MATERIALS SCIENCE

SSP 2412

MAGNETIC & OPTICAL PROPERTIES

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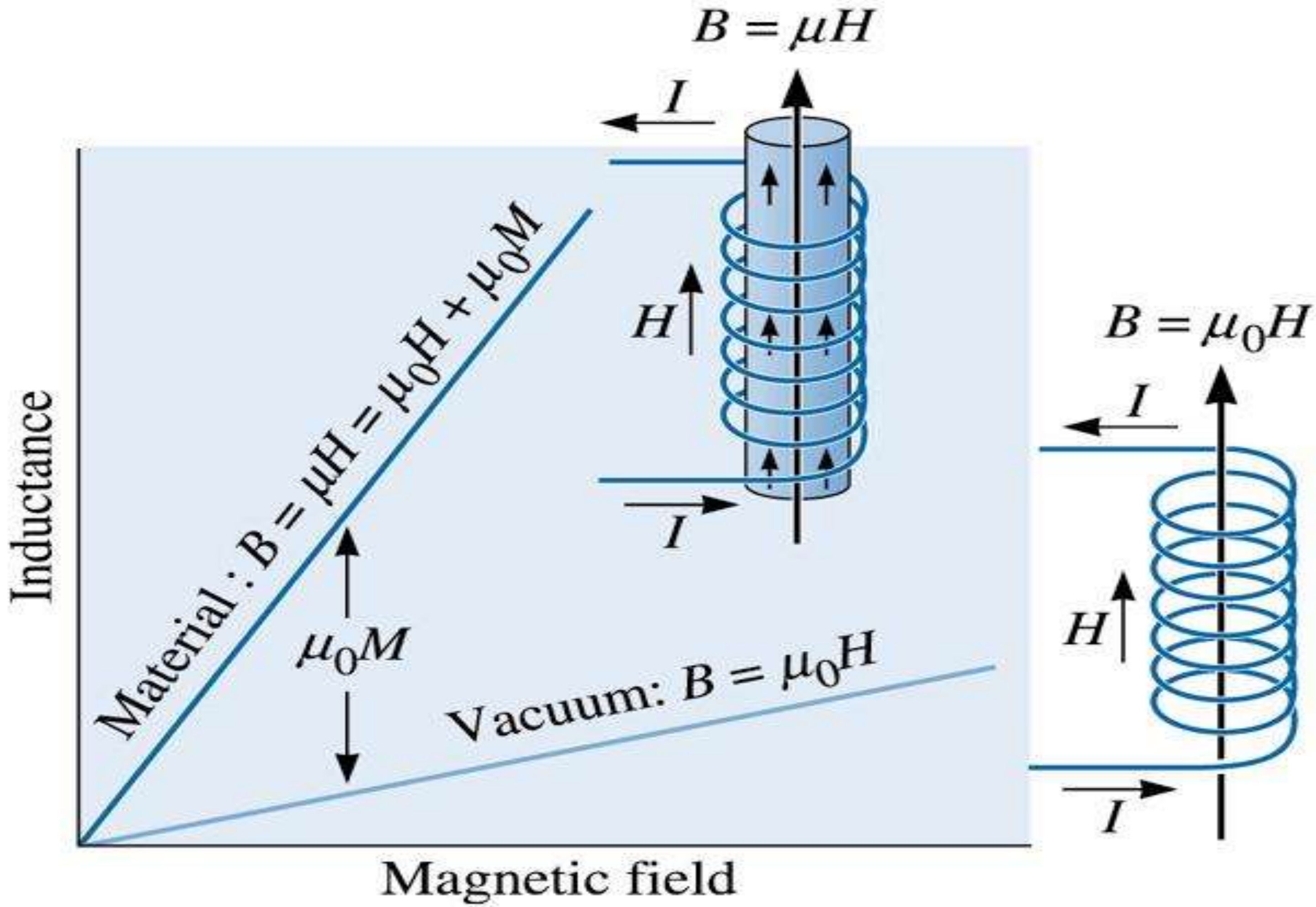
Main Topics

- Introduction to Magnetic Properties
- Magnetism on the Microscopic Scale.
- Diamagnetism.
- Paramagnetism.
- Ferromagnetism.
- Applications



A current passing through a coil sets up a magnetic field *H* with a flux density *B*. The flux density is higher when a magnetic core is placed within the coil.

EXAMPLE &SOLUTION

The magnetic field *H* produced by the coil.

$$H = \frac{nI}{l} = \frac{(10)(0.01\ \text{A})}{0.01\ \text{m}} = 10\ \text{A/m}$$

$$H = (10\ \text{A/m})(4\pi \times 10^{-3}\ \text{oersted/A/m}) = 0.126\ \text{oersted}$$

The permeability of the core material must be:

$$\mu = \frac{B}{H} = \frac{2000}{0.126} = 15{,}873\ \text{gauss/oersted}$$

The relative permeability of the core material must be at least:

$$\mu_r = \frac{\mu}{\mu_0} = \frac{15{,}873}{1} = 15{,}873$$

Macroscopic description of magnetism

in vacuum

magnetic induction → magnetic field

$$\mathbf{B} = \mu_0 \mathbf{H}$$

$$\mu_0 = 4\pi 10^{-7} \mathrm{Vs/Am} = 4\pi 10^{-7} \mathrm{T^2 m^3 J^{-1}}$$

in matter

magnetization

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) = \mathbf{B}_0 + \mu_0 \mathbf{M}$$

we interpret $\mathbf{B}_0$ as the “external field”

magnetic susceptibility

$$\mu_0 \mathbf{M} = \chi \mathbf{B}_0$$

magnetic dipole moment

$$\mathbf{M} = \frac{N}{V} \mu$$

potential energy of one dipole in the external field:

$$U = -\mu \mathbf{B}_0$$

Units

T $\quad$ $\mathrm{T^2 m^3 J^{-1}}$ $\quad$ T $\quad$ $\mathrm{T^{-1} m^{-3} J}$

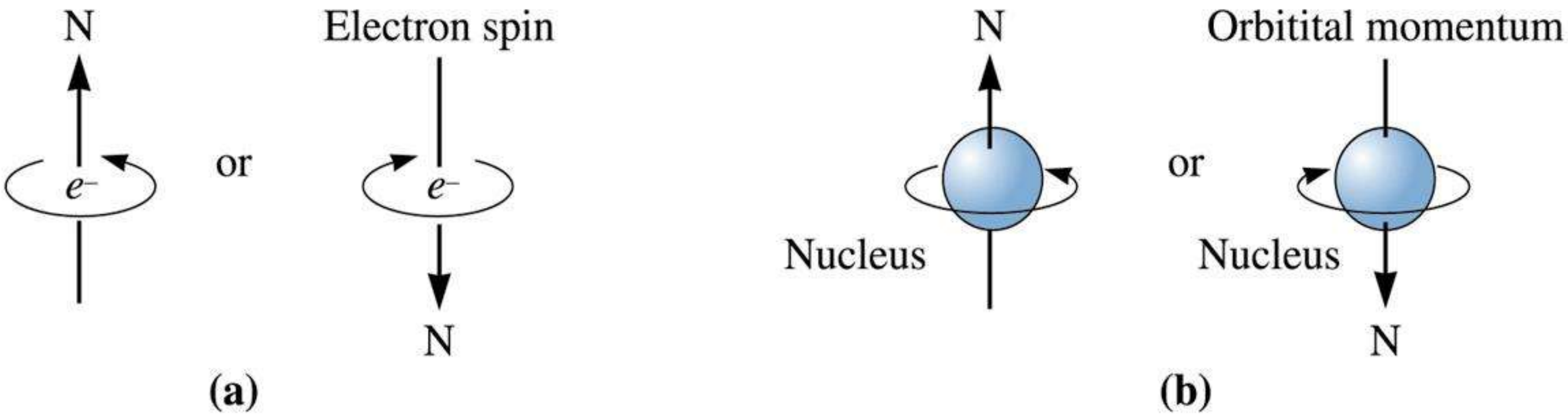
$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) = \mathbf{B}_0 + \mu_0\mathbf{M}$$

- Both, $\mathbf{B}$ and $\mathbf{B}_0$ are measured in Tesla (T)
- 1 T is a strong field. The magnetic field fo the earth is only in the order of 10^{-5} T.

Magnetism on Microscopic Scale

- Electrons can generate magnetism in three ways: i) As moving charges as current, ii) Due to their spin and iii) Due to their orbital rotation around a core.
- The later two mechanisms (spin, orbital) are responsible for magnetic behavior in matter.
- **Bohr magneton** (symbol μ_B) is a physical constant and the natural unit for expressing an electron magnetic dipole moment (Magnetic moment of an electron)

Spin & Obit



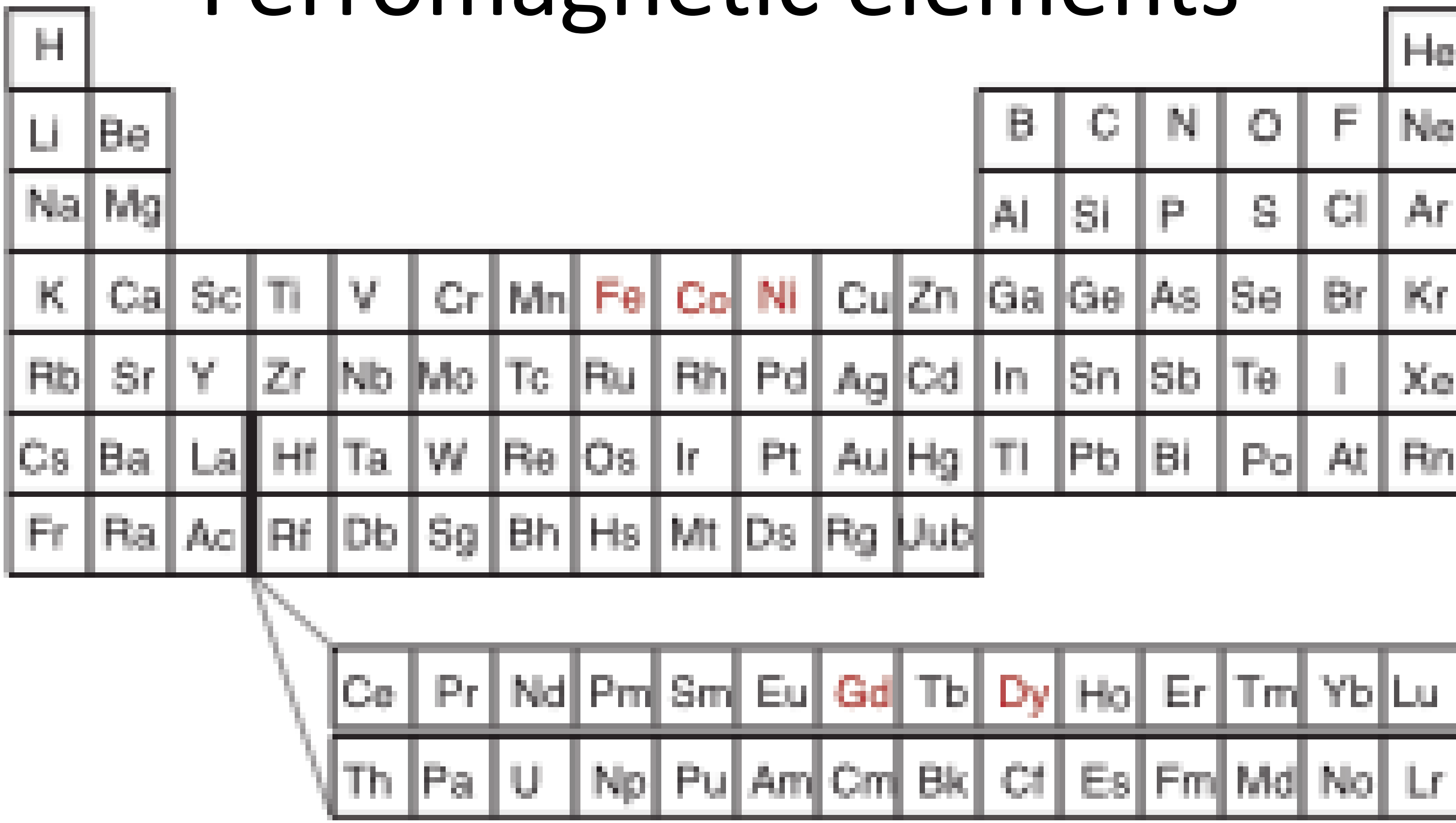
Origin of magnetic dipoles: (a) The spin of the electron produces a magnetic field with a direction dependent on the quantum number m_s. (b) Electrons Electrons orbiting around the nucleus create a magnetic field around the atom.

