CHAPTER 21: OPTICAL PROPERTIES

- Electromagnetic Radiation
- Light Interaction with Solids
- Optical Properties of Metals
- Optical Properties of Nonmetals
  - Refraction, - Reflection, - Absorption,
  - Transmission, - Color, - Opacity
- Application
  - Luminescence, - Photoconductivity
  - Laser, - Optical Fiber

INTRODUCTION

- **Optical Property**

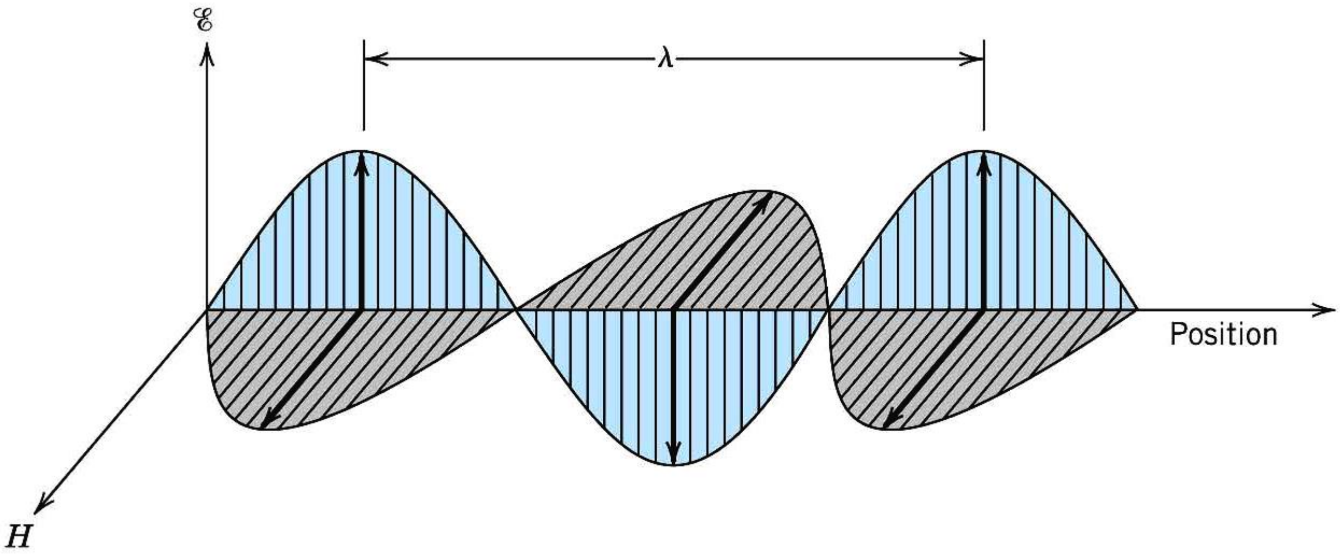
  a material's response to exposure to visible light

- **Visible Light- electromagnetic radiation**

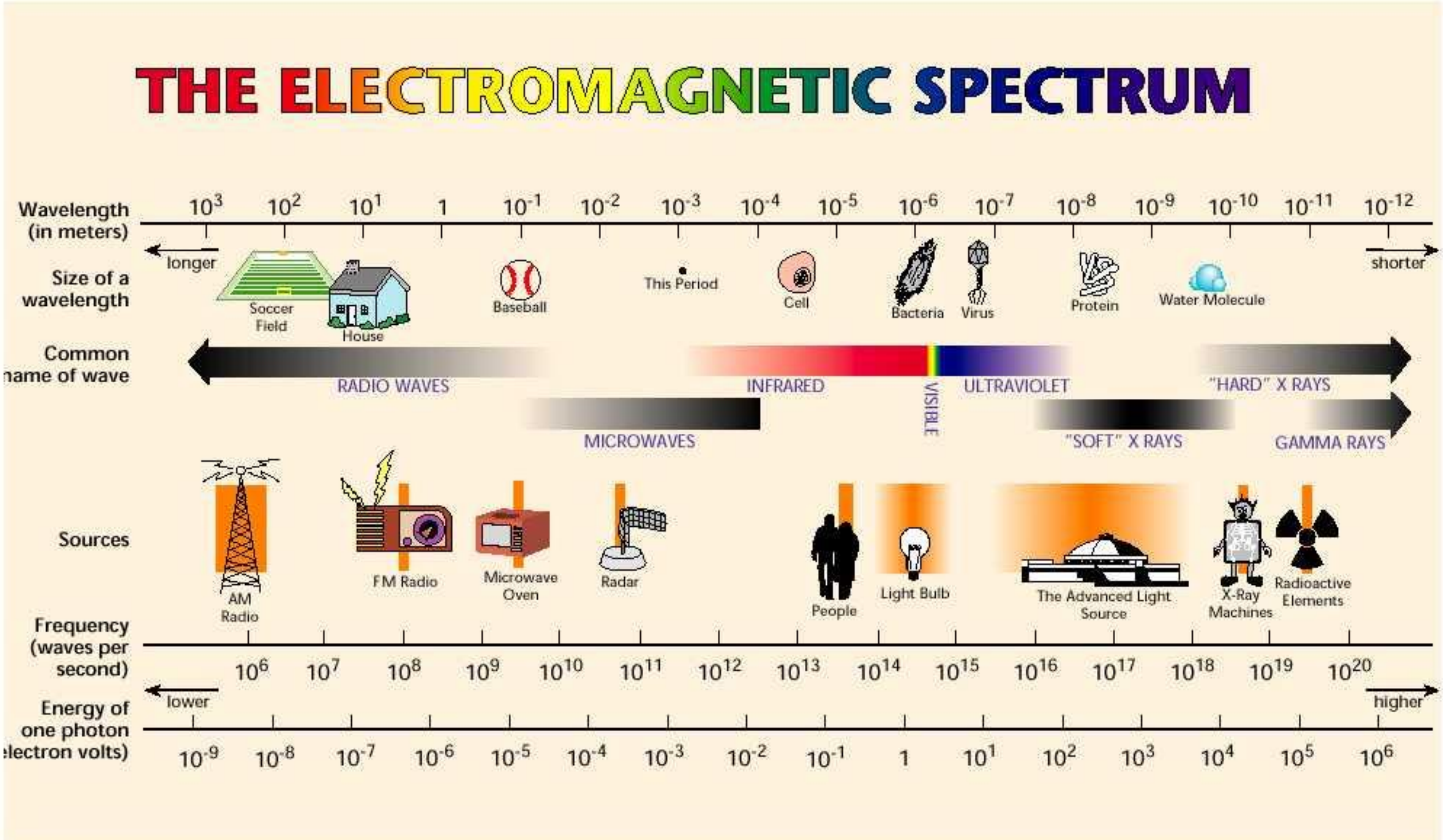
INTRODUCTION

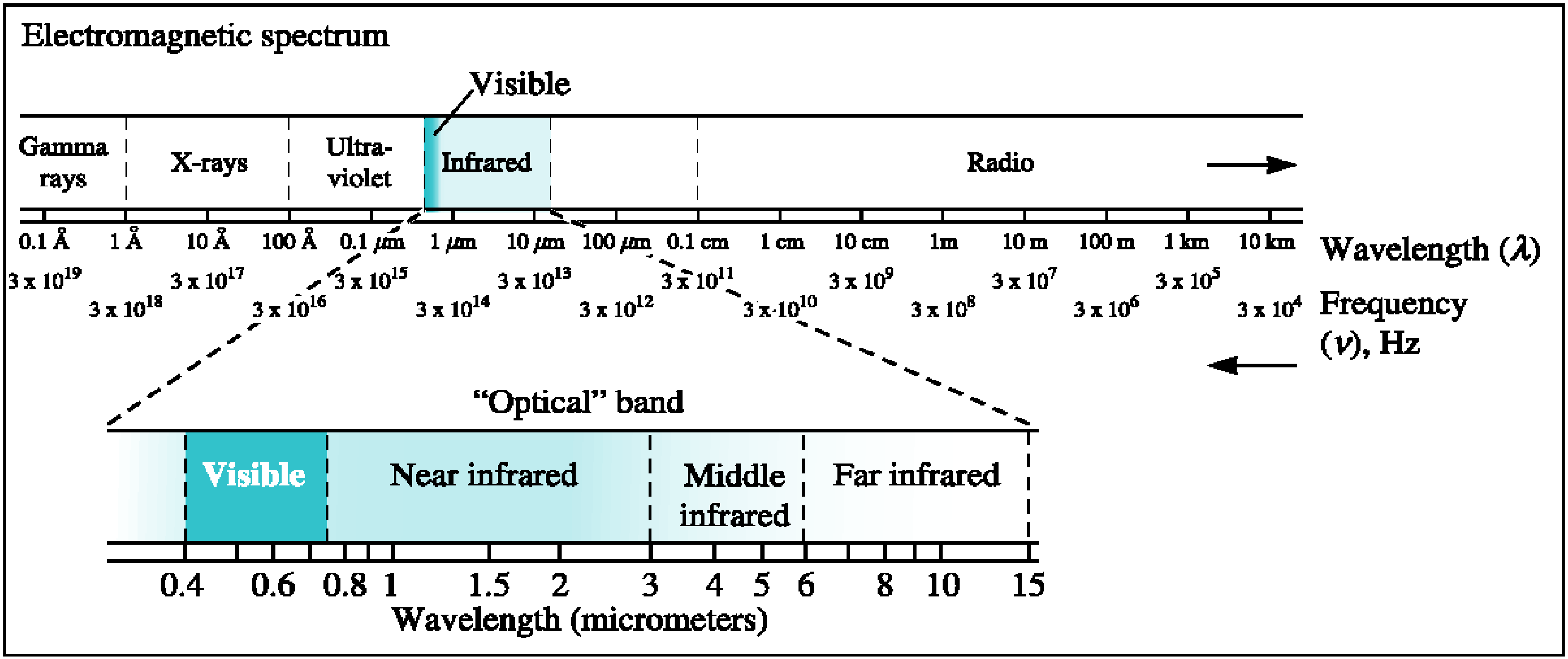
- Light is energy, or radiation, in the form of waves or particles called photons that can be emitted from a material.
- The important characteristics of the photons—their energy E, wavelength λ, and frequency ν—are related by the equation

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



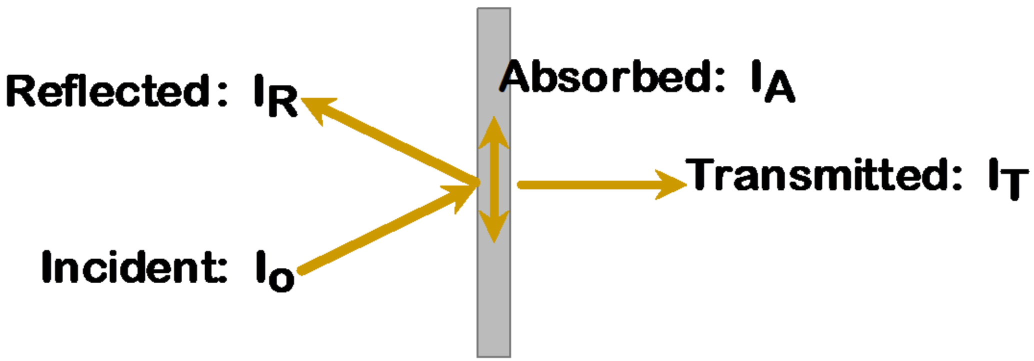
$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}}$$


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
FM Radio
Microwave Oven
Radar
People
Light Bulb
The Advanced Light Source
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

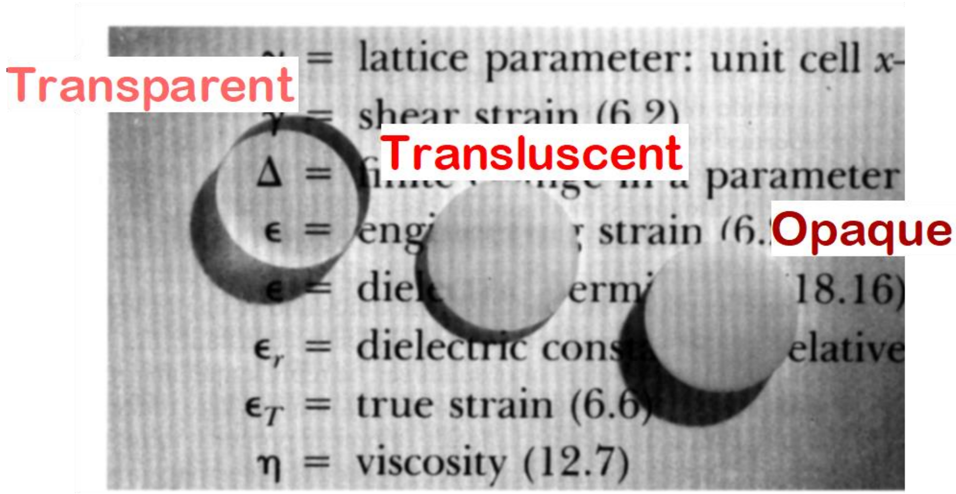

Electromagnetic spectrum
Visible
Gamma rays
X-rays
Ultra-violet
Infrared
Radio
0.1 Å
1 Å
10 Å
100 Å
0.1 μm
1 μm
10 μm
100 μm
0.1 cm
1 cm
10 cm
1m
10 m
100 m
1 km
10 km
Wavelength (λ)
3 x 10^19
3 x 10^18
3 x 10^17
3 x 10^16
3 x 10^15
3 x 10^14
3 x 10^13
3 x 10^12
3 x 10^11
3 x 10^10
3 x 10^9
3 x 10^8
3 x 10^7
3 x 10^6
3 x 10^5
3 x 10^4
Frequency (ν), Hz
"Optical" band
Visible
Near infrared
Middle infrared
Far infrared
0.4
0.6
0.8
1
1.5
2
3
4
5
6
8
10
15
Wavelength (micrometers)

LIGHT INTERACTION WITH SOLIDS

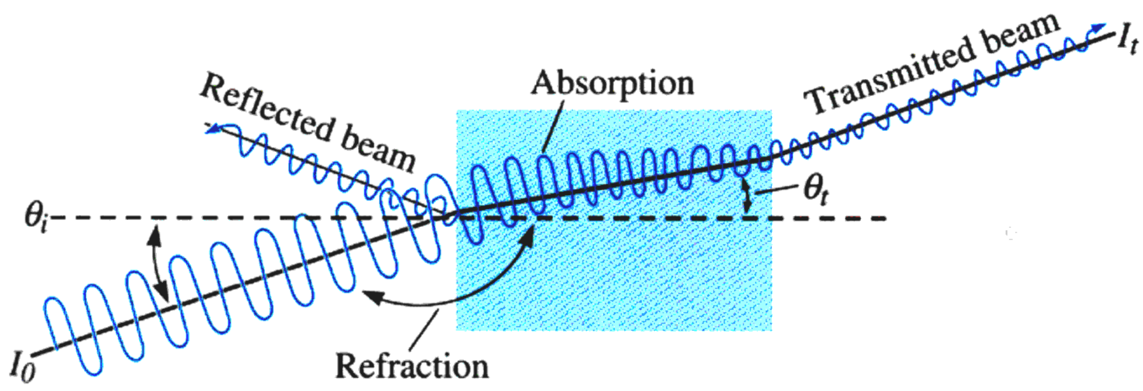
- Incident light is either reflected, absorbed, or transmitted: $I_o = I_T + I_A + I_R$



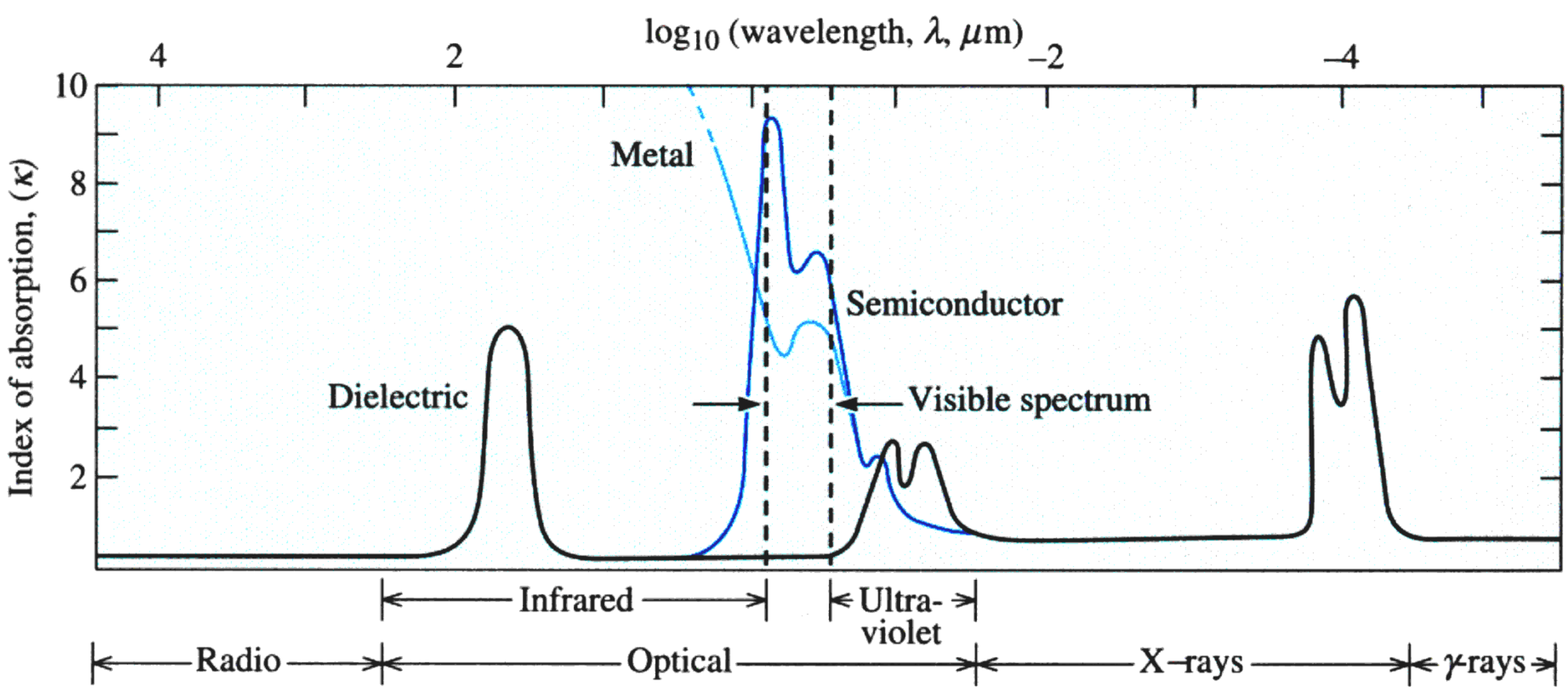
- Optical classification of materials:



