Part 5

Functional Properties

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Electrical Properties

Aim

To understand the relationship between electrical properties and atomic structure, bonding and microstructure

Conductivity

Depends on number of free carries
and how easily they move

Ohm's Law

$V=IR$

$\rho = RA/L$

$\sigma = 1/\rho$

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Conductivity

- Metals
  - $\sigma \sim 10^{7}\ (\Omega\ m)^{-1}$

- Semi-conductors
  - $\sigma \sim 10^{-6} - 10^{4}\ (\Omega\ m)^{-1}$

- Insulators
  - $\sigma \sim 10^{-20} - 10^{-10}\ (\Omega\ m)^{-1}$

Applications

- Interconnect
- Resistor
- Insulator
- Non-ohmic device
  - Diode
  - Transistor
- Thermistor
- Piezoresistor
- Photoconductor
- Magnetoresistor

Conductivity

- Electronic conductivity depends on band structure
  - Arrangement of outermost energy bands and the way in which they are filled with electrons
- Only electrons with energies greater than the fermi energy can participate in conduction process – free electrons
- Holes are empty states below the fermi level – holes also contribute to the conduction process
- Drift velocity $v_d = \mu_e E$
- Conductivity $\sigma = n_e|e|\,\mu_e + n_h|e|\,\mu_h$

Conductivity - metals

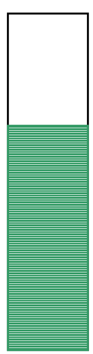
Metals - Good conductors

$(\sigma \sim 1 \times 10^{7}\ (\Omega m)^{-1})$

Cu $\sigma \sim 6 \times 10^{7}\ (\Omega m)^{-1}$ most commonly used

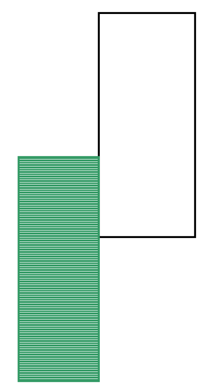
Al $\sigma \sim 4 \times 10^{7}\ (\Omega m)^{-1}$ used when weight important

Ag $\sigma \sim 6 \times 10^{7}\ (\Omega m)^{-1}$ expensive



Little energy required to promote electrons into low lying empty states

Relatively large number of free electrons



Partially filled band (eg Cu)

Overlapping bands (eg Mg)

Conductivity of metals

- Positive cores in sea of valence electrons
- Force on electron
  - $F=-eE$
  - $v = -(eE/m)t$
  - Constant E gives increasing v (not observed)
- Collisions introduce frictional damping term
  - $dv/dt + v(t)/\tau = F/m$
  - $dv/dt = - v(t)/\tau - eE/m$
- In steady state v is constant (v_s)
  - $v_s = -eE\tau/m = -\mu E$ (definition of μ)
  - □ $\mu = e\tau/m$

Ohm's Law

- Number of electrons crossing plane in time dt $= n(dx\ A) = n(v\ dt\ A)$
- Current density $(j=I/A)$
- $j = n(v\ dt\ A)(-e)/dt\ /A = -nev = (ne^2\tau/m)E$
- $j = \sigma E$ where $\sigma = ne^2\tau/m = ne\mu$

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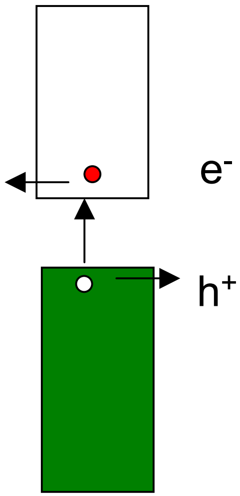
Resistivity

- Conductivity reduced (resistivity increased) by
  - Increasing temperature $\rho_T = \rho_0 + aT$
    - Electrons scattered by phonons
    - Electrons scattered by increased defect concentration
  - Impurities $\rho i = A\, c_i(1-c_i)$
    - A depends on charge difference between ionic cores of host and impurity atoms
  - Plastic deformation
    - Increased dislocation density to scatter electrons

- Matthiessen's rule $\rho_{total} = \rho_t + \rho_i + \rho_d$

Intrinsic semi-conductors

- Covalent materials
  - Si, Ge, III/V GaAs, II/VI ZnTe
- Small band gaps (< 2eV)
- As ionic character increases band-gap increases and become more insulating
- Electrons thermally excited to conduction band leaving hole in valence band
- Both electrons and holes move under applied voltage $\sigma = n|e|(\mu_e + \mu_h)$
- Temperature dependence of conductivity
  - $\ln \sigma = C - E_g/2\,kT$



Extrinsic semi-conductors

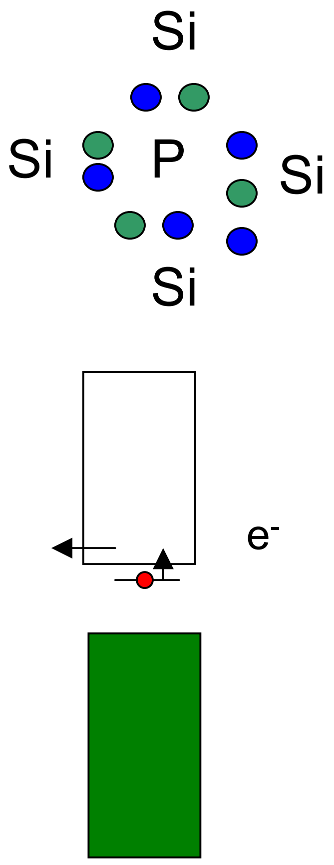
- Nearly all commercial semi-conductors are extrinsic
- Added impurities introduce extra electrons or holes
- n-type
  - Impurity with a valence of 5 added (P, As, Sb) to Si
  - Only 4 electrons involved in covalent bonding
  - Extra electron only weakly bound (~0.01eV) to impurity atom – moves easily

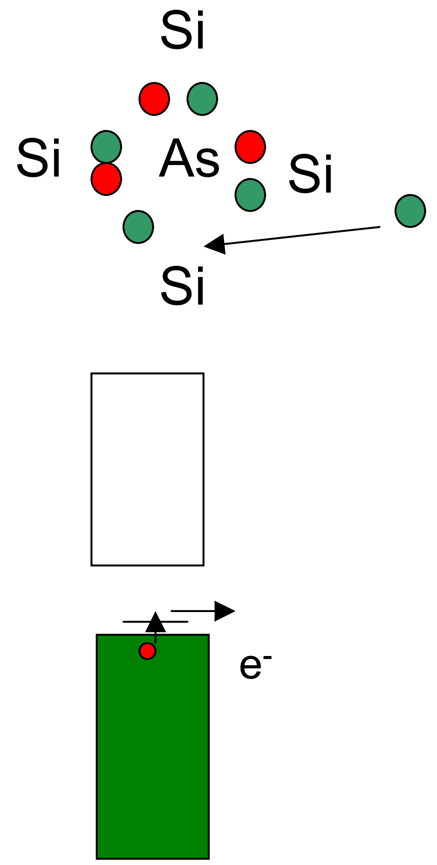
    $\sigma = n|e|\,\mu_e$

- p-type
  - Impurity with a valence of 3 added (Ga, In, B) to Si
  - 1 covalent bond is deficient in electrons
  - Nearby electrons can move easily into bond – acceptor state

  $\sigma = p|e|\,\mu_h$

Extrinsic semi-conductors





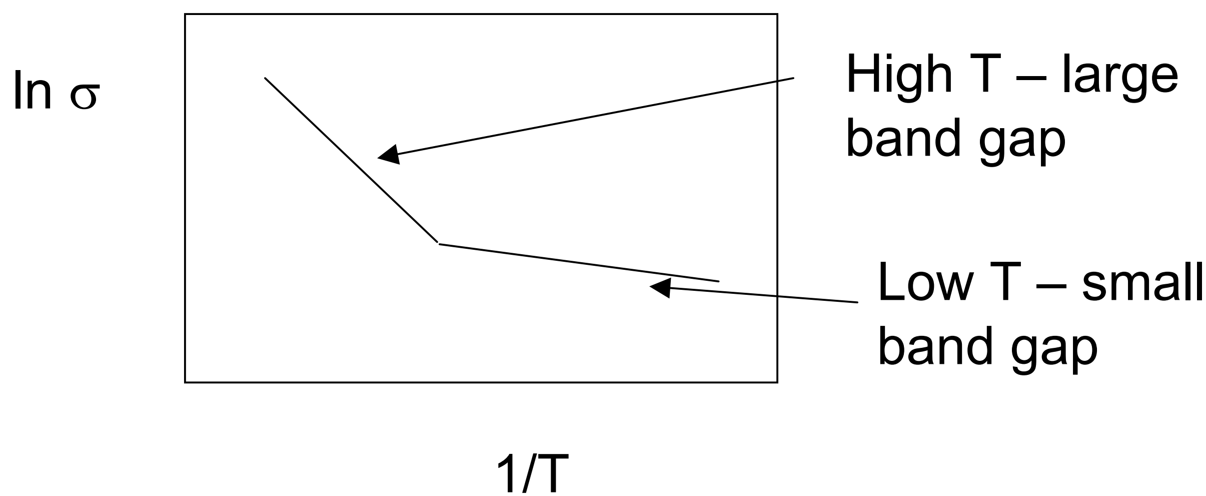
Temperature dependence of conductivity

As with intrinsic semi-conductors

$$\ln \sigma = C - E_g/2kT$$

But E_g is very small (~0.02eV)

Above a critical temperature all impurity electrons (or holes) are excited and temperature dependence resembles that of an intrinsic semi-conductor



Semi-conductor devices

- p-n rectifying junction
  - Current flows when voltage applied in one direction (forward bias)
  - No current when voltage applied in reverse direction

- Transistor
  - Narrow n-type region between 2 p-type regions
  - 2 p-n junctions back to back
  - Small change in gate voltage amplified across high impedance reverse bias junction

- Light emitting diodes
  - Light emitted when electrons combine with holes
  - Wide band-gap semiconductors (GaP, GaAs)

Conduction in ceramics

- Typical band gaps > 3 eV – insulating
- Typical conductivities
  - Graphite ~ 10^5 $(\Omega m)^{-1}$
  - Al_2O_3 ~ $10^{-13}(\Omega m)^{-1}$
  - Fused silica ~ $10^{-18}(\Omega m)^{-1}$
- Conduction combination of ionic and electronic components
- Ionic mobility
  - $\mu_i = n_i\, e\, D_i / kT$

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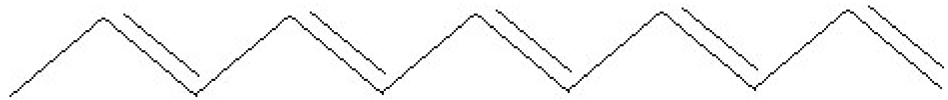
Conduction in polymers

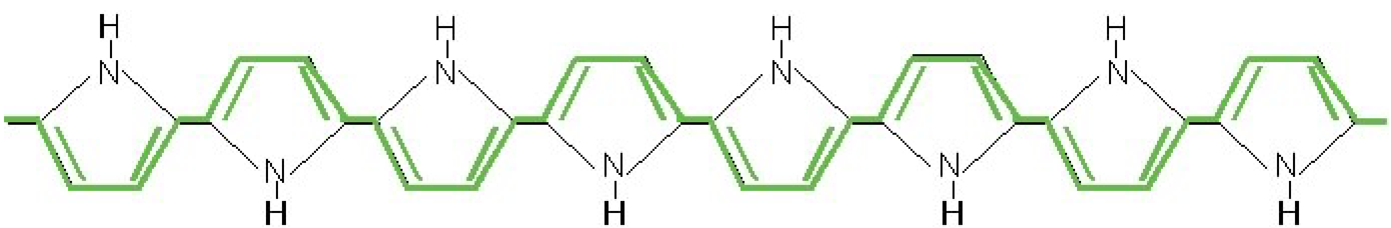
- Most polymers are insulating but new polymers with conductivities as high as $10^7(\Omega m)^{-1}$ have recently been developed

- Extended π orbitals (cf graphite)



