

ENGINEERING TRIPOS

PART IIB

Thursday 30h April 2009

2.30 to 4

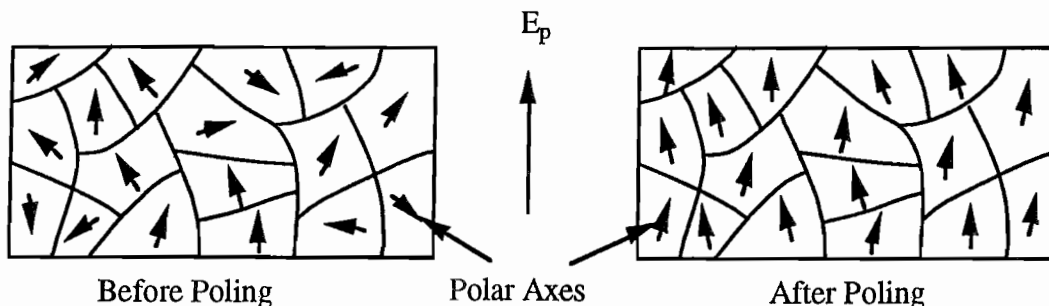
Module 4C3 : ELECTRICAL MATERIALS SOLUTIONS

1. (a) Pyroelectric materials are polar dielectrics 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, \mathbf{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;

$$\mathbf{p} = \frac{\Delta \mathbf{P}_s}{\Delta T} = \frac{d \mathbf{P}_s}{dT}$$

Ferroelectrics are the most useful pyroelectric materials from an applications point of view since they can be fabricated in polycrystalline (ceramic) form and poled by the application of a large electric field ($E_p \sim 1 - 5 \text{ V}\mu\text{m}^{-1}$). 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%]

$$(b) \quad \Delta T = \frac{\eta W_0 e^{i\omega t}}{G_T + i \omega H}$$

η is the emissivity of the absorbing electrode, G_T is the thermal conductance to the surroundings and H is the thermal capacity.

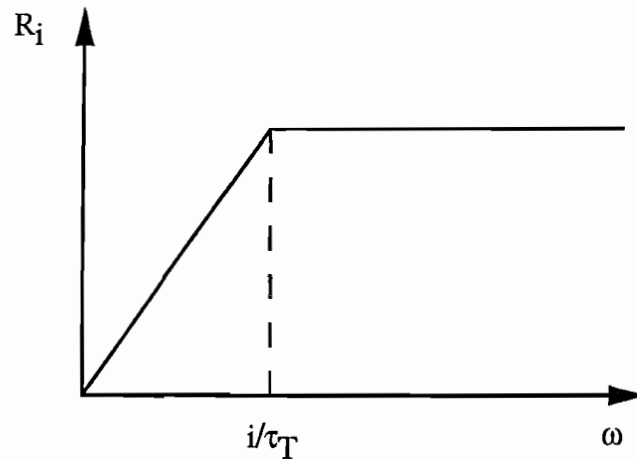
Current responsivity is defined as; $R_i = \frac{i_p}{W_0}$ where i_p is the current which flows in an external circuit due to charge release associated with the temperature change.

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

$$R_i = \frac{i_p}{W_0} = \frac{\eta p A i \omega e^{i\omega t}}{G_T (1 + i \omega \tau_T)} = \frac{\eta p A i \omega e^{i\omega t} (1 - i \omega \tau_T)}{G_T (1 + \omega^2 \tau_T^2)} \quad (\text{Since } H = \tau_T G_T)$$

$$|R_i| = \left| \frac{\eta p A \omega e^{i\omega t} (i + \omega \tau_T)}{G_T (1 + \omega^2 \tau_T^2)} \right| = \frac{\eta p A \omega \sqrt{1 + \omega^2 \tau_T^2}}{G_T (1 + \omega^2 \tau_T^2)} = \frac{\eta p A \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2}}$$

Sketch of variation of R_i with ω ;



R_i is directly proportional to frequency for $\omega \ll 1/\tau_T$, i.e.;

$$\omega^2 \tau_T^2 \ll 1, \text{ so } \sqrt{1 + \omega^2 \tau_T^2} \sim 1 \quad \rightarrow \quad |R_i| = \frac{\eta p A \omega}{G_T}$$

