UNIVERSITY OF
CAMBRIDGE

ENGINEERING TRIPOS PART IIB

Thursday 5 May 2005 2.30 to 4

Module 4C3

ELECTRICAL AND NANO MATERIALS

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

There are no attachments to this paper.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

(TURN OVER

1 (a) Describe carefully how magnetic flux density is generated in;

(i) homogeneous bulk type II superconductors, such as Y-Ba-Cu-O, and

(ii) permanent magnets, such as Nd-Fe-B.

In each case state whether the volume magnetisation varies with sample volume, giving reasons for your answer. [30%]

(b) Sketch the variation of magnetic moment with applied magnetic field at constant temperature for a bulk type II superconductor that contains flux pinning centres. Your diagram should show $M(H)$ for a field cycle of 0 T to H_{max} to 0 T, assuming the material to be in an initially unmagnetised state. On the same axes draw the corresponding curve for a type II material that contains no flux pinning centres. Identify the important features in each case.

Explain qualitatively how increased flux pinning in bulk type II superconductors produces higher critical current density, J_c. [40%]

(c) J_c varies with the inverse of applied magnetic flux density B, i.e. $J_c = \frac{K}{B}$ where K is a constant, in a slab of Y-Ba-Cu-O (YBCO) magnetised as shown in Fig. 1. Derive the functional dependence of the maximum trapped magnetic flux density on the thickness of the slab, d.

The slab described above is of initial thickness 5 mm. Calculate the increase in thickness of the slab if the maximum magnetic flux density it can trap is required to increase by a factor of two. [30%]

(cont.

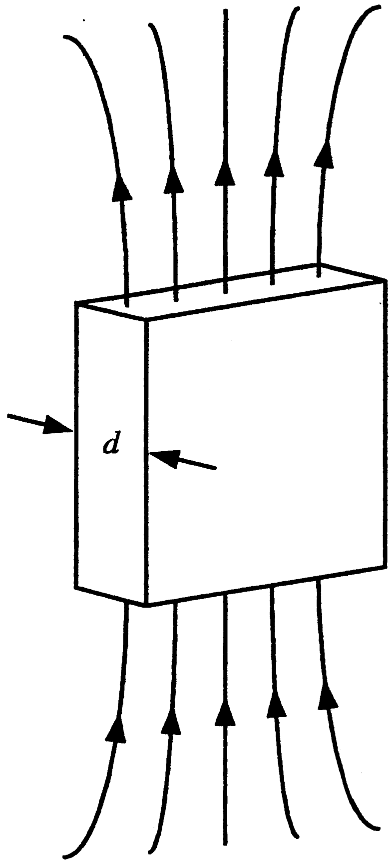

Fig. 1

2 (a) Outline the polar properties of some materials that determine their classification as either pyroelectric and piezoelectric, making specific reference to the symmetry of the crystallographic lattice. Hence explain the microscopic basis of the pyroelectric and piezoelectric effects that are observed in some dielectric materials.

Describe briefly the difference between direct and indirect piezoelectric effects. [40%]

(b) The temperature difference ΔT between a pyroelectric element and its surroundings when exposed to incident sinusoidally modulated radiation, $W = W_0 \, e^{i\omega t}$, is given by ;

$$\Delta T = \frac{\eta \, W_0 \, e^{i\omega t}}{G_T + i\,\omega H}$$

where η is the emissivity of the absorbing electrode, G_T is the thermal conductance to the surroundings and H is the thermal capacity. Define the current responsivity, R_i , of the detector. Hence derive the following expression;

$$|R_i| = \frac{\eta p A \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2}}$$

where p is the pyroelectric coefficient, A is the area of the absorbing electrode and τ_T is the thermal time constant $(= H/G_T)$ of the device.

Sketch the variation of R_i with ω and state the frequency conditions under which R_i is constant. [40%]

(c) A pyroelectric element is constructed from PVDF of thickness 30 μm and absorbing electrode emissivity 0.9. Calculate its current responsivity in the constant frequency regime.

Materials constants for PVDF are; $p = 27\ \mu\text{Cm}^{-2}\text{K}^{-1}$ and $c = 2.6\ \text{MJm}^{-3}\text{K}^{-1}$. [20%]

3 (a) Define the atomic number and atomic weight of an element. Explain carefully the extent to which atomic number and atomic weight are correlated. [20%]

(b) A hydrogen atom can be modelled by an electron of charge $-e$ and mass m travelling in a circular orbit around a nucleus of charge e at a velocity v such that the electrostatic attraction is balanced by the centrifugal force. Use the de Broglie relation;

$$mv = \frac{h}{\lambda}$$

where h is Planck's constant and λ represents wavelength, and the condition that there are a whole number of wavelengths around the orbit, to derive an expression for the radius of a hydrogen atom in the ground state. [30%]

(c) Explain why most atoms are of a similar size, despite the large variation in the number of electrons. Given that the magnitude of the ionisation energy of atoms is typically a few electron-volts, list the material parameters that depend directly on this energy and explain their connection. [20%]

(d) Describe carefully the technique of molecular beam epitaxy (MBE). Your answer should explain what the method is used for and describe its advantages and disadvantages.

What methods of analysis can be performed within the MBE machine to monitor the growth of a film layer-by-layer? Describe briefly how these methods work and what they measure. [30%]

4 (a) Explain substitutional and interstitial doping in semiconductors. In each case describe the mechanism by which conduction occurs. Which group of elements should be used to dope IV and III-V semiconducting compounds? [30%]

(b) The energy levels of the hydrogen atom are given by the following equation;

$$R = \frac{e^4 m}{32 \pi^2 \varepsilon^2 \hbar^2},$$

where the symbols are as defined in the lectures. Use this equation to explain how the binding energy of donor electrons may be modelled by the hydrogenic atom. [30%]

(c) Explain why doping is difficult in some semiconductors and give three reasons to support your answer.

Explain which of these reasons, if any, might be a significant limitation in doping the following semiconductors;

(i) Si,
(ii) diamond,
(iii) GaAs,
(iv) SiO_2

Use the data in table 1 to support your answer. [40%]

Material	ε_r	m^* electrons	m^* holes	Band gap eV
Si	12.0	0.26		1.1
Diamond	5.7	1.30		5.5
GaAs	10.9	0.06		1.5
SiO_2	2.2	0.50	12.00	9.0

Table 1

5 (a) Explain what *E-k* curves represent in crystalline solids. [10%]

(b) Sketch *E-k* curves for direct and indirect bandgap semiconductors. Explain why a direct bandgap semiconductor is needed for opto-electronic applications. [20%]

(c) Explain how it is possible to vary the colour emitted in a light emitting diode (LED). Identify materials for generating red and blue light in an LED. [30%]

(d) Describe the key material design requirements for the fabrication of the following devices;

(i) a light emitting diode and
(ii) a quantum well laser.

Describe briefly the important materials and interface requirements in (ii) and explain why alloying is an important aspect of materials design in this device. [40%]

END OF PAPER