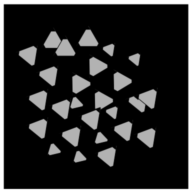
Photographic Emulsions

- More difficult to quantify



- Light-sensitive "grains" of silver halide in the emulsion
- Placed "randomly" in emulsion
- "Random" sizes
- "large" grains are more sensitive
  (respond to few photons)
- "small" grains produce better resolution

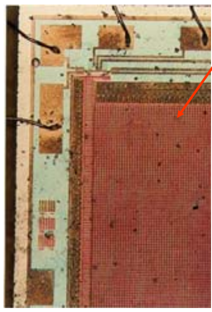
Sensors with "Pixels"

- Regularly spaced "grid" of sensing elements
  - Different from random character inherent in emulsions
  - Easy to "characterize" the sensitivity and to compensate

Charge-Coupled Devices (CCDs)

- Standard light detection medium in digital cameras
  - Price has decreased significantly
- Advantages over photochemical emulsions:
  - Most incident photons are "counted" (i.e., have a detectable effect on sensor)
    - *Quantum Efficiency* (QE) is "large" (may be 80%)
  - *Linear Response*
    - Measured signal proportional to number of incident photons
  - Fast processing (CCD readout speeds ≈1 sec)
    - NO development of emulsion!
  - Regular grid of sensor elements (pixels)
    - vs. random distribution of AgX grains
  - Image delivered in computer-ready form

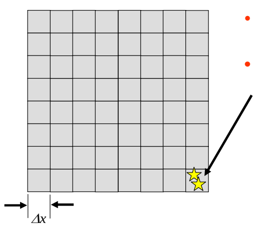
Charge-Coupled Device = CCD



- Individual Sensors
  - "Picture Elements" = Pixels"
- Convert photons to electrons
- Pixel Size ⇒ Image "Resolution"
- Area of Pixels ⇒ "coverage" or "field of view"
- Sensitive over wide range of wavelengths ("colors")
  - from Ultraviolet to Infrared
  - $350 \text{ nm} \leq \lambda \leq 1000 \text{ nm}$
- Pixels are "read out" in sequence
  - cannot be randomly accessed!!

Sensor Resolution

- Obvious for Electronic Sensors (e.g., CCDs)



- Elements (pixels) have finite size
  - ⇒ limited "resolution"
- Light summed over sensor area
  - "integrated" signal

What is a CCD?

- "CCD" = "Charge-Coupled Device"
- Invented in 1970s, originally for:
  - Memory devices
  - Arithmetic data processing (computer chips)
- Usually made of Silicon ("*Si*")

  ⇒Has Same Light-Sensitive Properties as Silicon Light Meters

CCDs have Revolutionized Astronomy

- Improved Light-Gathering Power of Telescopes by nearly 100×
  - Telescope w/ diameter of 150-mm (6”) w/ CCD gets similar performance as 1960 Professional with 1-m (40") Telescope + Photographic Plates
- Now Considered to be “Standard” Sensor in Astronomical Imaging
  - Special Arrangements with Observatory Necessary to use Photographic Plates or Film

Film/Plates Still Useful!!

- Large sizes can be made
  ⇒Large field of view
- Cheap!
- May be scanned to make digital images

CCD

- Made from Crystalline Silicon (*Si*)
- Converts Photons of Light to Electronic Charges
  - Electrons
- Pattern of Light ⇒ Pattern of Charge ⇒ Image
- Electrons converted to current and read in sequence through amplifiers
  1. “Digitized”
     - Analog Measurements (“Voltages”) Converted to Integer Values at Pixels
  2. “Digitized” Measurements Stored as Computer File

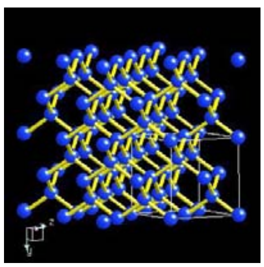
Silicon Atoms

http://www.webelements.com

- 14 protons and electrons
  - Atomic "number" = 14
- 14 neutrons
  - Atomic "weight" = 14 + 14 = 28
- Discrete energy levels for electrons
  - ⇒ discrete set of transitions
  - ⇒ discrete spectrum

