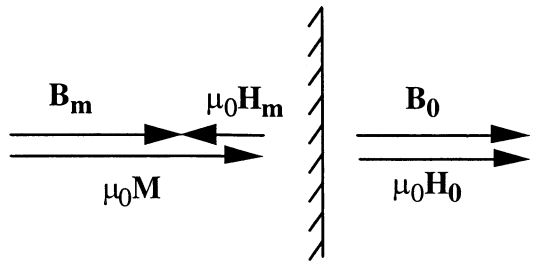
ENGINEERING TRIPOS PART IIB

Monday 26th April 2004 2.30 to 4.00

Module 4C3 : ELECTRICAL MATERIALS SOLUTIONS

1. The effects of exposed surface and shape are to reduce the flux density that can be generated by permanent magnet materials in practical applications. Exposed surface perpendicular to M generates a demagnetising field, which is then amplified by shape effects.

(i) The effect of exposed surface on the properties of a permanent magnet is to generate a demagnetising field within the interior of the permanent magnet material due to continuity of magnetic flux. The direction of the demagnetising field will be in the opposite direction to the mean applied magnetising field, which is in the same direction as the flux density in the material. This will cause the material to operate in the second quadrant of the B-H curve when the magnetising field is removed. This will reduce the flux density at the surface of the magnet.



$$\mathbf{B_m} = \mathbf{B_0}$$

$$\mathbf{B_m} = \mu_o\,(\mathbf{H_m} + \mathbf{M}) = \mathbf{B_0} = \mu_o\,\mathbf{H_0} \qquad \text{at the exposed surface}$$

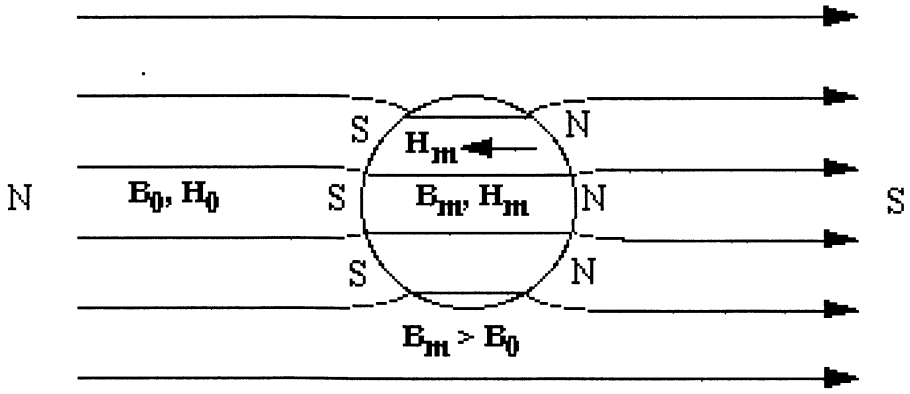
Hence, in the absence of shape effects (N=1);

$\mathbf{H_m} = \mathbf{H_0} - \mathbf{M}$, where $\mathbf{H_m}$ is the demagnetising field.

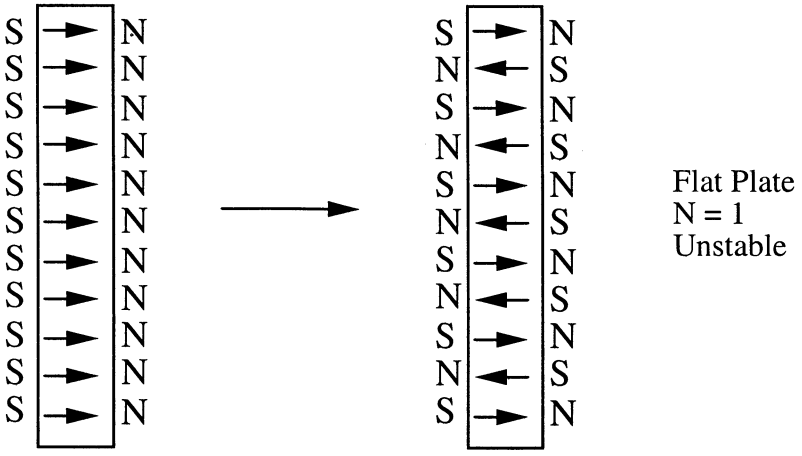
(ii) The effect of shape is to enhance the demagnetising field. In general the larger the surface area perpendicular to the direction of magnetising field compared to the length of the magnet parallel to the applied field, the greater the enhancement of the demagnetising field. A large exposed surface area perpendicular to the applied field will result in an increase in magnetic flux density within the interior of the magnet compared to that in free space at the magnet surface. In this case, the demagnetising field $\mathbf{H_m}$ will exceed $\mathbf{H_0} - \mathbf{M}$ (i.e. $\mathbf{H_m} > \mathbf{H_0} - \mathbf{M}$), which gives the following equation when the demag factor is introduced;

