# Chemical Engineering 378

*Science of Materials Engineering*

Lecture 37

Optical Properties

# Spiritual Thought

Face the future with optimism. I believe we are standing on the threshold of a new era of growth, prosperity, and abundance. Barring a calamity or unexpected international crisis, I think the next few years will bring a resurgence in the economy as new discoveries are made in communication, ***medicine***, ***energy***, ***transportation***, physics, ***computer technology***, and ***other fields*** of endeavor.

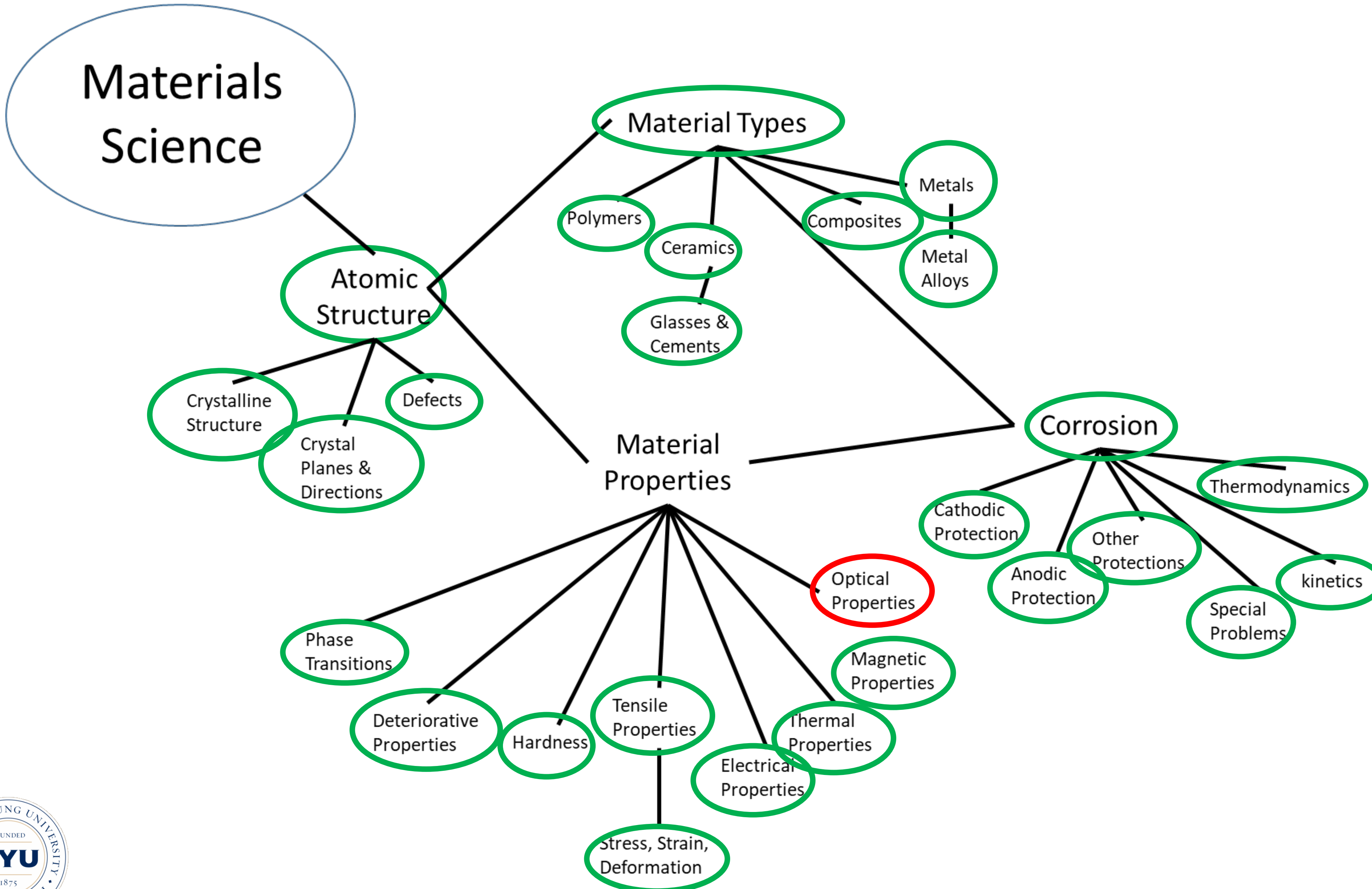
Many of these discoveries, as in the past, will be ***the result of the Spirit whispering insights into and enlightening the minds of truth-seeking individuals***. Many of these discoveries will be made for the purpose of helping to bring to pass the purposes and work of God and the quickening of the building of His kingdom on earth today. With these discoveries and advances will come new employment opportunities and prosperity *for those who work hard and especially to those who strive to keep the commandments of God*. This has been the case in other significant periods of national and international economic growth.

-Elder M. Russell Ballard

BYU Idaho Commencement Remarks

April 6, 2012

# Materials Roadmap



# OEP Hint

## Cylinder Hoop Stress Formula

$$\sigma_H = \frac{Pd}{2t}$$

$\sigma_H$ – cylinder hoop stress in Pa

$P$ – internal pressure in Pa

$d$ – cylinder inside diameter in m

$t$ – wall thickness in m

# Optical Properties

Light has both particulate and wavelike characteristics

- Photon - a quantum unit of light

$$E = h\nu = \frac{hc}{\lambda}$$

$E$ = energy of a photon

$\lambda$ = wavelength of radiation

$\nu$ = frequency of radiation

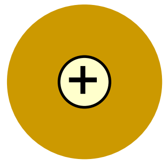
$h$ = Planck's constant ($6.62 \times 10^{-34}$ J·s)

$c$ = speed of light in a vacuum ($3.00 \times 10^{8}$ m/s)

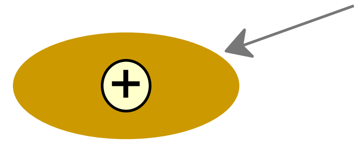
# Refraction

- Transmitted light distorts electron clouds.

no transmitted light



transmitted light

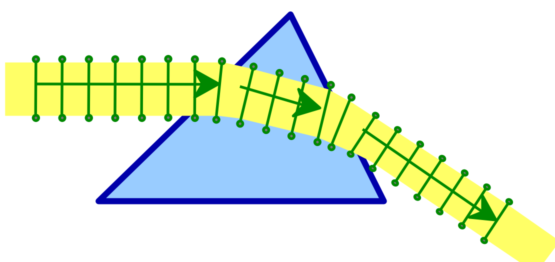


electron cloud distorts

- The velocity of light in a material is lower than in a vacuum.

$$n = \text{index of refraction} \equiv \frac{c\ (\text{velocity of light in vacuum})}{v\ (\text{velocity of light in medium})}$$

-- Adding large ions (e.g., lead) to glass decreases the speed of light in the glass.
-- Light can be "bent" as it passes through a transparent prism