R_i is constant for frequencies $\gg 1/\tau_T$, i.e.;

$$\omega^2 \tau_T^2 \gg 1, \text{ so } \sqrt{1 + \omega^2 \tau_T^2} \sim \sqrt{\omega^2 \tau_T^2} = \omega \tau_T \quad \rightarrow \quad |R_i| = \frac{\eta p A}{G_T \tau_T} = \frac{\eta p}{c d}$$

($\tau_T = H/G_T$ and $H = c d A$)

[30%]

(c) (i) F_V is the figure of merit used to select a pyroelectric material that generates a maximum voltage per unit input thermal signal. If the element capacitance C_E is large compared to the amplifier capacitance, C_A , the expression for R_V is;

$$R_V = \frac{p}{c \epsilon \epsilon_0} \times \frac{\eta}{A \omega}$$

Materials Design
term term

The full equation is not required.

Therefore $F_V = \frac{p}{c \epsilon \epsilon_0}$ needs to be evaluated for each material for maximum voltage response.

F_D is the figure of merit used to select a pyroelectric material optimum signal to noise ratio. 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.;

$$D = \frac{R_V}{\Delta V_J} = \frac{p}{c \sqrt{\epsilon_r \epsilon_0 \tan \delta}} \times \sqrt{\frac{\eta}{4kT d A}} \times \sqrt{\frac{1}{\omega}}$$

Materials term
Design term

Again, the full equation is not required.

Therefore $F_D = \frac{p}{c \sqrt{\epsilon_r \epsilon_0 \tan \delta}}$ needs to be evaluated for each material for maximum signal to noise ratio.

Material	T _c °C	p μCm ⁻² K ⁻¹	ε _r	tan δ × 10 ⁻³	c MJm ⁻³ K ⁻¹	F _V Arb. units	F _D Arb. units
PZFTU	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

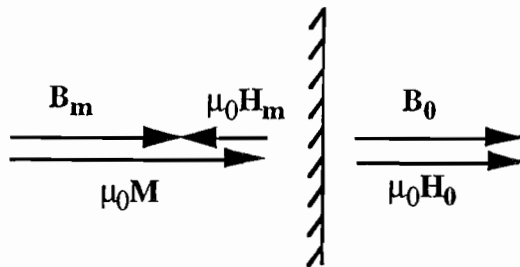
Order of potential for high voltage response is PGO, PVDF, SBN and PZFTU.

Order of potential for high signal to noise ratio is; PGO, SBN, PZFTU and PVDF.

[30%]

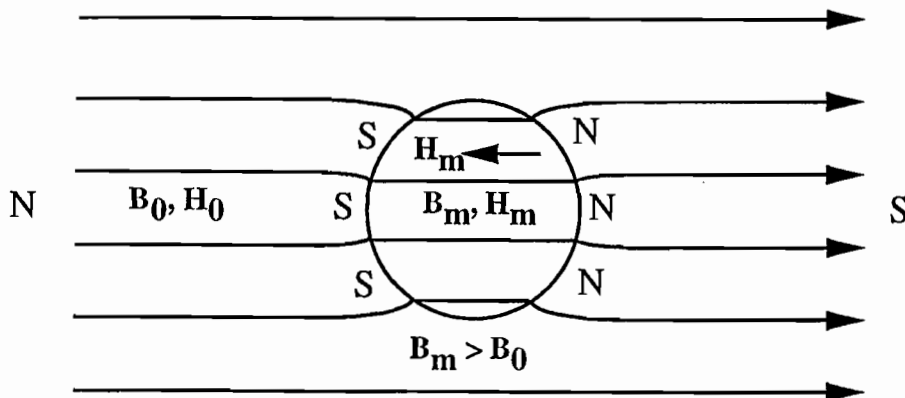
2. The effects of exposed surface and shape are to reduce the flux density that can be generated by permanent magnet materials in practical applications. Exposed surface perpendicular to M generates a demagnetising field, which is then amplified by shape effects.

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.



The effect of shape is to enhance the demagnetising field, H_m . 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.

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.



[309

(b) In general $B_m = \mu_0 (H_m + M)$

$B_m = B_0$ at the surface for continuity of magnetic flux.

From the first diagram, $B_m = \mu_0 (H_m + M) = B_0 = \mu_0 H_0$, at the exposed surface.

