MS31007 : Chapter 9

Optical Properties of Materials

Instructor: Prasana K. Sahoo, MSC, IIT Kharagpur
prasana@matsc.iitkgp.ac.in

ISSUES TO ADDRESS...

- What phenomena occur when light is shined on a material?
- What determines the characteristic colors of materials?
- Why are some materials transparent and others are translucent or opaque?
- **Optical applications**:
  -- luminescence
  -- photoconductivity
  -- solar cell
  -- optical communications fibers

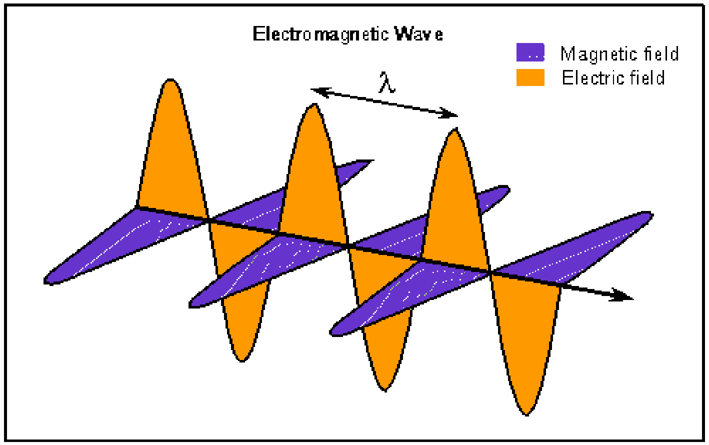
- How does a solar cell operate?
- How does a LED operate?
- How does a laser operate?
- Why Optical Fiber are necessary for communication?

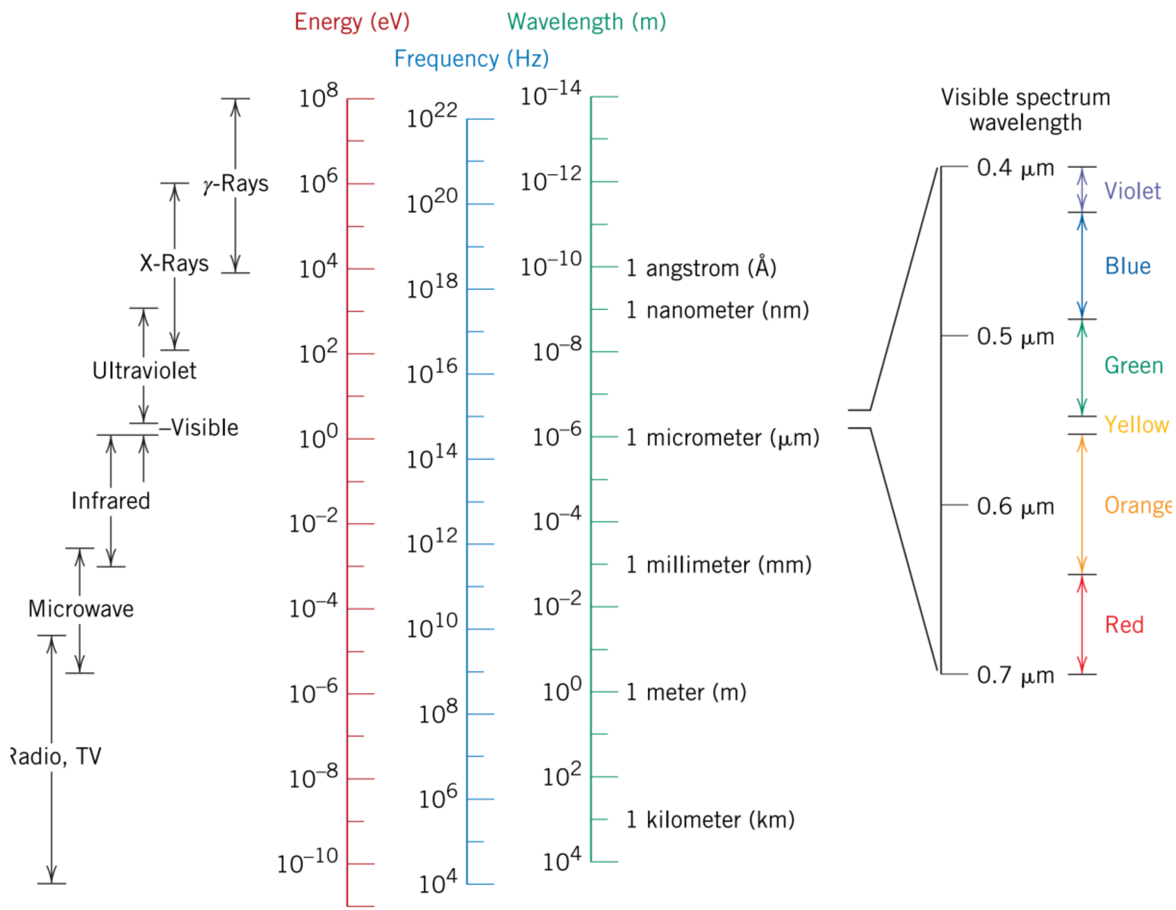
Optical Properties

Light has both particulate and wavelike characteristics

– Photon - a quantum unit of light

The spectrum of Electromagnetic Radiation





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

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)