Spins in 3d Metals

TABLE 19-1 ■ ***The electron spins in the 3d energy level in transition metals, with arrows indicating the direction of spin***

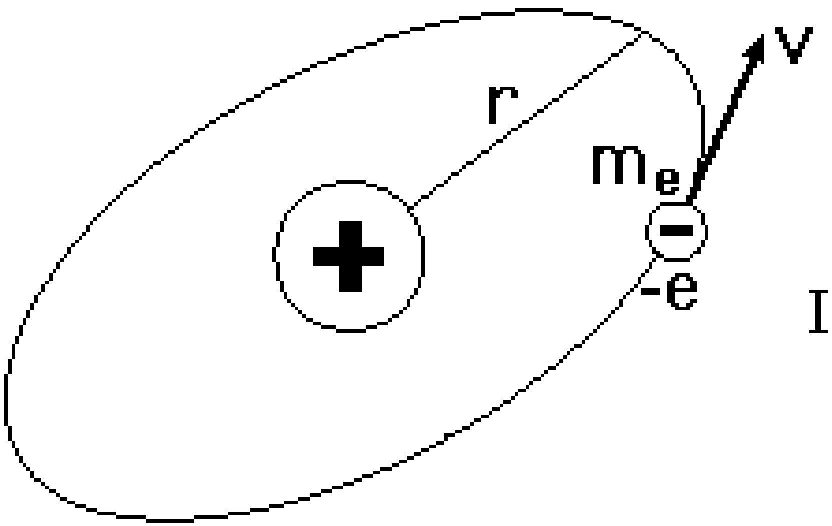
Metal	3*d*					4*s*
Sc	↑					↑↓
Ti	↑	↑				↑↓
V	↑	↑	↑			↑↓
Cr	↑	↑	↑	↑	↑	↑
Mn	↑	↑	↑	↑	↑	↑↓
Fe	↑↓	↑	↑	↑	↑	↑↓
Co	↑↓	↑↓	↑	↑	↑	↑↓
Ni	↑↓	↑↓	↑↓	↑	↑	↑↓
Cu	↑↓	↑↓	↑↓	↑↓	↑↓	↑

Ferromagnetic elements



and many alloys are also ferromagnetic

Electron Orbit Magnetic Moment



T = period of orbit

L = orbital **angular momentum**

Effective current is

$$I = \frac{-e}{T} = \frac{ev}{2\pi r} \quad \text{or} \quad I = \frac{-e m_e v r}{2\pi m_e r^2}$$

Magnetic moment,

$$\mu = IA = \frac{-e}{2m_e} L$$

The magnetic moment associated with an electron orbit is given by

$$\mu = IA = \frac{-e}{2m_e} L$$

Taking into account the quantization of angular momentum for such orbits, the magnitude of the magnetic moment can be written

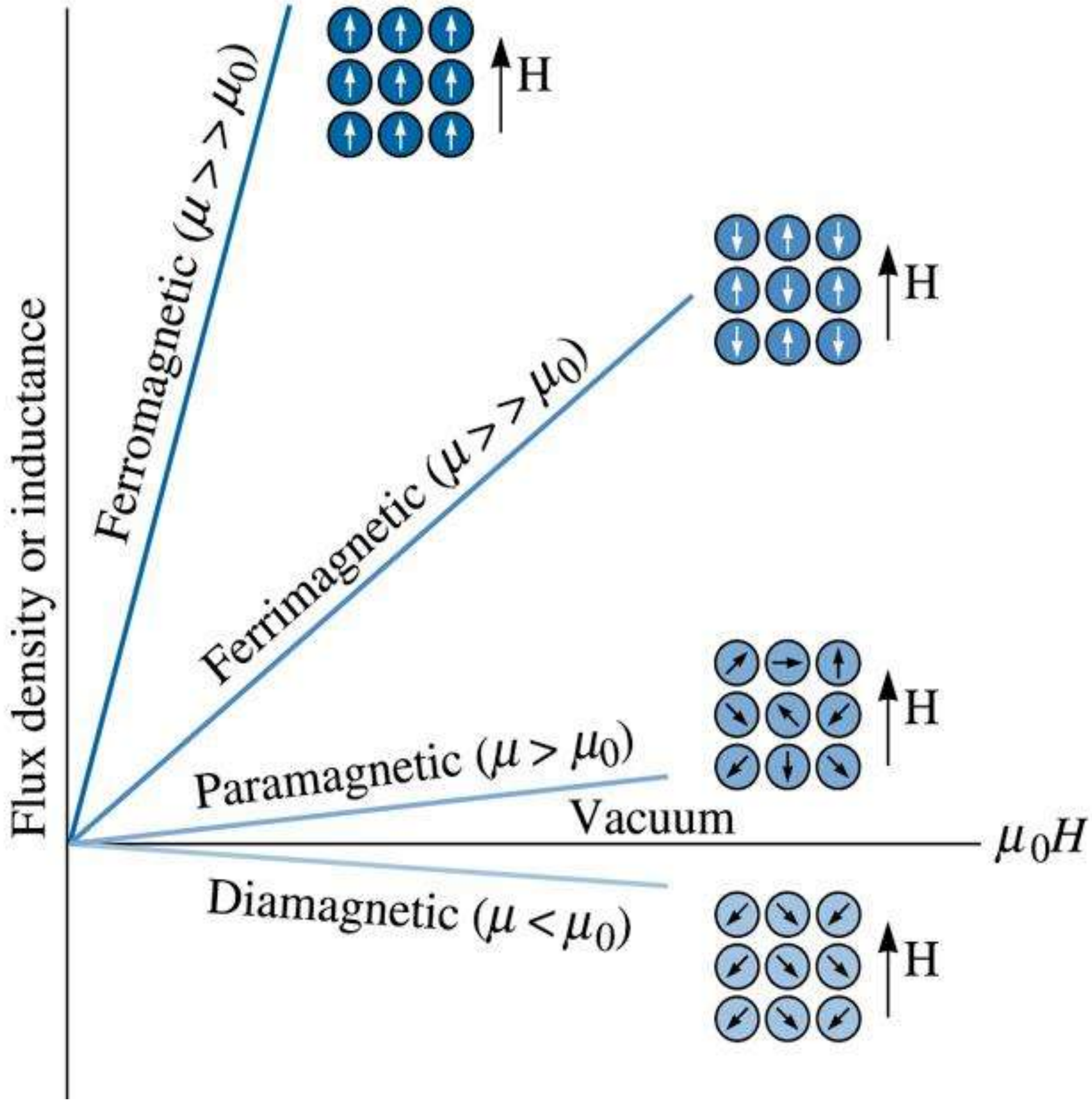
$$\mu = \frac{-e}{2m_e} L = \frac{-e}{2m_e} \sqrt{l(l+1)}\,\hbar = \sqrt{l(l+1)}\,\mu_B$$

A unit of magnetic moment called the **Bohr magneton** is,

$$\mu_B = \frac{e\hbar}{2m_e} = 9.27 \times 10^{-24}\ \mathrm{J/T} = 5.79 \times 10^{-5}\ \mathrm{eV/T}$$

Magnetic Properties

- There are three types of magnetic behavior. The external field in materials can be
  - weakened ($\chi_m < 0$ or $K_m < 1$) this is called diamagnetism
  - slightly intensified, ($\chi_m > 0$ or $K_m > 1$) this is called paramagnetism
  - considerably intensified, ($\chi_m >> 0$ or $K_m >> 1$) called ferromagnetism.



The effect of the core material on the flux density. The magnetic moment opposes the field in diamagnetic materials. Progressively stronger moments are present in paramagnetic, ferrimagnetic, and ferromagnetic materials for the same applied field.

DIAMAGNETISM

Diamagnetism: negative susceptibility, the magnetization opposes the external field, the potential energy is lowered when moving the magnetized bodies to a lower field strength. A diamagnet opposes both poles of a magnet. Diamagnetism is caused by “currents” induced by the external field. According to Lenz’ law, these currents always lead to a field opposing the external field.

Diamagnetism

- Due to an external magnetic field a radial force acts on the electron. It points toward or out of the center depending on the direction of the field. The force can't change the radius but if it points toward the center it speeds the electron and if out it slows it. This leads to a change in the magnetic moment which is always opposite to the field. So the field is weakened.

PARAMAGNETISM

Paramagnetism occurs in materials whose atoms have permanent magnetic dipole moments; it makes no difference whether these dipole moments are of the orbital or spin types.

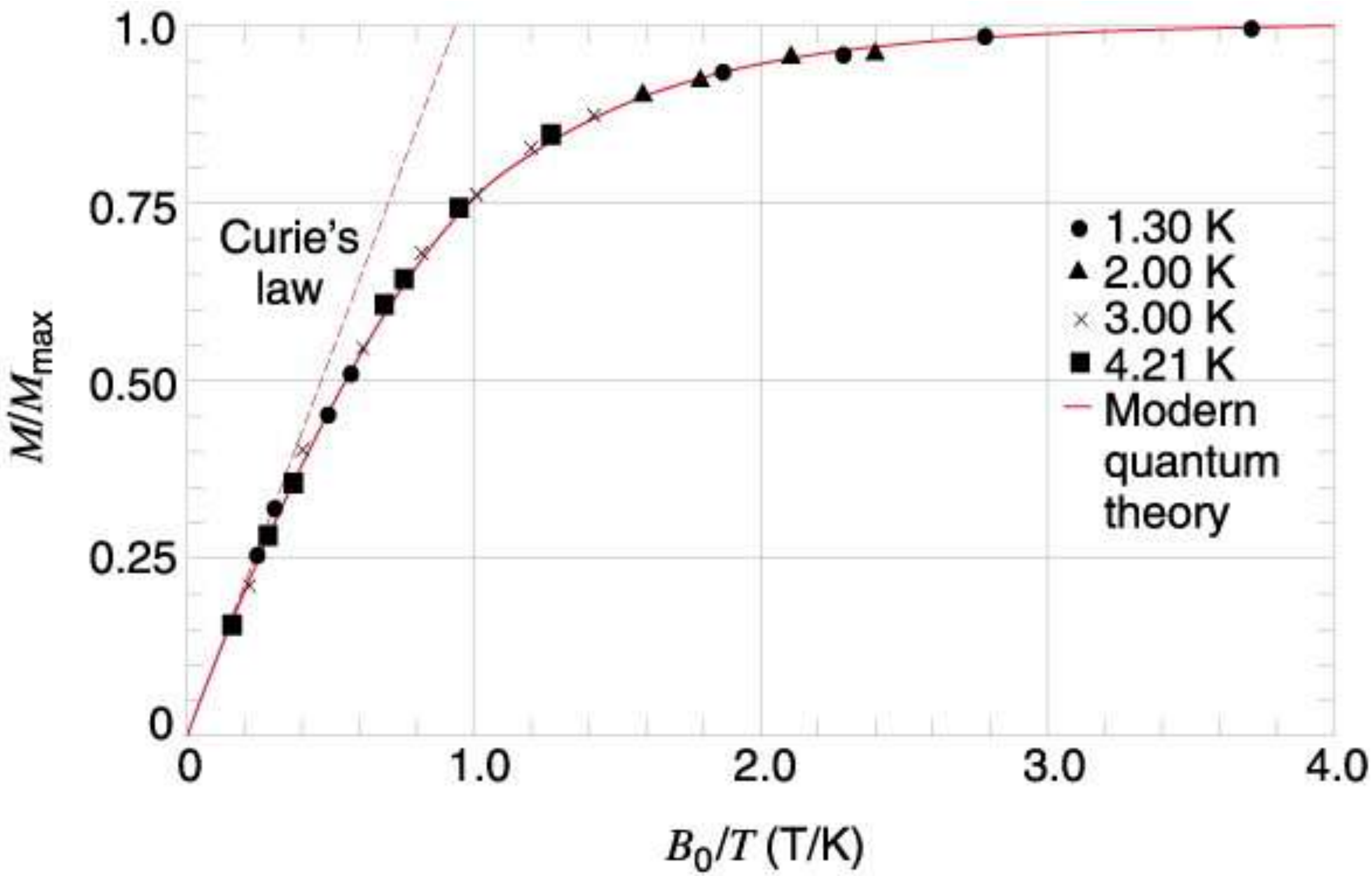
The paramagnetic materials at room temperature are Chromium, Tungsten, Aluminium, and Magnesium.

