ENGINEERING TRIPOS PART IIB

Wednesday 24 April 2013 9.30 to 11.00

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	SPECIAL REQUIREMENTS
Single-sided script paper	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) Explain carefully the relevant pinning mechanisms in:

(i) permanent magnetic materials;
(ii) bulk Y-Ba-Cu-O (YBCO) high temperature superconductors.

In each case describe the nature of the pinning and its effect on the magnetic and electrical properties of each class of material, using sketches to illustrate your answers where appropriate. [40%]

(b) State the relationship between demagnetising field, $\boldsymbol{H_m}$, of a magnetic material, applied field, $\boldsymbol{H_0}$, and sample magnetisation, $\boldsymbol{M}$. Hence show that the flux density, $\boldsymbol{B_m}$, in a magnetic material in the absence of an applied field, is given by:

$$\boldsymbol{B_m} = \mu_0 \, \boldsymbol{H_m} \left(\frac{N-1}{N} \right)$$

where N is the shape-related demagnetising factor.

Determine approximate values for $\boldsymbol{B_m}$, $\boldsymbol{H_m}$ and $\boldsymbol{M}$ in a fully magnetised sphere of Alcomax III. You may assume that a sphere has a demagnetising factor of 1/3. [30%]

(c) Compare the magnetic flux density of a fully magnetised Alcomax III sphere with that at the centre of a long superconducting cylinder of YBCO of diameter 2 cm, carrying a uniform circumferential current density of 10×10^3 A cm^{-2} (you may assume that critical current density does not vary with $\boldsymbol{B}$). Identify any difficulties in using the field generated by a bulk superconductor of cylindrical geometry in practical applications. [30%]

2 (a) Explain briefly why all pyroelectric materials are necessarily piezoelectric, but that the converse is not true. [20%]

(b) State the piezoelectric equations of state in tensor form for (i) passive and (ii) active applications of piezoelectric materials. Explain carefully how the number of piezoelectric coefficients, d_{ijk}, can be reduced to three for practical geometries, and illustrate how the key intrinsic and extrinsic variables relate to one another geometrically for each of the three cases. [35%]

(c) Identify the usual mode of operation of a piezoelectric device for use in (i) a microphone, (ii) a spark igniter and (iii) an accelerometer. For each device, give brief reasons to support your answer. [15%]

(d) Starting from the appropriate equation of state, derive an equation for the change in voltage ΔV generated by a piezoelectric element under thickness mode operation in terms of the applied force ΔF, the permittivity of free space ε_0, the relative permittivity of the piezoelectric material ε, 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 material properties only. [30%]

Material	**Density** kg cm^{-3}	ε	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

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3 Derive a simple expression for the mean free path, λ, of molecules in a gas in terms of molecular diameter, temperature and gas pressure using the kinetic theory of gases. Estimate the value of λ for air at atmospheric pressure and room temperature. Assume an average molecular diameter of 0.5 nm. [25%]

(b) Outline the basic operating principles of a turbomolecular pump. With reference to (a), explain why turbomolecular pumps typically employ a multiple stage rotor/stator design with a progressively decreasing blade spacing towards the outlet, and why a turbomolecular pump typically requires a backing pump attached to its outlet. [20%]

(c) An aluminium film is to be deposited onto a silicon chip, which features trenches that are 1 μm deep and 1 μm wide. Describe a suitable deposition technique to achieve a good conformal coverage of aluminium. [15%]

(d) The Al covered Si chip described in (c) is transferred into a vacuum system at room temperature.

(i) Calculate the background pressure at which it will take approximately 10 minutes for a monolayer of water molecules to form on the chip surface. Assume a water molecule diameter of 0.5 nm. [25%]

(ii) Outline a characterisation technique, including its principle of detection, suitable for verifying the presence of an adsorbed water layer and resultant possible oxidation of the Al layer. [15%]

4 (a) Describe carefully the advantages and disadvantages of Si, GaAs and GaN for use in computing, opto-electronic and power semiconductor devices. [25%]

(b) Explain why semiconductors have become more important recently as lighting sources, identifying the materials used and the competing technologies. Explain how an inorganic light emitting diode can act as a white light source. [25%]

(c) Explain with the aid of bond and band diagrams how conduction occurs in organic semiconductors. [25%]

(d) Explain the operation of organic semiconductors in light emitting diodes using a band diagram. How are band edge carriers provided in such devices? [25%]

5 (a) Explain the difference between volatile and non-volatile memory devices. Describe an example of each type, using diagrams to explain the storage mechanism in each case. [35%]

(b) Draw a labelled diagram of the various components of a Si-based MOSFET in an integrated circuit. [15%]

(c) Describe three roles of SiO_2 in a planar MOSFET. Explain which of these roles will be superseded by the use of high and low *K* (i.e. high and low dielectric constant) oxide materials, respectively, and why. [15%]

(d) Describe the performance limitations associated with the materials, other than SiO_2, used presently for the other components of the MOSFET. Give examples of how a new material will improve this performance in each case. [35%]

END OF PAPER