- Potential applications include molecular electronics, displays, rechargeable batteries

- Can be used to convert electrical energy to mechanical energy



Electrical properties – dielectric behaviour

A dielectric material is an insulating material that exhibits, or can be made to exhibit, an electric dipole structure

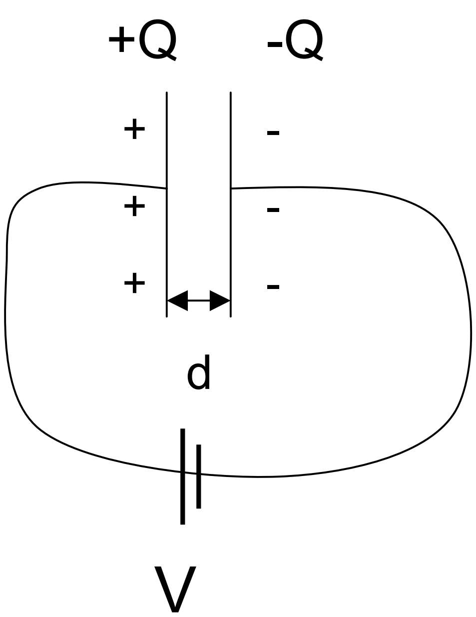
There is a separation of positive and negative charge at an atomic level

Capacitance

When a voltage V is applied across a parallel plate capacitor the plates acquire a charge of +/- Q

Capacitance C defined by

$$C = Q/V$$



For plates of area A and separation d

$C=\varepsilon_0 A/ d$ for vacuum between plates

$C=\varepsilon A/ d$ for a dielectric material between plates

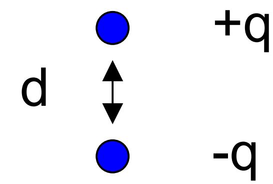
ε_0 is the permittivity of free space ($8.85\text{x}10^{-12}\ \text{Fm}^{-1}$)

$\varepsilon_r = \varepsilon/\varepsilon_0$ is the dielectric constant

Dielectric Polarization

The dipole moment

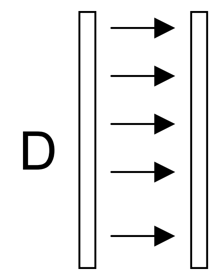
$$p = qd$$

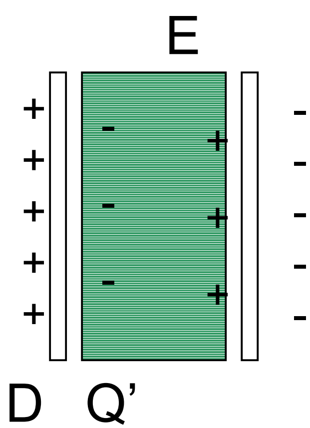


The surface charge density

$$D_0 = \varepsilon_0 E \quad \text{(vacuum)}$$

$$D = \varepsilon E \quad \text{(dielectric)}$$





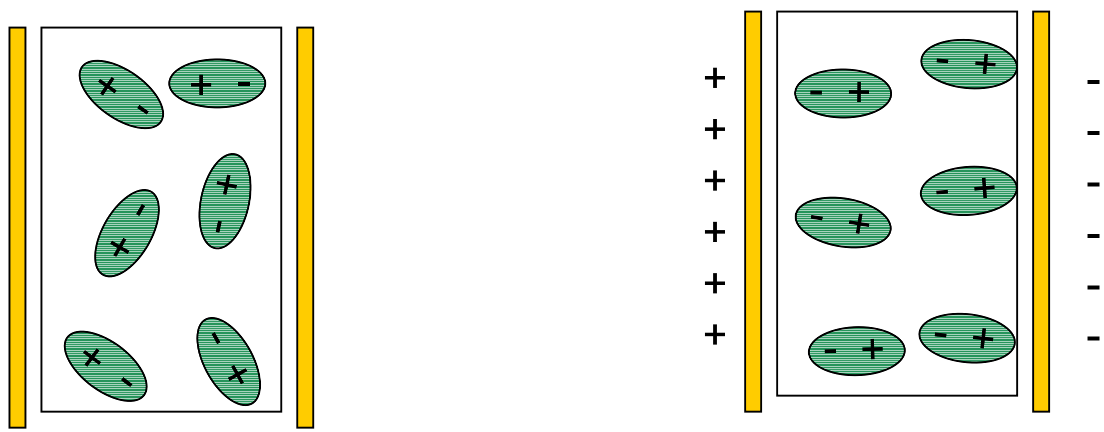
Dielectric Polarization

Under the influence of an applied field the dipoles of the dielectric align

Charge Q' = P x Area

P is dipole moment per unit volume

$D = \varepsilon_0 E + Q'/A = \varepsilon_0 E + P$



No field – random orientation of dipoles

Polarized by applied field –dipoles oriented in same direction

$$P=(\varepsilon_0(\varepsilon_r - 1))E$$

Types of Polarization

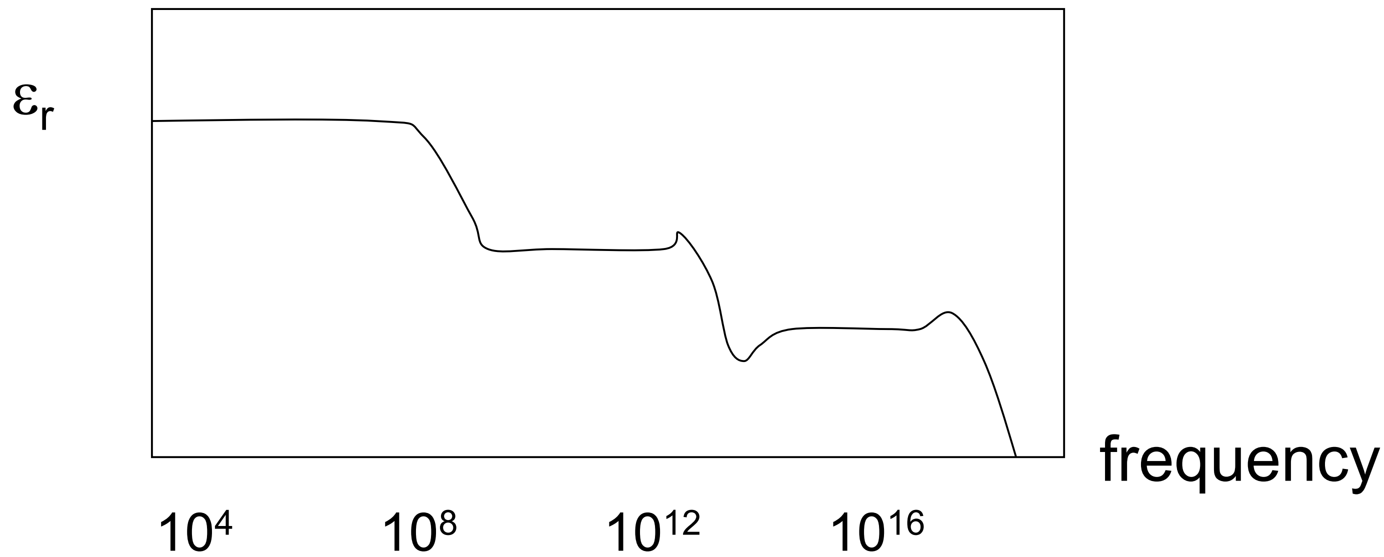
- Electronic - Electron clouds move with respect to positive nucleus
  - Dipoles exist only in the presence of a field
  - Eg Ar; ε_r =1.0 : Si; ε_r =11.9

- Ionic – anions move in one direction and cations in the other
  - Dipoles exist only in the presence of a field
  - Eg NaCl ; ε_r =5.9 : CsCl; ε_r =7.2

- Orientation polarization
  - Molecules have permanent dipole moment
  - Decreases with decreasing temperature
  - H_2O; ε_r =80, PVC; ε_r =7.0

Dielectric constant – frequency dependence

- The dielectric response to an alternating field depends on the response time of the dipole moments
  - Electrons respond quickly to electric field changes
  - Permanent dipoles have a much slower response to fluctuating fields



Dielectric Strength

- At very high electric fields breakdown may occur
  - The electrons may be excited into the conduction band – current flows
  - The high energy density may cause local heating leading to localised melting and degradation

- The electric field at which breakdown occurs is the dielectric strength of the material

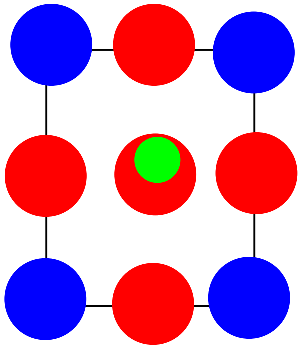
- Fused silica – dielectric strength 250-400 kV/cm

Capacitors

- Ideal properties
  - High dielectric constant
  - High dielectric strength
  - Low dielectric loss
- Metal Oxides make good capacitors
  - TiO_2
  - $BaTiO_3$
- Uses
  - Tuning devices and frequency selection
  - Energy storage in electronic flashes
  - Filtering in power supplies for electronic equipment

Ferroelectrics

- Ferroelectrics exhibit spontaneous polarization in the absence of an electric field
- eg $BaTiO_3$ – tetragonal unit cell
  - Ba^{2+} located at corners of cells
  - Ti^{4+} located just above cell centre
  - O^{2-} located just below face centre
- Above 130 °C structure becomes cubic – no net dipole moment
- Very high dielectric constant (~5000)
- Can be used for very small capacitors



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Piezoelectric Materials

- All ferroelectric crystals are also piezoelectric
  - The application of stress changes the polarisation and sets up an electric field
- A crystal can be piezoelectric but not ferroelectric
- Examples
  - $PbTiO_3$ and $PbZrO_3$
- Uses
  - Microphones
  - Strain gauges
  - Ultrasound generators
  - Quartz watches

Interconnects

- IC performance improvements achieved by reducing transistor size
- Signal delays now significant – limiting performance
- Delay depends on RC (figure of merit σ/ε_r)
- Traditionally Al/SiO_2 technology used
- Al now mostly replaced by Cu
- Require low k dielectric to replace SiO_2

Low k dielectrics

- Reduce polarizability
  - SiF, SiC, polymers
- Reduce density
  - Controlled porous material
- Requirements
  - Hydrophobicity
  - Mechanical stability
  - Thermal stability
  - Physical and Chemical stability
  - Compatablity

Electrical properties - Summary

- Conductivity
  - Ease with which a material is capable of transmitting an electric current
  - Depends on band structure
  - $j = \sigma E$
  - $\sigma = |e| (n_e\mu_e + n_h\mu_h)$

- Dielectric behaviour
  - Response of insulator to electric field
  - Electronic, ionic or orientational polarization
  - $D = \varepsilon_0\varepsilon_r E$
  - $P=(\varepsilon_0(\varepsilon_r – 1))E$

Magnetic Materials

Understanding the mechanisms that control magnetic behaviour will help us to tailor magnetic properties

Origin of Magnetism

- Electrons have an intrinsic magnetic moment (spin)

- In materials with closed shells (He, Ar, NaCl) the up spins are paired with down spins $\uparrow\downarrow$
  - No net magnetic moment

- All materials can have an induced moment in the presence of a magnetic field (diamagnetism)

- The atoms of some materials have unpaired spins
  - Net magnetic moment

Basic Definitions

Magnetic Field (H)	The applied field (A m^{-1})
Magnetic induction (B)	The total flux of magnetic field lines through unit cross section of material (Tesla T)
Magnetisation (M)	The magnetic moment per unit volume (A m^{-1})
Magnetic Permeability (μ)	The ratio of B/M
Permeability of free space (μ_0)	The ratio of B/M in a vacuum
Magnetic Susceptibly (χ)	The ratio H/M