Paramagnetism

$$M = \frac{\text{measured magnetic moment}}{\text{volume}}$$

$$M = C\frac{B_o}{T}$$

The thermal motion of the atoms tends to disturb the alignment of the dipoles, and consequently the magnetization (M) decreases with increasing temperature following Curie's law



Paramagnetism: Figure shows the ratio M/M_{max} as a function of B_{ext}/T. It is a magnetization curve.

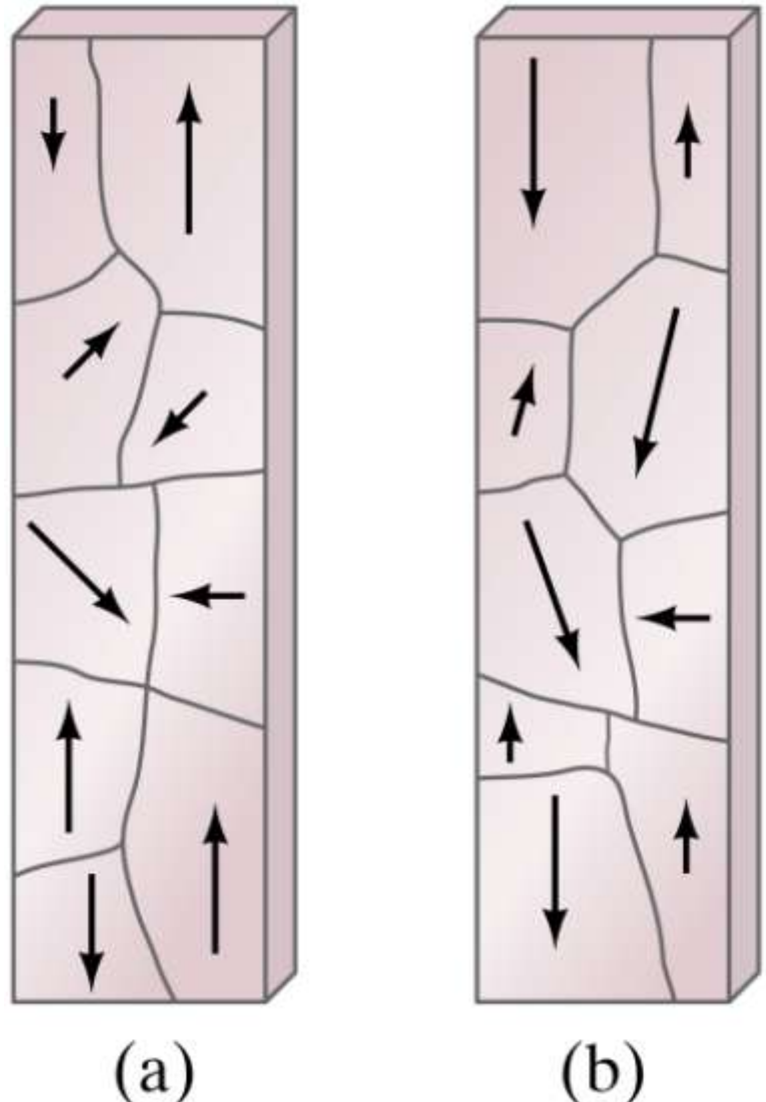
FERROMAGNETISM

Ferromagnetic materials are those that can become strongly magnetized, with all spins in parallel, such as Fe, Co, Gd and Ni. These materials are made up of tiny regions called domains; the magnetic field in each domain is in a single direction.

Changes in spin directions (antiferromagnetic) and reduction spin magnitude (ferrimagnetic) cause deviation from original ferromagnetic.

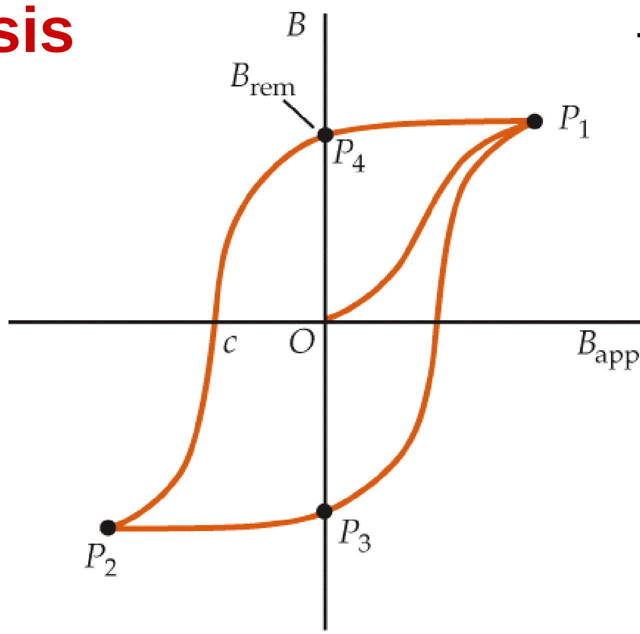
Domains and Hysteresis in Ferromagnetism:

When the material is unmagnetized, the domains are randomly oriented. They can be partially or fully aligned by placing the material in an external magnetic field.



Ferromagnetism

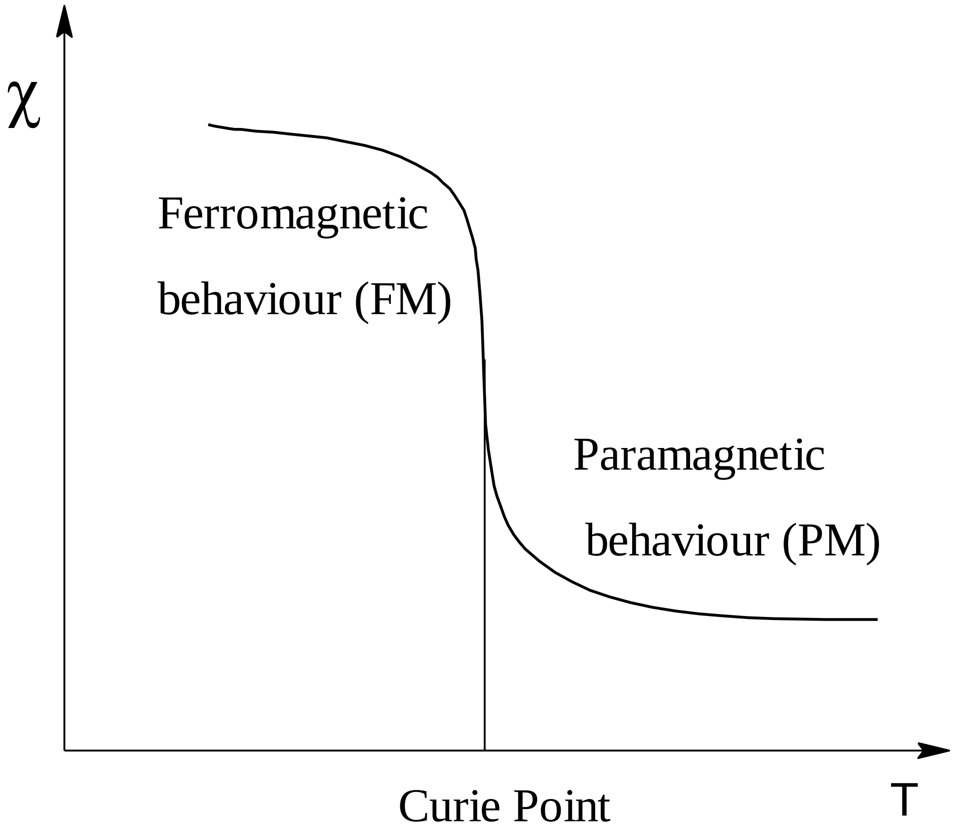
In ferromagnets, some magnetization will remain after the appliedfield is reduced to zero, yielding **permanent magnets**. Such materials exhibit **hysteresis**

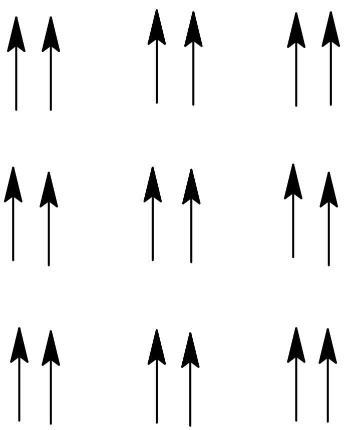


Starting with unmagnetized material and no magnetic field, the magnetic field can be increased, decreased, reversed, and the cycle repeated. The resulting plot of the total magnetic field within the ferromagnet is called a hysteresis curve.

Ferromagnetism

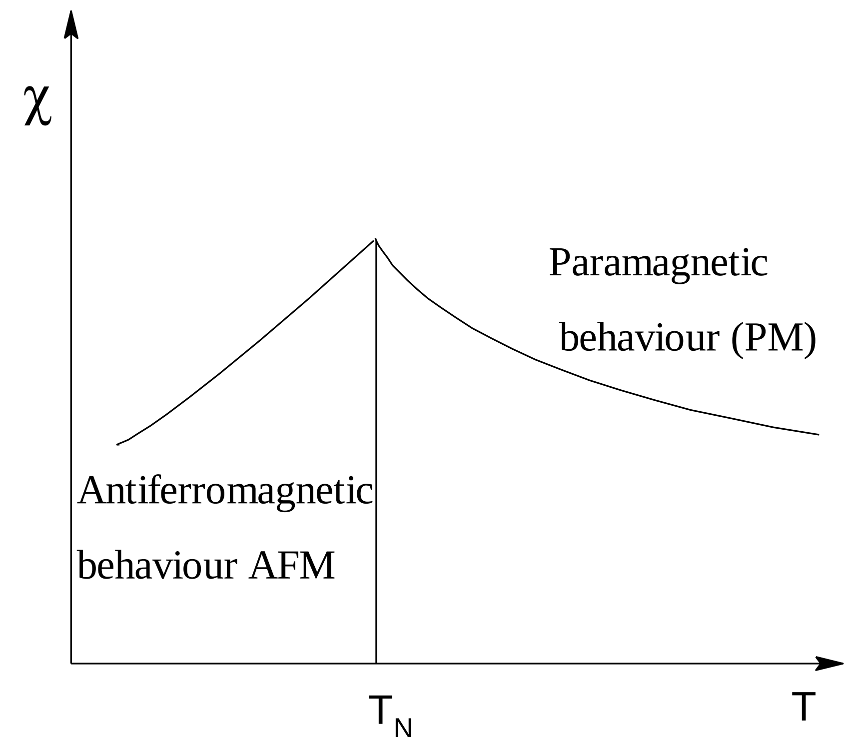
χ_m positive with spins parallel below T_c

