Version SH/5

EGT3
ENGINEERING TRIPOS PART IIB

Monday 28 April 2014 9.30 to 11

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.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

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

1 (a) Explain the origin of magnetisation in a magnetic material and its relationship to the external field. Provide a relationship between the B-field, **B**, in a long rod of magnetic material, the externally imposed H-field, $\mathbf{H}_0$, and the magnetisation, **M**, of the rod. [15%]

(b) Provide a careful explanation of the difference between hard and soft ferromagnetic materials. Give examples of engineering applications for both types of material. Sketch a B-H curve for a hard ferromagnetic material. Indicate on your sketch the position of the saturation field, the remanent field and the coercive field. [35%]

(c) Explain why the flux density inside a magnet fabricated in a shape other than a long rod is less than that shown on a B-H curve for the material. Explain how to determine the operating point of a permanent magnet of a particular shape and thus explain why many hard ferromagnetic materials cannot be fabricated into arbitrarily shaped permanent magnets. [35%]

(d) Find the value of the demagnetising factor, N, at which the magnetic energy density in a permanent magnet is largest. Give an example of a shape for which N approximates this value. Give two examples of hard ferromagnetic materials that are suitable for use as permanent magnets of such a shape. [15%]

2 (a) Explain the origin of the piezoelectric and pyroelectric effects in materials in terms of their crystal structure. With a sketch or otherwise indicate how strain, stress, temperature and electric field are related in a piezoelectric material. [40%]

(b) In a pyroelectric detector system (including read-out circuitry) the temperature difference, θ, between the detector and its surroundings is given by

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

where η is the emissivity, G_T the thermal conductance to the surroundings and H is the thermal capacity. This assumes that the incident radiation is sinusoidally modulated at angular frequency ω so that its power is given by $W = W_0 e^{i\omega t}$. Show that the equation for the current responsivity, R_i, is given by

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

where A is the electrode area, p is the pyroelectric coefficient and $\tau_T = \frac{H}{G_T}$ the thermal time constant. State under what circumstances the device will operate in current mode. [30%]

(c) State which range of incident radiation modulation frequencies is preferable in current mode. Explain your answer with reference to the thermal properties of the detector. [10%]

(d) Polyvinylidene fluoride (PVDF) is easy and cheap to fabricate into large area thin films, thus it is commonly used in cheap pyroelectric detectors. Under the optimum conditions determined in your answer to (c), calculate the current responsivity of a PVDF-based detector system. Assume $\eta = 0.95$, $p = 27\mu\text{Cm}^{-2}\text{K}^{-1}$, that the thickness, d, of the PVDF film is 500nm and that the specific heat capacity $c = \frac{H}{dA} = 2.6\text{MJm}^{-3}\text{K}^{-1}$. [20%]

3 (a) Explain the principles of sputtering as widely used in the semiconductor industry for thin film deposition. Give the advantages of sputtering compared to the evaporation of thin films. [20%]

(b) A silicon wafer is oxidised as part of substrate preparation. Outline a suitable non-destructive characterisation technique, including its principle of detection, to determine the thickness of the silicon dioxide. [10%]

(c) The oxidised silicon wafer substrate is transferred into a deposition chamber at room temperature. The deposition chamber has a background pressure due mainly to water vapour. The time for a monolayer of water molecules to form on the substrate is required to be longer than 10s. Calculate the necessary background pressure. State all assumptions made. [25%]

(d) A 1nm thick nickel film is sputtered on the oxidised silicon wafer substrate. Outline how carbon nanotubes can be grown from this nickel film. [20%]

(e) Describe a suitable technique, including its principle of detection, to characterise the diameter and length of as-grown carbon nanotubes. [15%]

(f) The carbon nanotubes are to be coated with a very thin titanium dioxide film for a gas sensor application. It is known that sputtering will degrade the carbon nanotube quality and hence cannot be used for this. Give a suitable deposition technique to achieve a good conformal coverage of titanium dioxide. [10%]

4 (a) Draw the band structure of a typical semiconductor. What is the difference between a direct and an indirect band gap, and what is its significance? [15%]

(b) Explain with diagrams two strategies for increasing the band gap of a light-emitting semiconductor like GaAs, while still retaining efficient light emission. [10%]

(c) Explain what is the effective mass of the bands, and its relationship to band curvature. Explain the effective mass or hydrogenic model of dopant states in a semiconductor. How does the donor binding energy vary with effective mass and dielectric constant of the semiconductor? [30%]

(d) Explain three problems which can occur in achieving doping in wider band gap semiconductors. [25%]

(e) Explain how transfer or modulation doping works in a semiconductor heterostructure. What limits the choice of materials? Give the density of mismatch dislocations per unit length for two semiconductors of lattice constant d and $d + \delta d$. [20%]

5 (a) Draw a schematic semiconductor band structure which includes the defect states. Explain the origin and energy levels of these states using simple bonding models. [25%]

(b) Explain what is meant by defect passivation. How are semiconductor surfaces passivated in a planar semiconductor device, and how does this remove defect states in this case? [20%]

(c) Draw a labelled diagram of an active-matrix liquid-crystal display (LCD) and explain briefly its mode of operation. What are its disadvantages compared to organic light emitting diodes? [25%]

(d) Draw a diagram of a thin-film transistor typically used in such a LCD display. Outline the various materials used in this transistor, in comparison to the CMOS equivalent. Why is amorphous silicon used and not crystalline silicon? With reference to (b), explain how defect and surface passivation occurs in such thin-film transistors. [30%]

END OF PAPER