKGROUND CONTRAST SIGNAL-TO-NOISE RATIO (CSNR)

\[
\text{CSNR} = \frac{\partial[E_p \eta A_d \tau]/\partial T}{[E_p \eta A_d \tau + \sigma_r^2 + E_p^2 \eta^2 A_d^2 U^2 \tau^2]^{1/2}}
\]

\begin{align*}
E_p & = \text{PHOTON IRRADIANCE (P/s-cm}^2) \\
\eta & = \text{QUANTUM EFF.} \\
A_d & = \text{PIXEL AREA} \\
\tau & = \text{INTEGRATION TIME} \\
\sigma_r & = \text{READ NOISE} \\
U & = \text{RMS NON-UNIFORMITY} \\
T & = \text{TEMPERATURE}
\end{align*}
CSNR vs BACKGROUND TEMPERATURE FOR VARIOUS AMOUNTS OF RESIDUAL NON-UNIFORMITY

1/NETD and CSNR

20
15
10
5

290 295 300
Background Temp.

Cal. Pt.

a. NO NON-UNIFORMITY; CSNR = 1/NETD
b. \( u = 1\% \)
c. \( > b \)
d. \( > c \)

UNIFORMITY CORRECTION IS LIMITED BY QUANTIZATION NOISE OF A/D CONVERTER
ARRAY TESTING IS APPLICATION DEPENDENT THEREFORE, FIGURES OF MERITS VARY

- HIGH BACKGROUND SENSOR SYSTEM
  
  NETD - NOISE EQUIV. TEMP. DIFFERENCE
  
  MRT - MINIMUM RESOLVABLE TEMPERATURE
  
  CSNR - CONTRAST SIGNAL-TO-NOISE RATIO

- LOW BACKGROUND SENSOR SYSTEM
  
  NEI - NOISE EQUIV. IRRADIANCE [PHOTONS/SEC-CM²]
  
  DQE - DETECTIVE QUANTUM EFFICIENCY
Detective Quantum Efficiency - DQE (single detector)

\[
DQE = \frac{(S/N)_{\text{meas}}^2}{(S/N)_{\text{in}}^2} \quad \text{iff BLIP; } \eta
\]

Apply to a 2-dimensional array

\[
(S/N)_{\text{in}} = \sqrt{E_p A_d \tau}
\]

\[
(S/N)_{\text{meas}} = \frac{E_p A_d \tau \eta}{[E_p A_d \eta \tau + \sigma_r^2 + (E_p A_d \eta \tau U)^2 + D_g \tau]^{1/2}}
\]

↑ ↑ ↑ ↑
shot read uniformity dark
generation

2-Dimensional DQE

\[
2-\text{DQE} = \frac{(S/N)_{\text{meas}}^2}{(S/N)_{\text{in}}^2} = \frac{1}{\frac{1}{\eta} + \frac{\sigma_r^2}{E_p A_d \eta^2 \tau} + \frac{E_p A_d \tau U^2}{E_p A_d \eta^2} + \frac{D_g}{E_p A_d \eta^2}}
\]

iff \(E_p\) is large enough to produce shot noise, or \(U, \sigma_r,\) and \(D_g\) are small, DQE is equal to quantum efficiency.
SAMPLE CALCULATION

\[ \eta = 0.6 \]

\[ N_{\text{full}} = 10^6 \]

\[ A_d = (50 \ \mu\text{m})^2 \]

\[ \tau = 0.001 \ \text{sec} \]

\[ \sigma_r = 50 \ \text{e}^- \]

\[ D_g = 10e/\text{sec-pixel} \]

\[ U = 0.005 \]

\[ 2 - \text{DQE} = 1/\left( \frac{1}{0.6} + \frac{2.79(10^{11})}{E_p} + E_p \cdot 6.25(10^{-13}) + \frac{1.11(10^6)}{E_p} \right) \]
READ NOISE INFLUENCE

Performance Reference:
Read Noise = 0 e⁻ rms
Uniformity = 0

Read Noise
25 e⁻ rms
100 e⁻ rms
400 e⁻ rms

ad
10E7 Background Flux 10E17

\[
\eta = .60 \\
\tau = .001 \text{ sec} \\
A_d = (50 \mu \text{m})^2 \\
D_g = 10e^-/\text{sec-pixel}
\]

NON-UNIFORMITY INFLUENCE

Performance Reference:
Read Noise = 0 e⁻ rms
Uniformity = 0

Read Noise @ 25e⁻ rms;
Uniformity Variation @

.5% rms
.05% rms
.005% rms

Uniformity

10E7 Background Flux 10E17
WHERE DOES SPATIAL NON-UNIFORMITY COME FROM

- Variations in dark current density
- Variations in detector active area
- Variations in the absolute value, or in some cases, variations in the spectral shape, of the quantum efficiency curve.
- Variations in the detector-to-detector non-linearity of response
- Variations in the 1/f noise associated with each detector or other unit-cell electronics.

FLAT FIELD CALIBRATION EFFECTS
DARK CURRENT EFFECTS

\[ 2 - \text{DQE} = \frac{1}{0.6 + \frac{27.7}{\tau} + 1.1(10^{-2})D_g} \]

DARK CURRENT SIMPLY LIMITS THE MAXIMUM DETECTIVE QUANTUM EFFICIENCY

- GOOD (1) DQE REQUIRES "LOW" READ NOISE AND "LOW" DARK CURRENT
CONCLUSIONS

TESTS ON ARRAYS

- MEAN VARIANCE
- DARK CURRENT GENERATION FRAMES
- SIGNAL MEASUREMENTS FOR Q.E. VALUES
- EFFECTIVE DETECTOR AREA

FIGURES OF MERITS FOR FPA

- 2-D* (CSNR - CONTRAST SIGNAL TO NOISE) RATIO
  - GOOD FOR HIGH BACKGROUNDs AND CALIBRATION ONCE AN HOUR

- DQE (DETECTIVE QUANTUM EFFICIENCY)
  - GOOD FOR LOW BACKGROUNDs
  - COMBINES READ NOISE, DARK CURRENT, QUANTUM EFFICIENCY AND NON-UNIFORMITY INTO ONE PARAMETER
ISSUES AND DIRECTIONS IN IR DETECTOR READOUT ELECTRONICS

Eric R. Fossum
Department of Electrical Engineering
Columbia University
New York, NY 10027

Abstract

An introduction to the major issues encountered in the read out of imaging detector arrays in the infrared will be presented. These include circuit issues such as multiplexing, buffering, and noise, as well as materials issues.

Future directions in infrared readout electronics will also be discussed. These include on-chip signal processing and advanced hybridization schemes. Finally, recent work at Columbia on 2DEG-CCDs for IR detector multiplexing will be described.
Issues in FPA Readout Electronics

Eric R. Fossum
Dept. of Electrical Engineering
Columbia University
NY NY 10027

Outline

1. Present Imager Readout Architectures
2. Special Problems in LWIR Readout
3. GaAs CCD Readout
4. On-chip Signal Processing
(a) METAL SiO₂ α-SILICON p-SILICON

(b) BULK CHANNEL

(c) SIGNAL CHARGE

\[ \phi \]

\[ V_G \]

\[ d_{ch} \]

\[ d_1, d_2 \]
4-PHASE CHARGE TRANSFER
Schematic illustration of a charge-coupled device (CCD) imager read-out structure.
## COMMERCIALLY-AVAILABLE CCDS

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<th>MANUFACTURER</th>
<th>DEVICE</th>
<th>FORMAT</th>
<th>STRUCTURE</th>
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<th>DIMENSIONS, mm</th>
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INTEGRATING INPUTS

1. DIRECT INJECTION

\[ Q_{\text{sig}} = \sum_{T} I(t) \, dt \]

2. GATE MODULATION

\[ Q_{\text{sig}} = \sum_{T} I(V_g(t)) \, dt \]

COULD BE SUBTHRESHOLD OR WEAK INVERSION OR INVERSION
Fig. 5. Pixel cross section of 256 x 256 element IR-CCD image sensor.

Fig. 3. Schematic diagram of 256 x 256 element IR-CCD image sensor.

Fig. 2. Various detector readout structures: (a) gate readout (GRO); (b) gate-coupled readout (GCRO) to CCD; (c) direct-injection (DI) current readout; (d) direct-injection ancillary current (DIAC) readout; (e) direct-injection bipolar (DIB) current readout; (f) direct-injection bipolar ancillary current (DIBAC) readout; (g) buffered direct-injection (BDI) current readout.

Fig. 8. Backside-Illuminated hybrid FPA.

Fig. 6. Direct-injection input circuit schematic for 64 x 64 multiplexer.
Comparison of CCD Technologies

IR Photon Flux

<table>
<thead>
<tr>
<th>Photonic Flux</th>
<th>3-5 um</th>
<th>5 x 10^{14}</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-12 um</td>
<td>3 x 10^{16}</td>
<td></td>
</tr>
</tbody>
</table>

Bucket: Capacity (/cm^2)

Bucket Voltage

Schematic illustration of a MOS-CCD imager read-out structure.
Fig. 5. Reset integrator input circuit: (a) functional block diagram, (b) MOSFET implementation.

Fig. 6. Buffered common gate input circuit: (a) functional block diagram, (b) MOSFET implementation.

Fig. 2. Simplified schematic of the direct readout circuit used for this array.

Fig. 5. Representation of the voltage across a single pixel during an integration interval at the detector node.

Fig. 8. Carrier modulation scheme used to upconvert detect signals to higher frequencies where MOSFET noise is low.

Fig. 9. Buffered common gate readout input circuit using chopper stabilization to reduce detector bias offsets and amplifier 1/f noise.

Fig. 10. Projected chopper-stabilized InSb focal plane performance.

IMAGE ACQUISITION

+ IMAGE PROCESSING

FOCAL PLANE IMAGE PROCESSING

<table>
<thead>
<tr>
<th>WHY</th>
<th>WHY NOT</th>
</tr>
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<tbody>
<tr>
<td>NOISE</td>
<td>YIELD</td>
</tr>
<tr>
<td>DISTORTION</td>
<td>CHIP SIZE</td>
</tr>
<tr>
<td>POWER</td>
<td>COOLING</td>
</tr>
<tr>
<td>SIZE</td>
<td>NON-UNIFORMITY CORRECTION</td>
</tr>
<tr>
<td>RELIABILITY</td>
<td></td>
</tr>
<tr>
<td>COST</td>
<td></td>
</tr>
</tbody>
</table>

Pipeline Vector Processor

Serial Shift Register

Output Amplifier

Original page is of poor quality.
NON-UNIFORMITY CORRECTION

MULTIPLYING CCD D/A CONVERTER

GAIN

SIG

CCD MDAC

REF

CCD MDAC

OFFSET

\[ \sum \]

\[ \frac{R}{2} \]

\[ \frac{R}{4} \]

\[ \frac{R}{8} \]

R

R

R

B1

B2

B3
Fig. 2. Photograph of (a) serial recursive circuit and (b) single stage of pipeline circuit.
Fig. 3. Oscilloscope photograph showing analog output of pipeline programmable gain control circuit in response to a digital ramp (upper trace) and MSB of digital control word (lower trace).

Fig. 4. Differential linearity error of pipeline circuit. Note that 1 LSB tic mark corresponds to 1/1024 of full scale.
CCD Programmable Gain Control Circuit

Performance Summary

<table>
<thead>
<tr>
<th></th>
<th>Pipeline</th>
<th>Serial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>3 μm CCD</td>
<td>3 μm CCD</td>
</tr>
<tr>
<td>Circuit Size</td>
<td>0.4 mm²</td>
<td>0.013 mm²</td>
</tr>
<tr>
<td>Resolution</td>
<td>10 bits</td>
<td>variable</td>
</tr>
<tr>
<td>Integral Linearity</td>
<td>8 bits</td>
<td>6 bits</td>
</tr>
<tr>
<td>Differential Linearity</td>
<td>8 bits</td>
<td>6 bits</td>
</tr>
<tr>
<td>Clock Voltage</td>
<td>10 volts</td>
<td>10 volts</td>
</tr>
<tr>
<td>Bucket Cap. (electrons)</td>
<td>5x10⁶</td>
<td>5x10⁶</td>
</tr>
<tr>
<td>Power (10³ conv/sec)</td>
<td>2 μW</td>
<td>2 μW</td>
</tr>
<tr>
<td>Max. Conversion Rate</td>
<td>&gt;8x10⁶/sec</td>
<td>&gt;0.5x10⁶/sec</td>
</tr>
</tbody>
</table>

Spatially Parallel Architecture (SIMD)
FPA CCC POWER CONSIDERATIONS

TO TRANSFER 1 BUCKET (HALF FULL) \( \Delta V = 10 \) VOLTS

\( \text{ENERGY} = 8 \text{ pJ} \)

ARRAY WITH 1500 PEs OPERATING IN PARALLEL

\( 12 \text{ nJ} \)

SAY EACH INSTRUCTION REQUIRES 10 TRANSFERS,
SAY 100 INSTRUCTIONS PER PIXEL TO PREPROCESS

\( 12 \mu\text{J} \) PER FRAME

SAY 1000 Hz FRAME RATE*

12 mW CHIP DISSIPATION

ADD IN DRIVERS, PARASITICS, MULTIPLY BY 2

\( \boxed{25 \text{ mW}} \)

FOR 1 kHz REAL TIME PREPROCESSED IMAGERY

* AT 100 nsec/TRANSFER, CAN OPERATE AT 1MHz INSTRUCTION RATE, OR 10 kHz FRAME RATE POSSIBLE

NOISE CONSIDERATIONS

SAY BIAS = 10 V \( \rightarrow \) 8 VOLT BUCKET

\( \sim 250,000,000 \) ELECTRONS/HOLES

SAY WANT 8-BIT EQUIVALENT ACCURACY W/ SNR = 4 ON LSB

\( \rightarrow \) MAXIMUM NOISE \( \sim 250,000 \) CARRIERS

NOISE SOURCES:

1) CAPACITIVELY COUPLED CIRCUITS

\[ n_{\text{RMS}} = \frac{\sqrt{2} k T}{q} \leq 1000 \text{ CARRIERS} \]

2) TRANSFER

\[ n_{\text{RMS}} = (2 E N_{\text{FULL}})^{1/2} \leq 5000 \text{ CARRIERS} \]

3) INTERFACE

\[ (1.4 k T D T A E)^{1/2} \leq 200 \text{ CARRIERS} \]

CCC PROGRAM, SAY 50 TRANSFERS AND 10 FILL & SPILLS

\( \rightarrow \) RMS 35,000 CARRIERS
WHY GaAs CCDs?

Device Structure

\[ dV = \frac{dQ}{C_g + C_o} \]

Features

- High Electron Mobility
- High Transfer Speed
- High \( f_t \) Transistors
- Wide Bandgap
  - Radiation Hard
  - Low Noise
- Semi-Insulating Substrate
  - Low Parasitic Capacitance
  - Mesa Isolation
- Compatibility with III-V Detectors
BAND DIAGRAM OF GaAs CCD

Without Signal Charge

\[ V_g > 0 \]

With Signal Charge

\[ V_g > 0 \]

\[ Q_{\text{sig}} = qN_d \Delta x \]
BAND DIAGRAM OF 2DEG CCD

$n^+\text{AlGaAs}$  Undoped-GaAs

Without Signal Charge

$V_g > 0$

With Signal Charge

$V_g > 0$
2DEG RGCCD

Device Structure

Features

- High Electron Mobility
- High Transfer Speed
- High Performance 2DEGFET
- Large Dynamic Range
  \[ n_s > 1 \times 10^{12} \text{ /cm}^2 \]
- High Sensitivity Input
- Enhanced Low Temperature Performance
OPERATION OF 2DEG RGCCDs

Room Temperature
4 Phase Clocking, 32 Stages (128 Transfers)
1 um Electrode Width, 4 um Spacing, 100 um Channel Width

Uniform-Doped 2DEG RGCCD
CTE = 0.999 At 1 GHz

Planar-Doped 2DEG RGCCD
CTE > 0.999 At 133 KHz

Advances in 2DEG CCDs

<table>
<thead>
<tr>
<th>Year</th>
<th>Group</th>
<th>Channel Layer Material</th>
<th>Gate Structure</th>
<th>Gap Size</th>
<th>Gate Length x Width (um)</th>
<th>Clock Frequency</th>
<th>CTE</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>Rockwell</td>
<td>AlGaAs /GaAs</td>
<td>Capacitive</td>
<td>2</td>
<td>40 x 400</td>
<td>&lt; 83 KHz</td>
<td>0.98</td>
<td>300 K</td>
</tr>
<tr>
<td>1983</td>
<td>Rockwell</td>
<td>AlGaAs /GaAs</td>
<td>Capacitive</td>
<td>1</td>
<td>5 x</td>
<td>&lt; 83 KHz</td>
<td>&lt; 0.9</td>
<td>300 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.989</td>
<td>77 K</td>
</tr>
<tr>
<td>1990</td>
<td>Columbia</td>
<td>AlGaAs /GaAs</td>
<td>Resistive</td>
<td>N/A</td>
<td>5 x 100</td>
<td>13 MHz - 1 GHz</td>
<td>0.999</td>
<td>300 K</td>
</tr>
<tr>
<td>1990</td>
<td>Columbia</td>
<td>AlGaAs /GaAs (6-Doped)</td>
<td>Resistive</td>
<td>N/A</td>
<td>5 x 100</td>
<td>130 KHz - 1 GHz</td>
<td>&gt; 0.999</td>
<td>300 K</td>
</tr>
<tr>
<td>1990</td>
<td>Columbia</td>
<td>InAlAs /InGaAs (6-Doped)</td>
<td>Resistive</td>
<td>N/A</td>
<td>5 x 100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ORIGINAL PAGE IS OF POOR QUALITY
DIRECT DETECTION

n-GaAs
S.l. GaAs

Cermét

φ₁ φ₂ φ₃ φ₄ φ₁ φ₂ φ₃ φ₄ φ₁

V_m

COLUMBIA

JPL

3510 ARDA

JIS 1990
INDIRECT DETECTION

Direct Injection

Gate Modulation
GaAs CCD MULTIPLEXER DESIGN

- Linear Arrays (32 Stages, RGCCD, CGCCD)
  Direct Detection
  Indirect Detection
    Direct Injection
    Gate modulation

- 2-D Arrays (32x32, RGCCD)
  Direct Detection

RESEARCH ISSUES

- Leakage Current Reduction
  Transport Mechanisms
  Materials Quality
  Structure

- Dynamic Range
  Pinch Off Voltage
  Leakage Current

- New Material System
  (InAlAs/InGaAs)
  Higher Electron Mobility
  Larger Dynamic Range
Planar-Doped In Al As / In Ga As RGCCD

- High Mobility ($\sim 20,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ at 77 K)
- Large Sheet Carrier Density
- SWIR Direct Detection
- Compatible with Fiber-optic Integration

### Present and Future Issues in Readout Electronics

- Hybridization Technology
  - center-to-center spacing
  - array size
  - buttability
  - reliability

- Multiplexer Material
  - thermal match
  - low 1/f noise devices

- On-Chip Signal Processing
  - random event correction
  - detector non-uniformity correction
  - image processing
  - signature recognition

4/15/90 EY
Abstract

RADIATION RESPONSE ISSUES
FOR INFRARED DETECTORS

Arne H. Kalma
MISSION RESEARCH CORPORATION
4935 North 30th Street
Colorado Springs, Colorado

One important issue facing space systems is survivability and operability in radiation environments. All space systems will be subject to the natural space environment, and most DoD and SDI systems must also be concerned with the much higher radiation environments produced by nuclear weapons. As a result, survivability and operability are necessary requirements that must be met by any space system.

Historically, infrared detectors (which are the key component in sensor subsystems) have been very vulnerable to nuclear radiation exposure. Most semiconductor components are subject to a variety of radiation-induced degradation mechanisms, and infrared detectors are no exception. In addition, high-quality infrared detectors are extremely sensitive detectors of optical photons, but this also makes them very sensitive to gamma photons, electrons, and protons.

Although some infrared detector technologies are less vulnerable to nuclear radiation than others, and hardening approaches have been developed for some of the technologies, there is no realistic expectation that the vulnerability problem will be completely eliminated for any infrared detector technology. Therefore, it is necessary to understand the vulnerability issues presented by nuclear radiation exposure, so that ones that impact sensor performance can be addressed.

In this paper, we will describe the most important radiation response issues for infrared detectors. In general, the two key degradation mechanisms in infrared detectors are the noise produced by exposure to a flux of ionizing particles (e.g.; trapped electrons and protons, debris gammas and electrons, radioactive decay of neutron-activated materials) and permanent damage produced by exposure to total dose. Total-dose-induced damage is most often the result of charge trapping in insulators or at interfaces. Exposure to short pulses of ionization (e.g.; prompt x-rays or gammas, delayed gammas) will cause detector upset. However, this upset is not important to a sensor unless the recovery time is too long. A few detector technologies are vulnerable to neutron-induced displacement damage, but fortunately most are not.
We will discuss the radiation responses of various infrared detector technologies, emphasizing where possible the responses of the newer technologies that are the subject of the Workshop. Because of the newness of most of these technologies, much of this will be analytical projections of the radiation response. In some cases, we will not even be able to accomplish the analytical predictions because of a lack of sufficient information about the use of the technology as an infrared detector. We will compare the responses of the newer technologies with those of the mainstream technologies of PV HgCdTe and IBC Si:As. One important reason for this comparison is to note where some of the newer technologies have the potential to provide significantly improved radiation hardness compared with that of the mainstream technologies, and thus to provide greater motivation for the pursuit of these technologies.
RADIATION RESPONSE ISSUES FOR INFRARED DETECTORS

PRESENTED AT:
INNOVATIVE LWIR DETECTOR WORKSHOP
JET PROPULSION LABORATORY
24-26 APRIL 1990

PRESENTED BY:
ARNE H. KALMA
MISSION RESEARCH CORPORATION
4036 N. 30TH STREET
COLORADO SPRINGS, COLORADO 80919

CONTRACT NO. 720601-88-C-0025
SUBCONTRACT NO. S-CUBED 1761/03003
MRC CONTRACT 88103

RADIATION HARDNESS IS A BASIC REQUIREMENT, NOT AN ADD-ON, FOR SPACE SYSTEMS

- NATURAL SPACE RADIATION ENVIRONMENT EXISTS AT ALL TIMES
  - NATURAL RADIATION ENVIRONMENT AROUND EARTH MAY BE RELATIVELY BENIGN, BUT LONG-DURATION MISSIONS CAN ACCUMULATE HIGH DOSE
  - NASA MISSIONS TO OUTER PLANETS CAN ENCOUNTER RADIATION ENVIRONMENTS MUCH HIGHER THAN EARTH'S

- SDI AND DoD SYSTEMS MUST SURVIVE THE NUCLEAR-ENHANCED ENVIRONMENTS

- IR DETECTORS WILL HAVE TO BE HARD, OR THEY WILL NOT BE USED FOR SPACE APPLICATIONS, PARTICULARLY IN THE SDS
  - ONE SHOULD NO LONGER ASSUME THAT ONE CAN DEVELOP A COMPONENT OR SUBSYSTEM, AND THEN THINK ABOUT HARDENING

- HARDENING MUST BE CONSIDERED FROM THE BEGINNING
THERE ARE SEVERAL RADIATION HARDNESS ISSUES THAT ARE IMPORTANT

- OPERABILITY DURING EXPOSURE TO A FLUX OF IONIZING PARTICLES
  - TRAPPED ELECTRONS OR PROTONS, DEBRIS GAMMAS OR ELECTRONS, DECAY OF ACTIVATED MATERIALS, ETC.

- SURVIVABILITY FOLLOWING TOTAL-DOSE EXPOSURE
  - TRAPPED ELECTRONS OR PROTONS, PROMPT X-RAYS OR GAMMAS, DELAYED OR SECONDARY GAMMAS, ETC.

- UPSET/RECOVERY WHEN EXPOSED TO PROMPT PULSE

- SURVIVABILITY FOLLOWING NEUTRON EXPOSURE

- ISSUES THAT ARE MORE SYSTEM-RELATED WILL NOT BE DISCUSSED
  - OPERABILITY IN THE PRESENCE OF NUCLEAR-INDUCED OPTICAL CLUTTER
  - RECOOLING FOLLOWING NUCLEAR-INDUCED HEATING
  - SGEMP/IEMP

OPERABILITY IN A GAMMA-FLUX ENVIRONMENT REMAINS A KEY ISSUE FOR INFRARED SENSORS

- DETECTORS ARE SO SENSITIVE THAT CHARGE DEPOSITED BY A SINGLE IONIZING PARTICLE CAN COMPLETELY MASK THE OPTICAL SIGNAL

- DETECTORS ARE RELATIVELY LARGE, SO EVENT RATES ARE HIGH
  - ALL PIXELS CAN BE CONTAMINATED AT RELATIVELY LOW FLUX

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IONIZATION-INDUCED PULSES IN LWIR DETECTORS ARE PARTICULARLY LARGE

- DETECTORS ARE VERY SENSITIVE ANALOG DEVICES
- PULSES PRODUCED BY IONIZING PARTICLES CAN COMPLETELY MASK OPTICAL SIGNALS
  - $< n > \approx (E/L) \cdot \frac{\langle x \rangle}{\epsilon_p}$
  - $R \approx \mu L < A_p > \gamma$
  - $i_n \approx 2e < n > (R(\Delta f))^{\frac{1}{2}}$
- EFFECT IS TRANSIENT, AND OCCURS ONLY WHEN DETECTORS ARE EXPOSED TO FLUX

SELECTION OF DETECTOR TECHNOLOGY CAN IMPACT OPERABILITY IN IONIZING-FLUX ENVIRONMENT

- HIGHER $\alpha$ FOR THINNER DETECTORS
- EXTRINSIC DETECTORS FOR HIGHER $\epsilon_p$
- ADVANCED HARDENING CONCEPTS ARE MORE LIKELY FOR EXTRINSIC DETECTORS

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ORIGINAL PAGE IS OF POOR QUALITY
MANY OF THESE INNOVATIVE DETECTOR CONCEPTS GIVE PROMISE OF IMPROVED HARDNESS TO IONIZING PARTICLE FLUX

- PRIMARY ADVANCE IS DETECTOR THINNESS
- MOST OF CURVES BASED ON ANALYTICAL PREDICTIONS
- GaAs/AlGaAs QUANTUM WELL CURVE BASED ON EXPERIMENTAL DATA

SURVIVABILITY FOLLOWING TOTAL-DOSE EXPOSURE IS ALSO AN IMPORTANT ISSUE

- DAMAGE MECHANISM IS TRAPPING OF RADIATION-INDUCED CHARGE IN INSULATORS OR AT INTERFACES
  - DAMAGE IS PERMANENT
- NARROW-BANDGAP SEMICONDUCTORS ARE PARTICULARLY VULNERABLE TO TUNNELING EFFECTS
- HIGH IMPEDANCE DEVICES ARE PARTICULARLY VULNERABLE TO SURFACE LEAKAGE
DETERMINING TOTAL-DOSE HARDNESS OF ANY TECHNOLOGY USUALLY ACCOMPLISHED ONLY BY EXPERIMENT

- MOST SEMICONDUCTOR TECHNOLOGIES WITH INSULATORS ARE VULNERABLE TO TOTAL DOSE
  - INCLUDES Si, Ge, AND MOST III-Vs
  - PINNED SURFACE POTENTIAL MAKES GaAs AN EXCEPTION

- HARDENING APPROACHES CAN BE DEVELOPED
  - TUNNELING MAKES PROBLEM MORE DIFFICULT FOR NARROW BANDGAP MATERIALS

HARDENING OF HgCdTe AGAINST TOTAL-DOSE EXPOSURE HAS PROVEN TO BE PARTICULARLY DIFFICULT

- DAMAGE MECHANISM NOT WELL UNDERSTOOD
  - ANY OF SEVERAL DIFFERENT MECHANISMS CAN DOMINATE OBSERVED DAMAGE

- STANDARD HARDENING APPROACHES HAVE NOT BEEN EFFECTIVE

- HARDNESS HAS NOT BEEN REPEATABLE
  - VARIATION IN HARDNESS OFTEN OBSERVED IN SAME ARRAY

- ONE QUESTION IS WHETHER SIMILAR PROBLEMS WILL BE ENCOUNTERED FOR ANY NARROW-BANDGAP SEMICONDUCTOR

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RECOVERY TIME IS KEY ISSUE FOR PROMPT-PULSE EXPOSURE

- UPSET THRESHOLD IS SO LOW THAT UPSET IS SURE TO OCCUR
- ISSUE IS RELATIVELY INDEPENDENT OF DETECTOR TECHNOLOGY
- SYSTEMS MUST BE DESIGNED TO IGNORE THIS UPSET
- RECOVERY, ESPECIALLY IN MULTI-BURST ENVIRONMENT, IS KEY
- READOUT OFTEN GOVERNS RECOVERY OF FPA, BUT DETECTOR RECOVERY MUST BE CONSIDERED
  - RECOVERY AT CRYOGENIC TEMPERATURE CAN BE LONG

MOST DETECTOR TECHNOLOGIES ARE RELATIVELY HARD TO NEUTRON EXPOSURE

- PERMANENT DEGRADATION PRODUCED BY NEUTRON-INDUCED DISPLACEMENTS
- Si:X AND InSb ARE EXCEPTIONS
- ANALYTICALLY PREDICTING THE NEUTRON RESPONSE OF A NEW TECHNOLOGY IS DIFFICULT
SUMMARY

- Radiation hardness is one of the basic requirements for LWIR detector technologies developed for space applications.
- Ionizing-particle-flux and total-dose hardness are the most important operability/survivability issues.
  - These issues exist for both natural-space and nuclear-weapon-enhanced environments.
- Recovery following prompt-pulse exposure and survivability following neutron exposure are secondary issues for most detector technologies.
  - Recovery time in multi-burst environment can be important.
  - These issues only exist for nuclear-weapon-enhanced environments.
- Many of the proposed innovative technologies have potential hardness advantages over the existing mainstream technologies of HgCdTe and IBC Si:As.
SESSION IV: High Performance Thermal Detectors

IV - 1  Fabrication of Sensitive High TCBolometers
        *M. Nahum, University of California, Berkeley*

IV - 2  Pyroelectric Detectors
        *E. Haller, Lawrence Berkeley Laboratory*

IV - 3  A Novel Electron Tunneling Infrared Detector
        *T.W. Kenny, Jet Propulsion Laboratory*
FABRICATION OF SENSITIVE HIGH $T_c$ BOLOMETERS*

M. Nahum, S. Verghese, Qing Hu†, and P.L. Richards  
Department of Physics, University of California,  
and Materials and Chemical Sciences Division,  
Lawrence Berkeley Laboratory, Berkeley, CA 94720

K. Char, N. Newman, and S.A. Sachtjen  
Conductus Inc., Sunnyvale, CA

The rapid change of resistance with temperature of high quality films of high $T_c$ superconductors can be used to make resistance thermometers with very low temperature noise. Measurements on c-axis YBCO films have given a spectral intensity of temperature noise less than $4 \times 10^{-8}$ K/Hz$^{1/2}$ at 10 Hz. Consequently, the opportunity exists to make useful bolometric infrared detectors that operate near 90 K which can be cooled with liquid nitrogen. This talk will summarize the fabrication and measurement of two bolometer architectures. The first is a conventional bolometer which consists of a 3000 Å thick YBCO film deposited in situ by laser ablation on top of a 500 Å thick SrTiO$_3$ buffer layer on a (1012) Al$_2$O$_3$ substrate. The sample was lapped to 20 μm thickness and diced into 1x1 mm$^2$ bolometer chips. Gold black smoke was used as the radiation absorber. The voltage noise was less than the amplifier noise when the film was current biased. Optical measurements gave an NEP of $5 \times 10^{-11}$ W/Hz$^{1/2}$ at 10 Hz. The second architecture is that of an antenna-coupled microbolometer which consists of a small (5x10 μm$^2$) YBCO film deposited directly on a bulk substrate with a low thermal conductance (YSZ) and an impedance matched planar lithographed spiral or log-periodic antenna. This structure is produced by standard photolithographic techniques. Measurements gave an electrical NEP of $4.7 \times 10^{-12}$ W/Hz$^{1/2}$ at 10 kHz. Measurements of the optical efficiency are in progress. The measured performance of both bolometers will be compared to other detectors operating at or above liquid nitrogen temperatures so as to identify potential applications.