$$c = 1/\sqrt{(\varepsilon_0 \mu_0)}$$

ε_0 electric permittivity &

μ_0 Magnetic permeability of a vacuum

$$\upsilon = \frac{1}{\sqrt{\varepsilon\mu}}$$

Light Interactions with Solids

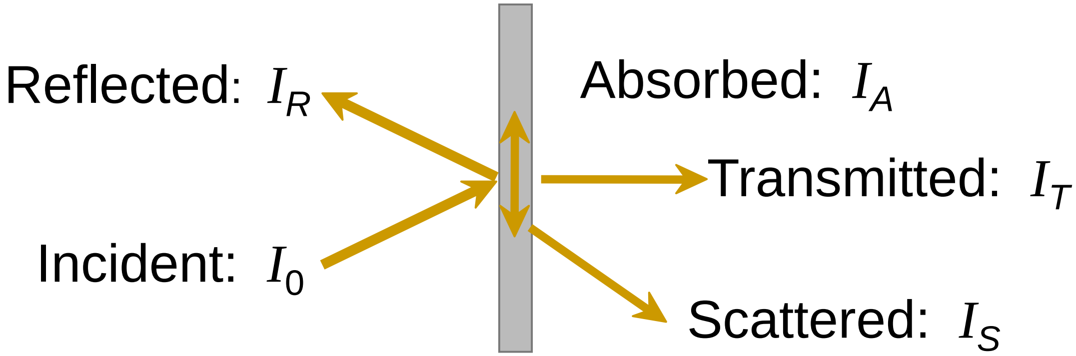
Incident light is reflected, absorbed, scattered, and/or transmitted:

$$I_0 = I_T + I_A + I_R + I_S$$

$$I_0 = I_T + I_A + I_R$$

I_o is the intensity (W/m^2) of incident light and subscripts refer to transmitted, absorbed, reflected and scattered

$$T + A + R = 1$$



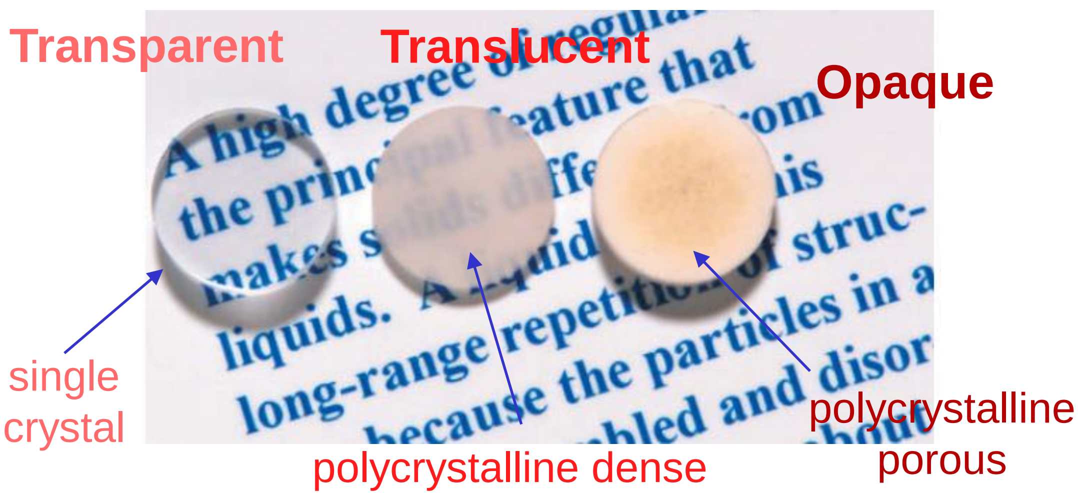
transmissivity (I_T/I_0)

absorptivity (I_A/I_0),

reflectivity (I_R/I_0)

The reflectivity *R* represents the fraction of the incident light (I_0) that is reflected at the interface (I_R)

- Optical classification of materials:

