ENGINEERING TRIPOS PART IIB

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Thursday 4 May 2006 2.30 to 4

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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 Bean model for type II superconductors. Describe qualitatively the current flow in a long rod of bulk superconductor in a previously unmagnetised state when a large magnetic field is applied parallel to the axis of the rod and then removed. [20%]

(b) Figure 1 shows schematically a fully magnetised type II superconducting slab of thickness $d$ in zero applied field. Explain why this geometry is particularly suitable for analysis by the Bean model, stating any assumptions you make. Hence derive an equation that relates the flux density gradient to critical current density $J_c$ for a type II superconductor of slab geometry. [30%]

(c) Sketch on one diagram the variation of magnetic flux density $B$ through the thickness of a fully magnetised slab of type II superconductor in zero external field for each of the following cases:

(i) $B$ is independent of $J_c$, and

(ii) $J_c = \frac{K}{B}$, where $K$ is a constant.

For assumption (i), what is the minimum field that must be applied in order to fully magnetise the slab? [20%]

(d) A fully magnetised 5 mm thick slab of $YBa_2Cu_3O_{7-\delta}$ (YBCO), of similar geometry to that in Fig. 1, carries a uniform field-independent critical current density of $20 \times 10^3$ A cm$^{-2}$ throughout its volume. Determine whether the YBCO slab traps a greater magnetic flux density than that generated at the centre of a fully magnetised, long, thin rod of nickel. [30%]

Nickel has an FCC crystal structure, with a lattice parameter of 0.35 nm and has 0.6 unpaired spins per atom. The permeability of free space $\mu_0 = 4\pi \times 10^{-7}$ H m$^{-1}$.

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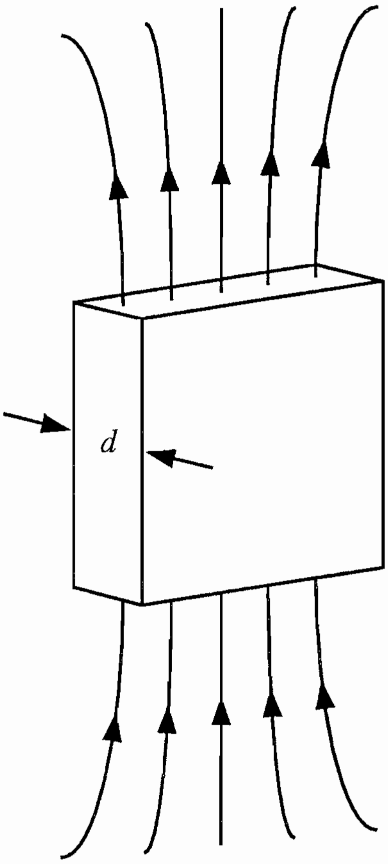

Fig. 1

2 (a) Describe briefly the classification of dielectric materials as piezoelectric, pyroelectric or ferroelectric. [25%]

(b) Write down the piezoelectric equations of state in tensor form relevant to (i) passive and (ii) active applications of piezoelectric materials. Explain carefully how the number of piezoelectric coefficients for application in passive mode $d_{ijk}$ can be reduced practically to three, and illustrate how the key intrinsic and extrinsic variables relate to one another geometrically in each case. [30%]

(c) Identify the usual mode of operation of a piezoelectric device for the following applications:

(i) a microphone;
(ii) a spark igniter;
(iii) an accelerometer.

In each case give brief reasons to support your answer. [15%]

(d) Starting from the appropriate equation of state, derive an equation for the change in voltage $\Delta V$ generated by a piezoelectric element under thickness mode operation in terms of the applied force $\Delta F$, the permittivity of free space $\varepsilon_0$, the relative permittivity of the piezoelectric material $\varepsilon$, the piezoelectric coupling coefficient $d_{33}$, the area $A$ of the element normal to the direction of applied force and the element thickness $t$. Hence rank the materials listed in Table 1 by their suitability for thickness mode application by considering materials properties only.