* Supported in part by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under contract No. DE-AC03-76SF00098, and by the Department of Defense.  
† Present address: Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, MIT.
Fabrication of Sensitive High Tc Bolometers

M. Nahum

Dept. of Physics, University of California, Berkeley and Materials and Chemical Sciences Division, Lawrence Berkeley Laboratory

Berkeley

Qing Hu (MIT)
M. Nahum
P. L. Richards
S. Verghese

Conductus Inc., Sunnyvale, CA

K. Char
N. Newman
S. A. Sachtjen
Outline

- Motivation and applications
- Conventional composite bolometer
- Microbolometer
- Conclusions

High background applications

Performance \( (D^* = \text{AREA}^{1/2}/\text{NEP}) \) of commercial photon detectors viewing 300K source.
Performance available at or above 77K

Applications above 77K:

- Laboratory IR spectrometers
- Earth observations from space

Elements of high $T_c$ infrared bolometers

<table>
<thead>
<tr>
<th></th>
<th>Conventional Bolometer</th>
<th>Microbolometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>sapphire</td>
<td>yttria stabilized zirconia (YSZ)</td>
</tr>
<tr>
<td>Radiation absorber</td>
<td>gold black Bi film</td>
<td>antenna-coupled YBCO</td>
</tr>
<tr>
<td>Thermometer $R(T)$</td>
<td>YBCO</td>
<td>YBCO</td>
</tr>
<tr>
<td>Thermal conductance $G$</td>
<td>Cu leads</td>
<td>thermal spreading resistance</td>
</tr>
</tbody>
</table>

![Diagram of Conventional Bolometer](image1)

![Diagram of Microbolometer](image2)
The high $T_c$ conventional bolometer

- Easy to make one that "works".
- Hard to get useful sensitivity.
- Good ones can be made now.
- Materials needs very specific.
- Low-noise and high $\frac{1}{R} \frac{dR}{dT}$.
- Proper optimization.

**Fabrication**

- Substrate 1x1 mm$^2$, 20 $\mu$m thick, \(\{1\bar{1}02\}\) sapphire.
  - Low specific heat
  - Strong
  - YBCO compatible
- Laser ablate 3000 Å YBCO on a 500 Å SrTiO$_3$ buffer layer on 6x6x0.5 mm$^3$ sapphire.
- Sputter clean YBCO surface and sputter deposit Ag electrical contacts.
- Polish and dice.
Sensitivity ⇒ YBCO film quality

\[ \text{high } \frac{1}{R} \frac{dR}{dT}, \text{ low noise} \]


- But there is excess voltage noise near \( T_c \) under current bias in these films.

![Graph of YBCO on Al\(_2\)O\(_3\) (Conductus) with noise and resistance vs temperature.](image)

- Using the 500Å SrTiO\(_3\) buffer layer ⇒ reduced voltage noise.

![Graph of YBCO on MgO (Stanford) with noise and resistance vs temperature.](image)
Bolometer optimization

Given: \( \frac{1}{R} \frac{dR}{dT}, \quad C \) -- heat capacity

Pick: \( I \) -- current bias
\( R \) -- operating resistance
\( G \) -- thermal conductance
\( \omega \) -- chopping frequency

\[
\text{NEP} = \left( 4kT^2G + \frac{4kTR + V_{\text{amp}}^2 + V_{1/f}^2}{|S|^2} \right)^{1/2}
\]

\[
S = I \frac{dR(T)}{dT} |G + i\omega C|^{-1}, \quad I^2R < 0.3G\delta T \quad \text{for stability.}
\]
\( \delta T \) -- transition width

For a sapphire bolometer:

\( \omega/2\pi = 10 \text{ Hz} \)
\( \delta T = 0.5 \text{ K} \)

1X1X0.02 mm\(^3\) sapphire

\( \text{NEP} \leq 10^{-11} \text{ W/Hz}^{1/2} \)
**Measurements**

- R(T) and load curve  ⇒  $S_{\text{electrical}} = 26 \text{ V/W, 10 Hz}$
- Chopped He-Ne laser  ⇒  $S_{\text{optical}} = 22 \text{ V/W, 10 Hz}$
- At present, noise is amplifier limited  ⇒  $\text{NEP} = 5 \times 10^{-11} \text{ W/Hz}^{1/2}, 10 \text{ Hz}$
Electrical measurements

Bolometer R(T)

Load Curve
Optical response

![Graph showing optical response with Signal and dR/dT data points.](image)
High Tc Microbolometer
Sensitive and fast

- Small area \( (A \approx 5 \, \mu m^2) \)
- Deposited directly on thick substrate
- Only small volume of substrate contributes thermally \( (V \approx 10 \, \mu m^3) \)
- NEP \( \propto A^{1/4} \)
- Response time \( \propto A \)
- Couple directly \( \lambda < 2 \, \mu m \)
- Couple with antenna \( \lambda > 100 \, \mu m \)
- Array compatible fabrication


Idea from: Hwang, Schwarz, Rutledge
Neikirk, Lam, Rutledge
Rutledge, Neikirk, Kasilingam
**Microbolometer thermal response**

\[ \text{NEP} = \left( 4kT^2G(f) \right)^{1/2}, \quad G(f) = ? \]

**Diffusion length**

\[ L = \left( \frac{\kappa_s}{c_s \pi f} \right)^{1/2} \]

\[ \text{L} > \sqrt{A} \]

\[ G = \sqrt{2\pi A \kappa_s} \]

\[ \text{NEP} \propto A^{1/4} \]

\[ \text{L} < \sqrt{A} \]

\[ G = \sqrt{2\pi A \left( \kappa_s c_s f \right)^{1/2}} \]

\[ \text{NEP} \propto A^{1/2} f^{1/4} \]

**Calculated NEP** (Area = 1X5 \( \mu \text{m}^2 \))

![Graph showing calculated NEP for different materials at various frequencies.](image)
How to couple long wavelengths into a small bolometer?

- Antenna-coupled microbolometer
- Self complementary planar antenna
  - Real antenna impedance
  - Broadband response $\lambda > 100 \, \mu m$
- Single mode throughput $A\Omega = \lambda^2$

Log-Periodic Antenna  
Spiral Antenna
Fabrication of microbolometer

- Single target sputtered 3000 Å YBCO on YSZ.
- Pattern YBCO into 5 µm wide strips in acid etch.
- Sputter clean YBCO surface and sputter deposit Ag.
- Wet etch Ag antenna pattern.
- Oxygen anneal 500° C for 1 hr.
Optical response of microbolometer

\[ I = 500 \mu A, f = 2 \text{ kHz} \]

\[ \text{Response (arb.)} \]
\[ \text{dR/dT (}\Omega/\text{K}) \]

Temperature (K)

\[ 84 \quad 88 \quad 92 \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \]

\[ 0 \quad 1 \quad 2 \]

\[ 100 \quad 10 \quad 1 \]

\[ .1 \quad 1 \quad 10 \quad 100 \]

\[ \text{Responsivity (V/W)} \]

Frequency (kHz)

\[ \text{Measured} \]

\[ \text{Calculated} \]
Electrical NEP of microbolometer

$T=88.3 \text{ K, } f=10 \text{ kHz}$

- Electrical NEP is G-noise limited.
- $R = 6\Omega \Rightarrow$ transformer - coupled.
- Optical efficiency measurements in progress.
Conclusions

- High $T_c$ bolometers have a future for applications where cooling is limited.

- Best opportunities are for $\lambda \geq 15 \, \mu m$.

- Require highest materials quality on the "right" substrates.

- We have made conventional bolometers and microbolometers with performance approaching theoretical predictions.
PYROELECTRIC DETECTORS

Eugene E. Haller, J. Beeman and W.L. Hansen

Lawrence Berkeley Laboratory and University of California at Berkeley
1 Cyclotron Road, Berkeley, California 94720

and

G. Scott Hubbard and R.E. McMurray, Jr.

NASA Ames Research Center, Moffett Field, California 94035

The multi-agency, long-term Global Change programs, and specifically NASA's Earth Observing system, will require some new and advanced photon detector technology which must be specifically tailored for long-term stability, broad spectral range, cooling constraints, and other parameters. Whereas MCT and GaAs alloy based photovoltaic detectors and detector arrays reach most impressive results to wavelengths as long as 12 μm when cooled to below 70 K, other materials, such as ferroelectrics and pyroelectrics, appear to offer special opportunities beyond 12 μm and above 70 K. These materials have found very broad use in a wide variety of room temperature applications. Little is known about these classes of materials at sub-room temperatures and no photon detector results have been reported. From the limited information available we conclude that the room temperature values of $D^* \gtrsim 10^9$ cm Hz$^{1/2}$/W may be improved by one to two orders of magnitude upon cooling to temperatures around 70 K. Improvements of up to one order of magnitude appear feasible for temperatures achievable by passive cooling.

The flat detector response over a wavelength range reaching from the visible to beyond 50 μm, which is an intrinsic advantage of bolometric devices, makes for easy calibration. The fact that these materials have not been developed for reduced temperature applications makes ferro- and pyroelectric materials most attractive candidates for serious exploration.
PYROELECTRIC MATERIALS
AND DETECTORS

Eugene E. Haller, J. Beeman and W.L. Hansen
Lawrence Berkeley Laboratory
and University of California at Berkeley
1 Cyclotron Road, Berkeley, CA 94720

and

G. Scott Hubbard and R.E. McMurray, Jr.
NASA Ames Research Center
Moffett Field, CA 94025

Contents

• Introduction

• Thermal Detectors

• Pyroelectric Devices
  – Operation below $T_c$
  – Operation above $T_c$ with an applied DC bias

• Materials Properties

• Summary
INTRODUCTION

- Global Change programs, including NASA's Earth Observing System (EOS) require a variety of detectors which can:
  - cover a broad spectral range from the visible to the LWIR and beyond
  - operate at temperatures $\geq 65$ K in actively cooled instruments
  - operate at temperatures $\geq 120$ K in passively cooled instruments
  - have long term stability
  - utilize simple and reliable calibration procedures
  - be integrated into imaging arrays

- Thermal detectors, including bolometers and pyroelectric detectors, fulfill a large number of the above requirements

- Operation of thermal detectors in the above given temperature ranges has not been explored in detail
THERMAL DETECTORS

- Basic parameters and equations:

  - Heat capacity \( H = \frac{dE}{dT} \) (J K\(^{-1}\))

  - Heat conductance \( G = \frac{dP}{dT} \) (W K\(^{-1}\))

    with \( E \) = total energy
    \( P \) = power
    \( T \) = temperature

  - Thermal circuit:

    \[ \eta P = H \frac{d\theta}{dt} + G \theta \]

    with \( \eta \) = quantum efficiency (fraction of incident power absorbed by detector)

    \( \theta \) = average temperature rise of the detector
    i.e. \( T_D = T_0 + \theta \)

    \( t \) = time

    for a radiation source with

    \( P = P_0 + P_\omega e^{i\omega t} \)

    one finds:

    \[ \theta_\omega = \eta P_\omega \left( G^2 + \omega^2 H^2 \right)^{-1/2} \]

    \[ \varphi = \tan^{-1}\left( \frac{\omega H}{G} \right) \]
thermal time constant

$$\tau_T = \frac{H}{G}$$

minimum value of $G$:

$$G_{\text{min}} = G_{\text{radiative}} = 4 \, A \eta \sigma T^3$$

with $A = \text{detector area}$

$$\sigma = \text{Stefan-Boltzmann constant}$$

$$(= 5.67 \times 10^{-12} \, \text{W cm}^{-2} \, \text{K}^{-4})$$

- **Background limited performance:**

  - Power fluctuation through thermal link:

    $$\Delta W_T = (4kT^2G)^{1/2}$$

  - Minimum detectable signal power $P_N$:

    $$\eta P_N = \Delta W_T = (16A \eta \sigma kT^5G)^{1/2}$$

    or $P_N = (16A \sigma kT^5/\eta)^{1/2}$

    $$P_N = (16A \sigma kT^5)^{1/2} = 5 \times 10^{-10} \, \text{W} \, \text{at} \, T=300 \, \text{K}$$

    (for 1 Hz bandwidth, $A = 1 \, \text{cm}^2$, 2$\pi$ field of view and $\eta = 1$)

    $$P_N \, (T=200 \, \text{K}) = 2 \times 10^{-11} \, \text{W}$$

    $$P_N \, (T=100 \, \text{K}) = 3.5 \times 10^{-12} \, \text{W}$$

    (equivalent to $D^* = 2.86 \times 10^{11} \text{cm} \sqrt{\text{Hz} \, \text{W}^{-1}}$)
PYROELECTRIC DEVICES

- Pyroelectric devices are thermal detectors
- No fundamental limits for wavelength of photons to be detected
- Flat wavelength response makes for easy calibration

- Figures of merit:
  - Pyroelectric coefficient:
    \[ p = \frac{dP_s}{dT} \]
    \( P_s \) = spontaneous polarization
  - pyroelectric current
    \[ I_p = A p \frac{dT}{dt} \]
  with:
  - \( c \) = volume specific heat
  - \( d \) = thickness of the detector
  - current responsivity:
    \[ R_i = \frac{I_p}{P_s} = \frac{n \pi A \omega}{G \left( 1 + \omega^2 \tau_T^2 \right)^{1/2}} \]
    at low frequencies \( \left( \omega \ll \tau_T^{-1} \right) \)
    \[ R_i \propto \omega \]
    at high frequencies \( \left( \omega \gg \tau_T^{-1} \right) \)
    \[ R_i = \frac{n \pi A}{H} = \frac{n \pi p}{c d} \]
Incident radiation (power $W/(t)$)

Electrode (area $A$, emissivity $\eta$)

Schematic diagram of a pyroelectric radiation detector.

(From R. W. Whatmore, Rep. Prog. Phys. 49, 1335 (1986), Fig. 5)

- voltage responsivity:

$$R_v = \frac{I_p}{V_P} = \frac{R \eta p A \omega}{G \left(1 + \omega \tau_T \right)^{1/2}} \left(1 + \omega \tau_E \right)^{1/2}$$

with $Y = R^{-1} + i\omega C$; $R =$ total input resistance, $C =$ total input capacitance, $\tau_E = R C$

- at high frequencies ($\omega >> \tau_T^{-1}, \tau_E^{-1}$):

$$R_v = \frac{\eta p}{C \varepsilon \varepsilon_o A \omega}$$

Pyroelectric material figure of merit:

$$F_v = \frac{p}{C \varepsilon \varepsilon_o}$$

(The larger $F_v$, the closer we can approach $D_{BLIP}$)

Pyroelectrics have a relative dielectric constant $\varepsilon$ which is temperature dependent. With a DC electric field $E$ applied one finds:

$$p = \frac{dD}{dT|_E} = \left(\frac{dP}{dT|_E}\right) + \frac{d\varepsilon}{dT|_E} E$$

Of special interest are ferroelectrics operated above $T_C$. Dielectric losses approach zero in this range.
Temperature dependence of the merit figure $F_v$ for some members of the TGS family.

Temperature dependence of $F_v$ in DTGFB at a normal cut and in a cut perpendicular to a direction that forms an angle of 74° with the pyroelectric axis (after Shaulov 1981).

(after R.W. Whatmore, Rep. Prog. Phys. 49, 1335 (1986), Figs. 15 (upper) and Fig. 16 (lower))
**MATERIALS PROPERTIES**

- Triglycine sulphate family (TGS) at room temperature:

  \[ p: \quad 5.5 - 7.0 \times 10^{-4} \text{Cm}^{-2} \text{K}^{-1} \]

  \[ \varepsilon: \quad 30 - 60 \]

  dielectric loss tangent at 1 kHz: 0.02 (typical)

  \[ c: \quad 2.5 \times 10^6 \text{J cm}^{-3} \text{K}^{-1} \]

  \[ F_V: \quad 0.4 - 0.6 \text{ m}^2 \text{C}^{-1} \]

  for room temperature application the TGS family offers the best set of materials properties

- Polar materials at 25°C

\[ F_V: (\text{m}^2 \text{C}^{-1}) \]

- Polyvinilidyne fluoride (PVDF) 0.1
- Li TaO₃ 0.17
- \( \text{Sr}_x\text{Ba}_{1-x}\text{Nb}_2\text{O}_6 \) (0.25 < \( x \) < 0.75) 0.07
- Lead zirconates (PZ) 0.06
- Improper ferroelectrics \( \leq 0.5 \)
Temperature dependence of $F_v$ in selected improper ferroelectrics (after Shaulov et al 1980).

Effect of DC bias on dielectric constant as a function of temperature in Pb(Zn$_{1/3}$Nb$_{2/3}$)O$_3$ (after Yokomizo et al 1970). ●, zero bias; ○, 3 kV cm$^{-1}$; ▲, 7 kV cm$^{-1}$; △, 11 kV cm$^{-1}$; □, 25 kV cm$^{-1}$.

(after R.W. Whatmore, Rep. Prog. Phys. 49, 1335 (1986), Fig. 22 (upper) and Fig. 23 (lower))
- **Pyroelectrics under DC bias**
  
  - above $T_c$ we find:
    
    $$ p = \left. \frac{d\varepsilon}{dT} \right|_{E} E $$
  
  - $T_c$ can be engineered through alloy formation:
    
    e.g. $\alpha$ Ta$_x$ Nb$_{1-x}$ O
  
  - at temperatures near the zero field $T_c$, both
    
    $$ \frac{dP}{dT} \quad \text{and} \quad \frac{d\varepsilon}{dT} $$
    
    increase with the applied DC
  
  - dielectric losses above $T_c$ vanish

- **Pyro and Ferroelectric Materials with**
  
  100 K < $T_c$ < 200 K

  - KDP (Potassium dihydrogen phosphate) family:
    
    $T_c$ depends on the specific chemical composition

  - KTN (Potassium tantalum niobium oxide) family:
    
    $T_c$ can be adjusted to any given temperature between 0 and 500 K by alloying. This materials system is fully miscible.
Temperature dependences of the spontaneous polarization of KH$_2$PO$_4$ type ferroelectrics.

(From T. Mitsui et al., "An Introduction to the Physics of Ferroelectrics", Gordon and Breach 1984)

D. RYTZ, A. CHATELAIN, AND U. T. HÖCHLI

Temperature dependence of the static dielectric constant $\varepsilon$ with concentration $x$ as a parameter. The data were obtained by a conventional bridge technique at 1 kHz. The temperature was changed at a rate of no more than 0.5 K/min. Note the change on the temperature scale for $x=0.057$.

(From D. Rytz et al., Phys. Rev. B27, 6830 (1983), Fig. 3)
SUMMARY

- Bolometric detection has specific advantages such as:
  - response to photon power unlimited by the photon wavelength
  - ease of calibration

- Background limited $D^* (100 \text{ K})$

$$= 2.86 \times 10^{11} \text{ cm} \sqrt{\text{Hz W}^{-1}};$$ this appears sufficient for a number of remote sensing applications, possibly including EOS LWIR focal plane arrays

- Passively cooled systems can make use of pyro- and ferroelectrics

- The critical temperature of pyroelectrics near which highest performance is achieved, can be engineered through alloying

- Low temperature pyro- and ferroelectrics offer great potential for exploratory research
A novel electron tunneling infrared detector

T.W. Kenny, S.B. Waltman, J.K. Reynolds, and W.J. Kaiser
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

All thermal detectors of infrared radiation include the following components: An absorber of infrared radiation converts the incoming photons to heat, producing a temperature rise in the detector. A thermo-electric transducer converts the change in the temperature of the detector to an electrical signal. The detector is connected to a temperature reference by a finite thermal conductance, G. Given the efficiency of the infrared absorber, the temperature coefficient of the thermo-electric transducer, the thermal conductance to the temperature reference and the heat capacity of the detector, the performance of the device may be fully characterized. Useful thermal detectors require the existence of sensitive thermo-electric transducers that operate at the required temperature with low heat capacity. If the sensitivity of the transducer is high enough, the performance of the detector is limited by thermal fluctuations, for which the Noise Equivalent Power (NEP) is given by $\sqrt{4kT^2G}$.

The pneumatic infrared detector, originally developed by Golay in the late 1940s, uses the thermal expansion of one cm$^3$ of xenon at room temperature to detect the heat deposited by infrared radiation. This detector was limited by thermal fluctuations within a 10 Hz bandwidth, but suffered from long thermal time constants and a fragile structure. Nevertheless, it represents the most sensitive room temperature detector currently available in the LWIR. Fabrication of this type of detector on smaller scales has been limited by the lack of a suitably sensitive transducer.

We have designed a detector based on this principle, but which is constructed entirely from micromachined silicon, and uses a vacuum tunneling transducer to detect the expansion of the trapped gas. Because this detector is fabricated using micromachining techniques, miniaturization and integration into one and two-dimensional arrays is feasible. The extreme sensitivity of vacuum tunneling to changes in electrode separation will allow a prototype of this detector to operate in the limit of thermal fluctuations over a 10 kHz bandwidth. A calculation of the predicted response and noise of the prototype is
presented within the general formalism of thermal detectors. Although the prototype
electron tunneling infrared detector has not been designed to optimize the sensitivity, it
should feature an NEP as low as $6 \times 10^{-11}$ W/$\sqrt{\text{Hz}}$ for a 1 mm$^2$ active area while operating
at room temperature. Some design changes that will allow reductions in the NEP by as
much as another order of magnitude for a 1 mm$^2$ area will be discussed. The dependence
of the characteristics upon the area of the detector will also be discussed.

At present, most of the components of the prototype have been fabricated and tested
independently. In particular, a characterization of the micromachined electron tunneling
transducer has been carried out. The measured noise in the tunnel current is within a
decade of the limit imposed by shot noise, and well below the requirements for the
operation of an infrared detector with the predicted sensitivity. Assembly and
characterization of the prototype infrared detector will be carried out promptly.

The work described in this paper was performed by the Center for Space
Microelectronics Technology, Jet Propulsion Laboratory, California Institute of
Technology and was sponsored by the Defense Advanced Research Projects
Agency/Information Science and Technology Office and the Strategic Defense Initiative
Organization/Innovative Science and Technology Office through agreements with the
National Aeronautics and Space Administration (NASA).
A Novel Electron Tunneling Infrared Detector

T.W. Kenny, S. B. Waltman, J.K. Reynolds, and W.J. Kaiser

Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

• General Considerations
• Electron Tunneling Thermo-electric Transducer
• Design and Analysis
• Conclusions

Research Supported by DARPA and SDIO/IST

IR Detector Classification

Quantum Detectors

• Incoming photons are converted to excited carriers in a semiconducting structure.

• The carriers propagate ballistically over barriers in the band structure and are counted. The barriers block the thermally generated carriers.

Thermal Detectors

• Incoming photons are converted to heat.

• The heat is detected by a change in temperature of a thermally sensitive element.
Thermal Infrared Detector Requirements

- Infrared Absorber
  Converts incoming radiation to heat.
  Should have low heat capacity and high efficiency.

- Thermo-Electric Transducer
  Converts change in temperature to electrical signal.
  Should have low heat capacity and high conversion coefficient.

- Thermal Conductance
  Connects detector to temperature reference.
  Usually used to provide mechanical support and electrical contact.

![Diagram of Absorber Transducer Conductance Sink](image)

Existing Thermal Detectors

- Bolometers
  Use temperature-dependent resistance of semiconductor or superconductor as thermo-electric transducer.
  Limited by availability of large resistance variations.
  State of the art detector for λ > 100 μm.

- Pyroelectrics and Thermoelectrics
  Use temperature-dependent potential which occurs due to pyroelectric or thermoelectric effect.
  Difficult to fabricate with low heat capacity and thermal conductance.
  Most convenient technology for room-temperature detection in the LWIR.

- Pneumatics
  Use thermal expansion of gas at STP coupled with mechano-electrical transducer. Requires production of thin, flexible membrane.
  Small detectors limited by transducer sensitivity.
  Most sensitive room-temperature detector in the LWIR.
Improving the Pneumatic Infrared Detector

Use silicon micromachining to fabricate sensor components.

- Photolithographic techniques allow μm-scale precision.
- Use single crystals of silicon as raw material.
- Free-standing silicon oxy-nitride membranes may be used.
- Miniaturization of sensor components to less than 100 μm.
- Eventual integration of sensor and electronics possible.

Problem:

As the area of the pneumatic detector is reduced, the capacitive transducer becomes less sensitive.

Solution:

Find a more sensitive transducer technology.

Electron Tunneling

- In the early 1980s, Binnig and Rohrer at IBM invented a new technique, Scanning Tunneling Microscopy (STM), for studying the structure of surfaces with atomic-scale resolution.

- In STM, a 'Tip' is positioned several Angstroms above the surface of interest. With the application of a voltage bias between the tip and the surface, a small tunneling current is observed.

- According to Quantum Mechanics, the probability for tunneling of individual electrons across the barrier depends exponentially on the thickness of the barrier, which is the separation between the electrodes in this case.

- For the conditions common to STM experiments, the tunnel current varies by an order of magnitude for each Å change in the electrode separation.

- This extreme sensitivity to changes in separation could be useful in an electro-mechanical transducer.
Transducer Sensitivity Comparison

Capacitive Motion Transducer

- Active area: 10 μm x 10 μm
- Voltage: 1 Volt
- Frequency: 200 kHz

<table>
<thead>
<tr>
<th>Separation</th>
<th>Capacitance</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 μm</td>
<td>0.88 fF</td>
<td>1.1 nA</td>
</tr>
</tbody>
</table>

1 % change in current represents a 90 Å change in separation.

Electron Tunneling Motion Transducer

- Active area: 10 Å x 10 Å
- Voltage: 100 mV
- Frequency: 10 Hz - 10 kHz

<table>
<thead>
<tr>
<th>Separation</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Å</td>
<td>1 nA</td>
</tr>
</tbody>
</table>

1 % change in current represents a 0.004 Å change in separation.

Prototype Tunnel Sensor

- Piezoelectric Bimorph as actuator.
- Rigid mechanical structure.
Design of the Micromachined Infrared Tunnel Sensor

- Air-filled cavity bounded on one side by 0.5 μm silicon oxy-nitride membrane.
- 80 Å Au film used as IR Absorber and tunneling electrode.
- Folded silicon cantilever spring with integral tip.
- Electrostatic deflection used to control electrode separation.

Design Parameters for the Prototype Infrared Tunnel Sensor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>$A = 10^{-2}$ cm²</td>
</tr>
<tr>
<td>Thermal conductance between membrane and surroundings:</td>
<td></td>
</tr>
<tr>
<td>Dominated by air in cavity</td>
<td>$G = 2 \times 10^{-4}$ W/K</td>
</tr>
<tr>
<td>Heat capacity of membrane and gas</td>
<td>$C = 8 \times 10^{-7}$ J/K</td>
</tr>
<tr>
<td>Dominated by membrane</td>
<td></td>
</tr>
<tr>
<td>Time constant (C/G)</td>
<td>$\tau = 4 \times 10^{-3}$ s</td>
</tr>
<tr>
<td>Response coefficient of thermo-electric transducer:</td>
<td>$\alpha = 2.3 \times 10^4$ /K</td>
</tr>
<tr>
<td>$\alpha = \frac{1}{T} \frac{dT}{dz}$</td>
<td></td>
</tr>
<tr>
<td>Detector responsivity :</td>
<td>$S = 0.38$ A/W</td>
</tr>
<tr>
<td>$S = \frac{1}{(G^2 + (\omega C)^2)^{1/2}}$</td>
<td></td>
</tr>
</tbody>
</table>
Fundamental Noise in the Tunnel IR Detector

\[(NEP)^2 = 4k_B T^2 G + 16Aσk_B T^5 + \frac{2eI(G^2 + (ωC)^2)}{I^2α^2} + \frac{I_n^2(G^2 + (ωC)^2)}{ωI^2α^2}\]

- Since $α$ is very large in this detector, the electron and amplifier noise terms are only important for frequencies $ω >> 1/τ$.

- At low frequencies, the phonon noise dominates. Improvements can only be obtained through reductions in $G$.

- The prototype Tunnel IR Detector is expected to have NEP of $6 \times 10^{-11}$ W/√Hz at frequencies below 10 kHz.

Calculated Contributions to the NEP

![Graph showing contributions to NEP over frequency]
Sensor Construction: Present Status

- Micromachined Springs: Fabricated
- Micromachined Tips: Fabricated
- Free-Standing Silicon Oxy-Nitride Membrane: Fabricated
- Metallization: Complete
- Transducer Characterization: Almost Complete
- Infrared Sensor Assembly: Next
- Sensor Characterization

Measured Current Noise

![Current Noise Chart]

Measur'd Current Noise

\[ \text{Current Noise (A/Hz}^{1/2}) \]

- \(4 \times 10^{-10} \text{ cm/}\sqrt{\text{Hz}}\)
- \(4 \times 10^{-11} \text{ cm/}\sqrt{\text{Hz}}\)
- \(4 \times 10^{-12} \text{ cm/}\sqrt{\text{Hz}}\)
- \(4 \times 10^{-13} \text{ cm/}\sqrt{\text{Hz}}\)
- \(4 \times 10^{-14} \text{ cm/}\sqrt{\text{Hz}}\)

Frequency (Hz)
Speculations

The NEP of the Tunneling IR Detector can be improved by reducing the thermal conductance to the heat sink as follows:

- Replace the air in the cavity with Xenon.
- Increase thickness of cavity to 400 μm
- Reduce the cavity area to 500 μm x 500 μm.

Combined effect is to reduce NEP by a factor of approximately 6.

Further reductions in the NEP of the prototype IR Tunnel Sensor are constrained by the thermal contact to the walls of the cavity, which act as a heat sink.

By vacuum-encapsulating a 'bag' of gas, the thermal conductance may be reduced much further. Improvements in the NEP of more than an order of magnitude are likely.

Vacuum-Encapsulated IR Sensor

- Air-filled silicon oxy-nitride balloon supported by silicon oxy-nitride ribbons.
- Au film on balloon for IR absorption and tunneling electrode.
- Active area = 50 mm x 50 mm.
- Thermal conductance to heat sink limited by ribbons : G = 16 nW/K
- Predicted NEP is limited by background fluctuations (BLIP Limit)
Conclusions

- We have designed a device based on the Pneumatic Infrared detector, but which is constructed entirely from micromachined silicon and uses a vacuum tunnel sensor to detect the expansion of the trapped gas.

- A calculation of the performance of this device, which is based only on thermal physics and the known characteristics of tunneling has been carried out.

- The performance of the prototype is expected to meet or exceed that of all room temperature detectors which operate in the LWIR.

- Fabrication and characterization of the components of the detector is under way.