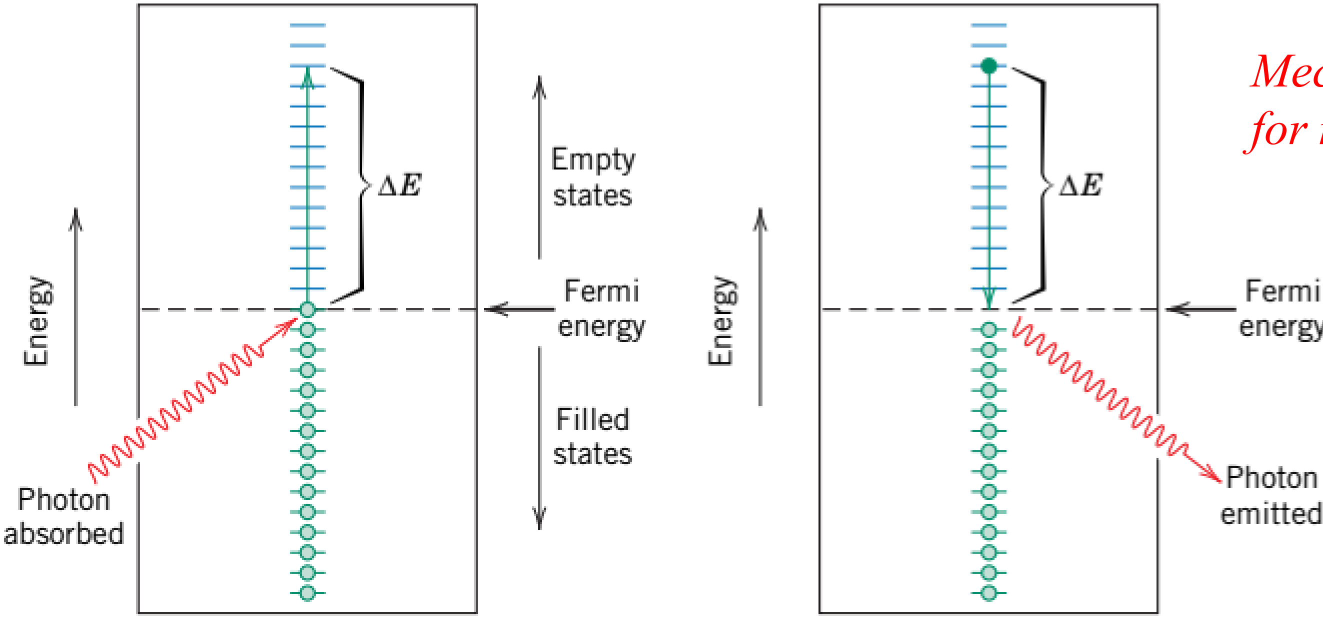


Photograph showing the light transmittance of three aluminum oxide specimens. From left to right: single-crystal material (sapphire), which is transparent; a polycrystalline and fully dense (nonporous) material, which is translucent; and a polycrystalline material that contains approximately 5% porosity, which is opaque

Optical Properties of Metals: Absorption

Absorption of photons by electron transitions:

- So what happens to the excited atoms in the surface layers of metal atoms?
  - they relax again, emitting a photon
- The energy lost by the descending electron is the same as the one originally incident



Mechanism of photon absorption for metallic materials

(a) an electron is excited into a higher-energy unoccupied state. The change in energy of the electron ΔE is equal to the energy of the photon.
(b) Reemission of a photon of light by the direct transition of an electron from a high to a low energy state.

- This structure for metals means that almost any frequency of light can be absorbed
- Since there is a very high concentration of electrons, practically all the light is absorbed within about 0.1µm of the surface

Metal films thinner than this will transmit light

Penetration depths ($I/I_0 = 1/e$) for some materials are:

water: 32 cm ; glass: 29 cm
graphite: 0.6 µm = 600 nm
gold: 0.15µm = 150 nm

Optical Properties of Metals

Reflectivity = I_R/I_0 is between 0.90 and 0.95. (metal reflects the light very well)

- metals are both opaque and reflective
- the remaining energy is usually lost as heat

- In terms of electrostatics, the field of the radiation causes the free electrons to move and a moving charge emits electromagnetic radiation

  hence the wave is re-emitted = reflected

The metal appears “silvery” since it acts as a perfect mirror

OK then, why are gold and copper not silvery?

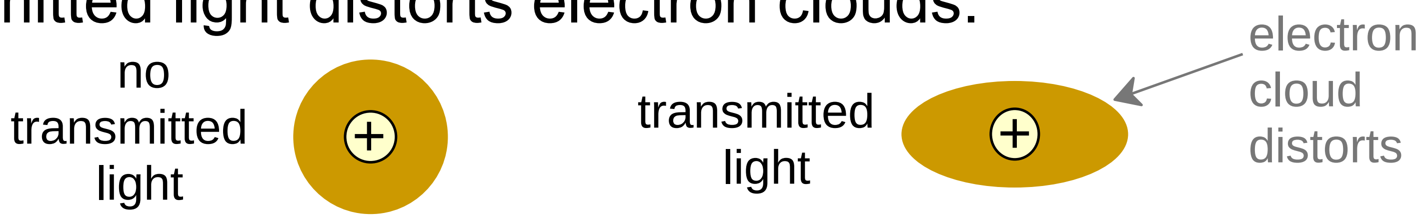
- because the band structure of a real metal is not always as simple as we have assumed
- there can be some empty levels below E_F and the energy re-emitted from these absorptions is not in the visible spectrum

- Metals are more transparent to very high energy radiation (x- & γ- rays) when the inertia of the electrons themselves is the limiting factor

Optical Properties of Nonmetals

Nonmetallic materials may be transparent to visible light: electron energy band structures
in addition to reflection and absorption, **refraction and transmission phenomena** also considered

- Transmitted light distorts electron clouds.

