Topics You Know By Now!

- **From Physics Courses**
  - EM radiation and its properties
  - Diffraction
  - Refraction
  - Coherent and incoherent radiation
  - Polarization of radiation
  - Scattering of radiation

- **From Chemistry Courses**
  - Photoelectric effect
  - Electromagnetic spectrum
  - Beer’s Law, etc.
  - Quantized states in atoms
    - lead to line spectra
  - Quantized states in molecules
    - lead to broad or continuum spectra
Components of Optical Instruments: The generic spectrometer

- General Designs
- Sources and Sample Holders
- Wavelength Separators
- Slits
- Detectors
Figure 7-1 Components of various types of instruments for optical spectroscopy:
(a) absorption; (b) fluorescence, phosphorescence, and scattering; (c) emission and chemiluminescence.
<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>700</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>7000</th>
<th>10,000</th>
<th>20,000</th>
<th>40,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral region</td>
<td>VAC</td>
<td>UV</td>
<td>Visible</td>
<td>NEAR IR</td>
<td>IR</td>
<td>FAR IR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ar lamp</td>
<td>Xe lamp</td>
<td>H₂ or D₂ lamp</td>
<td>Tungsten lamp</td>
<td>Nernst glower (ZrO₂ + Y₂O₃)</td>
<td>Nichrome wire (Ni + Cr)</td>
<td>Globar (SiC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hollow cathode lamps</td>
<td>Lasers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Detector</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photographic plate</td>
<td>Photomultiplier tube</td>
<td>Phototube</td>
<td>Photocell</td>
<td>Silicon diode</td>
<td>Charge-transfer detector</td>
<td>Photoconductor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon detectors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermocouple (voltage) or bolometer (resistance)</td>
<td>Golay pneumatic cell</td>
<td>Pyroelectric cell (capacitance)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
“LASER”

- Light Amplification by Stimulated Emission of Radiation
- Emits very intense, *monochromatic* light at high power (intensity)
- All waves *in phase* (unique), and parallel
- All waves are polarized in one plane
- Used to be expensive
- Not useful for *scanning* wavelengths
(a) $E_0$  

Pump  

Relaxation  

$E_2$  

Relaxation  

$E_1$  

Laser action  

Population inversion $n_2 > n_1$  

(b)  

Lasing medium  

Mirror 0% T  

Energy  

Mirror 1% T  

$hv$
Laser Setup

Advantages of Lasers

- Low Beam Divergence ("Small dot")
- Nearly Monochromatic ("narrow bandwidth")
- Coherent ("constructive interference")
Population Inversion is Necessary for Amplification

Pumping: Usually Electrical or Optical

Stimulated Emission

- A photon incident on an excited state species causes emission of a second photon of the same frequency, returning the species to the lower state

- $M^* + h\nu \rightarrow M + 2h\nu$
Overall

Figure 7-7  Energy level diagrams for two types of laser systems.

Light Amplification in the Resonance Cavity.

Figure 13.6 The first ruby-laser configuration, just about life-sized.

Optical Resonance

- Form a resonant cavity, with mirrors on each end
- **Length of cavity is an integral multiple of the desired wavelength**

![Diagram of optical resonance with mirrors and active medium]
Types of Lasers

- **Solid state lasers**
  - Nd:YAG
    - neodymium yttrium aluminum garnet
    - 1064 nm

- **Gas lasers**
  - lines w/ specific λs in UV/vis/IR
    - He/Ne
    - Ar⁺, Kr⁺
    - CO₂
    - eximers (XeF⁺,....)

- **Dye lasers**
  - limited tunability in the visible

- **Semiconductor diode lasers**
  - limited tunability in the IR, red
Sample Holders (Cells)

- **Must:**
  - contain the sample without chemical interaction
  - be *more-or-less* transparent to the wavelengths of light in use
  - be readily cleaned for reuse
  - be designed for the specific instrument of interest

- **Examples**
  - quartz is good from about **190-3000 nm**
  - glass is a less expensive alternative from about **300-900 nm**
  - NaCl and KBr are good to much higher wavelengths (**IR range**)

- **Cells can be constructed to:**
  - transmit light absorbed at 180 degrees to the incident light
  - allow emitted light to exit at 90 degrees from the incident light
  - contain gases (lower concentrations) and have long path lengths (**1.0 and 10.0 cm cells are most common**)
Absorbance: usually in a matched pair!