- Simple modifications to the design of the prototype can improve its NEP by a factor of 6. More complicated modifications can lead to more substantial improvements in the NEP.
SESSION V: III-V Quantum Well and Heterojunction Detectors

V - 1 Quantum Well Infrared Photodetectors (QWIP)
   B.F. Levine, AT&T Bell Laboratories

V - 2 Photovoltaic Quantum Well Infrared Detectors
   S.A. Lyon, Princeton University

V - 3 Characteristics of AlGaAs/GaAs Multiple Quantum Well Infrared Detectors
   B.K. Janousek, The Aerospace Corporation

V - 4 Resonant Tunneling IR Detectors
   J.M. Woodall, IBM

V - 5 Low Dark Current Photovoltaic Multiquantum Well Long Wavelength
   Infrared Detectors
   C.S. Wu, Hughes Aircraft Company

V - 6 Fundamental Limits to Performance of Quantum Well Infrared Detectors
   A. Yariv, California Institute of Technology

V - 7 New Heterojunction LWIR Detector Options
   J. Maserjian, Jet Propulsion Laboratory
Quantum Well Infrared Photodetectors (QWIP)

B. F. Levine
AT&T Bell Laboratories
Murray Hill, NJ 07974

There has been a lot of interest in III-V long wavelength detectors in the $\lambda = 8 - 12 \, \mu m$ spectral range as alternatives to HgCdTe. Recently high performance quantum well infrared photodetectors (QWIP) have been demonstrated. They have a responsivity of $R = 1.2 \, A/W$, and a detectivity $D^*_\lambda = 2 \times 10^{10} \, cm \, Hz^{1/2} / W$ at 68 K for a QWIP with a cutoff wavelength of $\lambda_c = 10.7 \, \mu m$ and a $R = 1.0 \, A/W$, and $D^*_\lambda = 2 \times 10^{10} \, cm \, Hz^{1/2} / W$ at $T = 77 \, K$ for $\lambda_c = 8.4 \, \mu m$. These detectors consist of 50 periods of MBE grown layers doped $n = 1 \times 10^{18} \, cm^{-3}$ having GaAs quantum well widths of 40 Å and barrier widths of 500 Å of Al$_x$Ga$_{1-x}$As.

Due to the well-established GaAs growth and processing techniques these detectors have the potential for large, highly uniform, low cost, high performance arrays as well as monolithic integration with GaAs electronics, high speed and radiation hardness.

Our latest results on the transport physics, device performance and arrays will be discussed.

Quantum Well Infrared Photodetectors

QWIP

Research

B. F. Levine
C. G. Bethea
S. D. Gunapala
R. J. Malik
G. Hasnain

Government Systems

C. L. Allyn
V. O. Shen

Development

P. J. Anthony
W. A. Gault
J. W. Stayt
K. G. Glogovsky
R. A. Morgan
Y. M. Wong
M. T. Asom
S. J. Hsieh
R. M. Braun

LWIR GaAs Quantum Well Detectors

Esaki, Sakaki
Smith, Chiu, Margalit, Yariv, Cho
Coon, Karunasiri
Goosen, Lyon
Capasso, Mohammed, Cho
Kastalsky, Duffield, Allen, Harbison
Janousek, Daugherty, Bloss, Rosenbluth,
O'Loughlin, Kauter, DeLuccia, Perry
Woodall
Wu, Sato, Wen
Maserjian
Döhler
Mii, Karunasiri, Wang, Bai
Abstreiter et al.
MATERIAL FOR 10 μm DETECTORS
HgCdTe DETECTORS

• DIFFICULT GROWTH AND PROCESSING TECHNOLOGY
• POOR UNIFORMITY OF ARRAYS
• LOW QUALITY CdTe SUBSTRATES

GaAs DOPED QUANTUM WELL DETECTORS

• PERFORMANCE COMPARABLE TO HgCdTe
• MATURE GROWTH AND PROCESSING TECHNOLOGY
• EXCELLENT 3” GaAs SUBSTRATES
• MONOLITHIC INTEGRATION WITH GaAs ELECTRONICS

MONOLITHICALLY INTEGRATED
GaAs QUANTUM WELL DETECTOR ARRAY
AND IMAGE PROCESSING ELECTRONICS
VERTICALLY INTEGRATED GaAs QUANTUM WELL INFRARED SPECTROMETER

INFRARED RADIATION

RESPONSIVITY

WAVELENGTH $\lambda$ (\mu m)

SUBSTRATE

GaAs WELL

$V, \tau$

40 Å GaAs WELL

300 Å $Al_{0.31}Ga_{0.69}As$ BARRIER

VERTICALLY INTEGRATED GaAs QUANTUM WELL INFRARED SPECTROMETER

INFRARED RADIATION

$V_1$, $V_2$, $V_3$
\[ V_b = 3V \]
\[ T = 77K \]

WAVELENGTH \( \lambda \) (\( \mu \text{m} \))

\[ L_b = 500 \AA \]

WAVELENGTH \( \lambda \) (\( \mu \text{m} \))
DARK CURRENT CALCULATION

\[ n(V) = \frac{m^*}{\pi \hbar^2 L_p} \int_{E_0}^{\infty} f(E)T(E)dE \]

\[ E > E_b \text{ Thermionic} \]

\[ E < E_b \text{ Tunneling} \]

\[ I_D = nevA \]
Bias Voltage, $V_b$ (V)

Dark Current, $I_d$ (A)

Temperature

$\lambda_C = 8.4 \mu m$

$\lambda_C = 10.7 \mu m$
\[ \lambda_c = 10.7 \ \mu m \]

\[ D^* = 1 \times 10^{10} \ \text{cm} \sqrt{\text{Hz}} / \text{W} \]

\[ T = 68 \ \text{K} \]

\[ \lambda_c = 10 \ \mu m \]

\[ D^*(\text{theory}) > 10^{10} \ \text{cm} \sqrt{\text{Hz}} / \text{W} \]

\[ T = 77 \ \text{K} \]
LWIR

(a)

SAWTOOTH GRATING
n⁺ GaAs CONTACT LAYER
GaAs/AlGaAs
MULTI-QUANTUM WELL
Au/Ge

SEMI-INSULATING GaAs SUBSTRATE

(b)

SAWTOOTH GRATING
n⁺ GaAs CONTACT LAYER
GaAs/AlGaAs
MULTI-QUANTUM WELL
Au/Ge

SEMI-INSULATING GaAs SUBSTRATE

LWIR

RESPONSIVITY (A/W)

45°

GRATING

(a)

(b)

WAVELENGTH (μm)

219
a) ZERO BIAS

b) FORWARD BIAS

c) REVERSE BIAS
\[ \lambda = 13.5 \, \mu m \]

50 Å/500 Å GaAs/Al_{0.2}Ga_{0.8}As

Optical Gain

\[ g = \frac{\tau_L}{\tau_T} = \frac{L}{\ell} \]
Go

As,

0.5 μm CONTACT LAYER

Au-Ge CONTACTS

SEMI-INSULATING GaAs SUBSTRATE

WAVELENGTH (μm)

20 QW

0.4 V

2 QW

T = 25K

2 QW @ 0.4V

20 QW @ 2.8V

RESPONSIVITY (A/W)

WAVELENGTH (μm)

0.0

0.1

0.2

0.3

0.4
\[ \text{NEAT} = \frac{(A\Delta f)^{1/2}}{D^* D_B (dP_B/dT) \sin^2(\theta/2)} \]

\[ A = (50 \mu m)^2 \]

\[ \Delta f = 60 \text{ Hz} \]

\[ f/2 \text{ optics (}\theta/2 = 14^\circ) \]

\[ D^* = 1 \times 10^{10} \text{ cm} \sqrt{\text{Hz/W}} \]

\[ \text{NEAT} = 0.01 \text{ K} \]
ARRAY NONUNIFORMITY

To Obtain Background Limited Array Performance

\[ U < \frac{1}{\sqrt{N}} \]

\( U \) = uniformity

\( N \) = number of photoelectrons

\( N = 10^6 \Rightarrow U < 0.1\% \)

\[ (\text{NEAT})_U = \frac{T_B^2 \lambda U}{1.44} \]

\( T_B = 295 \text{ K}, \; \lambda = 10 \mu \text{m}, \; U = 0.1\% \)

\( (\text{NEAT})_U = 0.06 \text{ K} \)
64 X 64 ARRAY 50 \( \mu \text{m} \) PIXELS
Conclusions

- Demonstrated detectors having $\lambda_c = 4 - 13.5 \, \mu m$
- Spectral width $\Delta \nu/\nu = 13\% - 36\%$
- $D_{BB}^* = 1 \times 10^{10} \, \text{cm} \sqrt{\text{Hz}/\text{W}} \quad T = 68 \, \text{K} \quad \lambda_c = 10.7 \, \mu m$
- $D_{BB}^* = 3 \times 10^{10} \, \text{cm} \sqrt{\text{Hz}/\text{W}} \quad T = 77 \, \text{K} \quad \lambda_c = 8.4 \, \mu m$
- $D_{BB}^* = 1 \times 10^{13} \, \text{cm} \sqrt{\text{Hz}/\text{W}} \quad T < 40 \, \text{K} \quad \lambda_c = 10.7 \, \mu m$
- $D^*$ sufficiently large (arrays uniformity limited)
- Calculated dark current (thermionic, tunneling)
- Hot electron continuum transport resonances
- High speed $\tau < 200 \, \text{psec}$
- Optical gain
- Graded barrier tunable spectral response
- Demonstrated grating detectors
- High uniformity
- Large arrays
- Camera demonstration
Quantum well infrared photodetectors are a promising new approach to long-wavelength infrared detector arrays. Both single-well photovoltaic and multiple-well photoconductive devices have been demonstrated. I will discuss noise considerations as they apply to photovoltaic devices, grating coupling of the infrared light into QWIPs, and recently demonstrated electrically tunable detectors. The use of "light trapping" to enhance the quantum efficiency and reduce cross-talk in an array will also be addressed.
LONG WAVELENGTH QUANTUM WELL DETECTORS
(Quantum Well Infrared Photodetectors) = QWIP's

S. A. Lyon

Electrical Engineering, Princeton

Theory & Measurements

Keith Goossen – now at AT&T Bell Labs
Sanjay Parihar – Princeton

Materials

Kambiz Alavi (Siemens) – now at U. of Texas
Mike Santos & Mansour Shayegan – Princeton

I. Background on IR detectors and Quantum Wells
II. Single Well detectors
III. Grating enhanced detectors
VI. Voltage Tunable Detectors
V. Summary

QUANTUM WELL DETECTOR

Advantages:
— Easily change structure for different wavelengths
— Long wavelength sensitivity with simple materials
— Voltage tunable

Problems:
— Not many electrons ⇒ low quantum efficiency
— Short relaxation time (intersubband scattering)
  ⇒ high dark current

ALGaAs

CB

E_0

hv

E_1

E_0

A
Conduction Band

Valence Band

\[ \text{Absorption} \]
\[ E_g \quad \text{Photon Energy} \]

Band-to-Band

\[ E \]
\[ E_1 \]
\[ E_0 \]

\[ Z \]

Quantum Well (Intersubband)

\[ \Delta E \quad \text{Photon Energy} \]

\[ \phi \rightarrow 90° \Rightarrow \theta 
\]

\[ \sim 20° \]

\[ \text{GaAs} \]

\[ \text{Al}_{y}\text{Ga}_{1-y}\text{As} \]

\[ \text{GaAs} \]

\[ \text{Al}_x\text{Ga}_{1-x}\text{As} \]

\[ \text{Al} \]

\[ \text{In} \]
DARK CURRENT (IDEAL)

Use Richardson -Dushman approach

1. Find the rate of electron capture by the well in thermal equilibrium

2. This will also be the emission rate $\Rightarrow$ dark current under small biases

3. Assume relaxation time of 1 ps

* Unlike usual assumption for a metal:
  - Capture probability $< 1$
  - Capture probability depends on energy

Dark current $\sim$100x less for QW than metal

Work function $\sim (E_1 - E_f)$ not $(V - E_f)$
STARING ARRAY COMPARISON

50 X 50 μm Pixel F2 Optics
30 ms frame (integration) time
T_{Detector} = 80K T_{Background} = 300K
10 μm

Ideal band-to-band detector

Single Well QWIP

τ - Auger Limited (Parameters for HgCdTe)

| Signal (e~/cm^2·sec) | 3 x 10^{16} | 3 x 10^{13} |
| Dark Current (e~/cm^2·sec) | 1.0 x 10^{14} | 1.5 x 10^{15} |
| Signal/Noise | 1.2 x 10^{5} | 1 x 10^{3} (NETD = 0.1K) |

τ - Intersubband Scattering

IMPROVING QUANTUM EFFICIENCY

1. Multiple Wells

Absorption ∝ # wells

Dark Noise ∝ \sqrt{# wells} (ideal)

\therefore D^* ∝ \sqrt{# wells}

2. "Light Trapping"

Surface Plasmons on gratings

Waveguiding in GaAs
WAVEGUIDING

K. W. Goossen, S. A. Lyon, and K. Alavi
WAVEGUIDING

Infrared

GaAs Substrate

Low Index Layer (AlAs)

AlGaAs

GaAs Well

AlGaAs

Contact to Well

Metal Grating

Out
PLASMON ENHANCEMENT

K. W. Goossen and S. A. Lyon

SURFACE PLASMON EXCITATION

\[ \lambda = 10.16 \, \mu m \]
\[ a = 10.0 \, \mu m \]
TUNABLE DETECTOR

Actual Sample (Santos & Shayegan)

$Al_xGa_{1-x}As$

$GaAs$

$x = 0.4$

$Al_yGa_{1-y}As$

$y = 0.25$

$50\text{Å} 300\text{Å} 600\text{Å} 2000\text{Å}$
ENERGY SHIFT VS BIAS FOR GRADED WELL

$\Delta E$ (cm$^{-1}$)

Bias (V)

S. A. Lyon, MSS-4 (July 1989).
S. R. Parihar, S. A. Lyon, M. Santos and M. Shayegan

Transition Energy (meV)

Wavelength (μm)

Applied Electric Field (kV/cm)
CONCLUSIONS

1. Single-well QWIP's work as expected
   — Quantum Efficiency (~1/2 – 1%)
   — Dark Current

2. Incorporation of a diffraction grating allows operation at normal incidence

3. As a single element detector QWIP's cannot compete with photoconductive HgCdTe

4. Single-well QWIP's can compete in a staring array

5. Waveguiding shows promise for enhancing quantum efficiency without the noise penalty of multiple wells

6. Voltage tunable detectors have been demonstrated
   — Similar structures expected to show large optical nonlinearities
Characteristics of AlGaAs/GaAs Multiple Quantum Well Infrared Detectors

Bruce K. Janousek, Mary L. Rosenbluth, Michael J. O'Loughlin, Walter L. Bloss, Frank J. De Luccia, Helmut Kanter, L. Elaine Perry, and Michael J. Daugherty

The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009

We have fabricated and characterized several AlGaAs/GaAs multiple quantum well infrared detectors to evaluate the ultimate performance of these devices for low infrared background applications. The detectors were designed to have a single bound state in the quantum well and the first excited state in the continuum above the AlGaAs conduction band edge. The difference in energy between the two levels, as determined by the quantum well width and aluminum mole fraction in the barrier, was chosen such that peak absorption would occur near 8 \( \mu m \). The initial structures studied comprised 50 periods with 40 \( \AA \) well widths and 300 \( \AA \) Al\(_{0.28}\)Ga\(_{0.72}\)As barriers. The performance of these detectors can be summarized as follows:

1). Low dark current densities at 6K which are very sensitive to the device peak absorption wavelength (8.9 \( \mu m \) \( \Rightarrow \) 1E-06 A/cm\(^2\); 7.5 \( \mu m \) \( \Rightarrow \) 3E-08 A/cm\(^2\)).

2). Dark current activation energies (135-150 meV) in good agreement with the predicted quantum well transition energies.

3). Measured noise which is less than the predicted shot noise on the device dark current.

4). The absence of 1/f noise at frequencies down to 20 Hz.

5). Peak responsivities of approximately 0.3 A/W (uncorrected for reflection losses).

6). Peak detectivities in excess of 10\(^{12}\) cm\(\sqrt{Hz/W}\) at 6K.

7). Constant detectivity over the temperature range from 6K to approximately 50K.

To better interpret these results and design optimized detectors, we have modeled both the detector noise and tunneling currents. The noise model correctly predicts that multiple quantum well detectors will, indeed, exhibit noise lower than full shot noise. The tunneling current model predicts the dark current versus bias for any choice of design parameters in a multiple quantum well detector. This model predicts a substantially reduced dark current (x 10\(^{-4}\)) for samples with 400 \( \AA \) barriers.

To evaluate structures with thicker barriers, we have fabricated and characterized detectors with 400 \( \AA \) and 500 \( \AA \) barriers; a comparison of detector dark currents is shown in Fig. 1. These results are consistent with the predictions of our dark current model. Since the responsivity for these samples (0.3 A/W) is not compromised by the additional barrier width, these new devices have a significantly higher detectivity, as shown in Fig. 2 for the 400 \( \AA \) barrier sample where detectivities in excess of 10\(^{13}\) cm\(\sqrt{Hz/W}\) have been measured at temperatures above 30K. The behavior of this device as a function of temperature indicates that tunneling currents are no longer limiting the low-temperature performance of this device.
Fig. 1. Dark current density vs. bias at 6K for samples with 300Å, 400Å, and 500Å barriers.

Fig. 2. Detectivity vs. temperature for 400Å barrier sample.
Characteristics of AlGaAs/GaAs Multiple Quantum Well Infrared Detectors

B. Janousek, W. Bloss, M. Rosenbluth, M. O’Loughlin, H. Kanter, F. DeLuccia, L.E. Perry, and M. Daugherty

The Aerospace Corporation

Outline:

• Motivation
• Materials Preparation/Characterization
• Device Fabrication
• Detector Performance/Modeling Results
  • Noise, dark current models
  • Performance vs. barrier width
• Summary/Conclusions

Background/Motivation

• Aerospace role in IR detector development

• VG Semicon MBE machine operational January, 1989

• Are AlGaAs/GaAs quantum well IR detectors appropriate for low infrared background applications?

• What is the ultimate performance of these devices?
Approach

- Two wafers comprise the initial focus of this study:
  - Nominal structure: 40Å GaAs wells/300Å AlGaAs barriers (x=0.28) - 50 periods
  - Excited state in continuum above AlGaAs conduction band edge.
  - Predict ~ 8μm peak responsivity
    - Reproduce AT&T results?
    - Low-background, low temperature performance?
    - Noise sources?
- Additional structures grown to suppress device tunneling currents
  - 300Å, 400Å, 500Å barrier samples
FTIR Absorption Spectra of IR Quantum Well Samples

![FTIR Spectra Diagram]

Table of Measured Material Parameters

<table>
<thead>
<tr>
<th></th>
<th>041989-2</th>
<th>102089-4</th>
<th>010890-2</th>
<th>010890-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Wavelength (FTIR)</td>
<td>8.9µm</td>
<td>7.5µm</td>
<td>8.5µm</td>
<td>8.3µm</td>
</tr>
<tr>
<td>Superlattice Period (x-ray)</td>
<td></td>
<td>346Å</td>
<td>528Å</td>
<td>432Å</td>
</tr>
<tr>
<td>Superlattice Period (TEM)</td>
<td></td>
<td>320Å</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Mole Fraction (x-ray)</td>
<td>.35</td>
<td>.31</td>
<td>.31</td>
<td></td>
</tr>
<tr>
<td>Al Mole Fraction (Modulation Spectroscopy)</td>
<td>.29</td>
<td>.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IR Detector Fabrication

MBE Growth → Photoresist + Expose + Develop → Etching of Mesas

Metal Liftoff → Metal Deposition - AuGe/Ni/Au → High Temperature Alloy +Redeposition of Au

Photoresist + Expose + Develop → Angle Lapping + Wire Bonding

Graphical representation:

**** GRAPHICS PLOT ******
041989-2 5K

J ( )

1E-03

decade /div

1E-10
-6.000

VF
0
1.200/div (V)
6.000

Electronics Research Laboratory
THE AEROSPACE CORPORATION
Arrhenius Plots of Detector Dark Current

R and D* vs. Wavelength (6K) - Sample 041989-2
R and D* vs. Wavelength (6K) - Sample 102089-4

Spectral Noise Density vs. Dark Current (7K) - Sample 041989-2
Noise Model

- tunneling events are independent
- governed by Poisson statistics

Input parameters:
- Fraction of total tunneling current from an internal well that is emitted to the continuum
- Hot electron mean free path
- Number of periods

Key Results:
- Quantum well detectors are predicted to exhibit noise lower than full shot noise.

IR Quantum Well Detectivity (7K) - Sample 041989-2

![Graph showing detectivity vs bias voltage]
Tunneling Dark Current Model

- Approach: Nodal analysis in which analogs of Kirchhoff's current and voltage laws are applied
  - Net current into each internal well (node) is zero
  - Applied bias is the sum of the potential drops across barriers
  - Charge distribution in internal wells, cathode, and anode adjusted until Kirchhoff's laws are satisfied
- Results:
  - Model-generated I-V curves similar to experimental curves
  - Predict substantially reduced dark current \( \times 10^{-4} \) for detector with 400\( \AA \) barriers

- Dark current vs. bias for any choice of detector design parameters.

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Dark Current Density vs. Applied Bias

R vs. Wavelength 010890-4a 6K; V = 5 Volts

\[ \frac{R_{10 \, \mu m}}{R_{peak}} = \frac{0.11}{0.31} = 0.36 \]
Detectivity vs. T 010890-4a

Detectivity (cmHz/Watt)

Temperature (K)

DSTAR (10 UM) VERSUS INVERSE TEMPERATURE
HgCdTe PV, GaAs/AlGaAs MQW & Si:As IBC DETECTORS

HgCdTe PV
2.5E4 RoA @ 40K

HgCdTe PV
1.0E5 RoA @ 40K

HgCdTe PV
1.3E6 RoA @ 40K

GaAs/AlGaAs MQW (8.3 M)
50 WELLS, 300A BARR.

GaAs/AlGaAs MQW (8.3 M)
50 WELLS, 400A BARR.

Si:As IBC
QE = .40
Summary/Conclusions

- High detectivity quantum well IR detectors have been demonstrated
  - $D^* = 1\times10^{13} \text{ cm}\sqrt{\text{Hz/W}}$ at 10 $\mu$m and 20K

- Devices show excellent reproducibility, uniformity, and radiation hardness
  - Simple physical models correctly predict device performance

- Progress in the development of LWIR quantum well detectors has been very rapid, particularly given the small investment made to date

- Future efforts: Increase the device quantum efficiency and develop array concepts
We propose a novel semiconductor heterojunction photodetector which would have a very low dark current and would be voltage tunable. A schematic diagram of the device and its band structure are shown in Figure 1. The two crucial components of the device are a cathode (InGaAs) whose conduction band edge is below the conduction band edge of the quantum wells and a resonant tunneling filter (GaAs-AlGaAs). In a standard resonant tunneling device the electrodes are made of the same material as the quantum wells, and this device becomes highly conducting when the quantum levels in the wells are aligned with the Fermi level in the negatively biased electrode. In contrast, our device is essentially non-conducting under the same bias conditions. This is because the Fermi Level of the cathode (InGaAs) is still well below the quantum levels to that no resonant transport occurs and the barriers (AlGaAs) effectively block current flow through the device. However, if light with the same photon energy as the conduction-band discontinuity between the cathode and the quantum wells, $E_{c3} - E_{c1}$ is shone on the sample, free carriers will excited to an energy corresponding to the lowest quantum level in the well closest to the cathode ($h\nu + E_{c1} = E_0$). These electrons will resonantly tunnel through the quantum wells and be collected as a photocurrent in the anode (GaAs). To improve the quantum efficiency, the cathode (InGaAs) should be very heavily doped and capped with a highly reflective metal ohmic contact. The thickness of the device should be tailored to optimize thin film interference effects and afford the maximum absorption of light.

Because the device relies on resonant tunneling, its response should be very fast, and the small voltages needed to change the responsivity should allow for very high frequency modulation of the photocurrent. In addition, the device is tuned to a specific photon energy so that it can be designed to detect a fairly narrow range of wavelengths. This selectivity is important for reducing the photocurrent due to spurious light sources. Although we have cited the use of InGaAs, GaAs, and AlGaAs by way of example this device can be fabricated from a number of materials depending on the detector characteristics one desires. Also, the resonant tunneling filter may comprise any number of quantum wells to obtain the appropriate operating voltage so long as the filter region is not so thick that it significantly reduces the photocurrent when the electron energy is resonant with the levels in the wells.
**RESONANT TUNNELING**

\[ I_{\text{MAX}} = (e m^\alpha \Delta E / 2 \pi h^3) E_F \]

\( \Delta E \) is resonance width

\( \uparrow \) as \( d \) \( \downarrow \)

\( \uparrow \) as \( \phi_{\text{eff}} \)

\( \uparrow \) as \( m^\alpha \)

**PHOTOEXCITED RESONANT TUNNELING**

\( I_{\text{pe MAX}} \) When \( hv = E_0 \)

Photocurrent when \( (E_0 - E_F) \leq hv \leq E_0 \)
Fowler photoresponse for n⁺-n heterojunction

\[ R \propto A^* T^{3/2} \int_{\Delta E_c - h\nu}^{\infty} \frac{E_f}{kT} \cdot y^{-1/2} \ln \left[ 1 + \exp \left( \frac{E_f}{kT} \cdot y \right) \right] dy \]

RESONANT TUNNELING
IR-PHOTODETECTOR

- High IR absorption
- Low dark current
SCHOTTKY BARRIER
INTERNAL PHOTOEMISSION DEVICE

- IR Photon excites e\(^-\) over barrier
- High dark current – barrier \( \sim h\nu \)
- Low quantum efficiency
- \( \phi_{bn} = 0.8 \rightarrow -0.2 \) for GaInAs

\[ (I_{pc})^{1/2} \sim (h\nu - \phi_{bn}) \]
We have, for the first time, demonstrated photovoltaic detection for an 
multiple quantum well (MQW) detector. With a blocking layer, the MQW detector 
exhibits Schottky I-V characteristics with extremely low dark current and 
excellent ideality factor. The dark current is $5 \times 10^{-14}$ A for an 100x100 um$^2$ 10 
um detector at 40 K, 8-9 orders of magnitude lower than that of a similar 10 um 
MQW detector without blocking layer. The ideality factor is $\sim 1.01-1.05$ at 
T=40-80 K. The measured barrier height is consistent with the energy difference 
to between first excited states and ground states, or the peak of spectral 
response. We also, for the first time, report the measured effective Richardson 
constant (A**) for the GaAs/AlGaAs heterojunction using this blocking layer 
structure. The A** is low $\sim 2.3$ A/cm$^2$/K$^2$. 

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GaAs-BASED MULTIQUTANTUM WELL
LONG WAVELENGTH INFRARED DETECTOR

C. S. WU, C. P. WEN, R. N. SATO
HUGHES AIRCRAFT COMPANY

CONTRIBUTORS

(HUGHES) (UCSD) (NOSC)
M. HU C. W. TU L. FLESNER
LE PHAM J. ZHANG J. MERRIAM
P. S. NAYAR

HUGHES AIRCRAFT COMPANY
GaAs MQW SL DETECTOR
OUTLINE

- ADVANTAGES
- CONVENTIONAL VS HUGHES MQW
- MQW DETECTOR DESIGN
- TEST RESULTS
  - LOW DARK CURRENT OPERATION
  - PHOTOVOLTAIC DETECTION
- SUMMARY

ADVANTAGES OF MQW SUPERLATTICE LWIR DETECTOR

- BUILT-IN FILTER CHARACTERISTICS
- DESIGN FLEXIBILITY IN SPECTRAL RESPONSE
- RADIATION HARDNESS POTENTIAL
- POTENTIALLY EXCELLENT UNIFORMITY FROM PIXEL TO PIXEL
- COMPATIBLE WITH STANDARD GaAs IC PROCESSING TECHNOLOGY
MULTIPLE QUANTUM WELL DETECTOR OPERATION

PHOTON INDUCED CURRENT

\[ I_{\text{TOT}} = I_{\text{PH}} + I_{\text{TUN}} \]

DESIGN FLEXIBILITY

MQW DETECTOR WITH TUNNELING CURRENT BLOCKING LAYER

BLOCKING LAYER RESULTS IN LOW DETECTOR DARK CURRENT, IMPROVED SNR AND REDUCED PRIME POWER CONSUMPTION

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A periodic potential with rectangular sections
(Period length = a + b)

\[ \Psi(x) - \Psi(x+i(a+b)) \]

Schrödinger equation for Kronig-Penney potential:

\[
- \frac{\hbar^2}{2M} \frac{d^2 \Psi(x)}{dx^2} + V(x)\Psi(x) = E\Psi(x)
\]

(two unknowns: \( \Psi(x) \) (wave function) and \( E \) (electron energy))

where \( V(x) \) and \( \Psi(x) \) satisfy

PERIODICITY CONDITIONS:

\( V(x) = V(x+a+b) \) and

\( \Psi(x+a+b) = e^{i\theta} \Psi(x) \) (\( e^{i\theta} \): real)

MQW IR detector design considerations

* Spectral response
  - Well width, barrier height, barrier thickness

* Active region thickness
  - Carrier density, barrier thickness

* Carrier mean free path
  - Mobility, bias condition, carrier lifetime

* Dark current
  - Barrier thickness, barrier height
  - Blocking layer (thickness, height)
GaAs/AlGaAs MQW DETECTOR ARRAYS DESIGN

* DESIGNED FOR $\lambda = 10$ MICRONS

* BLOCKING LAYER FOR LOW DARK CURRENT
  - LOW BACKGROUND OPERATION

* 4 X 4 ARRAYS
  - 100 $\mu$M X 100 $\mu$M DETECTORS
  - 40 $\mu$M X 40 $\mu$M DETECTORS

* THIN DETECTOR STRUCTURE TO ENHANCE RADIATION HARDNESS

* STANDARD GaAs IC PRODUCTION LINE FABRICATION TECHNOLOGY

4 x 4 PHOTO DETECTOR ARRAYS

DETECTOR SIZE 100 x 100 $\mu$M

40 x 40 $\mu$M
DARK I-V CHARACTERISTICS

\[
\begin{align*}
I &= \text{(pA)} \\
A &= 100 \times 100 \text{ um}^2 \\
T &= 40 \text{ k}
\end{align*}
\]

MQW SL DETECTOR STRUCTURE WITH BLOCKING LAYER - QUANTUM WELL "SCHOTTKY" JUNCTION

- PHOTOVOLTAIC DETECTION LIKE PtSi DETECTOR
- LOW DARK CURRENT & HIGH RoA (NO THERMIONIC FIELD EMISSION)
- SELECTIVE SPECTRAL RESPONSE (ADJUSTABLE \( \Phi B \))
SCHOTTKY DIODE'S EQUATION

\[ J = J_s (e^{qV_{nkT}} - 1) \]

\[ J_s = A^{**} T^2 \exp \left( -\frac{q\phi_B}{kT} \right) \]

*\( \phi_B \) Schottky barrier height

*\( A^{**} \) effective Richardson constant

*\( n \) ideality factor

MEASUREMENT OF SCHOTTKY BARRIER HEIGHT, IDEALITY FACTOR & RICHARDSON CONSTANT

(A) \( \ln I_F \) versus \( V_F \) \( \longrightarrow \) solve for \( n \) & \( \phi_B \)

\[ \ln I_F = \ln I_s + \frac{qV_F}{nkT} \]

(B) \( \ln \left( \frac{I_F}{T^2} \right) \) versus \( 1/T \) (ACTIVATION ENERGY PLOT)

\( \longrightarrow \) solve for \( \phi_B \) & \( A^{**} \)

\[ \ln \left( \frac{I_F}{T^2} \right) = \ln(A A^{**}) - \frac{q(\phi_B - V_F)}{kT} \]
FORWARD DARK I-V CHARACTERISTICS

\[ I_F (A) \]

\[ I = 100 \times 100 \text{ um}^2 \]

\[ T = 60 \text{ k} \]

\[ n = 1.02 \]

\[ \phi_b = 120 \text{ mV} \]

\[ \text{Assumed } A^{**} = 2.3 \text{ A/cm}^2/\text{K}^3 \]

\[ n = \frac{q}{kT} \frac{\delta V}{\delta (\ln J)} \]

\[ \phi_B = \frac{kT}{q} \ln \left( \frac{A^{**}T^2}{J_s} \right) \]

FORWARD I-V CHARACTERISTICS
AT \( T = 30 \) TO \( 80 \text{ K} \)

****** GRAPHICS PLOT ******

**MOW. IV. AT. 30 TO 80K**

\[ V_F \]

\[ V = 0.001 \text{V} \]

\[ V = 2.00 \text{V} \]

\[ V = 0.000 \text{V} \]

\[ \text{EXTREMELY LOW PARASITIC LEAKAGE CURRENT} \]
SCHOTTKY BARRIER HEIGHT AND RICHARDSON CONSTANT OBTAINED FROM ACTIVATION ENERGY PLOT

DARK CURRENT VS TEMPERATURE FOR 10 µm PHOTOVOLTAIC MQW DETECTOR
GaAs Based MQW IR Detector
Dark Current Characterization

GaAs/AIGaAs MQW IR DETECTOR
PHOTOVOLTAIC IR DETECTION
I - V CURVE

A_d = 100 x 100 µm
Q_B = 3.9 x 10^{14} ph/cm^2-sec
T = 10°K
SUMMARY

- GaAs MQW LW IR DETECTORS DEMONSTRATED
  - LOW DARK CURRENT
  - POTENTIAL LOW NOISE
  - PHOTOVOLTAIC DETECTION (LOW DETECTOR BIAS REQUIRED)
  - POTENTIAL RADIATION HARDNESS
  - EXCELLENT DESIGN FLEXIBILITY
    PEAK PHOTO RESPONSE BANDWIDTH

- GaAs IC PRODUCTION TECHNOLOGY COMPATIBLE
  - MATURED TECHNOLOGY
  - HIGH YIELD, GOOD UNIFORMITY
Fundamental Limits to Performance
of Quantum Well Infrared Detectors

Amnon Yariv
California Institute of Technology
Pasadena, California 91125

ABSTRACT

Radiometric, density of states (material), and thermal considerations are used to obtain the figure of merit of the quantum-well GaAs/GaAlAs infrared detectors described by Smith et. al\(^{(1)}\). The results are compared with HgCdTe, the present industry standard, as well as with recent experiments at other laboratories.

