Chapter 21: Optical Properties

ISSUES TO ADDRESS...

- What ______________ when light is shined on a material?
- What determines the characteristic colors of materials?
- Why are some materials ___________ and others are ___________ or opaque?
- How does a laser operate?

Optical Properties

Light has both ________ and _________ characteristics

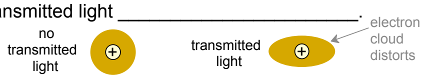
– __________ - a quantum unit of light

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

E = energy of a photon
λ = wavelength of radiation
ν = frequency of radiation
h = Planck's constant (6.62×10^{-34} J·s)
c = speed of light in a vacuum (3.00×10^{8} m/s)

Refraction

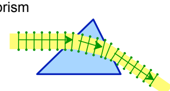
- Transmitted light _______________________.



- The velocity of light in a material ____________________.

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

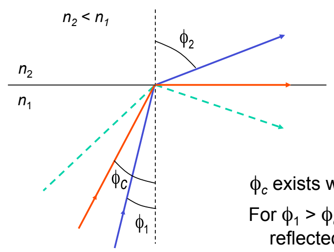
-- Adding _______ ions (e.g., lead) to glass decreases the speed of light in the glass.
-- Light can be "bent" as it passes through a transparent prism



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 8e.*

Total Internal Reflectance



$$\frac{n_1}{n_2} = \frac{\sin \phi_2}{\sin \phi_1}$$

ϕ_1 = incident angle

ϕ_2 = refracted angle

ϕ_c = critical angle

ϕ_c exists when $\phi_2 = 90°$

For $\phi_1 > \phi_c$ light is internally reflected

- Fiber optic cables are clad in low n material so that light will experience total internal reflectance and not escape from the optical fiber.

Example: Diamond in air

- What is the critical angle ϕ_c for light passing from _______ (n_1 = 2.41) into air (n_2 = 1)?
- Solution: At the _____ angle, $\phi_1 = \phi_c$ and $\phi_2 = 90°$

Rearranging the equation $\frac{n_1}{n_2} = \frac{\sin \phi_2}{\sin \phi_1}$

$$\sin \phi_1 = \sin \phi_c = \frac{n_2}{n_1} \sin(90°) = \frac{n_2}{n_1}$$

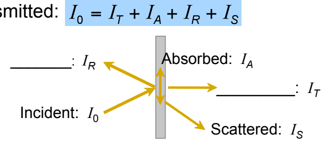
Substitution gives

$$\sin \phi_c = \frac{1}{2.41}$$

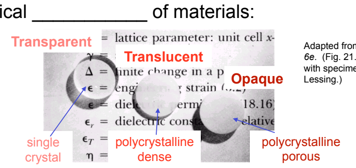
ϕ_c =

Light Interactions with Solids

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



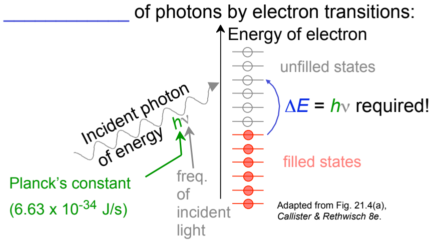
- Optical ____________ of materials:



Adapted from Fig. 21.10, *Callister 6e*. (Fig. 21.10 is by J. Telford, with specimen preparation by P.A. Lessing.)

Optical Properties of Metals: Absorption

- ____________ of photons by electron transitions:



- Unfilled ____
- Near-surface electrons absorb visible light.

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Light Absorption

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

____

β = ___________ coefficient, cm^{-1}
ℓ = sample thickness, cm
I'_0 = _________ light intensity
I'_T = transmitted light intensity

Rearranging and taking the _________________ of the equation leads to

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

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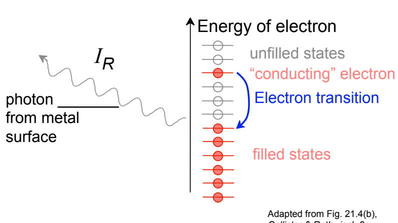
Reflection of Light for Metals

- ______________ from an excited state produces a photon.



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Reflection of Light for Metals (cont.)