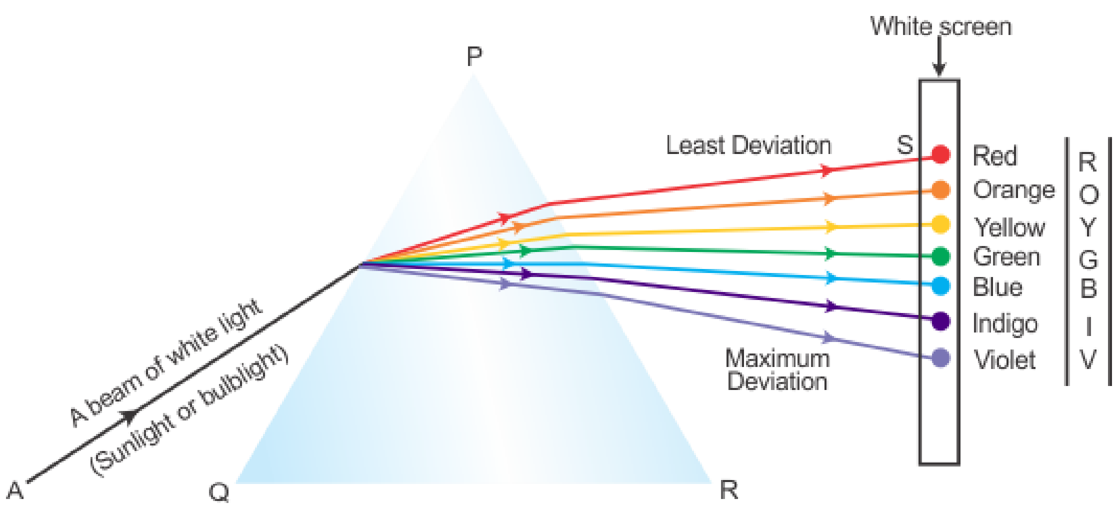


Refraction: light that is transmitted into the interior of transparent materials experiences a decrease in velocity and, as a result, is bent at the interface

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

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

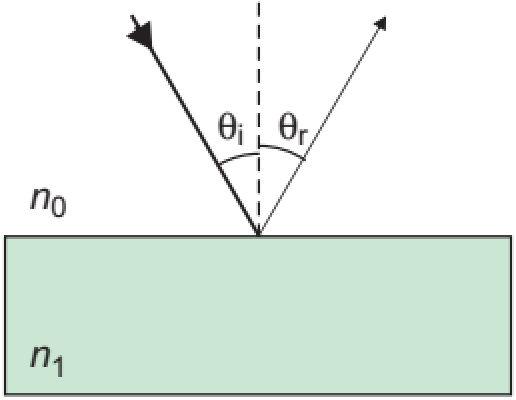
$$n = \frac{c}{v} = \frac{\sqrt{\varepsilon\mu}}{\sqrt{\varepsilon_0\mu_0}} = \sqrt{\varepsilon_r\mu_r}$$

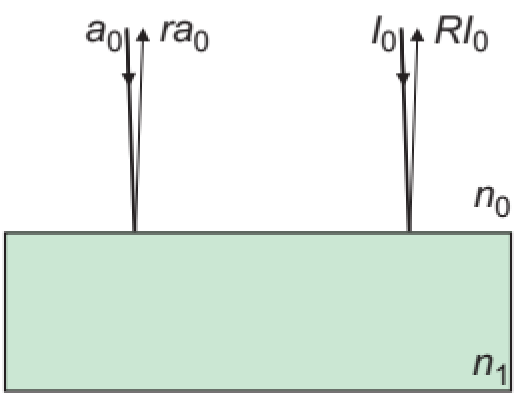


Material	*Average Index of Refraction*
Ceramics	
Silica glass	1.458
Borosilicate (Pyrex) glass	1.47
Soda–lime glass	1.51
Quartz (SiO_2)	1.55
Dense optical flint glass	1.65
Spinel ($MgAl_2O_4$)	1.72
Periclase (MgO)	1.74
Corundum (Al_2O_3)	1.76

Reflectivity of Nonmetals

The reflectivity *R* represents the fraction of the incident light (I_0) that is reflected at the interface (I_R)





$$R = \frac{I_R}{I_0}$$

The amount of light reflected from a single surface at normal incidence is given by the coefficient of reflection, r:

$$r = \frac{n_0 - n_1}{n_0 + n_1}$$

Incident amplitude a_0, amplitude of the reflected wave is ra_0

Irradiance, I_0, the flux of radiant energy per unit area, is proportional to the square of the amplitude $(a_0)^2$

Reflected irradiance is proportional to $(ra_0)^2$

$$R = r^2 = \left(\frac{n_0 - n_1}{n_0 + n_1}\right)^2$$

R, for a plate of a transparent material of refractive index n in air is:

