Astronomy 3310  

Lecture 3:  
Introduction to CCD and CMOS Imaging Devices

In this Lecture:  
(Detector Technology)

• Introduction to Solid State Detectors  
  – CCD, CMOS, and IRFPA

• Basic CCD / CMOS / IRFPA Operation  
  – Readout, ADC Digitization

• Basic CCD / CMOS / IRFPA Properties  
  – Noise, QU, CTE, Gain, Bandpass, Coatings

• SNR Calculations  
  – Poison Distribution, Background Limited Performance

Nomenclature

• CCD = Charge-Coupled Device
• CMOS = Complimentary Metal-Oxide Semiconductor  
  – Photon detecting devices that exploit the photoelectric effect and the semiconducting properties of silicon  
  – The voltage generated by the device is coupled to the intensity of the incident light
• Pixel = Picture Element  
  – A CCD is an array of pixels, each of which is an independent photon detector
• DN = Data Number (or ADU = Analog to Digital Unit)  
  – The output signal from a photon detector. Value and range depend on the nature of the voltage digitization. For example, an 8-bit CCD will generate DNs from 0 to $2^8 - 1 = 0$ to 255.
Some Physics

- The photoelectric effect:
  - The emission, or ejection, of electrons from the surface of a metal in response to incident light
  - Observed in experiments in 1902 by German physicist Philipp Lenard
  - Albert Einstein won the Nobel Prize for explaining this...

Reference:
Physics 252, University of Virginia (2005)
When atoms come together to form a crystal, the outer energy levels overlap and blend to create bands.

The outermost filled band is called the valence band.

Above the valence band, one finds a forbidden energy gap—the "band gap"—and (at higher energies) conduction bands populated by thermally excited electrons.

In metals, the valence and conduction bands overlap resulting in conduction. In insulators, the band gap is wider resulting in very poor conduction.

Semiconductors occupy column IV of the Periodic Table

Outer shells have four empty valence states

An outer shell electron can leave the shell if it absorbs enough energy

Silicon Bandgap

1.1 eV = minimum amount of energy it takes to initiate the photoelectric effect

(12340 Å/ eV) 1.1 eV / = 11280 Å = deep deep red

Maximum energy of photoelectric effect dictated by point where more than one electron liberated by incident high-E photon:

occurs around 3000 Å (UV)
Periodic Table Continued

- The column number gives the number of valence electrons per atom. Primary semiconductors have 4.
- Compounds including elements from neighboring columns can be formed. These alloys have semiconductor properties as well (e.g. HgCdTe & InSb).
- Mercury-cadmium-telluride (HgCdTe; will be used in JWST) and indium-antimonide (InSb; used in SIRTF) are the dominant detector technologies in the near-IR.

The Band Gap Determines the Long Wavelength Limit

Forbidden energy gaps and long-wavelength photo-absorption limits for some common semiconductors

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>T (K)</th>
<th>$E_g$ (eV)</th>
<th>$\lambda$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium sulphide</td>
<td>CdS</td>
<td>295</td>
<td>2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Cadmium selenide</td>
<td>CdSe</td>
<td>295</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Gallium arsenide</td>
<td>GaAs</td>
<td>295</td>
<td>1.35</td>
<td>0.92</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>295</td>
<td>1.12</td>
<td>1.11</td>
</tr>
<tr>
<td>Germanium</td>
<td>Ge</td>
<td>295</td>
<td>0.67</td>
<td>1.82</td>
</tr>
<tr>
<td>Lead sulphide</td>
<td>PbS</td>
<td>295</td>
<td>0.42</td>
<td>2.95</td>
</tr>
<tr>
<td>Indium antimonide</td>
<td>InSb</td>
<td>295</td>
<td>0.18</td>
<td>6.9</td>
</tr>
<tr>
<td>Mercury-cadmium</td>
<td>HgCd, Te</td>
<td>295</td>
<td>0.1 (~0.8)</td>
<td>12.4</td>
</tr>
<tr>
<td>Telluride</td>
<td></td>
<td>77</td>
<td>0.23</td>
<td>5.4</td>
</tr>
</tbody>
</table>

$$E_g = \hbar \nu = \frac{hc}{\lambda} \quad (1)$$
OK, so what?

- The key to using silicon as a photon counter is to figure out a way to prevent the liberated conduction band electrons from recombining back into the valence band...
- That’s what a CCD does!
- Electronic circuitry is combined with the Silicon to make small, unique regions (pixels) where the charge is stored for later readout (essentially, a capacitor)

![3-D view of a pixel: p' areas are silicon doped with boron, n areas are silicon doped with phosphorus.]

2-D view of a pixel:

- In a PN junction, positively charged holes diffuse into the n-type material. Likewise, negatively charged electrons diffuse in the p-type material.
- This process is halted by the resulting E-field.
- The affected volume is known as a "depletion region".
- The charge distribution in the depletion region is electrically equivalent to a 2-plate capacitor.