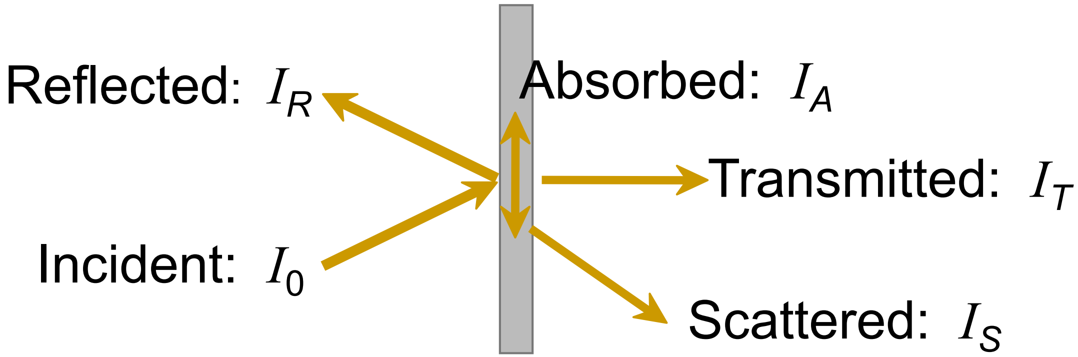


| Material | *n* |
|---|---|
| Typical glasses ca. | 1.5 -1.7 |
| Plastics | 1.3 -1.6 |
| PbO (Litharge) | 2.67 |
| Diamond | 2.41 |

Selected values from Table 21.1, *Callister & Rethwisch 9e*.

# Light Interactions with Solids

- Incident light is reflected, absorbed, scattered, and/or transmitted: $I_0 = I_T + I_A + I_R + I_S$




- Optical classification of materials:

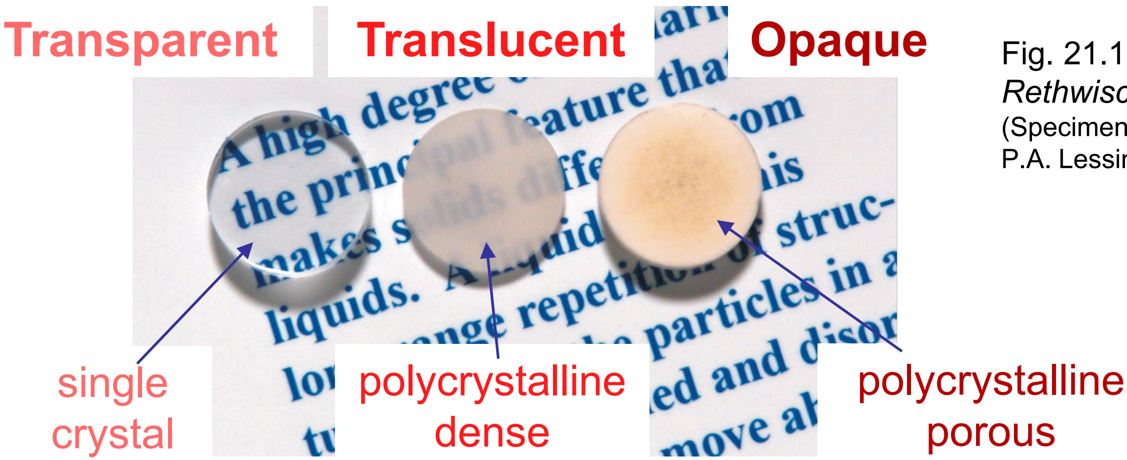
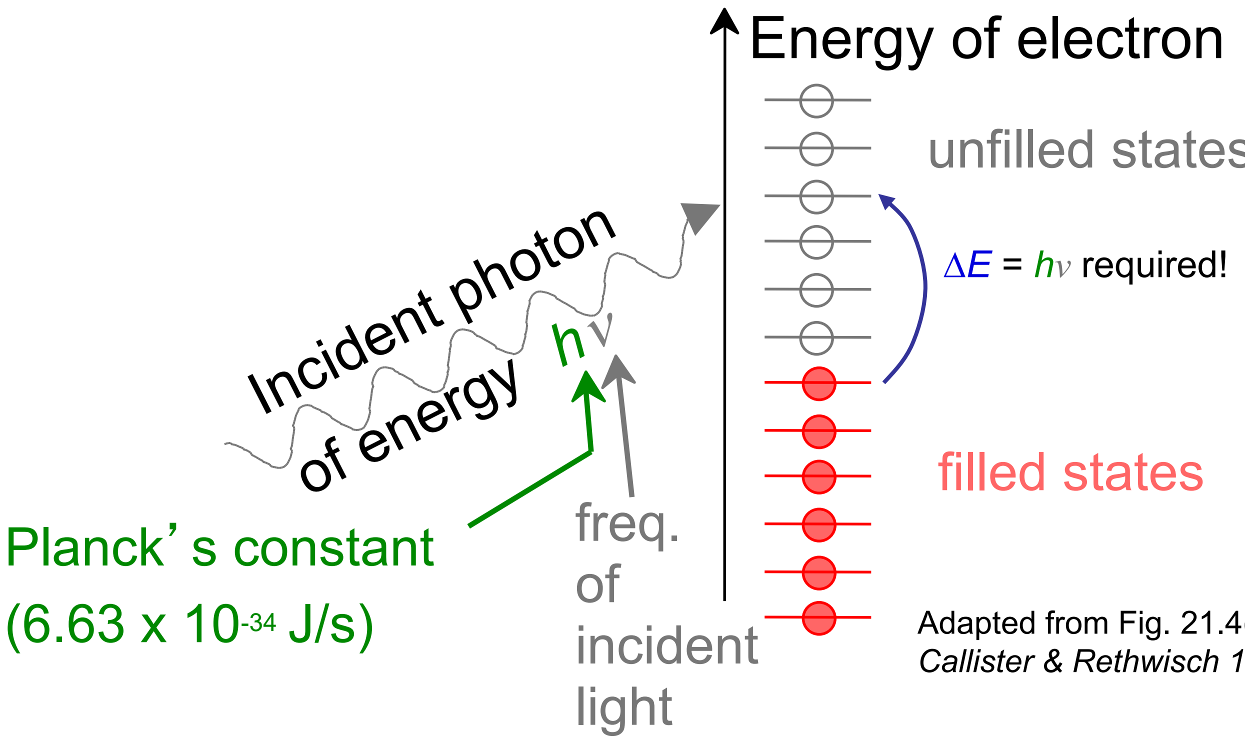



Fig. 21.10, *Callister & Rethwisch 10e*.
(Specimen preparation P.A. Lessing.)

# Optical Properties of Metals: Absorption

- Absorption of photons by electron transitions:




Adapted from Fig. 21.4(a), *Callister & Rethwisch 10e*.

- Unfilled electron states are adjacent to filled states
- Near-surface electrons absorb visible light.

