ENGINEERING TRIPOS PART IIB

Thursday 1 May 2008 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.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book

CUED approved calculator allowed

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

1 (a) Describe the classification of pyroelectric and piezoelectric materials in terms of the polar properties of their crystallographic lattice. Describe the pyroelectric and piezoelectric effects that are observed in some dielectric materials, explaining the microscopic basis of their occurrence. [40%]

(b) Explain briefly the following observations:

(i) piezoelectric materials are classified as either hard or soft; [10%]

(ii) only three piezoelectric coefficients are important in practical piezoelectric devices; [10%]

(iii) ferroelectrics are particularly suitable for the fabrication of practical pyroelectric devices; [10%]

(iv) the response of pyroelectric detectors varies significantly with frequency. [10%]

(c) Figure 1 shows schematically a piezoelectric microphone of rectangular cross-sectional area operating in longitudinal mode. Using the appropriate piezoelectric equation of state, show that the charge generated by this microphone is proportional to the aspect ratio of the device area A/a . State whether a hard or soft piezoelectric material would be most suitable for this application.

The microphone illustrated in Fig. 1 consists of a poled ferroelectric rod of PZT-4 with dimensions $1\text{ mm} \times 1\text{ mm} \times 10\text{ mm}$. The direction of polarisation P is indicated in the figure. Calculate the charge Q generated by the microphone if an instantaneous force of 1 N is applied to the rod perpendicular to area a . [20%]

$d_{31} = 123\text{ pC N}^{-1}$ for PZT-4.

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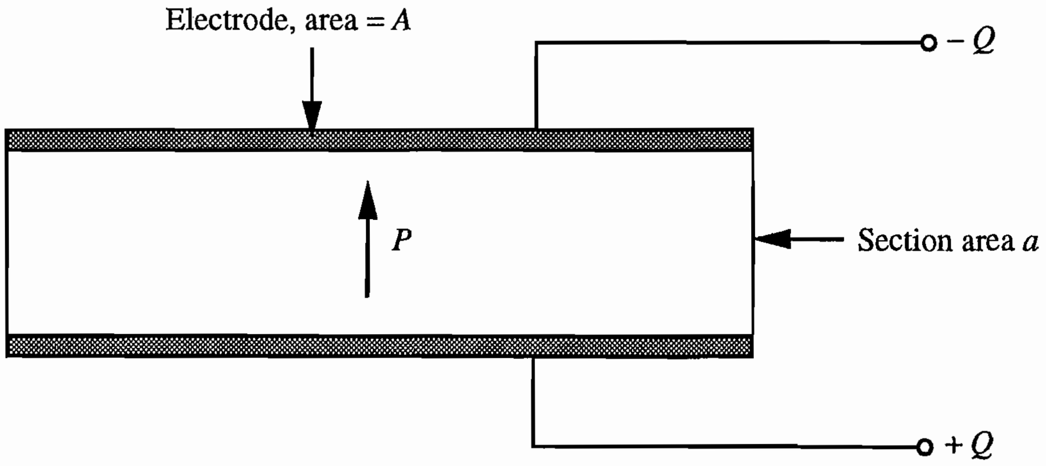

Fig. 1

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2 (a) Describe briefly how magnetic fields are generated in permanent magnets and bulk type II superconductors. Sketch the variation of magnetisation with applied magnetic field at constant temperature over a full field cycle for:

(i) a hard permanent magnet material;

(ii) a bulk superconductor.

Indicate the key parameters of each material on your sketches. [30%]

(b) Figure 2 shows a fully magnetised type II superconducting slab of thickness d in zero applied field. Derive an equation that relates the flux density gradient to the critical current density J_c for a type II superconductor of this geometry, stating clearly any assumptions you make. Illustrate your result with sketches of the distribution of flux density through the thickness of the slab for various magnitudes of applied field compared to that required to achieve full penetration. [30%]

(c) Determine the maximum theoretical magnetic flux density generated by nickel at room temperature. You may assume that nickel has a FCC crystal structure with 0.6 unpaired electrons per atom, 4 atoms per unit cell and a lattice parameter of 0.35 nm. One Bohr magnetron $\mu_B = 9.27 \times 10^{-24}$ A m^2 and the permeability of free space $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}. [20%]

(d) Compare the magnetic flux density generated:

(i) at the end of a long, thin rod of nickel;

(ii) at the centre of a long cylinder of Y-Ba-Cu-O (YBCO) of diameter 1 cm that carries a uniform, field-independent critical current density of 10^4 A cm^{-2}.