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Equations

Permeability $\mu = B/H$

Relative permeability $\mu_r = \mu/\mu_0$

Magnetic Susceptibility $\chi = M/H$

$\chi = \mu_r - 1$

Magnetic Induction $B = \mu_0(H + M)$

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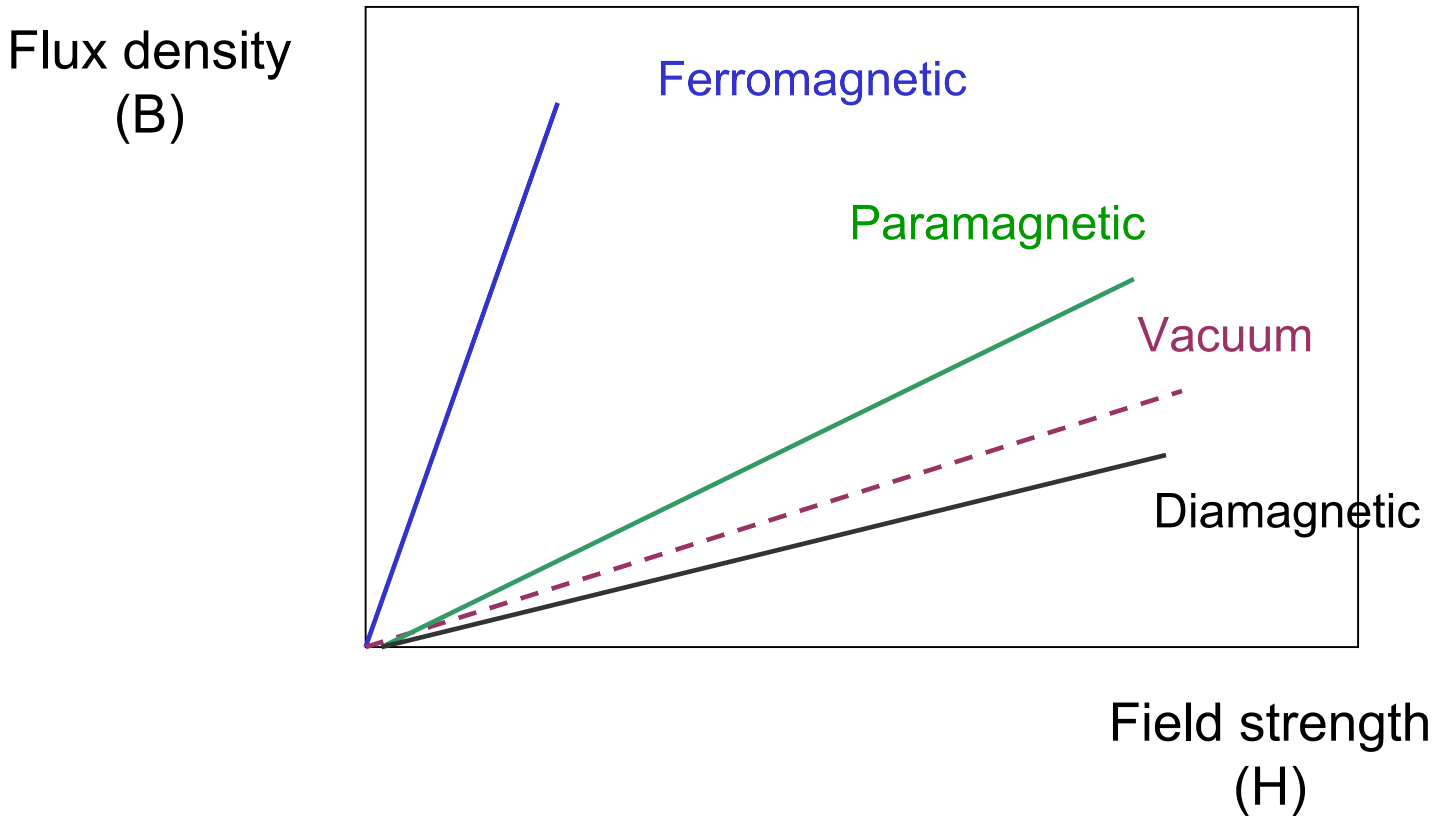
Types of Magnetism



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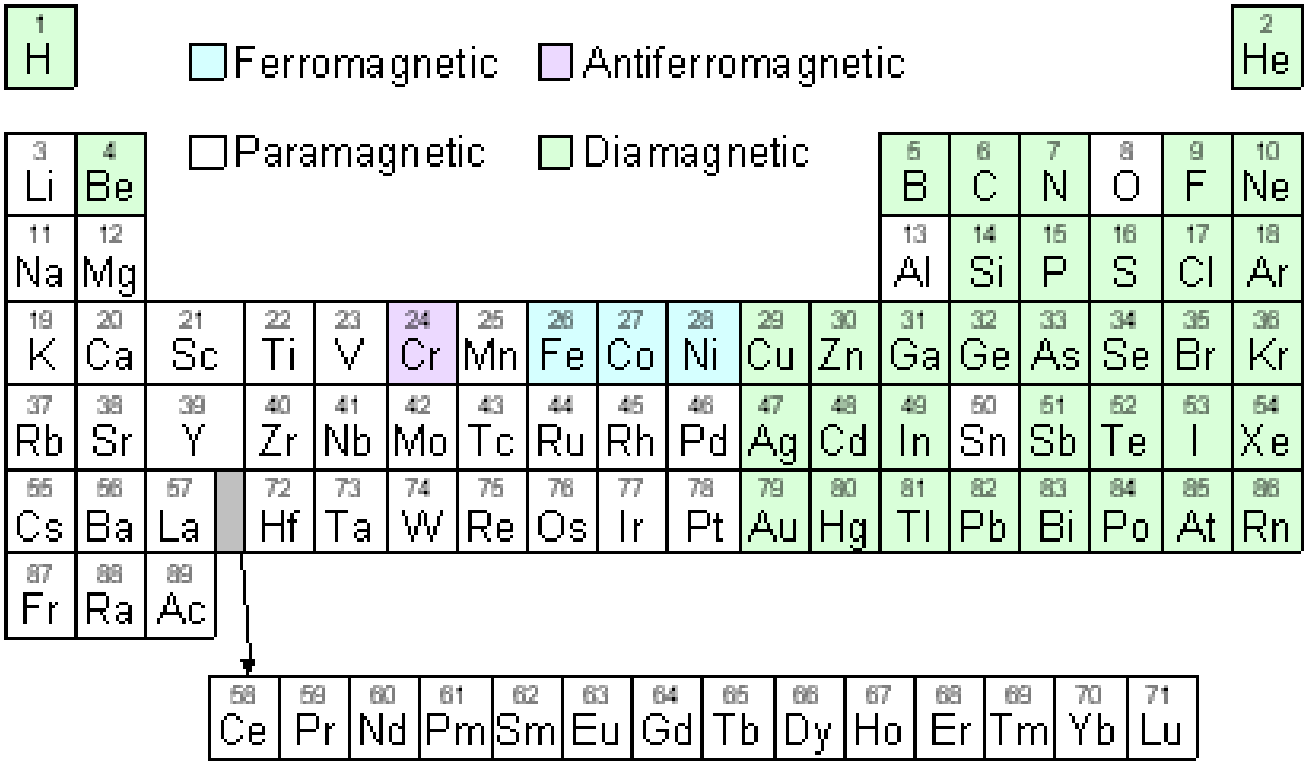
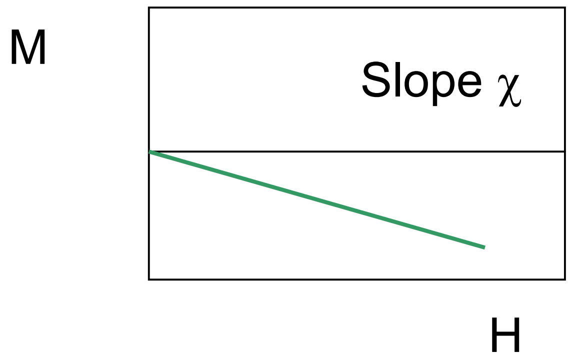
Magnetic Materials

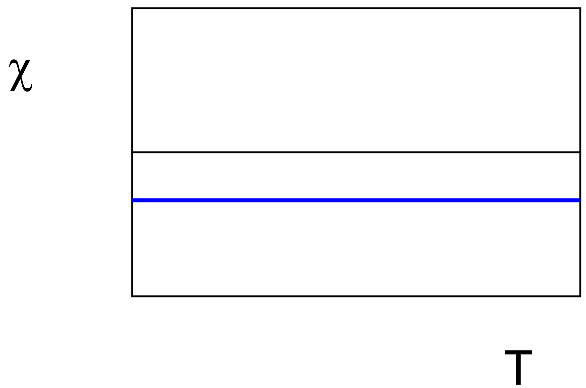


From www.aacg.bham.ac.uk/magnetic_materials.type.htm

Diamagnetism

- Diamagnetism originates from the response of the orbiting electrons to a magnetic field
- All materials exhibit diamagnetism
- Very weak – only apparent in materials with closed shells
- Susceptibility is very small and negative – induced moment opposes applied field





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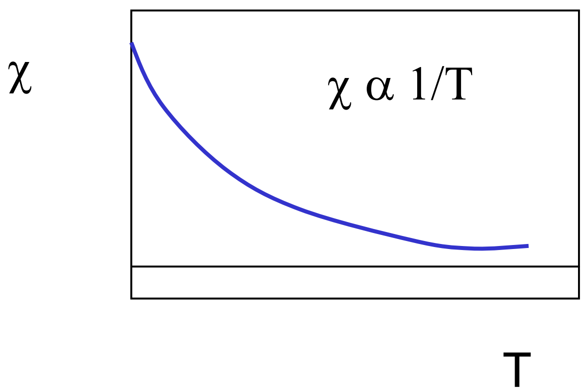
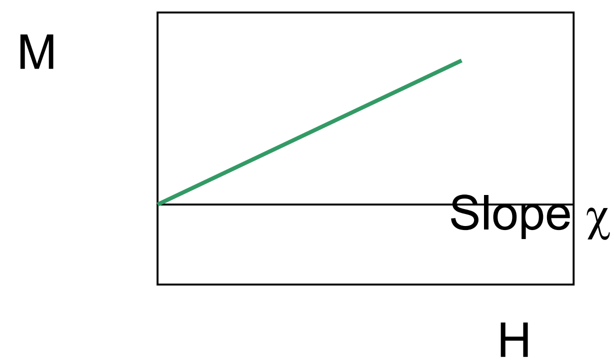
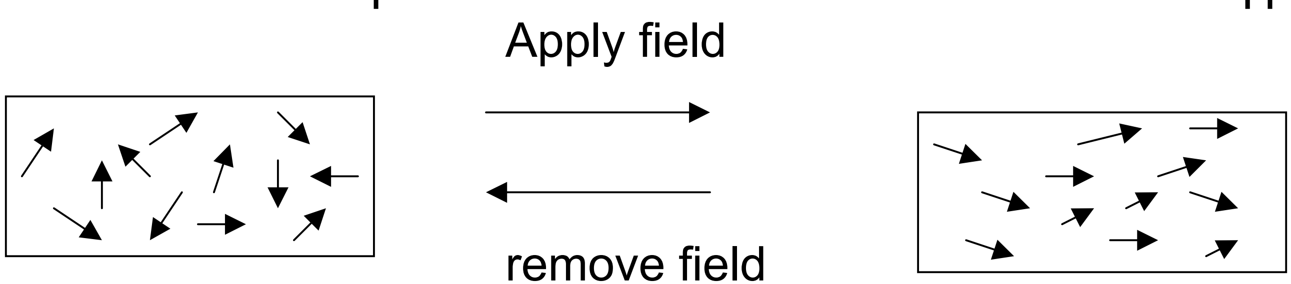
Paramagnetism

- Some atoms have unpaired electrons and therefore a net magnetic moment
- The atomic moments partially align with applied field
- Moments do not interact with each other therefore direction randomise on removal of the field







