Optical and Infrared Detectors for Astronomy

Basic Principles to State-of-the-art

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Optics in Astrophysics

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Goals of the Detector Course

The student should gain an understanding of:

3. The role detectors play in an astronomical observatory
   Why detectors are the MOST important technology!

2. Fundamental detector physics
3. Standard detector architecture
4. What affects quantum efficiency and readout noise
5. The state-of-the-art today
6. Special applications / areas of research & development
Course Outline

Lecture 1: Role of detectors in observatory
Detector physics
Standard architecture

Lecture 2: Quantum efficiency
Readout noise
Detector imperfections

Lecture 3: Manufacturers
Bigger devices / Mosaics
Electronics
Special applications
Optical CMOS and CMOS + CCD
Course Outline

Lecture 1: Role of detectors in observatory
Detector physics
Standard architecture
Optical and Infrared Astronomy
(0.3 to 25 m)

Two basic parts

Telescope to collect and focus light

Instrument to measure light
Okay, maybe a bit more complicated – 4 basic parts

1. Telescope to collect and focus light
2. Adaptive Optics
3. Instrument to measure light
4. Detector
Instrument goal is to measure a 3-D data cube.

But detectors are 2-dimensional!

- Our detectors are **black & white**.
- Can not measure color, only intensity.

So the optics of the instrument are used to map a portion of the 3-D data cube on to the 2-D detector.
<table>
<thead>
<tr>
<th>SOURCE</th>
<th>SPECTROGRAPHIC MODES</th>
<th>VLT INSTRUMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended Continuum</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
<td>ISAAC, FORS 1/2, CONICA, VISIR</td>
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<tr>
<td>Extended Emission</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
<td>CONICA</td>
</tr>
<tr>
<td>Single Point Continuum</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
<td>UVES (CRIRES)</td>
</tr>
<tr>
<td>Diluted-Point Continuum</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
<td>FORS 1/2 (NIRMOS/WFIS), FUEGOS</td>
</tr>
<tr>
<td>Single Small Continuum</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
<td>FUEGOS (SINFONI)</td>
</tr>
</tbody>
</table>
Where detectors are used in an observatory

Scientific:  Imaging  
Spectroscopy  

Technical:  Acquisition / guiding  
Active optics  
Adaptive optics  
Interferometry (fringe & tip/tilt tracking)  
Site monitoring (seeing, clouds, LGS)  

General:  Surveillance  
Safety
In this course, we concentrate on **2-D focal plane arrays.**

- **Optical** – silicon-based (CCD, CMOS)
- **Infrared** – IR material plus silicon CMOS multiplexer

**Will not address:**
- APD (avalanche photodiodes)
- STJs (superconducting tunneling junctions)
The Ideal Detector

• Detect 100% of photons
• Each photon detected as a delta function
• Large number of pixels
• Time tag for each photon
• Measure photon wavelength
• Measure photon polarization

✓ Up to 99% quantum efficiency
✓ One electron for each photon
✓ over 355 million pixels
☒ No - framing detectors
☒ No – defined by filter
☒ No – defined by filter

Plus READOUT NOISE and other “features”
5 basic steps of optical/IR photon detection

1. **Get light into the detector**
   - Anti-reflection coatings

2. **Charge generation**
   - Popular materials: Silicon, HgCdTe, InSb

3. **Charge collection**
   - Electrical fields within the material collect photoelectrons into pixels.

4. **Charge transfer**
   - If infrared, no charge transfer required.
   - For CCD, move photoelectrons to the edge where amplifiers are located.

5. **Charge amplification & digitization**
   - Amplification process is noisy. In general, CCDs have lowest noise, CMOS and IR detectors have higher noise.
• Optical and IR focal plane arrays are similar in many ways
  – I will combine information about optical and IR detectors as much as possible.
• But optical and IR detectors are different in some important ways
  – I will try to be careful to differentiate when necessary.
• Please ask if you are ever confused whether the subject is optical and/or IR detectors.
Step 1: Get light into the detector

Anti-reflection coatings

- AR coatings will be discussed in lecture 2 when quantum efficiency is presented.
Step 2: Charge Generation