Discuss briefly the factors that limit the practical use of these materials in these geometries. [20%]

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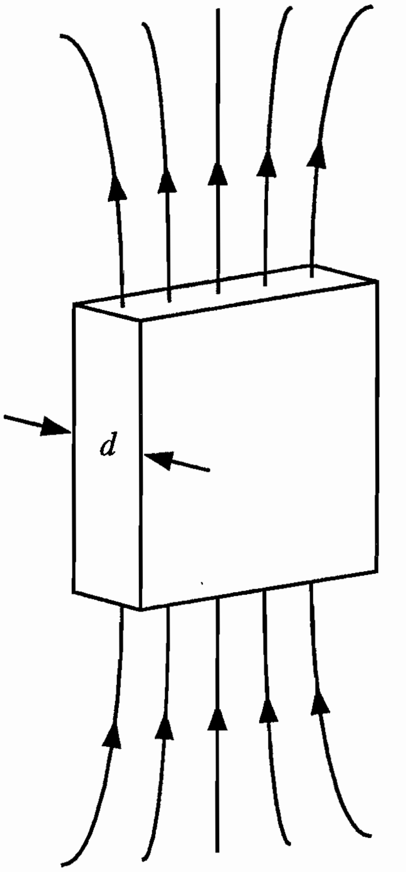

Fig. 2

3 (a) (i) Explain what is meant by a thermally activated process, including how such a process can be identified. Give three examples of thermally activated processes. [20%]

(ii) The vapour pressures of lead (Pb) at 700 K and 2000 K are 8×10^{-9} Pa and 1 Pa, respectively. Determine the activation energy of the vapourisation of lead in eV. [15%]

(iii) Account carefully for the use of eV to quantify activation energy. [15%]

(b) Describe carefully an analytic technique for each of the following applications, stating in each case state what is detected and how it is related to the data required:

(i) the production of an image of the distribution of a selected element in a scanning electron microscope; [15%]

(ii) the analysis of the composition of a thin film to give the concentration of the elements present as a function of depth; [20%]

(iii) the production of information on the surface layers of a film growing in an MBE machine. [15%]

4 (a) Explain the concept of effective mass of an electron in a semiconductor, and describe its relationship to the curvature of the band structure. Outline the effective mass, or hydrogenic, model of dopant states in a semiconductor and explain carefully how the binding energy of an electron to a dopant depends on the effective mass and dielectric constant of the material. [25%]

(b) The relationships between conductivity σ, mobility μ and carrier density n and between mobility and effective mass m^* are given, respectively, by

$$\sigma = ne\mu$$

and

$$\mu = \frac{e\tau}{m^*}$$

where e is the charge on an electron and τ is the mean free time between collisions. Use these relationships and your answer to part (a) to explain the benefits of using a semiconductor of low effective mass in a semiconductor device. [25%]

(c) Draw a labelled diagram of the main components of a modern metal oxide field effect transistor (MOSFET). What are the main materials required for the various components of this device? Explain how the materials used in the manufacture of MOSFETs have changed recently for the case of interconnects, gate oxide and channel components. In each case, give reasons to account for these changes. [50%]

5 (a) Draw a schematic diagram of a semiconductor band structure that includes defect states. Explain the origin of these states in terms of simple bonding models.. [25%]

(b) Explain what is meant by defect passivation. What elements are effective passivants for point defects? How are semiconductor surfaces passivated in a planar semiconductor device, and how does this remove defect states from the band structure? [20%]

(c) Draw a labelled diagram of an active matrix liquid crystal display and explain briefly its mode of operation. [25%]

(d) Draw a separate diagram of the cross-section of the thin film transistor that controls a pixel element of an active matrix liquid crystal display. Identify the various materials used in this transistor compared to the CMOS equivalent. Explain carefully how defect and surface passivation occurs in the thin film version of the transistor. [30%]

END OF PAPER