![PN Junctions]

Photon detection in PN junctions

- A photon can interact with the semiconductor to create an electron-hole pair.
- The electron will be drawn to the most positively charged zone in the PN junction, located in the depletion region in the n-type material.
- Likewise, the positively charged hole will seek the most negatively charged region.
- Each photon thus removes one unit of charge from the capacitor. This is how photons are detected in both CCDs and most IR arrays.

![Photon detection in PN junctions]
CCD Coatings

- **Enhance QE:**
  - Example: "Lumogen" coating consisting of phosphorescent materials that enhance the UV responsivity of the CCD
  - Works because all electrons look alike to a CCD!
    (This fact produces other problems we'll have to deal with later...)

- **Antireflective (AR) Coating**
  - Increases QE and helps minimize stray/scattered light problems
Noise

• “To understand your signal, you must first understand your noise” (Howell)
• There are many sources of noise!
  – “Read noise” from the clocking/transfer process
  – “Digitization noise” from the ADC process
  – “Thermal noise” from random thermal agitation of silicon electrons (generates *dark current*)
• Will be discussed in greater detail soon...

CCD Operation

• Circuitry is used to “clock” the charge trapped during the exposure out of the device
Light Bucket Analogy

Styles of Clocking/Readout
- **Frame Transfer**: Device is split into two equal parts, the *active area* which detects the signal, and the masked-off *storage area*, where the charge is stored while being clocked out.
- **Interline Transfer**: Active and masked-off storage areas are adjacent and aligned.

NOTE: Shift of the charge from active to storage areas is fast.

CCD vs. CMOS
- CMOS: Complementary Metal Oxide Semiconductor
- Both are pixelated MOS and have the same process in charge generation and charge collection
- However, charge transfer and charge detection are different
- CCD: all pixels share one charge to voltage converter
- CMOS: every pixel has its own charge to voltage converter
Infrared Hybrid Array

- Infrared arrays use light-sensitive material that can detect infrared photons, wavelengths beyond ~1 μm.
- Therefore, silicon cannot be used as the light-sensitive layer.
- This poses a problem because the readout circuit is most easily implemented in silicon.
- Therefore, infrared arrays are “hybrids” – they use one material to detect light and silicon for the readout circuit.

Pixel-level Cross Section: HgCdTe

- Fig. 18. Cross section of a mesa-stacked HgCdTe photodiode. An n-type layer of HgCdTe is grown on a CdZnTe substrate, followed by a p-type layer to form the junction. Mesa etching defines the individual devices. The surface is passivated to prevent surface accumulation or inversion. Contacts are made to the p-type layer in each pixel and to the n-type layer at the edge of the array (not shown). Infrared flux is incident through the IR-transparent substrate.
Teledyne Family Arrays

CCD/CMOS Properties/Characterization

- Bias or Offset
- Dark Current
- Quantum Efficiency
- Gain, Digitization Range, and Full Well
- Linearity
- Flatfield and "Hot", "Gray", and "Dead" pixels
- Noise
  - Photon (source or shot) noise
  - Thermal ("dark") noise
  - Readout (read) noise
  - Digitization noise (typically small)
  - Interference (external) noise

Bias or Offset

- A CCD measures differences between constant supply voltages and voltage induced by the photoelectric effect
- Even in the absence of any input photons, there is still usually a small voltage running through the device: zero input does not give zero output
- This small voltage offset is put there intentionally to bias the device against returning zero values if the responsivity drifts due to temperature, radiation effects, electronics aging, etc.
**Dark Current**

- Because the CCD is at a finite temperature, thermal vibrations can free electrons from the silicon substrate. This is *dark current*.
- When trapped in a pixel well, these "thermal" photons are indistinguishable from "true" photoelectrons.
- Strongly temperature dependent:
  - $DN_{\text{dark}} = e^{\alpha T}$ (thousands of $e$/sec typical at room $T$)
  - $DN_{\text{dark}}$ typically doubles for every $\Delta T \approx 5-10^\circ C$.
- Will vary from pixel to pixel on the CCD...

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**Gain, Digitization Range, and Full Well**

- *Full Well* = the average total number of electrons that can be stored in each pixel.
- *Digitization Range* = number of DN available in the ADC (8 bit = $2^8 = 256$, 12 bit = $4096$, ...)
- *Gain* = number of electrons per DN
  - Set by resistors, etc. in the output signal circuitry.
  - An optimized gain matches the full well & ADC range.
  - Some instruments offer gain choices based on need:
    - Few photons, long exposures: want low gain (low noise).
    - Bright sources, short exposures: high gain OK.
    - Nice examples on p. 43 of Howell's paperback book...

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**Measuring a CCD’s Gain**

- "Photon Transfer" method:
  - Worked example from MER CCDs next Lecture...

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Beware the Curse of Saturation!

- Two ways to saturate the device:
  - Overfill the buckets: Collect more photons than each pixel can store
    - Can lead to bleeding, blooming, residual images, ...
  - Max out the ADC: Can’t digitize a number of $e^-$ greater than digitization range times gain
    - Can lead to flat-topped stars/features
- Saturation represents an irreversible loss of information.
- Bad bad bad.