Fundamental Limits to Quantum Well Infrared Detectors

Amnon Yariv
California Institute of Technology

Michael Kinch
Texas Instruments

S. Borenstain
Jet Propulsion Laboratory

I. Gravé
California Institute of Technology
Fig. 3. (a) A schematic drawing of the proposed detector. (b) Band diagram of the proposed structure.

(Smith et al., Infrared Phys., Vol 23, p. 93, 1983)
Absorbance

Photoresponse

Wavelength (μm)

λ PEAK = 8.00 μm

Δλ
λ = 20%

#1045
L = 300 Å
d = 50 Å
50 periods
Ga .76 AL .24 As
DARK CURRENT OF GaAs/GaAlAs MQW DETECTOR AT 77K

V_B = 0  I_d ~ 10^{-11} A
V_B = 10V  I_d ~ 10^{-6} A
V_B = 5V
I_d ~ 10^{-9} A
Configuration
NOISE PHYSICS — P.C. DETC.

\[ \bar{I} = (n_B + n_t) e \bar{V} A \]

\[ \frac{i_N^2}{\Delta v} = 4e \bar{I} \frac{\tau_0}{\tau_d} \Delta v \]

\[ \frac{\tau_0}{\tau_d} = g \quad \tau_d \equiv \frac{t}{v} = \text{DRIFT TIME} \]

GENERATION-RECOMBINATION NOISE

\[ = 4e (n_B + n_t) e \bar{V} A \left( \frac{\tau_0}{\tau_d} \right) \Delta v \]

\[ n_B = \frac{(P_B/A) \eta \tau_0}{hvt} = \frac{2\pi h v^3 \Delta v (\sin^2 \theta/2)}{c^2 (e h v/k T_B - 1)} \left( \frac{\eta \tau_0}{h v t} \right) \]

NEED TO COOL TILL

\[ n_t < n_B \quad \text{BLIP} \]
BLIP AND D\textsubscript{B}\textsuperscript{*}

\textbf{ASSUME} \( n_t < n_B \) (BLIP)

\[
\overline{i}^2_{NB} = 4e \left(n_B e^{\nu A} \right) \frac{\tau_0}{\tau_d} \Delta \nu, \quad \tau_d = \frac{t}{v}
\]

\[
= \frac{4e^2 P_B \eta \Delta \nu}{h \nu} \left(\frac{\tau_0}{\tau_d}\right)^2, \quad n_B = \left(\frac{P_B \eta \tau_0}{Ah \nu t}\right)
\]

\[
\overline{i}^2_s = \left(\frac{\eta P_s e}{h \nu}\right)^2 \left(\frac{\tau_0}{\tau_d}\right)^2
\]

\textbf{DEFINE: NEP = VALUE OF} \( P_s \) \textbf{WHICH MAKES}

\[
\overline{i}^2_s = \overline{i}^2_{NB}
\]

\[
\text{NEP} = 2\sqrt{A\Delta \nu (P_B/A)}
\]

\[\frac{\eta}{\eta}\]

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\[ D_B^* \equiv \frac{\sqrt{A \Delta \nu}}{\text{NEP}} = \frac{1}{2} \sqrt{\frac{\eta}{h \nu (P_B/A)}} \]

**REMINDER:**

TO OBTAIN \( D_B^* \) MUST COOL SO \( n_t < n_B \). SO NEED TO FIND DEPENDENCE OF \( n_t \) ON \( T \).
\[ n_t = n_0 \left( \frac{d}{L} \right) \frac{kT}{E_F} \exp \left[ -\frac{(V - E_F)}{kT} \right] \]
\[ D_B^* = \frac{1}{2} \sqrt{\frac{\eta}{h\nu(P_B/A)}} \]

\[ n_t < n_B \text{ FOR BLIP i.e.} \]

\[
\begin{array}{|c|c|c|c|}
\hline
n_0 & \frac{kT}{E_F} & \frac{d}{L} & \exp\left(-\frac{(V - E_F)}{kT}\right) \\
\hline
\text{BLIP} & \frac{P_B}{A}\eta\tau_0 \\
\hline
\end{array}
\]

\[ \Rightarrow \text{IF } \tau_0 \uparrow T \uparrow \]

Q. WELL \( \tau \sim 10^{-11} \text{ s} \)

HCT \( \tau \sim 10^{-6} \text{ s} \)
Thermal generation current vs temperature for GaAs/AlGaAs IR superlattices and HgCdTe alloys at $\lambda_c = 8.3$ and $10 \mu m$. The assumed effective quantum efficiencies are $\eta = 0.125$ and 0.7 for GaAs/AlGaAs and HgCdTe, respectively.

M. A. Kinch and A. Yariv 2094

$T_B = 300$
$B = 0.13 \nu$
$\nu = 3 \times 10^{13} \text{ Hz}$
$(\lambda = 10 \mu m)$
\[ t_q = \text{TIME OVER WELL} = \frac{d}{\mu \varepsilon} \approx 5 \times 10^{-14} \text{s} \]

\[ t_{\text{op}} = \text{TIME TO EMIT LO PHONON} \approx 10^{-13} \text{s} \]

\[ \frac{t_{\text{op}}}{t_q} \approx 2 - 5 \]

\[ P_{\text{cap}} (E) = 1 - \sum_{x=0}^{I_n (E > \hbar \omega_{\text{op}})} \left( \frac{t_{\text{op}}}{t_q} \right)^x \frac{x!}{e^{-t_{\text{opt}}/t_q}} \]
probability of capture by optical phonon emission as a function of the energy at injection and \( \tau_{op}/t_q \)

(S. Smith, Ph.D. Thesis, Caltech, April, 1986)
New Heterojunction LWIR Detector Options

J. Maserjian
Center for Space Microelectronics Technology
Jet Propulsion Laboratory

We investigate a heterojunction internal photoemission (HIP) approach that potentially offers LWIR photovoltaic detector performance (single pixel) that is competitive with the best of other approaches being considered. Most significantly, our approach offers a relatively simple device technology that promises producible and uniform FPA's. We emphasize an exciting process based on intervalence band absorption. We investigate both III-V and Si-based heterojunctions grown by molecular beam epitaxy (MBE) in which the barrier can be tailored to the desired cutoff wavelength. In addition, MBE allows one to optimize the device structure with precise control of doping profiles and layer thicknesses, and perform band structure engineering by control of composition and heterojunction strain.

We also consider free carrier absorption in heterojunctions. Acceptable absorption coefficients can be achieved in very heavily n⁺ doped semiconductor layers (=10²⁰ cm⁻³). However, in this case the appreciable filling of conduction band states leads to a Schottky-like photoresponse with a gradual (quadratic) turn-on above threshold. A more satisfactory approach would be to use p⁺ doping so that with the higher density of states in the heavy hole valence band there would be a narrow band of occupied states. This gives the desirable effect of a more rapid (linear) turn-on above threshold. Unfortunately, the higher hole effective mass also reduces (inversely) the free carrier absorption. For this and other reasons, the intervalence band absorption process looks much more promising.

The valence band structure of GaAs (and closely related alloys) is particularly attractive for achieving an optimum effect. The light and heavy hole bands become parallel at values of wave vector k away from the zone center, separated by a constant energy of about 80 meV along the <100> directions. The parallel E-k behavior leads to a large joint density of states and correspondingly, a large absorption coefficient α for photon energy hν equal to this separation (corresponding to wavelengths =15 μm). This effect requires heavy doping (>10¹⁹ cm⁻³) so that states are occupied to sufficient values of k. Extrapolation of theoretical work of E.O.Kane and published absorption data suggest α>10⁴ cm⁻¹ for our case of interest. Theoretical calculations are in progress to extend Kane's early work.

Some interesting features are immediately evident. The selection rules for these transitions prefer normal incidence of light (giving a sin²θ distribution of k-directions, where θ is the angle from the field vector in the plane of the layer). Furthermore, photoexcitations between the <100> E-k bands generate the dominant k-directions normal to the heterojunction interface of (100) oriented...
material. We have the opportunity of tailoring the interband separation to the desired value of $h\nu$ and matching with an optimum (slightly smaller) heterojunction barrier $\phi$. In this case the conservation of transverse momentum at the interface is satisfied for most $k$-directions of photoexcited holes. Holes excited in the reverse direction can be redirected in the forward direction by reflection from a higher barrier (e.g., AlGaAs/GaAs). Therefore, inelastic scattering losses can be minimized with an optimum layer thickness to achieve a maximum quantum efficiency $\eta$.

In the case of Si-based structures, we can still utilize transitions to the split-off valence band. In this case we lose some of the above advantages, but still retain strong absorption (large matrix element) and favorable selection rules. We can also use band structure engineering through control of composition and interface strain to optimize the intervalence band transition energies relative to the heterojunction barrier (i.e., the cutoff wavelength).

Preliminary results on Si$_{1-x}$Ge$_x$/Si heterojunctions are encouraging (see T-L. Lin, next session) and work on In$_x$Ga$_{1-x}$As/Al$_x$Ga$_{1-x}$As heterojunctions is just getting under way. The opportunity exists for fabricating photovoltaic detector structures designed to achieve maximum $\eta$ and the limiting thermionic emission dark current at the heterojunction. To minimize inelastic scattering loss of photoexcited holes while still obtaining adequate absorption per layer (e.g., $>1\%$), the p$^+$ layers must be of some optimum thickness (e.g., $\approx 40$ nm). The total absorption can be enhanced by multiple passes; for example, two passes with a single reflector or $2N$ passes in an optical cavity structure (as commonly done with SB detectors). The HIP structures can also be configured as two stacked diodes connected in parallel (straightforwardly with planar technology) to gain another factor of two.

Based on the above considerations, we project $\eta = 0.20$ in optimized detector structures. The thermionic emission limited detectivity \[ D^* \rightarrow (\eta/h\nu)(2J_0/e)^{1/2}, \text{ where } J_0 = 120(m^*/m)T^2\exp(-\phi/kT) \text{ A/cm}^2 \] becomes $D^* \approx 10^9$ cm-Hz$^{1/2}$/W, for 15$\mu$m peak response ($h\nu = 82$ meV), with $\phi = 0.9h\nu$ and $T = 65K$. This gives a noise equivalent differential temperature NEDT $\approx 0.04K$ for a background temperature of 300K (assuming f/2 optics, 50$\mu$m square pixels and 30Hz bandwidth). Therefore, even with relatively low $\eta$, the thermionic emission dark current of HIP detectors provides excellent pixel performance. Most important, the simplicity of the HIP structure offers real promise for producibility and uniformity which often are the limiting factors for FPA performance.
New Heterojunction Detector Options

Joseph Maserjian
Center for Space Microelectronics Technology
Jet Propulsion Laboratory

Contributors
Theory: Mark Huberman
Robert Terhune
Si MBE: Robert Fathauer
True-Lon Lin
III-V MBE: Frank Grunthaner
Anders Larsson
Readouts: Eric Fossum

Outline

- Motivation
- Heterojunction Approach
- Theoretical Considerations
- Detector Structure
- Predicted Performance
Technology Considerations

**Detector Performance**
- Detectivity ($D^*$)
- Quantum Efficiency (QE)
- Noise Equivalent Diff. Temperature (NEDT)
- Operating Temperature
- Thermal Generation Noise
- Excess Detector Noise (e.g., 1/f)

**Array Compatibility**
- Hybrid or monolithic readout circuits
- Zero or reverse bias resistance
- Dark current / power dissipation
- Detector capacitance
- Fill factor (front vs. backside illum.)
- Detector linearity and stability
- Frame rate and dynamic range
- Array uniformity

**Productivity & Robustness**
- Material manufacturability
- Material quality and uniformity
- Material stability / surface passivation
- Production yield / cost
- Radiation hardness

---

**Approach**

Heterojunction Internal Photoemission (HIP)

- Simple structure / normal incidence radiation
- Emphasis on intervalence band absorption
- Optimized HIP structure using MBE:
  - valence band engineering with control of composition and strain
  - optimize doping and layer thickness for maximum quantum efficiency
  - match heterojunction barrier to cutoff wavelength for minimum dark current
- Configure into high performance PV detector arrays:
  - stacked planar detector structures
  - optical cavities
Free Carrier Absorption
Classical Theory

\[ \varepsilon = \varepsilon_0 + 4\pi i \sigma/\omega, \quad n = \sqrt{\varepsilon} \]
\[ \sigma = \sigma_0 / (1 - i \omega \tau), \quad \sigma_0 = N e^2 \tau / m \]

\[ E = \hat{\mathbf{x}} E \exp\{i(nkz-\omega t)\} \]
\[ H = \hat{\mathbf{y}} nE \exp\{i(nkz-\omega t)\} \]

Match \( E \) and \( B \) at boundaries of thin layer:

Free Carrier Absorption
(classical theory for finite GaAs layer of thickness \( d \))

![Graph showing absorption vs. wavelength for different GaAs layers and doping levels](image-url)
GaAs Band Structure

GaAs Absorption Data
R. Braunstein and E. O. Kane (1956)
**Intervalance Band Absorption**

Valence Band $E - k^2$ Diagram

Heterojunction Internal Photoemission

$$\alpha = \frac{4\pi^2 e^2 \hbar^2}{nc \omega m^2} \sum_k |M(k)|^2 \delta(E_{lh}(k) - E_{hh}(k) - \hbar \omega)$$

Where:

$$|M(k)|^2 = \langle \psi_{lh}|\hat{\sigma} \cdot \nabla |\psi_{hh}\rangle^2$$

$$\sim \sin^2 \theta$$

**Selection Rules for k-Directions**

![Diagram showing selection rules for k-directions](image)
Si Valence Band Structure

Intervalance Band Absorption Matrixes for Ge

\[ W_{ij} = \frac{M_{ij}}{\mathbf{k}} \]
Quantum Efficiency ($\eta$)

$$\eta = (1 - e^{-2N\alpha d}) e^{-d/L_z}$$

$$\equiv 2N\alpha d \cdot e^{-d/L_z}$$

**Maximum $\eta$ when:** $d = L_z$

$$\eta_{\text{max}} = 2N\alpha L_z e^{-1}$$

**Assume:** $<v_z> \approx 2 \cdot 10^7 \text{ cm/s} \quad \text{Then:} \quad L_z = <v_z> \tau$

$$\tau \approx 3 \cdot 10^{13} \text{ s}$$

$$\alpha \approx 2 \cdot 10^4 \text{ cm}^{-1}$$

$$\eta_{\text{max}} \approx 0.09 N$$

**Stacked HIP Diode**

**Band Diagram**

[Diagram of Stacked HIP Diode Band Diagram]
Stacked HIP Diode
Planar Structure

Metal common contact
Metal pixel contacts
Si nitride layer
AlAs barriers
p+ Ga(In)As layers
IGaAs barriers
s.i. GaAs substrate

Detector Relations
(HIP Photovoltaic Diode)

\[ D^* = \frac{(A\Delta f)^{1/2}}{\text{NEP}} \]
\[ = \left( \frac{\eta \sqrt{2 \ h\nu}}{r_b + r_T + r_{ex}} \right)^{-1/2} \]

Background:
\[ r_b = \int_{v_1}^{v_2} \eta(v) \left[ S(v, T_B)/\hbar \nu \right] dv, \quad S = 2\pi \hbar v^3/\epsilon^2 / (e^{\hbar v/kT_B} - 1) \]

Thermal:
\[ r_T = [A^{**T^2/\epsilon}] \exp(-\phi/kT), \quad \phi \equiv 0.9 \ h\nu \]

\[ D^*(v, T) \rightarrow (\eta(v)/\hbar \nu) (2r_T)^{-1/2} \]

\[ \text{NEDT} = \frac{\text{NEP}}{dP/dT_B} = \frac{(A\Delta f)^{1/2}}{D^* dP/dT_B} \]

where for f-number F:
\[ P = A \int_{v_1}^{v_2} S(v, T_B) dv / 4F^2 \]
Summary

- HIP detector uses normal incidence radiation
- Intervalance band absorption offers high $\eta$
- Band structure / barrier tailoring for optimum response
- Thermionic current gives good performance at 65K
- Simple device structure -- easy to configure into stacked PV diode arrays
- Compatible with monolithic readout circuits
- Potential for low cost uniform arrays
SESSION VI:  Si-Based Detectors

VI-1  Intersubband Absorption in Si$_{1-x}$Ge$_x$/Si Superlattices for Long Wavelength Infrared Detectors
     Y. Rajakarunanayake, California Institute of Technology

VI-2  Possibilities for LWIR Detectors Using MBE-Grown Si(Si$_{1-x}$Ge$_x$) Structures
     R.J. Hauenstein, Hughes Research Laboratories

VI-3  Novel Si$_{1-x}$Ge$_x$/Si Heterojunction Internal Photoemission Long Wavelength Infrared Detectors
     T.L. Lin, Jet Propulsion Laboratory
Intersubband absorption in $\text{Si}_{1-x}\text{Ge}_x$/Si superlattices
for long wavelength infrared detectors

Y. Rajakarunanayake and T. C. McGill
California Institute of Technology
Pasadena, California 91125

ABSTRACT

We have calculated the absorption strengths for intersubband transitions in $n$-type $\text{Si}_{1-x}\text{Ge}_x$/Si superlattices. These transitions can be used for the detection of long-wavelength infrared radiation. A significant advantage in $\text{Si}_{1-x}\text{Ge}_x$/Si superlattice detectors is the ability to detect normally incident light; in $\text{Ga}_{1-x}\text{Al}_x\text{As}$/GaAs superlattices intersubband absorption is possible only if the incident light contains a polarization component in the growth direction of the superlattice. We present detailed calculations of absorption coefficients, and peak absorption wavelengths for [100], [111] and [110] $\text{Si}_{1-x}\text{Ge}_x$/Si superlattices. Peak absorption strengths of about 2000-6000 cm$^{-1}$ were obtained for typical sheet doping concentrations ($\simeq 10^{12}$ cm$^{-2}$). Absorption comparable to that in $\text{Ga}_{1-x}\text{Al}_x\text{As}$/GaAs superlattice detectors, compatibility with existing Si technology, and the ability to detect normally incident light make these devices promising for future applications.
Intersubband Absorption in Si/Ge Superlattices for Long Wavelength Infrared Detectors

Yasantha Rajakarunanayake
T. C. McGill

California Institute of Technology

Si/Ge Multi Quantum Wells for LWIR detection

• Similar to extrinsic Si detectors

• Can change wavelength response by varying layer thicknesses

• Possible to achieve absorption at normal incidence

• Can achieve high doping concentrations

• Improved uniformity

• Compatibility with Si readout electronics
Outline

- Introduction
- Possibilities with [111],[110]$^1$ directions
- Intersubband absorption coefficient
- Si/Ge band offsets
- Strain effects
- Results
- Conclusions


QW Absorption
Quantum well states of ellipsoidal valley materials

Consider the case where ellipsoids are not oriented in the growth direction

- Effective mass is a tensor; large anisotropy
- Possible to couple orthogonal components of vector potential and electron motion
Optical Matrix Element in Superlattices / Multi Quantum Wells

\[ M_{op} = \left( \frac{e}{mc} \right) \langle U_1 F_1 | \vec{A} \cdot \vec{P} | U_2 F_2 \rangle \]

- Interband Case: \( V \rightarrow C \)

\[ M_{op} \sim \left( \frac{e}{mc} \right) \langle U_C | \vec{A} \cdot \vec{P} | U_V \rangle \langle F_C | F_V \rangle \]

- Intersubband Case: \( C_1 \rightarrow C_2 \)

\[ M_{op} \sim \left( \frac{e}{mc} \right) \langle F_{C_1} | A_i \left( \frac{1}{m^*} \right) i_j P_j | F_{C_2} \rangle \]

Normal Absorption

\[ \alpha(\omega) \approx \left( \frac{e_x}{m^*_{xz}} + \frac{e_y}{m^*_{yz}} + \frac{e_z}{m^*_{zz}} \right)^2 \]

- \( 1/m^*_{xz} \) and \( 1/m^*_{yz} \neq 0 \) necessary

- shearing terms of the reciprocal effective mass tensor are important.

- large eccentricity improves absorption
Si/Ge system

- SiGe alloys; $X$ valleys, Si conc. $x < 0.85$
- SiGe alloys; $L$ valleys, Ge conc. $x > 0.85$

Other systems of interest

- GaAlAs alloys; $X$ valleys, Al conc. $x > 0.45$
- GaAlSb alloys; $L$ valleys, Al conc. $0.25 < x < 0.55$
- GaAlP, PbSnTe

Absorption

$$\alpha(w) = \frac{4\pi e^2 n^2}{nm^2cw} N_S |\langle F_2(z) \nabla_z F_1(z) \rangle|^2 \left( \frac{e_x}{m_{xz}^*} + \frac{e_y}{m_{yz}^*} + \frac{e_z}{m_{zz}^*} \right)^2$$

$$\int_0^{\pi/L} \frac{\Gamma/2\pi}{\left(\hbar w - E(k_z)\right)^2 + \Gamma^2/4} dk_z$$

- $\Gamma$ is the broadening due to lifetime $\approx$ (5 meV)
- Absorption depends on $m^*$. Shearing terms $m_{xz}^*$ and $m_{yz}^*$ important
- $e_j$ denotes the polarization direction of light
- $N_S$ is the sheet doping concentration
- $L$ is the length of a superlattice unit cell
- $E(k_z)$ is the subband separation energy
- $F_1$ and $F_2$ denote envelope functions
Band Offset

- Si/Ge average VB offset 0.54 eV
- Strain effects important
- CB offsets are small
- VB offsets are large
Strain Effects

- Lattice mismatch

- Splits the valence band degeneracy; HH and LH splitting
  * Compression → HH shifts up
  * Tension → LH shifts up

- Splits the conduction band degeneracy
  Six Δ valleys
  * Compression → 4-fold valleys shift down
  * Tension → 2-fold valleys shift down
Si [100] substrate

Si [111] substrate

Si [110] substrate

CRITICAL THICKNESS
(Si parameters)

- Bean & People, 1986
- Van der Merwe, 1963
- Matthews & Blakeslee, 1974

MISFIT (%)
cases:

- [100] 2-fold electrons
- [100] 4-fold electrons
- [111] 6-fold electrons
- [110] 4-fold electrons

[100] direction
parallel incidence
2-fold electrons

- purpose of study is to compare with GaAs
- effective masses large
- possible to achieve good confinement

- structures:
  * barrier layer, Ge rich: Si\textsubscript{0.4}Ge\textsubscript{0.6}
  * well layer, Si rich: Si
  * coherently strained to Ge rich Si\textsubscript{0.4}Ge\textsubscript{0.6} buffer
[100] direction
parallel incidence
4-fold electrons

- purpose of study is to compare with GaAs

- effective masses small

- poor confinement

- structures:
  * barrier layer, Ge rich: Si$_{0.2}$Ge$_{0.8}$
  * well layer, Si rich: Si$_{0.7}$Ge$_{0.3}$
  * coherently strained to Si rich Si$_{0.7}$Ge$_{0.3}$ buffer
[111] direction
normal incidence
6-fold electrons

- effective masses: medium
- wavefunction confinement: medium
- no preferred azimuthal dependence to absorption
- possible to grow on a buffer layer lattice matched to free standing SL
- structures:
  * barrier layer, Ge rich: Si$_{0.2}$Ge$_{0.8}$
  * well layer, Si rich: Si$_{0.8}$Ge$_{0.2}$
  * coherently strained to Si$_{0.5}$Ge$_{0.5}$ buffer
[110] direction
normal incidence
4-fold electrons

- effective masses: medium
  larger than [111]

- wavefunction confinement: medium
  better than [111]

- preferred azimuthal dependence
  for absorption in [110]
  polarized light

- structures:
  * barrier layer, Ge rich: Si_{0.2}Ge_{0.8}
  * well layer, Si rich: Si_{0.3}Ge_{0.7}
  * coherently strained to Si_{0.2}Ge_{0.8} buffer

Absorption Coefficient (cm\(^{-1}\))
lattice matched to Si_{2}Ge_{8} [110] buffer

![Absorption Coefficient Graph](image_url)
Other major issues

- Role of dislocations
- Excited state lifetime
- Intervalley scattering
- Responsivity, Detectivity
Conclusions

• Absorption of [100] Si/Ge superlattices is comparable to GaAs/AlGaAs (absorption coefficient \( \approx 5000 \text{ cm}^{-1} \)) for \( 10^{12} \text{ cm}^{-2} \) doping.

• Absorption of [111], and [110] Si/Ge superlattices is superior to GaAs/AlGaAs since normal incidence can be detected.

• Similar to extrinsic Si; Can vary absorption wavelength; Large absorption coefficients possible.
Possibilities for LWIR Detectors using MBE-grown Si/(Si$_{1-x}$Ge$_x$) Structures

R. J. Hauenstein, R. H. Miles, and M. H. Young
Hughes Research Laboratories
Malibu, California 90265

Traditionally, LWIR detection in Si-based structures has involved either extrinsic Si or Si/metal Schottky barrier devices. Molecular beam epitaxially (MBE) grown Si and Si/Si$_{1-x}$Ge$_x$ heterostructures offer new possibilities for LWIR detection, including sensors based on intersubband transitions as well as improved conventional devices. The improvement in doping profile control of MBE in comparison with conventional chemical vapor deposited (CVD) Si films has resulted in the successful growth of extrinsic Si:Ga, blocked impurity-band conduction detectors. These structures exhibit a highly abrupt step change in dopant profile between detecting and blocking layers which is extremely difficult or impossible to achieve through conventional epitaxial growth techniques. Through alloying Si with Ge, Schottky barrier infrared detectors are possible, with barrier height values between those involving pure Si or Ge semiconducting materials alone. For both n-type and p-type structures, strain effects can split the band edges, thereby splitting the Schottky threshold and altering the spectral response. Our measurements of photoresponse of n-type Au/Si$_{1-x}$Ge$_x$ Schottky barriers demonstrate this effect. For intersubband multiquantum well (MQW) LWIR detection, Si$_{1-x}$Ge$_x$/Si detectors grown on Si substrates promise comparable absorption coefficients to that of the Ga(Al)As system while in addition offering the fundamental advantage of response to normally incident light as well as the practical advantage of Si-compatibility. We have grown Si$_{1-x}$Ge$_x$/Si MQW structures aimed at sensitivity to IR in the 8 to 12 μm region and longer, guided by recent theoretical work. Preliminary measurements of our n- and p-type Si$_{1-x}$Ge$_x$/Si MQW structures will be presented.