$$\mathbf{H_m} = \mathbf{H_0} - \mathrm{NM}$$

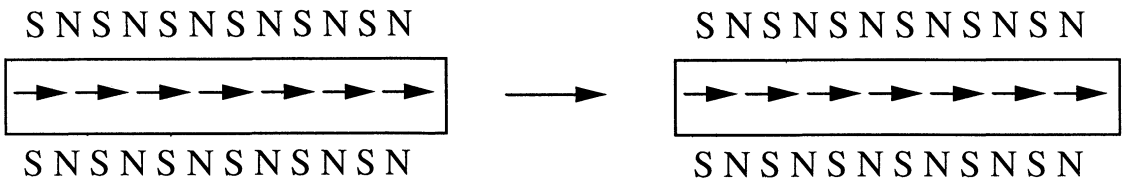
where N is the shape-related demagnetisation factor and $0 < N < 1$. Thus $\mathbf{H_m}$ becomes large and negative for values of $N \rightarrow 1$ (i.e. the operating point of the magnet moves further into the second quadrant of the B-H curve). An alternative way of thinking about this problem involves the generation of free magnetic poles at the surface of the magnetic material, which, in turn, generate an enhanced demagnetising field.



Soft magnetic materials in geometries with high demag. factors are unstable when the magnetising field is removed. E.g. a flat plate with magnetising field applied parallel to its thickness (N = 1);



As a result, hard magnetic materials, which contain pinning centres that restrict the movement of magnetic domains, such as Sm-Co and Nd-B-Fe are used for thin flat magnets, such as fridge magnets. Long, thin magnets magnetised parallel to their length, on the other hand, are stable when the magnetising field is removed. Soft magnetic materials, such as Fe, therefore, are suitable for applications in the form of long, thin cylinders, magnetised axially.



Long Cylinder, N = 0, Less untable

[40%]

(b) $B_m = \mu_0 (H_m + M)$ (i)

$H_m = H_0 - NM$

For no applied field, $H_0 = 0$, therefore;

$H_m = -NM \quad \Rightarrow \quad M = -H_m/N$ (ii)

Need B_m (H_m) to plot on B-H curve.

Substitute (ii) into (i); $B_m = \mu_0\left(H_m - \frac{H_m}{N}\right)$

i.e. $B_m = \mu_0 H_m\left(\frac{N-1}{N}\right)$

A sphere has a demag. factor of 1/3. Hence $(N - 1)/N = -2$ and $B_m = -2\ \mu_0 H_m$. The intersection of a straight line, gradient $-2\ \mu_0$ with the B-H curve for Alcomax III (Electrical Data Book) gives the following approximate values;

$B_m = 0.15$ T $\quad H_m = -5.25 \times 10^4$ A m^{-1}

Also, $M = -H_m/N \quad M = -\frac{-5.25 \times 10^4}{1/3} = -1.6 \times 10^5$ A m^{-1} [30%]

(c) Magnetic flux density at the centre of a long superconducting cylinder of YBCO of diameter 2 cm, carrying a uniform circumferential current density of 5×10^3 Acm^{-2} at 77K is given by;

$B = \mu_0 J_c d = 4\pi \times 10^{-7} \times 5 \times 10^7 \times 1 \times 10^{-3} = 0.062$ T

This is significantly smaller than that generated by the Alcomax III sphere.