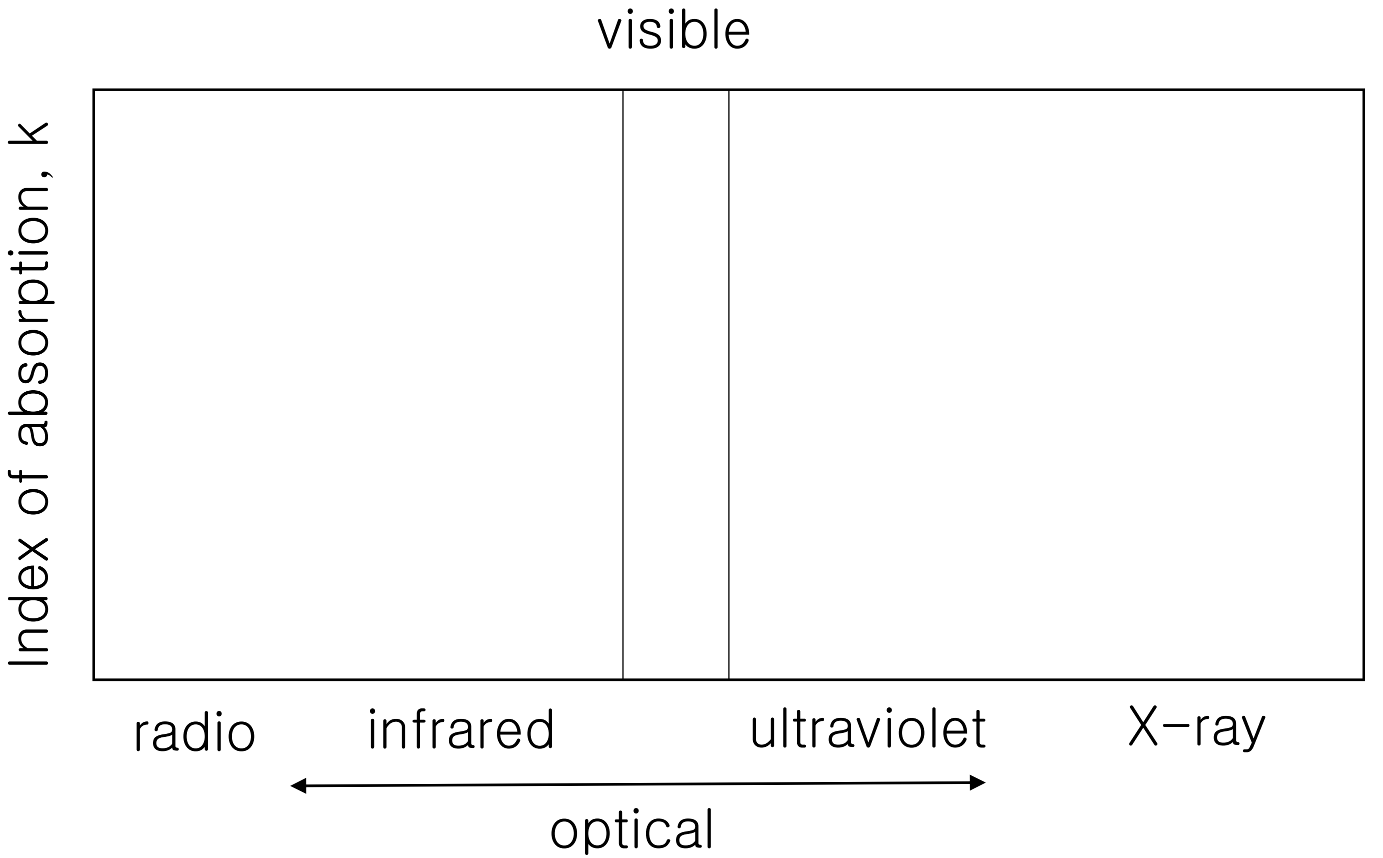
LIGHT INTERACTION WITH SOLIDS

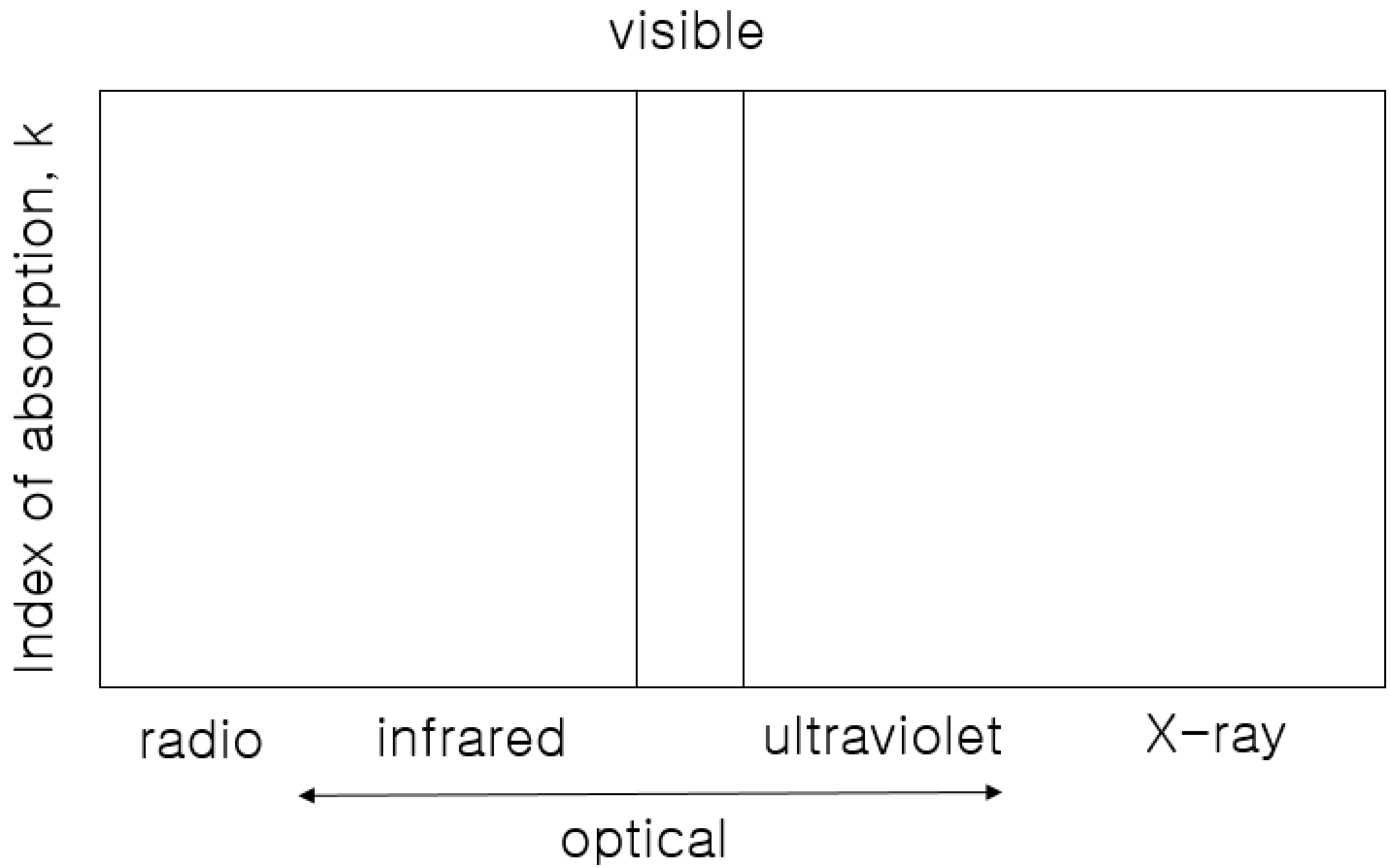


(a)



(b)

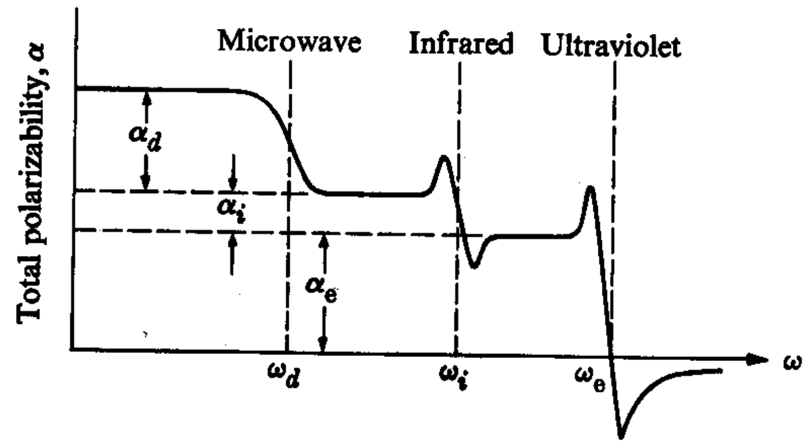

visible
Index of absorption, k
radio
infrared
ultraviolet
X–ray
optical


visible
Index of absorption, k
radio
infrared
ultraviolet
X-ray
optical

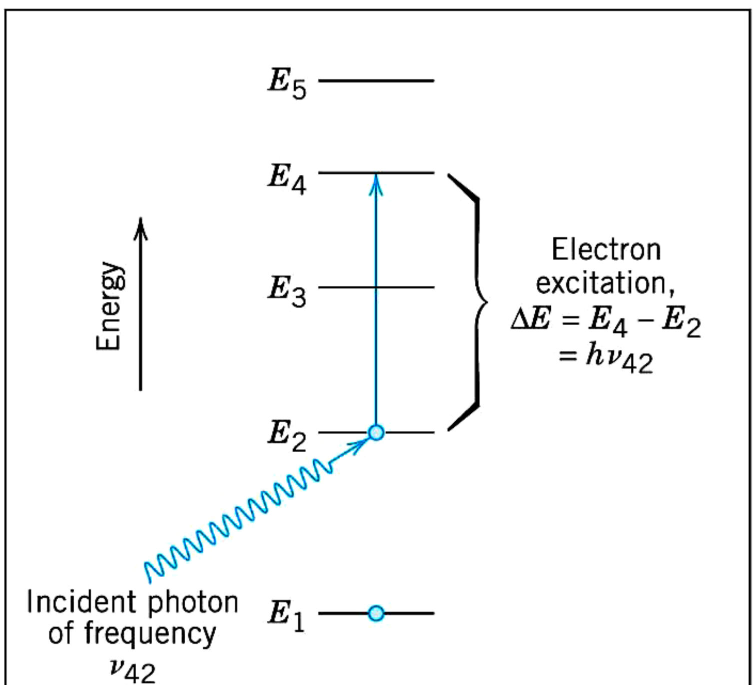
LIGHT INTERACTION WITH SOLIDS

➢ electronic polarization

- some of the radiation energy may be absorbed
- light waves are retarded in velocity as they pass through the medium



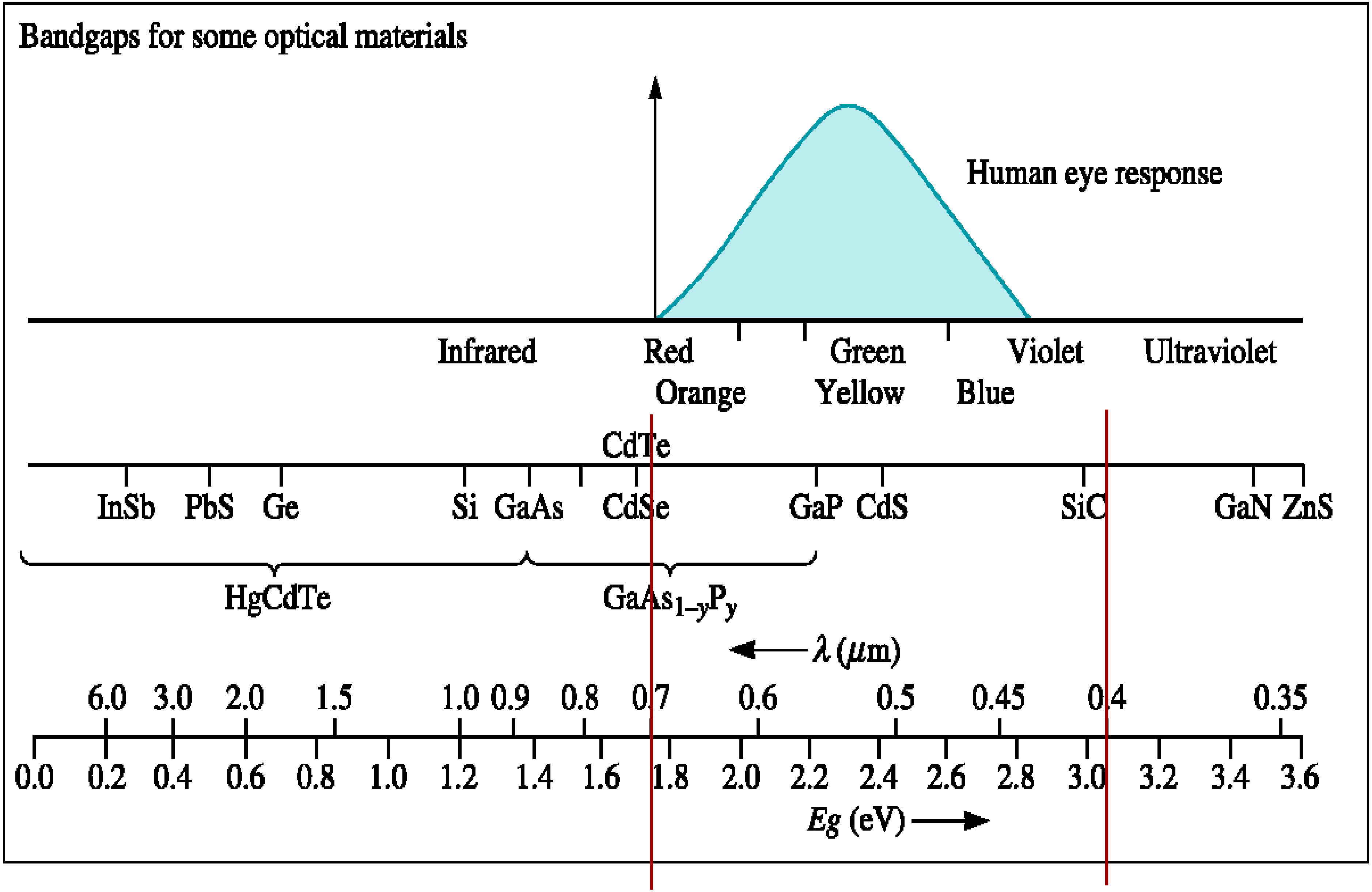
➢ electron transition



- discrete, specific energy

$$\Delta E = h\nu$$

- short stay in an excited state- decay back into its ground state

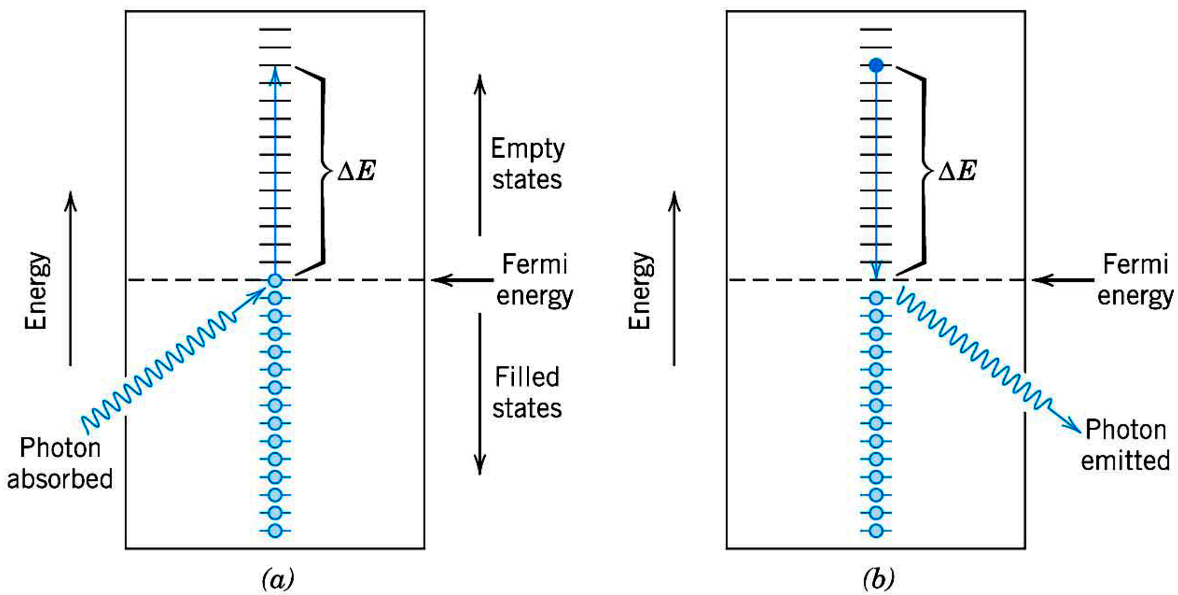

Bandgaps for some optical materials
Human eye response
Infrared
Red
Orange
Green
Yellow
Blue
Violet
Ultraviolet
CdTe
InSb
PbS
Ge
Si
GaAs
CdSe
GaP
CdS
SiC
GaN
ZnS
HgCdTe
$GaAs_{1-y}P_y$
λ (μm)
6.0 3.0 2.0 1.5 1.0 0.9 0.8 0.7 0.6 0.5 0.45 0.4 0.35
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6
E_g (eV)

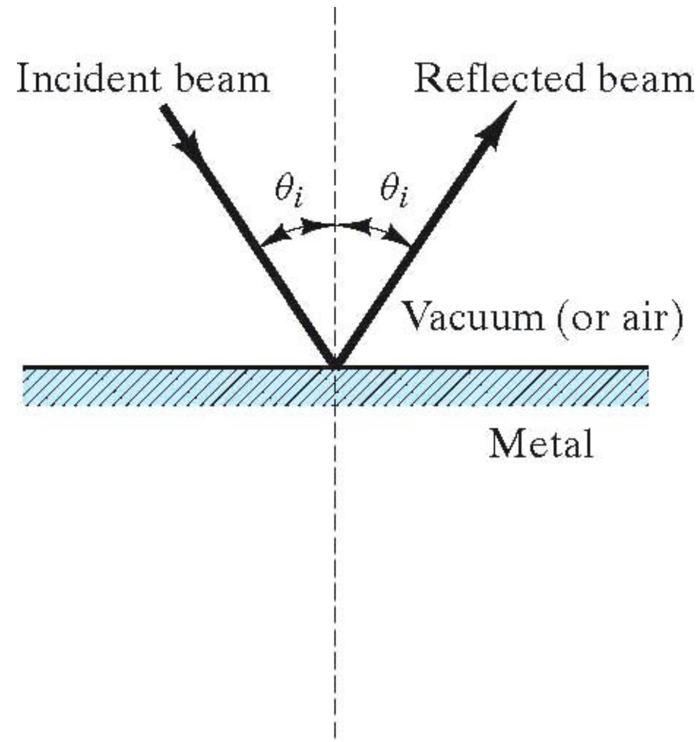
INTERACTION OF EM WAVE WITH SOLIDS

- refraction, reflection, absorption

- described by
  - **index of refraction**: ratio of the velocity of light in vacuum to the velocity of light in the material
  - **absorption constant**: the reciprocal of the absorption coefficient is a measure of how far the light will travel before being reduced by a factor of e
  - **penetration depth**: the distance with 1/e reduction in intensity
  - **dielectric constant**: related with the polarization of a material
  - **permeability**: related with the magnetization of a material