Hence, in the absence of shape effects (i.e. $N=1$);

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

H_m will exceed $H_0 - M$ (i.e. $H_m > H_0 - M$), which gives the following equation when shape effects are taken into account (this introduces the demagnetisation factor, N). i.e.;

$$H_m = H_0 - NM, \text{ where } 0 < N < 1.$$

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

$$H_m = H_0 - NM \quad (ii)$$

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

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

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

i.e.
$$B_m = \mu_0 H_m \left(\frac{N-1}{N} \right) \quad [40\%]$$

(c)(i) 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;

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

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

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

$$B_m = 0.08 \text{ T} \quad H_m = -5.25 \times 10^4 \text{ A m}^{-1}$$

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

Similar values of H_m and M yield values of B_m that differ by a factor of 2. [30%]

3 (a) Chemical vapour deposition (CVD): Volatile gases are introduced into the deposition chamber, which react and form the desired film on the surface of the substrate (see lecture notes). The overall film growth rate is limited either by mass transfer of reactants through the boundary layer between the laminar gas stream and substrate, or by surface reactions on the substrate. Low gas pressures (LP) enhance the mass flux of gaseous precursors and products through the boundary layer, and hence the dependence on gas transport can be eliminated (expanding the surface reaction controlled regime). Thus LPCVD offers more process control and throughput, greater uniformity, better step coverage, greater control over stoichiometry and contamination problems.

[20%]

(i) A molecule travels a distance x in one second. It will hit any molecules whose centres are within a distance d of the path. This corresponds to a cylinder of volume $= n \pi d^2 x$.

Number of molecules hit per second $= n \pi d^2 x$

Time between hits $= \frac{1}{n \pi d^2 x}$

Hence, the distance travelled = mean free path $= \frac{1}{n \pi d^2} = \lambda_{\text{mfp}}$

Ideal gas law; $n = \frac{p}{k T}$, hence $\lambda_{\text{mfp}} = \frac{k T}{p \pi d^2}$

Knudsen number $= K_n = \frac{\lambda_{\text{mfp}}}{L}$, where L is the dimension of the chamber.

For thermal evaporation: $K_n > 1$. Molecular, ballistic flow results in 'line of sight' deposition and poor step coverage.

For sputtering; A plasma is required and generally $K_n < 1$, viscous gas flow, λ_{mfp} is shorter and there is better step coverage.

[40%]

(c) (i) Ellipsometry is used commonly for measuring film thickness. This involves detecting a change in the polarisation of light upon reflection from a film/interface. The film thickness is calculated from the optical transparency and known optical properties of the film.

(ii) Only secondary ion mass spectroscopy (SIMS) can detect such low concentration levels associated with dopants. In SIMS, a source of ions bombards the surface, which causes sputtering of atoms from the surface of the sample. These enter a mass spectrometer, where they are counted according to their mass/charge ratio. The sputter rate can be adjusted to allow for depth profiling.

(iii) A silicon nanowire (SiNW) is typically 20-50 nm in diameter and $> 1 \mu\text{m}$ in length. The most suitable characterisation technique is scanning electron microscopy (SEM). This involves raster-scanning the sample surface with a finely focused beam of electrons. The SEM image is formed with electrons emitted from the sample. Secondary electrons (i.e. electrons from atoms within the samples that have been ejected by interactions with the primary beam) generally offer the best imaging resolution for determining the dimensions of the SiNW. The metal catalyst particle can be resolved from the backscattered electron signal.

Backscattered electrons are primary beam electrons that have been scattered back out of the sample by elastic collisions with the nuclei of the sample atoms. Contrast in backscattered images comes primarily from differences in the average atomic number of the atoms within the sample. i.e. the metal catalyst particle (such as Au) appears brighter. Energy dispersive X-ray analysis (EDX) would not give the spatial resolution for the detection of the particle at the tip of the SiNW, but could be used additionally to identify metal on the sample.

[40%]

4 (a) In substitutional doping, the dopant atom substitutes at the lattice site of the host (e.g. Si) so it forms bonds to the host. A substitutional donor element has a valency of 1 higher than the host atom it replaces and therefore supplies 1 electron more than is required for bonding. This electron becomes the donor electron. A substitutional acceptor element has a valency of 1 lower than the host atom it replaces and therefore supplies 1 electron less than is required for bonding. This creates a hole in the valence band.

An interstitial dopant enters an interstice or 'hole' in the lattice, and so is not bonded to the host lattice atoms. If it is a metal, it ionises and donates its electrons as donors. If it is a halogen, it forms a negative ion and leaves a hole in the valence band.