- ___________ = I_R/I_0 is between 0.90 and 0.95.
- Metal surfaces appear __________
- 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 _____________ absorb light in blue and green => reflected light has gold color

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Reflectivity of Nonmetals

- For ________________ 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

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

$\therefore$ 17% of light is reflected

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Scattering of Light in Polymers

- For highly _____________ and pore-free polymers
  - Little or no _____________
  - These materials are transparent
- _____________________ polymers
  - Different indices of refraction for amorphous and crystalline regions
  - _______________________________
  - Highly crystalline polymers may be opaque
- Examples:
  - Polystyrene (__________) – clear and transparent
  - Low-density polyethylene milk cartons – opaque

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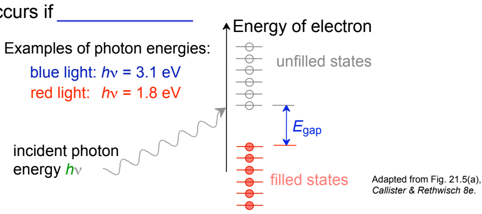
Selected Light Absorption in Semiconductors

Absorption of ______________ ν by by electron transition occurs if _____________



Adapted from Fig. 21.5(a), *Callister & Rethwisch 8e.*

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

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Computations of Minimum Wavelength Absorbed

(a) What is the minimum _________________________ Ge, for which E_g = 0.67 eV?

Solution:

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

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

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

$$\lambda_{Si}(\text{min}) = \_\_\_\_\_\_\_$$

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

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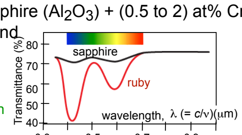
Color of Nonmetals

- Color determined by the distribution of wavelengths:
  - -- ________________________
  - -- re-emitted light from electron transitions
- Example 1: Cadmium Sulfide (CdS), ____________
  - -- _________ higher energy visible light (blue, violet)
  - -- color results from red/orange/yellow light that is transmitted
- Example 2: ______ = 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 :
    - ________________
    - blue and orange/yellow/green light is ____________
    - red light is transmitted
    - Result: Ruby is deep red in color



Adapted from Fig. 21.9, *Callister & Rethwisch 8e.* (Fig. 21.9 adapted from "The Optical Properties of Materials" by A. Javan, *Scientific American*, 1967.)

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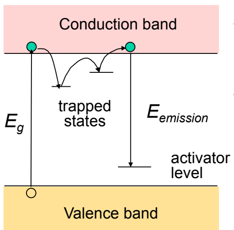
Luminescence

- Luminescence – ______________________________
  - Material absorbs light at one frequency and _________it at another (lower) frequency.
  - _________ (donor/acceptor) states introduced by impurities/ defects



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

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

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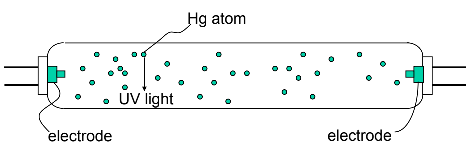
Photoluminescence



- Arc between electrodes excites electrons in mercury atoms in the lamp to higher energy levels.
- ____ (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+} __________
  - Mn^{2+} __________

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Cathodoluminescence

- Used in cathode-ray tube devices (e.g., TVs, computer monitors)
- Inside of tube is coated with a _________ material
  - Phosphor material bombarded with electrons
  - ____
  - 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 __________ is random in phase & direction
  - i.e., is noncoherent

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The LASER

- The laser generates light waves that are in phase (coherent) and that ___________________________
  - LASER
    - Light
    - Amplification by
    - S__________
    - Emission of
    - Radiation
- Operation of laser involves a _________________ of energy states process

Population Inversion

- More electrons in excited energy states than in ground states

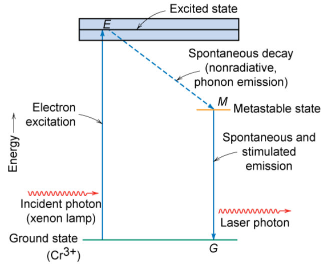

Fig. 21.14, *Callister & Rethwisch 8e.*

Operation of the Ruby Laser

- "pump" electrons in the lasing material to excited states
  - e.g., ________________________________.

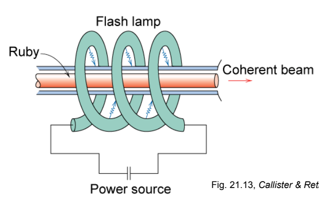

Fig. 21.13, *Callister & Rethwisch 8e.*

- Direct electron decay transitions – ____________________

Operation of the Ruby Laser (cont.)