# Light Absorption

The amount of light absorbed by a material is calculated using Beer's Law

$$I'_T = I'_0 e^{-\beta \ell}$$

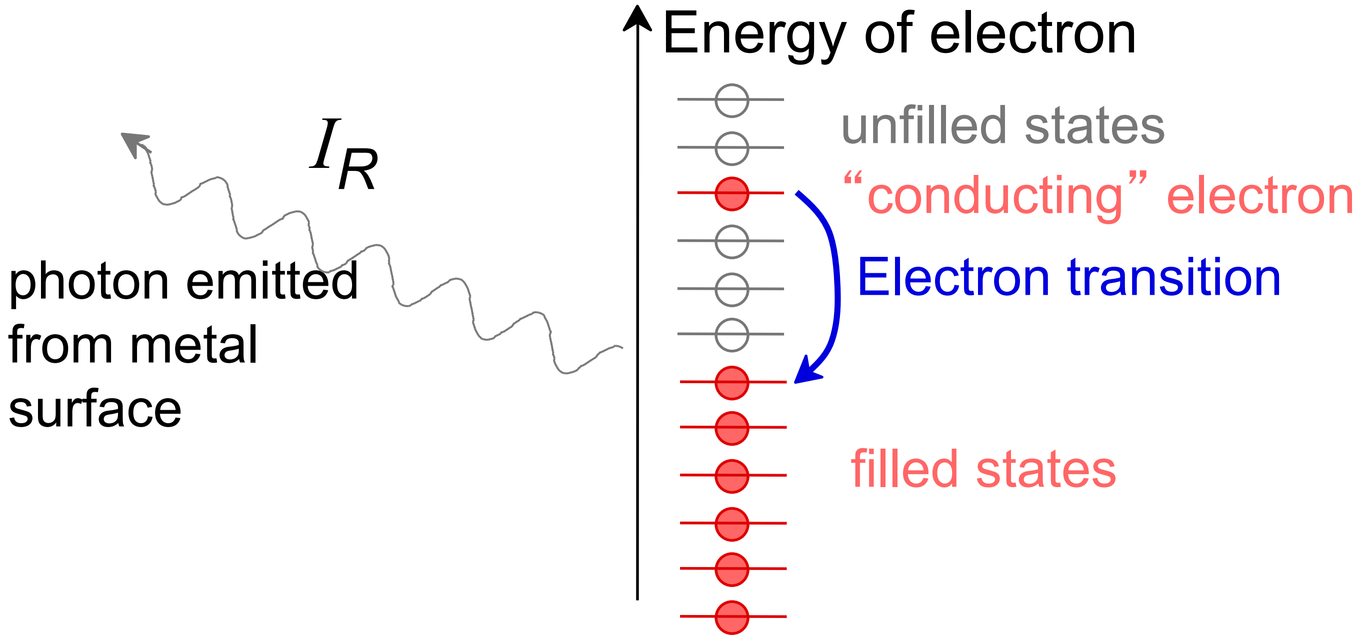
$\beta$ = absorption coefficient, $cm^{-1}$
$\ell$ = sample thickness, cm
$I'_0$ = incident light intensity
$I'_T$ = transmitted light intensity

Rearranging and taking the natural log of both sides of the equation leads to

$$\ln\left[\frac{I'_T}{I'_0}\right] = -\beta \ell$$

# Reflection of Light for Metals

- Electron transition from an excited state produces a photon.




Adapted from Fig. 21.4(b), *Callister & Rethwisch 10e*.

# Reflection of Light for Metals (cont.)

- Reflectivity = $I_R/I_0$ is between 0.90 and 0.95.
- Metal surfaces appear shiny
- Most of absorbed light is reflected at the same wavelength
- Small fraction of light may be absorbed
- Color of reflected light depends on wavelength distribution
  - Example: The metals copper and gold absorb light in blue and green => reflected light has gold color

# Reflectivity of Nonmetals

- For normal incidence and light passing into a solid having an index of refraction *n*:

$$R = \text{reflectivity} = \left(\frac{n-1}{n+1}\right)^2$$

- Example: For Diamond *n* = 2.41

$$R = \left(\frac{2.41-1}{2.41+1}\right)^2 = 0.17$$

$$\therefore \text{ 17\% of light is reflected}$$

# Scattering of Light in Polymers

- For highly amorphous and pore-free polymers
  - Little or no scattering
  - These materials are transparent
- Semicrystalline polymers
  - Different indices of refraction for amorphous and crystalline regions
  - Scattering of light at boundaries
  - Highly crystalline polymers may be opaque
- Examples:
  - Polystyrene (amorphous) – clear and transparent
  - Low-density polyethylene milk cartons – opaque

# Selected Light Absorption in Semiconductors

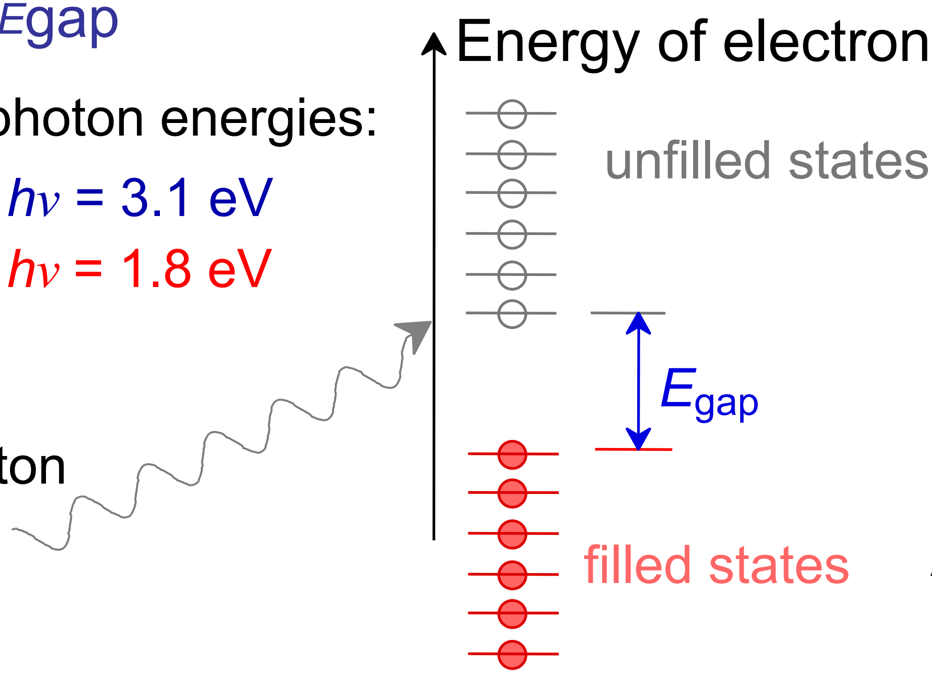
Absorption of light of frequency $\nu$ by by electron transition occurs if $h\nu > E_{gap}$

Examples of photon energies:

blue light: $h\nu = 3.1$ eV

red light: $h\nu = 1.8$ eV

incident photon energy $h\nu$




Adapted from Fig. 21.5(a), *Callister & Rethwisch 10e*.