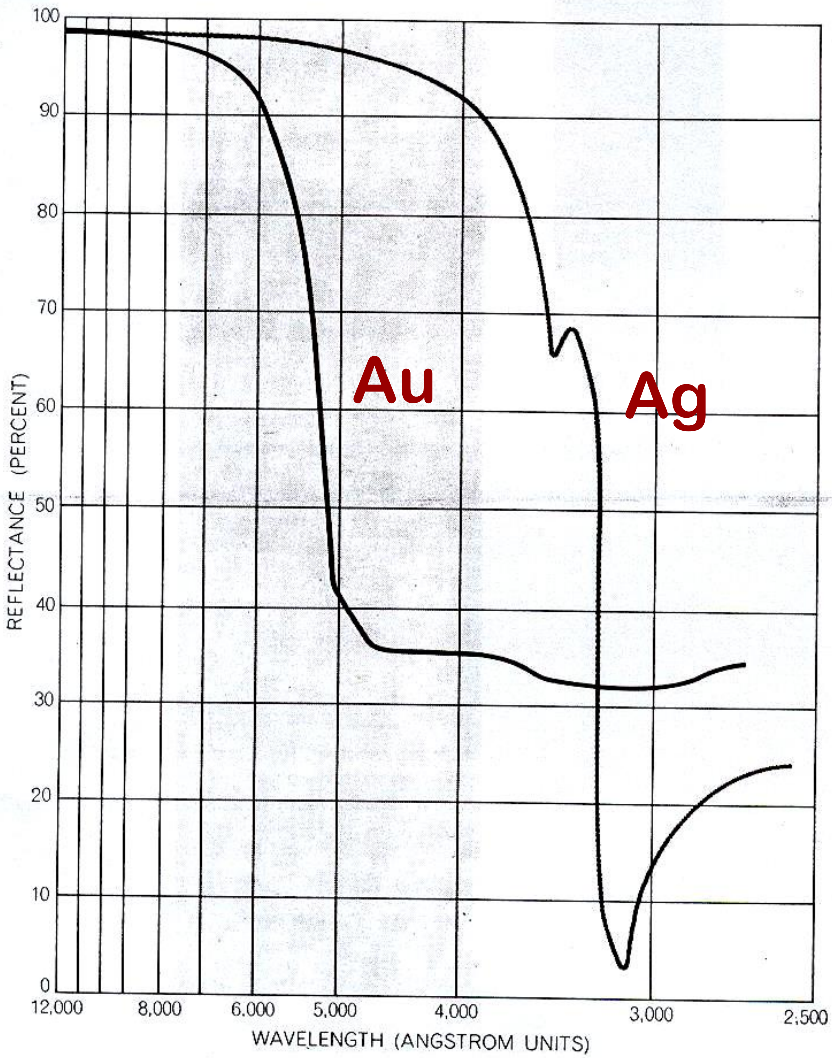
OPTICAL PROPERTIES OF METALS





- total absorption-less than 0.1μm
- all frequencies of visible light absorbed
- reemit in the form of visible light of same wavelength
- reflectivity- 0.90~0.95

OPTICAL PROPERTIES OF METALS



REFLECTANCE SPECTRA of gold (*black curve*) and silver (*gray curve*) are compared. Gold reflects red and yellow light strongly at the surface but allows some penetration by green rays, which are then completely absorbed within a small thickness of the bulk of the metal. Silver, on the other hand, strongly reflects incident light over most of the visible region of the spectrum (*color*) but allows considerable transmission in the ultraviolet.

- Al, Ag: bright silvery
  the composition of reemitted photons is approximately same as for the incident beam

- Cu, Au- red orange & yellow
  some of the energy associated with light photons having short wavelength is not reemitted as visible light

OPTICAL PROPERTIES OF NONMETALS

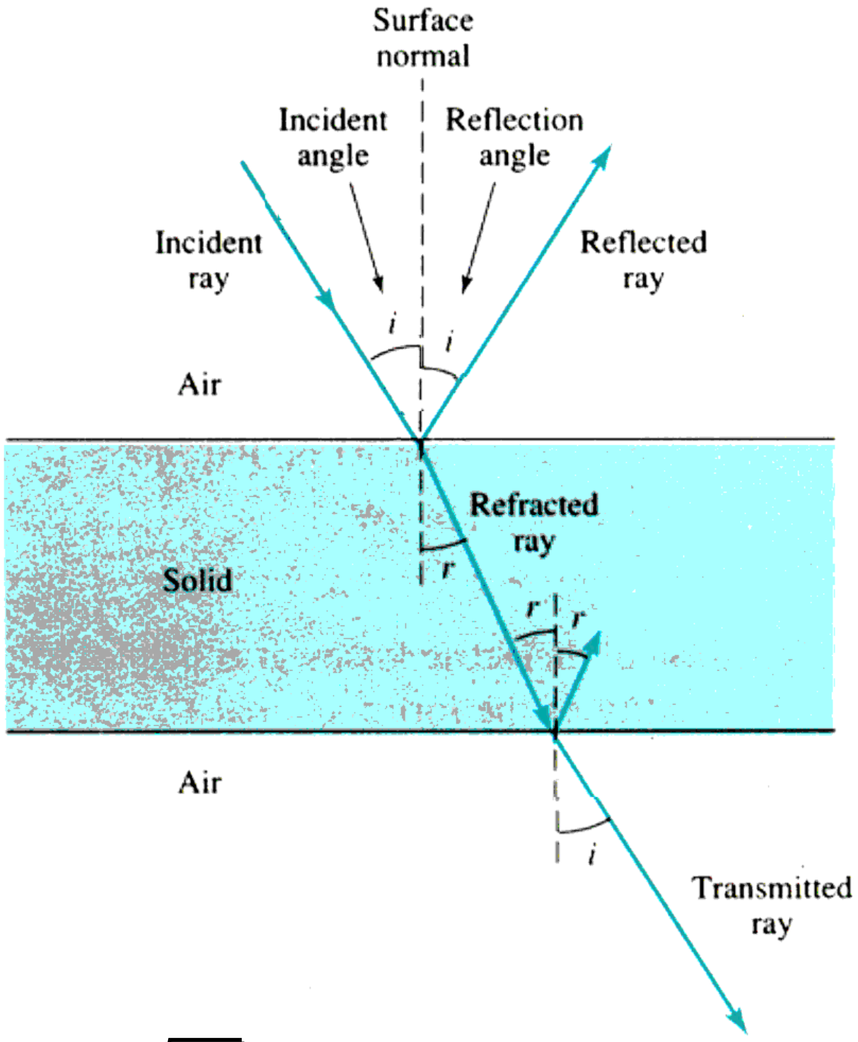
- refractive index

$$n = \frac{v_{vac}}{v_{mat}} = \frac{\lambda_{vac}}{\lambda_{mat}} = \frac{\sin i}{\sin r}$$

(snell's law)

- light travels from material 1 to material 2

$$\frac{v_1}{v_2} = \frac{n_2}{n_1} = \frac{\sin i}{\sin r}$$



- $n = \frac{v_{vac}}{v_{mat}} = \frac{\sqrt{\varepsilon\mu}}{\sqrt{\varepsilon_o\mu_o}} = \sqrt{\varepsilon_r\mu_r}$ $\quad n \simeq \sqrt{\varepsilon_r}$ for nonmagnetic

REFRACTION

- refractive index

Material	Average refractive index
Quartz (SiO_2)	1.55
Mullite ($3Al_2O_3 \cdot 2SiO_2$)	1.64
Orthoclase ($KAlSi_3O_8$)	1.525
Albite ($NaAlSi_3O_8$)	1.529
Corundum (Al_2O_3)	1.76
Periclase (MgO)	1.74
Spinel ($MgO \cdot Al_2O_3$)	1.72
Silica glass (SiO_2)	1.458
Borosilicate glass	1.47
Soda–lime–silica glass	1.51–1.52
Glass from orthoclase	1.51
Glass from albite	1.49

Polymer	Average refractive index
Thermoplastic polymers	
Polyethylene	
High-density	1.545
Low-density	1.51
Polyvinyl chloride	1.54–1.55
Polypropylene	1.47
Polystyrene	1.59
Cellulosics	1.46–1.50
Polyamides (nylon 66)	1.53
Polytetrafluoroethylene (Teflon)	1.35–1.38
Thermosetting polymers	
Phenolics (phenol-formaldehyde)	1.47–1.50
Urethanes	1.5–1.6
Epoxies	1.55–1.60
Elastomers	
Polybutadiene/polystyrene copolymer	1.53
Polyisoprene (natural rubber)	1.52
Polychloroprene	1.55–1.56

$$n^* = n - ik \text{ (k: index of absorption)}$$

$$n^{*2} = \varepsilon_r^* = \varepsilon_r' - i\varepsilon_r'' \quad \varepsilon_r' = n^2 - k^2 \quad \varepsilon_r'' = 2nk$$

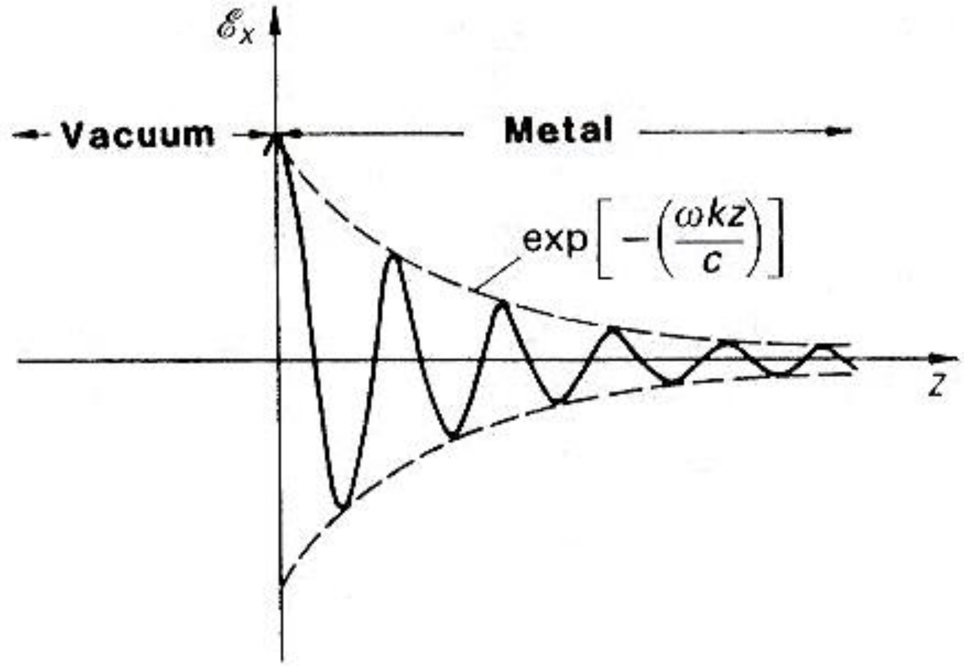


Figure 10.4. Modulated light wave. The amplitude decreases exponentially in an optically dense material. The decrease is particularly strong in metals, but less intense in dielectric materials, such as glass.

Table 10.1. Characteristic Penetration Depth, W, and Damping Constant, k, for Some Materials ($\lambda = 589.3$ nm).

Material	Water	Flint glass	Graphite	Gold
W(cm)	32	29	6×10^{-6}	1.5×10^{-6}
k	1.4×10^{-7}	1.5×10^{-7}	0.8	3.2

REFRACTION

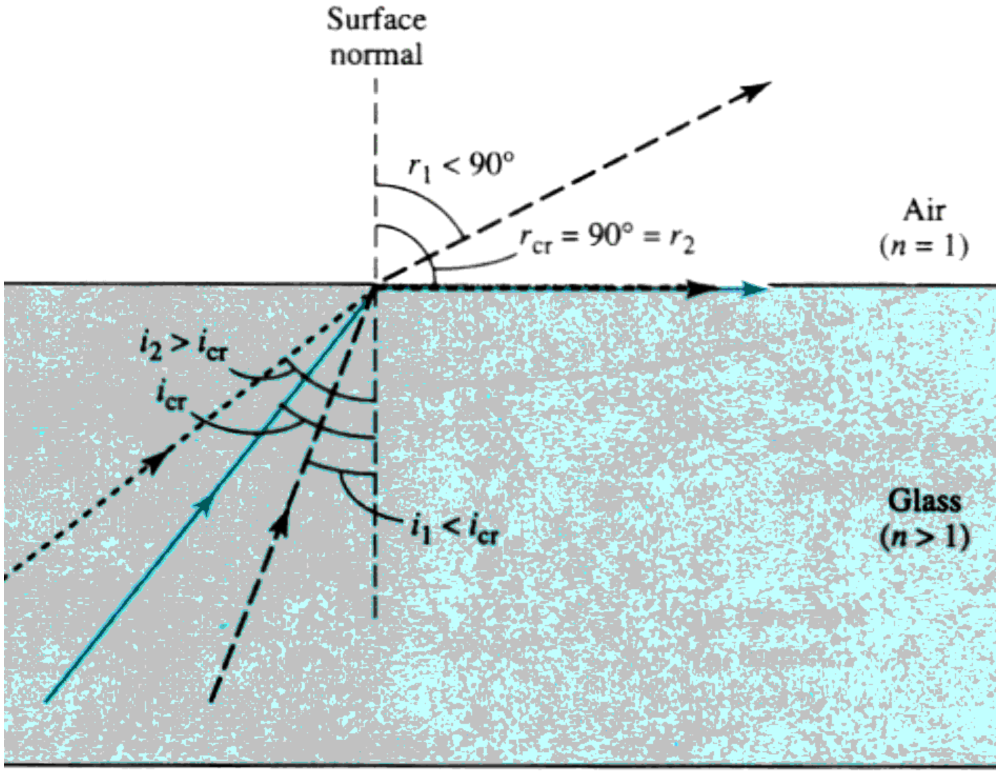
- total internal reflection

critical angle

$$\sin r = \sin i_{cr} (\frac{n_{mat}}{n_{vau}}) = \sin 90$$

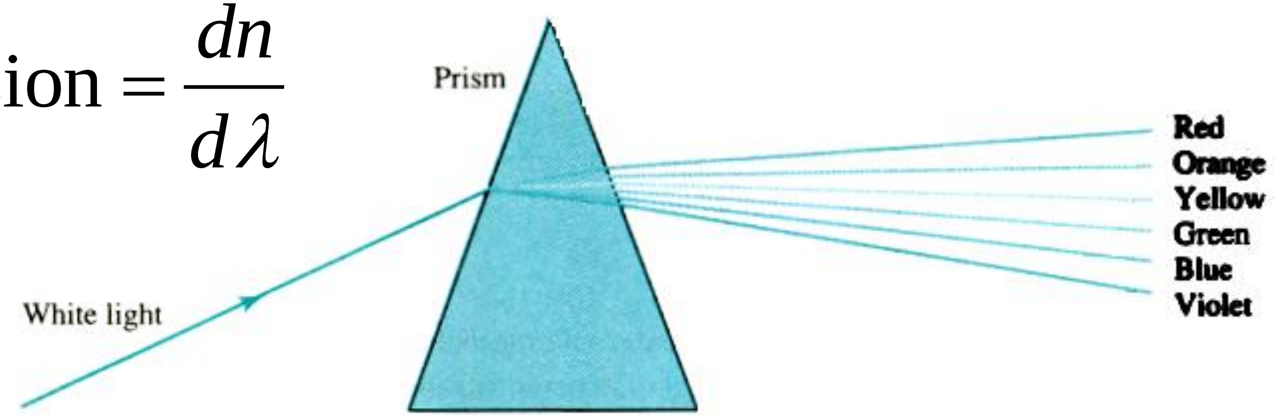
$$i_{cr} = \sin^{-1}(\frac{n_{vac}}{n_{mat}})$$