Silicon CCD
Similar physics for IR materials
Silicon Lattice constant 0.543 nm
Step 2: Charge Generation
Photon Detection

For an electron to be excited from the conduction band to the valence band:

\[ h E_g \]

where:
- \( h \) = Planck constant (6.6 \times 10^{-34} \text{ Joule} \cdot \text{sec})
- \( E_g \) = energy gap of material (electron-volts)

\[ E_g = \frac{c}{v} \]

\[ c = \frac{1.238}{E_g (\text{eV})} \]

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Symbol</th>
<th>( E_g ) (eV)</th>
<th>( c ) (m)</th>
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<tbody>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>1.12</td>
<td>1.1</td>
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<tr>
<td>Mer-Cad-Tel</td>
<td>HgCdTe</td>
<td>1.00 – 0.09</td>
<td>1.24 – 14</td>
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<tr>
<td>Indium Antimonide</td>
<td>InSb</td>
<td>0.23</td>
<td>5.9</td>
</tr>
<tr>
<td>Arsenic doped Silicon</td>
<td>Si:As</td>
<td>0.05</td>
<td>24</td>
</tr>
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</table>
Tunable Bandgap
A great property of Mer-Cad-Tel

Hg$_{1-x}$Cd$_x$Te

Modify ratio of Mercury and Cadmium
to “tune” the bandgap energy

<table>
<thead>
<tr>
<th>x</th>
<th>$E_g$ (eV)</th>
<th>$c$ (m)</th>
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<td>14</td>
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<td>0.21</td>
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<td>0.295</td>
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<tr>
<td>0.395</td>
<td>.41</td>
<td>3</td>
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<tr>
<td>0.55</td>
<td>.73</td>
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<tr>
<td>0.7</td>
<td>1.0</td>
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</table>
Step 2: Charge Generation
Photon Detection

For an electron to be excited from the conduction band to the valence band:

\[ h E_g \]

- \( h \) = Planck constant \((6.6 \times 10^{-34} \text{ Joule} \cdot \text{sec})\)
- \( E_g \) = energy gap of material (electron-volts)
- \( = \) frequency of light (cycles/sec) = \( /c \)

\[ c = 1.238 / E_g \text{ (eV)} \]

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Symbol</th>
<th>( E_g ) (eV)</th>
<th>( c ) ( m)</th>
<th>Operating Temp. (K)</th>
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<tbody>
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<td>1.12</td>
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<td>163 - 300</td>
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<td>HgCdTe</td>
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<td>Arsenic doped Silicon</td>
<td>Si:As</td>
<td>0.05</td>
<td>24</td>
<td>4</td>
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</table>
How small is an electron-volt (eV)?

1 eV = $1.6 \times 10^{-19}$ J

1 J = $N \cdot m = kg \cdot m \cdot sec^{-2} \cdot m$

1 kg raised 1 meter = 9.8 J = $6.1 \times 10^{19}$ eV
How small is an electron-volt (eV) ?

DEIMOS example

DEIMOS – Deep Extragalactic Imager & Multi-Object Spectrograph

• 8K x 8K CCD array – 67 million pixels
• If 100 images / night, then ~13.5 Gbyte/night
• If used 1/3 of the year & all nights clear, 1.65 Tbyte/year
• If average pixel contains 5,000 photoelectrons
  4.1 \times 10^{15} \text{ photoelectrons} / \text{year}
  4.6 \times 10^{15} \text{ eV} / \text{year}

Single peanut M&M candy (2 g) falling 15 cm (6 inches) loses potential energy equal to $1.85 \times 10^{16}$ eV, same as total bandgap energy from four years of heavy DEIMOS use.
Step 3: Charge Collection

- Intensity image is generated by collecting photoelectrons generated in 3-D volume into 2-D array of pixels.
- Optical and IR focal plane arrays both collect charges via electric fields.
- In the z-direction, optical and IR use a p-n junction to “sweep” charge toward pixel collection nodes.
Silicon CCD & HgCdTe and InSb are photovoltaic detectors. They use a pn junction to generate E-field in the z-direction of each pixel. This electric field separates the electron-hole pairs generated by a photon.
For silicon

n – region from phosphorous doping

p – region from boron doping

n-channel CCD collects electrons

p-channel CCD collect holes
Step 3: Charge Collection

- Optical and IR focal plane arrays are different for charge collection in the x and y dimensions.
- IR – collect charge at each pixel and have amplifiers and readout multiplexer.
- CCD – collect charge in array of pixels. At end of frame, move charge to edge of array where one (or more) amplifier(s) read out the pixels.
Infrared Pixel Geometry
Infrared Detector Cross-section
(InSb example)

