

ENGINEERING TRIPOS PART IIB

Thursday 3rd May 2007 2.30 to 4

Module 4C3 : ELECTRICAL AND NANO MATERIALS SOLUTIONS

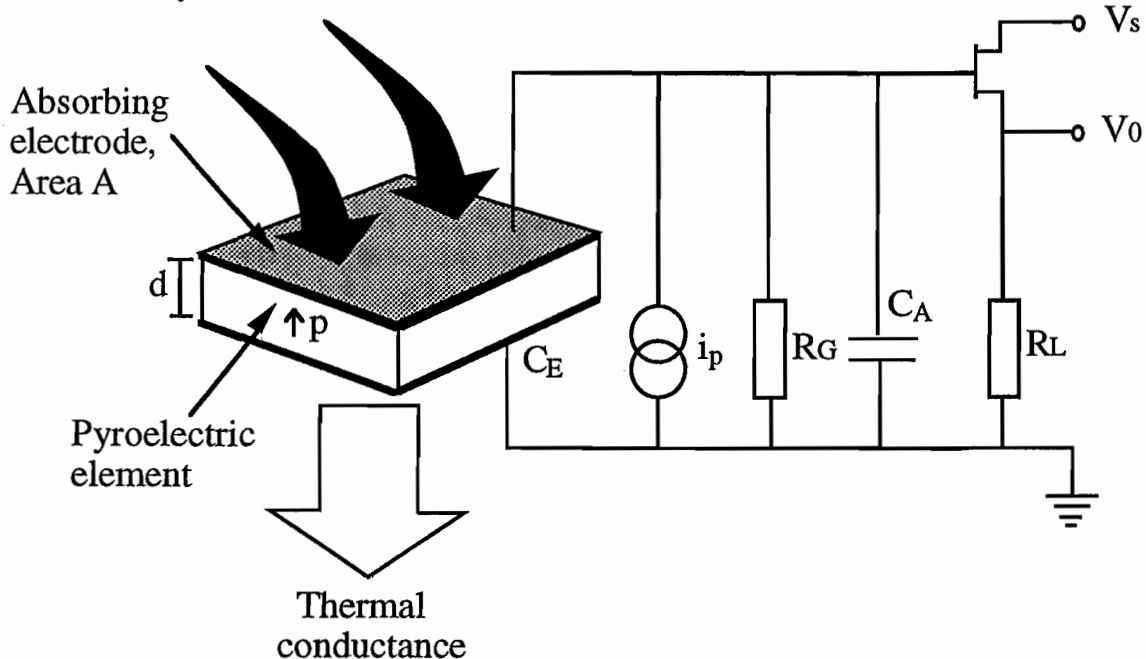
1(a) Pyroelectric materials are sub-classes of dielectrics, and are characterised by an asymmetry in their crystallographic structure, which leads to polar properties. Pyroelectricity occurs in polar dielectrics whose structure contains at least one *axis* along which an electric dipole moment exists (in contrast to piezoelectrics, which are characterised by point symmetry). Only 10 of the 21 dielectric structures, therefore, exhibit pyroelectric properties (orthorhombic, tetragonal and triclinic, for example). A pyroelectric material is necessarily piezoelectric, although the converse is not true.

Ferroelectrics are the most useful form of pyroelectric materials for the manufacture of pyroelectric devices, although not all pyroelectrics are ferroelectric. Ferroelectrics are polar materials in which the direction of the spontaneous dipole moment can be changed by the application of an electric field due to the presence of a number of polar axes in the crystal structure (which is a particular feature of the perovskite lattice). As a result, ferroelectrics may be processed in the form of ceramics (polycrystalline materials), and polarised using an applied electric field. This is cheaper and easier than using non-ferroelectrics such as LiTiO_3 , which has only one polar axis and, therefore, has to be processed in the form of a single crystal. This is both complex and expensive (although single crystals tend to have higher pyroelectric coefficients than polycrystalline materials). Finally, some ferroelectrics undergo a structural phase transformation to a lower crystal symmetry at the Curie temperature, T_c , which limits their pyroelectric response.