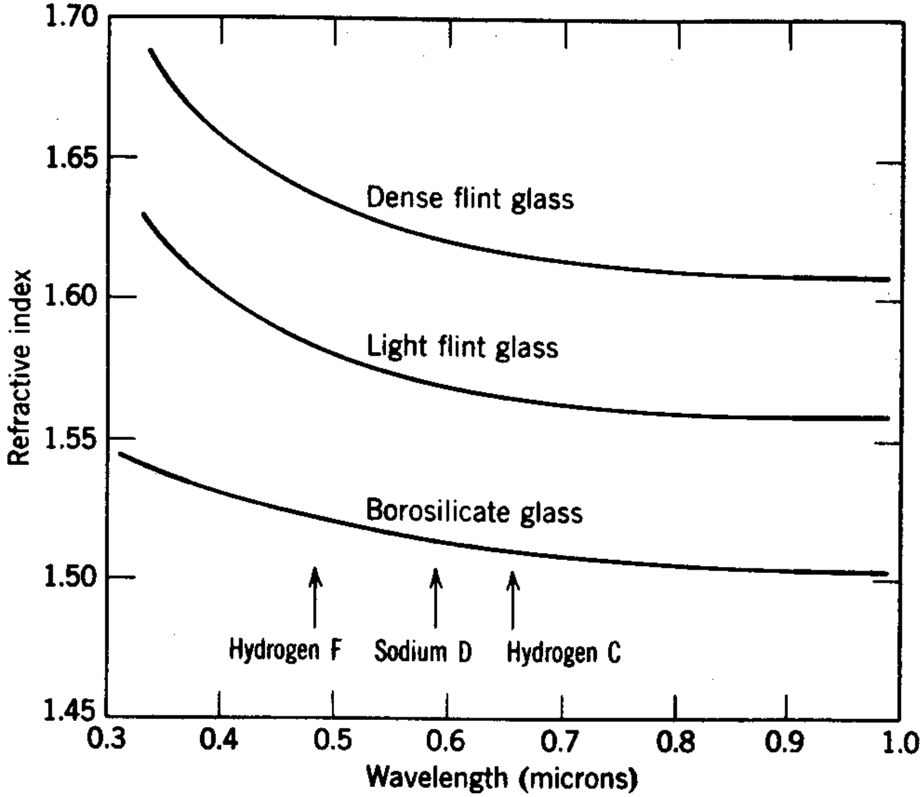
$$= \sin^{-1}(\frac{1}{n_{mat}})$$



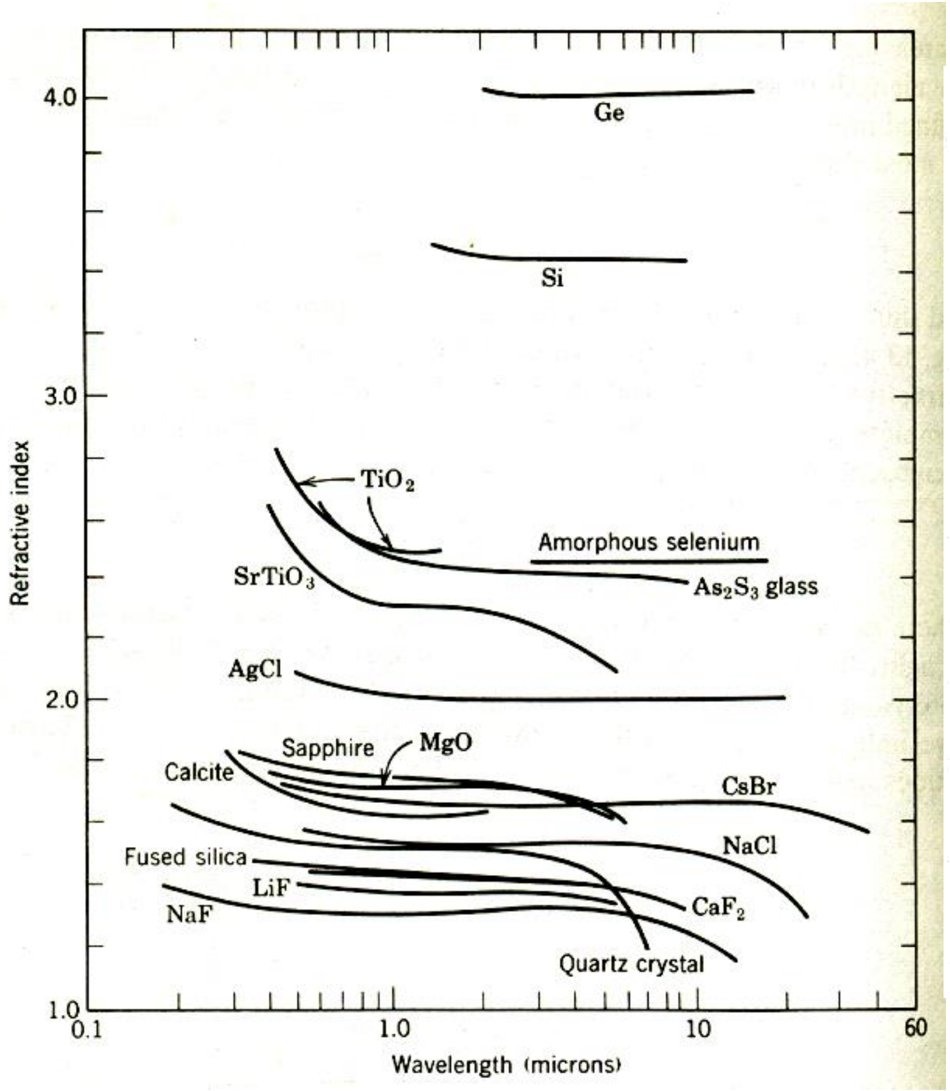
DISPERSION

- dispersion $= \dfrac{dn}{d\lambda}$

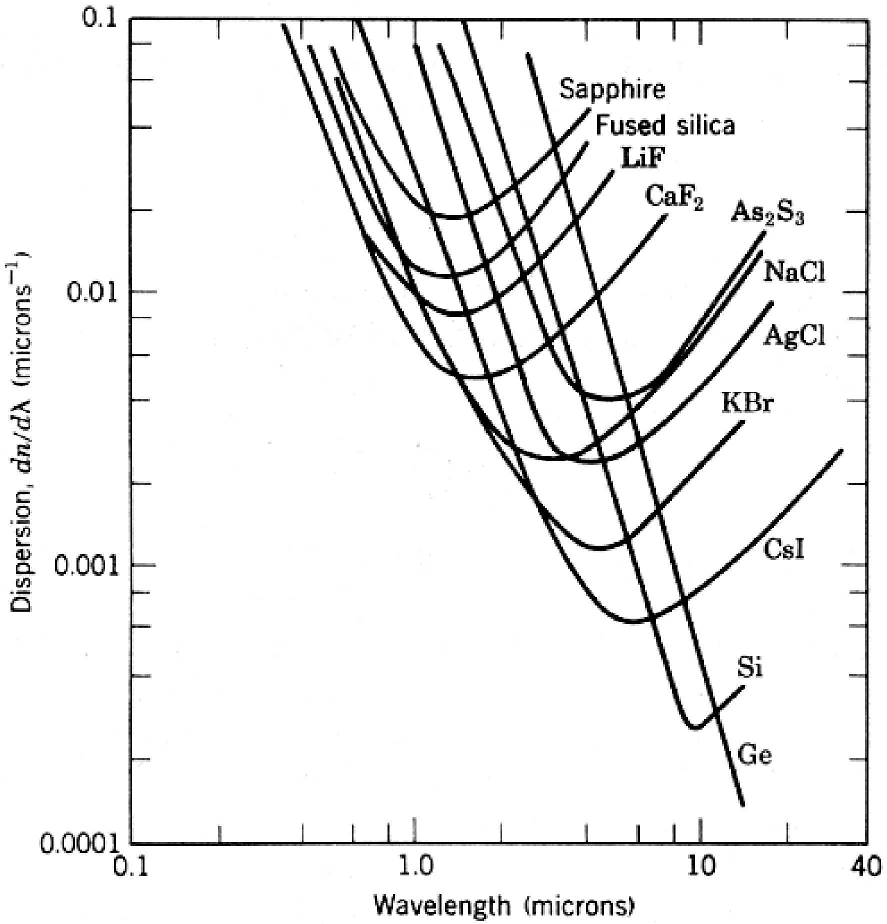




DISPERSION



Refractive index
Wavelength (microns)
4.0
3.0
2.0
1.0
0.1
1.0
10
60
Ge
Si
TiO2
Amorphous selenium
SrTiO3
As2S3 glass
AgCl
Sapphire
MgO
Calcite
CsBr
NaCl
Fused silica
LiF
CaF2
NaF
Quartz crystal



Dispersion, dn/dλ (microns^-1)
Wavelength (microns)
0.1
0.01
0.001
0.0001
0.1
1.0
10
40
Sapphire
Fused silica
LiF
CaF2
As2S3
NaCl
AgCl
KBr
CsI
Si
Ge

REFECTION

- reflection

  Fresnel's formula for normal incidence

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

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

n: $1.5 \rightarrow 1.9$

R: $4 \rightarrow 10\%$

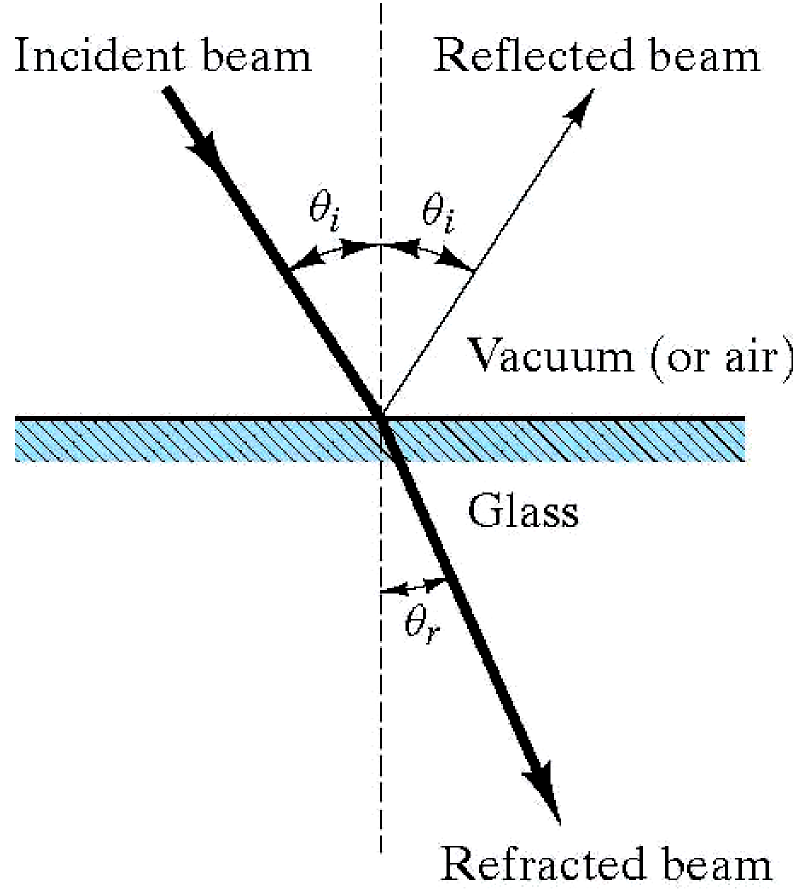


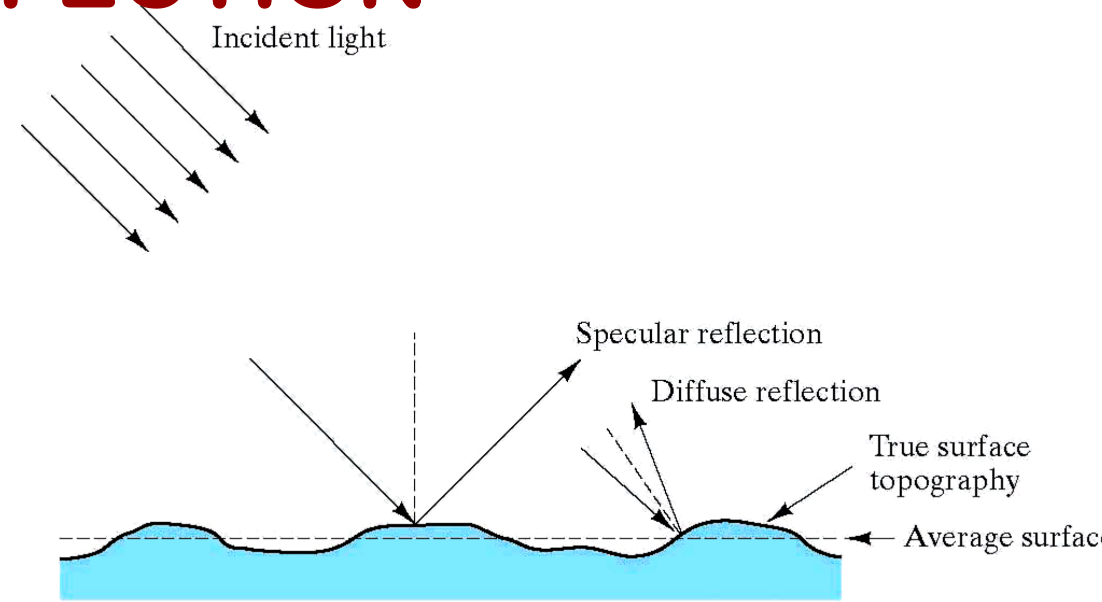
Table 10.2. Optical constants for some materials ($\lambda = 600$ nm)

	n	k	R %[b]
Metals			
Copper	0.14	3.35	95.6
Silver	0.05	4.09	98.9
Gold	0.21	3.24	92.9
Aluminum	0.97	6.0	90.3
Ceramics			
Silica glass (Vycor)	1.46	[a]	3.50
Soda-lime glass	1.51	[a]	4.13
Dense flint glass	1.75	[a]	7.44
Quartz	1.55	[a]	4.65
Al_2O_3	1.76	[a]	7.58
Polymers			
Polyethylene	1.51	[a]	4.13
Polystyrene	1.60	[a]	5.32
Polytetrafluoroethylene	1.35	[a]	2.22
Semiconductors			
Silicon	3.94	0.025	35.42
GaAs	3.91	0.228	35.26

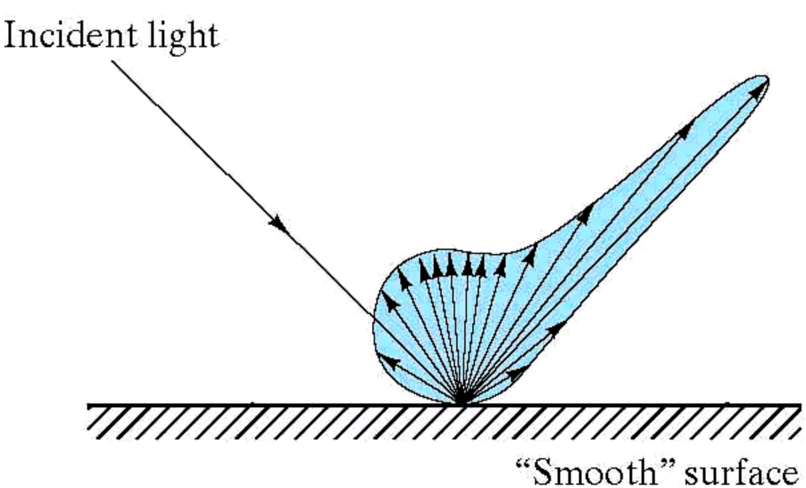
[a] The damping constant for dielectrics is about 10^{-7}; see Table 10.1.
[b] The reflection is considered to have occurred on one reflecting surface only.