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

Selected Light Absorption in Semiconductors

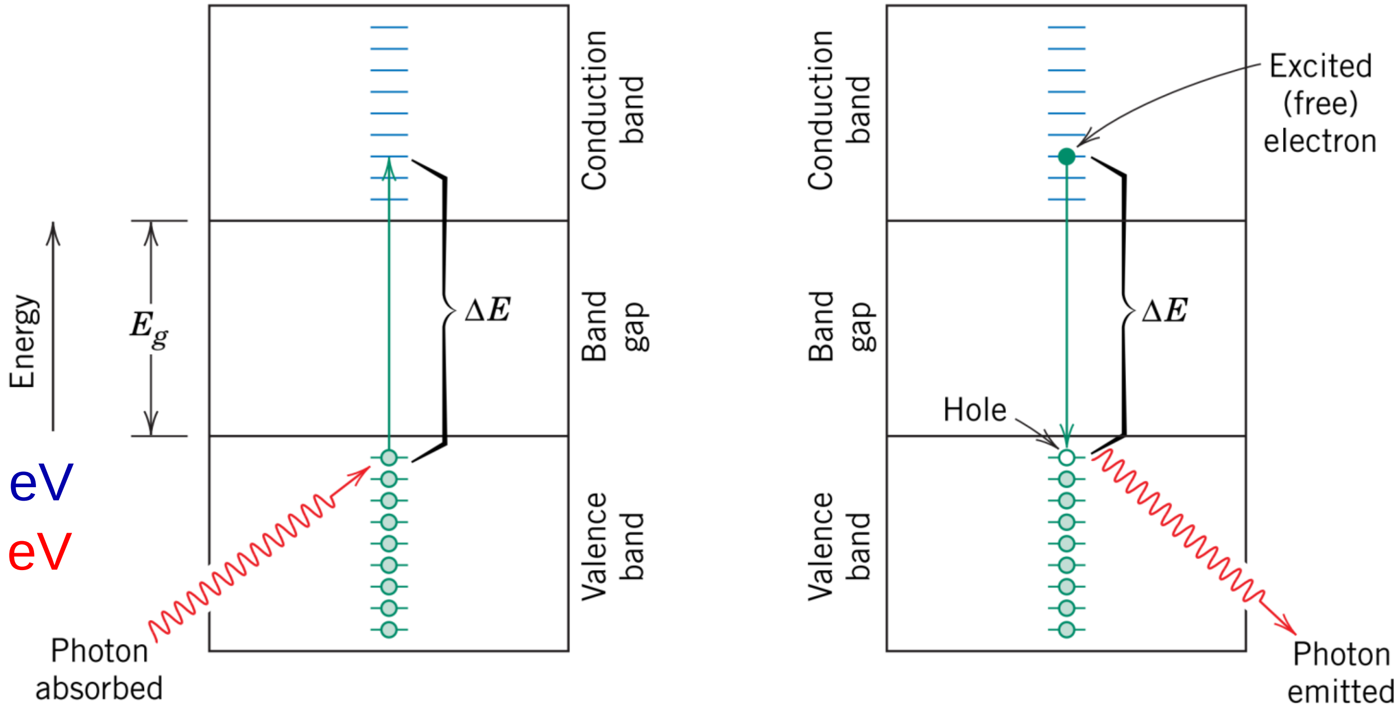
Absorption of light of frequency ν by electron transition occurs if

$h\nu > E_{gap}$

Examples of photon energies:

blue light: $h\nu$ = 3.1 eV

red light: $h\nu$ = 1.8 eV

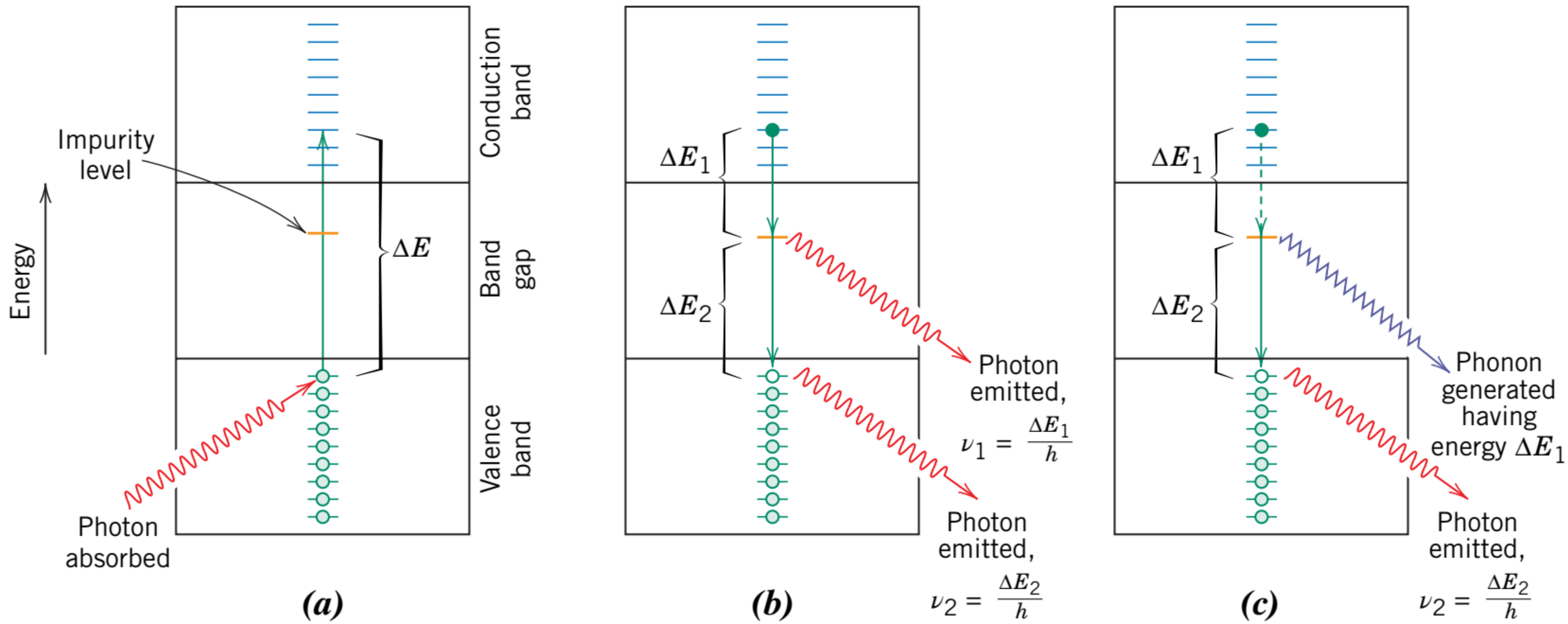


Visible spectrum (1.8 and 3.1 eV)

- 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

Selected Light Absorption

Interactions with light radiation with wide band gap semiconductor, dielectric solids having defects or impurity states



(*a*) Photon absorption via a valence band–conduction band electron excitation for a material that has an impurity level that lies within the band gap. (*b*) Emission of two photons involving electron decay first into an impurity state and finally to the ground state. (*c*) Generation of both a phonon and a photon as an excited electron falls first into an impurity level and finally back to its ground state.