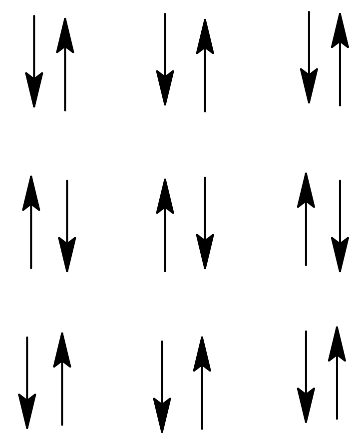




Antiferromagnetism

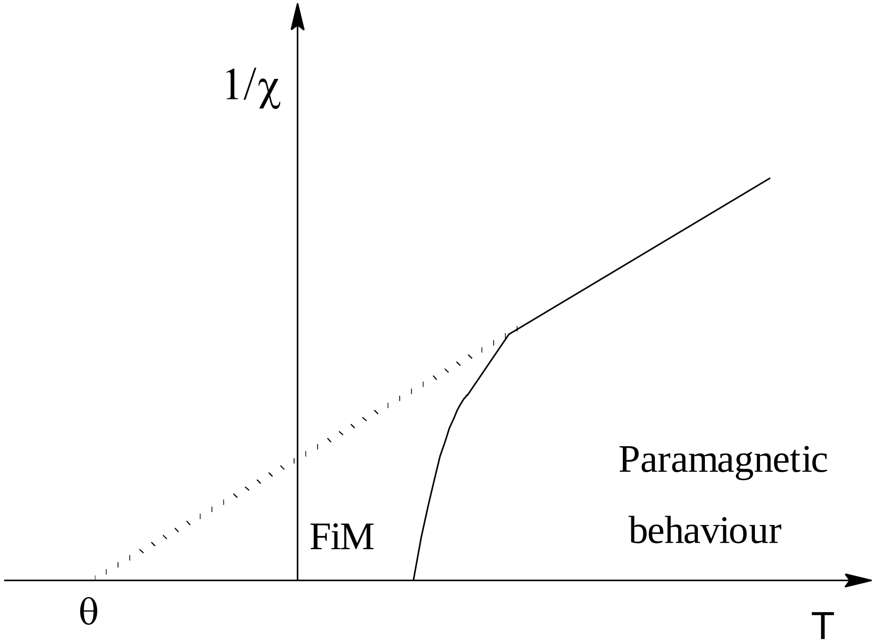
- χ_m negative with spins antiparallel below T_N

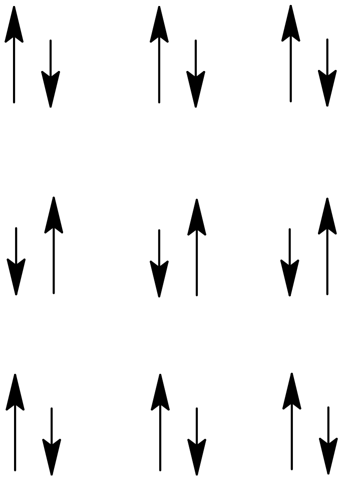




Ferrimagnetism

- χ_m negative with spins of unequal magnitude antiparallel below critical T





COMPARISON OF MAGNETIC PROPERTIES

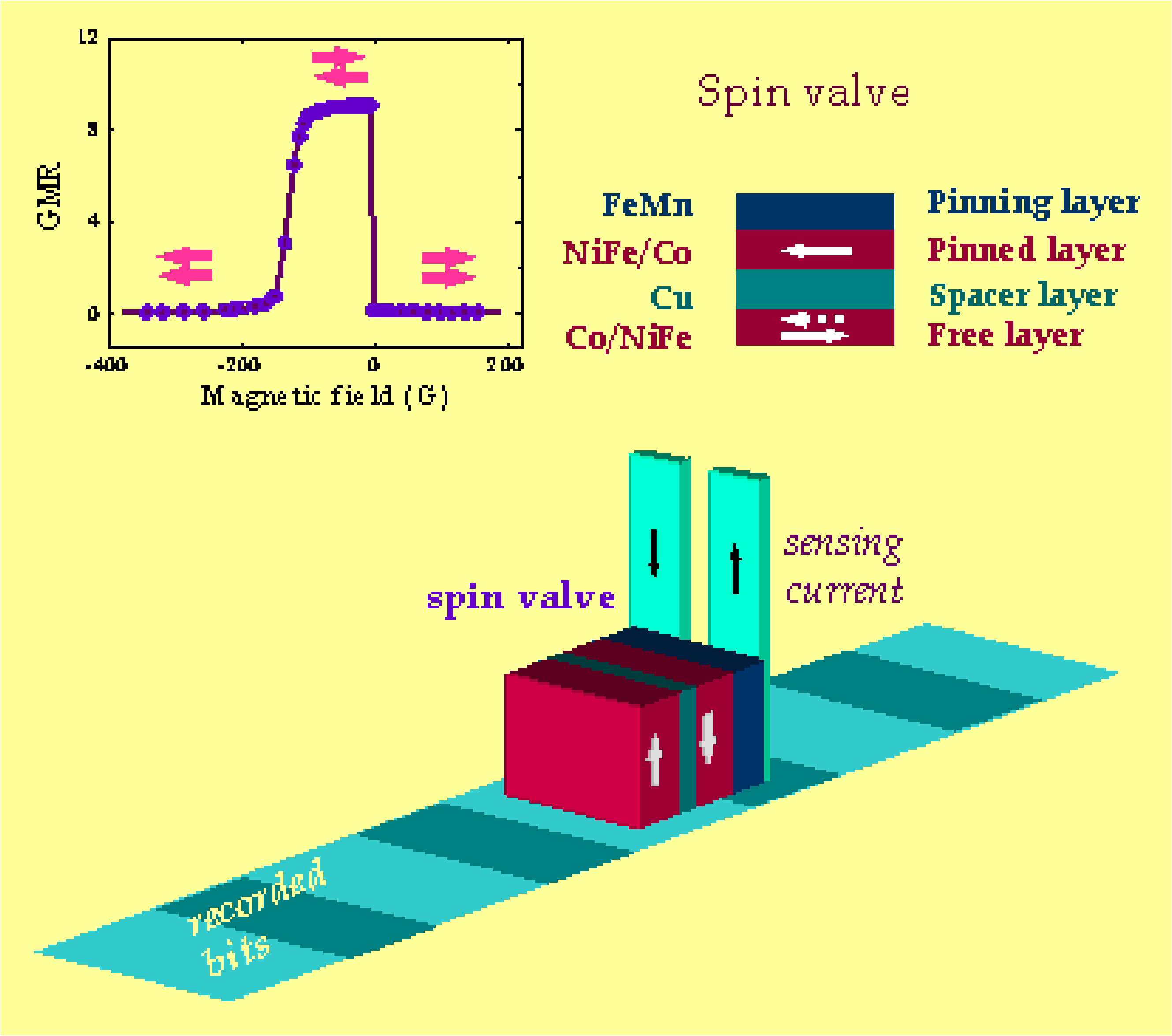
TYPE	SUSCEPTIBILITY χ_m	TEMPERATURE DEPENDENT, T	EXAMPLES
Diamagnet	a) small & negative b) medium & negative c) large & negative	a) $\chi_m \propto T$ b) $\chi_m \propto T$ and H c) Exist below critical temp. T_c	Organic materials, light elements and alkali metals
Paramagnet	a) small & positive b) large & positive	a) χ_m not $\propto T$ b) $\chi_m \propto 1/T$	Alkali metals, transition metals, rare earth metals
Ferromagnet	Very large and positive	$T>0$, $\chi_m = 1/(T-\theta)$ $T<0$, χ_m is complex	Transition metals and rare earth metals
Antiferromagnet	Small and positive	$T>T_N$, $\chi_m = 1/(T+\theta)$ $T<T_N$, $\chi_m \propto T$	Salts and transition metals
Ferrimagnet	Very large and positive	$T>T_N$, $\chi_m \propto 1/(T\pm\theta)$ $T<T_N$, χ_m complex	Ferrites, ferrous

T_N : Neel temperature; θ : Curie temperature

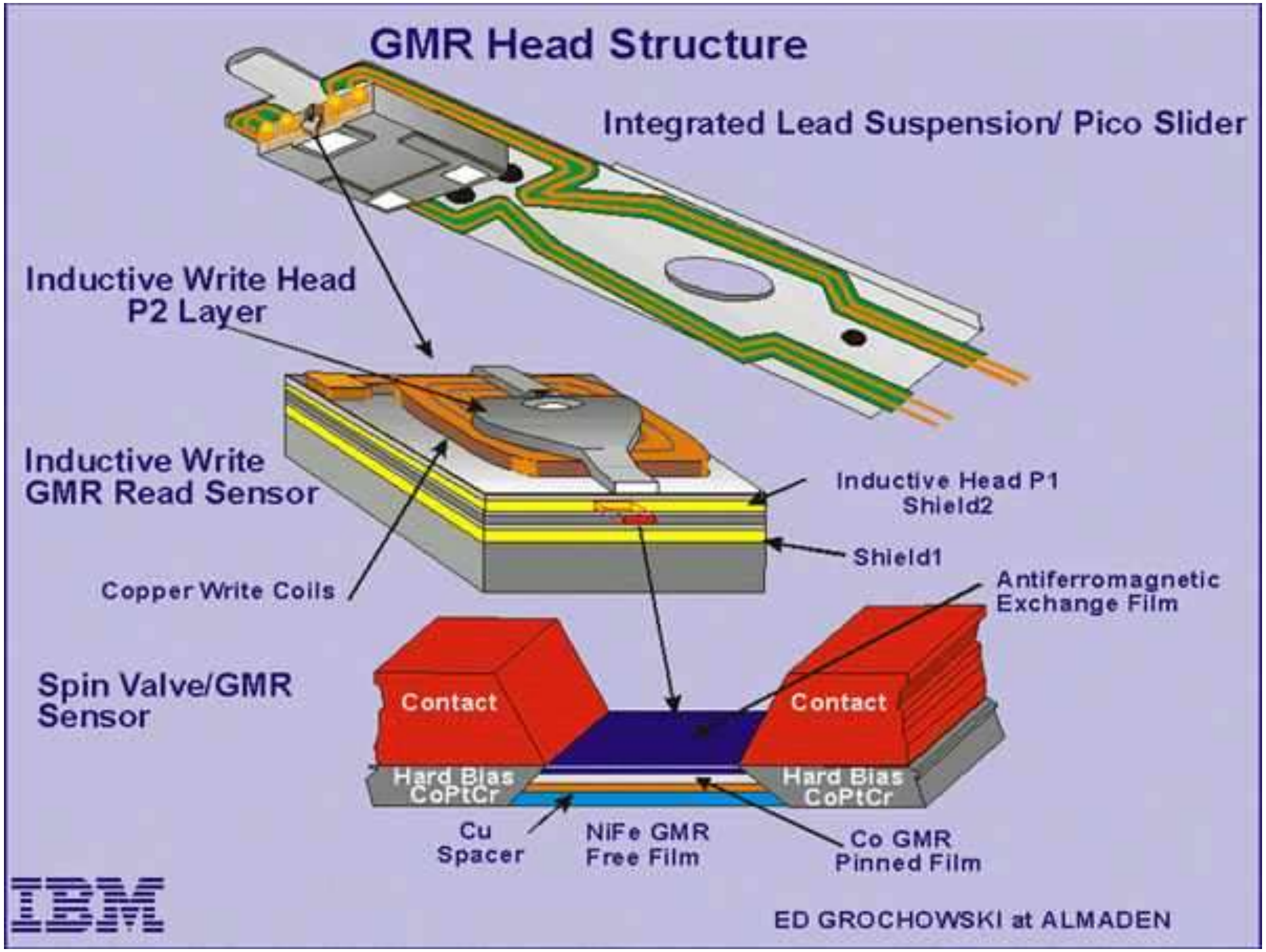
Applications of Magnetic Materials

- Soft Magnetic Materials - Ferromagnetic materials are often used to enhance the magnetic flux density (B) produced when an electric current is passed through the material. Applications include cores for electromagnets, electric motors, transformers, generators, and other electrical equipment.
- Data Storage Materials - Magnetic materials are used for data storage.
- Permanent Magnets - Magnetic materials are used to make strong permanent magnets
- Power - The strength of a permanent magnet as expressed by the maximum product of the inductance and magnetic field.
- Sensor – Based on giant magnetoresistance (GMR)