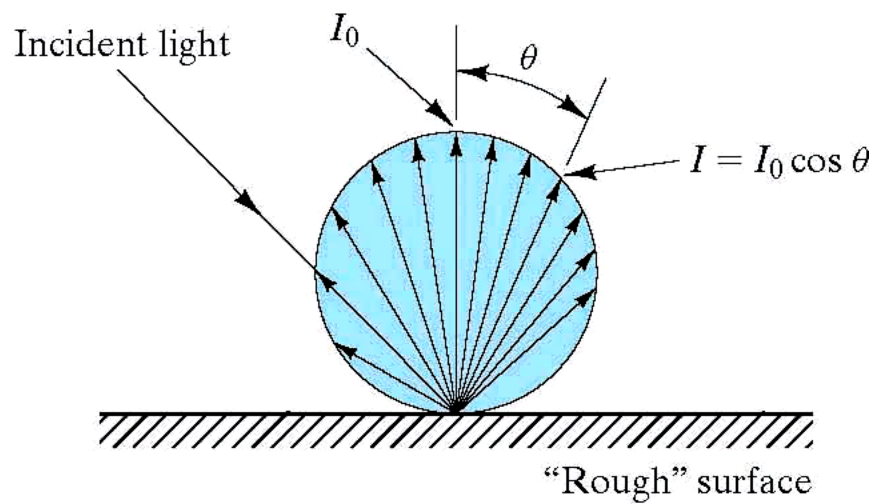
REFECTION

- reflection
  specular
  diffuse

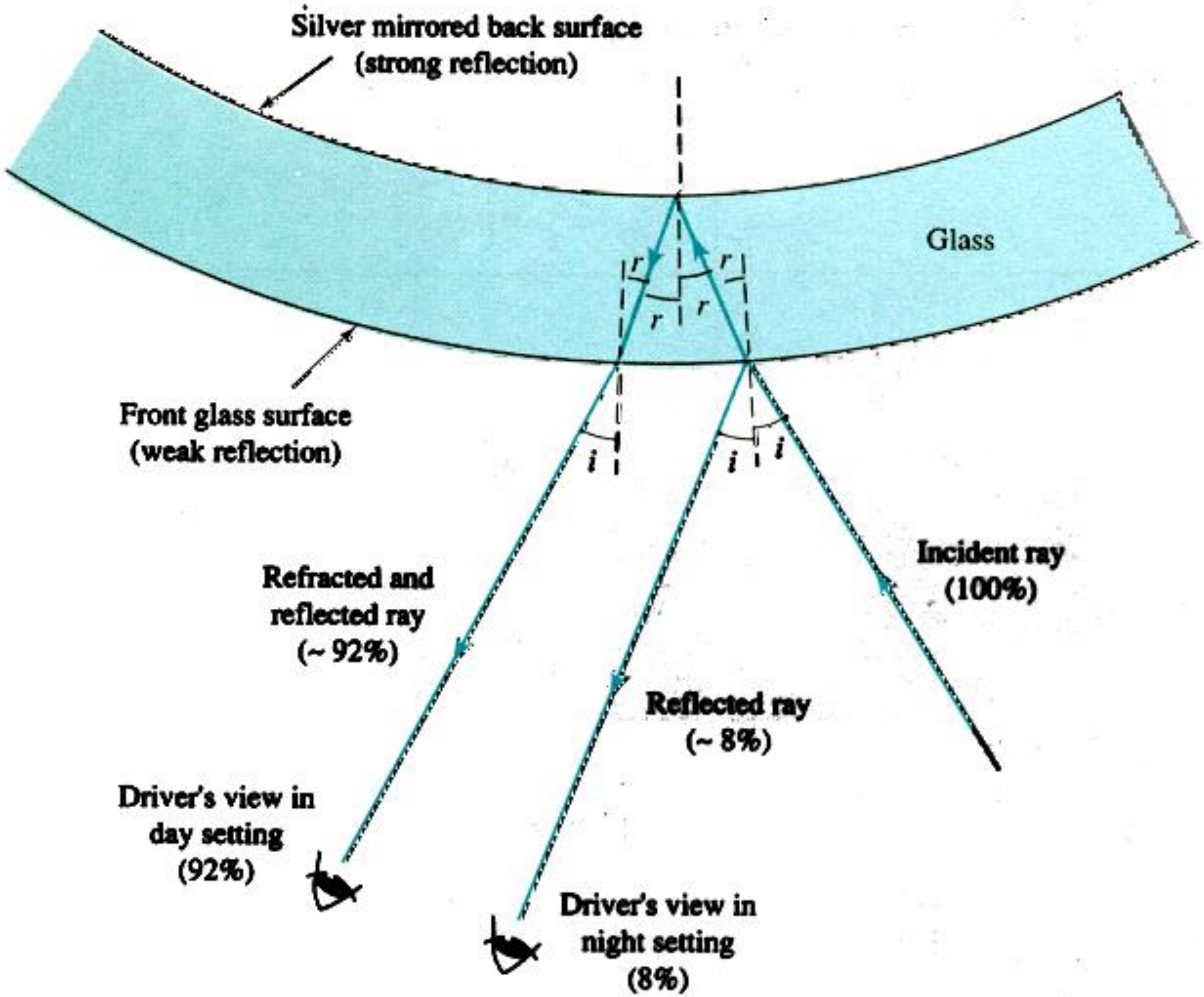


polar diagram





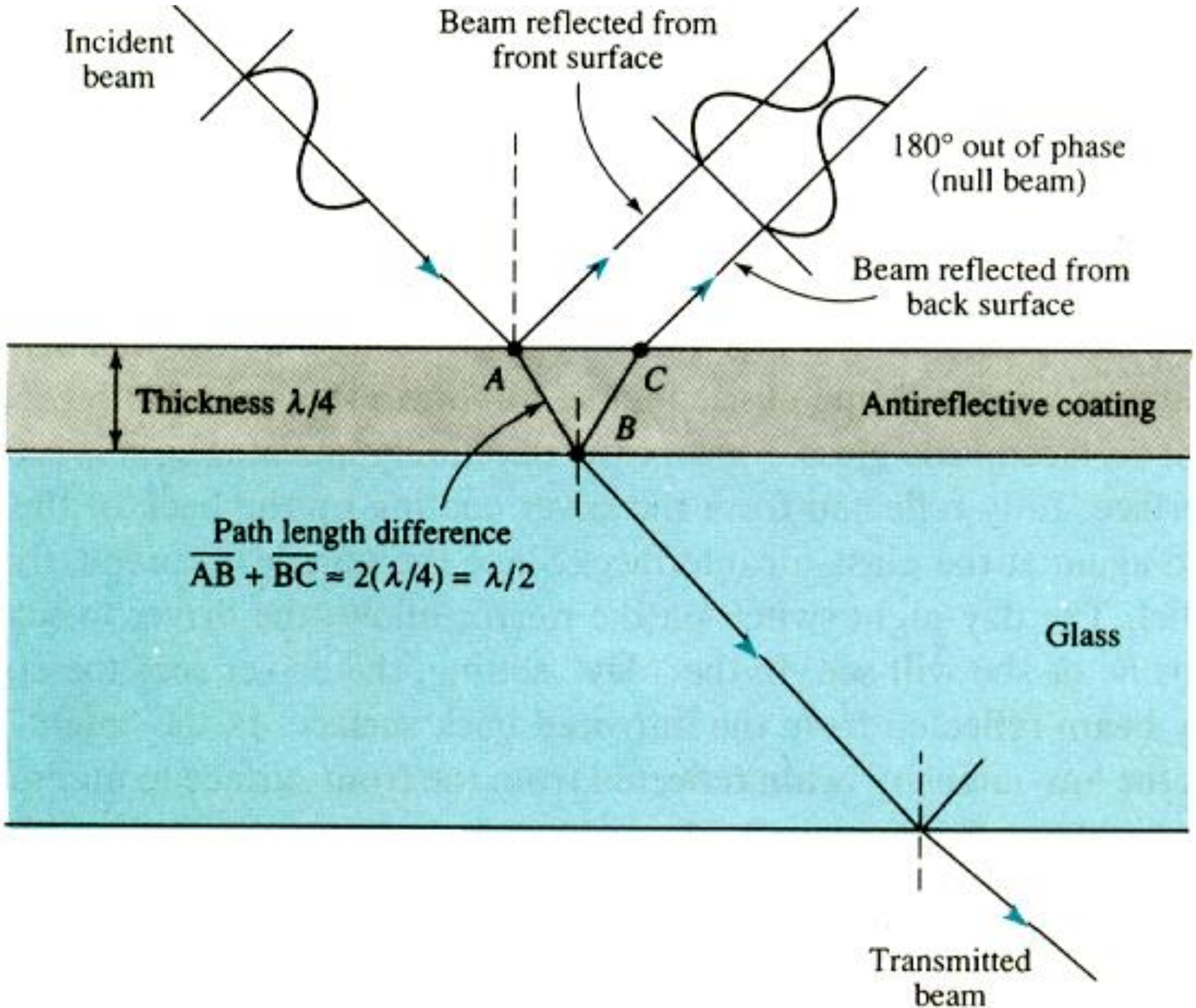
REFECTION



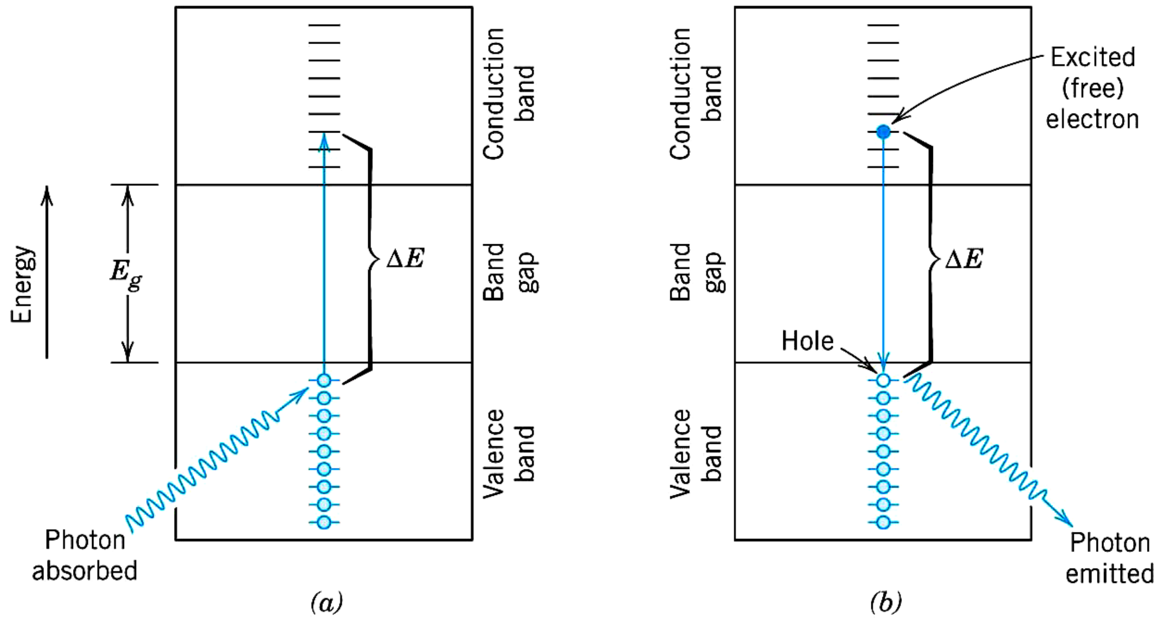
Silver mirrored back surface
(strong reflection)
Glass
r
r
r
r
Front glass surface
(weak reflection)
i
i
i
Refracted and
reflected ray
(~ 92%)
Incident ray
(100%)
Reflected ray
(~ 8%)
Driver's view in
day setting
(92%)
Driver's view in
night setting
(8%)

REFECTION

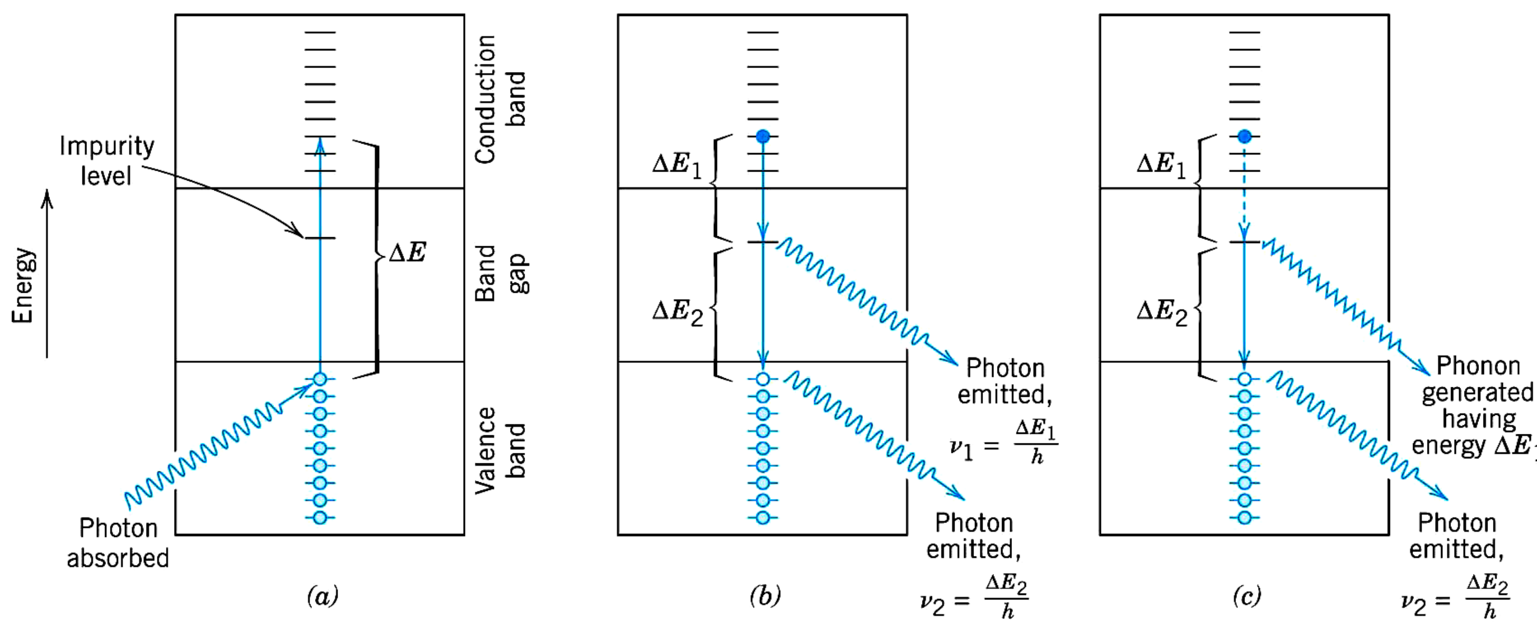
- antireflective coating-microscope, telescope



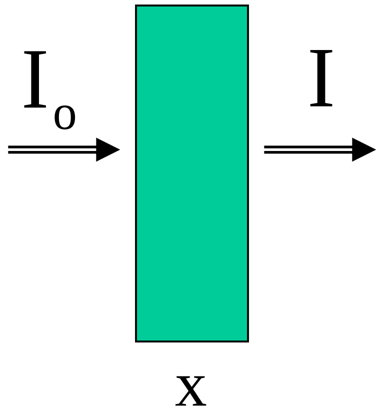
ABSORPTION



band gap E_g vs. $h\nu$

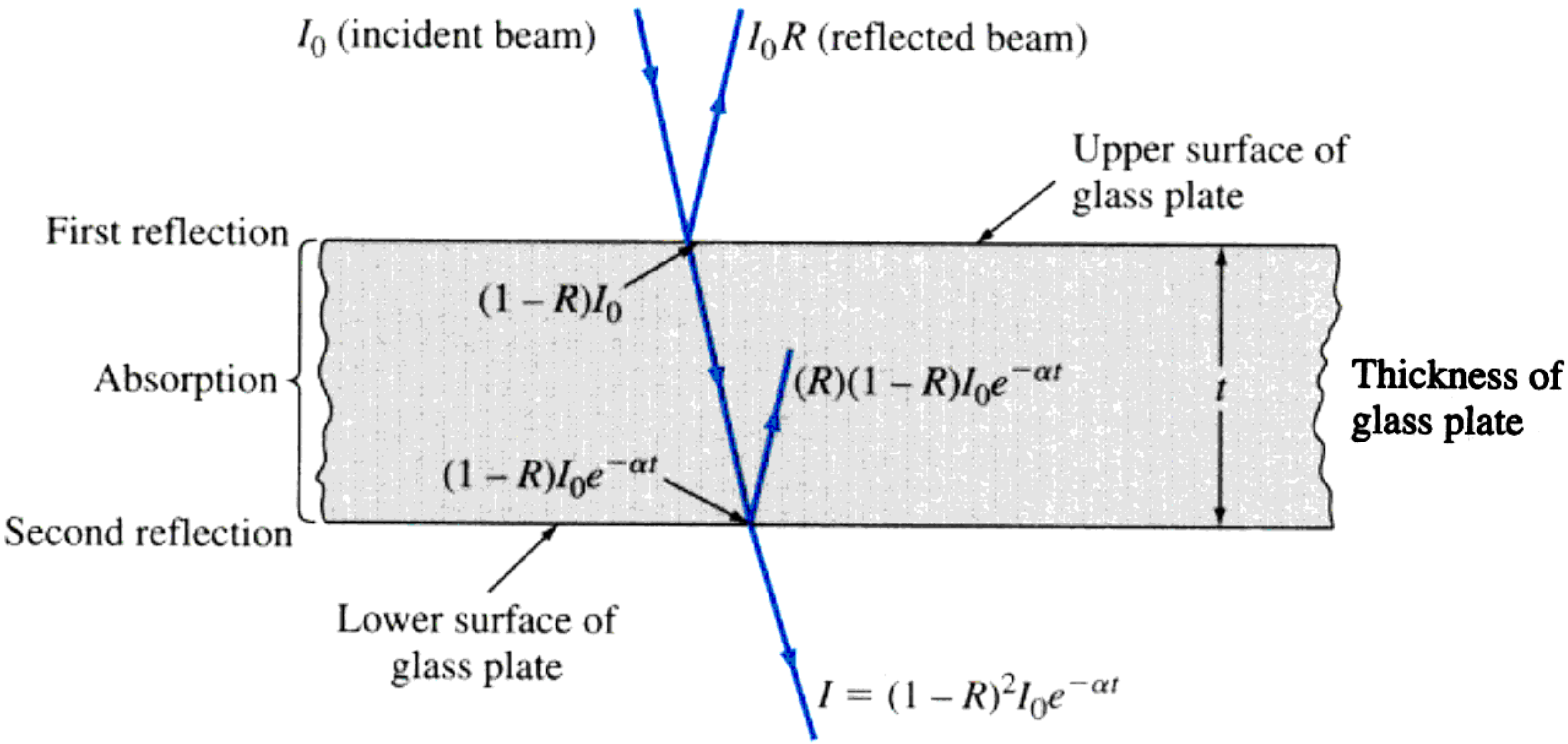


ABSORPTION

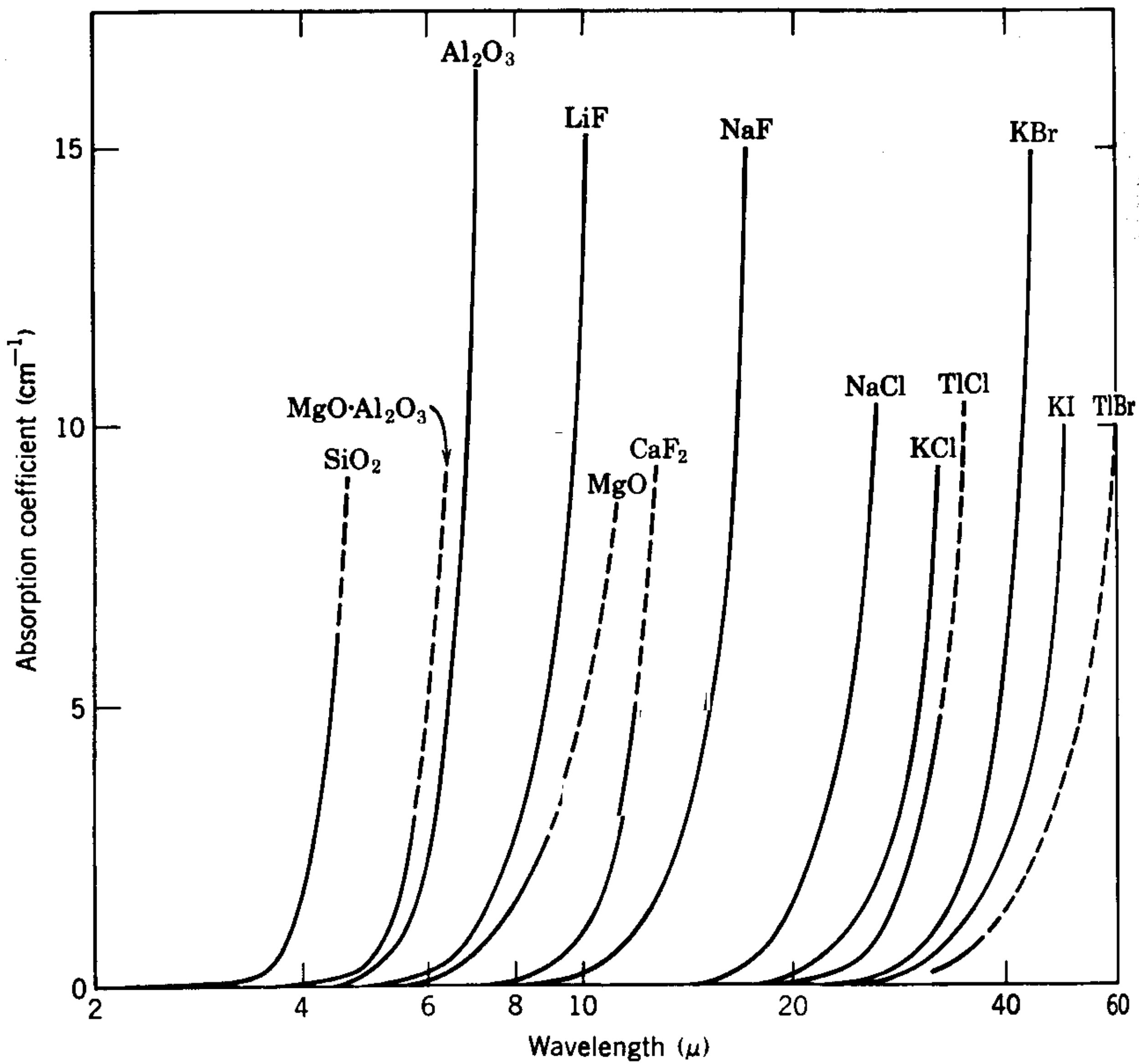


$$\frac{dI}{I_o} = -\beta dx \qquad I = I_o \exp(-\beta x)$$

β: absorption coefficient ($= \frac{4\pi k}{\lambda}$)