POSSIBILITIES FOR LWIR DETECTORS USING MBE-GROWN Si(/SiGe) STRUCTURES

R.J. HAUENSTEIN
HUGHES RESEARCH LABORATORIES

OUTLINE

• INTRODUCTION
• EXTRINSIC Si DETECTORS
• Si\textsubscript{1-x}Ge\textsubscript{x}/Si MQW DETECTORS
• SCHOTTKY BARRIERS ON Si\textsubscript{1-x}Ge\textsubscript{x}
• SUMMARY
TRADITIONAL MID TO LONG WAVELENGTH IR DETECTORS IN Si

- EXTRINSIC DETECTORS
  - PC TYPE
  - BLOCKED IBC TYPE

- SCHOTTKY DETECTORS
  - e.g., PtSi/Si

MATERIALS PRODUCED BY Si MBE

- MANY EPITAXIAL COMBINATIONS POSSIBLE
  - \( Si_{1-x}Ge_x \) (COHERENTLY STRAINED)
  - SILICIDES (\( M_xSi_y \))
  - SELECTIVELY DOPED Si
  - OTHER

325
EXTRINSIC Si DETECTORS

- MBE ⇒ SUPERIOR DOPANT PROFILE CONTROL FOR FAST DIFFUSERS (e.g., Ga IN Si)

CONCENTRATIONS > SOLID SOLUBILITY SOMETIMES POSSIBLE

- MBE + LOW-ENERGY ION IMPLANT PROVIDES GREAT FLEXIBILITY

<table>
<thead>
<tr>
<th>thk (µm)</th>
<th>N_{Ga} (cm^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>~1 x 10^{16}</td>
</tr>
<tr>
<td>5.0 TO 12.0</td>
<td>~1 x 10^{18}</td>
</tr>
</tbody>
</table>

BLOCKING LAYER (Si:Ga)

DETECTING LAYER (Si:Ga)

p⁺ (100) SUBSTRATE (Si:B)
DETECTOR CURRENT VS. VOLTAGE

DETECTOR BIAS (VOLTS)

DETECTOR CURRENT VS. 1/TEMPERATURE

1000/T (K⁻¹)
MBE Si:Ga BLOCKED IBC RESULTS

- IBC BEHAVIOR DEMONSTRATED

- WAVELENGTH RESPONSE GOOD (% 12 μm PEAK)
  HOWEVER: POOR Q.E. DUE TO
  - LIMITED PURITY (NEED ~ 10^{12} \text{ cm}^{-3})
  - TOO MANY PARTICULATES

HRL IS DEVELOPING A GAS-SOURCE Si MBE TECHNIQUE TO IMPROVE UPON ABOVE RESULTS
SiGe/Si MULTI–QUANTUM WELL DETECTOR

Intersubband Absorption

IR Photon

SiGe Si SiGe Si SiGe

c1
conduction band edge

c2

- Tunable response throughout infrared
- Normal-incidence absorption
- Predicted absorption stronger than GaAs–based

SiGe/Si MQWS – IMPORTANT ISSUES

- STRAIN
  - CRITICAL THICKNESS(ES)
  - EFFECT ON BAND STRUCTURE

- COND. BAND ANISOTROPY

- GROWTH ISSUES
  - GOOD "RELAXED" LAYER
  - n-TYPE DOPING
  - UNIFORMITY OF THIN LAYERS
Si$_{1-x}$Ge$_x$ ON Si

- **KEY FEATURE**
  - LATTICE CONSTANT MISMATCH
    (~ 4.2% Ge TO Si)

- **EPITAXIAL POSSIBILITIES**
  - COHERENTLY STRAINED GROWTH
  - UNSTRAINED (RELAXED) GROWTH

---

**SINGLE FILM CRITICAL THICKNESS**

(Si parameters)

- Van der Merwe, 1963
- Matthews & Blakeslee*, 1974
- People & Bean, 1986

* TH. EQ.
Si(Ge) BAND STRUCTURE

EFFECT OF STRAIN ON Si$_{1-x}$Ge$_x$ BANDSTRUCTURE

Si$_{1-x}$Ge$_x$ ON Si (100):

Si$_{1-x}$Ge$_x$ ON Si$_{0.5}$Ge$_{0.5}$ (100):
USEFUL GROWTH RANGE

2 - Fold Conduction Band Offset (eV)
(Lattice Matched to Substrate)

Ge Concentration in Epilayer

Ge Concentration in Substrate

500°C 350°C

STRAINED ON
(5000Å SL)

Free-Standing

Filename: h16  Sample: HA90.016 HRXRD (004)

HRXRD - SiGe/Si MQW

L = 200Å

$ t_{Si} = 170Å \quad t_{Ge_xSi_{1-x}} = 30Å \quad X = 53% $
**Sample:**

FTIR - TRANSMISSION THROUGH Si/SiGe MQW

**SYNOPSIS - SiGe/Si MQW'S - (100) FILMS**

<table>
<thead>
<tr>
<th>WELL</th>
<th>BARRIER</th>
<th>BUFFER</th>
<th>NON-PARAB.</th>
<th>MBE GROWTH</th>
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<tbody>
<tr>
<td>n-Type</td>
<td>Si</td>
<td>Si$_{1-x}$ Ge$_x$</td>
<td>Si$_{1-x}$Ge$_x$(RLX)</td>
<td>WEAK</td>
</tr>
<tr>
<td>p-Type</td>
<td>Si$_{1-x}$Ge$_x$</td>
<td>Si</td>
<td>Si(COH)</td>
<td>STRONG</td>
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</table>

<table>
<thead>
<tr>
<th>DETECTS NORM. ALUM.?</th>
<th>8 - 12mm?</th>
<th>$\alpha$ RAIC (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-(100)</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>n-(110)</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>n-(111)</td>
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**SCHOTTKY BARRIERS ON Si AND Ge**
FOR SELECTED METALS (300K)

<table>
<thead>
<tr>
<th></th>
<th>Ag</th>
<th>Al</th>
<th>Au</th>
<th>Cu</th>
<th>Ni</th>
<th>Pt</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n) Si</td>
<td>0.78</td>
<td>0.72</td>
<td>0.80</td>
<td>0.58</td>
<td>0.61</td>
<td>0.90</td>
<td>0.67</td>
</tr>
<tr>
<td>(p) Si</td>
<td>0.54</td>
<td>0.58</td>
<td>0.34</td>
<td>0.46</td>
<td>0.51</td>
<td>-</td>
<td>0.45</td>
</tr>
<tr>
<td>(n) Gr</td>
<td>0.54</td>
<td>0.48</td>
<td>0.59</td>
<td>0.52</td>
<td>0.49</td>
<td>-</td>
<td>0.48</td>
</tr>
<tr>
<td>(p) Ge</td>
<td>0.50</td>
<td>-</td>
<td>0.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$\Delta Q_n \gg \Delta Q_p$ IN MOST CASES

$\Rightarrow E_F^{\text{METAL}} \approx \text{PINNED TO VALENCE BAND EDGE}$

INTERPOLATE VALUES FOR UNSTRAINED Si$_{1-x}$ Ge$_x$?

FROM S.M. SZE, "PHYSICS OF SEMICONDUCTOR DEVICES," WILEY, 1981, CHAP. 5

**FOWLER PLOT (T = 300K)**
n - Si/Au SCHOTTKY

![Fowler Plot](image-url)
FOWLER PLOT (T = 300K)

COHERENTLY STRAINED $n$-Si$_{0.77}$Ge$_{0.23}$/Au SCHOTTKY

TWO-BARRIER FIT:
$Q_{HI} = 0.953$ eV (93%)
$Q_{LO} = 0.775$ eV (7%)

FOWLER PLOT (T = 300K)
n-Si$_{0.8}$Ge$_{0.2}$/Au SCHOTTKY

RLX

COH
SUMMARY

• Si MBE ⇒ MULTILAYERS IN A Si-PROCESS - COMPATIBLE TECHNOLOGY

• BETTER "CONVENTIONAL" DEVICES POSSIBLE (E.G., Si:Ga IBC)

• NOVEL DEVICES POSSIBLE (MQW)

• SiGe/Si MQW ADVANTAGE: DETECTS NORMALLY INCIDENT LIGHT

• Si(Ge) STRAINED SCHOTTKY BARRIERS: INTERESTING PROSPECTS FOR DEVICES AND PHYSICS
Novel Si$_{1-x}$Ge$_x$/Si Heterojunction Internal Photoemission
Long Wavelength Infrared Detectors

Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology

ABSTRACT

There is a major need for long-wavelength-infrared (LWIR) detector arrays in the range of 8 to 16 $\mu$m which operate with close-cycle cryocoolers above 65 K. In addition, it would be very attractive to have Si-based infrared (IR) detectors that can be easily integrated with Si readout circuitry and have good pixel-to-pixel uniformity, which is critical for focal plane array (FPA) applications. We report here a novel Si$_{1-x}$Ge$_x$/Si heterojunction internal photoemission (HIP) detector approach with a tailorable LWIR cutoff wavelength, based on internal photoemission over the Si$_{1-x}$Ge$_x$/Si heterojunction. The HIP detectors were grown by molecular beam epitaxy (MBE), which allows one to optimize the device structure with precise control of doping profiles, layer thickness and composition.

The HIP detector incorporates a degenerately doped p$^+$-Si$_{1-x}$Ge$_x$ layer as the photo emitter, and the Si substrate as the collector. The detection mechanism is IR absorption in the p$^+$-Si$_{1-x}$Ge$_x$ emitter followed by internal photoemission of photoexcited holes over the Si$_{1-x}$Ge$_x$/Si heterojunction barrier into the p-Si substrate. The valence band discontinuity between Si$_{1-x}$Ge$_x$ and Si layers determines the energy barrier, and can be adjusted by varying the Ge composition ratio $x$. Thus, the cutoff wavelength of the Si$_{1-x}$Ge$_x$/Si HIP IR detector is tailorable over a wide LWIR range; for example, 8 -16 $\mu$m with $x$ ranging from about 0.2 to 0.4. The tailorable cutoff wavelength can be used to optimize the trade-off between the LWIR response and the cooling requirements of the detector.

The Si$_{1-x}$Ge$_x$/Si HIP detector approach is made possible by the recent advance in MBE growth of degenerately doped p$^+$-Si$_{1-x}$Ge$_x$ layers with abrupt boron doping profiles. Doping concentrations to $10^{20}$ cm$^{-3}$ in the Si$_{1-x}$Ge$_x$ layers are achieved using boron from an HBO$_2$ source during MBE growth. The p$^+$ doping enables adequate IR absorption for photoexcited hole generation in the Si$_{1-x}$Ge$_x$ layers.

Compared to silicide Schottky-barrier detectors, the HIP detector offers a higher internal quantum efficiency (QE). One reason is the narrow band of hole occupied states in the p$^+$-Si$_{1-x}$Ge$_x$ layer due to its semiconductor band structure. In Schottky detectors, photons can excite carriers from states far below the Fermi energy such that they do not gain sufficient energy to overcome the barrier. Near threshold only a small fraction of the photoexcited carriers can exceed...
the barrier energy. Consequently, its QE rises only slowly with energy above the barrier cutoff energy. In contrast, the narrow band of absorbing states in the HIP detector leads to a sharper turn-on, which in turn results in useful sensitivities close to the cutoff. This property avoids a serious weakness of Schottky detectors where the Fowler's dependence provides reasonable QE only at wavelengths well below the cutoff, which requires lower operating temperatures for a given dark current. Another reason is that photoexcited holes traveling over the potential barrier can more easily conserve their lateral momentum because of the more favorable ratio of effective masses across the heterojunction. Furthermore, improvement is expected because of reduced inelastic hole scattering in the Si\textsubscript{1-x}Ge\textsubscript{x} layers compared with the silicides, and the ability to grow Si\textsubscript{1-x}Ge\textsubscript{x} layers with optimal thickness, doping and composition.

Preliminary HIP detectors have been fabricated by MBE growth of Si\textsubscript{1-x}Ge\textsubscript{x} layers with x = 0.2, 0.3 and 0.4 on patterned p-type Si substrates. The detectors incorporate n-type guard-rings defining the periphery of the active device areas to suppress leakage current. The photoresponses of the detectors were measured with front-side illumination using a blackbody source at 940 K. Photoresponses at wavelength 2 to 10 μm are obtained with QE above ~ 1% in these non-optimized structures. The tailorable cutoff wavelength of the proposed HIP detector has also been demonstrated by varying the Ge ratio x in the Si\textsubscript{1-x}Ge\textsubscript{x} layers. The photoresponses of Si\textsubscript{1-x}Ge\textsubscript{x}/Si HIP detectors with x = 0.2, 0.3 and 0.4 increase and extend to longer wavelengths as the Ge ratio x reduces from 0.4 to 0.2. Furthermore, the QE of the device can be improved by optimizing the layer thickness and the doping profile of the Si\textsubscript{1-x}Ge\textsubscript{x} layers. By reducing the thickness of Si\textsubscript{0.7}Ge\textsubscript{0.3} layers from 400 nm to 40 nm, and increasing the boron doping concentrations from 10\textsuperscript{19} to 10\textsuperscript{20} cm\textsuperscript{-3}, the QE's have been improved by two orders of magnitude (from 0.003 % to ~0.3% at 8 μm).

In conclusion, the feasibility of a novel Si\textsubscript{1-x}Ge\textsubscript{x}/Si HIP detector has been demonstrated with tailorable cutoff wavelength in the LWIR region. Photoresponse at wavelengths 2 to 10 μm are obtained with QE above ~ 1% in these non-optimized device structures. It should be possible to significantly improve the QE of the HIP detectors by optimizing the thickness, composition, and doping concentration of the Si\textsubscript{1-x}Ge\textsubscript{x} layers and by configuring the detector for maximum absorption such as the use of a cavity structure. With optimization of the QE and by matching the barrier energy to the desired wavelength cutoff to minimize the thermionic current, we predict near background limited performance in the LWIR region with operating temperatures above 65K. Finally, with mature Si processing, our relatively simple device structure offers potential for low-cost producible arrays with excellent uniformity.

*This work is supported by NASA and SDIO.*
Si$_{1-x}$Ge$_x$/Si Heterojunction Internal Photoemission Detectors for LWIR Focal Plane Array Applications


Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology

Supported by NASA/OAET and SDIO/ISTO

OUTLINE

- Introduction
- Advantages of the Si$_{1-x}$Ge$_x$ HIP detectors
- Growth and Fabrication of the HIP detectors
- Results and Discussion
- Summary
INTRODUCTION

Novelties
- Degenerately doped $p^+\text{Si}_{1-x}\text{Ge}_x$ layers for strong IR absorption
- $\text{Si}_{1-x}\text{Ge}_x$/Si valence band offset as the potential barrier, which is tailorable over a wide LWIR range

Detection mechanism
- IR absorption in the $p^+\text{Si}_{1-x}\text{Ge}_x$ layers
- Internal photoemission over the heterojunction barrier

IR Absorption in Degenerately Doped $P+$ Si$_{1-x}$Ge$_x$ Layers
- Degenerately doped $p^+\text{Si}_{1-x}\text{Ge}_x$ layers are required for strong IR absorption for photoexcited hole generation.
- Two IR absorption mechanisms
  - Free-carrier absorption
    \[ \alpha_f = \frac{Nq^2\lambda^2}{m^*8\pi^2nc^3\tau} \sim N^{1.5} \lambda^{1.5-3.5} \]
  - Intra-valence-band transition

Fig. 3-34 Valence subband structure and intraband transitions.

IR absorption increases with carrier concentration and photon wavelength
Low Temperature Boron Doping for P+ Si_{1-x}Ge_x Layers

The Si_{1-x}Ge_x /Si HIP detector approach is made possible by utilizing a low temperature boron doping technique developed at JPL.

Low growth temperatures required
- 2-dimensional (planar) Si_{1-x}Ge_x growth
- Abrupt boron doping profiles

\([B] > 10^{20} \text{ cm}^{-3}\) has been achieved using boron from an HBO_2 source during MBE growth

Advantages of Si_{1-x}Ge_x /Si HIP LWIR Detectors

- Si-based IR detector with similar advantages of Schottky-barrier IR detectors:
  - Integration with Si readout circuitry either monolithically or by In bond bounding
  - Good pixel-to-pixel uniformity
  - Allows normal IR illumination
  - High yield and low cost (cents/pixel)

- Feasible for large focal plane array application as demonstrated by commercially available 512x512 PtSi arrays, but extended to the LWIR regime

- Tailorable LWIR Cutoff
  - can be adjusted to match the desirable cutoff to minimize the dark current

- Relatively good QE's for large array applications
Tailorable Cutoff in LWIR Regime

- The cutoff wavelength $\lambda_c$ of the $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ HIP detector is determined by the valence band offset $\Delta E_v$ between $\text{Si}_{1-x}\text{Ge}_x$ and Si, which is equal to $\sim 90\%$ of the bandgap difference between $\text{Si}_{1-x}\text{Ge}_x$ and Si. The bandgap of $\text{Si}_{1-x}\text{Ge}_x$ can be varied by adjusting Ge ratio $x$ and strain. Consequently, the cutoff wavelength of $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ HIP detector is tailorable in a wide LWIR region.

$\Delta E_v$ as a function of Ge ratio $x$

The corresponding cutoff $\lambda_c$

Higher QE (compared with Schottky detectors)

- Narrow band of occupied hole states (due to its semiconductor band structure) in the $p^+\cdot\text{Si}_{1-x}\text{Ge}_x$ layer of the HIP detector leads to a sharper turn-on, resulting in useful sensitivities close to the cutoff

The more favorable ratio of effective masses across the heterojunction reduces the backscattering of photoexcited holes
Fabrication of Si$_{1-x}$Ge$_x$/Si HIP IR Detectors

- Surface preparation: using "spin-clean" technique

- MBE growth of p$^+$-Si$_{1-x}$Ge$_x$ layers on patterned p-type Si(100) wafers
  
  Growth temperature = 600°C
  
  [B] = $10^{19}$ to $10^{20}$ cm$^{-3}$
  
  Ge ratio x = 0.2, 0.3 and 0.4

- Device fabrication
  
  Six level mask set
  
  In-house fabrication

Current-Voltage Characteristic

400 nm thick Si$_{0.72}$Ge$_{0.28}$ layers, [B] = $10^{19}$ cm$^{-3}$

Temp = 77 K

Bias applied to p-Si substrate, with the Si$_{0.72}$Ge$_{0.28}$ layer grounded

Ideality factor n = 1.4, $J_0 \sim 2 \times 10^{-6}$ Acm$^{-2}$
**Activation Energy Measurement**

- **Bias** = -0.2 V
- **\( \phi_B = 0.14 \text{ eV} \)**
- **400 nm thick Si\(_{0.72}\)Ge\(_{0.28}\)**
- **[B] = 10\(^{19}\) cm\(^{-3}\)**
- **Temp = 90 - 145 K**

\[
\ln\left(\frac{J_0}{T^2}\right) = -\frac{q\phi_B}{kT} + \ln(A^*)
\]

**PHOTORESPONSE MEASUREMENTS**

- **400 nm thick Si\(_{0.72}\)Ge\(_{0.28}\)**
- **[B] = 10\(^{19}\) cm\(^{-3}\)**
- **-1.5 V bias**
- **77K measurement**
Optimization of Device Structure

- Two orders of magnitude QE improvement (from 0.003% to 0.3% at 8 μm) by reducing the thickness from 400 to 40 nm, and increasing [B] from $10^{19}$ to $10^{20}$ cm$^{-3}$

- Extended photoresponse as Ef moves further below Ev for degenerately doped p$^+$-Si$_{1-x}$Ge$_x$ layers

Tailorable LWIR Cutoff Wavelengths

- 40-nm-thick p$^+$-Si$_{1-x}$Ge$_x$ layers
- $x = 0.2$, 0.3 and 0.4
- [B] = $10^{20}$ cm$^{-3}$

- Photoresponse extends to longer wavelengths as Ge ratio $x$ decreases
- QE increases as Ge ratio $x$ decreases
- Demonstrated photoresponse improvement by optimizing the thickness, doping concentration and composition of the Si$_{1-x}$Ge$_x$ layers
Discussion

NEAT: Noise Equivalent Temperature change $NEAT$ (the minimum $\Delta T$ required to have S/N=1) is the array figure of merit

- **Uniformity-limited NEAT**
  
  \[
  NEAT_u = 7 \times 10^{-5} T^2 \lambda U
  \]

  $NEAT = 60 \text{ mK}$ for $U=0.1\%$, $T=293 \text{ K}$, and $\lambda=10 \mu\text{m}$

- **Single-pixel-limited NEAT**
  
  \[
  NEAT = \frac{(A\Delta f)^{1/2}}{D^* (dP/dT) \sin^2 (\theta/2)}
  \]

  For $D^* = 10^{10} \text{ cmHz}^{1/2}/\text{W}$, $NEAT = 10 \text{ mK}$ for 50 $\mu\text{m}$ square pixel, $\Delta f = 60 \text{ Hz}$, and f/2 optics.

  For $NEAT$ (pixel) $< 60 \text{ mK}$, $D^* > 1.6 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$

- **Detectivity $D^*$ is given by**
  
  \[
  D^* = 0.4 \eta \lambda (qJ_0)^{-0.5}
  \]

  For $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ HIP detectors with an 11$\mu\text{m}$ cutoff and $\eta = 0.3\%$ at 10 $\mu\text{m}$ operating at 65 K ($J_0 = 2 \times 10^{-4} \text{ Acm}^{-2}$), $D^* = 2 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$

Summary

- A new $p^+\text{Si}_{1-x}\text{Ge}_x/p-$Si HIP detector approach has been demonstrated at wavelengths ranging from 2 to 10 $\mu\text{m}$ with > 1% QE's.

- Cutoff is tailorable over a wide LWIR range by varying the Ge ratio $x$ in the $\text{Si}_{1-x}\text{Ge}_x$ layers.

- Initial improvement of detector performance has been demonstrated by optimizing the thickness, doping concentration and composition of the $\text{Si}_{1-x}\text{Ge}_x$ layers.

- The potential detector performance ($D^* \sim 2 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$, at 65K) allows the fabrication of large LWIR FPA's with uniformity-limited performance (assuming 0.1% uniformity).

- Potential for low cost and producible large focal plane array fabrication with mature silicon processing and our relatively simple device structure.
SESSION VII: Alternate II-VI Detectors

VII-1 MBE HgCdTe Heterostructure Detectors
   J.N. Schulman, Hughes Research Laboratories

VII-2 Growth and Properties of Hg-Based Quantum Well Structures and Superlattices
   J.F. Schetzina, North Carolina State University

VII-3 HgZnTe-Based Detectors for LWIR NASA Applications
   E.A. Patten, Santa Barbara Research Center
HgCdTe has been the mainstay for medium (3-5 μm) and long (10-14 μm) wavelength infrared detectors in recent years. Conventional growth and processing techniques are continuing to improve the material. However, the additional ability to tailor composition and placement of doped layers on the tens of angstroms scale using MBE provides the opportunity for new device physics and concepts to be utilized. MBE-based device structures to be discussed here can be grouped into two categories: tailored conventional structures and quantum structures.

The tailored conventional structures are improvements on familiar devices, but make use of the ability to create layers of varying composition and thus band gap at will. The heterostructure junction can be positioned independently of doping p-n junctions. This allows the small band gap region in which the absorption occurs to be separated from a larger band gap region in which the electric field is large and where unwanted tunneling can occur. Data from hybrid MBE/LPE/bulk structures will be shown.

Quantum structures include the HgTe-CdTe superlattice, in which the band gap and transport can be controlled by alternating thin layers (tens of angstroms thick) of HgTe and CdTe. The superlattice has been shown to exhibit behavior which is non-alloy like, including very high hole mobilities, two-dimensional structure in the absorption coefficient, resonant tunneling, and anisotropic transport.
QUANTUM / CLASSICAL STRUCTURES

I. Quantum effect structure
   Superlattice - New material properties.
   A. Layer thickness tailorable band gaps.
   B. Enhanced effective masses / reduced tunneling.
   C. New physics
      1. High hole mobilities
      2. 2-D density of states
      3. Intrinsic interface states
II. "Classical Devices"

A. Doping profile control.
B. Composition profile control.
C. Carrier generation / collection regions separated.
D. Hybrid devices - diodes, transistors, signal processing, lasers.

An MBE GROWN MULTILAYER STRUCTURE (In DOPED & UNDOPED)

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature</th>
<th>Thickness</th>
</tr>
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<tbody>
<tr>
<td>Hg$<em>{0.7}$Cd$</em>{0.3}$Te UNDOPED</td>
<td>800°C</td>
<td>0.8 µm</td>
</tr>
<tr>
<td>Hg$<em>{0.7}$Cd$</em>{0.3}$Te In DOPED</td>
<td>700°C</td>
<td>0.8 µm</td>
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<tr>
<td>Hg$<em>{0.7}$Cd$</em>{0.3}$Te In DOPED</td>
<td>600°C</td>
<td>0.8 µm</td>
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<td>Hg$<em>{0.7}$Cd$</em>{0.3}$Te UNDOPED</td>
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<td>CdTe BUFFER</td>
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<td>CdTe SUBSTRATE</td>
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A HYBRID p-on-n HETEROJUNCTION STRUCTURES

<table>
<thead>
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<th>Material</th>
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<tbody>
<tr>
<td>Hg_{0.7}Cd_{0.3}Te</td>
<td>As DOPED, 5 x 10^{16}/cm³</td>
<td>MBE GROWN, 2 μm</td>
</tr>
<tr>
<td>Hg_{0.8}Cd_{0.2}Te</td>
<td>In DOPED, 5 x 10^{14}/cm³</td>
<td>BULK GROWN</td>
</tr>
</tbody>
</table>
RELATIVE SPECTRAL RESPONSE OF p-on-n HETEROJUNCTION DIODES

V1658-3E DIODE 977K
AVERAGE CUTOFF 11.76 ±0.08 \( \mu \text{m} \)

MBE p ON n DLHJ WAFERS
MBE TECHNOLOGY PROVIDES EXCELLENT P+-N HETEROJUNCTION CHARACTERISTICS

V1658-B3/SW611H/MCT 204H
8 x 9 MIL TEST DIODES, MBE p-CN-n, AFTER CdTe PASSIVATION, T = 77K 1/30/89

CURRENT

VOLTS
DOUBLE LAYER HETEROJUNCTION STRUCTURE AND ITS BAND DIAGRAM

A HYBRID n-on-p HETEROJUNCTION STRUCTURE

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>Growth Method</th>
<th>Doping Level</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>HgCdTe</td>
<td>X=0.35, In DOPED</td>
<td>2 μm</td>
<td>MBE GROWN</td>
<td>5x10^{17} /cm³</td>
</tr>
<tr>
<td>HgCdTe</td>
<td>X=0.3, As DOPED</td>
<td>10 μm</td>
<td>LPE GROWN</td>
<td>5x10^{16} /cm³</td>
</tr>
<tr>
<td>CdTe</td>
<td></td>
<td></td>
<td>SUBSTRATE</td>
<td></td>
</tr>
</tbody>
</table>
I-V CHARACTERISTICS OF A HYBRID n-on-p HETEROJUNCTION DIODE (30 μm x 30 μm)

An ALL MBE GROWN DOUBLE LAYER HETEROJUNCTION STRUCTURES

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>HgCdTe (X=0.3)</td>
<td>As Doped 5 x 10^{17} /cm³ , 2 μm</td>
<td></td>
</tr>
<tr>
<td>HgCdTe (X=0.2)</td>
<td>In Doped 5 x 10^{15} /cm³ , 8 μm</td>
<td></td>
</tr>
<tr>
<td>CdTe BUFFER LAYER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdTe SUBSTRATE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hg(1-x)Cd(x) Te Band Gap versus x

CdTe Band Gap = 1.6 eV
HgTe Band Gap = -0.3 eV

Hg$_{0.15}$ Cd$_{0.85}$ Te/HgTe vs HgTe/CdTe SUPERLATTICES
HgTe–CdTe SUPERLATTICE BAND GAP

\[ E_{GS} = \text{SUPERLATTICE BAND GAP} \]

Contour interval = 50 meV

McGill, Wu, Hetzler, J. Vac. Sci. A4, 2091(86)
VALENCE TO CONDUCTION
SUBBAND ABSORPTION

HgTe/HgCdTe
Schulman, (+7), APL 53, 2420 (1988)
CONCLUSIONS

I. MBE alloy device-quality composition / doping control available. Much progress for variety of applications soon.

II. Superlattice composition control excellent, doping control in progress. New device structures utilizing new physics needed.
Growth and Properties of Hg-Based Quantum Well Structures and Superlattices

J.F. Schetzina

Department of Physics, North Carolina State University, Raleigh, NC 27695-8202

An overview of the properties of HgTe-CdTe quantum well structures and superlattices will be presented. These new quantum structures are candidates for use as new LWIR and VLWIR detectors, as well as for other optoelectronic applications. Much as been learned within the past two years about the physics of such structures. The valence band offset has been determined to be ~350 meV, independent of temperature. The occurrence of electron and hole mobilities in excess of $10^5$ cm$^2$/V·s is now understood on the basis of SL band structure calculations. The in-plane and out-of-plane electron and hole effective masses have been measured and interpreted theoretically for HgTe-CdTe superlattices. Controlled substitutional doping of superlattices has recently been achieved at NCSU, and modulation-doped SLs have now been successfully grown and studied. Most recently, a dramatic lowering of the growth temperature of Hg-based quantum well structures and SLs (to~100 C) has been achieved by means of photoassisted MBE at NCSU. A number of new devices have been fabricated from these doped multilayers.

Work supported by NSF grant DMR-88-13525 and NRL contract N00014-89-5-2024.
GROWTH AND PROPERTIES OF Hg-BASED
QUANTUM WELL STRUCTURES & SUPERLATTICES

J. F. Schetzina
Department of Physics

North Carolina State University, Raleigh, NC

NCSU II-VI SEMICONDUCTOR MBE PROGRAM
Collaborators and Students at NCSU

- Research Associates
  N.C. Giles
  S. Hwang
  Z. Yang
  J. Yu

- Graduate Students
  D. Dreifus
  J. Han
  Y. Lansari
  R. Vaudo
  R. Reed

- Technicians
  J. Matthews
  B. Sneed
  K. Bowers

- Secretary
  T. Hockenberger

- Undergraduates (4)
OVERVIEW OF PRESENTATION

- Photoassisted MBE at NCSU
  - Experimental Procedures
  - Summary of Materials Properties
- HgTe-CdTe Superlattices
  - Growth of VLWIR Structures (18 - 22 μm)
  - Controlled Doping Studies
  - Low Temperature Processing at NCSU
- Applications
  - Sources & Detectors
  - Amplifiers & Modulators

ENERGY BAND GAP vs LATTICE CONSTANT
OF SELECTED SEMICONDUCTORS

<table>
<thead>
<tr>
<th>Lattice Constant (Å)</th>
<th>Energy Band-Gap (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>0.0</td>
</tr>
<tr>
<td>6.0</td>
<td>1.0</td>
</tr>
<tr>
<td>6.5</td>
<td>2.0</td>
</tr>
<tr>
<td>7.0</td>
<td>3.0</td>
</tr>
<tr>
<td>7.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

- II-VI
- III-V
- IV

Selected Semiconductors:
- ZnS
- ZnSe
- CdS
- MnSe
- CdTe
- HgTe
PHOTOASSISTED MOLECULAR BEAM EPITAXY
A New Approach to Controlled Substitutional Doping

R.N. Bicknell, N.C. Giles, and J.F. Schetzina

- A Form of Energy-Assisted Epitaxy
- Growth Temperatures of II-VI Compounds are Low (150 - 350 °C)
- Photons Provide a Source of High Energy, Low Momentum Particles that Bathe the Substrate Surface during Film Growth & Induce Photochemical Reactions
- “It's all done with MIRRORS!!!”