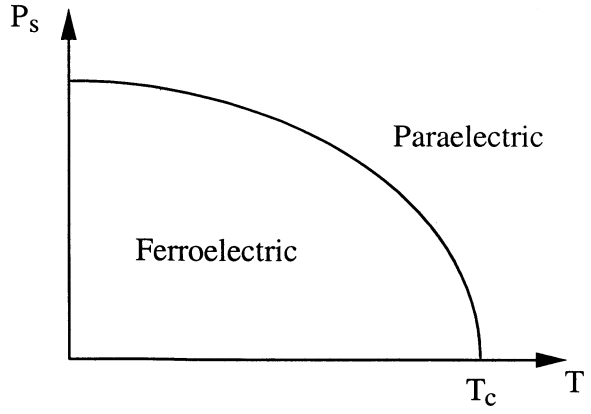
The main practical difficulty in using the field generated by a hollow cylindrical superconductor is the inaccessibility of the field at its centre. The field at the end of the cylinder is much more accessible, although this falls to half the value at the centre. The second practical difficulty is associated with the need to cool the superconductor below its transition temperature. The need for a cryostat limits proximity to the superconductor. [30%]

2. (a) The pyroelectric effect occurs in polar dielectric materials whose structure contains at least one *axis* along which an electric dipole moment exists. Only 10 of the 21 dielectric structures, therefore, exhibit pyroelectric properties (orthorhombic, tetragonal and triclinic, for example).

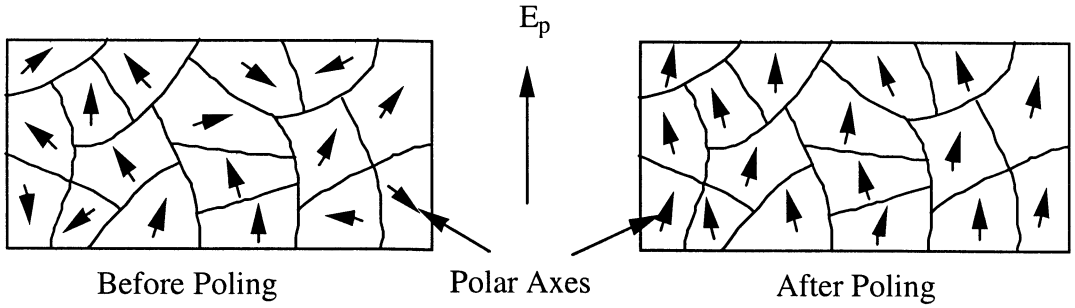
Pyroelectricity is the change in polarisation that occurs in pyroelectric materials as their temperature changes. Quantitatively this is described in terms of the pyroelectric coefficient, **p**, which is given by the rate of change of $\mathbf{P_S}$, the spontaneous polarisation, with temperature, i.e. the gradient of the $\mathbf{P_S}$ (T) curve;

$$\mathbf{p} = \frac{\Delta \mathbf{P_s}}{\Delta T} = \frac{d \mathbf{P_s}}{d T}$$

Ferroelectrics are the most useful pyroelectric materials from an applications point of view 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. This property is due to the presence of a number of polar axes in the crystal structure which is a particular feature of the perovskite lattice. All ferroelectrics undergo a structural phase transformation to a lower crystal symmetry at the Curie temperature, T_C.



Ferroelectric materials can be fabricated in polycrystalline (ceramic) form and poled by the application of a large electric field (E_p ~ 1 - 5 $V\mu m^{-1}$). This is technically much easier than fabricating polar materials in single crystal form to obtain a unique polar axis. The poling process of ferroelectrics aligns individual domains to yield a net overall polarisation.