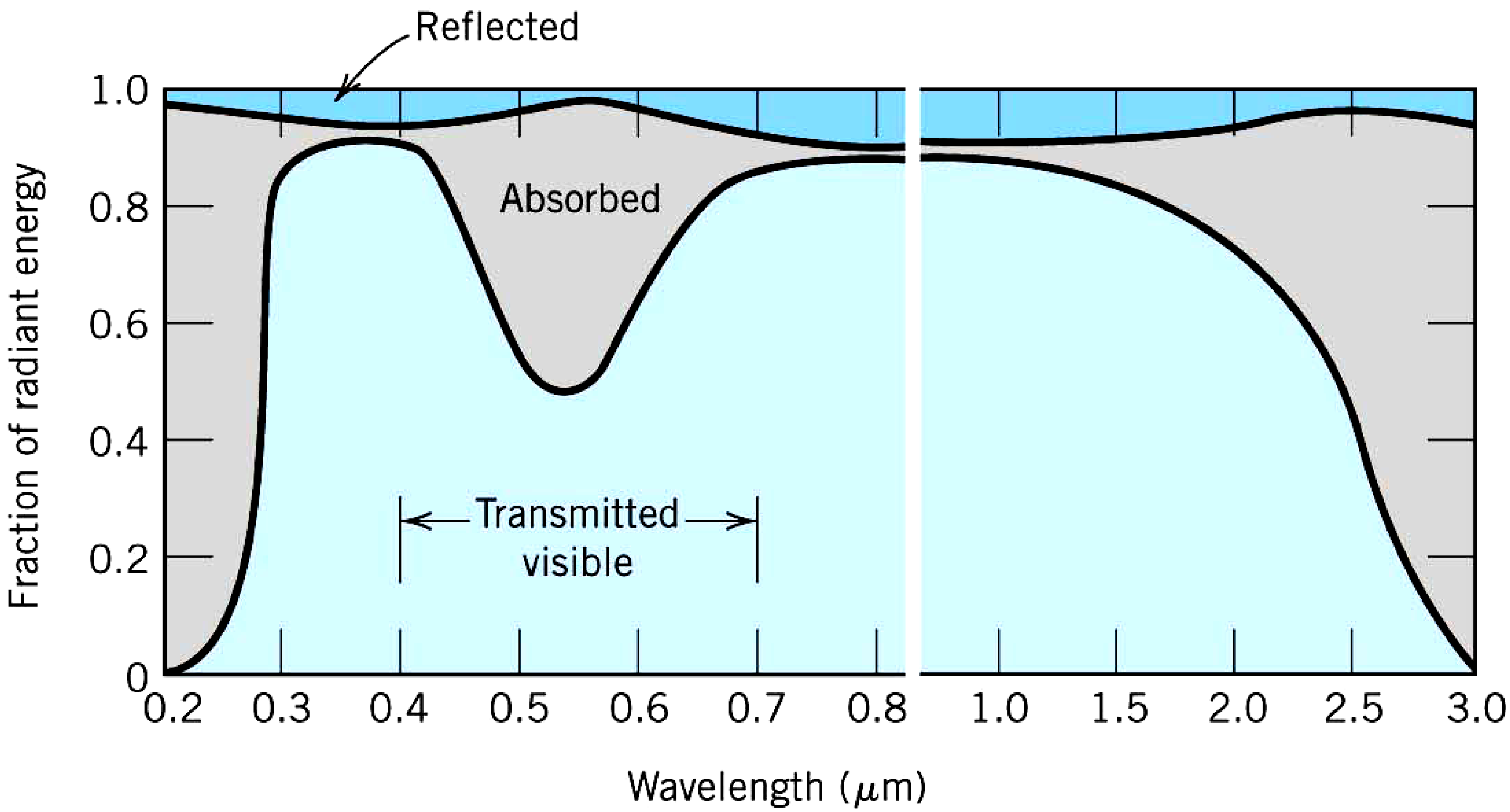


ABSORPTION



$$w^2 = 2\alpha\left[\frac{1}{M_1} + \frac{1}{M_2}\right]$$

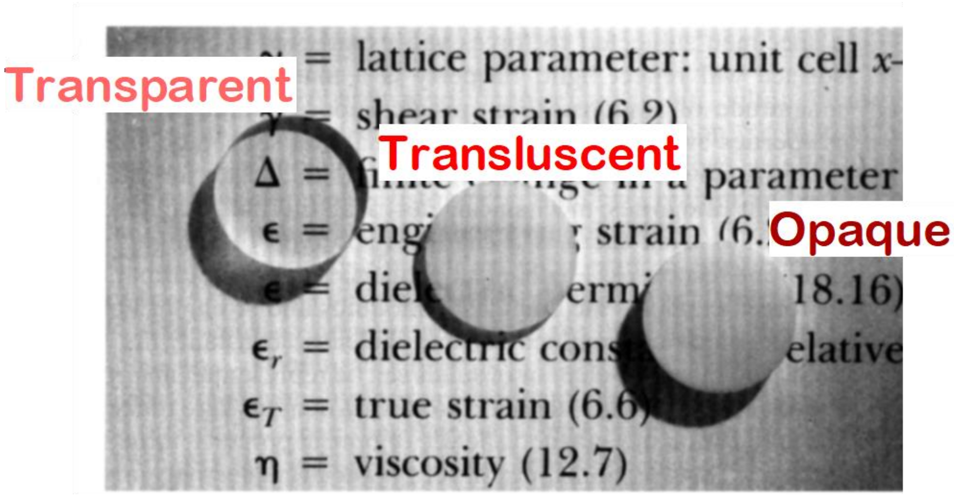
ABSORPTION

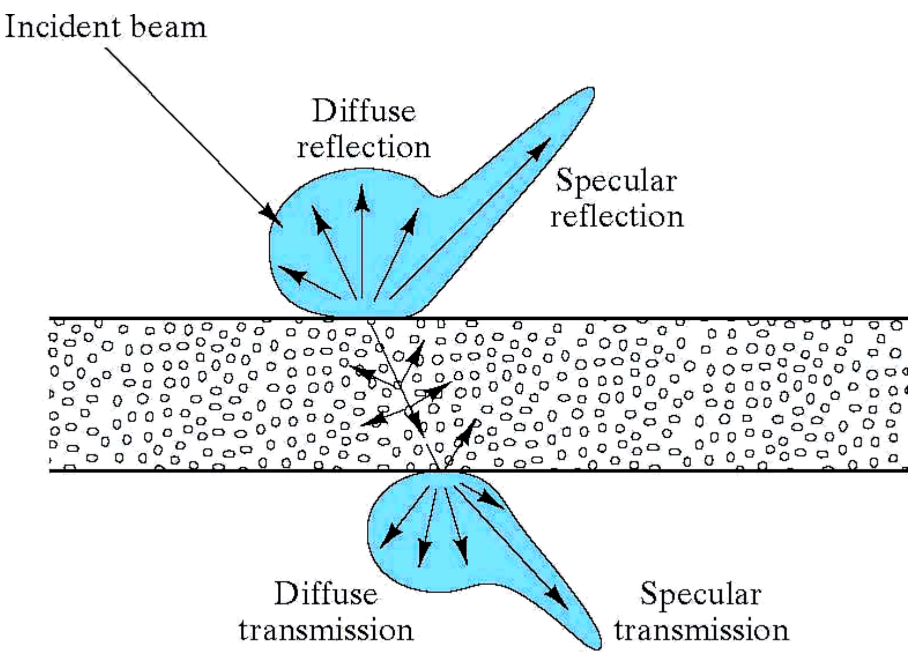


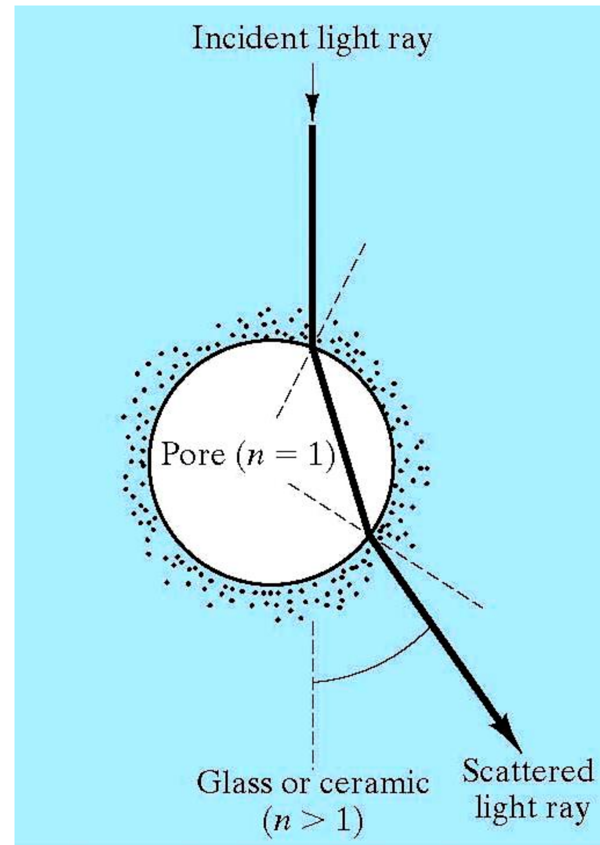
blue silicate glasses
impurities, additives→ chromophore

Optical Properties of Nonmetals

- transparency, translucency, opacity



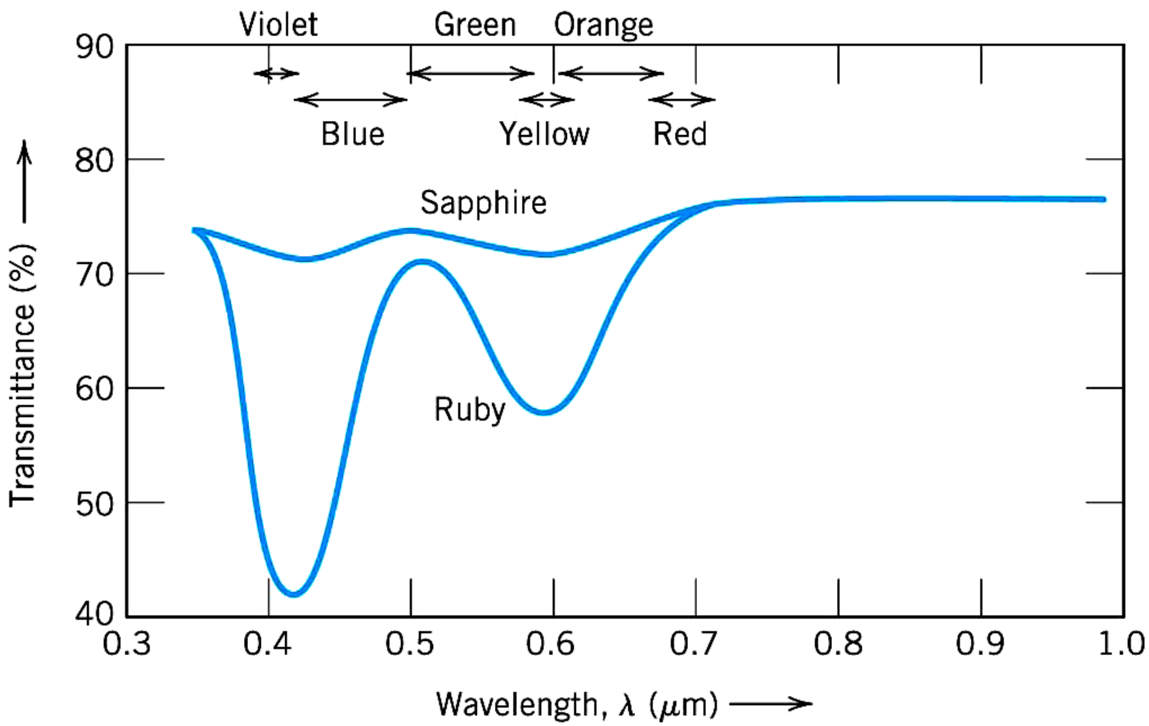




COLOR

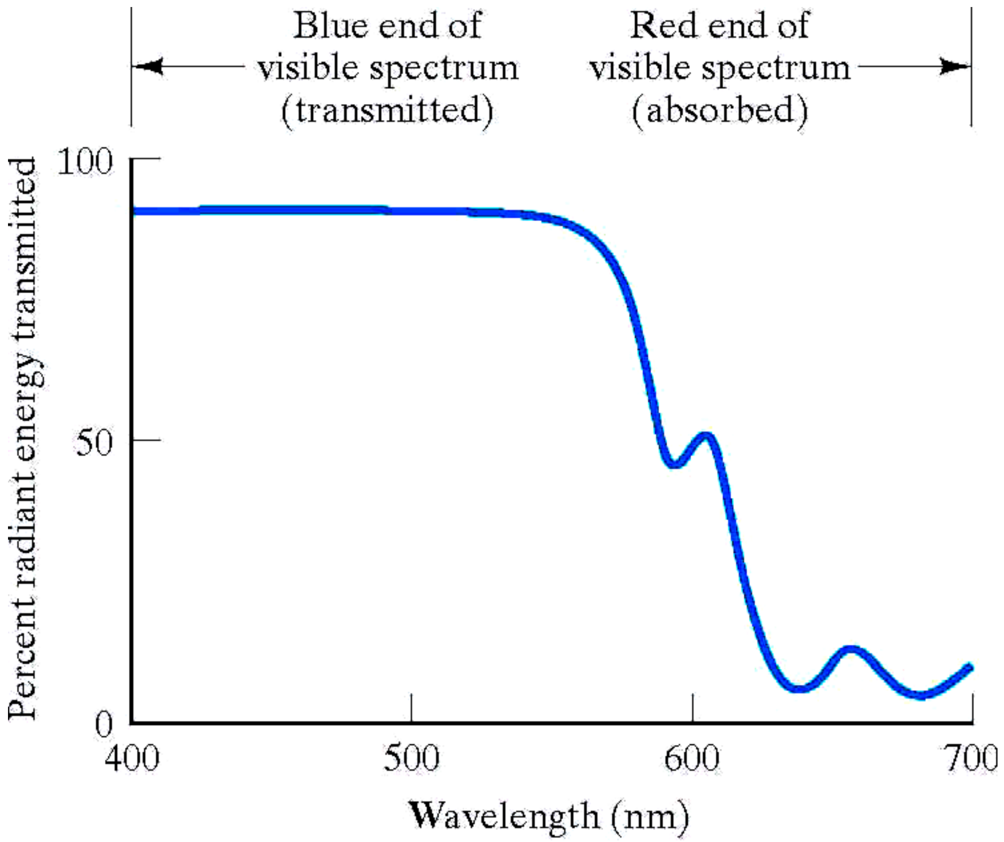
- Ruby: 0.5 to 2 wt% Cr_2O_3-doped Al_2O_3

impurity levels within the wide energy gap



strong absorption blue-violet yellow-green → deep red color

COLOR



1% cobalt oxide (Co^{2+})containing silicate glass

Blue color ← absorption of red end

COLOR

Various metal ions in silicate glasses

	In glass network		In modifier position	
Ion	Coordination number	Color	Coordination number	Color
Cr^{2+}				Blue
Cr^{3+}			6	Green
Cr^{6+}	4	Yellow		
Cu^{2+}	4		6	Blue-green
Cu^{+}			8	Colorless
Co^{2+}	4	Blue-purple	6–8	Pink
Ni^{2+}		Purple	6–8	Yellow-green
Mn^{2+}		Colorless	8	Weak orange
Mn^{3+}		Purple	6	
Fe^{2+}			6–8	Blue-green
Fe^{3+}		Deep brown	6	Weak yellow
U^{6+}		Orange	6–10	Weak yellow
V^{3+}			6	Green
V^{4+}			6	Blue
V^{5+}	4	Colorless		

APPLICATION: LUMINESCENCE

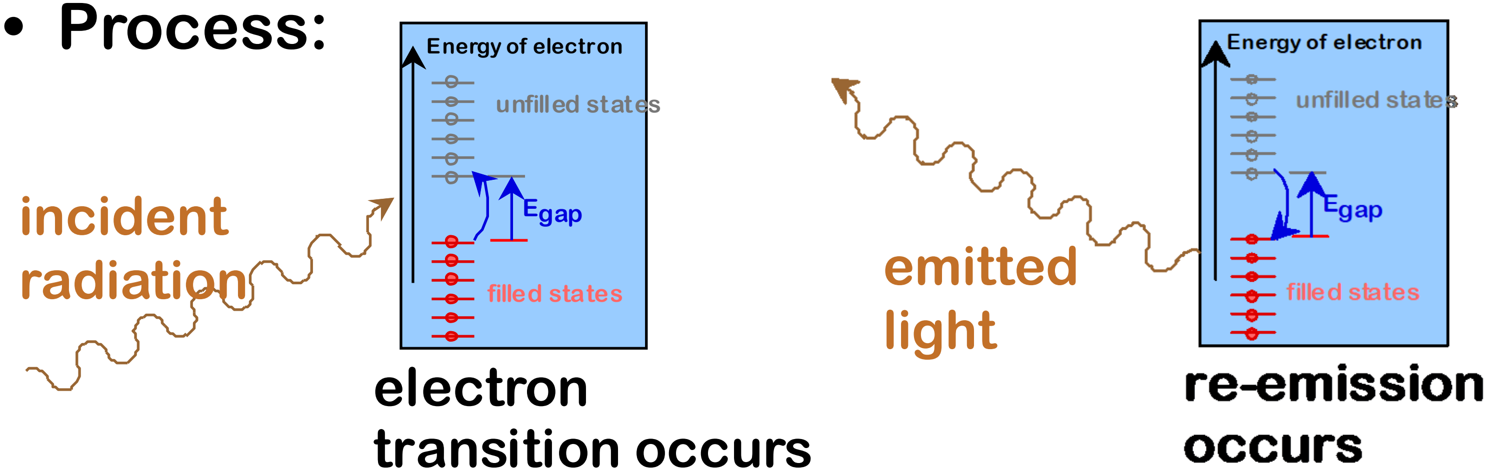
Luminescence- light emission in the visible spectrum accompanying the absorption of other forms of energy (thermal, mechanical, chemical or particles (high energy electrons) (photoluminescence, electroluminescence)

Fluorescence- emission of electromagnetic radiation that occurs within ~10^{-8} s of an excitation event

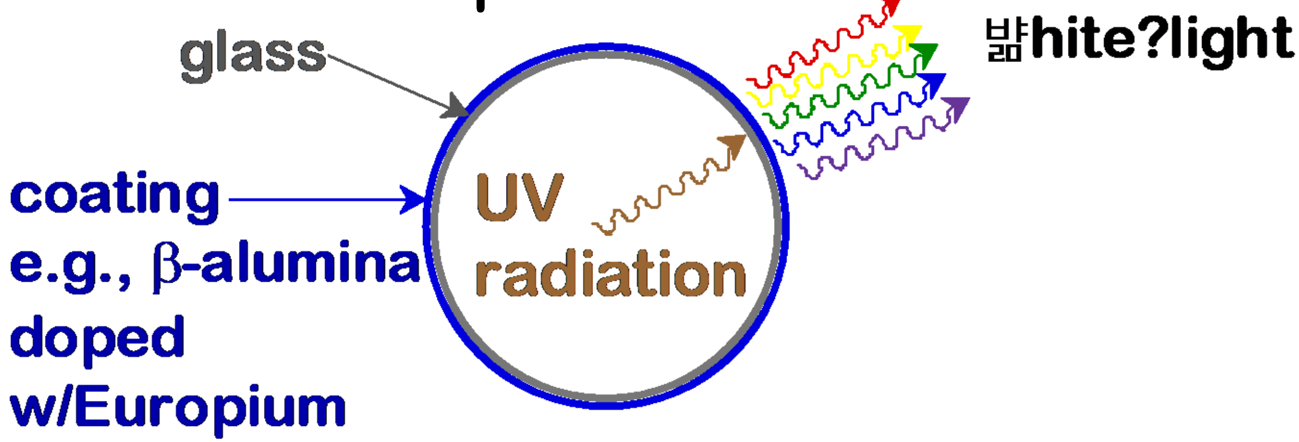
Phosphorescence- emission of electromagnetic radiation over an extended period of time after the excitation event is over