Fluorescence, Phosphorescence, Chemiluminescence

10 cm gas containing cell with transparent windows at the ends.
<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>700</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>7000</th>
<th>10,000</th>
<th>20,000</th>
<th>40,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral region</td>
<td>VAC</td>
<td>UV</td>
<td>Visible</td>
<td>NEAR IR</td>
<td>IR</td>
<td>FAR IR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Materials for cells, windows, lenses, and prisms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L.F.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fused silica or quartz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corex glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silicate glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NaCl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>KBr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TlBr or TII</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ZnSe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Wavelength selectors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorite prism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fused silica or quartz prism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass prism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaCl prism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KBr prism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuum {</td>
<td>3000 lines/mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gratings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 lines/mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interference wedge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interference filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7-2** (a) Construction materials and (b) wavelength selectors for spectroscopic in-
Wavelength Selectors…..

- Used to select the wavelength (or wavelength range) of light that either
  - impinges on the sample (fluorescence and phosphorescence)
  - is transmitted through the sample (absorption and emission)

- This selected wavelength then strikes the detector
  - the ability to select the wavelength helps you to discriminated between phenomena caused by your analyte and that caused by interfering or non-relevant species.

- Are often combined with a set of SLITS (discussed later)

- Various types
  - based on filters (CHEAP COLORED GLASS)
  - based on prisms (LIMITED APPLICATIONS)
  - based on gratings…. (GREAT STUFF)
Figure 7-11  Output of a typical wavelength selector.
Filters

- Simple, rugged (no moving parts in general)
- Relatively inexpensive
- Can select some broad range of wavelengths

- Most often used in
  - field instruments
  - simpler instruments
  - instruments dedicated to monitoring a single wavelength range.

- Two types of filters:
  - **Interference** filters depend on destructive interference of the impinging light to allow a limited range of wavelengths to pass through them (more expensive)
  - **Absorption** filters absorb specific wavelength ranges of light (cheaper, more common)...
**FIGURE 3-34** Transmittance of bandpass (a) and short-wavelength cutoff (b) filters. With the bandpass filter (a) the wavelength of maximum transmittance $\lambda_m$, the maximum transmittance $T_m$, and the full width at half maximum height $\Delta\lambda$ or FWHM are illustrated. For the cutoff filter (b) the cutoff wavelength $\lambda_c$ is the wavelength where $T(\lambda)_f = 10$, 1 or 0.1%. Wavelength $\lambda_m$ is the wavelength at which the transmittance reaches 90 or 99% of its maximum value $T_m$. Wavelength $\lambda_h$ is the wavelength at which $T(\lambda)_f = 0.5 T_m$. 
If $\theta_1 = 0^0$

Constructive Interference when $d = \lambda/2$.

$$\lambda_m = \frac{2t\eta}{m}$$

Calcium or Magnesium Fluoride (FLUORITE!)

1-2% of \( \lambda \) at 80\%T
0.1-0.2% \( \lambda \) at 10\%T

**Figure 7-13** Transmission characteristics of typical interference filters.
Absorption Filters

Typical Effective Bandwidths = 30 – 250 nm

![Graph showing absorption filters and typical transmittance curves.](image)

**FIGURE 6–10** Comparison of various types of filters for visible radiation.


Melles Griot Catalogue

BAND or CUT-OFF
Two basic functions:

- **cutoff filters** absorb light in a specific range of wavelengths. They “cutoff” this range from the detectors (e.g. cutoff for 550 nm)

- **bandpass filters** absorb light outside of a specific range (e.g. 350-550 nm)
  - often made of a combination of two cutoff filters!
Absorption Filters vs. Interference Filters

**FIGURE 6–7** Effective bandwidths for two types of filters.

Wavelength Selectors

• Filters
• Prisms
• Gratings
• Michelson Interferometer
Wavelength Selectors

![Graph showing transmittance as a function of wavelength, with key points labeled: Nominal wavelength, Effective bandwidth, and \( \frac{1}{2} \) peak height.]}
Why Wavelength Selectors?