[25%]

(b) The following circuit is used in a pyroelectric device;

Incident radiation,
sinusoidally modulated



Incoming infra-red radiation is modulated and focused onto the pyroelectric element (which has been coated in a radiation-absorbing surface, such as platinum-black). This causes the temperature of the element to rise, and for its intrinsic polarisation to decrease. This, in turn, causes charge to be released from the element (which is effectively the dielectric filling in a capacitor), with the amount of charge being directly proportional to the temperature change. The signal is then amplified using a FET, which has high input impedance to take the signal from a high impedance source. For a good response, a pyroelectric element should:

1. Absorb and retain as much heat as possible during charge release monitoring;
2. Have a low thermal capacity (for max. temperature rise for given heat input);
3. Retain the charge long enough for it to be amplified (long enough electrical time constant required).

The detector will operate under (i) current mode at low frequencies (~10 Hz - current has time to flow) and (ii) voltage mode at high frequencies (~kHz - current does not have time to flow).

[25%]

(c) Definition of R_V ; $R_V = \frac{i_p}{Y W_0}$ also $\Delta T = \frac{\eta W_0 e^{i\omega t}}{G_T + i\omega H}$ (given)

Substitute $Y = \frac{1}{R_G} + i\omega C$ ($C = C_E + C_A$) and $H = \tau_T G_T$;

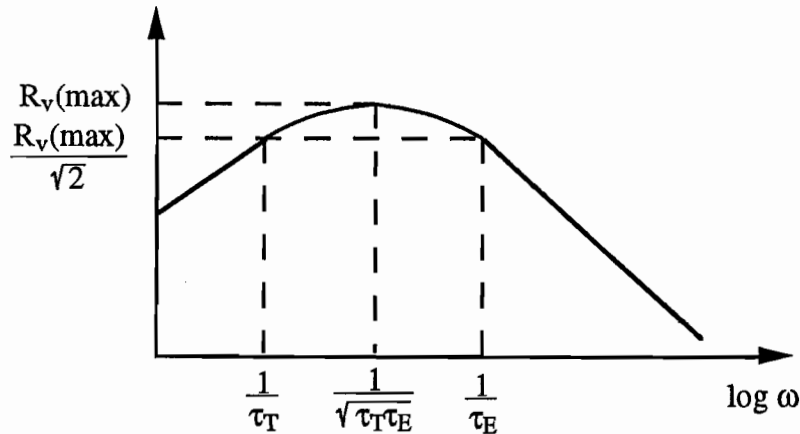
$$i_p = A p \frac{dT}{dt} = \frac{\eta p A i \omega W_0 e^{i\omega t}}{G_T + i \omega H}$$

$$R_V = \frac{i_p}{Y W_0} = \frac{\eta p A i \omega e^{i\omega t}}{G_T (1 + i \omega \tau_T) \left(\frac{1}{R_G} + i \omega C\right)}$$

But $C = \tau_E/R_G$ hence;

$$R_V = \frac{\eta R_G p A i \omega e^{i\omega t}}{G_T (1 + i \omega \tau_T) (1 + i \omega \tau_E)} = \frac{\eta R_G p A i \omega e^{i\omega t} (1 - i \omega \tau_T) (1 - i \omega \tau_E)}{G_T (1 + \omega^2 \tau_T^2) (1 + \omega^2 \tau_E^2)}$$

$$R_V = \frac{\eta p A R_G \omega e^{i\omega t} (i + \omega \tau_T) (i + \omega \tau_E)}{G_T (1 + \omega^2 \tau_T^2) (1 + \omega^2 \tau_E^2)} \quad |R_V| = \frac{R_G \eta p A \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2} \sqrt{1 + \omega^2 \tau_E^2}}$$



τ_T is the thermal time constant.

τ_E is the electrical time constant of the element and interface amplifier circuit.

τ_T and τ_E determine the frequency response of the detector, and the 3dB points in the response occur at frequencies of $1/\tau_T$ and $1/\tau_E$.