PHOTOASSISTED MOLECULAR BEAM EPITAXY

ILLUMINATED SUBSTRATE

MBE OVENS

MBE OVENS

LIGHT SOURCE

SUBSTITUTIONAL DOPING OF II-VI SEMICONDUCTORS
Major Long-Term Problems

- Poor Quality Bulk Crystals & Substrates
- Large Dislocation Densities
- Large Densities of Native Defects
- Low Percentage of Dopant Activation
- Compensation Effects Often Dominate
- Poor Electrical Properties - Low Mobilities
- Inferior Optical Properties - Deep Levels
PHOTOASSISTED MOLECULAR BEAM EPITAXY

Microscopic Mechanisms

- Conversion of Surface Molecules into Atoms
- Photochemical Changes in Atomic Bonding
- Enhancement of Surface Mobility of Atoms
- Photochemical Activation of Dopant Atoms
- Modification of Stoichiometry of Growth Surface

PHOTOASSISTED MOLECULAR BEAM EPITAXY

MBE Film Growth Systems at NCSU

SYSTEMS DESIGNED AND CONSTRUCTED AT NCSU

- Custom Features for II-VI Materials
  - Cost Effective

MBE FACILITIES

- Three Hg-Compatible Systems
- One System for Wide Gap II-VIs
- Special Hg Sources (NCSU)
- Two-Zoned Furnaces (NCSU)
- Computer-Controlled Shutters
- Spectra Physics Argon Ion Laser
PHOTOASSISTED MOLECULAR BEAM EPITAXY
WIDE-BAND-GAP & NARROW-BAND-GAP II-VIs

<table>
<thead>
<tr>
<th>MATERIALS GROWN</th>
<th>PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe:In</td>
<td>• Controlled Doping</td>
</tr>
<tr>
<td>CdTe:Sb</td>
<td>• High Carrier Mobilities</td>
</tr>
<tr>
<td>CdTe:As</td>
<td>• Narrow Rocking Curves</td>
</tr>
<tr>
<td>CdMnTe-CdTe Superlattices</td>
<td>• Bright Photoluminescence</td>
</tr>
<tr>
<td>HgTe-CdTe Superlattices</td>
<td>• p-n Junctions Fabricated</td>
</tr>
<tr>
<td>Modulation-Doped HgCdTe</td>
<td>• FETs Fabricated</td>
</tr>
</tbody>
</table>

HgTe-CdTe SUPERLATTICES

Growth Parameters

<table>
<thead>
<tr>
<th>SUBSTRATE:</th>
<th>(100) CdZnTe</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBSTRATE TEMPERATURE:</td>
<td>150 °C</td>
</tr>
<tr>
<td></td>
<td>140 °C (Photoassisted)</td>
</tr>
<tr>
<td>$T_{\text{In}}$:</td>
<td>400-475 °C</td>
</tr>
<tr>
<td>$T_{\text{As}}$:</td>
<td>220 °C</td>
</tr>
<tr>
<td>Hg FLUX:</td>
<td>1.5 X10^{-4} Torr</td>
</tr>
<tr>
<td>DEPOSITION RATE:</td>
<td>1-3 Å/sec</td>
</tr>
<tr>
<td>LAYER THICKNESSES:</td>
<td></td>
</tr>
<tr>
<td>HgTe</td>
<td>32-160 Å</td>
</tr>
<tr>
<td>CdTe</td>
<td>26-102 Å</td>
</tr>
</tbody>
</table>
Hg Te-CdTe SUPERLATTICES
Designation of Electronic Transitions

QUANTUM TRANSITIONS IN MULTILAYERS

Optical Properties

ORIGINaL PAGE IS OF POOR QUALITY
HgTe-CdTe SUPERLATTICES

Optical Properties

![Graph 1: HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice (SL3)]
- 200 Double-Layers
- $L_z = 51.7$ Å
- $L_b = 51.8$ Å
- Substrate: (100) CdTe
- $T_s = 175 ^\circ C$

![Graph 2: HgTe-Hg$_{0.15}$Cd$_{0.85}$Te Superlattice (SL21S)]
- 200 Double-Layers
- $L_z = 54.9$ Å
- $L_b = 42.1$ Å
- Substrate: (100) CdTe
- $T_s = 175 ^\circ C$

Optical Properties: VLWIR Structures

![Graph 3: HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice (A66B)]
- 200 Double-Layers
- $L_z = 77.8$ Å
- $L_b = 51.8$ Å

![Graph 4: HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice (A67B)]
- 200 Double-Layers
- $L_z = 81.0$ Å
- $L_b = 51.8$ Å

370
HgTe-CdTe SUPERLATTICES
Optical Properties: V LWIR Structures

HgTe-HgCdTe Superlattice (A68A)
200 Double-Layers
L_z = 77.8 Å
L_b = 48.6 Å

HgTe-HgCdTe Superlattice (A69A)
200 Double-Layers
L_z = 58.4 Å
L_b = 48.6 Å

HgTe-CdTe SUPERLATTICE BAND GAP

T = 77 K
SL Band Gaps in 2-5 μm Regime
For All Possible SL Layer Combinations

WAVELENGTH (μm)
HgTe-CdTe SUPERLATTICE BAND GAP

T = 77 K

SL Band Gaps in 8-14 \(\mu\text{m}\) Regime
For All Possible SL Layer Combinations

WAVELENGTH (\(\mu\text{m}\))

HgTe-CdTe SUPERLATTICE BAND GAP

T = 77 K

SL Band Gaps in 18-32 \(\mu\text{m}\) Regime
For All Possible SL Layer Combinations

WAVELENGTH (\(\mu\text{m}\))
HgTe-CdTe SUPERLATTICE BAND GAP

T = 77 K
All SL Band Gaps
For All Possible SL Layer Combinations

WAVELENGTH (μm)

Vertical Cross-Section TEM Photo
of Modulation Doped HgCdTe

N. Otsuka, Purdue University
HgTe-CdTe SUPERLATTICES

Structural Properties: X-Ray Diffraction

Substitutional Doping: n-Type (Indium)
HgTe-CdTe SUPERLATTICES

Substitutional Doping: n-Type (Indium)

Substitutional Doping: p-Type (Arsenic)
HgCdTe-CdTe SUPERLATTICES
Stimulated Emission

HgCdTe Double Heterojunction

Substrate: CdZnTe (100)

DARPA Selective-Area Epitaxy of HgTe-CdTe Superlattices

NCSU
Selective-Area Epitaxy of HgTe-CdTe Superlattices

Growth Parameters: CdZnTe Substrates, Ts = 150 °C,
Applications: Multicolored Sources and/or Detectors; Optical Waveguides; Light Modulators
T = 300 K
2.630 eV
FWHM = 54 meV

T = 77 K
2.699 eV

T = 4.2 K
2.786 eV
2.700 eV

ENERGY (eV)
HgTe-CdTe SUPERLATTICES
Summary of Properties

- An interesting infrared quantum structure
- Superlattice has many different states which exhibit very different properties
- A variable band gap structure as predicted
- Exhibits large absorption in infrared region
- Excellent electrical properties
- Excellent structural properties
- Short minority carrier lifetimes (10 - 20 ns)
- Detector applications: VLWIR region (18 - 24 μm)
HgZnTe has become of growing interest in recent years for IR detector applications because of the promise of equivalent performance but with greater producibility and reliability than HgCdTe-based detectors. The substitution of Zn for Cd in a dilute alloy with HgTe was predicted by Arden Sher et al (J. Vac. Sci. Technol. A 3(1), Jan/Feb 1985, pp. 105-111) to give a material with greater mechanical hardness along with other advantageous properties for IR detectors. Over the past four years, our group and others have grown and characterized HgZnTe and shown that it indeed has increased microhardness, lower Hg diffusion rates and equivalent crystal quality, electrical and optical properties as compared with HgCdTe. Other advantageous properties including higher Hg vacancy formation energies, sharper exciton line, and reduced Te antisite formation have been predicted and/or measured. Triboulet and coworkers in France have fabricated diodes from bulk-grown HgZnTe and have seen greater bake stability for these devices as compared with their HgCdTe diodes. We report here today on test results on our first lot of VLWIR HgZnTe photoconductors using the HIT approach developed for HgCdTe.

Our initial goal on this program was to grow and characterize HgZnTe and determine if it indeed had the advantageous properties that were predicted. We grew both bulk and liquid phase epitaxial HgZnTe and collaborating with SRI and Stanford we determined that HgZnTe had the following properties: 1) microhardness at least 50% greater than HgCdTe of equivalent bandgap, 2) Hg annealing rates of at least 2 - 4 times longer than HgCdTe, and 3) higher Hg vacancy formation energies. This early work did not focus on one specific composition (x-value) of HgZnTe since NASA was interested in HgZnTe’s potential for a variety of applications. Since the beginning of 1989, we have been concentrating, however, on the liquid phase growth of VLWIR HgZnTe (cutoff ~ 17 μm at 65K) to address the requirements of the Earth Observing System (Eos).

Since there are no device models to predict the advantages in reliability one can gain with increased microhardness, surface stability, etc., one must fabricate HgZnTe detectors and assess their relative bake stability (accelerated life test behavior) as compared with HgCdTe devices fabricated in the same manner. Fabrication of HgZnTe devices only became feasible for us in 1989 as we were able to reduce Te melt retention on the surface of our layers and obtain a reasonable yield of device quality layers. We have chosen to fabricate HIT detectors as a development vehicle for this program because high performance in the VLWIR has been demonstrated with HgCdTe HIT detectors and the HgCdTe HIT process should be applicable to HgZnTe. HIT detectors have a significant advantage for satellite applications since these devices dissipate much less power than conventional photoconductors to achieve the same responsivity.
Our first lot of HgZnTe HIT photoconductors exhibit high performance with cutoffs greater than 18 μm. We have performed initial radiometric testing at 30K and 80K and have achieved peak D* of $6 \times 10^{10}$ cm$^2$Hz/W at 30K which is within a factor of two of BLIP for the background level used ($3 \times 10^{16}$ ph/cm$^2$/sec). Peak responsivities at 80K of $3 \times 10^4$ V/W have been measured which are comparable with those typically seen for conventional HgCdTe photoconductors. These results are very exciting especially in view of the fact that this is our first lot of HgZnTe devices. Parameters of the starting material which may have limited performance of this first lot will be discussed. Also to be discussed are our plans to continue this year to refine the material parameters (thickness, cutoff, etc.) to achieve higher performance with our second lot to be processed in June.
HgZnTe-Based Detectors for LWIR NASA Applications

Elizabeth A. Patten and Murray H. Kalisher

Innovative LWIR Detector Workshop
April 25, 1990

Sponsored by NASA/Langley (W. E. Miller, Technical Monitor)

Outline

• Why HgZnTe?

• Early Program Results

• 1989 Materials Improvements

• First HgZnTe PC Results
HgZnTe Offers Many Potential Advantages for LWIR Applications

- HgZnTe offers same performance as HgCdTe but potentially with:
  - Greater stability against thermal and mechanical degradation
    - Short ZnTe bond

- Specific advantages predicted and/or measured:
  - HgZnTe mechanically harder (at least 50% for same bandgap)
    - Lattice matches to tougher substrate (20% CdZnTe)
  - Slower Hg diffusion (annealing data)
  - Larger Hg vacancy formation energies predicted
  - Greater bake stability of HgZnTe diodes (French data)
  - Concentration fluctuations suppressed - large binary lattice mismatch
    - Measured uniformity greater for THM HgZnTe vs HgCdTe
    - Exciton line is very sharp
  - Higher m* for same bandgap (15% for .1 eV)
EARLY PROGRAM RESULTS
NASA Has Funded HgZnTe At SBRC Since 1986

- NASA's main concern is device stability in satellite FPAs
- Began as coordinated program with SRI, Stanford:
  - SRI: Theory
  - Stanford: Hardness, Diffusion Measurements
  - SBRC:
    - Bulk HgZnTe Growth (SSR & ZM)
    - Bulk CdZnTe Growth (20% Zn for lattice matched substrates)
    - HLPE HgZnTe
    - Phase Diagram - Liquidus Measurements
    - Materials Characterization/Device Science
- Current goal is development for V LWIR EOS applications
  - 17 μm at ≥ 65 K
- Other HgZnTe work in France, Israel, Poland, Pittsburgh

Growth of HgZnTe is Difficult

- Initial goals to see if HgZnTe could be grown and had promised properties
- Issues concerning HgZnTe growth:
  - Low Zn solubility in Hg or Te-rich melt - much lower than Cd
    - Lowest in Hg melt
    - Same issues with Te-melt growth as for HCT (melt retention)
  - High segregation coefficient of Zn in Te-rich melt
    - 3.5 times that of Cd
    - Tends to increase layer grading
  - HgTe-ZnTe lattice mismatch large - 6% vs 0.3% for HgTe-CdTe
- Both bulk and epitaxial HgZnTe were goals for the program
All Early Program Goals Met

- Early focus of program on material issues
  - Can we grow HgZnTe?
  - Does it have predicted advantageous properties?

- In first year of program, growth goals achieved:
  - Successful bulk growth of HgZnTe ($x = 0.16$) of high quality - required for structural characterization
    - Mechanical hardness
    - Photoemission
  - Successful bulk growth of Cd$_{0.8}$Zn$_{0.2}$Te with high crystal quality - required for lattice-matched substrates
  - Successful growth of HLPE HgZnTe ($0.11 \leq x \leq 0.24$)
    - Good compositional uniformity/crystal quality

Many HLPE HgZnTe Properties Similar to LPE HgCdTe

- In first year, demonstrated that compared with LPE HgCdTe, HLPE HgZnTe has comparable:
  - Crystal quality
  - Vertical and lateral compositional uniformity
  - Low impurity densities (in annealed wafers)

- Experimentally and theoretically showed that HLPE HgZnTe has:
  - Comparable carrier lifetime with good lateral uniformity
  - Comparable electron mobility ($\mu$) and predicted factor of two smaller hole $\mu$

- Valence band offset measured in bulk HgZnTe by photoemission
  - Smaller than in HgCdTe ($\approx 200$ meV vs $350$ meV)
First Year Work Shows Advantages of HgZnTe

- Both bulk and epitaxial HgZnTe found at least 50% harder than same $E_g$ HgCdTe
  - Knoop microhardness measurements, nanoindenter
- Hg in-diffusion rate at least 2 - 4 times slower for HgCdTe
  - Annealing experiments
- Larger Hg vacancy formation energies predicted
  - HgZnTe should be more stable against Hg loss
- Larger electron $m^*$ predicted
  - Reduced tunneling

HARDENING OF ALLOY DUE TO Zn DEMONSTRATED BY MICROHARDNESS MEASUREMENTS

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>KHN</th>
<th>OTHER MATERIALS</th>
<th>KHN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg$<em>{0.25}$Zn$</em>{0.15}$Te</td>
<td>45.9</td>
<td>Cd$<em>{0.20}$Zn$</em>{0.80}$Te</td>
<td>78.5</td>
</tr>
<tr>
<td>Hg$<em>{0.20}$Zn$</em>{0.10}$Te</td>
<td>38.0</td>
<td>Cd$<em>{0.20}$Zn$</em>{0.80}$Te</td>
<td>46.3</td>
</tr>
<tr>
<td>Hg$<em>{0.20}$Cd$</em>{0.80}$Te</td>
<td>31.6</td>
<td>CdTe</td>
<td>36.1</td>
</tr>
</tbody>
</table>

KHN = KNOOP HARDNESS NUMBER

- THEORETICAL FOUNDATION — SRI
  - HARDNESS DETERMINED BY ENERGY REQUIRED TO FORM PAIRS OF DISLOCATIONS, $E_{PD}$
    - $E_{PD} \sim 1/d^{10} = d =$ CATION-ANION BOND LENGTH
  - $d_{ZnTe}/d_{CdTe} = 0.94 (d_{HgTe}/d_{CdTe} = 1)$
  - SMALLER ZnTe BOND LENGTH INHIBITS DISLOCATION FORMATION AND PROPAGATION
Concentration Fluctuations Probably Suppressed in HgZnTe

- Large lattice mismatch between HgTe and ZnTe favors uniform composition
  - Negligible mismatch between HgTe and CdTe

- Evidence of greater compositional uniformity in HgZnTe exists (Triboulet):
  - THM ingot uniformity
  - Sharpness of exciton line
  - Excellent diode cutoff uniformity

- Greater compositional uniformity offsets larger $dE_g/dx$ in HgZnTe
  - Bowing in $E_g$ vs $x$ also reduces $dE_g/dx$ at long wavelengths:
    - $dE_g/dx = 2.1$ eV for HgZnTe;
      - $= 1.9$ eV for HgCdTe
    (at $E_g = 0.1$ eV or 12.4 μm)

SAT in France Has Produced LWIR HgZnTe Diodes

- SAT achieved comparable diode performance to HgCdTe with bulk HgZnTe and modified SAT process:
  - 14.35 μm performance was achieved with implanted HgZnTe
French Data Implies Greater HgZnTe Diode Bake Stability

- Maximum temperature of vacuum bake before degradation is higher for HZT
- Evaluation of bake data requires details of separate processes for HCT and HZT

These performances of MIT are comparable to those of their MCT counterparts.

Over eight hundred elements have been submitted to thermal test to assess their reliability, under the following conditions of vacuum heating:

\[(100^\circ, 96 \text{ h}) + (120^\circ, 96 \text{ h}) + (140^\circ, 96 \text{ h}) + (160^\circ, 96 \text{ h}) + (180^\circ, 96 \text{ h})].\]

The great majority of the diodes display results as in figure 3. The shunt resistances are limited to 10 MO because of the precision of the measurements under automatic points. R (-10 mV) increases during the first stages of heating before falling, together with Rsh, after the last heating at 180°C. These results express well a very significant improvement in stability compared to MCT diodes of the same cut-off wavelength.

6. CONCLUSIONS

This study demonstrates clearly that the fundamental advantages predicted for MIT over MCT are now confirmed by many relevant experimental results. The reliability of the photodiodes together with their high performances make now MIT the successor designate of MCT for IR detection. The ready ability for MIT to be processed in existing MCT manufacturing facilities can be also considered to be a determining advantage.

Spie Vol. 1106 (1989)
RECENT PROGRESS

1989 Goal to Achieve/Process Device Quality VLWIR HgZnTe

- Focused on obtaining device quality VLWIR HgZnTe in 1989

  - Shifted to VLWIR ($\lambda_{\infty} \geq 16 \mu m @ 80K$) from LWIR

- Goals were to routinely achieve:
  - Good surface morphology - reduce melt retention
  - Desired electrical properties
  - High optical transmission below gap
  - Good carrier lifetimes
  - Cut-off, thickness in desired range

- Device goal was to process/test one lot of HgZnTe Common Module

- Use Trapping Mode approach demonstrated for VLWIR HCT
CURRENT GROWTH PARAMETERS

- GROWTH TECHNIQUE: Te MELT LPE, HORIZONTAL SLIDER
- TEMPERATURE RANGE: 462 - 455°C
- MELT COMPOSITION: 14 g Te, .07 g ZnTe, SEPARATE Hg SOURCE
- COOLING RATE: 0.1°C / MINUTE
- SUBSTRATES: CdTe, Cd_{0.96}Zn_{0.04}Te, Cd_{0.80}Zn_{0.20}Te (NOMINAL)
- SIZE: 1 X 1 INCH
- X-VALUE RANGE: X = .12 - .18

HgZnTe LPE Growth Improved Dramatically in 1989

- Layer Yield Historically Lowered by:
  - Te Melt Retention
  - Strong Composition/Thickness Dependence on Temperature
    - High Zn Segregation
- Sources of Recent Improvement (VLWIR HgZnTe, x = 0.14):
  - Reduced O₂ Contamination
  - Substrate Screening
  - Use of Lower Zn% Substrates
  - Improved Temperature Control
### HgZnTe PC Lot 1 Testing Overview

- Several wafers tested at both 80K and 30K with:
  - 800K blackbody, 30° FOV
  - Background Flux = \(3 \times 10^{16}\) photon/cm\(^2\)/sec

- **80K results:**
  - Blackbody \(D^* = 5 \times 10^{9}\) cm\(^2\)/Hz/W
  - Spectral measurements indicate cutoffs as great as 19 μm

- **30K results**
  - Blackbody \(D^* = 3 \times 10^{10}\) cm\(^2\)/Hz/W
  - Peak \(D^* = 6 \times 10^{10}\) cm\(^2\)/Hz/W (BLIP \(D^* = 1.2 \times 10^{11}\) cm\(^2\)/Hz/W)

- Initial results show cutoffs are longer than desired
80K Noise Increases as Expected at High Bias

![Graph showing 10K Noise (nV/Hz) vs. Field (V/cm)]

D* at 80K Limited by Noise from Long Cutoff

![Graph showing Blackbody D* (cm/Hz/W) vs. Field (V/cm)]

- 80K Blackbody $D^* = 5 \times 10^{-9}$ cm$^2$Hz/W
Spectral Cutoffs of 19 µm at 80K Measured for HgZnTe PCs

- Initial HgZnTe Devices Longer Than Desired
- Performance Should Improve With Decreased Wavelength

Excellent Blackbody Responsivity for HgZnTe Lot 1 at 30K

- Blackbody Responsivities up to $3 \times 10^4$ V/W at 30K
- Comparable with conventional HgCdTe PC
- Responsivity still not saturating at highest bias
Noise Reduced at 30K for HgZnTe PC Lot 1

Peak D* at 30K Close to BLIP

- Peak $D^*$ of $6 \times 10^{10}$ cm$^2$/Hz/W
Summary and Future Plans

• Excellent VLWIR performance demonstrated with initial HgZnTe PCs

• Results show that HgCdTe processing largely compatible with HgZnTe
  • Trapping mode PCs should perform as well in HgZnTe as in HgCdTe

• Sources for improving next HgZnTe device lot defined
  • Shorter cutoff
  • Thinner layers

• Ultimate test of HgZnTe's promise will be accelerated life testing
SESSION VIII: III-V Superlattice Detectors

VIII-1 Small Band Gap Superlattices as Intrinsic Long Wavelength Infrared Detector Materials
    D.L. Smith, Los Alamos National Laboratory

VIII-2 LWIR Detector Research in InAsSb/InAs
    P.S. Peercy, Sandia National Laboratories

VIII-3 InAs/Ga1-xInxSb Superlattices for Infrared Detector Applications
    R.H. Miles, Hughes Research Laboratories

VIII-4 IR Detectors Based on n-i-p-i Superlattices
    P.P. Ruden, University of Minnesota

VIII-5 InAs/GaAs and InAs Doping Superlattices
    F.J. Grunthaner, Jet Propulsion Laboratory
Intrinsic long wavelength (λ ≥ 10 μm) infrared (IR) detectors are currently made from the alloy (Hg, Cd) Te. There is one parameter, the alloy composition, which can be varied to control the properties of this material. The parameter is chosen to set the band gap (cut-off wavelength). The (Hg, Cd) Te alloy has the zincblend crystal structure. Consequently, the electron and light-hole effective masses are essentially inversely proportional to the band gap whereas the heavy-hole effective mass is essentially independent of the band gap. As a result, the electron and light-hole effective masses are very small \((M_{e^*}/M_0 < 0.01)\) whereas the heavy-hole effective mass is ordinary size \((M_{hh^*}/M_0 ∼ 0.4)\) for the alloy compositions required for intrinsic long wavelength IR detection. This combination of effective masses leads to rather easy tunneling and relatively large Auger transition rates. These are undesirable characteristics, which must be designed around, of an IR detector material. They follow directly from the fact that (Hg, Cd) Te has the zincblend crystal structure and a small band gap.

In small band gap superlattices, such as HgTe/CdTe, In(As, Sb)/InSb and InAs/(Ga,In)Sb, the band gap is determined by the superlattice layer thicknesses as well as by the alloy composition (for superlattices containing an alloy). The effective masses are not directly related to the band gap and can be separately varied. In addition, both strain and quantum confinement can be used to split the light-hole band away from the valence band maximum. These "band structure engineering" options can be used to reduce tunneling probabilities and Auger transition rates compared with a small band gap zincblend structure material. We discuss the different "band structure engineering" options for the various classes of small band gap superlattices.
SMALL BAND-GAP SUPERLATTICES
AS INTRINSIC IR DETECTOR MATERIALS

D.L. Smith - Los Alamos
C. Mailhiot - Lawrence Livermore

OUTLINE

1) Introduction
2) Band structure engineering
   a) Zincblende structure materials
   b) Small band-gap superlattices
3) An example InAs/GaInSb
4) Conclusion
IR DETECTORS

Optical Input
1) Signal
2) Background
3) Shot noise on background

Optical Input

Electrical Output
Transducer

\[ V_N = \left( v_1^2 + v_2^2 + \cdots \right)^{1/2} \]

BEST TRANSDUCER DOESN'T DEGRADE S/N (BACKGROUND LIMITED)

\[ V_N^2 = \text{STUFF} \frac{\eta Q_B \tau}{d} + n_T + \ldots \]

SHOT NOISE ON OPTICAL BACKGROUND

IDEAL DEVICE BEHAVIOR
1) MINORITY CARRIER DENSITY; INTRINSIC
2) THERMALLY IONIZED CARRIER DENSITY; EXTRINSIC

NONIDEAL BEHAVIOR
DIODE TUNNELING; 1/f ETC.

Want \( \frac{\eta Q_B \tau}{d} > n_T \)

Min \( \frac{n_T}{\alpha \tau} \)

\( d \sim \alpha^{-1} \)

\( \sim e^{-E_i kT} \)
BAND STRUCTURE PARAMETERS

PARAMETERS

- \( E_g \): Absorption threshold
- \( M_e^* (M_\perp; M_{||}) \): Recombination times (Auger; Radiative)
- \( M_h^* (M_\perp; M_{||}) \): Absorption coefficient
- \( P_{eh} \): Transport (Tunneling; Diffusion)

DESIGN PROCESS
1) Material Design
2) Device Design

AVOIDABLE PROCESSES

AUGER

\[ e^{-\frac{E_g}{kT} \frac{M_e}{M_h}} \]

TUNNELING
K\*P THEORY

\[
\left[ \frac{p^2}{2M} + V \right] \psi = \epsilon \psi
\]

\[
\psi = e^{ik \cdot r} u^k
\]

\[
\left[ \frac{p^2}{2M} + \frac{\hbar k \cdot p}{M} + \frac{(\hbar k)^2}{2M} + V \right] u^k = \epsilon u^k
\]

AT ZONE CENTER \((k = 0)\)

\[
\left[ \frac{p^2}{2M} + V \right] u_j^0 = \epsilon_j^0 u_j^0
\]

\[
U = \sum_j a_j u_j^0
\]

\[
0 = \sum_j \left[ \left( \epsilon_j^0 + \frac{(\hbar k)^2}{2M} - \epsilon \right) \delta_{ij} + \frac{\hbar k^2}{M} \langle u_i | \vec{p} | u_j \rangle \right] a_j
\]

ZINCBLENDE STRUCTURE MATERIALS

\begin{align*}
\text{ELECTRON AND LIGHT HOLE (SMALL } & \epsilon_g \text{) (LARGE } \Delta \text{)} \\
\begin{vmatrix}
\epsilon_c - \epsilon & \alpha \\
\alpha^* & \epsilon_v - \epsilon
\end{vmatrix} &= 0 \quad \alpha = \sqrt{2} i \frac{\hbar k}{3}
\end{align*}

\[
\frac{M_0}{M^*} = \pm \frac{2M}{\hbar^2} |\vec{P}|^2 \left( \frac{2}{3} \frac{1}{E_g} \right)
\]

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SMALL BANDGAP SUPERLATTICES

- HgTe/CdTe
- InAsSb/InSb
- InAs/GaInSb

Type I

Staggered

Type II
\[ \Psi = F U \]

\[ \langle F_1 U_1 | P | F_2 U_2 \rangle \]

\[ - \langle F_1 F_2 \rangle \langle U_1 | P | U_2 \rangle \quad S \]

\[ + \langle F_1 P | F_2 \rangle \langle U_1 | U_2 \rangle \quad W \]
InAs-Ga$_{0.5}$In$_{0.5}$Sb (001) SUPERLATTICE
$M_0 = N_b = 11$ LAYERS

\[
\frac{m^*}{m_0} \sim 0.04
\]

\[
E_{H_H_1}\quad E_{H_H_2}
\]

\[
E_{\text{G}}
\]

\[
E_{H_H_1}\quad E_{H_H_2}
\]

\[
x = 0.22 \quad \text{HgCdTe}
\]

\[
x = 0.4 \quad \text{InAs/GaInSb}
\]

\[
a = b \quad 33 \text{ Å}
\]

\[
(10^{-2} \text{Å}^{-1})
\]
SUMMARY

1) Small band-gap superlattices offer band structure engineering options which make them interesting IR materials

2) Examples of such superlattices include:
   a) HgTe/CdTe
   b) InAsSb/InSb
   c) InAs/GaInSb

3) Predictions on $E_g$ and $\alpha$ in InAs/GaInSb
LWIR DETECTOR RESEARCH IN InAsSb/InAs

P. S. Peercy
Sandia National Laboratories
Albuquerque, NM 87185-5800

The InAsSb/InSb strained-layer system forms a type-II superlattice in the Sb-rich region of the phase diagram. The band gap of InAsSb/InSb strained-layer superlattices grown on lattice-matched buffers can be varied continuously to produce semiconducting systems with band gaps ranging from that of InSb (0.23 eV with an absorption edge at 5.5 μm at 77 K) to 0. The semiconductor to semimetal transition occurs at As concentrations of approximately 30%, with the precise value dependent upon the strain and quantum well dimensions. At higher As content, the system is a semimetal. We have fabricated photovoltaic detectors with high D* at 77 K at wavelengths beyond 10 μm, and both photovoltaic and photoconductive detectors have been demonstrated with response to 15 μm. The photoconductive detectors exhibit gain of up to 100. This talk will discuss details of the materials growth, studies of the band structure and properties, device processing and the detector performance observed to date in these systems.
LWIR DETECTOR RESEARCH
IN InAsSb

P. S. Peercy

Sandia National Laboratories
Albuquerque, New Mexico

(Presented at the Long Wavelength Infrared Detector Workshop, April 24-26, 1990)

OUTLINE

• Summary of InAsSb SLS Properties
  Band structure
  Optical properties

• Photoconductive Detectors
  High gain type II superlattices

• Photovoltaic Detectors
  Electrical characteristics
  Detector response

• Extension to wavelengths beyond 10 μm

• Process Monitors and control
  REMS for on-line growth control
  PL for monitoring material quality
  Processing issues

• Summary
ENERGY GAP IN THE InAsSb ALLOY SYSTEM

\begin{align*}
\text{InAs}_{1-x}\text{Sb}_x
\end{align*}

\begin{align*}
E_g &\quad (\text{eV}) \\
\lambda &\quad (\text{um})
\end{align*}

\begin{align*}
77 \text{ K} \\
300 \text{ K}
\end{align*}

SLS
STRAINED-LAYER SUPERLATTICE (SLS)

THIN, MISMATCHED LAYERS

SUPERLATTICE: MISMATCH ACCOMMODATED BY STRAIN

GRADED LAYER

SUBSTRATE
TYPE I OFFSET:
(Spatially "direct", low energy transitions)

TYPE II OFFSET:
(Lower energy, spatially "indirect" transitions)
Infrared Photoluminescence (SLS)

InAs$_{0.13}$ Sb$_{0.87}$/InSb

260 Å SLS (X2)

106 Å SLS

PHOTO ENERGY (meV)

PHOTOLUMINESCENCE INTENSITY

QUANTUM WELL STRUCTURE
FROM PL DATA

CONDUCTION BAND

VALENCE BAND

InAs$_{0.13}$ Sb$_{0.87}$

InSb

236 meV

267 meV

153 meV

23 meV

hh

hh

84 meV lh

lh

168 meV

138 meV
Far IR Wavelength Accessibility of SLS InAsSb Detectors at 77K

N=1 Transitions For 20% As SLS
InAsSb SLS Photoconductive Detector

(a) Diagram showing the structure of the InAsSb SLS detector with a 2.5μm thick InAs_x Sb_{1-x} graded buffer on an InSb p-substrate.

(b) Energy scale for a 2-layer SLS: InSb/InAs_{0.11} Sb_{0.89}, showing the conduction band (CB) and heavy holes (hh) levels.

(c) Energy scale for a 4-layer SLS: InSb/InAs_{0.07} Sb_{0.93}/InAs_{0.11} Sb_{0.89}/InAs_{0.07} Sb_{0.93}, showing the CB, hh, and light holes (lh) levels.
Photoconductive Detector Responsivity

**WAVELENGTH (\(\mu m\))**

![Graph (a)](image)

- **2-layer SLS**
- **0.25V bias**

**PHOTON ENERGY (meV)**

**RESPONSIVITY (A/W)**

![Graph (b)](image)

- **4-layer SLS**
- **0.25V bias**

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InAsSb Photodiode (MBE)

SLS: 200Å InAs\textsubscript{0.15} Sb\textsubscript{0.85} / 200Å InSb

![Diagram of InAsSb Photodiode](image-url)
PHOTOVOLTAIC AND PHOTOCONDUCTIVE SLS DETECTOR PHOTORESPONSE TO 15 μm

Wavelength (microns)

Responsivity (a.u.)