Temperature Dependence

Paramagnetic Materials

No interaction between spins

Curie law

$\chi = C/T$

Curie Weiss Law

$\chi = C/(T-\theta)$

$\theta > 0$ ferromagnetic

$\theta < 0$ antiferromagnetic

Ferromagnetism

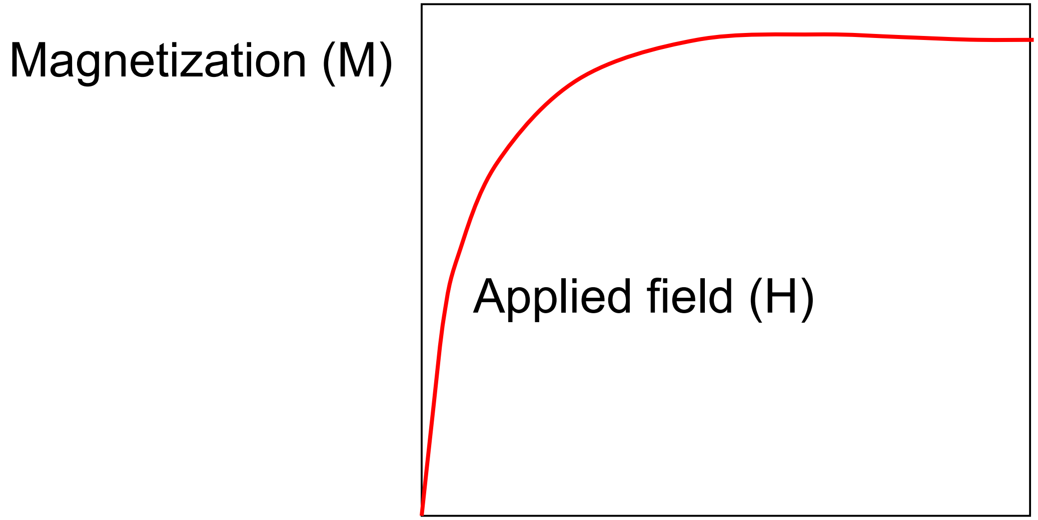
- Ferromagnetic metals Fe, Co, Ni
- Atoms have permanent magnetic moments
- Moments interact strongly (couple)
  - Significant gain in energy form aligning neighbouring spins
- Susceptibility much larger than paramagnets
  - Paramagnets $\chi \sim 5 \times 10^{-6}$
  - Ferromagnets $\chi \sim 10000 - 100000$
- Characteristics
  - Saturation magnetisation
  - Magnetic ordering temperature

Ferromagnetism

Saturation Magnetisation

The maximum induced magnetic moment that can be obtained in a magnetic field

The saturation magnetisation is an intrinsic property of a material

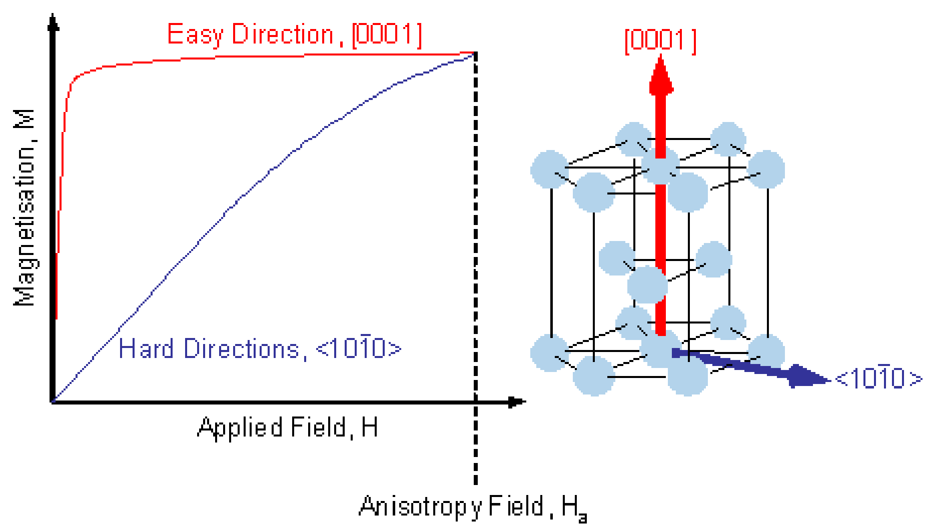


Magnetic Anisotropy

In crystalline magnetic materials the magnetic properties vary depending on the crystallographic direction along which the dipoles are aligned

Eg Co – easy direction (001)

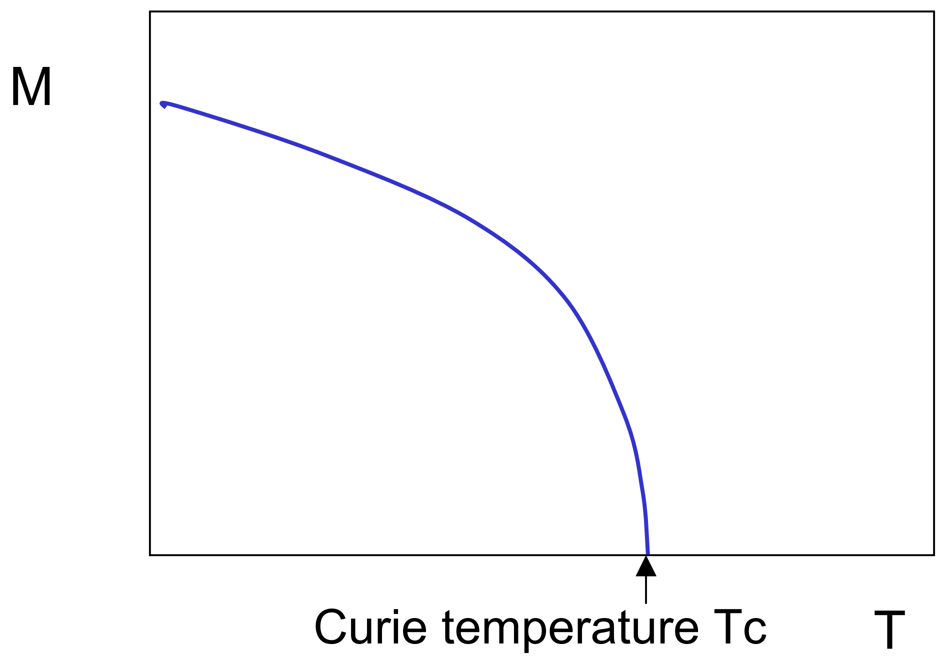
hard direction (100)



Temperature Dependence

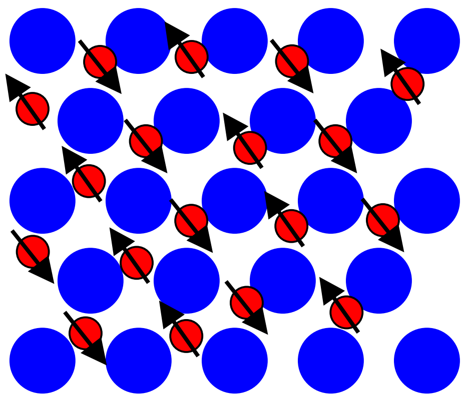
Thermal energy introduces a randomising effect which counteracts the exchange forces trying to align the moments

At some temperature, known as the Curie temperature the moments become disordered and the magnetisation goes to zero



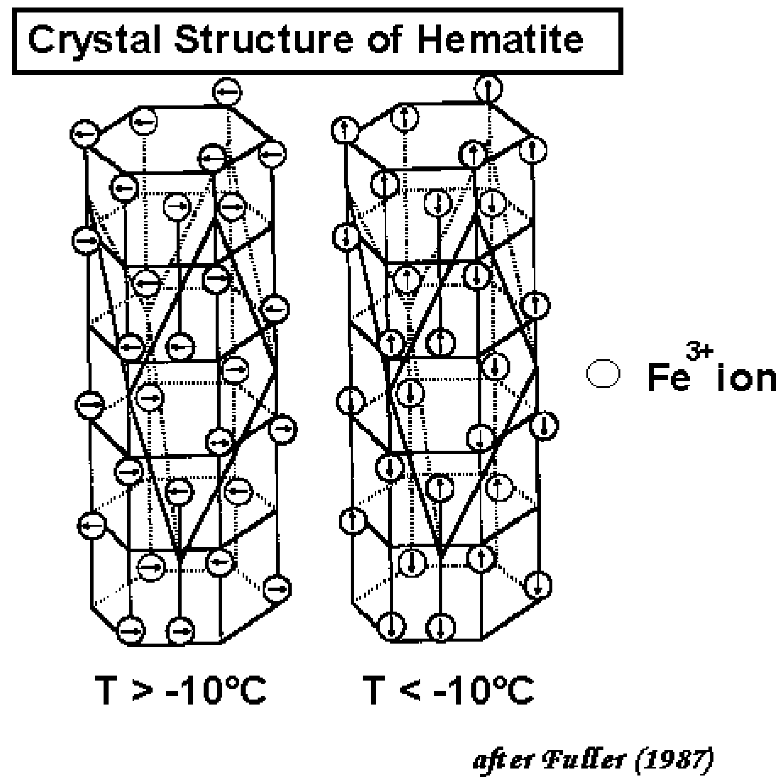
Antiferromagnetism

- Exchange interactions favour antiparallel alignment
- No net magnetic moment
- Cr only element displaying antiferromagnetism



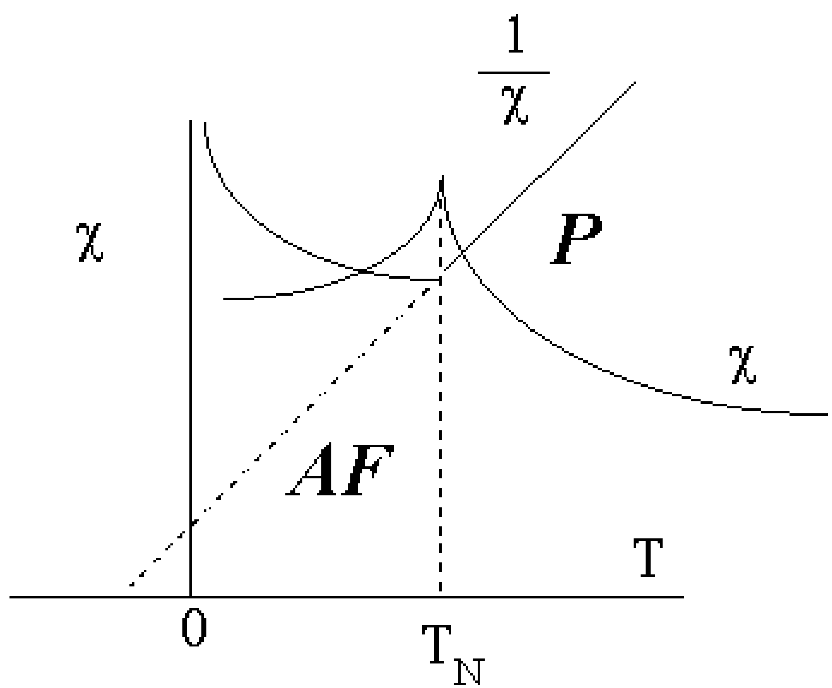
Hematite – α Fe_2O_3

- Corundum structure
- O^{2-} ions close packed hcp structure
- Fe^{3+} ferromagnetically coupled within planes and antiferromagnetically coupled between planes
- Transition at –10 C called spin-flop transition
- T_N = 673 C



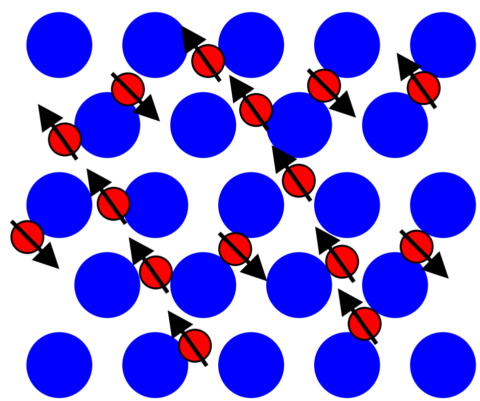
Antiferromagnetism - Susceptibility

- Critical temperature known as the Neel temperature (T_N)
- Above T_N Curie-Weiss susceptibilty – negative intersection is a feature of AF materials