Magnetic field sensor



GMR Head


GMR Head Structure
Integrated Lead Suspension/ Pico Slider
Inductive Write Head P2 Layer
Inductive Write GMR Read Sensor
Inductive Head P1 Shield2
Shield1
Copper Write Coils
Antiferromagnetic Exchange Film
Spin Valve/GMR Sensor
Contact
Contact
Hard Bias CoPtCr
Hard Bias CoPtCr
Cu Spacer
NiFe GMR Free Film
Co GMR Pinned Film
IBM
ED GROCHOWSKI at ALMADEN

SUMMARY

- A magnetic field can be produced by:
  --putting a current through a coil.
- Magnetic induction:
  --occurs when a material is subjected to a magnetic field.
  --is a change in magnetic moment from electrons.
- Types of material response to a field are:
  --ferro- or ferri-magnetic (large magnetic induction)
  --paramagnetic (poor magnetic induction)
  --diamagnetic (opposing magnetic moment)
- Hard magnets: large coercivity.
- Soft magnets: small coercivity.
- Applications: :
  -- Magnetic storage media
  -- GMR sensor

Optical Properties of Materials

Optical Properties of Materials

Interaction of electromagentic radiation (light) with a material

- Absorption
- Reflection
- Transmission

Absorptivity

Reflectivity

Transmissivity

Total Intensity / Initial Intensity I_0

$$I_0 = I_A + I_R + I_T$$

$$1 = I_A/I_0 + I_R/I_0 + I_T/I_0$$

$$1 = A + R + T$$

A material cannot simultaneously be highly absorptive, reflective and transmissive

Optical coefficients

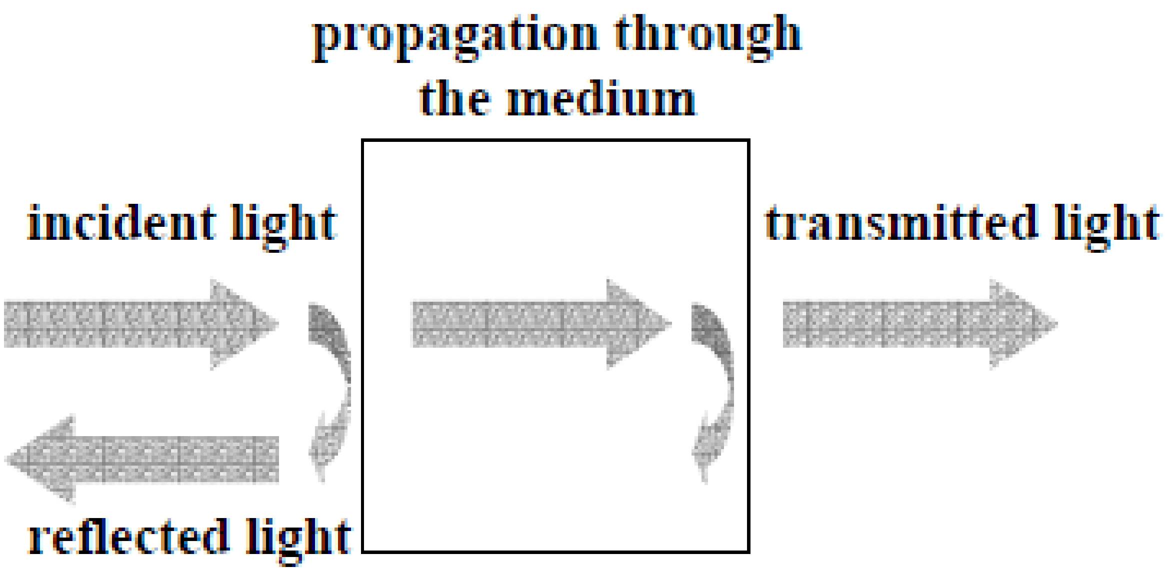


Figure 1.1: Optical coefficients

- Reflectivity = reflected / incident power
- Transmissivity = transmitted / incident power
- $T + R = 1$ if medium is transparent

Propagation

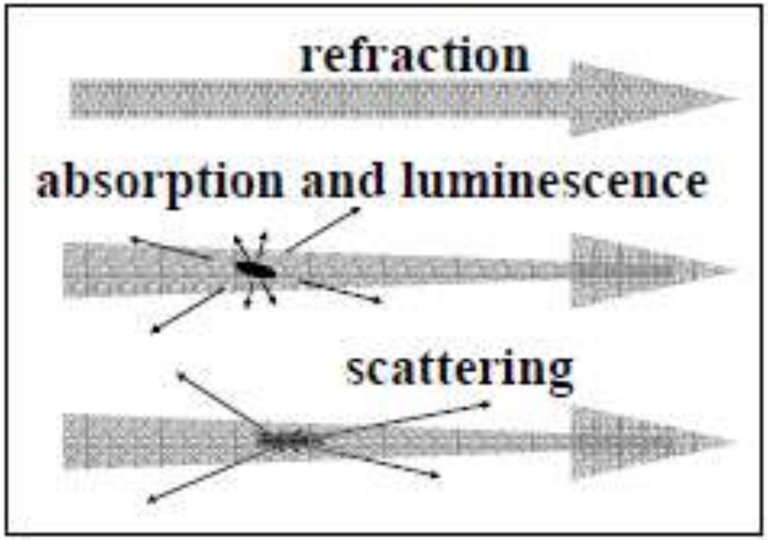


Figure 1.2: Propagation of light through a medium

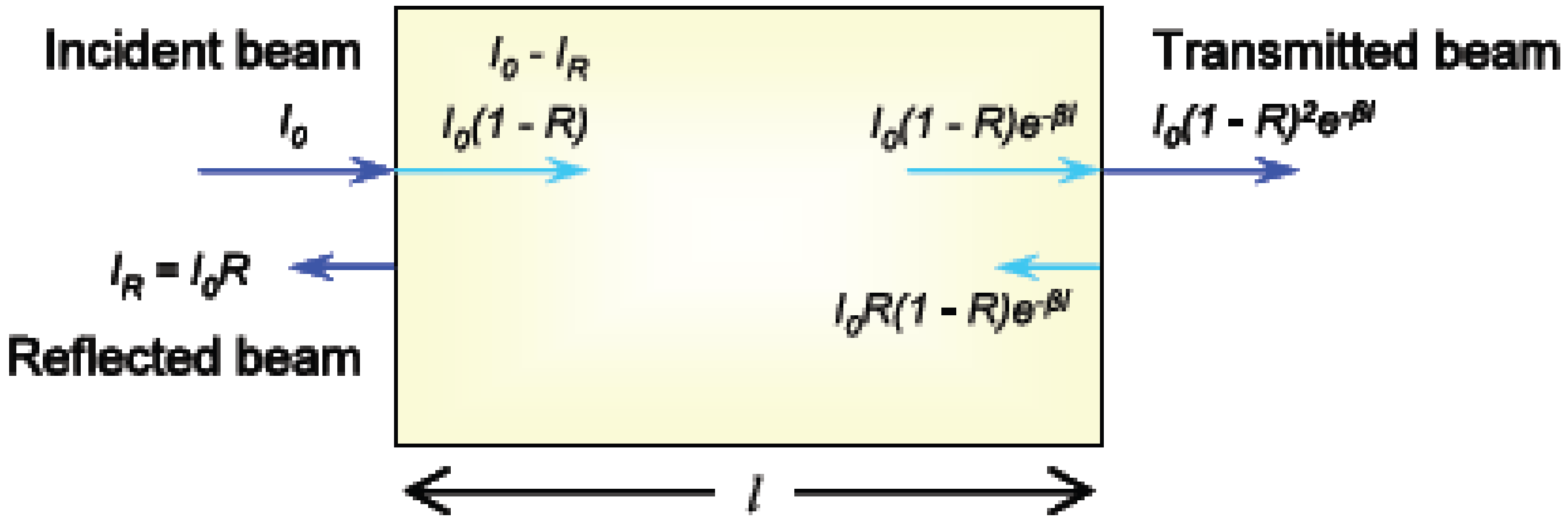
- Velocity $v = c/n$, n is the **refractive index**
- $I(z) = I_0 \exp(-\alpha z)$, α is the **absorption coefficient**
- $T = (1-R_1) \exp(-\alpha L) (1-R_2)$
- **Luminescence** : re-emission at lower frequency
- **scattering**: *elastic*- change of direction

  inelastic - change of direction and frequency

Optical Properties of Metals and Alloys

Shininess and inability to transmit visible light indicates

- high absorption   linear absorption coefficient β
- high reflection   (up to $R = 1$)



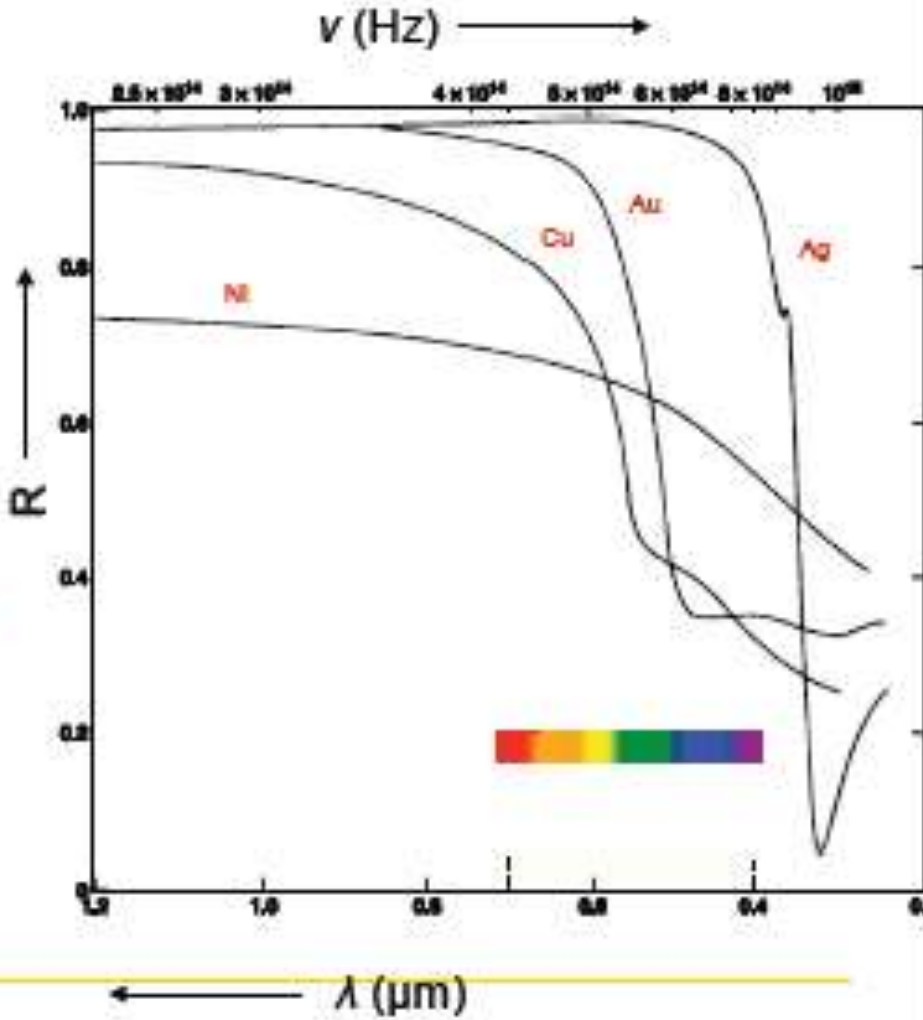
β and R determine how light interacts with a material