- Monochromators
  - based on diffraction gratings or prisms
  - a slit is used to select a particular wavelength coming off the grating at a particular angle
Figure 7-16 Two types of monochromators: (a) Czerny-Turner grating monochromator and (b) Bunsen prism monochromator. (In both instances, $\lambda_1 > \lambda_2$.)

Prisms

- First type of widely used, “scanning” wavelength selection devices (TURN PRISM)
- Often made of salts such as sodium chloride, fluorites etc (Remember figure 7-2b).
- VERY delicate. Often subject to damage in humidity and wide heat ranges.
- Not widely used today in spectroscopy equipment.
  - Great demonstration tools for kids
  - Nice on the cover of a Pink Floyd album
Prisms

FIGURE 3-37 Dispersion of light of two wavelengths by a prism of refractive index $n$, apex $\alpha$, and baselength $b$. Collimated rays of wavelength $\lambda_1$ (red) and $\lambda_2$ (blue) are refracted upon entering the prism material and upon exiting it according to Snell’s law. Normal prism materials show higher refractive indices at shorter wavelengths. Hence blue light of wavelength $\lambda_2$ is more highly refracted than red light ($\lambda_1$).

Reflection Gratings... (Transmission?)

- Widely used in instruments today.

- Light reflected off a surface, and not cancelled out by destructive interference, is used for selection of wavelengths.

- Constructed of various materials:
  - Polished glass, silica or polymer substrate
  - Grooves milled or laser etched into the surface
  - Coated with a reflective material (silvered) such as a shiny metal

- VERY FRAGILE!!
  - Sealed inside the instrument. DO NOT TOUCH!
Grating Equation

1 travels AB further than 2 after the reflection.

2 travels CD further than 1 to reach the grating.

For constructive interference:

\[ m\lambda = (CD - AB) \]

\[ CD = d \sin i \quad AB = -d \sin r \]

\[ d(\sin i + \sin r) = m\lambda \quad m = 0, \pm 1, \pm 2, \pm 3, \ldots \]

There are multiple orders of $\lambda$ at a single $r$.

For Example:
- 1st Order = 400 nm
- 2nd Order = 200 nm
- 3rd Order = 133 nm

First order = 90% T

Higher orders can be eliminated by filters

\[ d(\sin\alpha + \sin\beta) = m\lambda \]

Example 7-1

Grating with 1450 blazes/mm
Polychromatic light at $i=48$ deg

$L$ of the monochromatic reflected light at $R=+20,+10$ and 0 deg?

\[ d \sin i + \sin r = m \lambda \rightarrow 1 \) Calculate "$d$"

\[ d = \frac{1 \text{ mm}}{1450 \text{ blazes}} \rightarrow \text{convert to } \text{nm} \times 10^6 \rightarrow 689.7 \text{ nm per groove!} \]

\[ d \sin i + \sin r = m \lambda \rightarrow 2 \) Calculate "$\lambda$" for $n=1$ at $+20$ deg

\[ \lambda = 689.7 \text{ nm} \times \frac{\sin 48 + \sin 20}{1} = 748.4 \text{ nm!} \]

Grating will give a monochromatic beam of light of 748.4 nm at 20 deg, 632 nm at 10 deg and 513 nm at 0 deg. For $n=1$!
**Diffraction Gratings**

Plane or convex plate ruled with closely spaced grooves (300-2000 grooves/mm).

New holographic gratings can have up to 64K grooves!

More grooves = better resolving power

\[ R = \frac{\lambda}{\Delta \lambda} \quad (1K \text{ to } 10K) \]
\[ R = nN \quad (N = \text{grooves!}) \]

How well can you focus on two adjacent wavelengths!