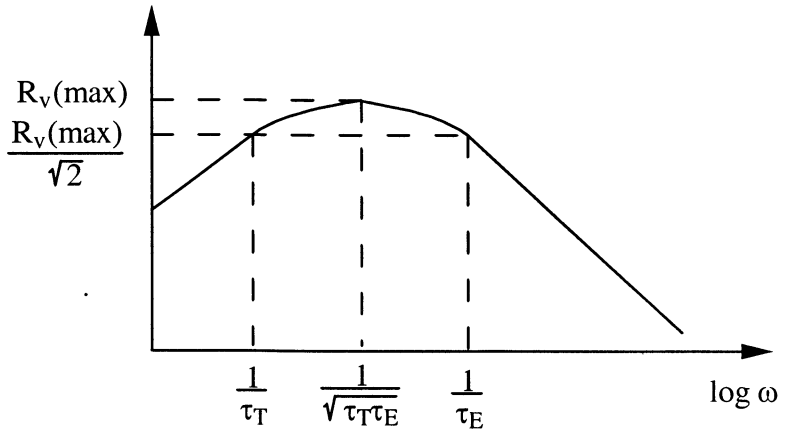


[40%]

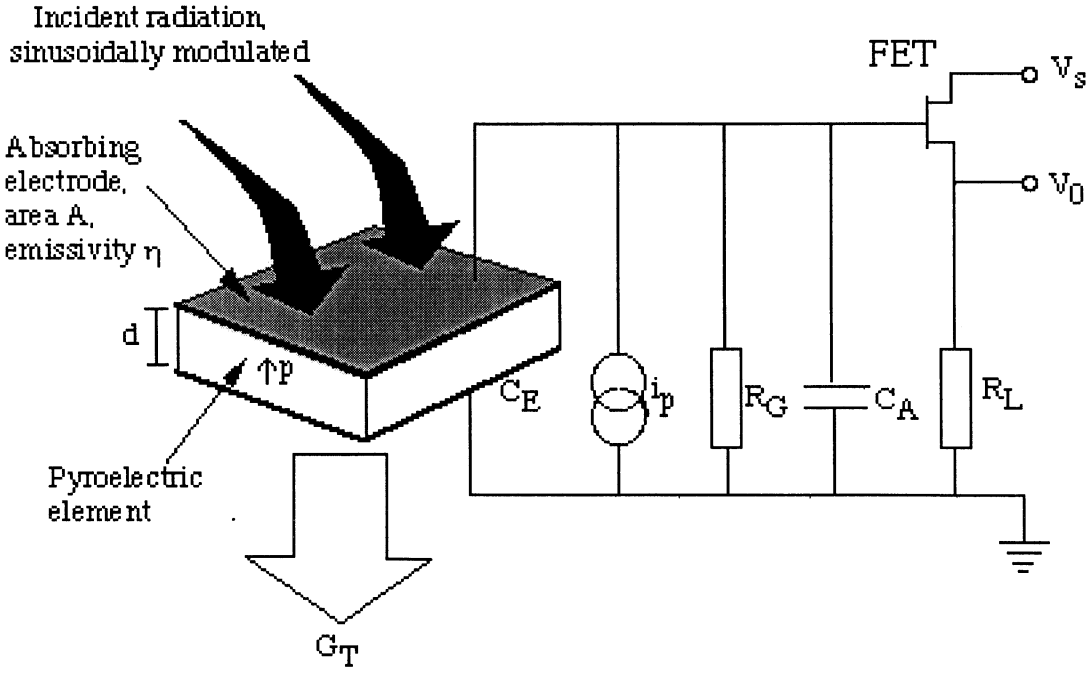
(b) $$R_V = \frac{i_p}{Y W_0} = \frac{R_G \eta p A \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2}\ \sqrt{1 + \omega^2 \tau_E^2}}$$

τ_T is the thermal time constant of the pyroelectric element
τ_E is the electrical time constant of the element and interface amplifier circuit
G_T is the thermal conductance between the element and its environment
R_G is the gate resistance
p is the pyroelectric coefficient
ω is the angular frequency
A is the absorbing area of the detector, η is the emissivity

Together τ_T ($\tau_T = \frac{H}{G_T}$) and τ_E determine the bandwidth of frequency response of the detector.