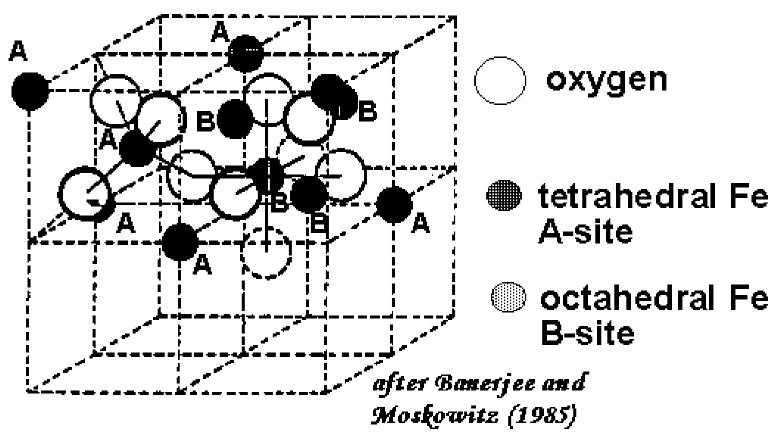
Ferrimagnetism

- In ionic crystals more complex magnetic ordering is possible as all the metal ions are not necessarily equivalent
- Example – an Iron oxide with 2 inequivalent Fe ions
  - Exchange interaction is mediated by O
  - Favours antiparallel spins
- Net magnetic moment as moment on one sublattice larger than the second



Magnetite - Fe_3O_4

- Well known example of a ferrimagnet
- Spinel structure
  - O^{2-} in FCC lattice
  - Fe ions fill gaps between the O^{2-} ions
  - 2 types of site
    - Tetrahedral – 4 O neighbours (A sublattice)
    - Octahedral – 6 O neighbours (B sublattice)
  - $(Fe^{3+})A(Fe^{3+},Fe^{2+})B\ O_4^{2-}$
  - Net moment comes from the Octahedral Fe^{3+} ions

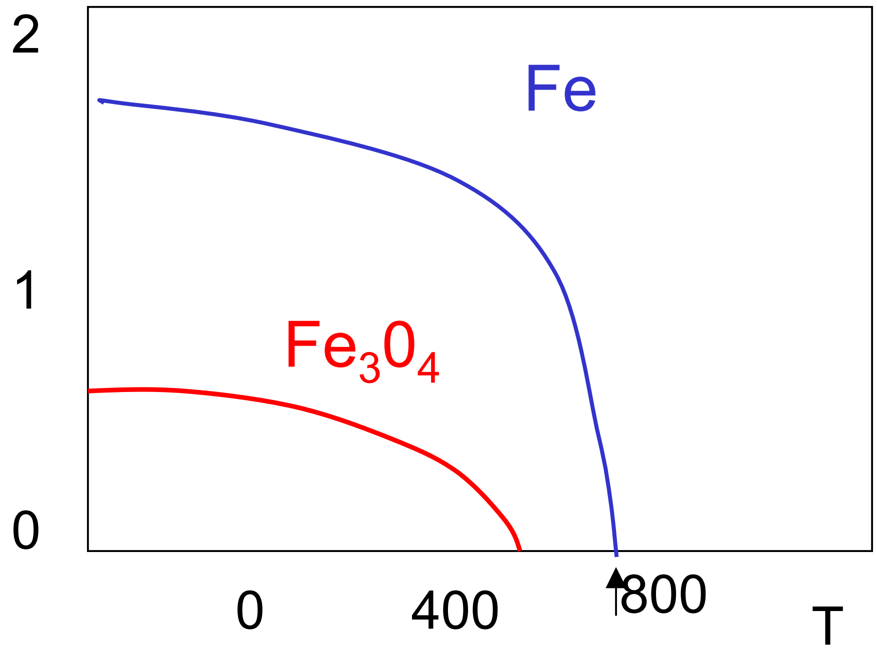


Saturation Magnetisation - temperature

Saturation

Magnetisation

10^6 A m^{-1}



Curie temperature Tc

Magnetic Domains

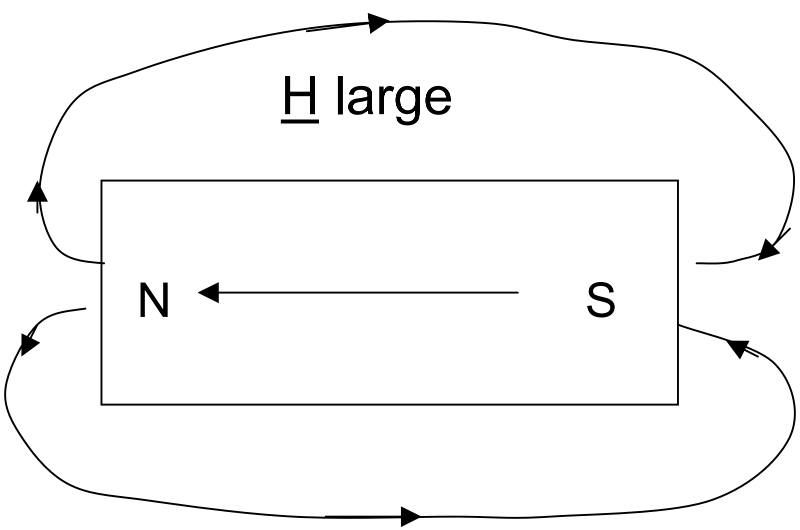
Hysteresis results from the domain structure of ferromagnets

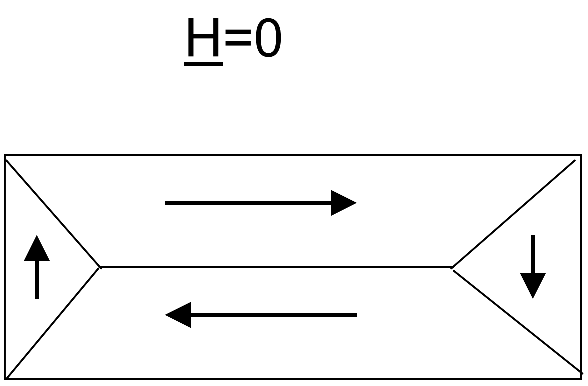
A demagnetised material has a number of volumes in which the magnetic moments are aligned

Domains minimize the magnetostatic energy $E = -\mu_o \int H.dM$

The number of domains depends on the shape of the sample and the intrinsic magnetic properties of the material

Largest domains have moments aligned along easy direction



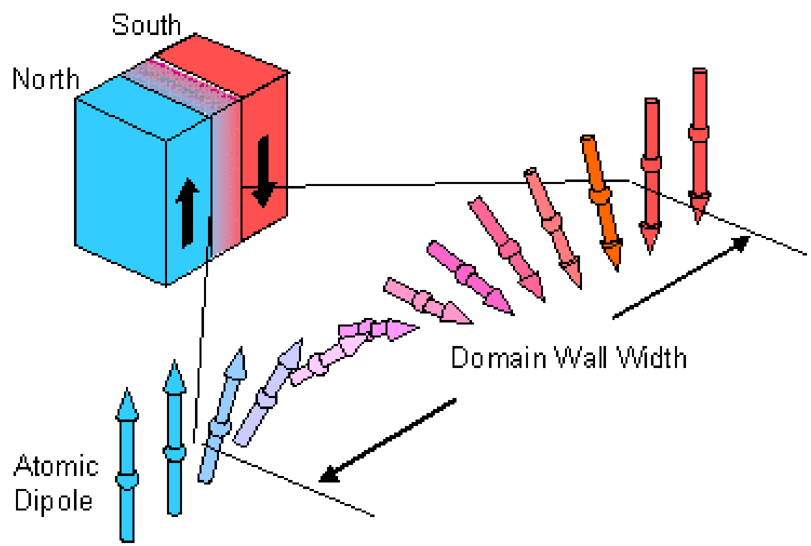


Domain walls

Magnetic domains are separated by domain walls

The magnetic moment rotates gradually in the wall

The rotation costs energy as the moments are not aligned



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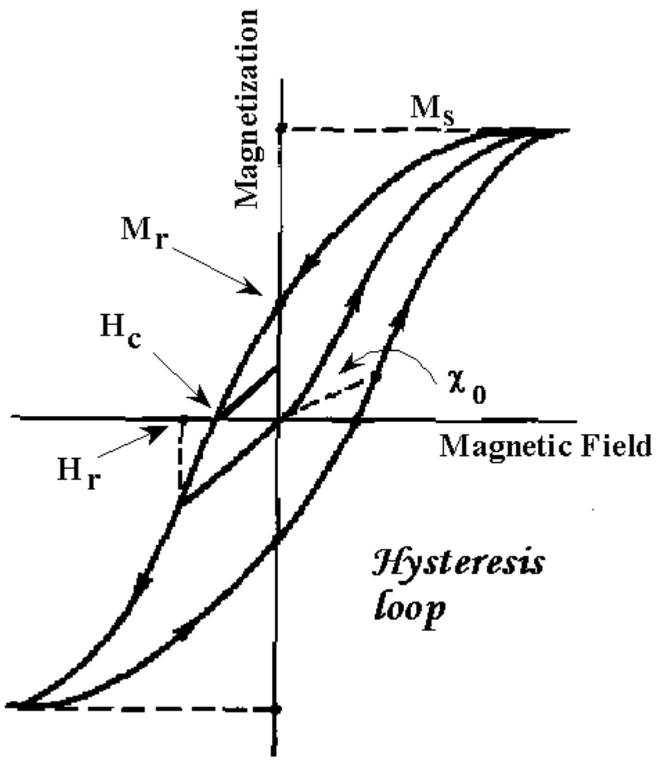
Hysteresis



Ferromagnets retain a memory of a magnetic field after it is removed

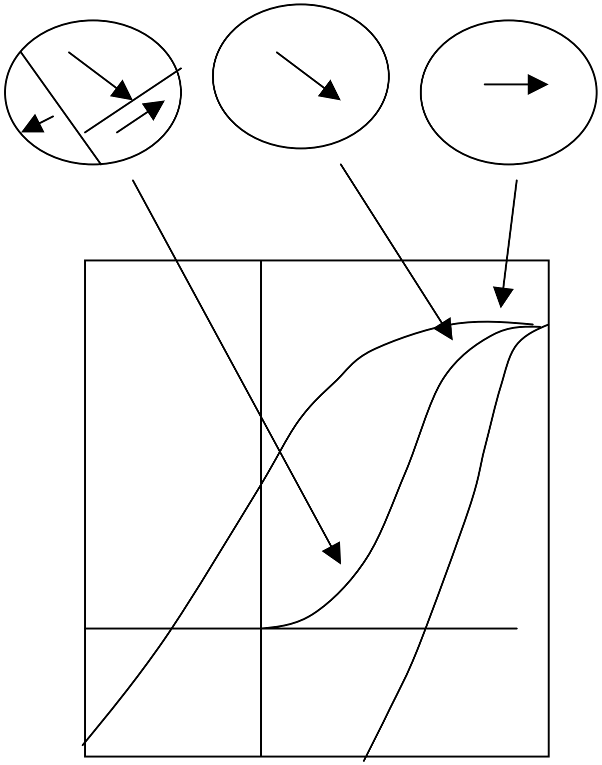
M_s is the saturation magnetisation

M_r is the remnant magnetisation (remanence)– the magnetisation remaining after field reduced to zero

H_c is the coercivity – reverse field required to reduce magnetisation to zero

Origin of Hysteresis

- As magnetic field is applied domains with most favourable orientations grow at the expense of the least favourable
- After size of most favourable domains reaches a maximum moment gradually rotates to align with the external field – saturation magnetisation
- On removal of the field the moments rotate to align with easy magnetisation direction
- On reversal of the field domains of opposite orientation form and grow