Linearity

- CCDs are awesome because they produce a simple linear relationship between the input number of photons and the output signal
- But linearity should not be assumed in a CCD: it must be verified
  - Many devices behave nonlinearly over some range
  - Saturation level must be measured
- You are doing this in Lab 2!

Responsivity Variations

- Also known as "Flatfield" characteristics
  - Imaging a perfectly uniform ("flat") field will generate an output image that is not flat!
- Every pixel is an independent detector
  - Responsivity variations depend on wavelength, temperature, signal level, ...
- Additional variations introduced by optics, filters, support structures, etc.
- Flatfield behavior cannot be assumed
Example Flatfield Images

Imager for Mars Pathfinder (IMP) 860 nm flat; 256x248 Si CCD

NASA/IRTF NSFCAM array 2850 nm flat; 256x256 InSb CCD

Example Flatfield Images

Mars Exploration Rover Pancam 750 nm flat; 1024x1024 Si CCD Laboratory flatfield image, using an integrating sphere

Mars Exploration Rover Pancam Same filter and CCD; "Sky Flat" Image acquired on Mars

Flatfielding matters...

← MER/Pancam images without proper flatfielding (stretched to emphasize sky)

← MER/Pancam images with proper flatfielding
Bad “Challenged” Pixels

- “Hot” pixels
  - Have much higher sensitivity than average
- “Gray” pixels
  - Have much lower sensitivity than average
- Both hot and gray pixels may be recoverable
- “Dead” pixels
  - No, or extreme sensitivity
  - Unrecoverable; usually replaced by local median

Noise

- “To understand your signal, you must first understand your noise” (Howell)
- There are many sources of noise!
  - Statistical photon noise
  - Read noise from the clocking/transfer process
  - Digitization noise from the ADC process
  - Thermal noise from random thermal agitation of silicon electrons (generates dark current)
  - Interference noise from external sources

Photon noise ($\sigma_p$)

- Detecting and storing large numbers of photons or electrons is a statistical process
- Poisson statistics: We are sampling a probability distribution function
  - The uncertainty on our ability to measure $N$ independent, uncorrelated events is equal to $\sqrt{N}$
- Also called “shot noise”, which is a general term for noise associated with any events that occur at constant arrival rates
- Photon noise is quoted in electrons, not DN
Readout Noise (σₚ)

- Or just “read noise”
- The intrinsic noise associated with the CCD’s on-chip circuitry and amplifiers, and any other noise sources that are independent of the signal level
  - Spurious electrons introduced by resistors, capacitors
  - Clocking signals can be noisy...
- Quoted as number of electrons added per pixel into the final signal recorded
- Added to signal every time CCD is read out

Digitization Noise (σ_ADC)

- Electrons from each pixel converted to a digital number by ADC depending on its dynamic range
- Unless the gain of the CCD is 1 e-/DN, a range of electron counts must be converted into a single digital number
- Example: CCD with full well of 200,000 e- optimized with a 12 bit converter: 200,000/4096 ≈ 50 e-/DN
  - 0 to 50 e- = 0 DN
  - 51 to 99 e- = 1 DN, etc.
- Also, digitization is a statistical process, so the conversion will not always be exactly the same, only the same on average

Thermal (‘dark’) noise (σ_d)

- Associated with generation of dark current
- To the CCD, dark current electrons are the same as photon-induced electrons
- So dark current is a statistical (Poisson) process that adds noise just like photons do: √N
- But this signal is a strong (exponential) function of temperature
• Dark Current for the Mars Reconnaissance Orbiter "MARCI" camera CCD
• Details published in:

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Interference Noise ($\sigma_{\text{rf}}$)
• Added in to CCD, ADC by external sources
• Examples:
  – Other circuitry in/near instrument (cooler, etc.)
  – Noise in the power supply, power source
  – Radio frequency interference
    • Natural (lightning, solar wind)
    • Artificial (spacecraft transmitter, AM/FM/Ham, etc.)

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Adding It All Up
• These noise sources are uncorrelated, therefore we combine them in quadrature:
  $$(\sigma_{\text{TOT}})^2 = \left\{ (\sigma_p)^2 + (\sigma_R)^2 + (\sigma_{\text{ADC}})^2 + (\sigma_d)^2 + (\sigma_{\text{rf}})^2 \right\}$$
• Signal to Noise Ratio (SNR) = $e_{\text{TOT}} / \sigma_{\text{TOT}}$
• Important: all values must be in electrons
• For a well-designed, cooled CCD operating in a benign environment: $\sigma_{\text{TOT}} \approx \sigma_p$
• Thus, greater well depth = higher SNR

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Summary/Main Points

- CCDs/CMOS Detectors exhibit many characteristics that must be understood well by the observer and analysts.
- Dedicated calibration tests/measurements must be made to characterize each sensor, each time it is used and/or over its expected operating range.
- These tests generate calibration files that must be used to remove instrumental artifacts and thus arrive at a measurement of the true source signal.
- Through it all, noise accumulates and must also be well-characterized and properly propagated.