Teledyne – NASA’s Partner in Astronomy

NICMOS, WFC3, ACS Repair

Bands 1 & 2

NIRCam, NIRSpec, FGS

HST

WISE

JWST

Hubble Ultra Deep Field

Mercury, Venus, Earth, Mars, Saturn, Jupiter, Uranus, Neptune, Pluto and Charon

Rosetta

Mars Reconnaissance Orbiter

Deep Impact & EPOXI

New Horizons

Lander (çiva)

CRISM (Vis & IR)

IR spectrograph

IR spectrograph

JDEM
Joint Dark Energy Mission
JWST - James Webb Space Telescope

15 Teledyne 2Kx2K infrared arrays on board (~63 million pixels)

- International collaboration
- 6.5 meter primary mirror and tennis court size sunshield
- 2013 launch on Ariane 5 rocket
- L2 orbit (1.5 million miles from Earth)

JWST will find the “first light” objects after the Big Bang, and will study how galaxies, stars and planetary systems form

**FGS (Fine Guidance Sensors)**
- Acquisition and guiding
- Images guide stars for telescope stabilization
- Canadian Space Agency

**NIRSpec (Near Infrared Spectrograph)**
- Spectrograph
- Measures chemical composition, temperature and velocity
- European Space Agency / NASA

**NIRCam (Near Infrared Camera)**
- Wide field imager
- Studies morphology of objects and structure of the universe
- U. Arizona / Lockheed Martin
Wide Field Camera 3
Hubble Space Telescope

- High quality, substrate-removed 1.7 μm HgCdTe arrays delivered to Goddard Space Flight Center
- Will be installed in Hubble Space Telescope in 2009
- Nearly 30x increase in HST discovery efficiency

Quantum Efficiency = 85-90%
Dark current (145K) = 0.02 e-/pix/sec
Readout noise = 25 e- (single CDS)
Teledyne provided both visible and mid-wave infrared detectors to CRISM instrument.
NASA’s and NOAA’s Partner for Earth Observation

- **NPOESS**
  - CrIS

- **CHANDRAYAAN-1**
  - Moon Mineralogy Mapper (Vis-IR)

- **GOES-R**
  - ABI (LWIR)

- **GLORY**
  - (SWIR)

- **AURA**
  - Tropospheric Emission Spectrometer
  - IR FT Spectrometer

- **EO-1**
  - LEISA
  - Atmospheric Corrector (IR arrays)

- **OCO**
  - Orbiting Carbon Observatory (Vis & IR)

Visible to 16.5 microns
Moon Mineralogy Mapper - Visible / Near Infrared Imaging Spectrometer
launched Wednesday, October 22, 2008

Sensor Chip Assembly
Focal Plane Assembly

Instrument at JPL before shipment to India

Teledyne Infrared FPA
- 640 x 480 pixels (27 μm pitch)
- Substrate-removed HgCdTe (0.4 to 3.0 μm)
- 650,000 e- full well, <100 e- noise
- 100 Hz frame rate (integrate while read)
- < 70 mW power dissipation
- Package includes order sorting filter
- Total FPA mass: 58 grams

Completion of Chandrayaan-1 spacecraft integration
Moon Mineralogy Mapper is white square at end of arrow

Chandrayaan-1 in the Polar Satellite Launch Vehicle
Launch from Satish Dhawan Space Centre

2 year mission will map the entire lunar surface

Moon Mineralogy Mapper resolves visible and infrared to 10 nm spectral resolution, 70 m spatial resolution

Journey Earth to Moon
100 km altitude lunar orbit
The Orbiting Carbon Observatory (OCO) is a NASA mission that will provide:
- precise, time-dependent global measurements of atmospheric carbon dioxide (CO₂) from an Earth orbiting satellite.
- distribution of CO₂ over the entire globe, enabling more reliable forecasts of future changes and their effect on the Earth’s climate.

The OCO is planned to launch in January 2009 with a planned operational life of 2 years.