Si Crystals

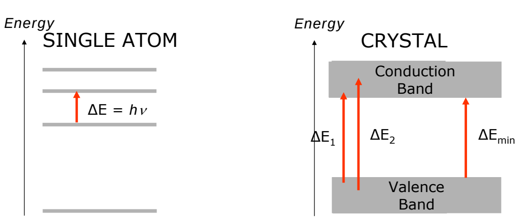
- Regular Pattern of *Si* atoms
  - Fixed Pattern of Spacings Between Atoms
- Atomic Structure Pattern
  - Forces "Perturb" Energy Levels and Changes Layout of Available Electron States



http://www.webelements.com/webelements/elements/text/Si/xtal.html

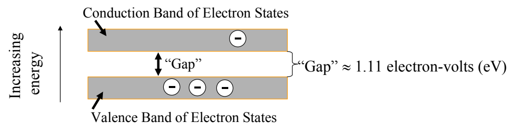
Effect of Crystal Structure on Energy Levels

- Forces from Neighboring Atoms "Perturb" Electron Orbitals (Energy Levels)
  - Changes "Layout" of Energy Levels from Discrete States to Continuous "Bands"



Electron States in *Si* Crystal

- Available States in Crystal Arranged in Discrete "Bands" of Energies
  - Lower Band ≡ *Valence Band*
    - More electrons
  - Upper Band ≡ *Conduction Band*
    - Fewer electrons, rove "free", can "conduct electricity"
- No States Exist in "Gap" Between Bands



Action of Light on Electron States

- Incoming Photon with Energy Larger than the "Gap" of *1.11 eV*
  - Absorbed and excites electrons from "Valence Band" to "Conduction Band"
- Electron in Conduction Band Roams through the Crystal "Lattice"
  - Not bound to any one atom
- Excited Electron e^- leaves "Hole" ("Lack of Electron" = h^+) in Valence Band
  - Hole = "Carrier" of Positive Charge

Action of "Charge Carriers"

- Carriers are "Free" to Move in the Corresponding Band
  - Electron e^- moves freely in Conduction Band
  - Hole h^+ moves freely in Valence Band
- Charge carriers move as "current" when under influence of "voltage" force
  - Electrons are "counted" by measuring current
  - Current ∝ Number of Electrons
    ∝ Number of Absorbed Photons

Wavelength λ corresponding to E = 1.11 electron Volts

⇒ Smallest measurable energy

⇒ Longest detectable wavelength of light

- 1 eV = 1.602 × 10^{-12} erg = 1.602 × 10^{-12} Joule

$$\lambda_{\max} = \frac{hc}{E_{\min}} = \frac{\left(6.624 \times 10^{-27}\,\text{erg}-\text{sec}\right)\cdot\left(3 \times 10^{8}\,\frac{\text{m}}{\text{sec}}\right)}{1.11\ \text{eV} \times \left(1.602 \times 10^{-12}\,\frac{\text{erg}}{\text{eV}}\right)}$$

$$= 1.117 \times 10^{-6}\,\text{m} = 1117\ \text{nm} = 1.12\ \mu\text{m}$$

⇒ To Energize Electron in Si Lattice Requires λ < 1.12 μm, near-Infrared wavelength

Imaging Science Fundamentals

Energy and Wavelength

- If Wavelength of Incident Light is too long (λ > 1.1 μm), Photon CANNOT be Absorbed!
  - Insufficient Energy to "Kick" Electron from Valence Band to Conduction Band

⇒ Silicon is "Transparent" to long λ

⇒ CCDs constructed from Silicon are Insensitive to Long Wavelengths

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After Electron is Excited into Conduction Band…

- Electron and Hole Usually "Recombine" Quickly
  - Charge Carriers are "Lost"
- Prevent Recombination by Applying External Electric Field to "Separate" Electrons from Holes
  - Voltage attracts e^- toward positive terminal, h^+ toward negative terminal
- Field Attracts "Sweeps" Electrons and Holes in Opposite Directions:

⇒They don't recombine

- Maintains Population of Charge Carriers
- Allows Carriers to be "Counted"
  - Proportional to Incident Photons

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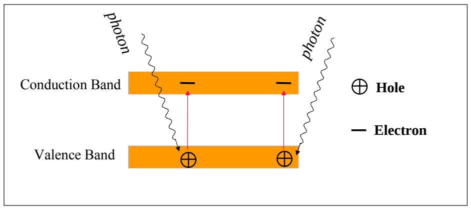
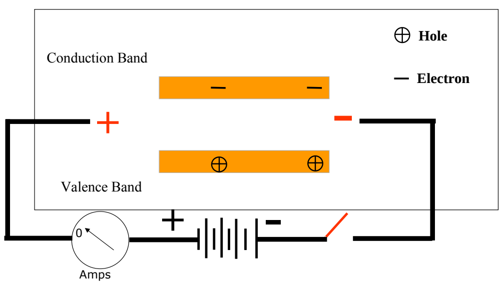
Generation of CCD Carriers