For group IV semiconductors, group V elements are donors and group III elements are acceptors.

For group III-V semiconductors, group VI elements at group V element sites are donors, group II elements at group III element sites are acceptors. Group IV elements at group V sites are acceptors and group IV elements at group III element sites are donors.

[30%]

(b) If a donor atom ionises, the electron is released and leaves a positively charged donor (e.g. P⁺). The electron around the donor ion experiences a coulombic field, as in the case of a hydrogen ion. In this case, however, the dielectric constant of the materials is ϵ and the electron has an effective mass m^* . As a result, the binding energy is;

$$R = R_0 \frac{m^*}{m \epsilon_r^2}$$

Here R_0 is the energy level of the hydrogen ion, 13.6 eV.

The reference energy for energy levels in the hydrogen atom is the vacuum level. The reference energy levels for donor and acceptor atoms are the conduction band minimum and valence band maximum, respectively.

[30%]

(c) Doping is difficult in semiconductors with wide band gaps, which causes m^* to increase and ϵ to decrease.

Three reasons that make doping difficult are;

1. The dopant is not soluble in the host lattice due to a mismatch between the atomic radii of the dopant and host.
2. The dopant levels become un-ionisable or deep, due to large values of m^* and small values of ϵ_r .

3. The dopant becomes compensated by the creation of defects in the case of wide bandgap semiconductors. [20%]

(d) Si has low m^* and high ϵ , and so has shallow donor energies, $e = 0.024$ eV, which are lower than kT at room temperature (0.025 eV). Hence there are no difficulties doping this semiconductor.

Diamond has higher m^* and high ϵ , and so has deeper donor energies, $e = 0.6$ eV, which are higher than kT at room temperature (0.025 eV). This leads to doping difficulties.

GaAs has very low m^* and reasonable high ϵ , and so has very shallow donor level energies, so there are no difficulties doping this semiconductor.

SiO_2 has low ϵ , and so has deep levels. A high hole mass leads to very deep holes (greater than the band gap, if that is possible). This leads to doping difficulties. [20%]

5 (a) Moore's law states that transistor density increases exponentially with year, doubling every 2-3 years. [10%]

(ii) Typical feature size of a particular Si device in 2003 was $0.13 \mu\text{m}$.

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

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 1980 and 2003 = 23 years.

$$23 \text{ years} \equiv \frac{23}{5} = 4.6 \text{ halving periods.}$$

$$\text{Therefore; } L = 0.13 \times (2)^{4.6} = 3.15 \mu\text{m.}$$

Size of feature in 1980 = $3.15 \mu\text{m}$.

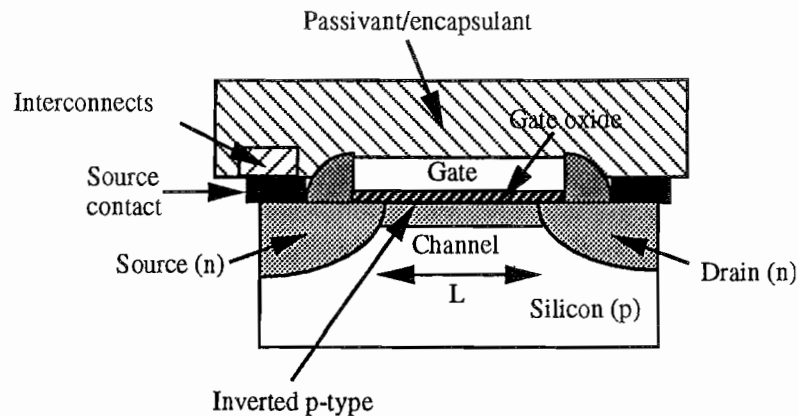
Period between 2011 and 2003 = 8 years.

$$8 \text{ years} \equiv \frac{8}{5} = 1.6 \text{ halving periods.}$$

$$\text{Therefore; } L = \frac{0.13}{2^{1.6}} = 0.043 \mu\text{m.}$$

Size of feature in 2011 = $0.043 \mu\text{m}$. [20%]

(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 1980 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)

[15%]

(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.

Carbon nanotubes can carry a current density that is 1000 times higher than that of copper before electromigration occurs. Thus they have potential for use as interconnects if they can be incorporated into the CMOS design.

[15%]