Light Absorption and Transmission

Intensity of non-absorbed radiation — dependence on the absorption coefficient and the distance light traverses through the absorbing medium

The amount of light absorbed by a material is $I'_T = I'_0 e^{-\beta \ell}$

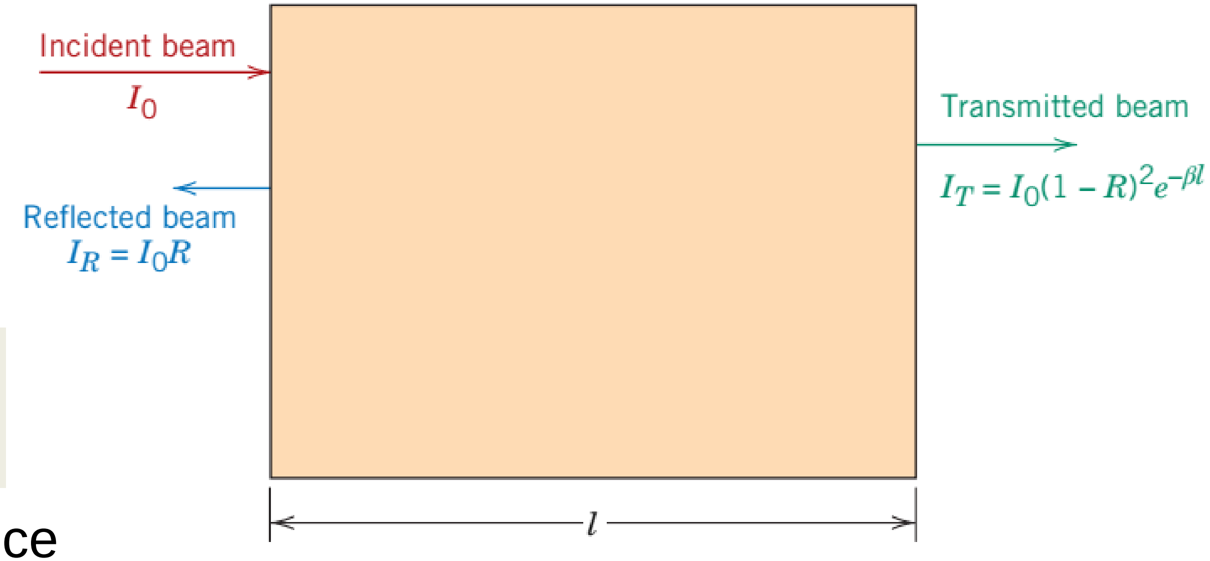
β = absorption coefficient, cm^{-1} ℓ = sample thickness, cm
I'_0 = incident light intensity, I'_T = transmitted light intensity

TRANSMISSION

For an incident beam that impinges on the front surface of a specimen of thickness *l* and absorption coefficient β, the transmitted intensity is

$$I_T = I_0(1 - R)^2 e^{-\beta l}$$

R is the reflectance



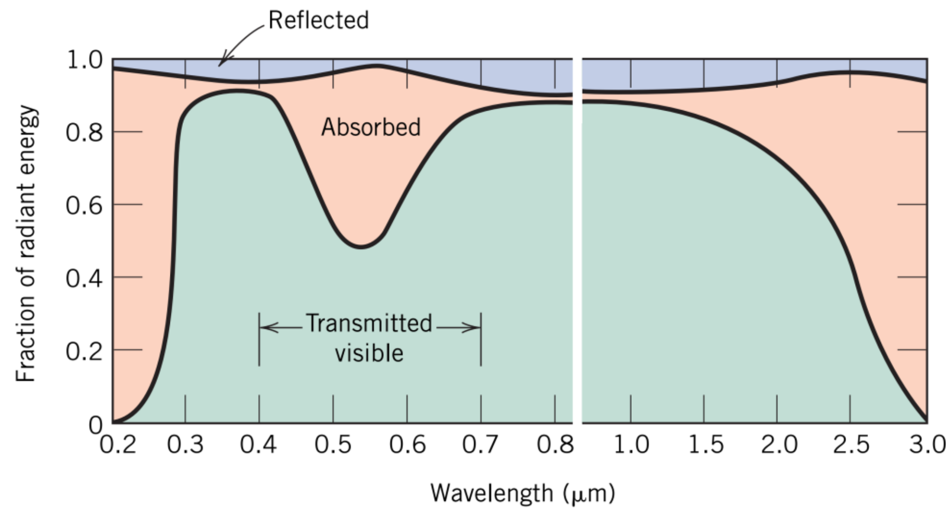
Color of Nonmetals

Color determined by the distribution of wavelengths:

-- re-emitted light from electron transitions

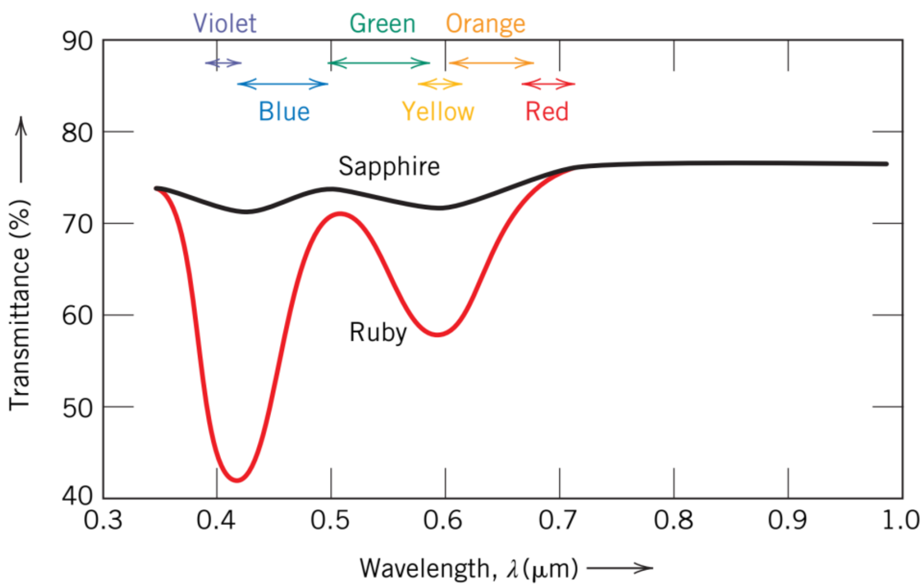
-- transmitted light

- Example 1: Green Glass
- Example 2: CdS, E_g = 2.4 eV
  - -- absorbs higher energy visible light (blue, violet)
  - -- color results from red/orange/yellow light that is transmitted



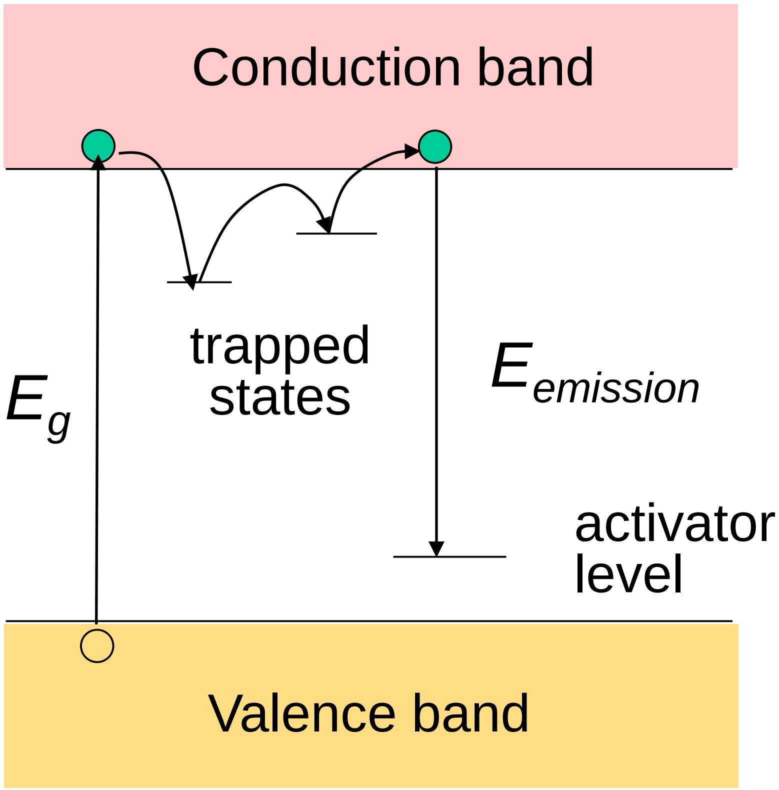
- Example 3: Ruby = Sapphire (Al_2O_3)

+ (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



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

Reemission of light over time—phosphorescence

- **For short residence times (< 10^{-8} s)** -- fluorescence

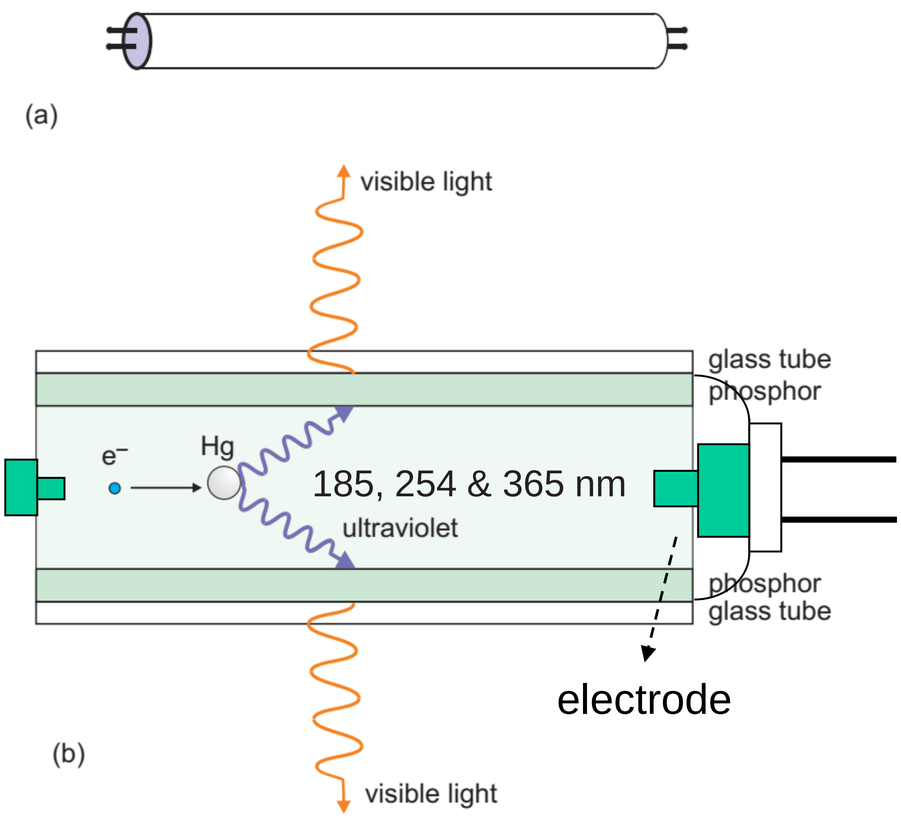
Example: Toys that glow in the dark. Charge toys by exposing them to light.