- If $E_{gap} < 1.8$ eV, all light absorbed; material is opaque (e.g., Si, GaAs)
- If $E_{gap} > 3.1$ eV, no light absorption; material is transparent and colorless (e.g., diamond)
- If 1.8 eV $< E_{gap} <$ 3.1 eV, partial light absorption; material is colored

# Computations of Minimum Wavelength Absorbed



(a) What is the minimum wavelength absorbed by Ge, for which $E_g$ = 0.67 eV?

Solution:

$$\lambda_{Ge}(\min) = \frac{hc}{E_g(\text{Ge})} = \frac{(6.63 \times 10^{-34}\ \text{J}\cdot\text{s})(3 \times 10^{8}\ \text{m/s})}{(0.67\ \text{eV})(1.60 \times 10^{-19}\ \text{J/eV})}$$

$$\lambda_{Ge}(\min) = 1.86 \times 10^{-6}\ \text{m} = 1.86\ \mu\text{m}$$

(b) Redoing this computation for Si which has a band gap of 1.1 eV

$$\lambda_{Si}(\min) = 1.13\ \mu\text{m}$$

Note: the presence of donor and/or acceptor states allows for light absorption at other wavelengths.

# Color of Nonmetals

- Color determined by the distribution of wavelengths:
  - -- transmitted light
  - -- re-emitted light from electron transitions
- Example 1: Cadmium Sulfide (CdS), $E_g$ = 2.4 eV
  - -- absorbs higher energy visible light (blue, violet)
  - -- color results from red/orange/yellow light that is transmitted
- Example 2: Ruby = Sapphire ($Al_2O_3$) + (0.5 to 2) at% $Cr_2O_3$
  - -- Sapphire is transparent and colorless ($E_g$ > 3.1 eV)
  - -- adding $Cr_2O_3$ :
    - alters the band gap
    - blue and orange/yellow/green light is absorbed
    - red light is transmitted
    - Result: Ruby is deep red in color

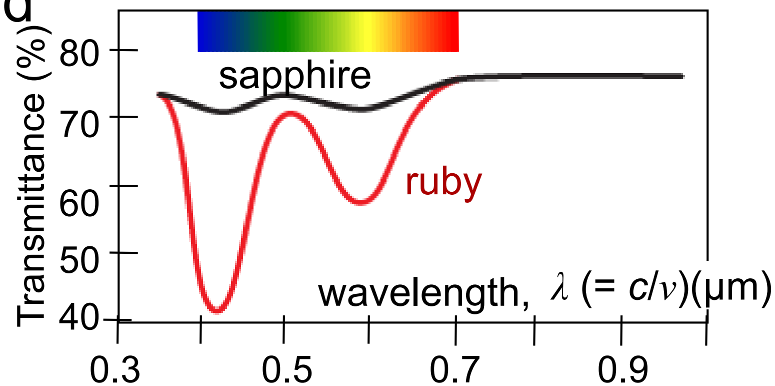
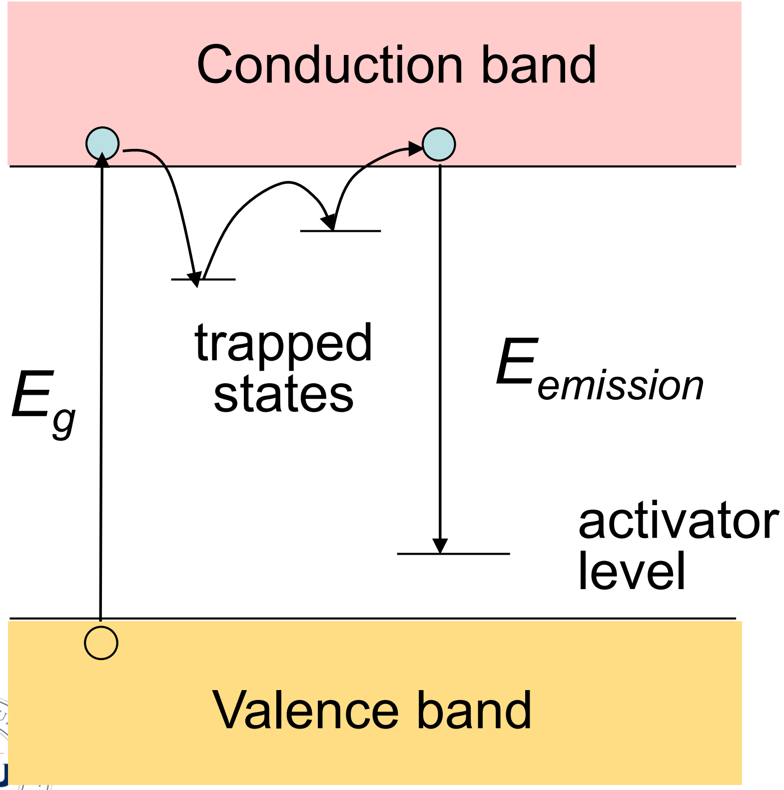



Fig. 21.9, *Callister & Rethwisch 10e*.
(Adapted from "The Optical Properties of Materials," by A. Javan. Copyright © 1967 by Scientific American, Inc. All rights reserved.)

# Luminescence

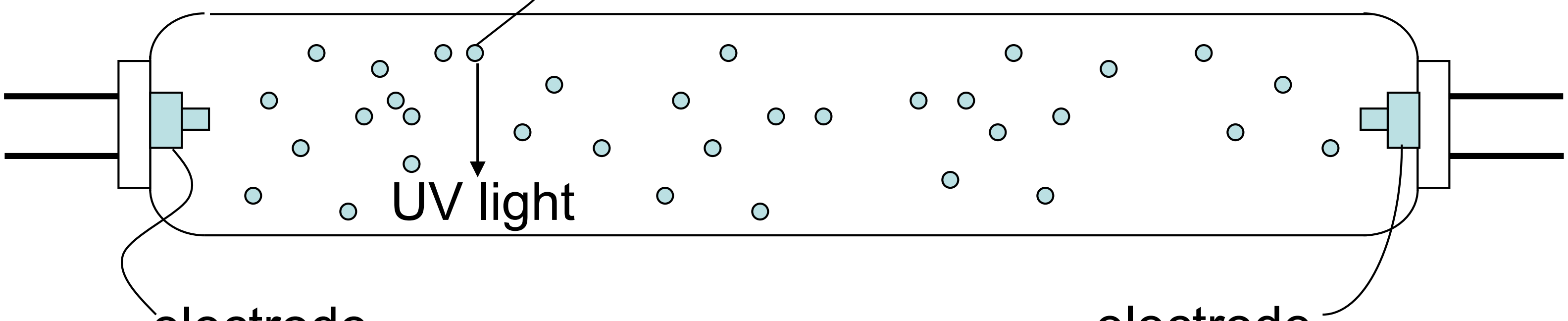
- Luminescence – reemission of light by a material
  - Material absorbs light at one frequency and reemits it at another (lower) frequency.
  - Trapped (donor/acceptor) states introduced by impurities/defects