APPLICATION: LUMINESCENCE

- Process:

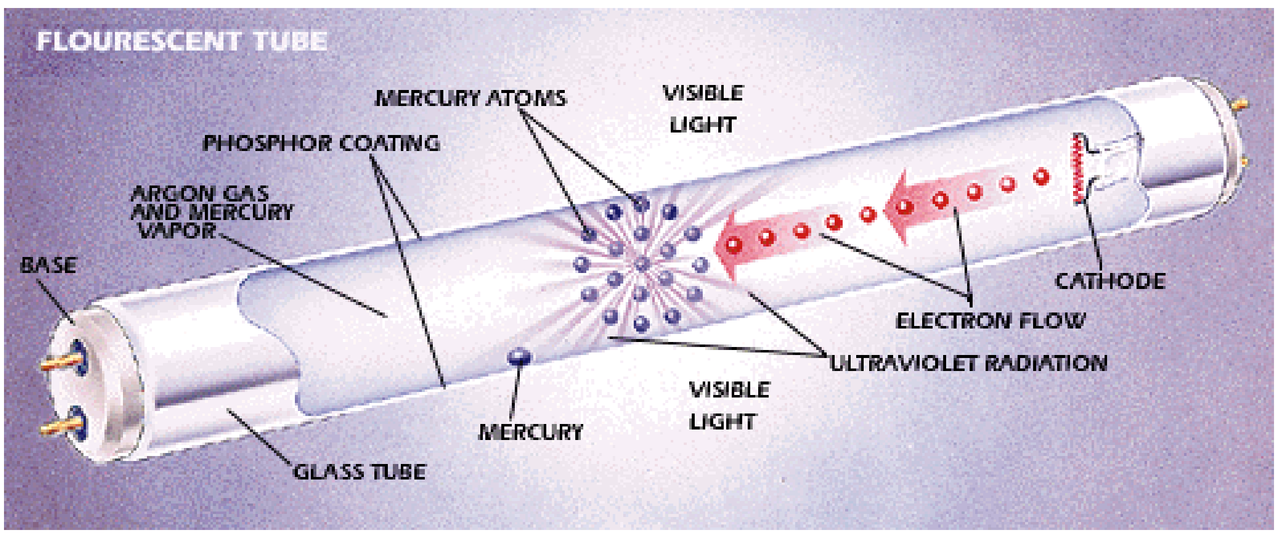


- Ex: fluorescent lamps



APPLICATION: LUMINESCENCE

A **fluorescent lamp** is a type of lamp that uses electricity to excite mercury vapor in argon or neon gas, resulting in a plasma that produces short-wave ultraviolet light. This light then causes a phosphor to fluoresce, producing visible light.



two rare-earth-doped phosphors, Tb^{3+}, Ce^{3+}:$LaPO_4$ for green and blue emission and Eu:Y_2O_3 for red.

APPLICATION: X-RAY FLUORESCENCE

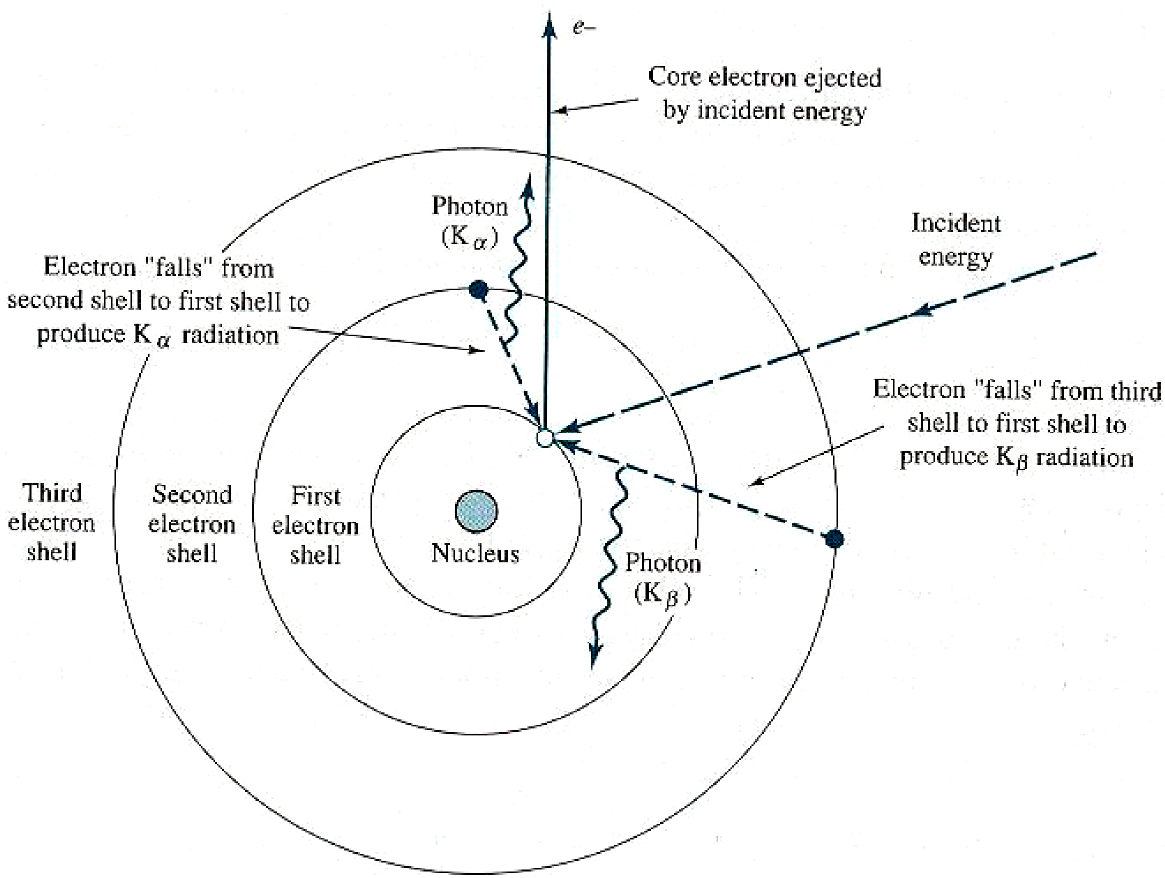


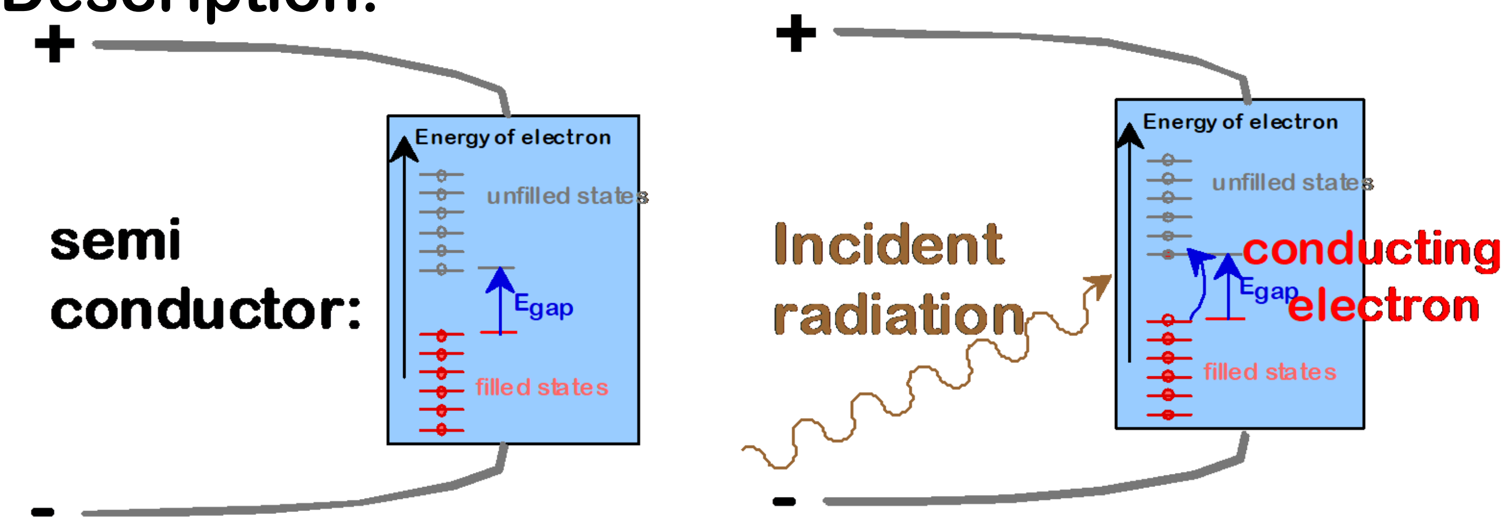
TABLE 11.7–1 Characteristic emission lines.

Element	Wavelength of emission (nm) K_α	K_β
C	4.47	—
N	3.16	—
O	2.36	—
F	1.83	—
Na	1.19	—
Mg	0.99	–
Al	0.834	0.796
Si	0.713	0.675
Cr	0.229	0.209
Fe	0.194	0.176
Co	0.179	0.162
Ni	0.166	0.150
Cu	0.154	0.139

Source: Courtesy of American Physical Society.

APPLICATION: PHOTOCONDUCTIVITY

- Description:



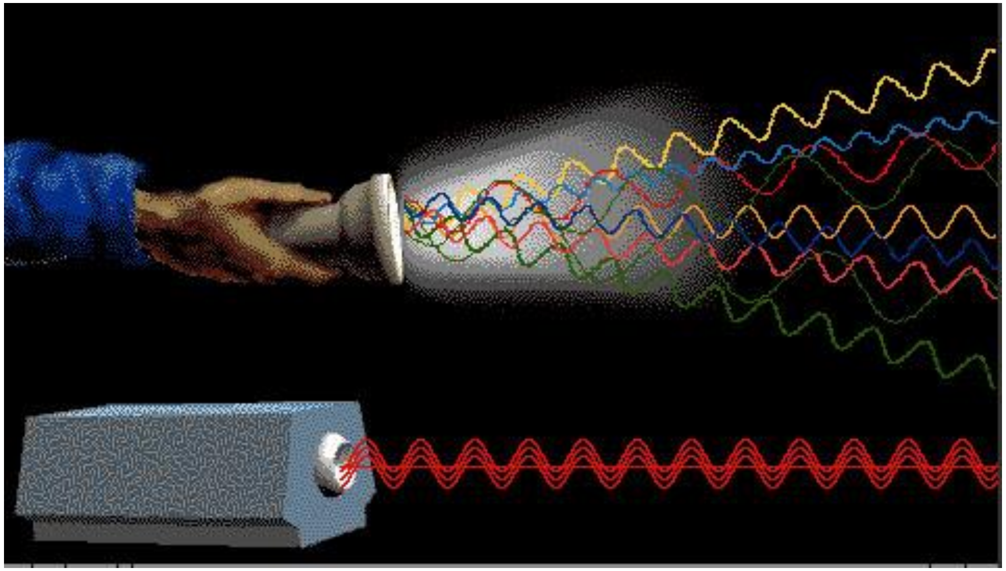
A. No incident radiation:
little current flow

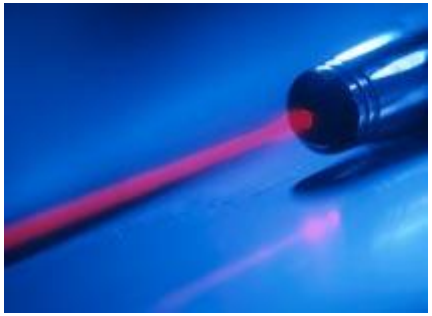
B. Incident radiation:
increased current flow

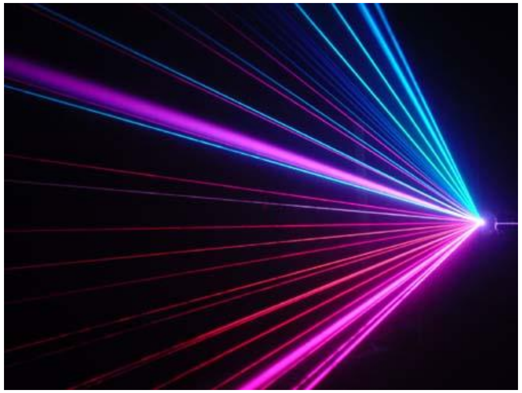
- Ex: Photodetector (Cadmium sulfide)

LASER

- light amplification by stimulated emission of radiation
  - coherent beam, - monochromatic
  - collimation, - pumping and population inversion







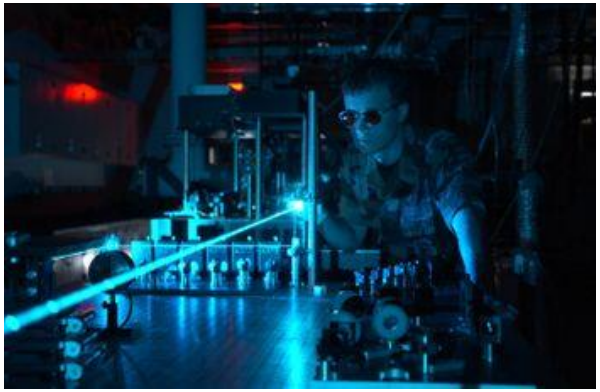
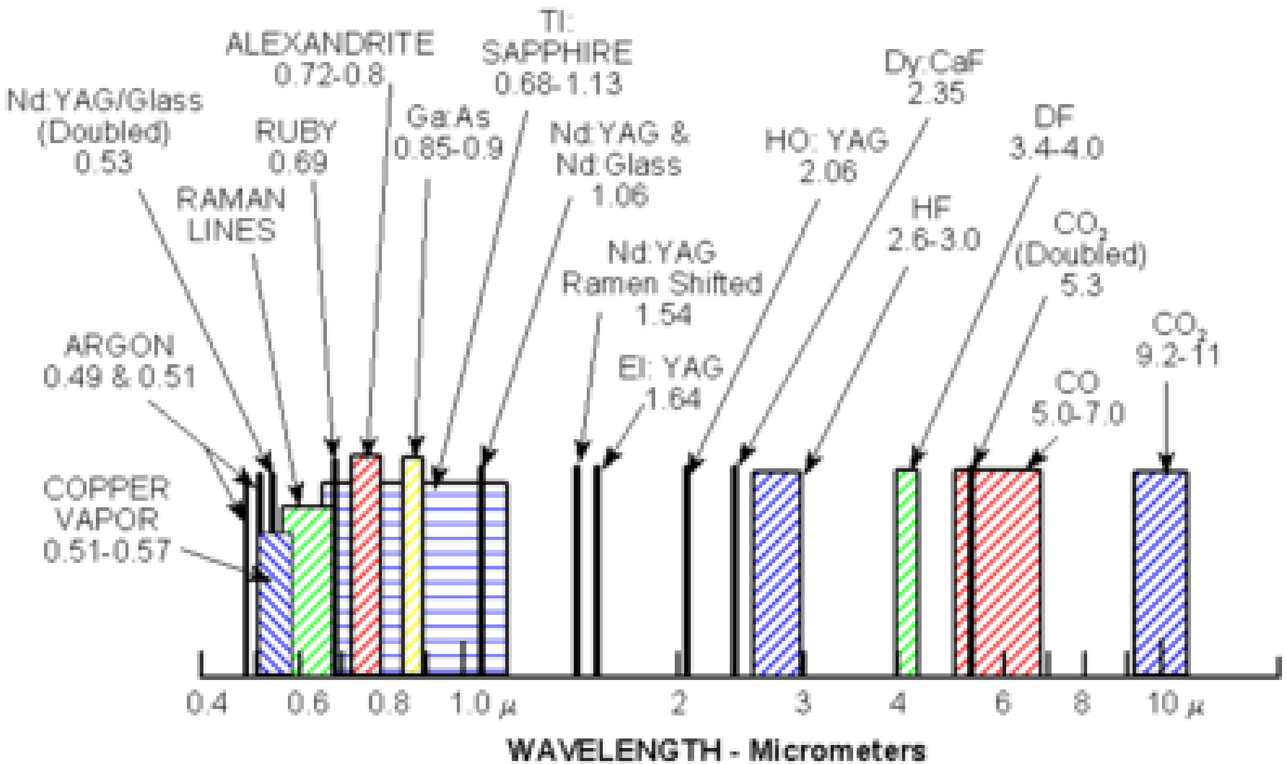


Table 13.1. Properties of Some Common Laser Materials.

Type of laser	Wave-length(s) (nm)	Beam diver-gence (mrad)	Peak power output (W)	Comments
Ruby (Cr^{3+}-doped Al_2O_3)	694.3	10 5 0.5	CW:[a] ~5 pulsed (1–3 ms): 10^6–10^8 *Q*-switched (10 ns): 10^9	Optically pumped three-level laser. Lasing occurs between Cr^{3+} levels. Low efficiency (0.1%). Historic device (1960).
Neodymium (Nd^{3+}-doped glass or YAG[b])	1,064	3–8	CW: 10^3 pulsed (0.1–1 μs): ~10^4	Optically pumped four-level laser. High efficiency 2%.
HeNe	632.8 (1150; 3390)	1	10^{-3}–10^{-2}	See Fig. 13.36 and text. Most widely used.
HeCd (gas/metal vapor)	441.6 325 353.6		150 mW CW 100 mW 20 mW	Similarly pumped as HeNe laser. Used for high-speed laser printers, and writing data on photoresists for CD-ROMs. Efficiency: up to 0.02%.
Argon ion	488		~25 CW	0.1% Efficiency
CO_2	10,600; 9,600	2	CW: 10–1.5×10^4 pulsed (10^2–10^3 ns): 10^5	High efficiency (20%). Lasing occurs between vibrational levels (Fig. 13.37).
Semiconductor GaAs GaAlAs[c]	 ~870 ~850	 250 500	Homojunction, pulsed: (10^2 ns) 10–30 Heterojunction, CW: 1–4 × 10^{-1}	Small size, direct conversion of electrical energy into optical energy. 10–55% efficiency. See Figs. 13.38 and 13.43.
Dye (organic dyes in solvents)	350–1000	3 10	CW: ~10^{-1} pulsed (6 ns) ~10^5	Lasing occurs between vibrational sublevels of molecules. Tunable by Littrow prism (Fig. 13.36(a)).