Applications of Optical Phenomena: **Luminescence**

Type	Source of energy
Photoluminescence	Photons, mainly ultraviolet
Triboluminescence	Mechanical bond-breaking, fracture or friction
Chemiluminescence	Chemical reactions
Cathodoluminescence	Electron bombardment
Thermoluminescence	Increase of temperature
Electroluminescence	Applied electric field
Bioluminescence	Life processes
Radioluminescence	Radioactive decay
Sonoluminescence	Ultrasonic waves

Fluorescent lamps

Fluorescent lamps utilize photoluminescence for light generation



- 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

  -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

Fluorescent lamps: (a) schematic fluorescent tube lamp; (b) e⁻ from the cathode collide with mercury (Hg) atoms in the tube which emit UV photons that are converted into visible light by a phosphor coating.

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

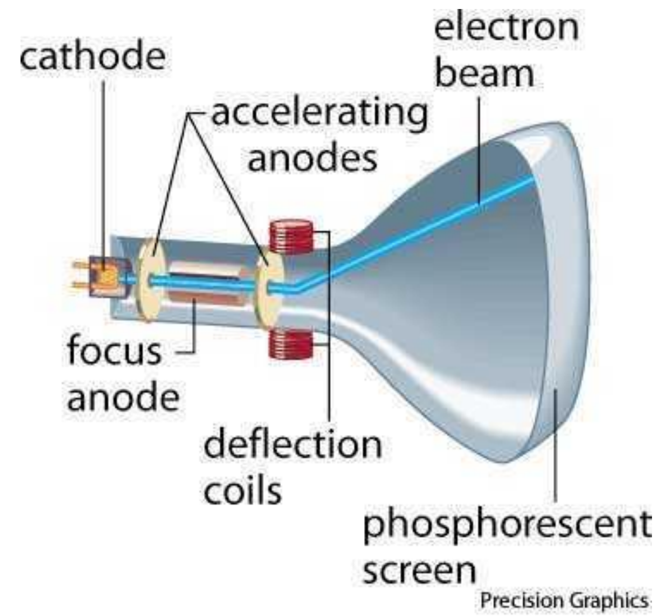
✓ Photon (visible light) emitted as electrons drop back into ground states

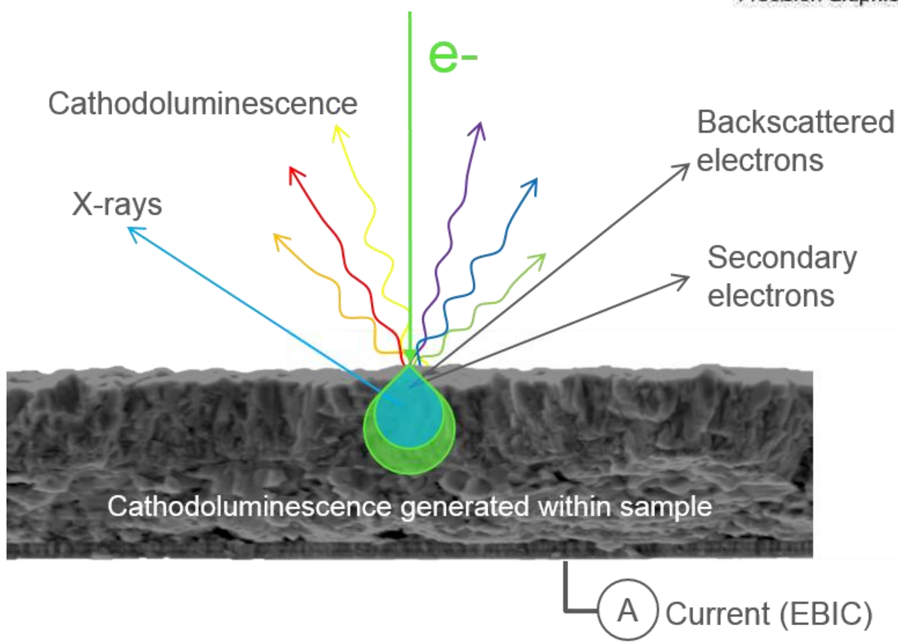
✓ Color of emitted light depends on composition of phosphor

✓ 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

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

Practice Questions

Q 13. 1 The fraction of nonreflected light that is transmitted through a 250-mm thickness of glass is 0.98. Calculate the absorption coefficient of this material.

Q 13.2 Are the elemental semiconductors silicon and germanium transparent to visible light? Why or why not?

Q 13. 3 Is the semiconductor Gallium Nitride (GaN), which has a band gap of 3.4 eV, photoconductive when exposed to visible light radiation? Why or why not?