- If residence time in trapped state is relatively long (> $10^{-8}$ s) -- phosphorescence
- For short residence times (< $10^{-8}$ s) -- fluorescence

Example: Toys that glow in the dark. Charge toys by exposing them to light. Reemission of light over time—phosphorescence

# Photoluminescence




- Arc between electrodes excites electrons in mercury atoms in the lamp to higher energy levels.
- As electron falls back into their ground states, UV light is emitted (e.g., suntan lamp).
- Inside surface of tube lined with material that absorbs UV and reemits visible light
  - For example, $Ca_{10}F_2P_6O_{24}$ with 20% of $F^-$ replaced by $Cl^-$
- Adjust color by doping with metal cations

$Sb^{3+}$ blue

$Mn^{2+}$ orange-red

# Cathodoluminescence

- Used in cathode-ray tube devices (e.g., TVs, computer monitors)
- Inside of tube is coated with a phosphor material
  - Phosphor material bombarded with electrons
  - Electrons in phosphor atoms excited to higher state
  - Photon (visible light) emitted as electrons drop back into ground states
  - Color of emitted light (i.e., photon wavelength) depends on composition of phosphor

| | |
|---|---|
| ZnS ($Ag^+$ & $Cl^-$) | blue |
| (Zn, Cd) S + ($Cu^+$+$Al^{3+}$) | green |
| $Y_2O_2S$ + 3% Eu | red |

- Note: light emitted is random in phase & direction
  - i.e., is noncoherent

# The LASER

- The laser generates light waves that are in phase (coherent) and that travel parallel to one another
  - LASER
    - Light
    - Amplification by
    - Stimulated
    - Emission of
    - Radiation
- Operation of laser involves a population inversion of energy states process

# Population Inversion

- More electrons in excited energy states than in ground states

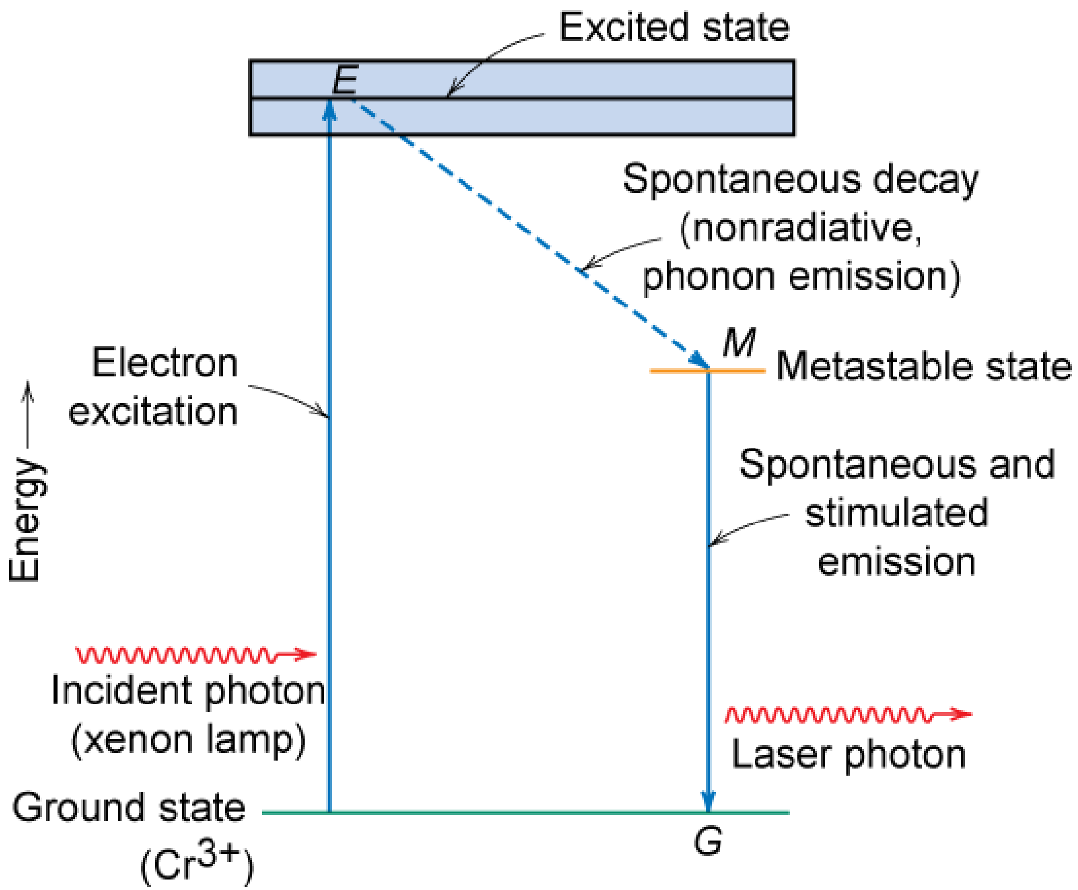



Fig. 21.14, *Callister & Rethwisch 10e*.

# Operation of the Ruby Laser

- "pump" electrons in the lasing material to excited states
  - e.g., by flash lamp (incoherent light).

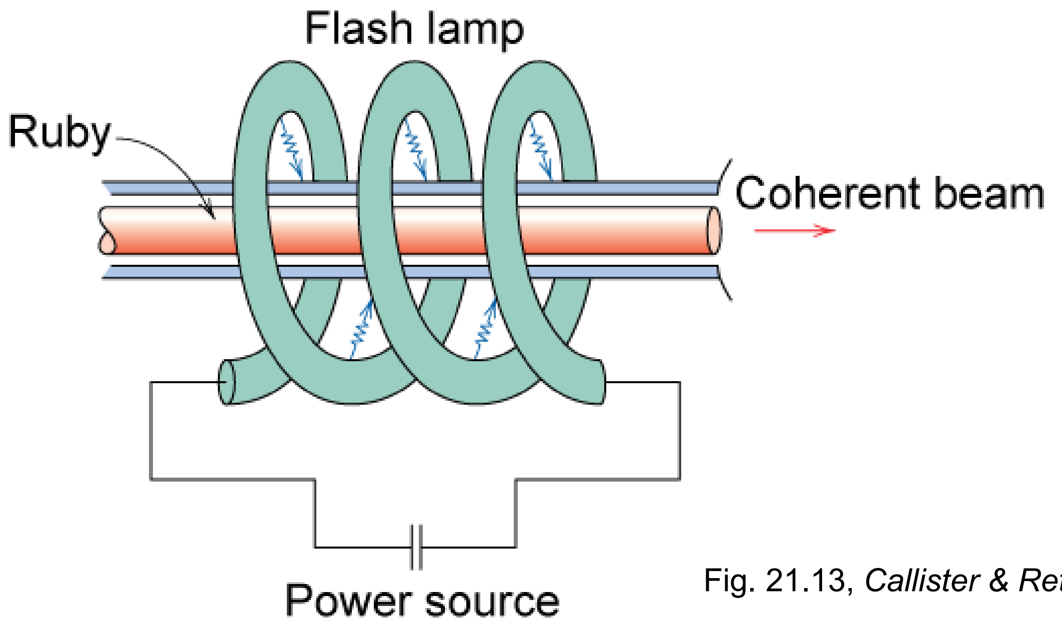



Fig. 21.13, *Callister & Rethwisch 10e.*

  - Direct electron decay transitions — produce incoherent light

# Operation of the Ruby Laser (cont.)

- Stimulated Emission
  - The generation of one photon by the decay transition of an electron, induces the emission of other photons that are all in phase with one another.
  - This cascading effect produces an intense burst of coherent light.
- This is an example of a pulsed laser