Identify briefly any other considerations that should be made before selecting a piezoelectric material for thickness mode application. [30%]

(cont.

| Material | Density kg cm$^{-3}$ | $\varepsilon$ | $d_{33}$ pC N$^{-1}$ |
|---|---|---|---|
| PZT-4 | 7750 | 1300 | 289 |
| PZT-5 | 7500 | 3400 | 593 |
| PZT-8 | 7600 | 1000 | 215 |
| PT | 7830 | 170 | 51 |
| BT1 | 5700 | 1000 | 120 |

Table 1

3 (a) Consider a vessel containing a gas at room temperature and low pressure. The molecules of the gas have an effective diameter of 1 nm and a sticking coefficient of unity when incident on the wall of the vessel. Calculate the number density of gas molecules per cubic metre if the time taken to form a monolayer is one minute, making reasonable estimates of any unknown quantities. [30%]

(b) Describe briefly the main characteristics of the method, the vacuum system requirements and the types of electrical materials that are deposited by each of the following thin film technologies:

(i) electron-beam evaporation;
(ii) molecular beam epitaxy;
(iii) sputter deposition.

Compare and contrast the quality of the material and the cost of production for the different technologies. [40%]

(c) Outline briefly how scanned electron beams are used to examine thin films and device topologies using as an example the secondary electron image of a silicon integrated circuit shown in Fig. 2, which dates from about 1990. What causes contrast at the edges of the features of the device? In the absence of a scale bar, estimate the size of the main features in Fig. 2. [30%]

(cont.

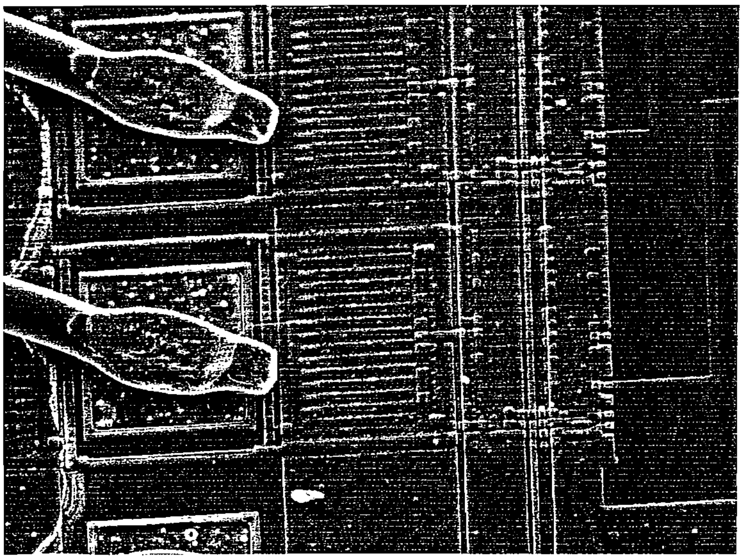

Fig. 2

(TURN OVER

4 (a) Explain carefully the difference between direct and indirect band gaps in semiconducting materials. Why is a direct band gap required for an opto-electronic device? [20%]

(b) Give two examples of a material with a direct band gap and two examples of a material with an indirect band gap. [10%]

(c) Describe carefully how carrier confinement is achieved in light-emitting semiconductor heterostructures, using a diagram of the band structure to illustrate your explanation. [30%]

(d) Explain the links between band gaps and crystal cell size. Why is lattice-matching important in heterostructures, and what happens in the case of mis-matched structures? [40%]

5 (a) Draw a schematic diagram of a silicon-based metal oxide structure field effect transistor (FET). Label the main features of the device and identify the materials present. [20%]

(b) Describe the various roles of $SiO_2$ in the MOSFET. Indicate which of these will be superseded by high-$K$ and low-$K$ oxides, respectively, giving the reasons. [20%]

(c) Explain how the free surface of a semiconductor can limit the performance of a device, and how $SiO_2$ has helped resolve this problem. [10%]

(d) Describe an interconnect in an electronic circuit, and the process that leads to its failure. Which metal is now used for interconnects in these circuits? [15%]

(e) Give examples of elements suitable for doping of groups IV, III-V and II-VI semiconductors. [20%]

(f) Which elements could be used for interstitial doping in semiconductors? What are the disadvantages of interstitial doping in real Si-based devices? [15%]

**END OF PAPER**

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**NUMERICAL SOLUTIONS**

1 (d) 0.63 T for YBCO, 0.65 T for Ni

2 (d) PT > PZT-4 > PZT-8 > PZT-5 > BT1

3 (a) $\approx 10^{14}$ $m^{-3}$
(c) Line width $\approx 3\mu m$

D. A. Cardwell
D. F. Moore
J. Robertson