ENGINEERING TRIPOS PART IIB

Thursday 3 May 2007 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	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

~~Version 2~~

1 (a) Describe carefully how materials are classified as pyroelectric. Explain which form of pyroelectric material is most useful for the manufacture of practical devices. [25%]

(b) Describe carefully the operation of a pyroelectric detector. Under what conditions will the detector operate under (i) current and (ii) voltage mode responsivity? [25%]

(c) 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 voltage responsivity R_V of the detector, and hence derive the following expression

$$R_V = \frac{R_G \, \eta \, p \, A \, \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2} \, \sqrt{1 + \omega^2 \tau_E^2}} ,$$

where the symbols have their usual meaning. Sketch the variation of $\log(R_V)$ with $\log(\omega)$, indicating any important features on your diagram. [25%]

(d) The pyroelectric materials listed in Table 1 are to be considered for use in a pyroelectric detector that exhibits high signal to noise. List these materials in rank order of performance. Explain briefly the origin of any equations you use. [25%]

The permittivity of free space $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1}.

(cont.

Material	T_c °C	p μCm^{-2}K^{-1}	ε_r	tan δ $\times 10^{-3}$	c MJm^{-3}K^{-1}
PZFNTU	230	380	290	10	2.5
SBN - 50	121	550	400	3	2.3
PVDF	80	27	12	15	2.6
PGO	178	110	40	0.5	2.0

Table 1

2 (a) Sketch the variation of flux density with applied magnetic field at constant temperature over a full field cycle for:

(i) a hard permanent magnet material;

(ii) a soft permanent magnet material.

Indicate the key parameters of each material on your sketches. [25%]

(b) Describe the microscopic features of hard and soft permanent magnet materials and explain how these relate to the geometries in which they are applied. Give two applications of each type of material. [20%]

(c) Explain carefully how magnetic flux density is generated by a homogeneous bulk type II superconductor, such as Y-Ba-Cu-O (YBCO). Describe qualitatively how a bulk type II superconductor of slab geometry can be magnetised to generate its maximum trapped field in the plane of the slab. Use sketches of the variation of trapped field with slab cross-section at different stages of the magnetisation process to illustrate your answer. [25%]

(d) Compare the magnetic flux density generated:

(i) at the centre of a 2000 turn cylindrical coil of length 10 cm that carries a current of 10 A;

(ii) at the surface of a long cylinder of YBCO of diameter 2 cm that carries a uniform, field-independent critical current density of 20×10^3 A cm^{-2}.

Discuss briefly the factors that may limit the field generating capacity in each case. [30%]

3 (a) (i) Derive the Bragg relation for the diffraction of electrons or X-rays from a crystal.

(ii) Explain how X-ray diffraction can be used to identify the nature and quantity of a particular phase in a solid.

(iii) Describe the generation of X-rays in commercial investigative apparatus and identify two techniques other than diffraction that use X-rays to probe the properties of materials.

(iv) Explain carefully how atomic number influences the generation of X-rays and how this translates to the detection of elements of different atomic mass.

[70%]

(b) Derive an expression for the mean free path of an atom in a gas in terms of the atomic diameter and the number of atoms per unit volume.

Explain carefully how the mean free path is chosen in the deposition of thin films by the following processes

(i) evaporation;

(ii) sputtering.

[30%]

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4 (a) Describe Moore's law and explain what is meant by 'transistor scaling'. [15%]

(b) Draw a labelled diagram of a Si-based MOSFET for use in an integrated circuit. Your diagram should include all the fey features of the device. [15%]

(c) Describe how the performance of the key components of a Si-based MOSFET is limited by the materials in current use for its construction. Give examples of how new materials would improve this performance in each case. [35%]

(d) The saturated source-drain current of a MOSFET is given by

$$I = \frac{Z \mu C}{2L} (V_G - V_T)^2 ,$$

where L is the source-drain channel width, μ is the semiconductor mobility, V_G is the gate voltage, V_T is the gate threshold voltage and C is the gate capacitance per unit gate area. In addition, $C = \varepsilon / t$, where ε is the dielectric constant of the gate insulator, and t is its thickness. The gate leakage current density is given by

$$J = J_0 \exp[-2kt] ,$$

where k is the tunnelling constant of the gate insulator. Explain carefully the mechanism of leakage current flow and identify the thickness of gate insulator at which it becomes a problem. Explain how increasing ε can result in a lower leakage current whilst retaining the desired source-drain current. [35%]

5 (a) Draw the band structure of a typical semiconductor material. Explain carefully the difference between direct and indirect band gaps in semiconducting materials. What is the significance of the nature of the band gap? [20%]

(b) Explain two strategies for increasing the band gap of a light-emitting semiconductor whilst retaining efficient light emitting properties. Use diagrams to support your answer. [20%]

(c) Explain the concept of band mass, and describe its relationship to band curvature. Outline the effective mass, or hydrogenic, model of dopant states in a semiconductor. [25%]

(d) Identify three problems that can occur in the doping of wider gap semiconductors. [15%]

(e) Describe carefully the operation of transfer or modulation doping in a semiconductor heterostructure. What limits thc choice of materials in this process? Determine the density of mismatch dislocations per unit length between semiconductors of lattice constant d and $d+\delta d$. [20%]

END OF PAPER