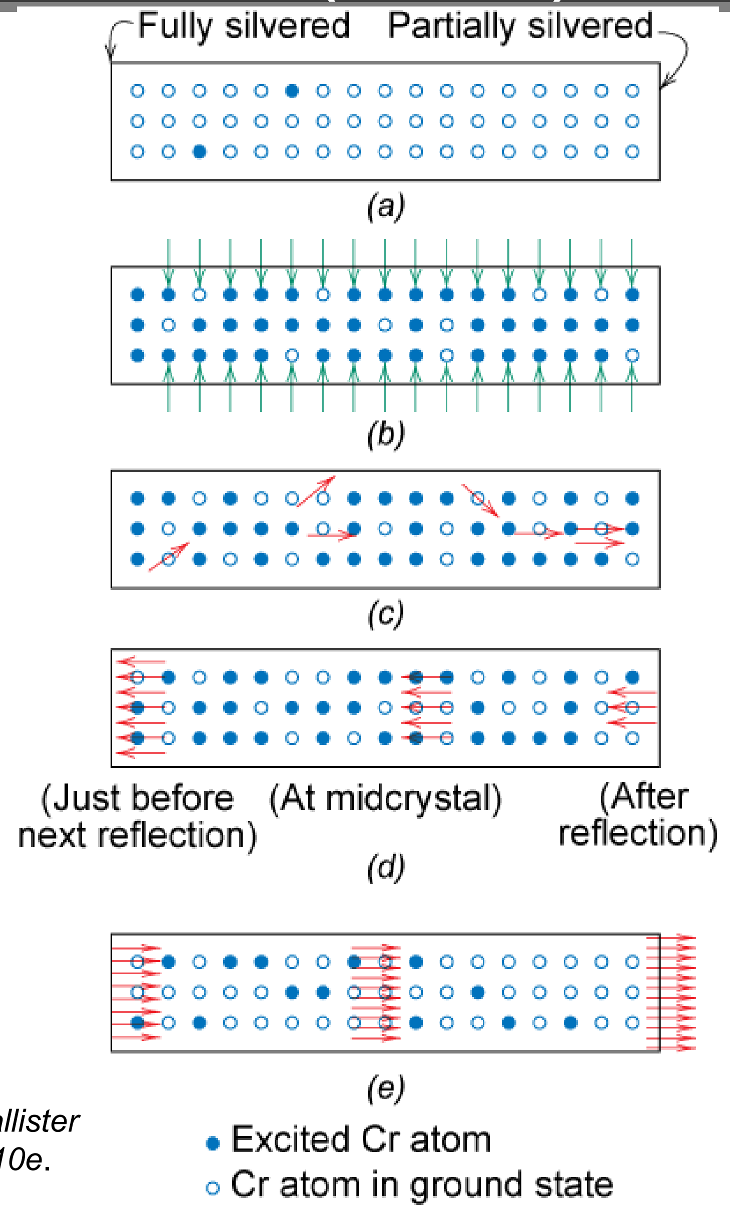



Fig. 21.15, *Callister & Rethwisch 10e*.

# Continuous Wave Lasers

- Continuous wave (CW) lasers generate a continuous (rather than pulsed) beam
- Materials for CW lasers include semiconductors (e.g., GaAs), gases (e.g., $CO_2$), and yttrium-aluminum-garnet (YAG)
- Wavelengths for laser beams are within visible and infrared regions of the spectrum
- Users of CW lasers
    1. Welding
    2. Drilling
    3. Cutting – laser carved wood, eye surgery
    4. Surface treatment
    5. Scribing – ceramics, etc.
    6. Photolithography – Excimer laser

# Semiconductor Lasers

- Apply strong forward bias across semiconductor layers, metal, and heat sink.
- Electron-hole pairs generated by electrons that are excited across band gap.
- Recombination of an electron-hole pair generates a photon of laser light

$$\underbrace{\text{electron} + \text{hole}}_{\text{recombination}} \rightarrow \underbrace{\text{neutral}}_{\text{ground state}} + h\nu$$

photon of light ($h\nu$)

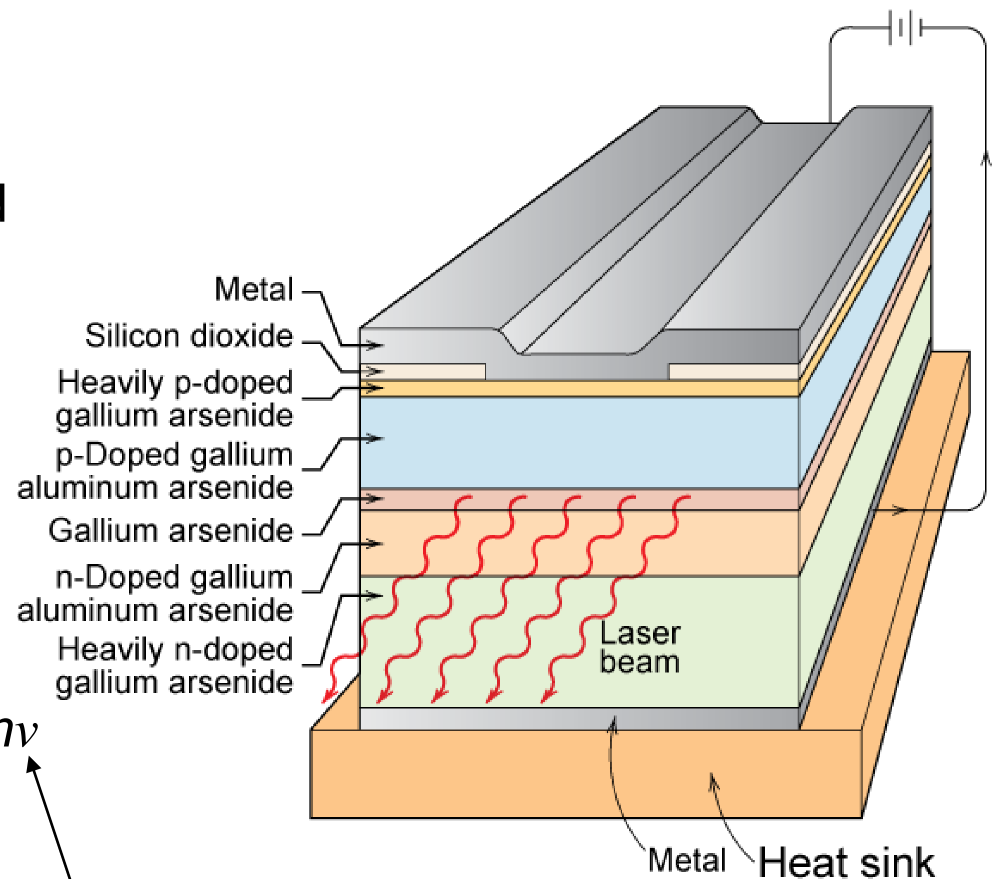



Fig. 21.17, *Callister & Rethwisch 10e*.