[a] CW: Continuous wave.
[b] Yttrium aluminum garnet ($Y_3Al_2O_{15}$).
[c] See Fig. 13.40.

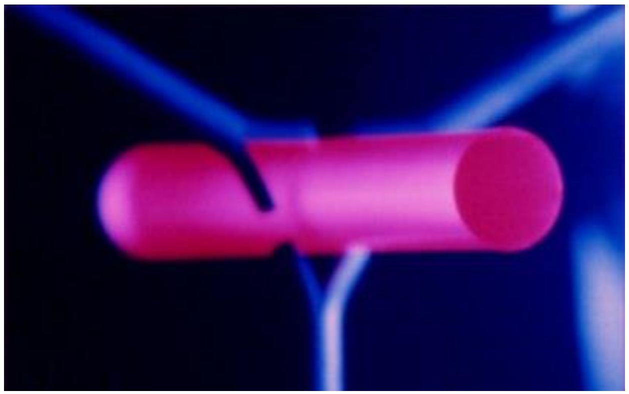
LASER

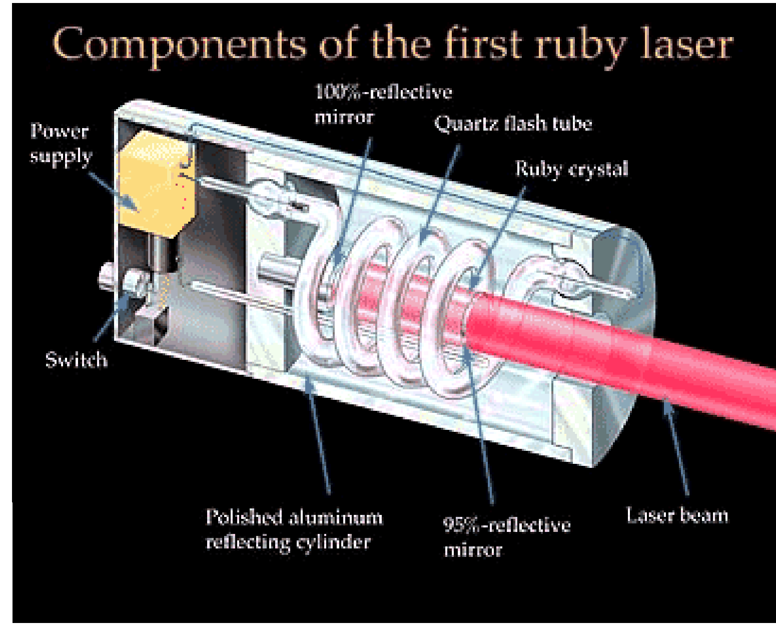


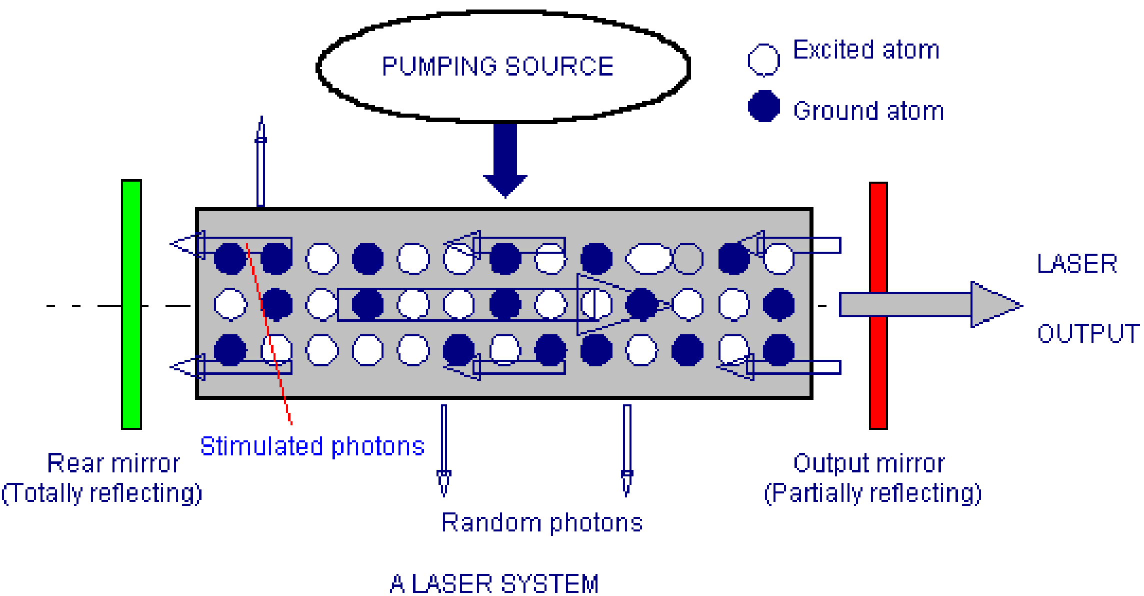
Spectral output of several types of lasers

Solid State Luby Laser

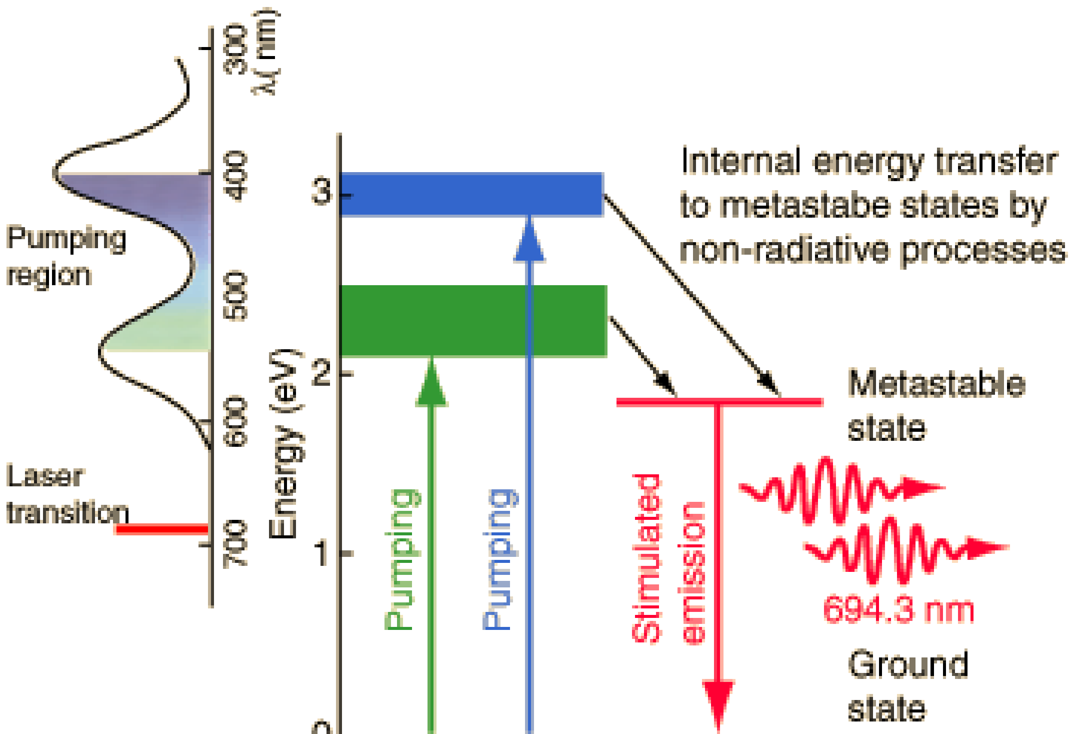
- Al_2O_3 single crystal (sapphire) with 0.05 wt% Cr

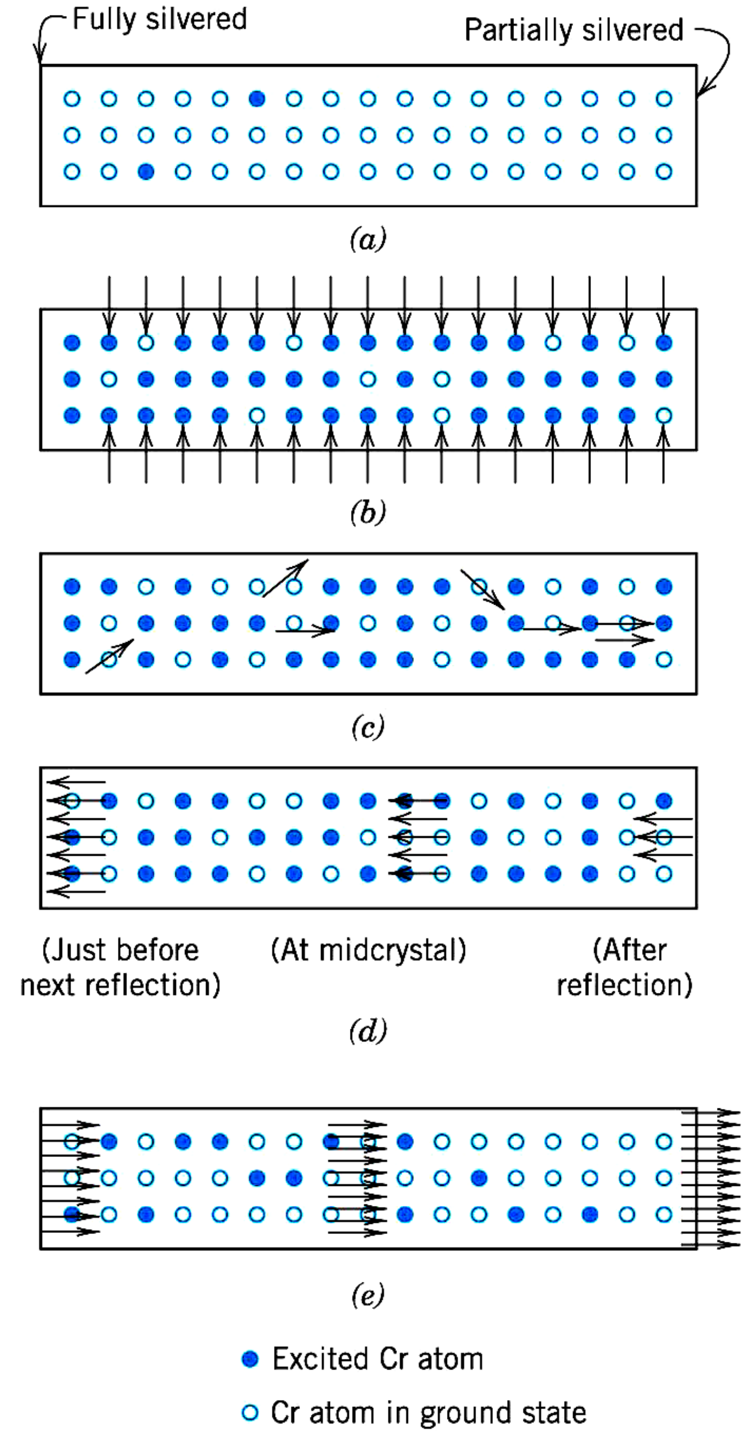




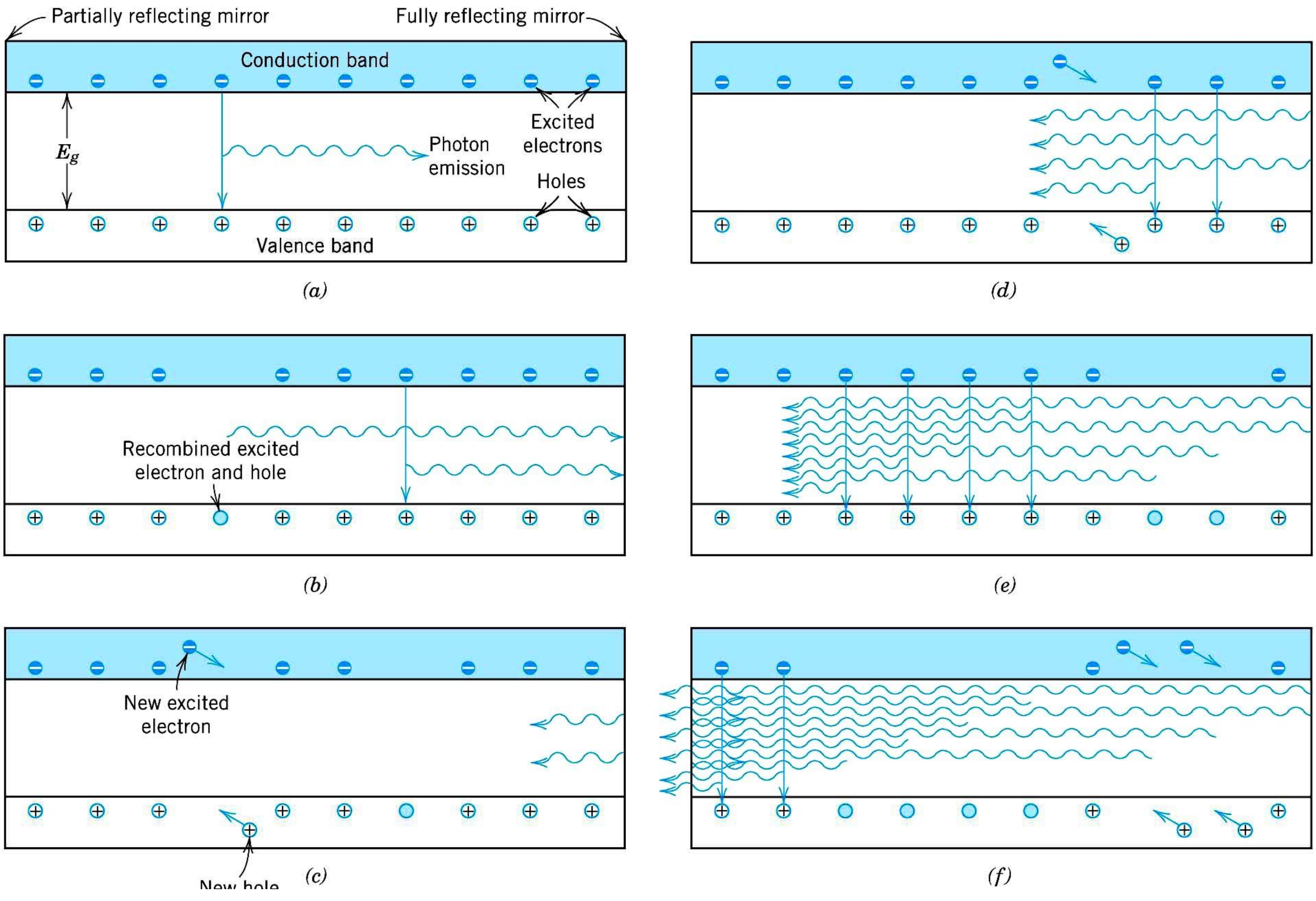


Solid State Luby Laser





Semiconductor Laser



Semiconductor Laser

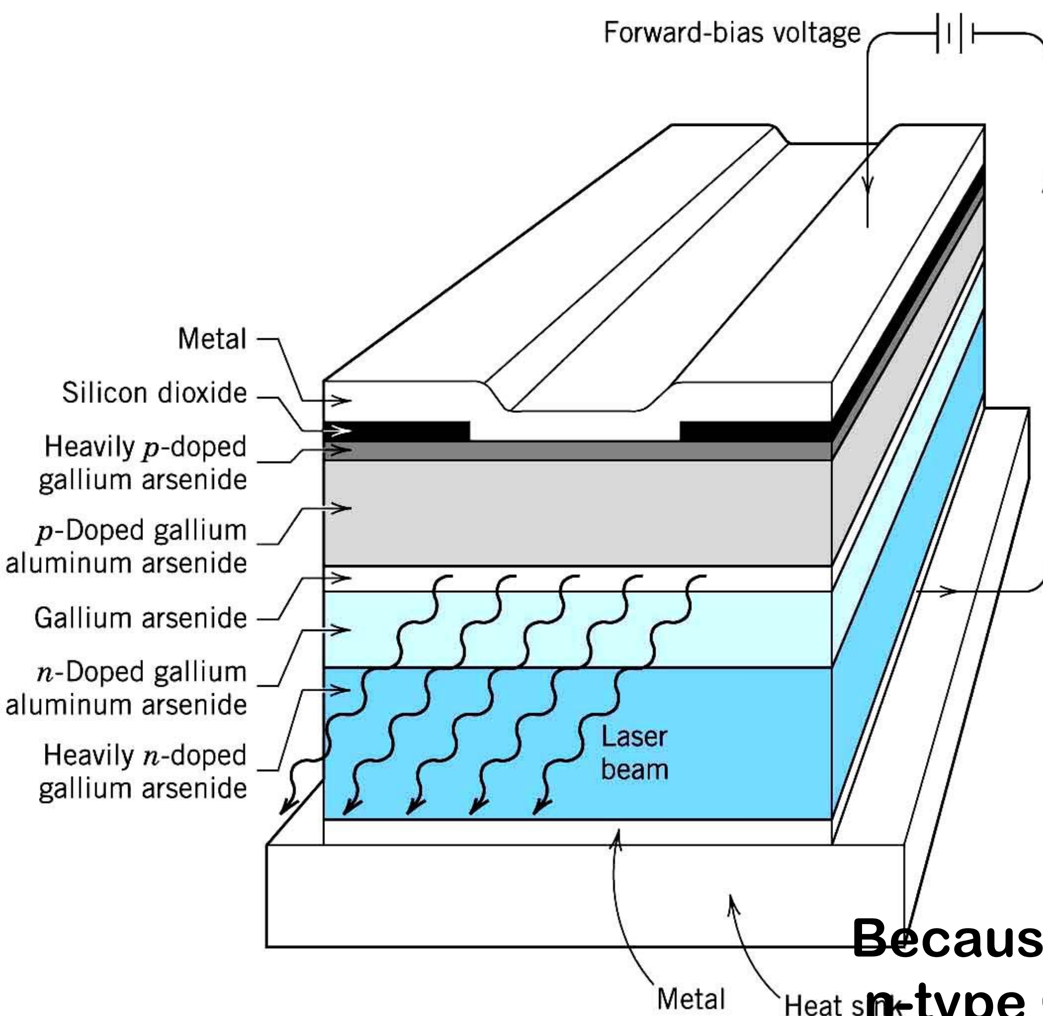


FIGURE 21.15 Schematic diagram showing the layered cross section of a GaAs semiconducting laser. Holes, excited electrons, and the laser beam are confined to the GaAs layer by the adjacent *n*- and *p*-type GaAlAs layers. (Adapted from "Photonic Materials," by J. M. Rowell. Copyright © 1986 by Scientific American, Inc. All rights reserved.)

Because the surrounding p- and n-type GaAlAs layers have a higher energy and a lower index of refraction than GaAs, the photons are trapped in the active GaAs layer