[25%]

(d) F_D is the figure of merit used to describe the optimum signal to noise ratio of the pyroelectric material. This is derived from the materials term in the expression for the detectivity of the device (this represents the responsivity to Johnson noise ratio) i.e.

$$D = \frac{R_V}{\Delta V_J} = \frac{p}{c \sqrt{\epsilon_r \epsilon_0 \tan \delta}} \times \sqrt{\frac{\eta}{4kT d A}} \times \sqrt{\frac{I}{\omega}}$$

Materials term
Design term

The full equation is not required!

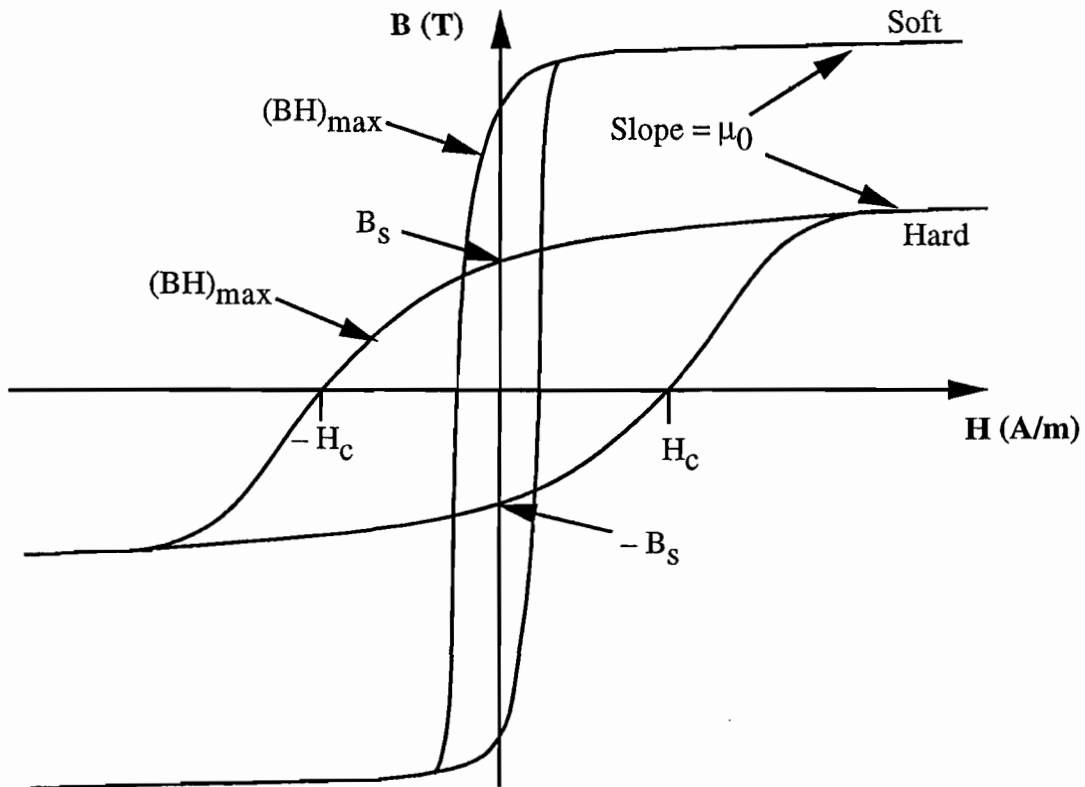
Therefore $F_D = \frac{p}{c \sqrt{\epsilon_r \epsilon_0 \tan \delta}}$, which needs to be evaluated for each material.

Material	T_c °C	p $\mu\text{Cm}^{-2}\text{K}^{-1}$	ϵ_r	$\tan \delta$ $\times 10^{-3}$	c $\text{MJm}^{-3}\text{K}^{-1}$	F_D $\times 10^{-6}/\sqrt{\text{Pa}}$
PZFNUTU	230	380	290	10	2.5	30
SBN - 50	121	550	400	3	2.3	73
PVDF	80	27	12	15	2.6	8
PGO	178	110	40	0.5	2.0	131

Order of potential is PGO, SBN, PZFNUTU and PVDF.