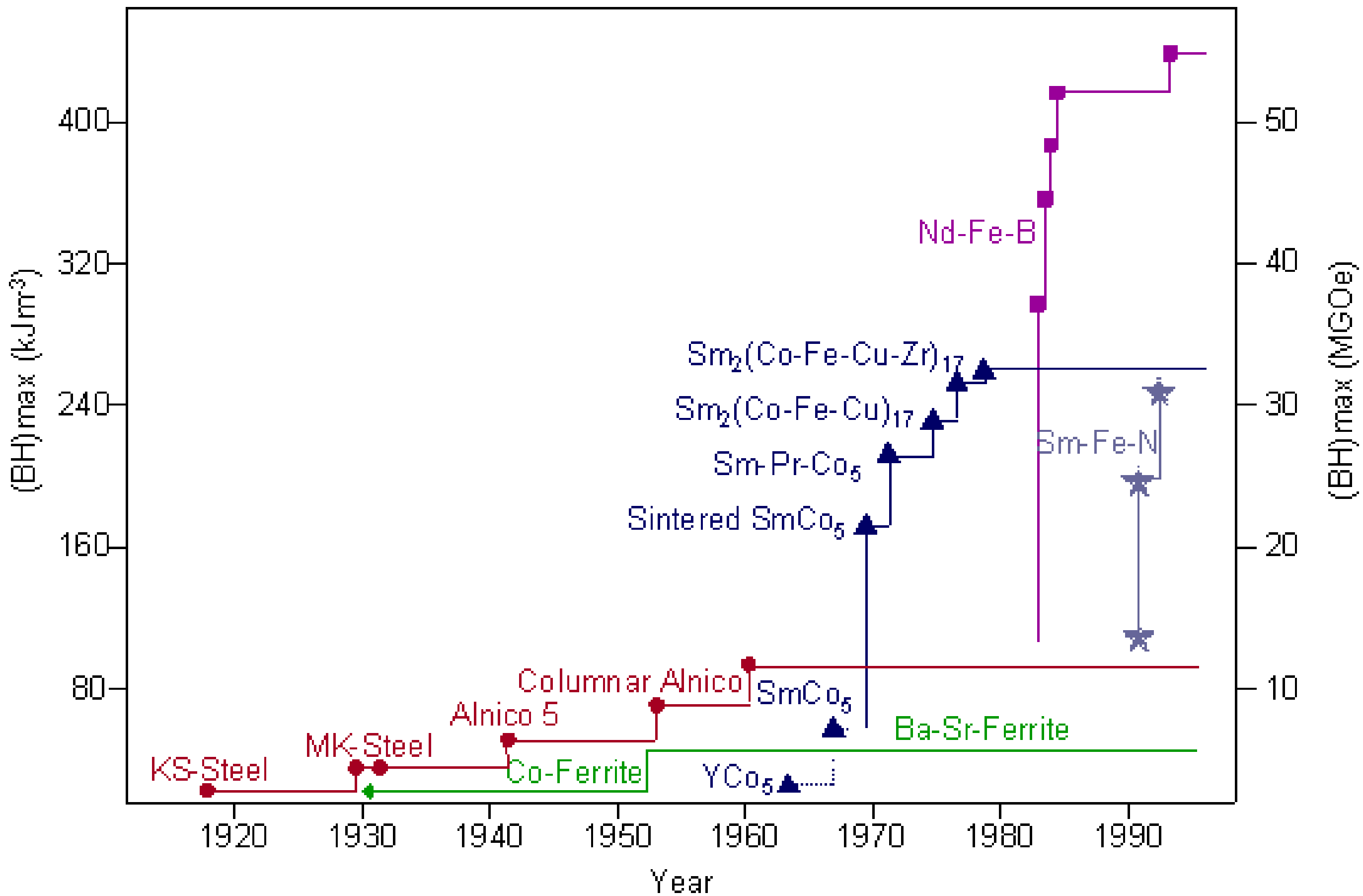
Hard and Soft Magnetic Materials

- The area within the hysteresis loop represents the magnetic energy loss per magnetisation cycle
- Hard magnetic materials
  - large loops
  - large energy loss
  - Difficult to magnetise and demagnetise
  - Permanent magnets
- Soft magnetic materials
  - Easily magnetised and demagnetised
  - Narrow loops
  - Small energy loss per cycle
  - Transformer cores

Hard Magnetic Materials

- High coercivity
- High magnetic remanence
- Strong anisotropy to inhibit easy rotation of domain walls
- Defects or precipitates to inhibit domain wall motion
- Examples
  - Conventional – 2-80 kJ m^{-3}
    - Cunife, alnico, hexagonal ferrites
  - High energy
    - SmCo, Neodynium-iron-boron

Hard magnetic materials



Alnicos

- First improvements over steel (early 1930's)
- Based on Ni, Co, Fe with Al, Cu, Ti
- Typical composition Fe35 Co35 Ni15 Al7 Cu4 Ti4
- High Curie temperature (~ 850 C)
  - Operate at high temperatures
- Low coercivity (~50 kA m^{-1})
- Microstructure
  - Oriented rods of strongly magnetic Fe-Co in matrix of weakly magnetic Ni-Al
  - Rod shaped grains give shape anisotropy
  - Domain walls pinned in weakly magnetic Ni-Al phase

Hard Ferrites

- Developed in 1950's
- Ferrimagnetic – hexagonal ($BaO.6Fe_2O_3$ and $SrO.6Fe_2O_3$)
- Low remanence
- High coercivity – far in excess of any other material
- Low $(BH)_{max}$
- Low cost
- Sintered in magnetic field – aligns easy magnetisation direction
- Most widely used permanent magnet material

SmCo type

- First rare-earth, transition metal alloy found to have permanent magnetic properties

- Rare earth provides anisotropy – transition metal provides magnetisation

- Very high $(BH)_{max}$ (240 kJ m^{-3})

- Careful control of microstructure
  - Ground to fine powder – aligned in magnetic field - sintered
  - Grain boundaries enriched with Cu
  - Domain wall energy reduced in boundary
  - Domain walls pinned

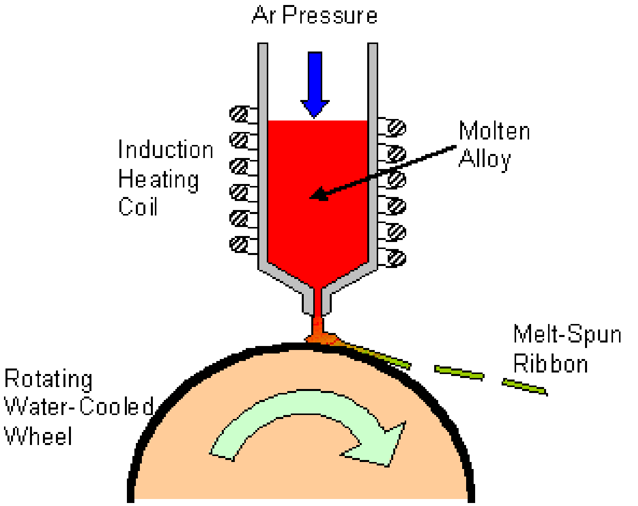
- Expensive raw materials

NdFeB

- Developed in 1984
- Based on $Nd_2Fe_{14}B$ alloys
- Very high $(BH)_{max}$
- Sintered (Japan)
  - As cast ingot broken to powder
  - Each particle single crystal – aligned in field
  - Sintered 1060 C for 1 hour

NdFeB – Melt spinning (USA)

- Molten alloy ejected onto surface of rotating water cooled wheel
- Microstructure very sensitive to quench rate
  - Optimum quench rate gives spherical $Nd_2Fe_{14}B$ grains ~ 20-100 nm
  - Single domain grains
- Powder then
  - Blended with resin to give isotropic magnet
  - Hot pressed (10% alignment)
  - Hot pressed followed by plastic deformation to reorientate grains



Hard magnets - Applications

- Motors – smaller and more efficient than electromagnets
- Cars
  - Starter motors, motor drives for wipers
- Telecommunications
  - loud speakers, microphones, switches and relays
- Consumer electronics
  - washing machine motors, drills, speakers
- Industrial
  - Motors for tools, Magnetic separators for metals and ores, lifting apparatus
- Aerospace
  - Instrumentation, compass

Soft Magnetic Materials

- Low coercivity - less than 1000 Am^{-1}
- Low magnetic remanence
- High relative permeability ($\mu_r = B/\mu_0 H$)
- Narrow hysteresis loop (low energy loss)
- Minimise structural defects for easy domain wall motion
- High electrical resistivity to reduce eddy currents
- Used for devices that are subjected to alternating magnetic fields

Soft Magnetic Materials - Fe-Si alloys

- Transformer cores - Low frequency AC (50-60 Hz)
- 3-4% Si - limited by embrittlement
  - increases resistivity
- Laminated (0.3-0.7mm) – reduces eddy currents
- Cold rolling orients grains in [100] direction for easy magnetisation

Amorphous & Nanocrystalline alloys

- Produced by melt spinning – rapid quenching
- Fe, Ni and Co with B, C, P or Si
- Extremely low coercivity (0.1 Am^{-1})
- High permeability (10^6)
- Low magnetisation therefore unsuitable for high current applications
- Nano-crystalline materials produced by annealing amorphous metals
  - Grains 5-50 nm
  - High resistivity and low anisotropy

Permalloy – Ni-Fe alloys

- Extremely versatile
- 30-80% wt Ni
- High Ni alloys have high permeability
- 50% wt Ni have high saturation magnetisation
- Low Ni alloys have high electrical resistance
- Special alloys (with Cu and Cr) have extremely high relative permeability (300000) and low coercivity $0.4 Am^{-1}$

Soft Ferrites

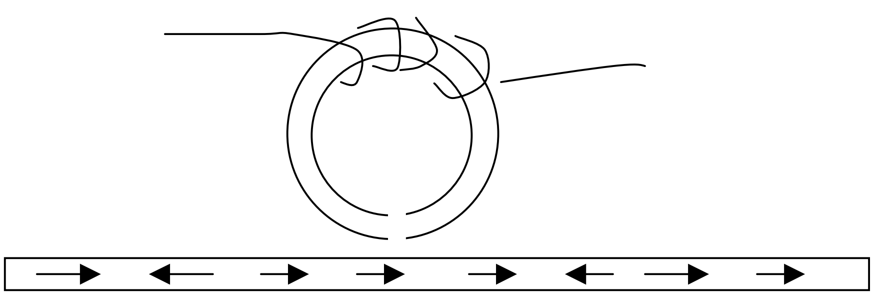
- At high frequencies eddy currents degrade the performance of soft magnetic metals
- Soft ferrites ($MO.Fe_2O_3$) normally used
  - M is Ni, Mn, Zn
  - Insulating
  - ferrimagnetic
- MnZn ferrite sold as ferroxcube used for telephone transmitters and receivers (10 MHz)
- YIG used for very high frequencies (microwave devices) (100MHz-500GHz)

Applications

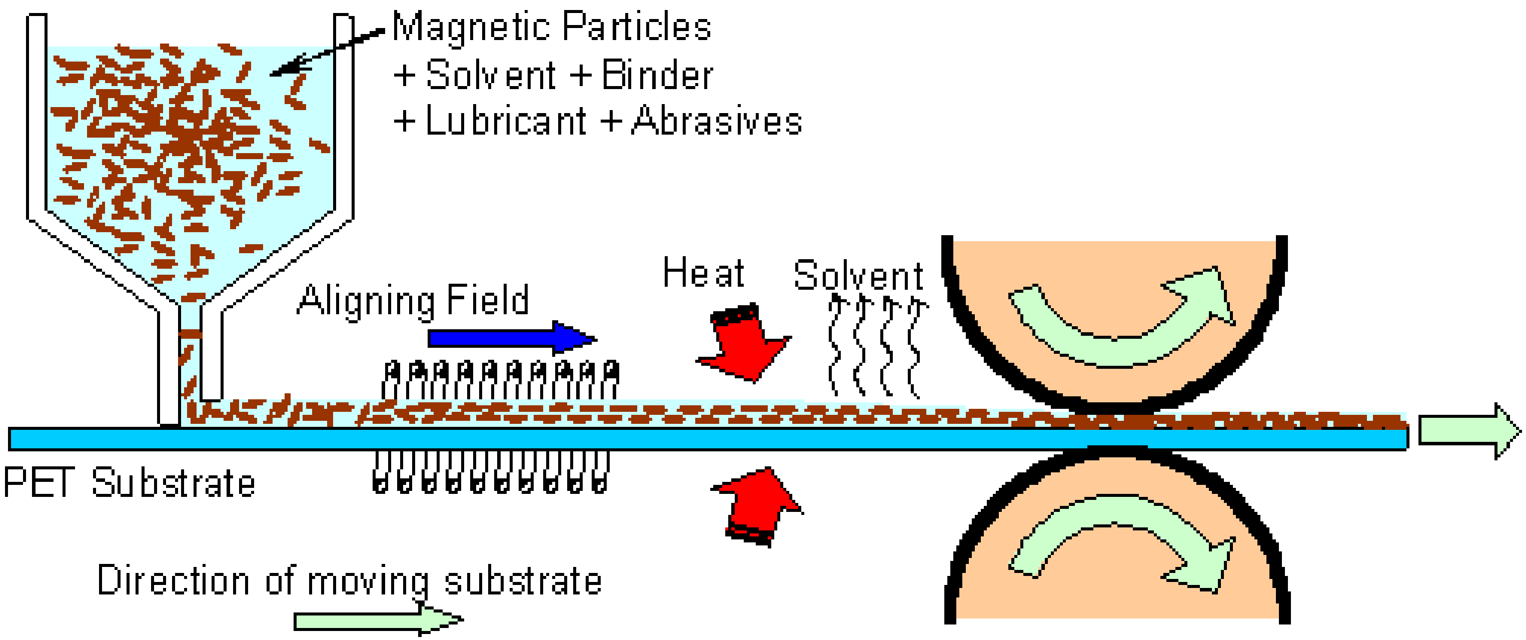
- AC
  - Transformers – converting one AC voltage to another
  - Electric motors
- DC
  - Magnetic shielding – high permeability magnet used to encapsulate device that requires shielding
    - $S = B_o/B_i = (4/3)\ \mu_r d/D$
  - Solenoid switches
  - Used to channel flux lines from permanent magnets

