ENGINEERING TRIPOS PART IIB

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Thursday 30 April 2009 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 ndicated in the right margin.*

*There are no attachments to this paper.*

| STATIONERY REQUIREMENTS | SPECIAL REQUIREMENTS |
|---|---|
| Single-sided script paper | Engineering Data Book<br>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 properties of materials that lead to their classification as pyroelectric and explain the microscopic basis of the pyroelectric effect. Explain carefully why ferroelectrics are particularly important in the manufacture of pyroelectric detectors. [40%]

(b) A thermal detector consists of a pyroelectric element and its associated circuitry. The temperature difference $\Delta T$ between the element and its surroundings when exposed to incident sinusoidally modulated radiation, $W = W_0\, e^{j\omega t}$, is given by

$$\Delta T = \frac{\eta\, W_0\, e^{j\omega t}}{G_T + j\omega H}$$

Explain the meaning of the terms in the right-hand side of this equation. Define the current responsivity $R_i$ of the detector and hence derive the following expression

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

where $p$ is the pyroelectric coefficient, $A$ is the area of the absorbing electrode and $\tau_T$ is the thermal time constant of the device.

Sketch the variation of $R_i$ with $\omega$. Over which frequency range is $R_i$ constant? [30%]

(c) Assuming that the element capacitance is large compared to the amplifier capacitance of the thermal detector, rank the ferroelectric materials listed in Table 1 in order of potential for use in a pyroelectric detector that exhibits:

(i) a high voltage response;
(ii) a high signal to noise ratio.

The permittivity of free space $\varepsilon_0 = 8.85 \times 10^{-12}$ F m$^{-1}$. [30%]

(cont.

| Material | $T_c$ °C | $p$ $\mu$Cm$^{-2}$K$^{-1}$ | $\varepsilon_r$ | $\tan\delta$ $\times 10^{-3}$ | $c$ 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) Describe the effects of surface and shape on the magnetic properties of permanent magnet materials. Use diagrams to illustrate your answer. [30%]

(b) Show that the demagnetising field $\mathbf{H}_\mathrm{m}$ of an exposed surface of a magnetic material is related to the applied field $\mathbf{H}_0$ and the magnetisation $\mathbf{M}$ by

$$\mathbf{H}_\mathrm{m} = \mathbf{H}_0 - N\mathbf{M}$$

where $N$ is the shape-related demagnetising factor. State the range of $N$ and show that the flux density $\mathbf{B}_\mathrm{m}$ in a magnetic material in the absence of an applied field is given by

$$\mathbf{B}_\mathrm{m} = \mu_0\,\mathbf{H}_\mathrm{m}\left(\frac{N-1}{N}\right).$$

[40%]

(c) Determine *approximate* values for the magnitudes of the flux density $\mathbf{B}$, magnetic field $\mathbf{H}$ and magnetisation $\mathbf{M}$ in fully magnetised Alcomax III in the absence of an applied field for the following geometries:

(i) spherical;

(ii) cylindrical, magnetised perpendicularly to the cylinder axis.

Comment briefly on your answers. [30%]

3 (a) Describe briefly the chemical vapour deposition (CVD) process for the fabrication of thin films. Explain why it is advantageous to operate a CVD reactor at a pressure lower than atmospheric. [20%]

(b) Derive a simple expression for the mean free path of molecules in a gas in terms of molecule diameter, temperature and gas pressure. Define the Knudsen number and identify the gas flow regimes in which the processes of thermal evaporation and sputtering are typically performed. Explain briefly how these regimes affect the step coverage of as-deposited thin films. [40%]

(c) Outline a suitable characterisation technique for each of the following properties, in each case describing carefully the principle of detection:

(i) the thickness of a thin, uniform nickel film on a silicon wafer; [10%]

(ii) the dopant concentration of a silicon film as a function of depth; [10%]

(iii) the length and diameter of a silicon nanowire and the presence of a metal catalyst particle in its tip. [20%]

4 (a) Describe substitutional and interstitial doping in semiconductors, explaining in each case the mechanism of conduction. Identify the groups of elements that are used to dope IV and III-V semiconducting compounds. [30%]

(b) The following equation gives the energy levels of the hydrogen atom

$$R = \frac{e^4 m}{32 \pi^2 \varepsilon^2 h^2}$$

where the symbols are as defined in the lectures. Use this equation to explain how the binding energy of donor electrons may be modelled by the hydrogenic atom. [30%]

(c) The extent to which some semiconductors can be doped is limited. Explain why this is the case, giving three reasons to support your answer. [25%]

(d) Explain which of the reasons identified in part (c), if any, might limit significantly the doping of each of the semiconductors listed in Table 2. [15%]

| Material | $\varepsilon_r$ | $m^*$ electrons | $m^*$ holes | Band gap eV |
|---|---|---|---|---|
| Si | 12.0 | 0.26 | 0.4 | 1.1 |
| Diamond | 5.7 | 1.30 | 0.4 | 5.5 |
| GaAs | 10.9 | 0.06 | 0.1 | 1.45 |
| $SiO_2$ | 2.2 | 0.50 | 12.00 | 9.0 |

Table 2

5 (a) Describe Moore's law. [10%]

(b) The typical feature size of a silicon device in 2003 was 0.13 μm. Estimate the size of a silicon device in 1980 and its projected size in 2011. [20%]

(c) Sketch the structure of a typical n-type MOS (NMOS) FET (field effect transistor). Identify the materials used currently for each part of a modern FET and compare these with the materials used in 1980. Explain the physical reasons that led to the change in materials in each case. [40%]

(d) Identify three roles of silicon dioxide layers in a planar FET. [15%]

(e) Describe how electromigration causes problems in the operation of an FET. How could carbon nanotubes be used in future to address this problem? [15%]

**END OF PAPER**