[25%]

2(a) Variation of flux density with applied field for hard and soft permanent magnet materials over a full field cycle;



Key features; B_s - saturation flux density

H_c - strength of domain wall pinning centres (i.e. microstructural imperfections)

Loop area = energy density per cycle

$(BH)_{max}$ occurs closer to the B axis for soft materials and closer to the H axis for hard materials.

[25%]

(b) Hard permanent magnet materials, such as Nd-Fe-B or $SmCo_5$, contain pinning centres that inhibit the movement of domain walls, and hence have a high coercive field, H_c (of the order of 100 kAm^{-1}). Hard permanent magnets are able to retain their magnetisation and are able to resist the effects of de-magnetisation. As a result, they are used primarily in short, fat geometries. Soft permanent magnet materials, such as pure iron and permalloy, contain very few domain wall pinning centres and, as a result, are unable to resist the effects of de-magnetisation. They have a low H_c (of the order of Am^{-1}) and are used typically in long, thin geometries. The remanent field associated with hard permanent magnetic materials is typically lower than that associated with soft materials ($< 1 \text{ T}$, compared to $> 1 \text{ T}$).

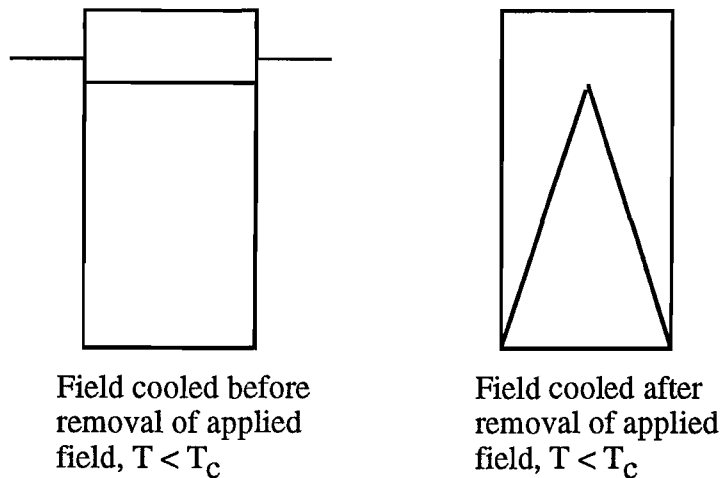
Applications of hard permanent magnet materials include (i) rotors for dc permanent magnet motors, (ii) magnetic sensors in alarm systems, (iii) fridge magnets, (iv) generators in Faraday devices such as 'kinetic' watches and torches, (v) water pumps in washing machines and (vi) magnetic stirrers and holders (2 examples required).

Applications of soft permanent magnet materials include (i) transformer cores, (ii) magnetic shielding in MRI, (iii) magnetic circuits in motors and generators, (iv) electromagnets and (v) linear motors (2 examples required).

[20%]

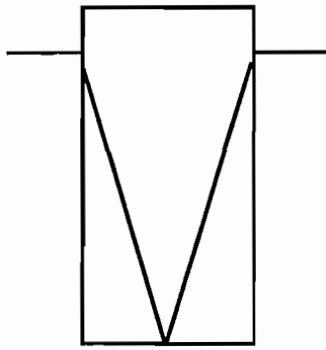
(c) Magnetic flux density is generated in bulk superconductors by the Faraday effect. This involves applying a changing magnetic field to the superconductor, which induces an e.m.f., which causes an Eddy current to flow throughout the bulk material. The Eddy current, in turn, generates magnetic flux. As a result, bulk superconductors generate fields in a way analogous to wire-wound solenoids. The magnitude of the net magnetic moment depends on the magnitude of these induced currents and the area over which they flow. Hence the volume magnetisation (defined as the net magnetic moment per unit volume) increases in direct proportion to the cross sectional area of the sample, normal to the direction of applied magnetic field (i.e. in proportion to r^2). This mechanism is different to that of field generation in permanent magnets, which is based on the alignment of individual electron spins.