Three flight FPAs (and flight spares):
- O₂A band at 0.758-0.772 µm
- weak CO₂ band at 1.594 - 1.619 µm
- strong CO₂ band at 2.042-2.082 µm

Hawaii-1RG readout is used for both HyViSI and SWIR FPAs with same mechanical and nearly same electrical interface for all three OCO spectrometers.
Leading Supplier of IR Arrays To Ground-based Astronomy

- H2RG (2048×2048 pixels) is the leading IR FPA in ground-based IR astronomy
- 4096×4096 pixel mosaic commissioned at European Southern Observatory in July 2007
  - 6th mosaic at major telescope, two more mosaics to be commissioned in 2009
### Energy of a photon

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Energy (eV)</th>
<th>Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>4.13</td>
<td>UV</td>
</tr>
<tr>
<td>0.5</td>
<td>2.48</td>
<td>Vis</td>
</tr>
<tr>
<td>0.7</td>
<td>1.77</td>
<td>Vis</td>
</tr>
<tr>
<td>1.0</td>
<td>1.24</td>
<td>NIR</td>
</tr>
<tr>
<td>2.5</td>
<td>0.50</td>
<td>SWIR</td>
</tr>
<tr>
<td>5.0</td>
<td>0.25</td>
<td>MWIR</td>
</tr>
<tr>
<td>10.0</td>
<td>0.12</td>
<td>LWIR</td>
</tr>
<tr>
<td>20.0</td>
<td>0.06</td>
<td>VLWIR</td>
</tr>
</tbody>
</table>

- Energy of photons is measured in electron-volts (eV)
- eV = energy that an electron gets when it “falls” through a 1 volt field.
An electron-volt (eV) is extremely small

\[
1 \text{ eV} = 1.6 \times 10^{-19} \text{ J} \quad (\text{J = joule})
\]

\[
1 \text{ J} = \text{N} \times \text{m} = \text{kg} \times \text{m} \times \text{sec}^{-2} \times \text{m}
\]

\[
1 \text{ kg raised 1 meter} = 9.8 \text{ J} = 6.1 \times 10^{19} \text{ eV}
\]

- The energy of a photon is **VERY** small
  - The energy of a SWIR (2.5 μm) photon is 0.5 eV
- Drop a peanut M&M® candy from a height of 5 cm
  - Energy is equal to \(6 \times 10^{15}\) eV (a peanut M&M® is ~2 g)
  - This is equal to \(1.2 \times 10^{16}\) SWIR photons
    - 1 million x 1 million x 12,000
    - The number of photons that will be detected in ~1 million images from the James Webb Space Telescope (JWST)
    - **A 2-inch peanut M&M® drop is about same energy that will be detected during the 5 years operation of the James Webb Space Telescope!**

\[
E = h\nu
\]

\[
h = \text{Planck constant} \ (6.6310^{-34} \text{ Joule\cdot sec})
\]

\[
\nu = \text{frequency of light} \ (\text{cycles/sec}) = \frac{\lambda}{c}
\]
Do you sell ultraviolet bull?

Excuse me?

What about regular violet bull?

No.

Blue bull?

No.

Green bull?

No.

Yellow bull?

No.

Orange bull?

No.

Rats, ok, I'll take a red bull.

I was hoping for something a little higher-energy.

At least it isn't infrared bull.
Hybrid CMOS Infrared Imaging Sensors

Large, high performance IR arrays

Three Key Technologies

1. Growth and processing of the HgCdTe detector layer
2. Design and fabrication of the CMOS readout integrated circuit (ROIC)
3. Hybridization of the detector layer to the CMOS ROIC
6 Steps of CMOS-based Optical / IR Photon Detection

1. Light into detector
2. Charge Generation
3. Charge Collection
4. Charge-to-Voltage Conversion
5. Signal Transfer
6. Digitization

- Anti-reflection coating
- Substrate removal
- Detector Materials
  - HgCdTe, Si
- Electric Fields in detector
  - collect electrical charge
  - p-n junction
- Source follower
  - Random access
  - or full frame read
- Sidecar ASIC
  - HYBRID SENSOR
  - CHIP ASSEMBLY (SCA)

Quantum Efficiency
Point Spread Function
Sensitivity
Crystals are excellent detectors of light

- Simple model of atom
  - Protons (+) and neutrons in the nucleus with electrons orbiting

- Electrons are trapped in the crystal lattice
  - by electric field of protons

- Light energy can free an electron from the grip of the protons, allowing the electron to roam about the crystal
  - creates an “electron-hole” pair.