- ____________________
  - 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 ________ effect produces an intense burst of coherent light.
- This is an example of a ________________

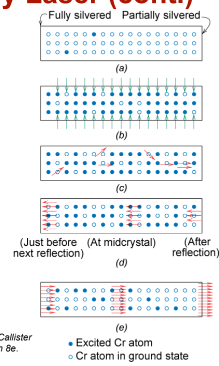

Fig. 21.15, *Callister & Rethwisch 8e.*

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 ___________________________
- Wavelengths for laser beams are within visible and infrared regions of the ___________
- Uses of CW lasers
  1. __________
  2. Drilling
  3. Cutting – laser carved wood, eye surgery
  4. Surface treatment
  5. Scribing – ceramics, etc.
  6. Photolithography – Excimer laser

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Semiconductor Laser Applications

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

_______ + hole → neutral + $h\nu$

recombination — ground state — photon of light

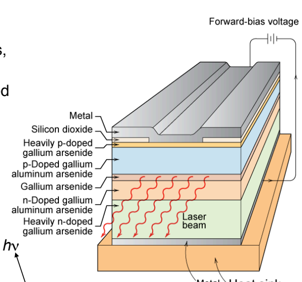

Fig. 21.17, *Callister & Rethwisch 8e.*

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Semiconductor Laser Applications

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

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Other Applications of Optical Phenomena

- New materials must be developed to make new & improved optical devices.
  - _____________________________________
    - More than one color available from a single diode
    - Also sources of ______________ (multicolor)

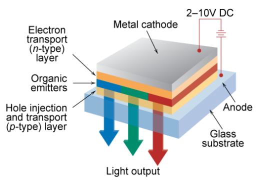

Fig. 21.12, *Callister & Rethwisch 8e.* (Reproduced by arrangement with *Silicon Chip* magazine.)

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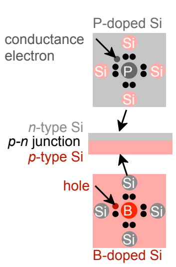
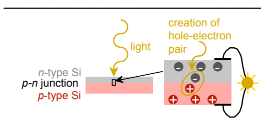
Other Applications - Solar Cells

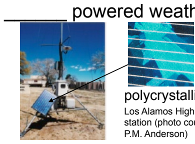
- *p-n* junction:



- Operation:
  - -- ______________________________.
  - -- typical potential of 0.5 V produced across junction
  - -- ______________________________.



- ______ powered weather station:



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

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Other Applications - Optical Fibers

Schematic diagram showing components of a

____

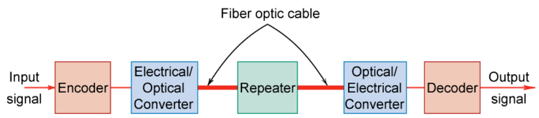

Fig. 21.18, *Callister & Rethwisch 8e.*

Optical Fibers (cont.)

- fibers have diameters of _______ or less
- plastic cladding ________ thick is applied to fibers

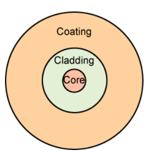

Fig. 21.20, *Callister & Rethwisch 8e.*

Optical Fiber Designs

Step-index Optical Fiber

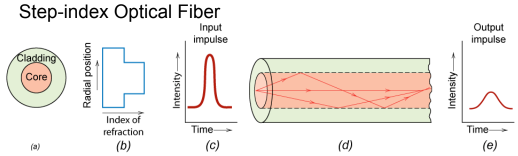

Fig. 21.21, *Callister & Rethwisch 8e.*

Graded-index Optical Fiber

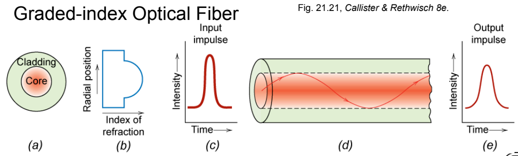

Fig. 21.22, *Callister & Rethwisch 8e.*

SUMMARY

- Light radiation impinging on a material may be reflected from, absorbed within, and/or transmitted through
- Light transmission characteristics:
  -- transparent, translucent, opaque
- Optical properties of metals:
  -- opaque and highly reflective due to electron energy band structure.
- Optical properties of non-Metals:
  -- for E_{gap} < 1.8 eV, absorption of all wavelengths of light radiation
  -- for E_{gap} > 3.1 eV, no absorption of visible light radiation
  -- for 1.8 eV < E_{gap} < 3.1 eV, absorption of some range of light radiation wavelengths
  -- color determined by wavelength distribution of transmitted light
- Other important optical applications/devices:
  -- luminescence, photoconductivity, light-emitting diodes, solar cells, lasers, and optical fibers

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