A bulk type II superconductor can be magnetised *either* by cooling in an applied magnetic field of magnitude at least the equal to the maximum trapped field and then removing the field (the field cooling, or FC, method) *or* by cooling the superconductor in the absence of a magnetic field (zero field cooled, or ZFC) and then applying and removing a field of magnitude at least twice that of the maximum trapped field (assuming J_c is independent of B). In the field cooled case, immediately before the field is removed, the field in the slab is uniform and equal to the maximum trapped field. Removal of the field results in the loss of flux from the slab and the formation of the characteristic Bean distribution;

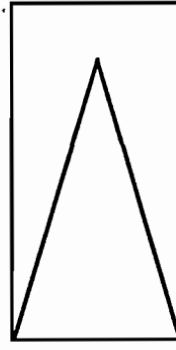


In the zero field cooling case, application of a field below T_c causes field to penetrate the superconductor from the outside surface inwards, with the gradient in field directly proportional to the critical current density, J_c , i.e. $\frac{\partial B}{\partial x} = \mu_0 J_c$. This field distribution is

inverted when the field is removed (since the sign of $d\phi/dt$ changes). Full inversion of the profile is only achieved if the magnetising field is at least twice the trapped field;



Zero field cooled before
removal of applied
field, $T < T_c$



Zero field cooled after
removal of applied
field, $T < T_c$

In each case, the final trapped field profile is described by $\frac{\partial B}{\partial x} = \mu_0 J_c$. [25%]

(d) (i) The field generated at the centre of the long solenoid is given by;

$$B = \mu_0 \frac{N}{L} I = 4\pi \times 10^{-7} \times \frac{2000}{0.1} \times 10 = 0.25 \text{ T}$$

(ii) The field generated at the surface of the YBCO disc is given by;

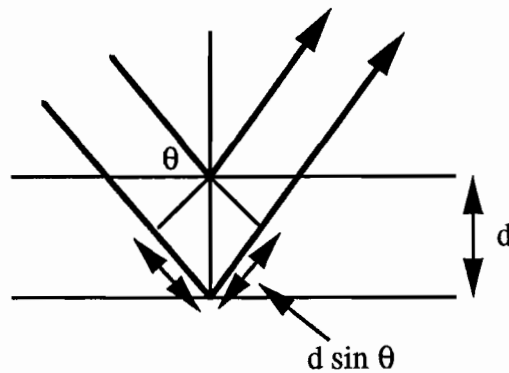
$$B = \mu_0 \frac{J_c d}{4} = 4\pi \times 10^{-7} \times \frac{20 \times 10^7 \times 0.02}{4} = 1.25 \text{ T}$$

The superconductor generates approximately $5 \times$ the field of the solenoid.

The factors that may limit realising these fields are;

Solenoid: Coil heating effects, which will reduce the current or cause the coil to melt.
YBCO: Bursting stress (pr/t) due to the magnetic pressure (YBCO is brittle, with a relatively low fracture toughness) and field dependence of J_c , which will reduce the trapped field at the surface of the cylinder. [30%]

3(a)(i)



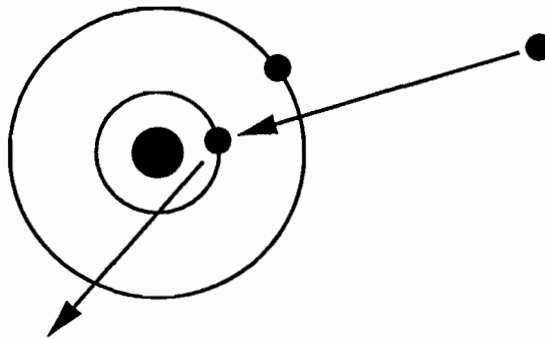
Path difference = $2d \sin \theta$

Constructive interference ('intensity spot') when $2d \sin \theta = n\lambda$

The angle at which diffraction peaks are found is measured either by the use of powder diffraction or by rocking a single crystal to tune into a particular X-ray frequency. [15%]