Reflectance and color - Electronic effects

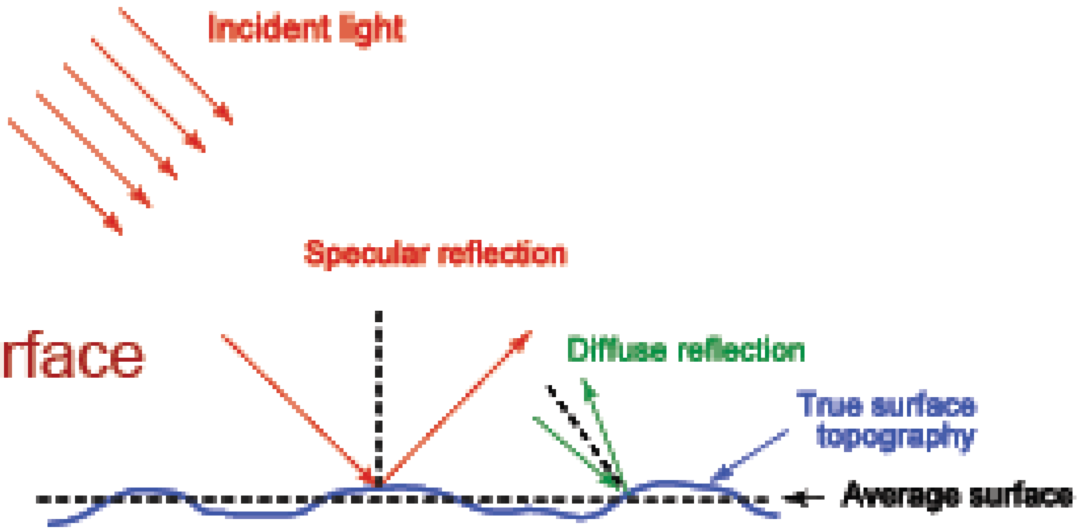
Empty electronic states above occupied levels

Light absorption:

- e⁻ promotion
- decay
- reemission
- reflectivity
- dependent on frequency



Reflectance and color - Surface texture

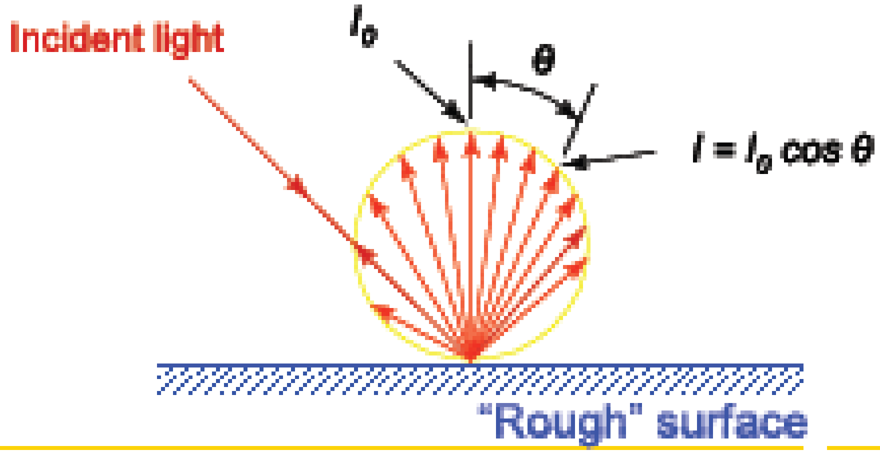


Specular reflection

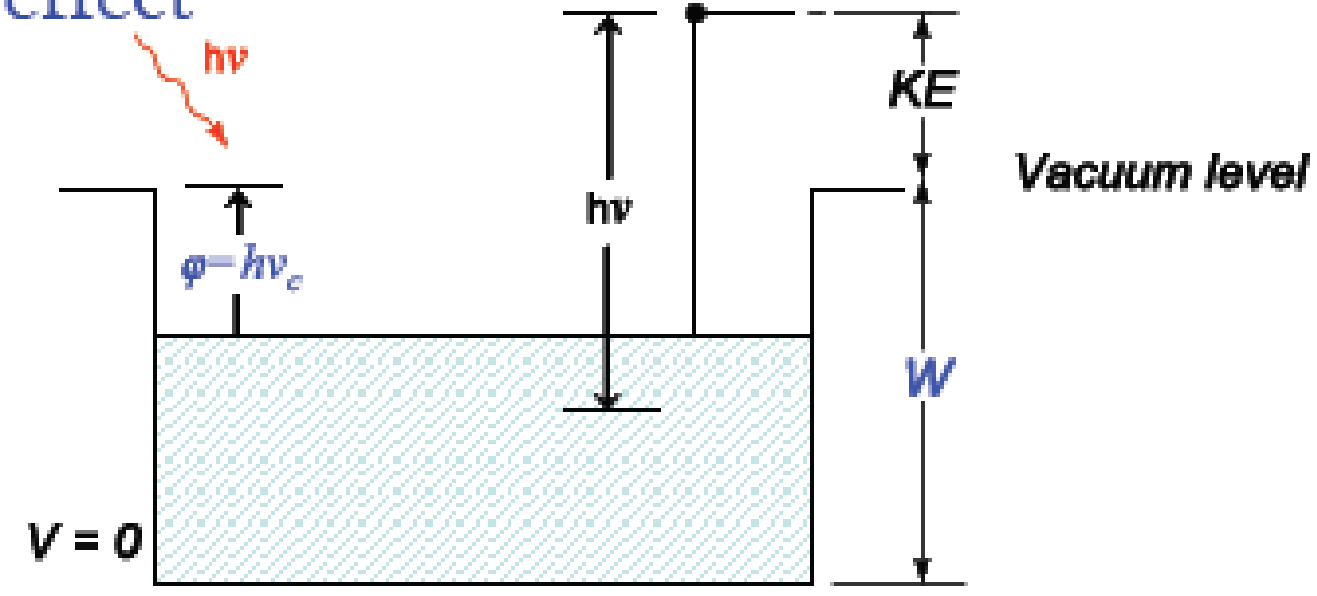
- smooth or mirror-like surface

Diffuse reflectance

- rough surfaces
- at all angles
- $I_\theta = I_0 \cos\theta$



Photoelectric effect

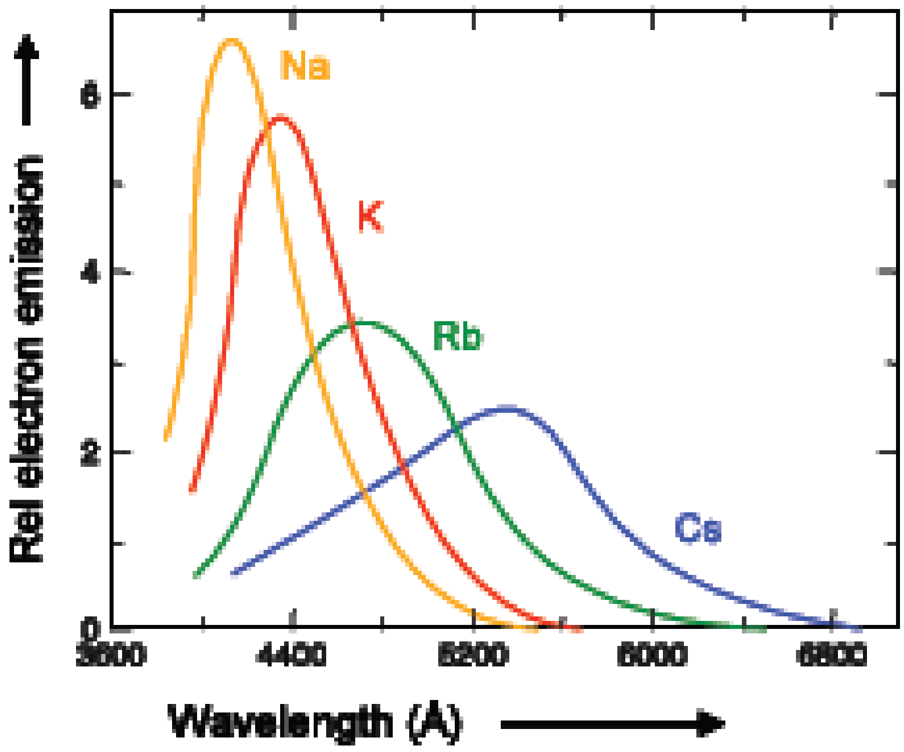


Release of electrons due to absorption of light energy

- potential energy barrier for surface electrons is finite
- critical energy for release: $\varphi = W - E_f = h\,v_c$
- below v_c: no ejection of photoelectrons
- φ characteristic measure

Photoelectric effect

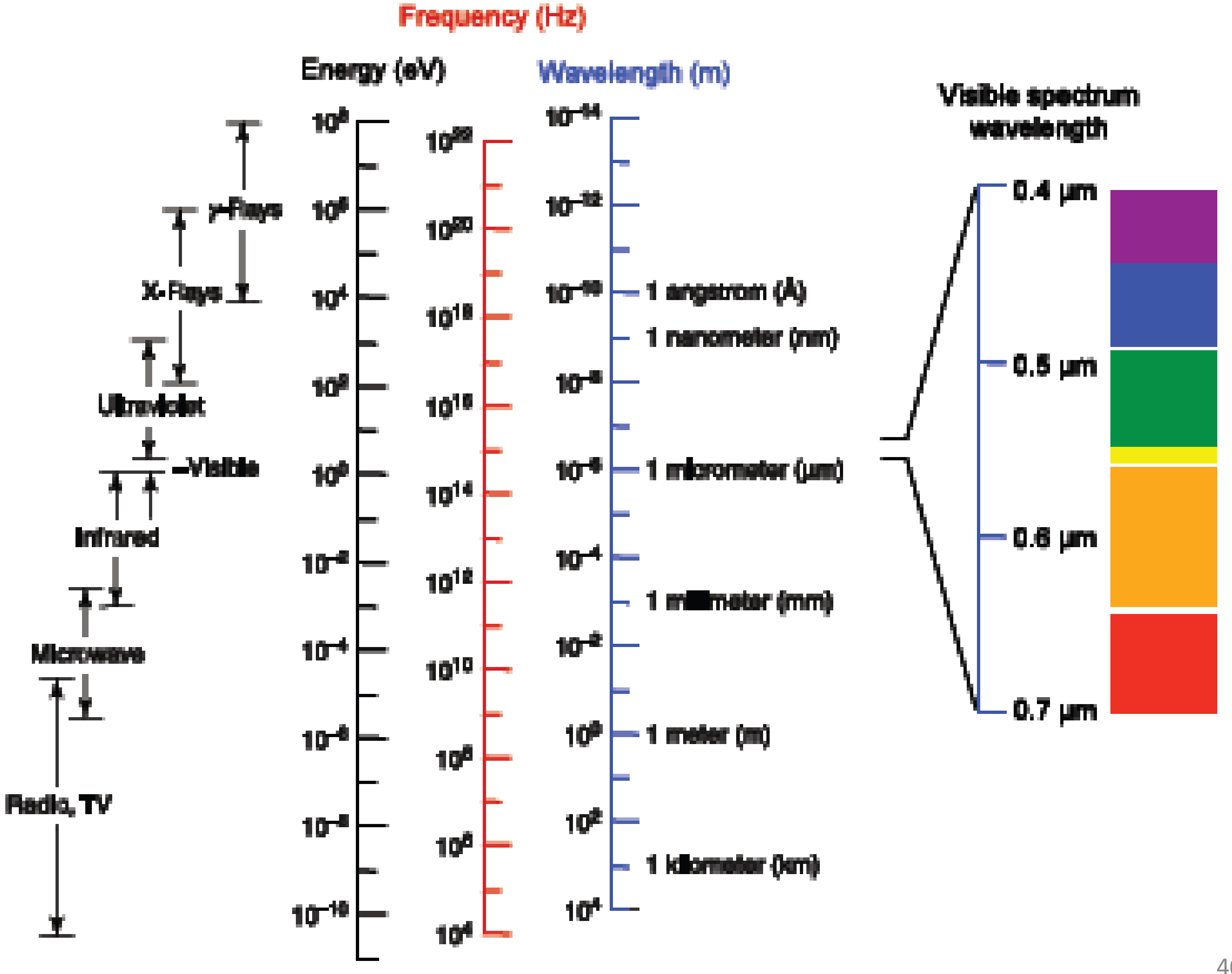
$$\varphi = h\nu_c = \frac{hc}{\lambda_c}$$