- The photocharge can be collected and amplified, so that light is detected

- The light energy required to free an electron depends on the material.
Detector Families

- Si - IV semiconductor
- HgCdTe - II-VI semiconductor
- InGaAs & InSb - III-V semiconductors
Tunable Wavelength: Unique property of HgCdTe

Hg$_{1-x}$Cd$_x$Te Modify ratio of Mercury and Cadmium to “tune” the bandgap energy

Bandgap and Cutoff Wavelength as function of Cadmium Fraction ($x$)

![Graph showing Bandgap and Cutoff Wavelength as function of Cadmium Fraction ($x$)](image)

\[ E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35 \times 10^{-4} T(1 - 2x) \]

Absorption Depth of Photons in HgCdTe

**Rule of Thumb**
Thickness of HgCdTe layer needs to be about equal to the cutoff wavelength

<table>
<thead>
<tr>
<th>Absorption Depth (%)</th>
<th>Thickness of detector material required</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.2%</td>
<td>≥ 3 absorption depths</td>
</tr>
<tr>
<td>86.5%</td>
<td>≥ 2 absorption depths</td>
</tr>
<tr>
<td>95.0%</td>
<td>≥ 1 absorption depth</td>
</tr>
<tr>
<td>98.2%</td>
<td>≥ 1 absorption depth</td>
</tr>
</tbody>
</table>

**Temperature = 77K**

- $\lambda_{\text{co}}$: 1.7 microns
- 2.5 microns
- 5 microns
- 12 microns

Teledyne Imaging Sensors
A Teledyne Technologies Company
Molecular Beam Epitaxy (MBE) Growth of HgCdTe

RIBER 3-in MBE Systems

3 inch diameter platen allows growth on one 6x6 cm substrate

RIBER 10-in MBE 49 System

10 inch diameter platen allows simultaneous growth on four 6x6 cm substrates

More than 7500 HgCdTe wafers grown to date
HgCdTe Cutoff Wavelength

“Standard” Ground-based astronomy cutoff wavelengths

- Near infrared (NIR) 1.75 µm J,H
- Short-wave infrared (SWIR) 2.5 µm J,H,K
- Mid-wave infrared (MWIR) 5.3 µm J,H,K,L,M
6 Steps of CMOS-based Optical / IR Photon Detection

1. Light into detector
2. Charge Generation
3. Charge Collection
4. Charge-to-Voltage Conversion
5. Signal Transfer
6. Digitization

Quantum Efficiency
Point Spread Function

Detector Materials:
HgCdTe, Si

Electric Fields in detector collect electrical charge at p-n junction

Anti-reflection coating
Substrate removal

Source follower
Random access or full frame read

SIDECAR ASIC

HYBRID SENSOR CHIP ASSEMBLY (SCA)
HgCdTe hybrid FPA cross-section (substrate removed)
Hybrid Imager Architecture

Mature interconnect technique:
- Over 16,000,000 indium bumps per Sensor Chip Assembly (SCA) demonstrated
- >99.9% interconnect yield

H4RG-10
- 4096x4096 pixels
- 10 micron pixel pitch
- HyViSI silicon PIN

Example of indium bumps

MOSFET = metal oxide semiconductor field effect transistor
Cosmic Rays and Substrate Removal

- Cosmic ray events produce clouds of detected signal due to particle-induced flashes of infrared light in the CdZnTe substrate; removal of the substrate eliminates the effect.

2.5um cutoff, substrate **on**  
1.7um cutoff, substrate **on**  
1.7um cutoff, substrate **off**

**Substrate Removal Positive Attributes**

1. Higher QE in the near infrared
2. Visible light response
3. Eliminates cosmic ray fluorescence
4. Eliminates CTE mismatch with silicon ROIC

Images courtesy of Roger Smith
Quantum Efficiency of substrate-removed HgCdTe

Quantum Efficiency of 1.7 micron HgCdTe at 145K

Quantum Efficiency of 2.3 micron HgCdTe
Example Anti-reflection coatings for HgCdTe

![Graph showing transmission into the HgCdTe layer for different coating configurations.](image)

- Single Layer (WFC3)
- Double Layer
- Three Layer (NIRCAM SWIR)
Dark Current
Undesirable byproduct of light detecting materials

- The vibration of particles (includes crystal lattice phonons, electrons and holes) has energies described by the Maxwell-Boltzmann distribution. Above absolute zero, some vibration energies may be larger than the bandgap energy, and will cause electron transitions from valence to conduction band.

- Need to cool detectors to limit the flow of electrons due to temperature, i.e. the **dark current** that exists in the absence of light.