(ii) The values of the spacing, d , between the different lattice planes is characteristic of the structure of the material. As a result, the material can be identified from the diffraction pattern using tables. The amount of a particular phase present in a solid is determined from the intensity of the diffraction peaks corresponding to its structure. [20%]

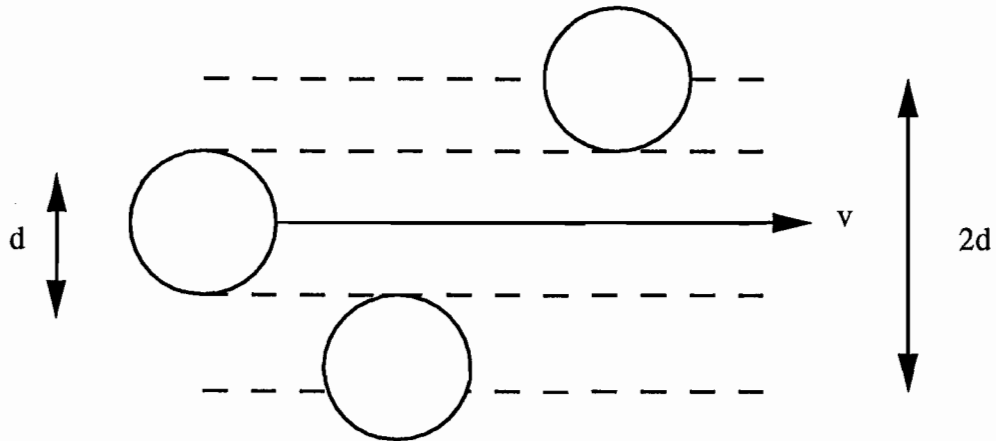
(iii) X-rays are generated when electrons hit a target material. The deceleration of the incident electrons gives a broad spectrum of X-rays. Electrons are 'knocked-out' of the inner orbits and, when another electron falls into the gap, an X-ray characteristic of the material is emitted.



[20%]

(iv) The energy of the X-rays depends on the square of the nuclear charge and the atomic number. Hence X-rays from light elements have little energy and are easily absorbed so these are difficult to detect. [15%]

(b)



A molecule moves a distance v in 1 second. It hits all those molecules whose centres are within d of the path; i.e. those within a cylinder of volume $\pi d^2 v$.

$$\text{Number of molecules hit per second} = N\pi d^2 v$$

$$\text{Time between hits} = \frac{1}{N\pi d^2 v}$$

$$\text{Distance travelled} = \frac{1}{N\pi d^2} \quad [10\%]$$

(i) For evaporation, the mean free path must be larger than the vacuum vessel so that atoms travel directly to the target. [10%

(ii) A plasma is required for sputtering so the mean free path cannot be too long and it is normally a fraction of the chamber size so that sputtered atoms make several collisions before arriving at the substrate. [10%

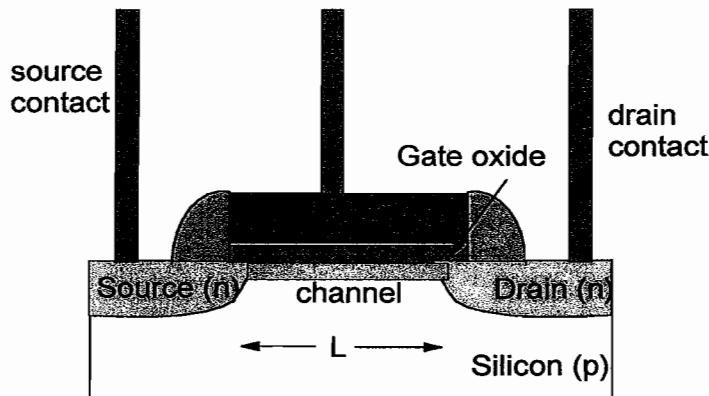
4(a) Moore's law is the observation that the size of transistors on an integrated circuit (scale) decreases (and hence) their operating speed increases in an exponential fashion with date (the packing density roughly doubles every 2-3 years).

Scaling means the same basic design is retained, but the size is reduced by a common factor in each dimension.