Magnetic recording media

- Disks and tapes of flexible plastic with dispersions of γ-Fe_2O_3 or $BaFe_{12}O_{19}$ magnetic particles
- Large quantity of data at low cost
- Read/write head – wire coil wrapped round a magnetic core with a gap
- Writing data – very small area magnetised by electrical signal to coil
- Reading data – change induced in coil by magnetised area of disk
- Needle-like particles aligned along direction of motion of head



Magnetic recording media - tape



From www.aacg.bham.ac.uk/magnetic_materials.type.htm

Magnetic disks

- Floppy disks – similar to tapes
- Hard disks
  - Al substrate
  - 10 mm Nickel phosphide
  - 5-10nm Cr
  - Magnetic layer 50 mm PtCo with Ta, P, Ni, Cr
  - 10 –20 nm ZrO_2
  - Monolayer of fluorocarbons

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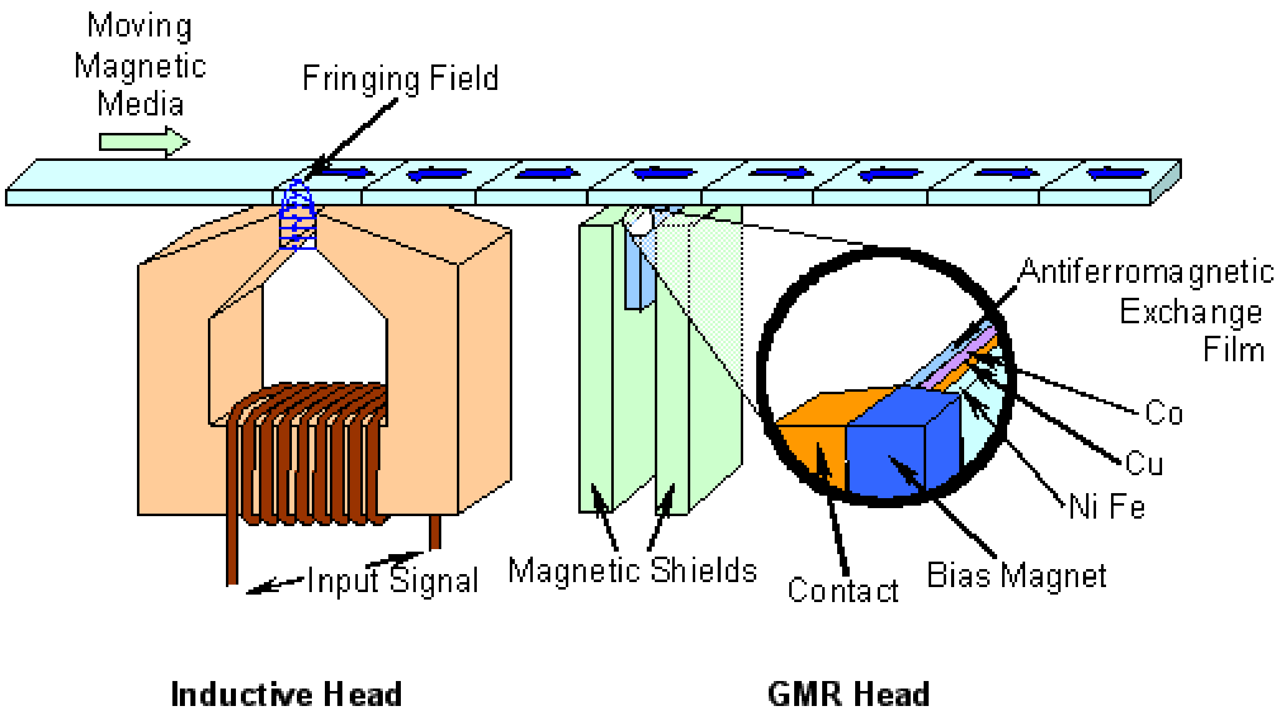
Read – Write head



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Magnetic Properties - Summary

- 3 Types of magnetic materials –depends on exchange interactions
  - Ferromagnetic
  - Antiferromagnetic
  - Ferrimagnetic

- Magnetic properties
  - Saturation magnetisation (intrinsic material property)
  - Curie temperature (intrinsic material property)
  - Relative permeability
  - Remanence
  - Coercivity
  - Energy loss per cycle
  - Maximum energy product

Optical Properties of Materials

Optical properties

The response of a material to an electromagnetic field

How well do materials

transmit, reflect and absorb light

Velocity of light in vacuum $c = 1/\sqrt{\varepsilon_0 \mu_0} = 3 \times 10^8$ m s^{-1}

$$c = \lambda \nu$$

$$E = h\nu$$

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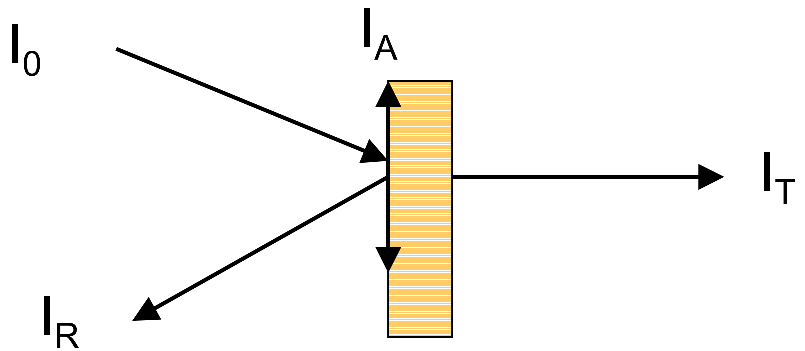
Interaction of Light with Solids

- When light proceeds from one medium to another some is
  - Transmitted to the 2nd medium
  - Reflected at the interface
  - Absorbed by the 2nd medium
- The total intensity of the incident beam is the sum of the intensities of the 3 processes
  - $I_0 = I_T + I_R + I_A$



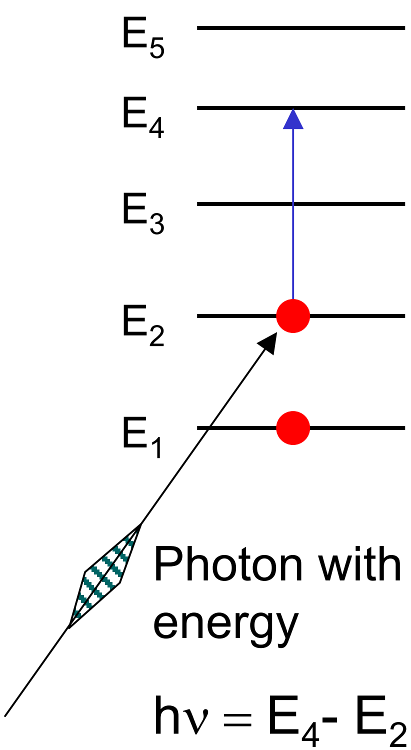
Optical Classification

- Transparent
  - Material is capable of transmitting light with little absorption or reflection
  - One can see through them
- Translucent
  - Materials through which light is transmitted diffusely
  - Light is scattered within the material
  - Objects are not clearly visible through the material
- Opaque
  - Materials which are impervious to the transmission of visible light

Atomic and electronic Interactions

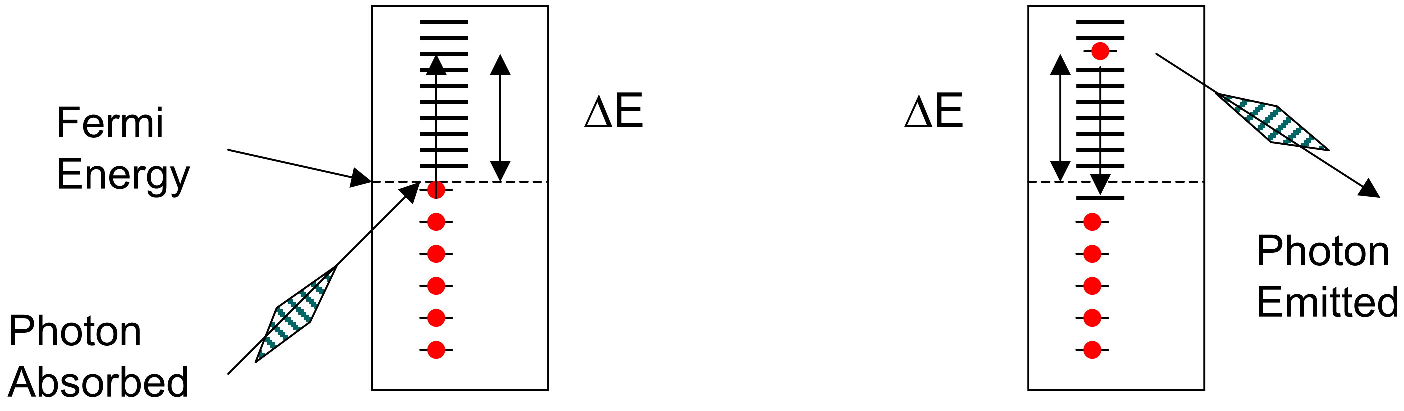
- Electronic polarization
  - An electromagnetic wave has a rapidly fluctuating electric field
  - This interacts with the electron cloud of the atoms
  - Some EM radiation is absorbed
  - The wave velocity is reduced – refraction

- Electron Transitions
  - A photon (energy $h\nu$) may be adsorbed by an electron
  - The electron is excited from an occupied state to a vacant higher energy state
  - Only photons with "allowed" energies (hence wavelengths) can be absorbed



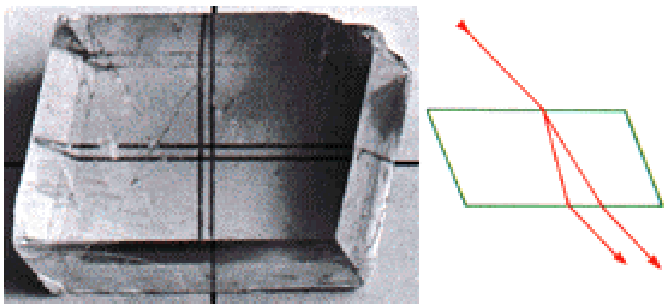
Optical Properties of Metals

- All frequencies of light absorbed
  - Continuum of available states
  - Total absorption within .1 μm of metal
- Most of the absorbed radiation reemitted as light of the same wavelength
  - Appears as reflected light
  - Reflectivity ~0.9 –0.95
  - Small proportion of energy from electron decay is dissipated as heat