---

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Echelle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>0.5 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Groove density</td>
<td>1200/mm</td>
<td>79/mm</td>
</tr>
<tr>
<td>Diffraction angle, $\beta$</td>
<td>10°22'</td>
<td>63°26'</td>
</tr>
<tr>
<td>Order $n$ (at 300 nm)</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>Resolution (at 300 nm), $\lambda/\Delta\lambda$</td>
<td>62,400</td>
<td>763,000</td>
</tr>
<tr>
<td>Reciprocal linear dispersion, $D^{-1}$</td>
<td>16 Å/mm</td>
<td>1.5 Å/mm</td>
</tr>
<tr>
<td>Light-gathering power, $f$</td>
<td>$f/9.8$</td>
<td>$f/8.8$</td>
</tr>
</tbody>
</table>

Mathematics of Gratings: Important Considerations...

- **Dispersion:**
  - Angular dispersion is the change in the angle of reflection with a change in the wavelength of light \( \frac{dr}{d\lambda} \)
  - Linear dispersion is the change in the wavelength of light along some distance on the focal plane of the grating \( \frac{dy}{d\lambda} \)

- **Resolving Power:**
  - The ability of a grating to resolve separate wavelengths of light

\[
R = \frac{\lambda}{\Delta \lambda} = nN
\]

- \( n \) = the diffraction order
- \( N \) = the number of blazes illuminated
Slits = hole in the wall

- Control the entrance of light into and out from the monochromator. They control quality!

- **Entrance** slits control the **intensity** of light entering the monochromator and help control the range of wavelengths of light that strike the grating
  - Less important than exit slits

- **Exit** slights help select the **range of wavelengths** that exit the monochromator and strike the detector
  - More important than entrance slits

- **Can be:**
  - Fixed (just a slot)
  - Adjustable in **width** (effective bandwidth and intensity)
  - Adjustable in **height** (intensity of light)
**Figure 7-11** Output of a typical wavelength selector.

**Figure 7-22** Illumination of an exit slit by monochromatic radiation $\lambda_2$ at various monochromator settings. Exit and entrance slits are identical.
Figure 7-23  The effect of the slit width on spectra. The entrance slit is illuminated with \( \lambda_1 \), \( \lambda_2 \), and \( \lambda_3 \) only. Entrance and exit slits are identical. Plots on the right show changes in emitted power as the setting of monochromator is varied.
Michelson Interferometer

Figure 7-42  Schematic of a Michelson interferometer illuminated by a monochromatic source.
Interferograms

\[ f = \frac{2\pi}{\lambda} \]

FIGURE 6-35 Comparison of interferograms and optical spectra.

Fourier Transform of the Interferogram gives the Spectrum

FIGURE 3-59 Detector output vs. mirror distance in Michelson interferometer for (a) monochromatic source and (b) broadband source. Zero distance refers to equal optical pathlengths in both arms. The interferogram and spectrum from a Fourier transform IR spectrometer are shown in (c).

Ingle and Crouch, *Spectrochemical Analysis*
Optical Fibers

- Used to transmit light waves over non-linear paths.
- Often used in remote sensing, solution sampling (dipping probes) and field instruments.
- Based on the fact that light inside a fiber can be continuously (totally internally reflected) if the angle it strikes the fiber surface at is correct (determines radius of bends, etc.).
- Used in construction of optodes (optical fiber based chemical sensor).
Snell's Law

\[ n_1 \times \sin \theta_i = n_2 \times \sin \theta_r \]

1 is the core, 2 is the cladding

if \( \frac{n_1 \sin \theta_i}{n_2} \rangle 1 \)

no light goes from core to cladding

since \( \sin \theta_r \langle 1 \)
DETECTORS

Just photon transducers!
- Respond to the intensity of EMR striking them by changing a voltage or current emitted or required by themselves.

- Do NOT respond selectively to specific wavelengths (that is what the wavelength selector is for) but work over a range of wavelengths (DUMB COUNTERS OF PHOTONS!)