Moore's law is an economic law, not a scientific law.

[15%]

(b)



[15%]

(c) Performance limits;

channel - limit of mobility, operating speed

source, drain - doping density – limit conductivity, and thus maximum current density

source, drain contacts - higher conductivity, limit maximum current density

gate oxide - leakage current

channel length - speed, packing density

gate electrode - voltage range, switching

interconnects - current density

Materials improvements;

channel - Ge, GaAs or other high mobility s/cs

dopants – just implantation density

contacts - silicides

gate oxide - high dielectric constant oxide like HfO_2

interconnects - Cu

gate metal - new metal instead of poly-Si

[35%]

(d) The main conduction method through the gate oxide is by direct tunnelling. This varies exponentially on the oxide thickness as;

$$J = J_0 \exp(-2k t)$$

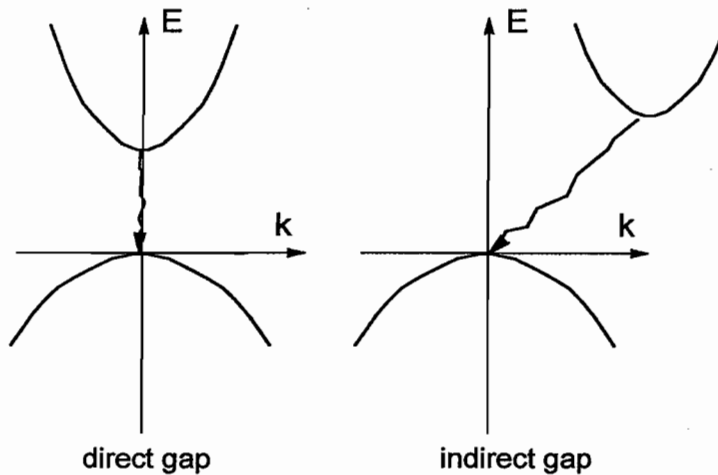
where k is the wave number, and t is the oxide thickness. Also $\hbar^2 k^2 / 2m = E$.

Current can only be decreased by increasing t , although C can be kept constant (and thus the FET operation) by increasing ϵ by the same amount. This is because

operation is determined from source-drain current equation by the capacitance per unit area, $C = \epsilon/t$.

[35%]

5(a) Band structure of typical semiconductor material;



valence band at bottom – filled states
conduction band at top – empty states
band gap of forbidden energy range in middle – no states

Differences between direct and indirect band-gap materials;

Direct gap material has a valence band and conduction band extrema at the same k point.

Indirect gap material has extrema at different k points.

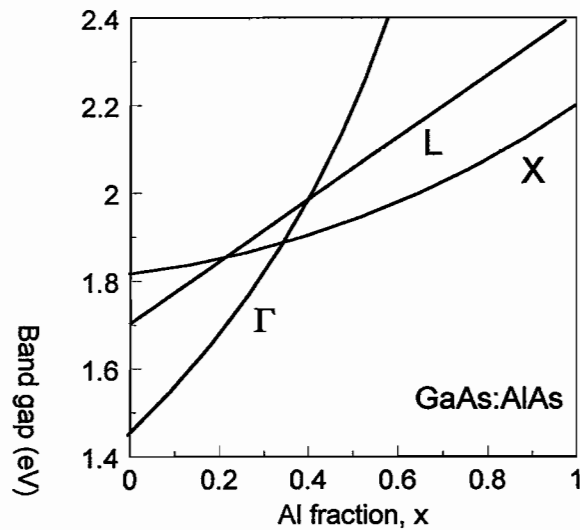
Significance of the nature of the band gap;

A direct gap is necessary for strong optical transitions to avoid the need for phonon participation by momentum conservation.