Optical Properties of Non-metals

- Optical properties of non-metals depends on the band gap E_g
- For $E_g > 3.1$eV there are no states available to absorb visible light – transparent
- Light transmitted into the interior of a transparent material experiences a decrease in velocity (v)
  - Refractive index $n = c/v = \sqrt{\varepsilon_r \mu_r}$
  - Refraction is a function of electronic polarization
  - Increasing polarization by introducing large ions increases n (eg adding Pb to glass increases n from 1.5 to 2.1)
  - Different crystallographic directions have different values of n in non-cubic crystals - birefringence



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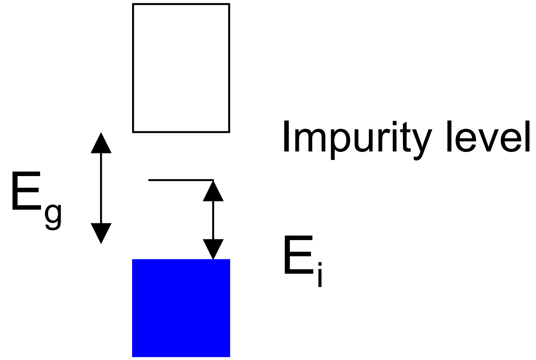
Reflection

- When light travels from one medium to another some of the light is reflected at the interface
  - $R = I_R/I_0 = ((n_2-n_1)/(n_2+n_1))^2$
  - For air n = 1
  - Therefore $R = ((n_2-1)/(n_2+1))^2$
  - Higher index of refraction the higher the reflectivity

- Reflection losses minimised by coating with very thin layer of dielectric material (eg MgF_2)

Absorption

- When Eg < 3.1 eV absorption may occur by the excitation of and electron into the conduction band
  - Eg > 3.1 eV material is transparent
    - No light absorbed
  - 1.8 eV < Eg < 3.1 eV material is coloured
    - Some wavelengths absorbed
  - Eg < 1.8 eV material is black
    - All wavelengths absorbed
- Impurities may introduce energy levels into the band gap – selective absorption at E_i



Transmission

- Incident beam I_0 falls on specimen length l and absorption coefficient β
- Transmitted intensity I_T
  - $I_T = I_0(1-R)^2 e^{-\beta l}$
- Depends on wavelength

Transparency in insulators

- Many ceramic insulators are intrinsically transparent but real materials are translucent or opaque

- Al_2O_3
  - Single crystal is transparent
  - Fully dense polycrystalline is translucent
  - Microporous material is opaque

- Polymers
  - Highly amorphous polymers are transparent
  - Semi-crystalline polymers are translucent
  - Highly crystalline polymers are opaque

Applications - Transmission

- Windows
- Lenses – shape or graded refractive index
- Diffraction gratings
  - Surface with parallel grooves
  - Separates light into separate wavelengths
  - Used for measuring atomic spectra
- Optical fibres
  - Thin filaments of glass or plastic
  - Grades refractive index to promote internal reflection

Applications - Reflection

- Mirrors
  - Micromechanical switches for optical fibre applications
  - Reflecting telescopes
- Antireflective coatings
  - Create a double interface to give 2 reflected waves
  - Waves totally or partially cancel
  - Multiple layers for cancellation of several wavelengths

Applications - Absorption

- Photochromic sunglasses
  – Glass with AgCl and CuCl crystals

- Photography
  – AgCl -> Ag on absorption of photon

- Xerox
  – Based on Selenium
  – Maintains electrostatic charge

- Photocells
  – Absorb light to create free carries

- Liquid crystal displays

Colour

- Light of single wavelength has definite colour
  - 700 nm – 1.77eV – Red
  - 400 nm – 3.1 eV – Blue
- Observed colour of light of several wavelengths is a function of how the eye responds to light and how the brain interprets the signal
- Colour is a result of the combination of wavelength that are transmitted
- A transparent material with uniform absorption appears colourless (Glass, diamonds, pure Al_2O_3)

Colour – Selective absorption

- Semiconducting materials with band-gaps between 1.8 eV and 3.1eV will absorb fraction of visible light with energy greater than the band-gap by electronic excitations

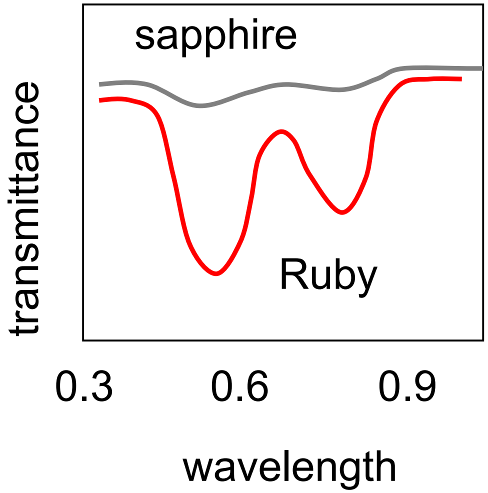
- Electron – hole recombination reemits some of the absorbed energy but not necessarily with the same wavelength

- Resultant colour depends on frequency distribution of both absorbed and reemitted light

- Example CdS – band-gap 2.4eV
  - Absorbs blue and violet – appears yellow/orange

Colour – Impurity absorption

- Ruby - Al_2O_3 + 2% Cr_2O_3
  - Cr ions introduce impurity levels into the band gap
  - Absorbs green and violet
  - Strong red colour



- Blue sapphire - Al_2O_3 + Fe + Ti
  - $Fe^{2+} + Ti^{4+} \rightarrow Fe^{3+} + Ti^{3+}$

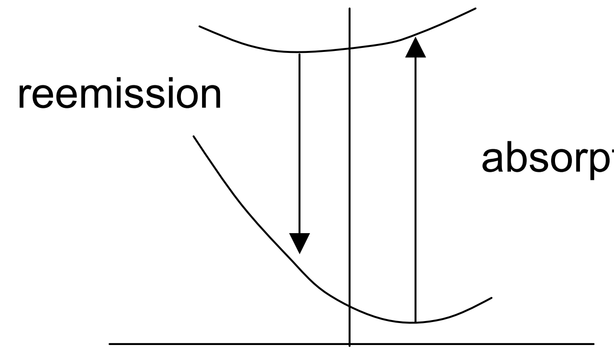
- Inorganic glasses coloured by adding rare-earth and transition metal ions
  - Unpaired d-electrons have allowed transitions in the visible range

Colour - Scattering

- Blue sky / red sunset
- Stained glass –colloidal metal particles
- Photochromic glass
- Birds feathers
  - Air cavities in a matrix of keratin

Luminescence

- Spontaneous emission of radiation from an electronically excited material
- Sources of energy
  - UV radiation
  - High energy electrons
  - Heat
  - Chemical reactions
- Fluorescence
  - Reemission time < 1 second
- Phosphorescence
  - Reemission time > 1 second



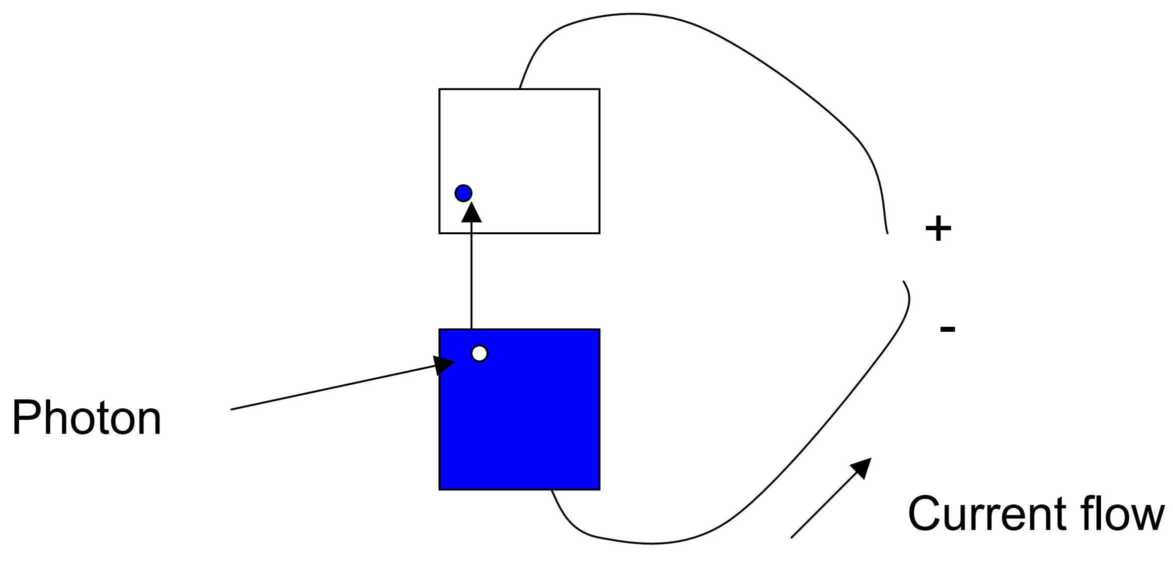
Energy difference dissipated as phonons

Luminescence - applications

- Fluorescent lights
  - Glass housing coated with silicates or tungstates
  - UV light generated from mercury glow discharge
  - Coating fluoresces and emits visible light
- TV screens
  - Electron beam causes coating to fluoresce
- Electroluminescence
  - LED's
    - Eg GaN – band gap 3.4 eV
    - Alloying with InN AIN modify band gap (1.9 eV – 6.2 eV)

Photoconductivity

- The conductivity of semiconductors depends on the number of free electrons in the conduction band
- Photon induced electronic transitions increase number of electrons in conduction band
- Applications
  - Light metres (CdS)
  - Solar cells



Lasers

- Electron transitions initiated by external stimulus

- Ruby laser (pulsed)
  - Rod of ruby (Al_2O_3 0.05% Cr^{3+})– one end totally reflecting, other end partially transmitting
  - Ruby rod illuminated with light from xenon flash light
  - Light (0.56μm) excites electrons from Cr^{3+} ground state
  - Some fall back directly to ground state
  - Others fall into metastable state where they reside for up to 3ms
  - Initial spontaneous emissions trigger avalanche of stimulated photons

Semi-conductor lasers

- Wavelength associated with band-gap energy must be in range of visible light (0.4-0.7μm)
- Voltage applied to material excites electrons across band-gap
- A few electron-hole pairs recombine – spontaneous emission of photon
- Emitted photons stimulate emission of further photons
- Continuous operation

Lasers - Applications

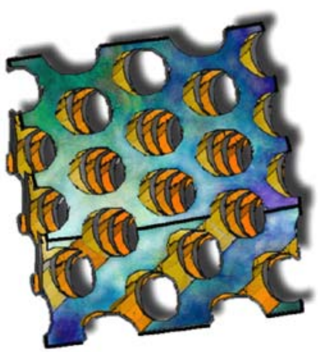
Laser	Wavelength (μm)	Power (W)	Applications
He-Ne	0.63,1.15, 3.39	0.0005-0.	line of sight communications
CO_2	9.6, 10.6	500-15000	welding, cutting
Ar	0.488,0.5145	0.005 – 20	surgery, distance measurement
Ruby	0.694	pulsed	hole piercing
Nd Glass	1.06	$5x10^{14}$ (pulsed)	pulse welding
Diode	0.33-4	0.6	bar-code, CD, optical communications

Optical fibres

- Optical fibres have revolutionised communication
- Replaced Cu wires for many applications
- Signal transmission is photonic
- Electrical signal converted to optical signal by semiconductor laser (IR)
- Fibres must guide light pulses over long distances without significant signal power loss or distortion
- High purity silica glass fibres (5-100μm diameter) – relatively flaw free
- Containment of light achieved by varying refractive index – total internal reflection

Optoelectronics

- The merger of optics and electronics
- Examples
  - TV
  - CD’s
  - Fibre optic communications
  - Displays
  - Bar code scanners
  - IR detectors
  - Optical sensors
  - Photonics



Summary

- Optical behaviour is a function of interaction with EM radiation

- Materials either
  - Transparent
  - Translucent
  - Opaque

- Metal absorb then reemit light

- Insulators either intrinsically transparent or opaque
  - Opacity can be varied by microstructure