Photovoltaic Detector (MBF) - 150 Å layers
Photoconductive Detector (MOCVD) - 230 Å layers

Photon Energy (meV)

PROCESS CONTROLS

- On-line monitors and control during growth

  REMS (MBE)

  UV absorption (MOCVD)

- Monitor of superlattice quality

  Photoluminescence
Reflection Mass Spectrometry and III/V MBE

"REMS" Reflection Mass Spectrometry

Reflection Mass Spectrometry and III/V MBE

Composition Control using REMS

$\text{(Al}_x\text{Ga}_{1-x})\text{As}$

$\text{In(As}_x\text{Sb}_{1-x})$

Area: $Y_{Al} = 4.8 \text{nA-s}$
Area: $Y_{Ga} = 5.0 \text{nA-s}$
Photoluminescence Linewidth Characterization of Wafer Quality

InAsSb/InSb SLS

"Best" SLS
FWHM = 10 meV

Surface Limited Response
FWHM = 12 meV

Bulk Limited Response
FWHM = 24 meV

Photon Energy (meV)
PROCESSING TECHNIQUES

ETCHING - STANDARD WET-CHEMICAL TECHNIQUES USING STANDARD PHOTORESIST PROCESSES

METALLIZATION - NON-ALLOYED Ti/Au OR Cr/Au OHMIC CONTACTS DEFINED BY CONVENTIONAL LIFTOFF TECHNIQUES

PASSIVATION - VARIOUS SCHEMES ARE BEING INVESTIGATED WITH POSITIVE RESULTS

PACKAGING - STANDARD PACKAGES AND ADHESIVES WITH ULTRASONIC LEAD BONDING HAVE BEEN USED SUCCESSFULLY

INTERFACING - ISSUE NOT ADDRESSED YET

Superlattice Mesa Photodiode:

Lateral Superlattice Photodiode:
SUMMARY

- InAsSb SLS detectors can span the 8-15 μm spectral region

- LWIR photovoltaic detectors have been demonstrated with $D^* > 10^{10}$ cm$^2$/Hz/W at 10 μm

- LWIR photoconductive detectors with high gain have been demonstrated

- REMS and PL have been demonstrated to be valuable growth and process monitors
InAs/Ga$_{1-z}$In$_z$Sb Superlattices for Infrared Detector Applications

R. H. Miles
Hughes Research Laboratories
Malibu, California 90265

D. H. Chow and T. C. McGill
California Institute of Technology
Pasadena, California 91125

InAs/Ga$_{1-z}$In$_z$Sb superlattices have been proposed as possible alternatives to Hg$_{1-z}$Cd$_z$Te for infrared detector applications, particularly in the 8–12 $\mu$m region and beyond.\(^1,2\) Long wavelength response has been predicted based on the strongly misaligned (type-II) band alignment of the superlattice. Semimetallic behavior consistent with this band alignment has been demonstrated in InAs/GaSb superlattices ($\Delta E_v \simeq 510$meV), but only for comparatively thick layers ($\simeq 100$Å).\(^3\) As type-II structures confine electrons and holes in different layers, electron-hole overlap is poor for layers this thick, and as a consequence the optical absorption coefficients are small. It was proposed that long wavelength response could be achieved for substantially thinner layers by replacing the GaSb layers with Ga$_{1-z}$In$_z$Sb, further misaligning the bands through strain effects and reducing the antimonide band gap.\(^1,2\) Calculated absorption coefficients for these structures are comparable to those of Hg$_{1-z}$Cd$_z$Te.

We report the successful growth of InAs/Ga$_{1-z}$In$_z$Sb superlattices and their optical and structural characterization. Samples were grown by molecular beam epitaxy at fairly low substrate temperatures (< 400 °C). Structural quality was assessed by reflection high energy electron diffraction, transmission electron microscopy, and x-ray diffraction. Excellent structures were achieved for growth on thick, strain relaxed GaSb buffer layers on GaAs substrates, despite a residual threading dislocation density of $10^9$cm$^{-2}$ originating at the GaSb/GaAs interface. Despite a lattice mismatch of 1.7%, InAs/Ga$_{0.75}$In$_{0.25}$Sb superlattices are observed to be free of misfit dislocations at the thicknesses examined here, owing to the close lattice match between the superlattice and GaSb, which evenly distributes compressive and tensile stresses between the InAs and Ga$_{0.75}$In$_{0.25}$Sb layers.

Photoluminescence and photoconductivity measurements indicate that the energy gaps of the strained-layer superlattices are smaller than those of InAs/GaSb superlattices with the same layer thicknesses, and are in agreement with the theoretical predictions of Smith and Mailhiot. Energy gaps of 80-250meV (15 – 5 $\mu$m) have been measured for InAs/Ga$_{0.75}$In$_{0.25}$Sb superlattices with 45 – 25 Å/25 Å layer thicknesses. Our results demonstrate that far-infrared cutoff wavelengths are compatible with the thin superlattice layers required for strong optical absorption in type-II superlattices.

InAs/Ga$_{1-x}$In$_x$Sb SUPERLATTICES FOR INFRARED APPLICATIONS

R. H. Miles & J. N. Schulman, HRL
D. H. Chow & T. C. McGill, Caltech

OUTLINE

- Motivation

- Growth & structural properties
  - TEM
  - x-ray diffraction

- Optical properties
  - photoconductivity
  - photoluminescence
  - absorption

- Conclusion, comparison with theory

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• Proposed as IR detectors by D. L. Smith and C. Mailhiot (J. Appl. Phys. 62, 2545 (1987)).
  - IR energy gaps tunable over entire spectrum
  - large absorption coefficients
  - favorable transport properties ($m^*_{e,L}/m_e \simeq 0.04$)
  - III-V processing

ALIGNMENT OF ENERGY BAND EDGES

InAs/Ga$_{1-x}$In$_x$Sb SUPERLATTICE BAND EDGES

(Smith and Mailhiot)
InAs/Ga$_{1-x}$In$_x$Sb Superlattices

Growth and Structural Characterization

A. Growth
- PHI 430 MBE system
- As$_2$ and Sb$_2$ (cracker) sources
- (100) GaAs substrates
- Substrate temperature monitoring

B. Structural Characterization Techniques
- Surface Morphology
- \textit{in situ} Reflection High Energy Electron Diffraction (RHEED)
- X-ray diffraction
- Transmission Electron Microscopy (TEM)
As-incorporation in InGaSb Layers

I. Experimental

- Grew 2500 Å GaSb(As) layer on InAs Buffer
- X-ray diffraction to determine As-incorporation

II. Growth Parameters Varied

- Substrate Temperature
- As background pressure
- Sb flux

III. Results

- Virtually no Sb incorporated in InAs layers
- Up to 30% As found in GaSb(As) layers
- Reduced As incorporation at lower substrate temperatures, reduced As background (< 7%)
- Sb flux has no effect on As incorporation in GaSb(As)

InAs/Ga$_{1-x}$In$_x$Sb Superlattice

Growth Conditions

I. Substrate Temperature

- Poor surface morphology, x-ray diffraction for $T > 400^\circ$C
- Excellent surfaces, x-ray diffraction for $370 < T < 400^\circ$C

II. Growth Fluxes

- InAs growth rate = 0.5 Å/sec
- Ga$_{1-x}$In$_x$Sb growth rate = 2.0 Å/sec
- Sb flux >> As flux

III. Surface Reconstruction

- 1 x 3 for Ga$_{1-x}$In$_x$Sb
- 1 x 2 for InAs
SCHEMATIC LAYER DIAGRAM

InAs/Ga$_{1-x}$ln$_x$Sb superlattice

InAs

In$_{0.7}$Ga$_{0.3}$As/GaAs superlattice, 2mL/2mL

GaAs

GaAs substrate

0.5 $\mu$m

5 periods

0.3 $\mu$m

10 periods

InAs/Ga$_{1-x}$ln$_x$Sb superlattice

GaSb

GaSb/GaAs superlattice, 1mL/1mL

GaAs

GaAs substrate
• OPTICAL EXCITATION
  - AlGaAs laser diode
  - Ar ion laser
  - 40 kHz modulation

• DETECTION OF LUMINESCENCE
  - Bomem Fourier Transform Infrared Spectrometer (FTIR)
  - lock-in amplifier
  - InSb or Si:As detector

---

InAs/Ga$_{1-x}$In$_x$Sb SLS PHOTOLUMINESCENCE

T=5K

- x=0
  - 28Å/28Å

- x=0.25
  - 25Å/25Å

- x=0.25
  - 37Å/25Å

---

ENERGY (meV)
PHOTOCONDUCTIVITY

- SAMPLE PREPARATION
  - conventional photolithography
  - 60 x 160 μm mesas etched with Br₂:HBr:H₂O
  - Al contacts to mesas and etched surface

- MEASUREMENT
  - blackbody illumination from back (substrate) side of device
  - sample cooled over 5-300K range
  - sample used as detector in FTIR

```
InAs/Ga₁₋ₓInₓSb SLS PHOTOCONDUCTIVITY
(T=4.2K)

x=0.25
45Å/28Å

x=0.25
37Å/25Å

x=0.25
25Å/25Å

x=0
28Å/28Å
```

ENERGY (meV)

CURRENT (arbitrary units)
TABLE I. Comparison of energy band gaps derived from photoluminescence, photoconductivity, and theory for the InAs/Ga$_{1-x}$In$_x$Sb superlattices examined here.

<table>
<thead>
<tr>
<th>LAYER THICKNESS (Å)</th>
<th>InAs</th>
<th>Ga$_{1-x}$In$<em>x$Sb$</em>{1-y}$As$_y$</th>
<th>z</th>
<th>y</th>
<th>PL (meV)</th>
<th>PC (meV)</th>
<th>Theory (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>28</td>
<td>0</td>
<td>0.07</td>
<td>330±10</td>
<td>350±10</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>0.25</td>
<td>0.08</td>
<td>240±10</td>
<td>250±10</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>25</td>
<td>0.25</td>
<td>0.05</td>
<td>150±10</td>
<td>170±10</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>25</td>
<td>0.25</td>
<td>0</td>
<td>*</td>
<td>110±10</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>28</td>
<td>0.25</td>
<td>0</td>
<td>*</td>
<td>80±10</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing absorption spectra for InAs/Ga$_{1-x}$In$_x$Sb superlattices](image)
InAs/Ga$_{1-x}$In$_x$Sb SUPERLATTICES: CONCLUSIONS

- **GROWTH & STRUCTURAL PROPERTIES**
  - GaAs substrates
  - $x = 0, 0.25, 0.35$
  - no misfit dislocations, $10^9\text{cm}^{-2}$ threading dislocations
  - best structure for $370 < T < 400^\circ\text{C}$

- **OPTICAL CHARACTERIZATION**
  - infrared photoluminescence observed
  - photoconductive response beyond 15 $\mu$m
  - energy gaps shift with strain as predicted
  - thin layers ($75\,\text{Å}$ period) yield far-infrared energy gaps
  - 10 $\mu$m absorption comparable to bulk Hg$_{1-x}$Cd$_x$Te
It has been demonstrated that the internal electric fields present in n-i-p-i doped semiconductor superlattices give rise to interband photo absorption well below the bandgap of the host semiconductor material. In addition, the internal fields separate the photo generated electrons and holes resulting in large non-equilibrium charge carrier lifetimes and, consequently, in large photoconductive gain. Experimental results on GaAs n-i-p-i superlattices have confirmed these expectations for photon wavelengths in the near infrared (\(\lambda < 1.5 \ \mu m\)). For an extension of the wavelength range to the mid and far infrared, semiconductors with smaller bandgaps are more suitable than GaAs as n-i-p-i superlattice host materials. Strong candidate materials are InAs and InSb because of their favorable growth and doping properties.

In this paper the principles of operation of n-i-p-i photodetectors will be discussed. Special consideration is given to issues that are relevant to the performance of IR detectors such as noise, dark current, and surface effects. In addition, we will discuss a novel IR detector that promises to provide information about the spectral distribution of the infrared radiation emitted from an object and, consequently, about its temperature, independent of the distance between detector and object. This detector makes use of the possibility to modulate the internal electric fields of an n-i-p-i superlattice with an applied voltage. By this technique the spectral responsivity of the detector may be controlled electrically and some information about the shape of the emission spectrum may be obtained.
IR DETECTORS BASED ON DOPING SUPERLATTICES

P. Paul Ruden
University of Minnesota
Department of Electrical Engineering

Outline

- Introduction, optical absorption in nipi SL
- Electroabsorption GaAs, InAs, InSb
- Noise in nipi detectors
- Spectrally agile detector
- Inhomogeneous excitation and surface effects
- Summary

Doping Superlattice
(n-i-p-i)

Materials: GaAs, AlGaAs, InP, GaP, InAs, InSb, InGaAs, PbTe, Si,...?
Schematic Doping Profile and Band Diagram of NiPd Superlattice

Photon Absorption in Doping Superlattice
Two modes of operation:

1) Photovoltaic mode:
\[ \delta I_{np} \]

2) Photoconductive mode:
\[ \delta I_{nn} \text{ or } \delta I_{pp} \]

**Blackbody spectra** $T=200K, 300K, 400K$
**InSb El. Abs. T=77K**

![Graph showing InSb electron absorption at T=77K.](image)

**Example**

**InSb nipi BLIP**

$n_D^{(2)} = 3.5 \times 10^{12} \text{ cm}^{-2}$

$d_i = 100 \text{ A}$

$\rightarrow F_{bi}d_i \sim E_0$

$\hbar\omega_0 = 108 \text{ meV} \Delta \lambda_0 = 11.5 \mu\text{m}$, $T_B = 300 \text{K}$

$\alpha(\hbar\omega_0) = 130 \text{ cm}^{-1}$

$\bar{\alpha} = 51 \text{ cm}^{-1}$ with cut-off $\hbar\omega_c = 100 \text{ meV}$  

$\bar{\alpha} = 107 \text{ cm}^{-1}$ without cut-off

$N_{SL} = 1750 \rightarrow D^* = 1.1 \times 10^{10} \text{ cm} \sqrt{\text{Hz} / \text{W}}$

compared to BLIP with $\eta = 1 \lambda_c = 11 \mu\text{m}$

$D^* = 3.4 \times 10^{10} \text{ cm} \sqrt{\text{Hz} / \text{W}}$
Noise Sources in nipi IR Detectors

Detectivity

\[
D^* = \sqrt{A} \frac{R}{I_{\text{noise}}} \sqrt{\Delta f}
\]

Thermal g-r noise limited

\[
\bar{\alpha} d_i \sigma_p T_B^3 < p^{(2)}/\tau
\]

Background g-r noise limited

\[
\bar{\alpha} d_i \sigma_p T_B^3 > p^{(2)}/\tau
\]

\[
D^* = \frac{1}{2\hbar \omega} \frac{\alpha(\omega) d_i}{\sqrt{p^{(2)}}} \sqrt{\tau} \sqrt{N_{\text{SL}}}
\]

\[
D^* = \frac{1}{2\hbar \omega} \frac{\alpha(\omega)}{\sqrt{\left(\bar{\alpha} \sigma_p T_B^3\right)^{1/2}}} \sqrt{d_i} \sqrt{N_{\text{SL}}}
\]

\[
\bar{\alpha} = \frac{\int dE \alpha(E) M_p(E, T_B)}{\sigma_p T_B^3}
\]

TARGET DISCRIMINATION BASED ON TARGET TEMPERATURE
BANDPROFILE OF n-i-p-i CRYSTAL

a) Ground State
b) Reverse Bias $U_{np}$
c) Forward Bias $U_{op}$

---

ENERGY (eV)

NORMALIZED PHOTOCURRENT $\Delta I_{ph}(lu)$ (ARBITRARY UNITS)

WAVELENGTH (µm)

C.J. Chang-Hasnain, et al. (1986)
Spectrally Agile nipi Detector

incident spectrum: $\phi_0 M_p(E,T_T)$

\[ I_{\text{ph}}(U_{np}) = \frac{q\mu \tau(U_{np}) V_a}{L} \phi_0 \int dE \eta(U_{np},E) M_p(E,T_T) \]

\[ = \frac{q\mu \tau(U_{np}) V_a}{L} \phi_0 \eta(U_{np},T_T) \]

\[ \frac{I_{\text{ph}}(U_{np1})}{I_{\text{ph}}(U_{np2})} = \frac{\tau(U_{np1}) \eta(U_{np1},T_T)}{\tau(U_{np2}) \eta(U_{np2},T_T)} \rightarrow T_T \]
Schematic Band Diagram
for Doping Superlattice

A: Ground state
B: Excited state

DIRECTION OF PERIODICITY \( z \)
Comparison of Theoretical and Experimental Results for Doping SL Transmission Nonlinearity

Theoretical Calculation of Optically Modulated Transmission
(GaAs Doping SL for Different Excitation Levels)

Optically Modulated Transmission
(GaAs Doping SL for Different Excitation Levels)

Lateral Charge Carrier Distribution

\[ j_n \propto [(V(n^{(2)})) - V_0] \left( \frac{dn^{(2)}}{dx} \right) \]

\[ R(n^{(2)}) \propto n^{(2)}p^{(2)} \exp \left( -\frac{V(n^{(2)})}{kT} \right) \]

\[ n^{(2)}(x) = n_0^{(2)} \exp \left( -\frac{x}{L(n^{(2)})} \right) \]
Potential At Surface

Surface Recombination May Reduce Effective Lifetime
→ Reduce Photoconductive Gain

Surface Potential Barrier
\[ \sigma V_S \sim \frac{2V_0}{2E_S} \]
CONTOUR FROM -0.200E+04 TO 0.200E+04
CONTOUR INTERVAL OF 0.200E-01

ORIGINAL PAGE IS OF POOR QUALITY
Summary

- IR detection with nipi SL based on InAs or InSb is feasible.
- Detector performance can be competitive.
- Spectrally agile detectors may be practical.
- Non-uniform excitation, surface and contact effects are critical.
- Optical nonlinearity can be useful.
InAs/GaAs and InAs Doping Superlattices*

F.J. Grunthaner, B.R. Hancock and J. Maserjian
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

The extension of the optical response of narrow band gap III-V semiconductors into the LWIR regime for high sensitivity sensor applications is a challenging problem. Recent advances in nipi doped GaAs superlattices, lattice mismatched epitaxy and the heteroepitaxial growth of III-V compound semiconductors on silicon substrates offer a number of opportunities. In this paper, we describe two different device approaches based on the MBE growth of superlattice materials which are directed to LWIR focal plane array technology. The first of these uses nipi superlattices fabricated in bulk InAs which has been grown on either GaAs or Si substrates. The second is based on the growth of a new pseudomorphic tetragonal phase of InAs on GaAs to create a semimetal/semiconductor superlattice material.

Considerable progress has been made in recent years in the design, fabrication, and characterization of nipi superlattices in GaAs. The key property of the nipi doping superlattice is the incorporation of alternating planes of dopant atoms in the z-direction as the crystal is grown. This results in an undulating or sawtooth potential superimposed on the existing conduction and valence band electronic structure. At sufficiently high doping levels, the effective gap of the host crystal can be reduced to that of a semimetal. Because of the spatial separation of electron and hole wave functions, the anticipated quantum efficiency of a doping superlattice detector is relatively low. Recent calculations have shown that by shortening the nipi period and by using high doping levels one can achieve practical values for the absorption coefficient at extended wavelengths beyond that corresponding to the bulk bandgap. These calculations indicate that the low effective mass and the intrinsic gap of InAs can be used to create a high quantum efficiency (QE) detector with tailored response over the range 3 - 17 \( \mu \text{m} \). In this device concept, we propose to grow high quality InAs epitaxially on Si substrates, and fabricate InAs nipi photodetectors on this substrate. Although the lattice mismatch between InAs and Si is slightly greater than 11%, heteroepitaxy of high structural quality material has already been achieved. In the final implementation of the concept, the Si substrate would be the backside of a fully processed multiplexer and carriers collected in the InAs would be injected into the Si device for areal image processing.

In this paper, we report the growth of high performance InAs pin photodiode arrays on GaAs substrates. These structures were grown at JPL using RHEED controlled MBE

---

*This work was sponsored by NASA
growth techniques, and were processed into photodiode arrays by Cincinnati Electronics. Performance results show quantum efficiencies, dark currents, reverse bias breakdown, and component-to-component variation in characteristics equal to or better than the corresponding performance of CE's benchmark material which is based on InAs bulk wafers. The device yield was greater than 85%. Esaki InAs tunnel diodes grown by MBE at a doping level of mid $10^{18}$ cm$^{-3}$ on GaAs (100) substrates show a peak to valley ratio of 14:1 at 77 K. This compares to values of 7 to 10 obtained for InAs epi on InAs bulk substrates at 4 K. These results demonstrate the high electronic quality of heteroepitaxial InAs grown on GaAs. We will also present cross-sectional TEM data and RHEED surface lattice constant measurements to show defect control in InAs growth on GaAs and silicon substrates. IR absorption spectral measurements are currently ongoing.

In the second device concept, we propose to grow superlattices with the pseudomorphic tetragonal high pressure phase of InAs interleaved with GaAs to create a semimetal/semiconductor system. Recent data characterizing high pressure phases of InAs have shown the existence of a $\beta$-Sn and a rock salt crystal structure, both of which are semimetals. As demonstrated in the HgTe/CdTe system, choosing different thicknesses of the component layers of the superlattice should give a material with selectable small bandgaps in the range from 0.7 to 0.070 eV. This would correspond to cutoff wavelengths of up to 20 $\mu$m. This material will then be fabricated into photovoltaic arrays on GaAs substrates. In the mature concept, the detector structure could be grown on a preprocessed GaAs wafer which could include CCD structures or other control functions for intelligent sensors.

Using specialized MBE growth techniques specifically engineered for lattice mismatched epitaxy, we have succeeded in growing InAs films on GaAs substrates which are lattice matched to GaAs in the growth plane. This represents a 7.4% compression in the x and y axes of the InAs film on the 100 surface. RHEED surface lattice constant data are consistent with a tetragonal symmetry for the InAs layer. Recent data characterizing high pressure phases of InAs have shown that the $\beta$-Sn crystal structure exists for pressures greater than 7 GPa. The calculated equivalent hydrostatic pressure exerted on the pseudomorphic InAs phase which has been grown lattice matched to GaAs by MBE is greater than 70 GPa. The in plane lattice constant on the 100 surface of the high pressure phase of InAs is lattice matched to GaAs within 1.2%.

In this paper, we will report recent results on the growth and characterization of pseudomorphic InAs grown on GaAs (100) surfaces. In a systematic study of growth by RHEED, electronic structure and composition by x-ray photoemission, coordination geometry by EELFS, and defect structure by Transmission Electron Microscopy, we demonstrate the existence of new phases of InAs in single quantum structures.
InAs/GaAs and InAs Doping Superlattices

F. J. Grunthaner, B. Hancock, and J. Maserjian,
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

Collaborators: K. Delgadillo, J. K. Liu*, A. Ksendzov, F. D. Schowengerdt#, M. E. Greiner^*

* TRW, Los Angeles, California
# Colorado School of Mines, Golden, Colorado
^Cincinnati Electronics Corporation, Cincinnati, Ohio

Outline

- Objectives
- Doping Superlattices
- InAs (bulk) / GaAs Material Growth
- Tunnel Diode Results
- InAs / GaAs Strained-Layer Epitaxy
- Future Directions
- Summary
Objectives

- Investigate new quantum engineering device concepts with III-V MBE for LWIR detectors.
- Achieve near background limited performance at 16\(\mu\)m and at operating temperatures above 65K.
- Demonstrate detector arrays integrated with multiplexers.
- Develop with industry LWIR (6-17\(\mu\)m) focal plane arrays (64x64).
- Explore Doping Superlattice Concepts.
- Apply Strained Layer Epitaxy To LWIR Detector Problem.

Doping Superlattice Concept

Band Diagram of Hole-Impeded-Doping-Superlattice (HIDS)
Calculated detectivity of nipi detector at 20 μm wavelength. F is optics F-number. Other assumed parameters are described in the text.

**nipi Design Parameters**

<table>
<thead>
<tr>
<th>Material</th>
<th>$\epsilon/\mu$</th>
<th>$m_p/m$</th>
<th>$m_n/m$</th>
<th>$\text{E}_g^{0}(77 \text{ K})$ (eV)</th>
<th>$N_D, N_A$ (cm$^{-3}$)</th>
<th>$a$ (Å)</th>
<th>$b$ (Å)</th>
<th>$P$</th>
</tr>
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<tbody>
<tr>
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<td>17.7</td>
<td>0.015</td>
<td>0.40</td>
<td>0.23</td>
<td>$2 \times 10^{12}$</td>
<td>113</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$6 \times 10^{18}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InAs</td>
<td>14.6</td>
<td>0.023</td>
<td>0.40</td>
<td>0.41</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td>$5 \times 10^{12}$</td>
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<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>$6 \times 10^{18}$</td>
<td>$149$</td>
<td>66</td>
<td>$1.4 \times 10^{-2}$</td>
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<td></td>
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<td></td>
<td>$3 \times 10^{19}$</td>
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<td>67</td>
<td>$1.2 \times 10^{-4}$</td>
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<tr>
<td>GaAs</td>
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<td>0.067</td>
<td>0.48</td>
<td>1.51</td>
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<td>$6 \times 10^{18}$</td>
<td></td>
<td>270</td>
<td>$3.5 \times 10^{-21}$</td>
<td></td>
</tr>
</tbody>
</table>
Hole-Impeded Doping Superlattice

Fig. 2. HIDS Photoconductor Detector Structure

HIDS Photovoltaic Detector Structure

Metal

n+ InAs

p+ InAs

Common

SL Buffer

s.i. GaAs (Si) Substrate

AR Coating
p/n Diode Result Summary

- 1.5 - 3.0 μm response, high η (70% at 77K, 20% at 298K)
- Low dark current --good R0A
- Compares with best bulk InAs
- Higher yield (85%), uniformity
- Transparent GaAs substrate
  --backside illumination for arrays
- Compatible with MUX integration
  --monolithic InAs/GaAs or hybrid

Electrical Properties of InAs on GaAs
Schematic drawing of in vacuo growth and characterization facilities. The lower left hand portion shows the laser sources; the pre-insertion sample preparation glove boxes are shown on the lower right; the analysis chamber and the hemispherical XPS analyzer are shown in ascending order.

InAs pn structure photocurrent at 77 K

![Graph showing photocurrent vs. wavelength](image-url)
InAs on GaAs RHEED

- MEASURE GROWTH RATE TO 0.01 ML
- DETERMINE FILM/SURFACE QUALITY
- FOLLOW AND CONTROL SURFACE DYNAMICS

RHEED Surface Lattice Constant

![Graph showing RHEED Surface Lattice Constant]
High Resolution XPS Data for InAs Quantum Well on GaAs

REFLECTED-ELECTRON ANALOG OF EXAFS

GaAs
InAs
GaAs

AES
EELF3
PRIMARY

E →
Radial Distribution Function For Bulk InAs

<table>
<thead>
<tr>
<th>EELFS - BULK InAs 1400 eV</th>
<th>COMPARISON WITH EXAFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>(b)</td>
</tr>
</tbody>
</table>

SUMMARY OF EELFS RESULTS ON BULK InAs STANDARD:

$$R_{NN} = 2.40 \pm 0.04 \text{ Å}$$
EELFS Distribution Function for 4 ml InAs QW

EELFS Result Summary

- Bulk Data Agrees with EXAFS Results
- Uncapped Strained Layers Show One First Nearest Neighbor Distance
- Capped Quantum Wells Give Two Nearest Neighbor Distances with 0.32 Å Difference
- Distances in β-Sn Phase 0.15 Å
GaAs. Calculated total energy per molecule vs. reduced volume (volume relative to experimental equilibrium volume) for five possible structures [83F].
Conclusions

- High Quality InAs grown on GaAs Substrates
- Epitaxial Approach Compatible with Si Substrates
- nipi Concept Requires High Doping Level - Delta Doping Experiments Under Way
- Demonstrated First Structural Results Suggesting Tetragonal Phase of InAs
- Optical Response and Characterization
SESSION IX: New Materials Systems

IX-1 InAsSbBi, A Direct Band-Gap, III-V, LWIR Material
   G.B. Stringfellow, University of Utah

IX-2 AlSb/InAs/AlSb Quantum Wells
   H. Kroemer, University of California, Santa Barbara
InAsSbBi, A Direct Band-gap, III-V, LWIR Material

G. B. Stringfellow
Dept. of Materials Science and Engineering, University of Utah
Salt Lake City, Utah 84112

Colin E. Jones
Santa Barbara Focalplane
Goleta, CA 93117

and

John Frodsham
Space Systems Engineering
Logan, Utah 84321

ABSTRACT

There has been extensive progress in the last twenty years in the growth of device quality III-V mixed alloys. Most of this work has centered around the wider band-gap alloys like AlGaAs and InP. In the last several years some of this effort has been extended to the narrower band-gap InAsSb system. This ternary has a direct band gap ranging from 145 meV for InAs(0.35)Sb(0.65) to 415 meV for InAs with the other end point being at 235 meV for InSb. It is possible to lower the band gap even further by adding bismuth. Bismuth is a large atom and its equilibrium solubility is estimated to be only 0.02 % in InAs and 2 % in InSb. Several attempts at adding 1 to 2 % Bi to III-V alloys by LPE or MBE have shown poor quality material with phase separations and precipitates.

In the last several years Dr. Stringfellow's group at the University of Utah has reported success in incorporating over 3 % Bi in InAs and 1.5 % in InAsSb using OMVPE growth techniques. For InAs the lattice constant increase is linear with \( a = 6.058 + 0.966x \) (InAs(1-x)Bi(x)), and a decrease in band gap energy of \( \frac{dE_g}{dx} = -55 \text{meV} \) at % Bi. (1) Extrapolating this to the ternary minimum band gap at InAs(0.35)Sb(0.65) an addition of 1 to 2 % Bi should drop the band gap to the 0.1 to 0.05 eV range (10 to 20 microns). These alloys are direct band gap semiconductors making them candidates for far IR detectors. The end points InAs and InSb are used extensively as MWIR detectors now.

The current status of the InAsSbBi alloys is that good crystal morphology and X-Ray diffraction data has been obtained for up to 3.4 % Bi. The Bi is metastable at these concentrations but the OMVPE grown material has been able to withstand the 400 C growth temperature for several hours without phase separation.
The electrical evaluation of the material has only just started. Hall data on OMVPE InSb has shown an n-type mobility of greater than 20,000 cm² / V·sec at 200 K and carrier concentrations in the low E14 range. The ability of these alloys to show luminescence implies reasonable electrical quality over the range of alloy studied. (2) Both luminescence and transmission have been used to determine the change in band gap with Bi concentration. Some increase in the luminescence band width is seen with increasing Bi suggesting some compositional variation. Alloys have been grown near the InAs end with up to 30 % Sb. InSb has also been grown by OMVPE but the low band gap region has not yet been explored. At present there is no optical detector data on these alloys.

This effort is to continue with Dr. Stringfellow's group at the University of Utah growing material and with Santa Barbara Focalplane extending the material characterization and starting the processing of test detectors and arrays.