- The smaller the bandgap, the colder the required temperature to limit dark current below other noise sources (e.g. readout noise)
Dark Current of MBE HgCdTe

HgCdTe cutoff wavelength (microns)

Typical InSb Dark Current

Temperature (K)

Dark Current
Electrons per pixel per sec
18 micron square pixel

10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

30 50 70 90 110 130 150 170 190 210 230
### 6 Steps of CMOS-based Optical / IR Photon Detection

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
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<tr>
<td>1.</td>
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**Anti-reflection coating**
- Substrate removal

**Detector Materials**
- HgCdTe, Si

**Electric Fields in detector**
- collect electrical charge
- p-n junction

**Sensitivity**
- Quantum Efficiency
- Point Spread Function

**HYBRID SENSOR CHIP ASSEMBLY (SCA)**

**SIDECAR ASIC**

**Source follower**
- Random access or full frame read

**SIDECAR ASIC**

**SIDECAR ASIC**
MOSFET Principles

MOSFET = metal oxide semiconductor field effect transistor

Turn on the MOSFET and current flows from source to drain.

Add charge to gate & the current flow changes since the effect of the field of the charge will reduce the current.

Fluctuations in current flow produce “readout noise”
Fluctuations in reset level on gate produces “reset noise”
IR multiplexer pixel architecture

$V_{dd}$
amp drain voltage

Photovoltaic Detector

Detector Substrate

Output
IR multiplexed pixel architecture

- $V_{\text{reset}}$: reset voltage
- $V_{\text{dd}}$: amp drain voltage

- "Clock" (green)
- "Bias voltage" (purple)

- Reset
- Photovoltaic Detector
- Detector Substrate
- Output
IR multiplexer pixel architecture

- $V_{reset}$: reset voltage
- $V_{dd}$: amp drain voltage
- Enable
- "Clock" (green)
- "Bias voltage" (purple)
- Photovoltaic Detector
- Detector Substrate
- Output
Reduction of noise from multiple samples

Non-destructive readout enables reduction of noise from multiple samples

13.1 e- single CDS

3.5 e- Fowler-32

CDS = correlated double sample
General Architecture of CMOS-Based Image Sensors

- Control & Timing Logic (optional)
- Vertical Scanner for Row Selection
- Pixel Array
- Horizontal Scanner / Column Buffers
- Bias Generation & DACs (optional)
- A/D conversion (optional)
- Analog Amplification
  - Analog Output
  - Digital Output
Pixel Amplifier Options

Source follower (SF)
- Integration on detector node
- Low power & compact (3 FETs / pixel)
- Ideal for small pixels & low flux
- Poor performance for high flux
- Full Well: ~100,000 electrons
- Readout Noise: <15 e-

Capactive TransImpedance Amplifier (CTIA)
- Versatile circuit suitable for all backgrounds and detectors
- High linearity
- High power, higher noise and larger circuit than SF for low flux
- Worse performance than DI for high flux
- Full Well: ~1 to 10 million e-
- Readout Noise: <50 e-

Direct Injection (DI)
- Extremely small circuit
- Large integration density in pixel
- High well capacity for high flux applications
- Ultra low power
- Poor injection efficiency for low flux applications
- Full Well: tens of millions of e-
- Readout Noise: <1000 e-
High Performance Hybrid CMOS Arrays
High Quality MBE HgCdTe + High Performance CMOS Design + Large Area Hybridization

High Quantum Efficiency

High Quality Detectors

Low Dark Current

High Performance Amplifiers

High Performance Readout Circuits

Imaging System on Chip Architecture

Bias Generation & DACs (optional)
A/D conversion (optional)
Analog Amplification
Digital Output
Analog Output

Control & Timing Logic (optional)
Vertical Scanner for Row Selection
Pixel Array
Horizontal Scanner / Column Buffers

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Typical InSb Dark Current

Electrons per pixel per sec
18 micron square pixel

Temperature (K)

Typical InSb Dark Current
- ~9
- ~5
- ~2.8
- ~1.7

Quantum Efficiency of 1.7 micron HgCdTe at 145K

Dark Current

Wavelength (nm)

Substrate-removed
Substrate on
HAWAII-2RG 2048×2048 pixels

HAWAII-2RG (H2RG)

- 2048×2048 pixels, 18 micron pitch
- 1, 2, 4, 32 ports
- “R” = reference pixels (4 rows/cols at edge)
- “G” = guide window
- Low power: <1 mW (4 port, 100 kHz rate)
- Detector material: HgCdTe or Si
- Interfaces directly to the SIDECAH ASIC

Qualified to NASA TRL-6
- Vibration, radiation, thermal cycling
- Radiation hard to ~100 krad