Circuit diagram;



[30%]

(c) (i) F_V is the figure of merit used to describe the optimum signal to noise ratio of the pyroelectric material. If the element capacitance C_E is large compared to the amplifier capacitance, C_A, the expression for R_v becomes;

$$R_v = \underbrace{\frac{p}{c\,\varepsilon\,\varepsilon_0}}_{\text{Materials term}} \times \underbrace{\frac{\eta}{A\,\omega}}_{\text{Design term}}$$

Full equation is not required!

Therefore $F_V = \dfrac{p}{c\,\varepsilon\,\varepsilon_0}$, which needs to be evaluated for each material for maximum voltage response.

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.;

$$D = \frac{R_V}{\Delta V_J} = \underbrace{\frac{p}{c\sqrt{\varepsilon_r\,\varepsilon_0 \tan\delta}}}_{\text{Materials term}} \times \underbrace{\sqrt{\frac{\eta}{4kT\,d\,A}} \times \sqrt{\frac{1}{\omega}}}_{\text{Design term}}$$

Again, full equation is not required.

Therefore $F_D = \frac{p}{c\sqrt{\varepsilon_r \varepsilon_0 \tan \delta}}$ which needs to be evaluated for each material for maximum signal to noise ratio.

Material	T_c °C	p $\mu Cm^{-2}K^{-1}$	ε_r	tan δ × 10^{-3}	c $MJm^{-3}K^{-1}$	F_V Arb. units	F_D Arb. units
PZFNTU	230	380	290	10	2.5	0.059	0.949
SBN - 50	121	550	400	3	2.3	0.068	2.320
PVDF	80	27	12	15	2.6	0.098	0.260
PGO	178	110	40	0.5	2.0	0.155	4.134

Order of potential for high voltage response is PGO, PVDF, SBN and PZFNTU.
Order of potential for high signal to noise ratio is; PGO, SBN, PZFNTU and PVDF. [30%]

3 (a) (i) In one second a molecule travels a distance v. It will hit any molecules whose centres are less than a distance d from the path. This corresponds to a volume = $\pi d^2 v$.

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

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

Hence, the distance travelled = mean free path = $\frac{1}{N \pi d^2}$

(ii) The number of atoms per m^2 in a monolayer is $\frac{1}{d^2}$.

All atoms within a distance of the surface arrive in 1 s.

Number of atoms arriving per second = $\frac{N v}{6}$

Hence the time for $\frac{1}{d^2}$ atoms to arrive = $\frac{6}{N v d^2}$ [30%]

(b) The problems encountered in achieving a high vacuum and the precautions taken to avoid them are;

(i) pinholes
Avoided by using specially processed stainless steel.

(ii) contamination
Avoided by wearing gloves.

(iii) degassing

Avoided by using materials with intermediate vapour pressures, for examples Pb in solder or Zn in brass. [20%]

(c) Techniques are evaporation, MBE, sputtering, chemical vapour deposition and laser ablation.

MBE
Slow and carefully controlled evaporation of (usually) semiconductors. Because of the slow rate a very high vacuum is needed. Expensive but can be used to put down compounds layer by layer, with the appropriate composition in each layer.

Sputtering
Uses a low pressure plasma so molecules diffuse to substrate. This is at about 300 volts so arrival energies can be high and considerable rearrangement takes place. Can also be used for layer by layer deposition. Much slower than evaporation. Good for alloys with either an alloy target or separate elemental targets. Can also be used for polymers.

Other techniques are described in the notes. [50%]

4 (a)(i) Moore's law states that transistor density increases exponentially with year, doubling every 2-3 years.
(ii) Typical feature size of a particular Si device in 2003 was 0.13 μm.

$$\text{Area} = (\text{length})^2$$

If size (area) halves every 2-3 years then length halves every 4-6 years. Assume length halves every 5 years as a reasonable approximation.