# Semiconductor Laser Applications

- Compact disk (CD) player
  - Use red light
- High resolution DVD players
  - Use blue light
  - Blue light is a shorter wavelength than red light so it produces higher storage density
- Communications using optical fibers
  - Fibers often tuned to a specific frequency
- Banks of semiconductor lasers are used as flash lamps to pump other lasers

# Other Applications of Optical Phenomena



- New materials must be developed to make new & improved optical devices.
  - Organic Light Emitting Diodes (OLEDs)
    - More than one color available from a single diode
    - Also sources of white light (multicolor)

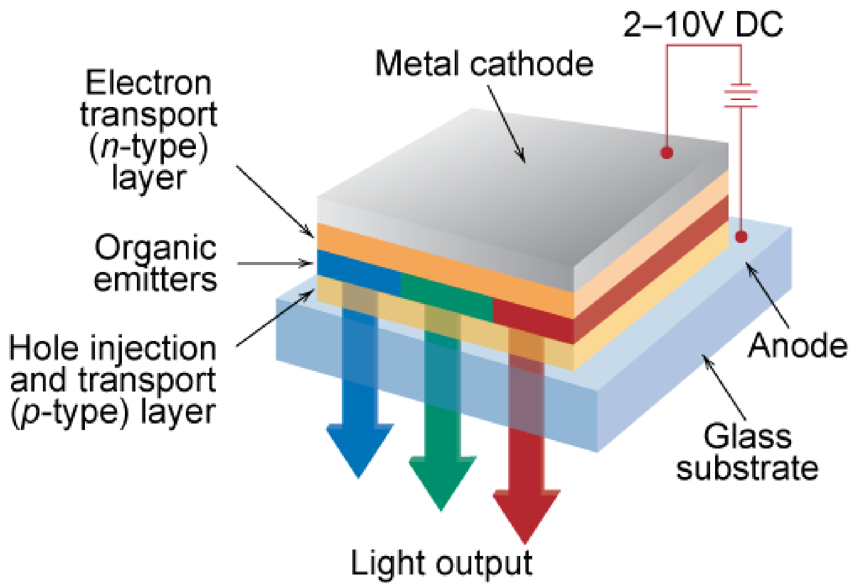
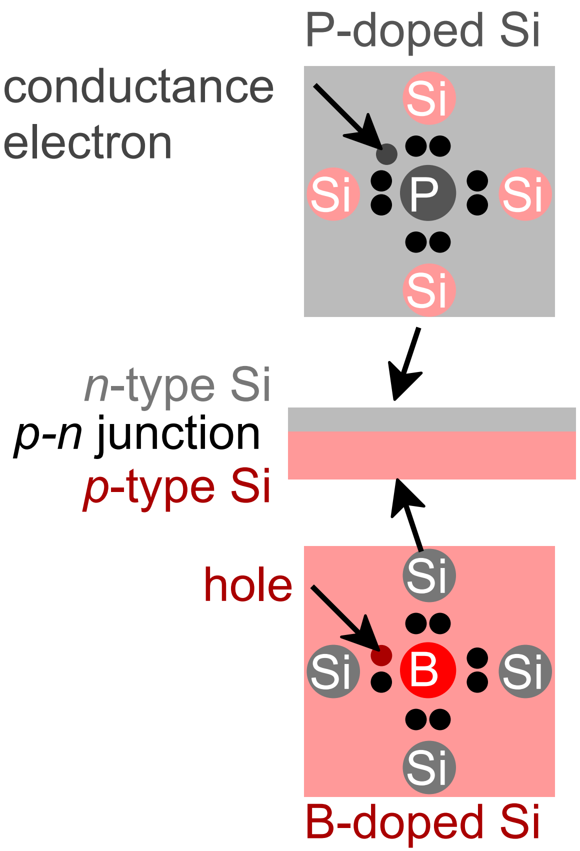


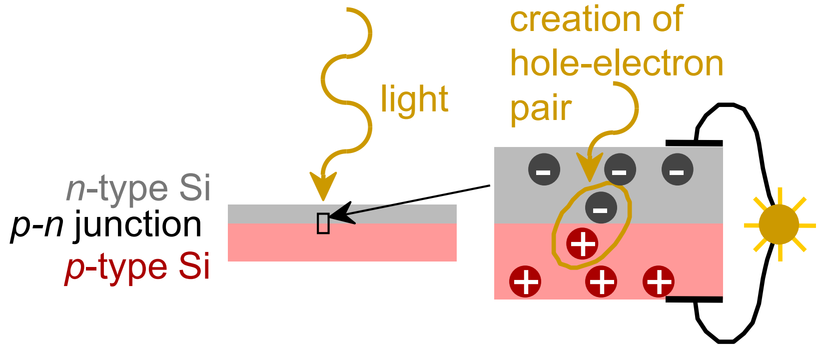

Fig. 21.12, *Callister & Rethwisch 10e*. (Reproduced by arrangement with *Silicon Chip* magazine.)

# Other Applications - Solar Cells

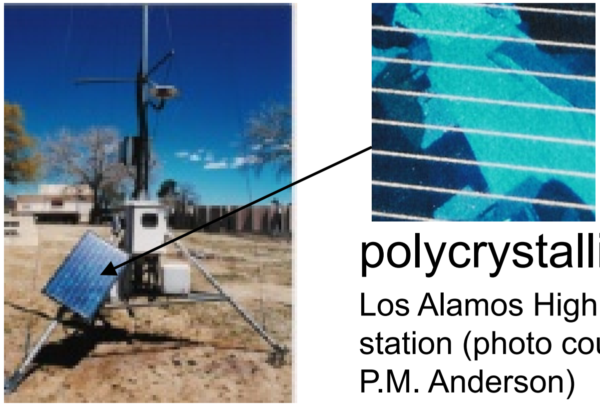
- *p-n* junction:




- Operation:
  -- incident photon of light produces elec.-hole pair.
  -- typical potential of 0.5 V produced across junction
  -- current increases w/light intensity.