Apply Voltage, Measure Current



Thermal “Noise” in Measurement

- BUT: Other forms of energy have same effect as light
- Thermally Generated Electrons are *Indistinguishable* from photon-generated Electrons
  - Heat Energy can “Kick” *e*$^-$ into Conduction Band
  - Thermal Electrons appear as “Noise” in Images
    - “Dark Current”
  - Keep CCDs ***COLD*** to Reduce Number of Thermally Generated Carriers (Dark Current)

How to "Count" Charge Carriers ("Photoelectrons")?

- Must "Move" Charges (electrons and/or holes) to an "Amplifier"
- Professional CCDs: Amplifier Located at "Edge" of Light-Sensitive Region of CCD
  - Most of CCD Area "Sensitive" to Light
  - Charge Transfer is "Slow"
- CCDs in Video and Amateur Digital Cameras: Must Transfer Charge QUICKLY to take next shot
  - Less Sensor Area Available to Collect Light

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"Bucket Brigade" CCD Analogy

- Electron Charge Generated by Photons is "Transferred" from Pixel to "Edge" of Array
- Transferred Charges are "Counted" to Measure Number of Photons

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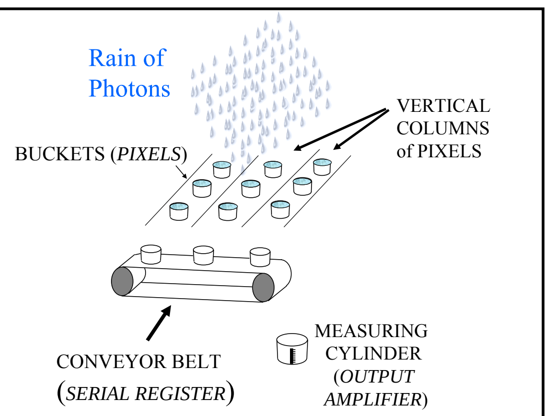
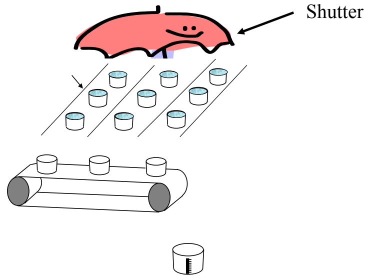
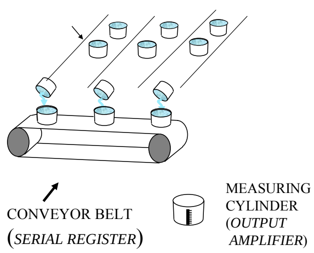
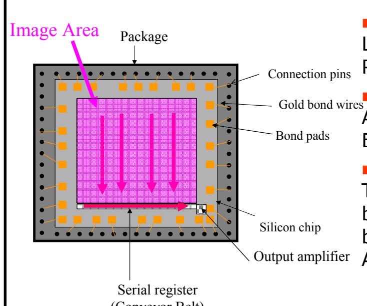




Empty First Buckets in Column Into Buckets in Conveyor Belt



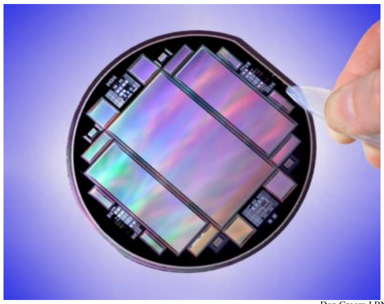
Structure of CCDs



- Image Area of CCD Located at Focal Plane
- Electrons Accumulate During Exposure
- Image Transferred, pixel-by-pixel and line-by-line to Output Amplifier

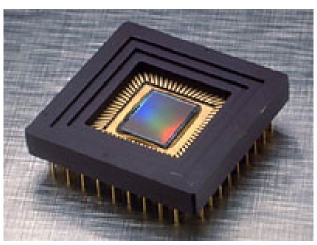
Imaging Science Fundamentals

CCD Manufacture



Don Groom LBNL

Fabricated CCD



Kodak KAF1401 1317 × 1035 pixels (1,363,095 pixels)