Photoelectric emission depending on wavelength

- optimal emission at λ_c
- below λ_c: insufficient energy
- above λ_c : decrease of electronic excitations efficiency

Electromagnetic spectrum



Optical Properties of ceramics and glasses

Refractive index n

- velocity of light in vacuum: c = 299 792 458 m/s
- velocity of light in any other medium: v ($v < c$)
- refractive index $n = c/v$

- c can be related to ε_0 and μ_0
- v can be related to ε and μ

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

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

$$n = \sqrt{\frac{\varepsilon_r}{(1+\chi)}}$$

- ceramics posess small susceptibilities:

$$n \approx \sqrt{\varepsilon_r}$$

Refractive index

Values between ≈ 1 and ≈ 4

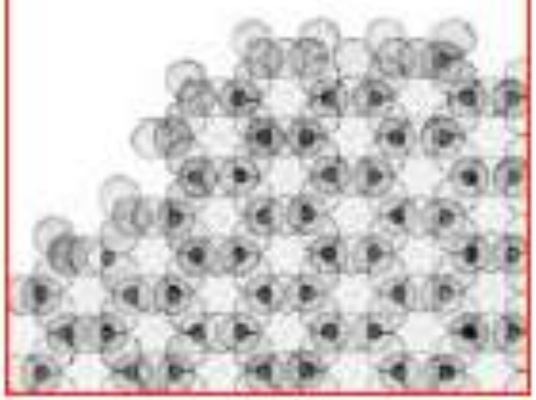
- air: 1.003
- silicate glasses: 1.5 to 1.9
- solid oxide ceramics: ≈ 2.7

Dependent on structure-type and packing geometry

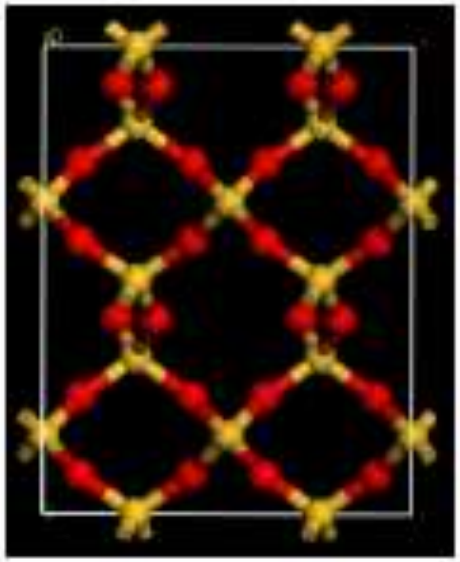
- glasses and cubic crystals: *n* is independent of direction
- other crystal systems: *n* larger in closed-packed directions
- SiO_2: glass = 1.46, tridymite = 1.47, cristobaltite = 1.49
  quartz = 1.55

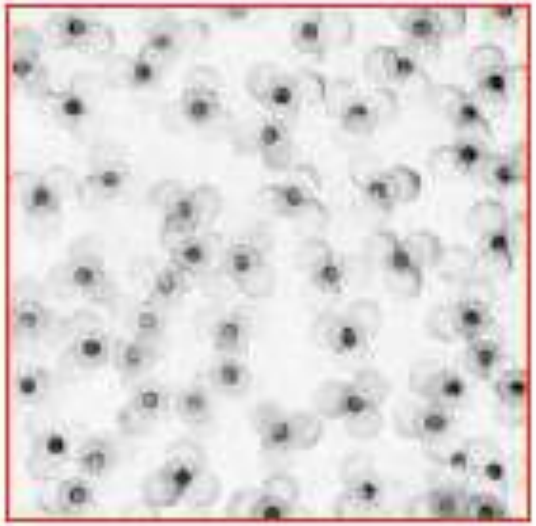
Cristalline silicate *vs* glass

TEM images

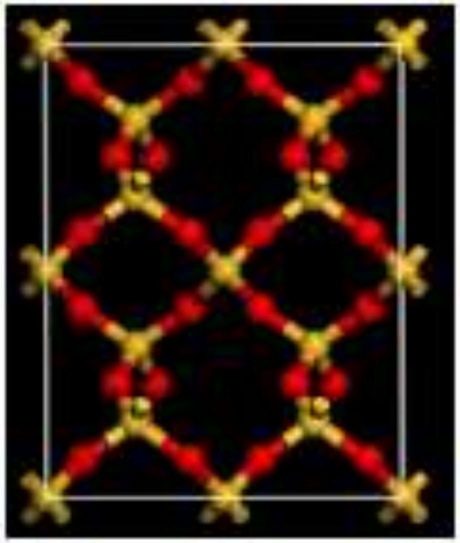


Quartz





Addition of large ions (Pb, Ba) to SiO_2 structures increases *n* significantly



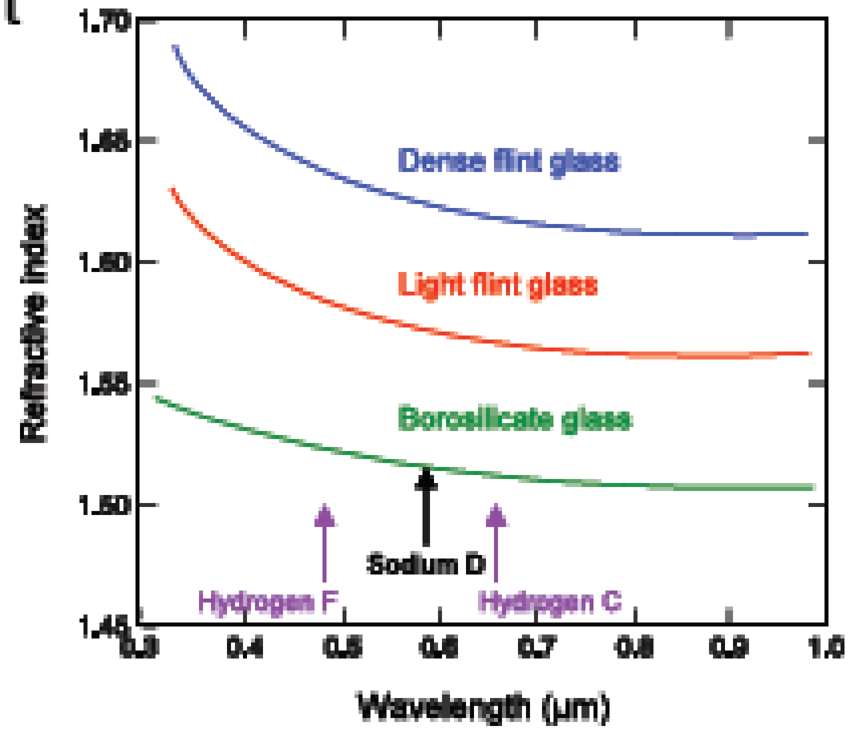
Refractive index

Mechanical distortions of isotopic glasses changes *n*

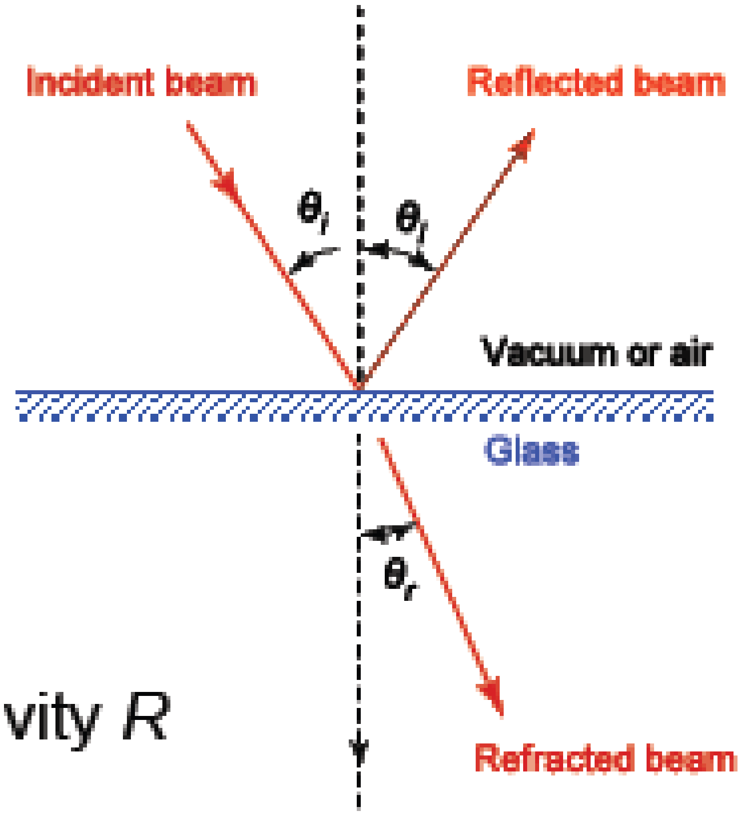
- tensile stress: lower *n* normal to direction of applied stress
- compression: higher *n* normal to direction of applied stress

n dependent on frequency of light

$$Dispersion = \frac{dn}{d\lambda}$$



Reflection and refraction



n can be expressed with the angles of incidence and refraction

$$n = \frac{\sin\theta_i}{\sin\theta_r}$$

n can be used to describe reflectivity *R*

$$R = \frac{I_R}{I_0} = \frac{(n-1)^2}{(n+1)^2}$$

n and *R* vary with wavelength

Absorbance and color

Non-reflected light can be transmitted or absorbed

Absorption process is a function of energy (wavelength)

Absorption: fractional change of light intensity $$\frac{dI}{dt} = -\beta\, dx$$

Absorption coefficient β is a material property and a function of the wavelength $$\beta = \frac{4\pi k}{\lambda}$$