- Incident Photons
- Thinned bulk n-type InSb
- Implanted p-type InSb (collect holes)
- Indium bump bond
- Silicon multiplexer
- MOSFET input
- AR coating
- Epoxy
- Output Signal
Infrared Detector Cross-section (new Rockwell HgCdTe design)

- Buried Junction Intersection
- Metal
- Thin Film CdTe External Passivant
- P-Type Implant (collect holes)
- One Step Growth
- N-MWIR MCT
- MCT Cap Layer
- Active Absorber Layer
- CdZnTe Substrate
- Incident Photons
CCD Architecture
CCD Pixel Architecture – column boundaries

- Channel Stop
- ~2 μm wide
- 3-phase CCD Pixel

Phases:
- Phase 1
- Phase 2
- Phase 3
### Periodic Table

<table>
<thead>
<tr>
<th>2</th>
<th>He</th>
<th>Helium</th>
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<td>Neon</td>
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</tr>
<tr>
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<td>B</td>
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<td>Al</td>
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<tr>
<td>14</td>
<td>Si</td>
<td>Silicon</td>
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<tr>
<td>53</td>
<td>Br</td>
<td>Bromine</td>
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<tr>
<td>86</td>
<td>Rn</td>
<td>Radon</td>
<td>222.0</td>
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</tbody>
</table>

**Types of Elements Key:**
- [ ] Alkalimetals
CCD Pixel Architecture – column boundaries

- Channel Stop
  - ~2 μm wide
- 3-phase CCD Pixel
- 15 μm
### Periodic Table

<table>
<thead>
<tr>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tbody>
<tr>
<td>He</td>
<td>Li</td>
<td>Be</td>
<td>B</td>
<td>C</td>
<td>N</td>
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<td>4.0</td>
<td>3.0</td>
<td>9.0</td>
<td>10.8</td>
<td>14.0</td>
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<tr>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
<td>Cl</td>
<td>Ar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.0</td>
<td>28.1</td>
<td>31.0</td>
<td>32.1</td>
<td>35.5</td>
<td>40.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Aluminum (Al)**
- **Silicon (Si)**
- **Phosphorus (P)**
- **Sulfur (S)**
- **Chlorine (Cl)**
- **Argon (Ar)**

### Types of Elements Key:

- Alkaline Earth Metals
- Alkaline Metals
- Transition Metals
- Noble Gases
- Non-Metals
- Halogens
- Post-Transition Metals
- Lanthanides
- Actinides
For silicon

n – region from phosphorous doping

p – region from boron doping

n-channel CCD collects electrons

p-channel CCD collect holes
CCD Pixel Architecture – parallel phases

CHANNEL STOP
≈ 2 mm wide

3-phase CCD Pixel

PHASE 1

PHASE 2

PHASE 3
CCD Fabrication Process
Step 4: Charge transfer

- IR detectors have amplifier at each pixel, so no need for charge transfer.
- CCDs must move charge across the focal plane array to the readout amplifier.
CCD Architecture
CCD Charge transfer
The good, the bad & the ugly

• “Bad & ugly” aspects of charge transfer
  – Takes time
  – Can blur image if no shutter used
  – Can lose / blur charge during move
  – Can bleed charge from saturated pixel up/down column
  – Can have a blocked column
  – Can have a hot pixel that releases charge into all passing pixels

• “Good” aspects of charge transfer
  – Can bin charge “on-chip” – noiseless process
  – Can charge shift for tip/tilt correction or to eliminate systematic errors (“va-et-vient”, “nod-and-shuffle”)
  – Can build special purpose designs that integrate different areas depending on application (curvature wavefront sensing, Shack-Hartmann laser guide star wavefront sensing)
  – Can do drift scanning
  – Have space to build a great low noise amplifier!
CCD Timing