- Solar powered weather station:



polycrystalline Si

Los Alamos High School weather station (photo courtesy P.M. Anderson)

# Other Applications - Optical Fibers

## Schematic diagram showing components of a fiber optic communications system

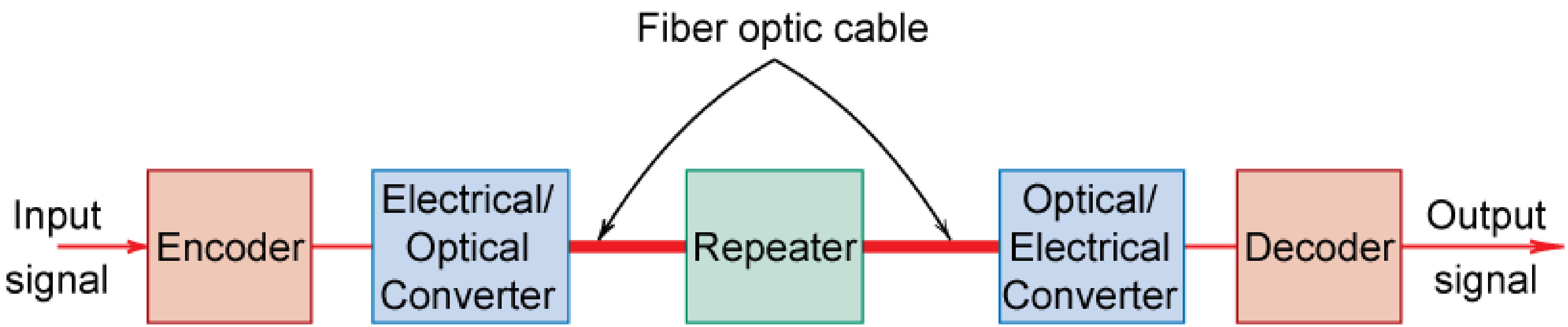



Fig. 21.18, *Callister & Rethwisch 10e*.

# Optical Fibers (cont.)

- fibers have diameters of 125 μm or less
- plastic cladding 60 μm thick is applied to fibers

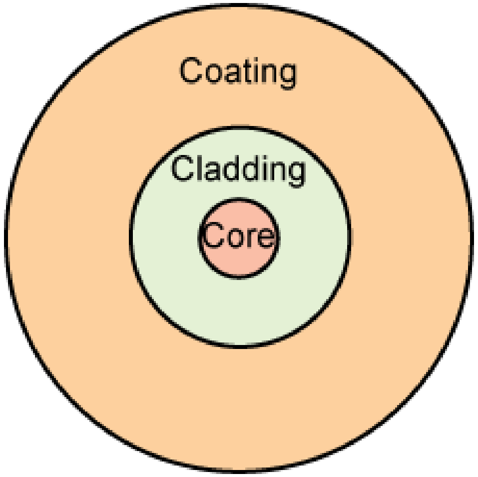



Fig. 21.20, *Callister & Rethwisch 10e*.

# Optical Fiber Designs

## Step-index Optical Fiber

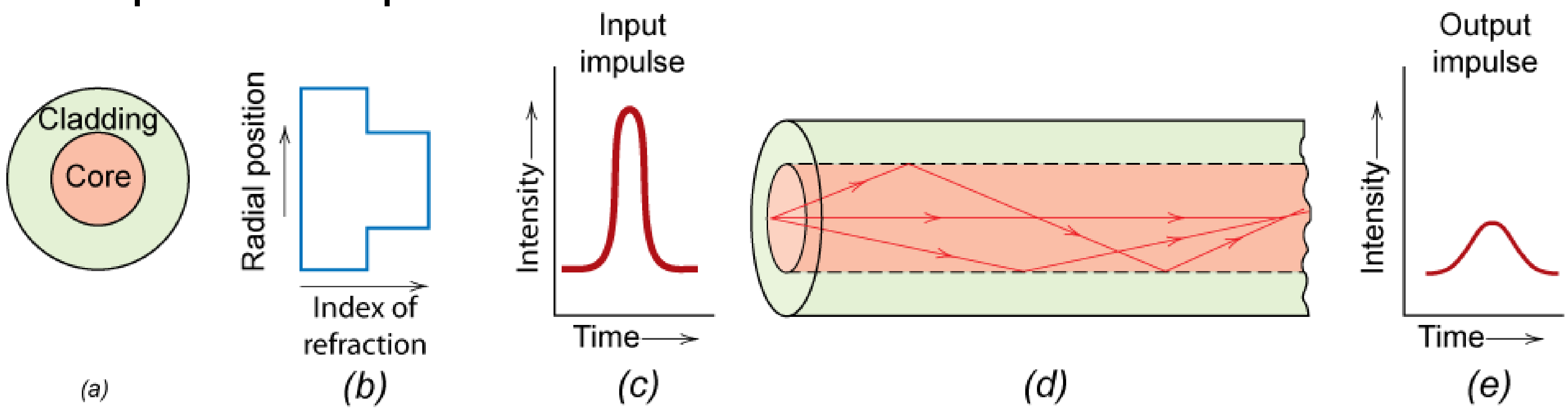



Fig. 21.21, *Callister & Rethwisch 10e*.

## Graded-index Optical Fiber

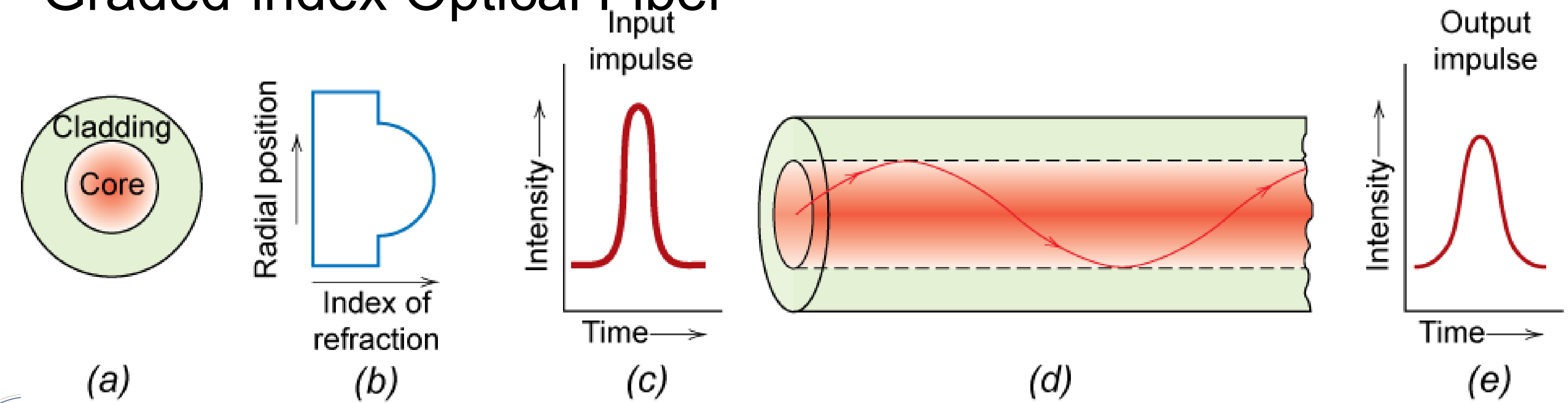



Fig. 21.22, *Callister & Rethwisch 10e*.