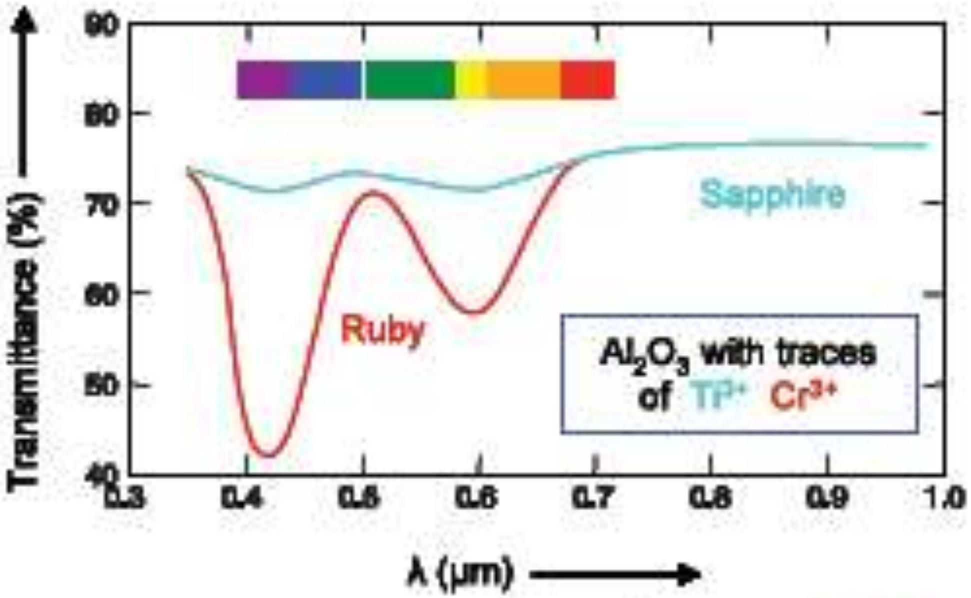
Absorption of photon: excitation of electron from valence to conduction band. Only if photon energy > band gap $h\nu \geq E_g$

Magnitute of band gap determines if the material

- does not absorb (transparent)
- absorbs certain wavelength (opaque)

Absorbance and color

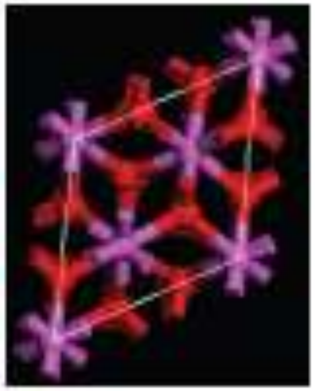
Absorption of certain wavelength results in color



Generating color in ceramics:

Addition of transition elements with incomplete d band filling

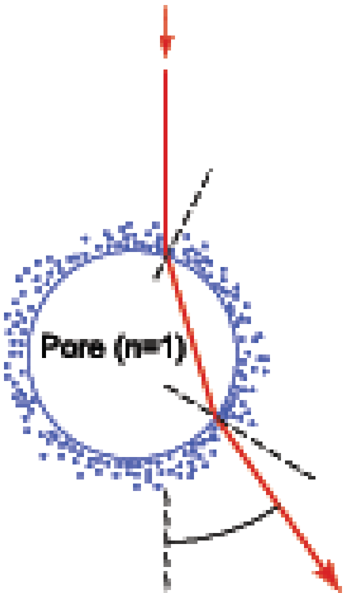
V, Cr, Mn, Fe, Co, Ni



Ruby: Corundum structure with point defects of Cr^{3+}

Light scattering in solids

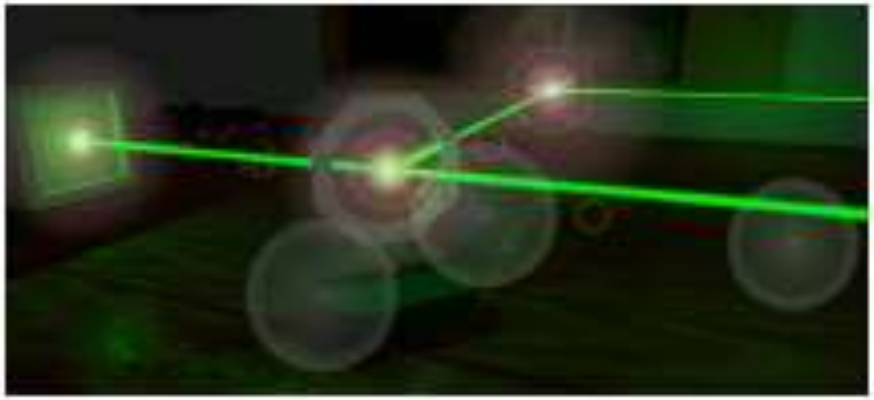
Some inherently transparent materials appear "milky": translucency"



Scattering

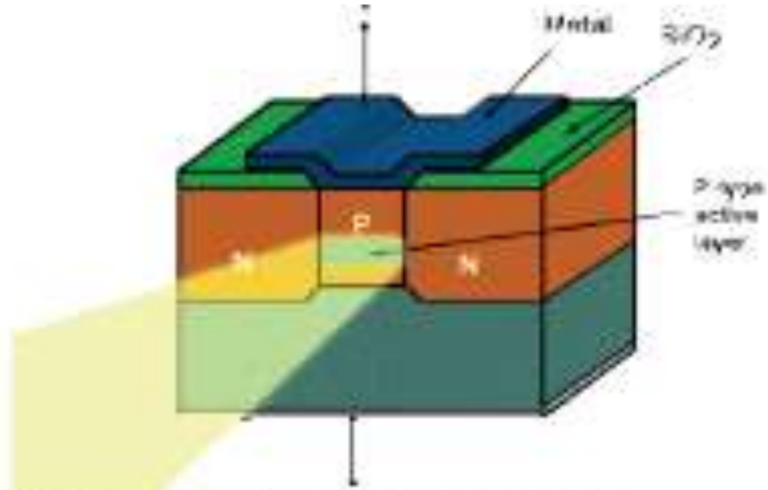
- Pores ($n_{pore} < n_{solid}$)
- second-phase particles (SnO_2) ($n_{2nd\ phase} > n_{solid}$)

Optical devices



Examples: laser, photodiodes, optical fiber, light emitting diodes

Semiconductor lasers



Increasingly important in

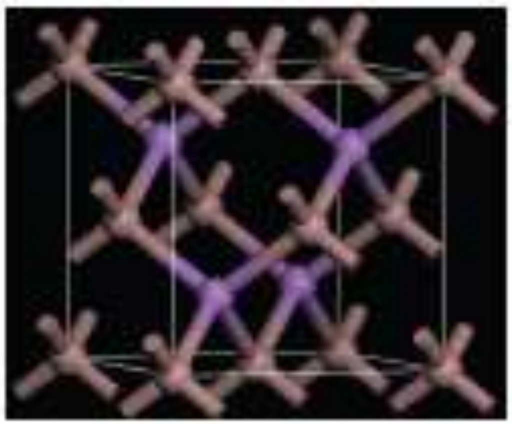
- information storage (CD, DVD)

Layered semiconductor

- applied voltage excites electrons into conduction band
- recombination of electron-hole pair leads to emission

III-V semiconductors

- GaAs (IR, red)

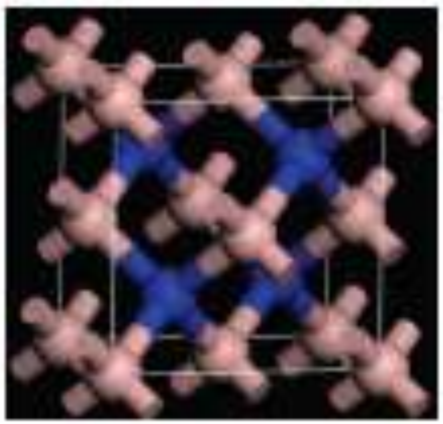


CD

nitrides

- (B,Al,Ga,In)N (blue)

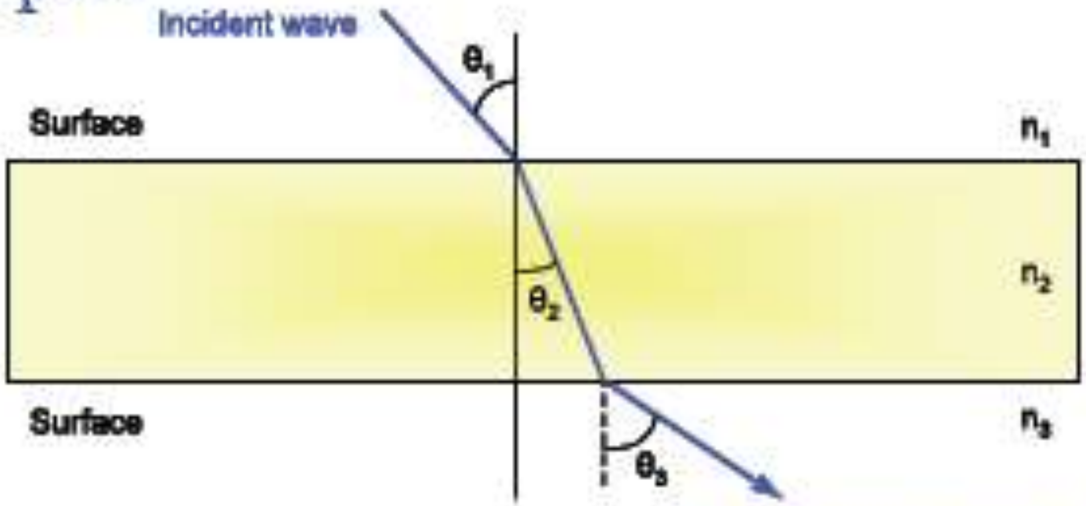
DVD



Optical fibers - principles

Total internal reflection

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2} \qquad \frac{n_3}{n_2} = \frac{\sin\theta_2}{\sin\theta_3}$$

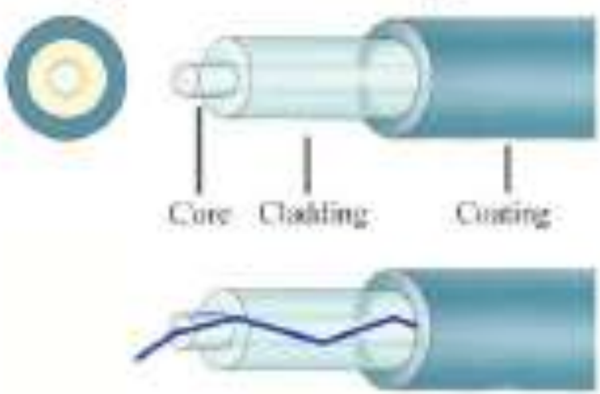


At some angles of θ_2: $\theta_3 = 90°$ (backreflection)

Critical angle for total internal reflectance θ_c

Example: Medium 1 and 3: air, Medium 2: glass with $n_2 = 1.5$

- $\theta_3 = 90°$ if $\theta_c = °42$



Optical fibers:

Medium 3: glass with $n_3 < n_2$

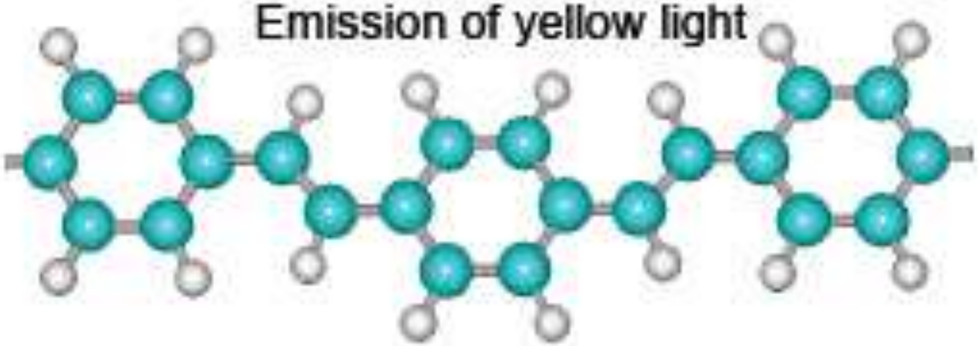
Core and cladding structure

Electroluminescence

applied voltage excites electrons into conduction band
recombination of electron-hole pair leads to emission

First visible light emitting polymer: poly(p-phenylene vinylene)

Emission of yellow light



Polythiophene

Emission of blue light