Movement of charge is “coupled”

Charge Coupled Device
3-Phase serial register

THREE PHASE IMAGE ARRAY

CONVENTION

"Down" VERTICAL/PARALLEL

"Across" HORIZONTAL/SERIAL

CHANNEL STOP

SERIAL REGISTER 3-PHASE ALSO

OUTPUT AMPLIFIER
Rain bucket analogy
CCD Architecture
Step 5: Charge amplification

- Similar for CCDs and IR detectors.
- Both use MOSFETs (metal-oxide-silicon field effect transistors) to amplify the signal.
- Show CCD amplifier first and then relate to IR pixel.
CCD – Serial register and amplifier
100 micron diameter human hair
For SiTe type amplifier:

- $4 \times 25 \mu m$ gate, $\frac{1}{2} \mu m$ thick, $10^{20}$ doping
- $3 \times 10 \mu m$ Al strap, $\frac{1}{2} \mu m$ thick
- Capacitance (gate) $\approx 100 \ fF$, $1 \mu V/e^-$

- $5 \times 10^9$ phosphorous "donor" atoms on the gate
- $10^{12}$ conduction band electrons on the Al strap
- $6 \times 10^6$ electrons removed to bias to +9V

Fig. 4. Buried channel MGSFET with source and drain edges separated from the gate.
For SITe type amplifier: 4 x 25 μm gate, ½ μm thick, $10^{20}$ doping
3 x 10 μm Al strap, ½ μm thick
Capacitance (gate) = 100 fF, 1 μV/e⁻

~ 5 x 10⁹ phosphorous “donor” atoms on the gate
~ 10¹² conduction band electrons on the Al strap
~ 6 x 10⁶ electrons removed to bias to +9V

\[ \text{GATE} \quad \text{DRAIN} \]

[Diagram showing a MOSFET with labeled source, gate, and drain]

Fig. 4. Buried channel MOSFET with source and drain edges separated from the gate

Add 1 electron to the source node and the flow of current under the MOSFET gate is reduced by 300 million per second!
MOSFET symbols

Source

Gate

Drain
Charge Detection

See all kinds of clock feedthroughs

\[ e^- \rightarrow \]

\[ 3V \quad -8V \quad 3V \]

Reference

Drain

12V

Reset

Node

MOSFET bias node & the outside world

Feedthrough pulse

Reset

This is 12V

Horizontal Register

Sense Cap.

Load Resistor

Video

Node sensitivity

\(-4\mu V/e^-\) (or a little lower or higher)

Smaller capacitance
Greater response

Less noise

Source follower

With slight gain difference
Amplifier Responsivity  
(SITE example)

\[
Q = CV \\
V = \frac{Q}{C}
\]

Capacitance of MOSFET = $10^{-13}$ F (100 fF) 
Responsivity of amplifier = 1.6 V / e⁻

More recent amplifier designs have higher responsivity, 5 – 10 V/e⁻, which give lower noise, but less dynamic range. Research is being done on 50xx amplifier designs which may lead to sub-electron read noise.
Infrared Detector Cross-section
(InSb example)

- AR coating
- Implanted p-type InSb (collect holes)
- Epoxy
- MOSFET input
- Indium bump bond
- Silicon multiplexer
- Output signal
- Thinned bulk n-type InSb
- Incident photons
IR multiplexer pixel architecture

$V_{dd}$

amp drain voltage

Photovoltaic Detector

Detector Substrate

Output
IR multiplexer pixel architecture

- Reset
- Photovoltaic Detector
- Detector Substrate
- Output

- $V_{\text{reset}}$: reset voltage
- $V_{\text{dd}}$: amp drain voltage
IR multiplexer pixel architecture

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

- Enable
- Reset
- Photovoltaic Detector
- Detector Substrate

- “Clock” (green)
- “Bias voltage” (purple)

Output
Review of Lecture 1

5 basic steps of optical/IR photon detection

1. Get light into the detector
   Anti-reflection coatings - Lecture 2

2. Charge generation
   Conduction Band
   Valence Band

3. Charge collection

4. Charge transfer

5. Charge amplification