- Various types
  - Photographic films (not widely in use any more)
  - Phototubes (used in simpler instruments)
  - Photomultiplier tubes (used in more complex instruments)
  - Multichannel transducers
    - Diode arrays
    - Charged coupled devices (CCD’s, like in many camcorders)
Different wavelengths require different detectors!!

Most UV-VIS instruments have two photomultiplier tubes. Why? → Different work functions for the cathode materials. Remember what the work function is?
Phototubes (found in SPEC 20’s, for example)

- **Function based on the photoelectric effect**

**Figure 6-13** Apparatus for studying the photoelectric effect.
Photomultiplier tubes (found in more advanced, scanning UV-VIS and spectroscopic instruments)

- Also function based on the photoelectric effect

- Additional **signal is gained by multiplying the number of electrons produced** by the initial reaction in the detector.

- Each electron produces a series of photo-electrons, multiplying its signal. Thus the name PMT!

- Very sensitive to incoming light.
  - Most sensitive light detector in the UV-VIS range.
  - VERY rugged. They last a long time.
  - Sensitive to excessive stray light (room light + powered PMT = DEAD PMT)

- Always used with a scanning or moveable wavelength selector (grating) in a monochromator
Many electrons emitted from dynode 1 for each electron striking dynode 1

Photoelectrons emitted from cathode

Transparent window

Incident radiation (hv)

Grill

Photoemissive cathode

Dynode

Anode, \(>10^6\) electrons for each photon
Photomultiplier Tube

8–19 dynodes (9-10 is most common).

Gain (m) is # e\(^{-}\) emitted per incident e\(^{-}\) (\(\delta\)) to the power of the # of dynodes (k).

\[ m = \delta^k \]

e.g. 5 e\(^{-}\) emitted / incident e\(^{-}\) 10 dynodes.

\[ m = \delta^k = 5^{10} \approx 1 \times 10^7 \]

Typical Gain = 10\(^4\) - 10\(^7\)
Silicon Diodes

- Constructed of charge depleted and charge rich regions of silicon (silicon doped with other ions)

- Light striking the detector causes charge to be created in each region.

- The charge collected is then measured and the array is ‘reset’ for the next collection.

- Used in instruments where the grating is fixed in one position and light strikes an array of silicon diodes (aka the diode array)
  - Can have thousands of diodes on an array
  - Each diode collects light from a specific wavelength range
  - The resolution is generally poorer than with a PMT
  - However, you can scan literally thousands of times a minute since there are NO moving parts!

- Charge coupled devices work differently, but are arranged in similar arrays.
Silicon or Germanium are common.

**n-type:** Si (or Ge) doped with group V element (As, Sb) to add electrons.

**p-type:** Doped with group III element (In, Ga) to added holes.

*Figure 9.8* Conduction band, C, and valence band, V, in (a) a conductor, (b) a semiconductor, and (c) an insulator.

Photodiode

- A photon promotes an electron from the valence band (filled orbitals) to the conduction band (unfilled orbitals) creating an electron(-) - hole(+) pair
- The concentration of these electron-hole pairs is dependent on the amount of light striking the semiconductor
**Photodiodes**

**FIGURE 6-24** (a) Schematic of a silicon diode. (b) Formation of depletion layer, which prevents flow of electricity under reverse bias.

---

Photodiode Arrays (PDA or DAD)

FIGURE 6–25 A reverse-biased linear diode array detector: (a) cross section; (b) top view.

Diode-Array Spectrophotometer

Schematic of a diode-array spectrophotometer
Diode-Array Spectrophotometer

Optical diagram of the HP 8453 diode-array spectrophotometer
Optical system of the HP 8450A diode-array spectrophotometer
Thermal Detectors

(infrared detectors)

- **Thermocouples**
  - potential difference developed at a junction of two different metal-metal junctions at two different temperatures
  - junction is black to absorb light

- **Bolometers**
  - resistance thermometer

- **Pyroelectric transducers**
  - changes in temperature change the polarization behavior of specific materials
  - triglycine sulfate (TGS)