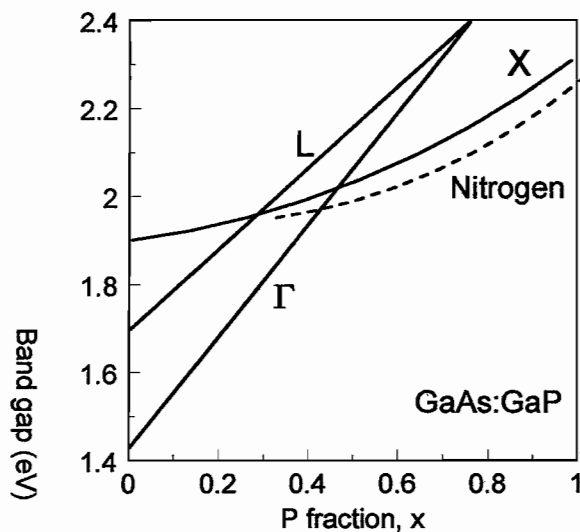
[20%]

(b) Strategies for increasing band gap;

(i) Alloying



(ii) Introduction of deep levels



[20%]

(c) The effective mass is the curvature of a band extrema. It is defined from the dispersion equation;

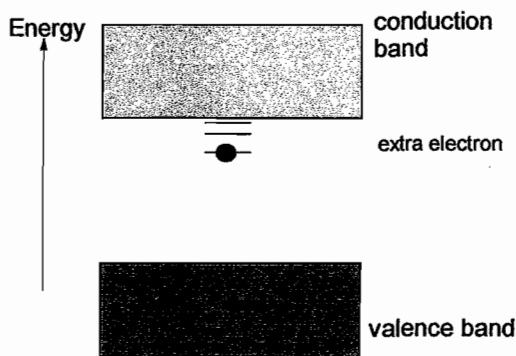
$$E = \hbar^2 k^2 / 2m^*$$

where k is the electron's wave vector, E is the electron energy, h is Planck's constant. m^* is the effective mass. Thus the band curvature in this quadratic equation is the effective mass.

Effective mass model of dopants = hydrogenic model

Assuming donors (positive), the electron is attracted to the positive ionised donor atom by Coulombic force. This situation is effectively the same as in the hydrogen atom, but m is now m^* and the force is screened by the dielectric constant ϵ .

Binding energies of the donor levels are given by $E_b = R_0 m^* / \epsilon^2$.



(d) Wide band gap semiconductors have 3 problems;

(i) The solubility of the donor atom

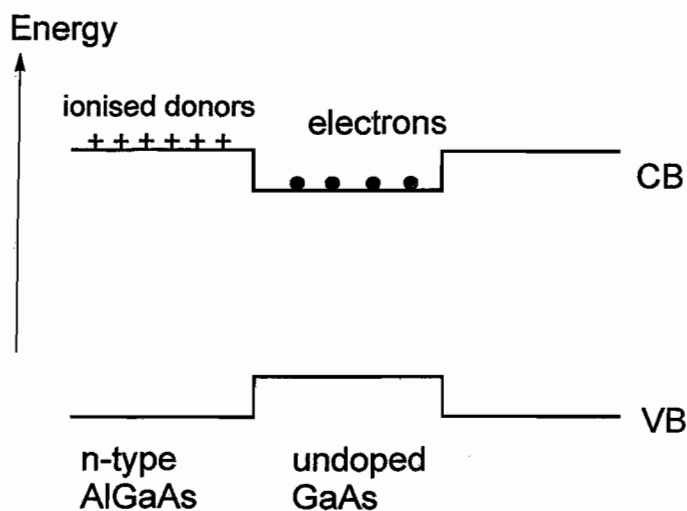
(ii) Large effective mass, low dielectric constant \rightarrow large E_b .

(iii) Donor electrons trapped by compensating defects, so no net donor action.

[25%]

[15%]

(e) Transfer or modulation doping in semiconductor heterostructure;



Donor electrons are transferred from wide gap material with the donors, into narrower gap intrinsic material. This separates electrons from the positive donor ions, reduces Coulombic scattering and thereby increases mobility. Lattice matching is required for this process, which is difficult because of the restricted range of available materials.

Fraction of dislocations = $\delta d / d$. Thus the spacing of dislocations = $d / \delta d$ unit cells, or $d^2 / \delta d$ Angstroms.

[20%]

D. A. Cardwell
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