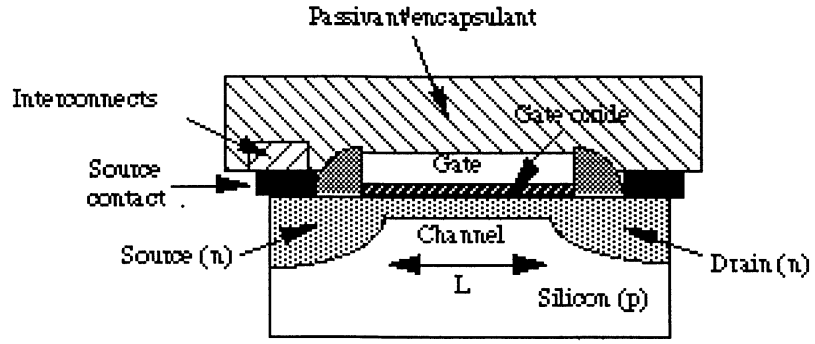
Period between 1975 and 2003 = 28 years.

$$28 \text{ years} \equiv \frac{28}{5} = 5.5 \text{ halving periods.}$$

Therefore; $L = 0.13 \times (2)^{5.5} = 5.88$ μm.

Size of feature in 1975 = 5.88 μm. [30%]

(b) Sketch of a typical n-type MOS (NMOS) FET with electrodes;



Materials used currently:

Substrate; lightly p-doped Si
Source and drain; heavily doped n-type silicon
Channel; n-type silicon by inversion.

In 1970 the following conducting materials were used:

Gate electrode; Al
Contacts; Al
Interconnects; Al

In 2003 the following conducting materials are used for an NMOS transistor:

Gate electrode; Polycrystalline Si
Contacts; Silicides
Interconnects; Cu [40%]

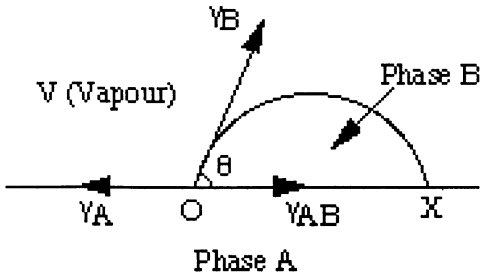
(c) Three roles of silicon dioxide in a planar FET are;

Use as a passivant
Use as a gate oxide
Used as a spacer between interconnects (wires) [10%]

(d) Electromigration is the movement of metal atoms in a wire under the influence of a high electric current density (i.e. self-electrolysis). The electric field acts on positively charged nuclei separately to the electrons and causes them to move, so that the atoms of the wire are moved. This, in turn, ultimately causes the wire to break, first along the grain boundaries and other weak regions.

Cu has recently replaced Al to achieve higher maximum current densities. [20%]

5 (a) Derivation of Young's equation for the contact angle for wetting;



The surface energies of the phases A and B are γ_A and γ_B, respectively, and the interface energy is γ_{AB}.

Resolving forces along OX gives;

$$\gamma_A = \gamma_B \cos\theta + \gamma_{AB}$$

This is Young's equation. [40%]

(b) The limiting cases of contact angle for wetting and non-wetting are;

For $\gamma_A \geq \gamma_{AB} + \gamma_B$ then $\theta = 0°$ (wetting)
For $\gamma_A \geq \gamma_{AB} + \gamma_B$ then $\theta = 180°$ (non-wetting)

Non-wetting is defined approximately as when $q > 90°$, or $\gamma_A \leq \gamma_{AB}$ [20%]

(c) For 3D non-island growth of B or A, we want wetting and $\theta \sim 0$.

Thus; $\gamma_A \geq \gamma_{AB} + \gamma_B$ [20%]

Because the contact angle is 0 in this case, the droplet in the above diagram will be flat, and B will grow as a smooth (non-island) layer over the A substrate. For the angle on the left at θ, phase B will grow to the left, covering the underlying A.

(d) For growth of phase A on the surface of phase B, simply switch A and B in the previous analysis;

$$\gamma_B \geq \gamma_{AB} + \gamma_A$$

As all g's are positive, these two equations cannot hold at the same time. Thus, if B grows 3D on A, A will not grow 3D on B. [20%]