REFERENCES


InAsSbBi, A DIRECT BAND-GAP, III-V, LWIR MATERIAL

G.B. Stringfellow
University of Utah

Colin E. Jones
Santa Barbara Focalplane

John Frodsham
Space Systems Engineering

REASONS FOR INTEREST IN InAsSbBi

1. DIRECT BAND-GAP SEMICONDUCTOR

2. GAP TUNABLE FROM <0.05eV TO 0.415eV

3. EXTENSION OF CURRENT OMVPE III-V MATERIALS GROWTH TECHNOLOGY PRODUCING DEVICES IN GaAs, AlGaAs, InP ......
Energy Bandgap vs. Composition $x$

**Figure 1:** Energy Bandgap of $\text{InAs}_{1-x}\text{Sb}_x$ vs. Composition $x$ at 10 K.

**Figure 2:** Energy Bandgap of $\text{InAs}_{1-x}\text{Sb}_x$ plotted against InAs and InSb composition. Symbols indicate data from:
- Coderre and Woolley, 1968
- Yen et al., 1988
- Present results
• SOLUBILITY OF Bi IS LOW
  2.1% IN InSb, 0.02% IN InAs

• OMVPE GROWTH HAS BEEN ABLE
  TO GROW METASTABLE COMPOSITIONS
  OF MANY ALLOYS AND OF Bi IN InAsSb

<table>
<thead>
<tr>
<th>Alloy</th>
<th>T_c(°C)</th>
<th>Range of Immiscibility</th>
<th>Reference</th>
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<tbody>
<tr>
<td>GaAsSb</td>
<td>750</td>
<td>0.2-0.8 (600°C)</td>
<td>Cherng et al (1984)</td>
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</tr>
<tr>
<td>GaInAsSb</td>
<td>1467</td>
<td>90% of Phase Field (600°C)</td>
<td>Cherng et al (1986)</td>
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<tr>
<td>InPSb</td>
<td>1046</td>
<td>0.03-0.98 (460°C)</td>
<td>Jou et al (1988)</td>
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<tr>
<td>GaPSb</td>
<td>1723</td>
<td>0.01-0.99 (540°C)</td>
<td>Jou et al (1988)</td>
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</tr>
</tbody>
</table>
A number of growths have been made for InAsBi and InAsSbBi to up to 3% Bi and 30% Sb.
InAs$_{0.988}$Bi$_{0.012}$ InAs

$K_\alpha_1$ $K_\alpha_1$

20 $\mu$m

60.5 61.0 61.5 62.0 62.5

2$\theta$ (degrees)

InAs$_{0.889}$Sb$_{0.096}$Bi$_{0.015}$ InAs

$K_\alpha_1$ $K_\alpha_1$

20 $\mu$m

60.0 60.5 61.0 61.5 62.0 62.5

2$\theta$ (degrees)
FIG 4

InAs$_{1-x}$Bi$_x$

Molar Fraction of InBi, $x$

Energy (meV)

PL Intensity (arbitrary units)

Wavelength ($\mu$m)
at.% of Bi: 0

300 K
InAsBi/InAs

Wavenumbers [cm$^{-1}$]

Molar Fraction of InBi, X [%]

Fang Fig.5

10 K Photoluminescence

300 K Absorption Coefficient

InAs$_{1-x}$Bi$_x$
EXTRAPOLATION OF DATA TO $\text{InAs}_{0.35} \text{Sb}_{0.65}$ suggests that 2% Bi would yield GAP EN. $\approx 0.034$ eV (36 microns) making a direct band-gap VLWIR material.

**Energy Bandgap vs. Composition $x$**

- **InAs$_{1-x}$Sb$_x$** at 10 K
- **Energy Bandgap (meV)** vs **Wavelength (μm)**
- **% Bi**

![Graph showing energy bandgap vs composition](image-url)
STATUS

- OMVPE GROWTHS HAVE BEEN MADE WITH UP TO 3.4% Bi AND UP TO 30% Sb

- Bi SEEMS TO BE SUBSTITUTIONAL

  LATTICE INCREASE IS LINEAR, BAND GAP SHIFT IS LINEAR, X-RAY DATA IS SHARP, NO SIGN OF TWO PHASES, MORPHOLOGY IS GOOD

STATUS CONTINUED

- ENERGY DECREASES BY 55meV per % Bi

- a = 6.058 + 0.966 x FOR InAs(1-x)Bi(x)

- LUMINESCEENCE SEEN
  - IMPLIES LIFETIME AND ELECTRICAL QUALITY TO BE AT LEAST GOOD
  - BROADENING IMPLIES SOME COMPOSITIONAL VARIATION

- THICKNESS - 8 micron THICK InSb GROWN p-TYPE, 3 E 14
• PROGRAM FUTURE DIRECTION

- OMVPE GROWTH NEAR InAs \( Sb_{0.34} \; 0.64 \; Bi_{0.02} \)

- EXTENDED ELECTRICAL AND OPTICAL TESTING TO OPTIMIZE THE GROWTH AND PROVIDE INITIAL OPTICAL DETECTOR DATA

THE LATTER IS A JOINT PROJECT BETWEEN UNIVERSITY OF UTAH AND SANTA BARBARA FOCALPLANE, A COMPANY THAT PROCESSES AND TESTS IR ARRAYS AND MATERIALS

SBF MATERIALS CHARACTERIZATION

<table>
<thead>
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<th>PROPERTY</th>
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<td>PC DECAY</td>
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<td>MULTI-WAVELENGTH ELLIPSOMETRY</td>
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### DEVICE AND ARRAY TESTING

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<td>NOISE, 1/F</td>
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<td>GATED, UNGATED</td>
<td>EL. TRAPPING DLTS</td>
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<td>CAPACITORS</td>
<td>CV, GV, Nss, ZERBST, Tgen, Qss, Vfb, Vh</td>
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<td>SURFACE MOBILITY</td>
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<td>D*, QUANTUM EFFICIENCY,</td>
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<td>UNIFORMITY, YIELD</td>
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</tbody>
</table>

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Much heterostructure and quantum well work is now devoted to materials combinations other than GaAs/(Al,Ga)As. One of the most interesting is the InAs/(Al,Ga)Sb system. In the InAs/GaSb limit, it exhibits a broken gap, which offers a number of interesting possibilities for new kinds of physical phenomena, most of which remain unexplored.

In the InAs/AlSb limit, it offers quantum wells of exceptional depth (1.35 eV), combined with the low effective mass (0.023 $m_0$) and high mobilities of InAs, a combination of interest for several potential device applications. The lattice mismatch (1.3%), while not negligible, is sufficiently small that in quantum well structures with well widths of practical interest ($\leq 10$ nm) the growth should be pseudomorphic, with the mismatch taken up by elastic strain, rather than leading to disastrous misfit dislocation formation.

We have been exploring the InAs/AlSb system recently, obtaining 12nm wide quantum wells with room temperature mobilities up to 28,000 cm$^2$/V·s and low-temperature mobilities up to 325,000 cm$^2$/V·s, both at high electron sheet concentrations in the $10^{12}$/cm$^2$ range (corresponding to volume concentrations in the $10^{18}$/cm$^2$ range). These wells were not intentionally doped; the combination of high carrier concentrations and high mobilities suggest that the electrons are due to not-intentional “modulation doping” by an unknown donor in the AlSb barriers, presumably a stoichiometric defect, like an antisite donor. Inasmuch as not intentionally doped bulk AlSb is semi-insulating, the donor must be a deep one, being ionized only by draining into the even deeper InAs quantum well.

The excellent transport properties are confirmed by other observations, like excellent quantum Hall effect data, and the successful use of the quantum wells as superconductive weak links between Nb electrodes, with unprecedentedly high critical current densities. The system is promising for future FETs, but many processing problems must first be solved. Although
we have achieved FETs, the results so far have not been competitive with GaAs FETs.

Although most of our work until recently has stressed the transport properties of the system, its optical properties should also be interesting. The large well depths should make the system promising for superlattices with exceedingly short periods. The latter presumably have interesting optical properties, such as strong inter-sub-band absorption effects, of potential use for detector applications. Work exploring the optical properties has been initiated, but we do not have any results to report yet.

Any superlattice applications require particular attention to the quality of the hetero-interfaces, and in this regard the InAs/AlSb system differs fundamentally from the GaAs/(Al,Ga)As and (Ga,In)As/(Al,In)As systems: Because both the cation and anion change across an InAs/AlSb (or InAs/GaSb) interface, two distinctly different interface structures may occur. In one case, the InAs would be terminated with a final layer of In, and the adjoining AlSb would start with a layer of Sb, leading to InSb bonds across the interface. We call this the “InSb-like” interface. The complement to this is the “AlAs-like” interface, in which Al atoms from the AlSb side are bonded to As atoms on the InAs side. Experiments show that different kinds of interfaces can indeed be generated by choosing suitable MBE growth parameters, yielding drastically different quantum well properties. All our high-mobility wells were grown under conditions presumably leading to InSb-like interfaces.

A systematic study of the effect of differently grown interfaces showed that wells having AlAs-like bottom (i.e. first) interfaces had properties quite different from wells with InSb-like bottom interfaces, while nature of the upper (i.e. second) interfaces played little role in determining the properties of the quantum well. More specifically, wells with AlAs-like interfaces at the bottom (but not at the top!) yield a higher electron concentration but much lower mobilities, indicating the presence of a charged defect at those interfaces, believed to be a (deep) As antisite donor on Al sites. Several observations strongly support this interpretation: The magnitude of the effect correlates strongly with the length of exposure of the Al-stabilized AlSb surface to the As flux prior to turning on the In beam. Furthermore, by interrupting the growth of the AlSb barrier some distance away (~10 nm) from the InAs/AlSb interface, and exposing the stagnant AlSb surface to an As flux, we were able to “modulation-dope” the quantum well, with results very similarly to conventional modulation doping with Te donors.
Quantization Energy in an Infinitely Deep Quantum Well of Width $L$:

$$\Delta E = \frac{\hbar^2 \pi^2}{2m^* L^2}$$

For $m^* = 0.026 m_0$ and $L = 100\text{Å}$:
$$\Delta E = 0.145 \text{eV}$$
(a) Concentration (cm$^{-2}$) vs. Temperature (K)

- LED flash
- Cooling
- Warming
- Dark
- After LED flash

(b) Mobility (cm$^2$/V·s) vs. Temperature (K)

- LED flash
- Cooling
- Warming
- Dark
- After LED flash
(a)  

(b)  

![Graph showing mobility vs. concentration](image-url)
AlSb quantum well

(a)

503
(a) Concentration (10^{12} \text{cm}^{-2})

(b) Mobility (\text{cm}^2/\text{V}\cdot\text{s})
(a) Interruption for As soak

(b) Time diagram with Al, Sb, and As layers, with times and mL notations.

(c) Time diagram with Al, Sb, and As layers, with times and mL notations.
(a) Concentration (10^12 cm^-2)

(b) Mobility (cm^2/V-s)

Temperature (K)
(a) Conventional and antisite doped concentrations.

(b) Conventional and antisite doped mobilities.

Temperature (K)

Concentration (10^{12} \text{ cm}^{-2})

Mobility (\text{cm}^{2}\text{V}^{-1}\text{S}^{-1})

- ■ conventional
- ○ antisite doped
Antisites 100Å below the well

Temperature (K)

Concentration ($10^{12}$ cm$^{-2}$)

Mobility (cm$^2$/V·s)

- Concentration
- Mobility
Adams, F.W.
Lockheed Missiles & Space Co.
3251 Hanover St.
Palo Alto, CA 94304-1191
(415)424-2227

Bahraman, A.
Northrop Electronics Systems Div.
One Research Park
Palos Verdes, CA 90274
(213)544-5336

Bandara, Sumith
Microtronics Assoc.
4516 Henry St., Ste. 403
Pittsburgh, PA 15213-3728
(412)681-0888

Barton, Jeffrey
Amber Engineering
5736 Thornwood Dr.
Goleta, CA 93117
(805)683-6621

Beeman, Jeffrey
Lawrence Berkeley Laboratory
5110 University Ave.
Berkeley, CA 94709
(415)486-4439

Bharat, R.
Rockwell International Corp.
3370 Miraloma Ave., 031-BC16
Anaheim, CA 92803
(714)762-1460

Bloss, Walter
The Aerospace Corp.
PO Box 92957, MS M2-244
Los Angeles, CA 90009
(213)336-9269

Boisrert, Joseph
S-CUBED
3020 Callan Rd.
San Diego, CA 92121-1095
(619)430-2404

Boyle, Jack
Charles Stark Draper Lab
555 Technology Dr.
Cambridge, MA 02139
(617)258-3238

Brown, Duncan
Advanced Technology Materials
520-B Danbury Rd.
New Milford, CT 06776
(203)355-2681

Allario, F.
NASA/Langley Research Center
1289 Langley Rd.
Hampton, VA 23665-5225
(804)864-6027

Balcerak, R.
DARPA
1400 Wilson Blvd.
Arlington, VA 22209
(202)693-4278

Baron, Robert
Hughes Research Labs
3011 Malibu Canyon Rd.
Malibu, CA 90265
(213)317-5392

Beck, William
Martin Marietta Lab
1456 S. Rolling Rd.
Baltimore, MD 21227
(301)247-2291

Berding, Marcy
SRI International
333 Ravenswood Ave. LOC 140-33
Menlo Park, CA 94025
(415)859-4267

Bickel, Thomas
Sandia National Laboratory
PO Box 5800, Dept. 6220
Albuquerque, NM 87185
(505)844-2392

Bly, Vincent
US Army
Infrared Technology Division
Fort Belvoir, VA 22060-5677
(703)664-1588

Borenstain, Shmuel
Jet Propulsion Laboratory
MS 302-306, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-5046

Braun, Robert
AT & T Bell Laboratories
600 Mountain Ave.
Murray Hill, NJ 07974-2070
(201)582-2996

Brown, Gail
Air Force Materials Laboratory
WRDC/MLPO
Wright Patterson AFB, OH 45433
(513)255-4098
Brown, Kenneth
The Aerospace Corporation
2nd & B Sts., PO Box 9045
Albuquerque, NM 87119
(505)844-0113

Capps, Richard
Jet Propulsion Laboratory
MS 303-210, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-6305

Chahine, Moustafa
Jet Propulsion Laboratory
MS 180-904, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-6057

Cheung, Derek
Rockwell International Science Cntr
1409 Camino Dos Rios
Thousand Oaks, CA 91360
(805)373-4269

Clouse, Larry
TRW
12610 Venice Blvd., Apt. A
Los Angeles, CA
(213)812-0182

Collins, Stewart
Jet Propulsion Laboratory
MS 168-222, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-7734

Crowe, Thomas
University of Virginia
Thornton Hall
Charlottesville, VA 22903-2442
(804)924-7693

Davidson, Richard
Jet Propulsion Laboratory
MS 300-315, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-7812

DePaula, Ramon
NASA Headquarters
Code R
Washington, DC 20546
(202)453-2748

DeJewski, Susan
Jet Propulsion Laboratory
MS 303-210, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-1292

Brown, Lyn
US Air Force
WRDC/MLPO
Wright Patterson AFB, OH 45433
(513)255-4098

Casselman, Tom
Santa Barbara Research Center
750 Coromar Dr.
Santa Barbara, CA 93117
(805)562-2981

Chang, Nien Chich
The Aerospace Corp.
P.O. Box 92957
Los Angeles, CA 90009-2957
(213)354-7186

Choi, Kwong-kit
US Army Elect. Tech. & Devices Lab
ATTN: SLCET-ED
Fort Monmouth, NJ 07703-5000
(201)544-3806

Cole, Terry
Jet Propulsion Laboratory
MS 180-500, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-5458

Correa, Craig
Booz Allen & Hamilton
1725 Jefferson Davis Hwy.
Arlington, VA 22202
(703)271-1654

Dafesh, Philip
The Aerospace Corp.
P.O. Box 92957
El Segundo, CA 90009-2957
(213)354-8733

De Luccia, Frank
The Aerospace Corp.
2350 E. El Segundo Blvd.
El Segundo, CA 90245
(213)354-9312

DeVaux, Lloyd
DeVaux Associates
466 Camino Talavera
Goleta, CA 93117
(805)964-3384

Denison, Robert
Wright Rsch. & Devlp. Center
WRDC/MLPO
Wright-Patterson AFB, OH 45433
(513)255-4474
Dereniak, E.
University of Arizona

Dickerman, Ronald
Army Space Tech & Rsch Office
2902 Adams St.
Dale City, VA 22193
(703)355-2709

Eaton, Larry
TRW
One Space Park
Redondo Beach, CA 90278
(213)812-0155

Fathouer, Robert
Jet Propulsion Laboratory
MS 302-231, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-4962

Forrest, Kate
NASA/Goddard Space Flight Center
Bldg. 5 Rm. 324
Greenbelt, MD 20771
(301)286-7138

Goldberg, Arnold
Martin Marietta Laboratories
1450 S. Rolling Road
Baltimore, MD 21227
(301)247-0700

Grave, Ilan
Caltech
Pasadena, CA 91125
(818)356-4823

Grunthaner, Frank
Jet Propulsion Laboratory
MS 302-306, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-5564

Gulkis, Samuel
Jet Propulsion Laboratory
MS 169-506, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-5708

Haller, Eugene
Lawrence Berkeley Laboratory
1 Cyclotron Rd., MS 2-200
Berkeley, CA 94720
(415)486-5294

Devine, Michael
Kirtland AFB
HQ AFSTC/SWS
Kirtland AFB, NM 87117-6008
(505)846-5788

Duston, Dwight
SDIO/TNI
Washington, DC
(202)693-1527

Empson, Kevin
DOD/IAO
5733 Evergreen Knoll Ct.
Alexandria, VA 22303
(703)351-2143

Fischler, Fred
Texas Instruments Inc.
13532 N. Central Expway, MS 28
Dallas, TX 75265
(214)995-1089

Fossum, Eric
Columbia University
Dept. EE, 1312 S.W. Mudd Bldg.
New York, NY 10027
(212)854-3107

Golding, Terry
University of Houston
Science & Research 1
Houston, TX 77204-5507
(713)749-1641

Greiner, Mark
Cincinnati Electronics Corp.
7500 Innovation Way
Mason, OH 45040-9699
(513)573-6151

Grunthaner, Paula
Jet Propulsion Laboratory
MS 302-231, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-0360

Haas, T.W.
US Air Force
WRDC/MLBM
Wright Patterson AFB, OH 45433
(513)255-5992

Hancock, Bruce
Jet Propulsion Laboratory
MS 302-306, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-8801
Hansen, William
Lawrence Berkeley Laboratory
1 Cyclotron Rd., MS 2-200
Berkeley, CA 94720
(415) 486-5632

Herring, Mark
Jet Propulsion Laboratory
MS 11/116, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818) 354-6817

Hubbard, G. Scott
NASA/Ames Research Center
MS 244-14
Moffett Field, CA 94035
(415) 604-5697

Huffman, James
Rockwell Science Center
3370 Miraloma Ave., MS BC18
Anaheim, CA 92803
(714) 762-2901

Jack, Michael
Santa Barbara Research Center
75 Coromar Dr.
Santa Barbara, CA 93117
(805) 562-2981

Jindal, Bal
XACTON Corp.
PO Box 3129
Tempe, AZ 85280
(602) 986-8765

Jones, Richard
Charles Stark Draper Lab
555 Technology Dr.
Cambridge, MA 02139
(617) 258-3236

Kahn, Cynthia
Jet Propulsion Laboratory
MS 168-222, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818) 354-4101

Kenny, T.
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109

Kohn, Stanley
The Aerospace Corp.
PO Box 92957
El Segundo, CA 90249-2957
(213) 336-8047

Hauenstein, Robert
Hughes Research Laboratories
3011 Malibu Canyon Rd., MS RL63
Malibu, CA 90265
(213) 317-5819

Hinkley, David
TRW
One Space Park
Redondo Beach, CA 90278
(213) 814-0295

Huberman, Mark
Jet Propulsion Laboratory
MS 302-306, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818) 354-7452

Ito, Chris
Ford Microelectronics Inc.
9965 Federal Dr.
Colorado Springs, CO 80921
(719) 528-7727

Janousek, Bruce
The Aerospace Corporation
M 2/244, PO Box 92957
Los Angeles, CA 90009
(213) 336-1820

Jones, Colin
Santa Barbara Focalplane
69 Santa Felicia Dr.
Goleta, CA 93117
(805) 562-8777

Jost, Steven
General Electric Company
EP3-223, PO Box 4840
Syracuse, NY 13221
(315) 456-2934

Kalma, Arne
Mission Research Corporation
4935 North 30th Street
Colorado Springs, CO 80919
(719) 528-8080

Khanna, Satish
Jet Propulsion Laboratory
MS 302-205, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818) 354-4489

Koliwad, Kris
Jet Propulsion Laboratory
MS 302-205, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818) 354-5197
Miller, William
NASA/Langley Research Center
MS 474
Hampton, VA 23665-5225
(804)864-1720

Mink, J.
US Army Research Office
PO Box 12211
Research Triangle Pk, NC
(919)549-0641

Moldovan, Anton
Ford Aerospace
Ford Road, PO Box A
Newport Beach, CA 92658-8900
(714)720-6417

Nelms, Richard
NASA/Langley Research Center
MS 186
Hampton, VA 23665-5225
(804)864-1726

Nelson, Michael
US Army Research Office
PO Box 12211
Research Triangle Pk, NC
(919)549-0641

Moldovan, Anton
Ford Aerospace
Ford Road, PO Box A
Newport Beach, CA 92658-8900
(714)720-6417

Nelms, Richard
NASA/Langley Research Center
MS 186
Hampton, VA 23665-5225
(804)864-1726

Nelson, Richard
Ford Aerospace
Ford Road
Newport Beach, CA 92660
(714)720-6417

Norton, Paul
Santa Barbara Research Center
75 Coromar Dr.
Goleta, CA 93117
(805)562-2746

Odenwald, Sten
SFA, Inc.
Code 4033.6
Washington, DC 20375
(202)767-2746

Pawlik, Eugene
Jet Propulsion Laboratory
MS 198-133, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-2746

Peercy, Paul
Sandia National Labs
Organizations 1140
Albuquerque, NM 87185
(505)844-4309

Piroch, Ronald
Grumman Corp. Research Center
MS A02-26
Bethpage, NY 11714
(516)575-0612

Pirich, Ronald
Grumman Corp. Research Center
MS A02-26
Bethpage, NY 11714
(516)575-0612

Plotkin, Henry
NASA/Goddard Space Flight Center
NASA/GSFC
Greenbelt, MD 20771
(301)286-6185

Milnes, A.G.
Carnegie Mellon University
ECE Dept., 5000 Forbes Ave.
Pittsburgh, PA 15213
(412)268-2463

Mitchel, William
Wright Research & Development Ctr
WRDC/MPD
Wright-Patterson, OH 45433
(513)255-4474

Nahum, Michael
UC Berkeley
Dept. of Physics
Berkeley, CA 94720
(415)642-1247

Nelson, Edward
Eastman Kodak Company
Bldg. 81, P.O. 6, RL
Rochester, NY 14650-2008
(716)722-0245

Nelson, Snadra
TRW
601 Anderson
Manhattan Beach, CA 90266
(213)814-1303

Nouhi, Akbar
Jet Propulsion Laboratory
MS 302-306, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-7135

Nelson, Snadra
TRW
601 Anderson
Manhattan Beach, CA 90266
(213)814-1303

Nouhi, Akbar
Jet Propulsion Laboratory
MS 302-306, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-7135

Patten, Elizabeth
Santa Barbara Research Center
75 Coromar Drive, B2/8
Goleta, CA 93117
(805)562-2168

Peercy, Paul
Sandia National Labs
Organizations 1140
Albuquerque, NM 87185
(505)844-4309

Pham, Le Thanh
Hughes Micro Electronics
6135 El Camino Real, MS 119
Carlsbad, CA 92009
(619)731-5087

Plotkin, Henry
NASA/Goddard Space Flight Center
NASA/GSFC
Greenbelt, MD 20771
(301)286-6185

517
<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Address</th>
<th>Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proffitt, Shellba</td>
<td>US Army Strategic Defense Command</td>
<td>Huntsville, AL</td>
<td>(205)895-4820</td>
</tr>
<tr>
<td>Rajakarunanayake, Y.</td>
<td>Caltech</td>
<td>Pasadena, CA 91125</td>
<td></td>
</tr>
<tr>
<td>Reine, M.</td>
<td>Loral Infrared &amp; Imaging Systems</td>
<td>MS 146, 2 Forbes Rd.</td>
<td>(617)863-3043</td>
</tr>
<tr>
<td>Richards, P.</td>
<td>UC Berkeley</td>
<td>Berkeley, CA</td>
<td></td>
</tr>
<tr>
<td>Ritchie, Donald</td>
<td>Jet Propulsion Laboratory</td>
<td>MS 303-210, 4800 Oak Grove Dr.</td>
<td>(818)354-6305</td>
</tr>
<tr>
<td>Ruden, P. Paul</td>
<td>University of Minnesota</td>
<td>Dept. of EE, 200 Union Street</td>
<td>(612)624-6350</td>
</tr>
<tr>
<td>Sarohia, Virendra</td>
<td>Jet Propulsion Laboratory</td>
<td>MS 180-606, 4800 Oak Grove Dr.</td>
<td>(818)354-6798</td>
</tr>
<tr>
<td>Scheiling, John</td>
<td>AF Electronic Tech. Lab</td>
<td>Wright-Patterson AFB, OH 45433</td>
<td>(513)255-5147</td>
</tr>
<tr>
<td>Schnitzler, Alvin</td>
<td>BDM International Inc.</td>
<td>1300 N. 17th Street, Ste. 950</td>
<td>(703)247-0376</td>
</tr>
<tr>
<td>Schueler, Donald</td>
<td>Sandia National Laboratory</td>
<td>PO Box 5880, Dept. 6220</td>
<td>(505)844-4041</td>
</tr>
<tr>
<td>Quelle, Fred</td>
<td>QNR Boston</td>
<td>495 Summer St., Boston, MA 02210</td>
<td>(617)431-3171</td>
</tr>
<tr>
<td>Randall, Rick</td>
<td>Aerojet ElectroSystems</td>
<td>1100 W. Hollyvale St. Azusa, CA 91702</td>
<td>(818)812-2952</td>
</tr>
<tr>
<td>Reitz, Larry</td>
<td>AF Electronic Technology Lab</td>
<td>MS WRDC/ELOD</td>
<td></td>
</tr>
<tr>
<td>Riffee, Lyle</td>
<td>US Air Force</td>
<td>WRDC/MLPO</td>
<td></td>
</tr>
<tr>
<td>Rodgers, Richard</td>
<td>USASDC</td>
<td>106 Wynn Dr. (POB1900)</td>
<td></td>
</tr>
<tr>
<td>Sachtjen, Scott</td>
<td>Conductus, Inc.</td>
<td>969 W. Maude Ave.</td>
<td></td>
</tr>
<tr>
<td>Sato, Robert</td>
<td>RNS Electronics &amp; Technology</td>
<td>50 Montemalaga Plaza</td>
<td></td>
</tr>
<tr>
<td>Schetzina, J.</td>
<td>N. Carolina State University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schoolar, Richard</td>
<td>Aerospace Corp.</td>
<td>MS M4-978, PO Box 92957</td>
<td></td>
</tr>
<tr>
<td>Schulman, Joel</td>
<td>Hughes Research Laboratories</td>
<td>3011 Malibu Canyon Rd.</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Affiliation</td>
<td>Address</td>
<td>Phone</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Shu, Peter</td>
<td>NASA/Goddard Space Flight Center</td>
<td>NASA/GSFC, Greenbelt, MD 20771</td>
<td>(301)286-7606</td>
</tr>
<tr>
<td>Silver, Arnold</td>
<td>TRW</td>
<td>One Space Park, Redondo Beach, CA 90278</td>
<td>(213)812-0155</td>
</tr>
<tr>
<td>Seng, J.J.</td>
<td>Oklahoma State University</td>
<td>Dept. of Physics, Stillwater, OK 74078-0444</td>
<td>(405)744-9877</td>
</tr>
<tr>
<td>Spears, David</td>
<td>MIT Lincoln Laboratory</td>
<td>240 Wood St., Lexington, MA 01720</td>
<td>(617)981-7855</td>
</tr>
<tr>
<td>Stapelbroek, M.G.</td>
<td>Rockwell International</td>
<td>3370 Miraloma Ave., MS D/781, Anaheim, CA 92803</td>
<td>(714)762-4528</td>
</tr>
<tr>
<td>Stevens, Christopher</td>
<td>Jet Propulsion Laboratory</td>
<td>MS 168-227, 4800 Oak Grove Dr., Pasadena, CA 91109</td>
<td>(818)394-5545</td>
</tr>
<tr>
<td>Swenson, H.R.</td>
<td>SDIO/TNS</td>
<td>7601 Sweet Hours, Columbia, MD</td>
<td>(301)381-6302</td>
</tr>
<tr>
<td>Taylor, Mark</td>
<td>Institute for Defense Analysis</td>
<td>1801 N. Beauregard St., Alexandria, VA 22311-1772</td>
<td>(703)578-2986</td>
</tr>
<tr>
<td>Thompson, Les</td>
<td>NASA/Goddard Space Flight Center</td>
<td>Code 925, Greenbelt, MD 20771</td>
<td>(301)286-8362</td>
</tr>
<tr>
<td>Vydymanath, H.R.</td>
<td>Aerojet ElectroSystems</td>
<td>1100 W. Hollyvale St., Azusa, CA 91702</td>
<td>(818)812-2892</td>
</tr>
<tr>
<td>Silberstein, Robert</td>
<td>Grumman Corp. Research Center</td>
<td>MS A02-26, Bethpage, NY 11714-3580</td>
<td>(516)575-8196</td>
</tr>
<tr>
<td>Smith, Darryl</td>
<td>Los Alamos National Laboratory</td>
<td>MEE-11, D429, Los Alamos, NM 87545</td>
<td>(505)667-2056</td>
</tr>
<tr>
<td>Song, Jong-In</td>
<td>Columbia University</td>
<td>Dept. of Electrical Engineering, New York, NY 10027</td>
<td>(212)854-6588</td>
</tr>
<tr>
<td>Staller, Craig</td>
<td>Jet Propulsion Laboratory</td>
<td>MS 303-210, 4800 Oak Grove Dr., Pasadena, CA 91109</td>
<td>(818)354-9143</td>
</tr>
<tr>
<td>Starr, Ron</td>
<td>Ford Aerospace</td>
<td>Ford Road., MS 2/59, Newport Beach, CA 92658-8900</td>
<td>(714)720-6538</td>
</tr>
<tr>
<td>Swanson, Paul</td>
<td>Jet Propulsion Laboratory</td>
<td>4800 Oak Grove Dr., Pasadena, CA 91109</td>
<td>(818)354-6707</td>
</tr>
<tr>
<td>Takei, William</td>
<td>Westinghouse Electric Corp.</td>
<td>STC, 1310 Beulah Rd., Pittsburgh, PA 15235</td>
<td>(412)256-1992</td>
</tr>
<tr>
<td>Tennant, William</td>
<td>Rockwell Intl. Science Center</td>
<td>1049 Camino Dos Rios, Thousand Oaks, CA 91360</td>
<td>(805)373-4247</td>
</tr>
<tr>
<td>Turner, Gary</td>
<td>Rockwell International</td>
<td>M/S D/781, 031-BC17, Anaheim, CA 92803-3105</td>
<td>(714)762-2969</td>
</tr>
<tr>
<td>Wagner, Robert</td>
<td>Naval Research Laboratory</td>
<td>4555 Overlook Ave., SW, Washington, DC 20375-5000</td>
<td>(202)767-3665</td>
</tr>
</tbody>
</table>
Wen, Cheng
Hughes
3100 W. Lomita
Torrance, CA 90509
(213)517-6997

Wilkenfeld, Jason
S-CUBED
3020 Callan Rd.
San Diego, CA 92121
(619)450-2435

Winston, Jan
Aerojet ElectroSystems
1100 W. Hollyvale St.
Azusa, CA 91702
(818)812-1454

Woodall, J.M.
IBM

Wu, Owen
Hughes Research Laboratories
3011 Malibu Canyon Rd.
Malibu, CA 90265
(213)317-5749

Young, Mary
Hughes Research Lab
3011 Malibu Canyon Rd.
Malibu, CA 90265
(213)317-5465

Wigdor, Marc
Nichols Research Corp.
8618 Westwood Center Dr.
Vienna, VA 22182-2222
(703)893-9720

Wilson, Barbara
Jet Propulsion Laboratory
MS 302-306, 4800 Oak Grove Dr.
Pasadena, CA 91109
(818)354-2969

Witteles, Eleonora
WIT
4714 Browndeer Lane
Palos Verdes, CA 90274
(213)541-9934

Wu, C.S.
Hughes Aircraft Co.

Yariv, Amnon
Caltech
EE & Applied Physics
Pasadena, CA 91125
(818)356-4821