Teledyne Imaging Sensors
HAWAII-2RG™
Visible & Infrared Focal Plane Array

4Kx4K mosaic of 4 H2RGs
The **SIDECAR ASIC** – Focal Plane Electronics on a Chip

**Replace this**

**with this!**

**1% volume**
**1% power**
**1% hassle**

**SIDECAR:** System for **Image Digitization, Enhancement, Control And Retrieval**
SIDECAR ASIC – Focal Plane Electronics on a Chip

**SIDECAR ASIC**
- 36 analog input channels
- 36 16-bit ADCs: up to 500 kHz
- 36 12-bit ADCs: up to 10 MHz
- 20 output bias channels
- 32 digital I/O channels
- Microcontroller (low power)
- LVDS or CMOS interface
- Low power:
  - <15 mW, 4 channels, 100 kHz, 16-bit ADC
  - <150 mW, 32 channels, 100 kHz, 16-bit ADC
- Operating temperature: 30K to 300K
- Interfaces directly to H1RG, H2RG, H4RG
- Qualified to NASA TRL-6
  - Vibration, radiation, thermal cycling
  - Radiation hard to ~100 krad
Spaceflight packaging: JWST Fine Guidance Sensor

- Package for H2RG 2048x2048 pixel array
- TRL-6 spaceflight qualified
- Interfaces directly to the SIDECAR ASIC
- Robust, versatile package

- Thermally isolated FPA can be stabilized to 1 mK when cold finger fluctuates several deg K
SIDECAR ASIC & large mosaic focal plane arrays

H2RG 2K×2K 2×2

Mechanical Prototype 5×7

H2RG 4x4

4x4 Mosaic for Space Mission
HyViSI™ – Hybrid Visible Silicon Imager

Focal plane array performance independently verified by:
- Rochester Institute of Technology
- European Southern Observatory
- US Naval Observatory & Goddard Space Flight Center

Readout noise, at 100 kHz pixel rate
- 7 e- single CDS, with reduction by multiple sampling

Pixel operability > 99.99%
HyViSI Array Formats

**Ground-based Astronomy (Rochester Institute of Technology)**
- Crab Nebula (M1) 1K×1K H1RG-18
- NGC2683 Spiral Galaxy 2K×2K H2RG-18
- Hercules Cluster (M13) 4K×4K H4RG-10

**Mars Reconnaissance Orbiter (MRO)**
- TCM 6604A
  - 640×480 pixels
  - 27 µm pitch
  - CTIA
- TEC Package by Judson

**Orbiting Carbon Observatory**
- 1K×1K H1RG-18 (same used by IR)
- Launch: Jan 2009
High Speed, Low Noise, Event Driven Readout

**Speedster128**
- 128×128 pixels, 40 micron pitch
- Detector material: HgCdTe or Si
- Pixel design
  - Next generation CTIA pixel amplifier
  - Global snapshot, integrate while read
  - In-pixel CDS (correlated double sampling)
  - Readout noise: <5 e- for HgCdTe
  - <4 e- for Si
- Digital input
  - All clocking produced on-chip
- Single analog output
- Up to 900 Hz frame rate

2008/9: Fabricate and demonstrate Speedster128 arrays
2009: Modify design for event driven readout

Designed for IR AO and interferometry
High speed, low noise, event driven HyViSI is optimal detector for soft x-ray astronomy
Large IR Astronomy Focal Plane Development
The Next Step: 4096×4096 pixels

- 4096×4096 pixels, 15 µm pitch with embedded SIDECAR ASIC
- Design readout circuit for high yield (4 ROICs per 8-inch wafer)
  - New design process
- Minimize detector cost by growing HgCdTe on silicon substrate
- 4-side buttable for large mosaics
- Option: SIDECAR ASIC integrated into SCA package
Teledyne – Your Imaging Partner for Astronomy & Civil Space

State-of-the-art & high TRL
- CMOS Design
- Detector Materials
- Packaging
- Electronics
- Systems Engineering

CMOS Design Expertise
- Pixel amplifiers – lowest noise to highest flux
- High level of pixel functionality (LADAR, event driven)
- Large 2-D arrays, pushbroom, redundant pixel design
- Hybrids made with HgCdTe, Si, or InGaAs
- Monolithic CMOS
  - Analog-to-digital converters
  - Imaging system on a chip
  - Specialized ASICs
  - Radiation hard
  - Very low power