EGT3
ENGINEERING TRIPOS PART IIB

Thursday 26 April 2018   9.30 to 11.10

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

10 minutes reading time is allowed for this paper at the start of the exam.

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

1 (a) Practical ferromagnetic materials are often described as *soft* or *hard*.

(i) Explain carefully, using a sketch, the difference in the response to an external magnetic field of soft and hard magnetic materials. [15%]

(ii) Give examples of key magnetic properties of materials and how these vary between soft and hard magnetic materials. [15%]

(iii) Provide one example of a hard magnetic material and one example of a soft magnetic material and give a possible practical application of each. [10%]

(b) Explain why the maximum magnetisation, $\boldsymbol{M}_s$, obtained in a conventional ferromagnet is a materials property, whereas in a bulk superconductor it depends on sample size. [20%]

(c) The field at the surface of a practical hard magnet is determined by its shape as well as its remnant magnetisation.

(i) Explain the origin of the demagnetisation field, $\boldsymbol{H}_m$, in a practical magnet. State the relationship between $\boldsymbol{H}_m$, the demagnetisation factor, N, and sample magnetisation, $\boldsymbol{M}$. [10%]

(ii) From your answer to (c)(i) show that the flux density in a magnet, $\boldsymbol{B}$, is given by:

$$\boldsymbol{B} = \mu_0 \boldsymbol{H}_m \left(\frac{N-1}{N} \right).$$

Explain, with the aid of a sketch of the B-H curve for a hard ferromagnet, how this relation can be used to determine the operating point, and thus the energy product $(\boldsymbol{BH})$, in a magnet. [20%]

(iii) Find the value of N which maximises the energy product in a magnet at its operating point and give an example of a shape that approximates this demagnetisation factor. [10%]

2 (a) Three technologically useful classes of electrical materials are pyroelectric materials, which exhibit polarisation in response to changes in temperature; piezoelectric materials, which exhibit polarisation in response to strain; and ferroelectrics which exhibit spontaneous polarisation. In these materials the electric dipole per unit cell is given by $q\boldsymbol{r}$ where q is the electronic charge and $\boldsymbol{r}$ is the displacement between positive and negative charge centres.

(i) Explain how the charge displacement arises and consequently gives rise to the observed behaviour for the case of each of piezo- and pyro- electric materials. [15%]

(ii) Explain why, when pyroelectric or piezoelectric behaviour is required, the material of choice is, in fact, often a ferroelectric. [10%]

(iii) Explain how the spontaneous polarisation, $\boldsymbol{P}_s$ relates to the dipole per unit cell and write an appropriate equation to relate the two quantities. [10%]

(b) The piezoelectric coefficient, d, is properly expressed as a tensor of order 3. Consequently for the case of the direct piezoelectric effect polarisation in a particular axis, P_i and the applied tensile and shear stresses, σ_{jk} are related by the state equation $P_i = \sum_{jk} d_{ijk}\sigma_{jk}$.

(i) Explain, without formal derivation, how this can be simplified so as to express the state equation for the direct piezoelectric effect using a piezoelectric coefficient which is a matrix of order 2. [15%]

(ii) Explain why, although there are 18 components to the reduced piezoelectric coefficient, only three piezoelectric coefficients are normally of technological interest. [15%]

(iii) List the three operating modes that these coefficients correspond to. For one specified mode illustrate in a sketch how the mode functions. [20%]

(c) Starting from your answer to (b), or otherwise, derive an equation for the change in voltage ΔV generated by a piezoelectric element used in thickness mode operation. The equation should be expressed 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. [15%]

3 (a) The Magdeburg hemispheres are a pair of copper hemispheres designed by Otto von Guericke to demonstrate the mechanical vacuum pump that he invented. The hemispheres, with a radius of 25 cm, were pressed together with a leather seal to form a sphere and the interior volume pumped to vacuum. Estimate the force holding the two hemispheres together once under vacuum. How many horses would van Guericke have required to pull the hemispheres apart? Assume that a horse can produce a pulling force roughly equivalent to its own weight. (The mass of a typical horse is $\sim$500 kg). [10%]

(b) 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 at room temperature in the vacuum produced by von Guericke. [25%]

(c) The concept of mean free path is also used for electron transport in solids.

(i) Sketch the electron inelastic mean free path in a solid versus electron energy, which is referred to as the universal curve. [10%]

(ii) Outline the basic principles of X-ray photoelectron spectroscopy (XPS). Based on (c)(i), outline two approaches to tuning the surface sensitivity of XPS. [20%]

(d) Supersaturation can be seen as the driving force for the nucleation and growth of a crystal or film.

(i) Plot the growth rate versus level of supersaturation for: the continuous growth regime and the 2D nucleation growth regime. [10%]

(ii) Outline the catalytic chemical vapour deposition process for the growth of a semiconducting silicon nanowire. Referring to (d)(i), explain how supersaturation is built up and how nanowire crystal growth proceeds. [15%]

(e) Outline a suitable characterisation technique for determining the thickness of the native oxide layer that forms on the silicon nanowire once exposed to air. [10%]

4 (a) Draw a labelled diagram of the main components of a modern metal oxide semiconductor field effect transistor (MOSFET). [10%]

(b) Explain how the materials employed in MOSFETs have changed recently for the cases of gate oxide; channel material; interconnects and interconnect dielectric. Explain the reasons for those changes. [40%]

(c) Draw a schematic semiconductor band structure which includes defect states. Explain in terms of simple bonding models where these states come from. [15%]

(d) Summarise the various factors that might cause defects to exist in a semiconductor, both in the bulk and at the surface. [15%]

(e) Explain what is meant by defect passivation. What elements are effective passivants for point defects? Explain how semiconductor surfaces are passivated in a planar semiconductor device, and how this removes defect states. [20%]

5 (a) Draw a labelled diagram of an active matrix liquid crystal display, controlled by amorphous silicon thin film transistors, and explain briefly its mode of operation. [20%]

(b) Draw a separate diagram of the associated thin film transistor (TFT). State the various materials in the transistor and explain its operation. Compare this with a conventional metal oxide semiconductor field effect transistor (MOSFET). [20%]

(c) Describe the nature of states in amorphous silicon (a-Si) in the different energy ranges, in terms of their origin and conduction properties, and explain how they are related to those of crystalline silicon. [25%]

(d) Briefly discuss how effectively doping can be made to work in hydrogenated amorphous silicon (a-Si:H). [25%]

(e) At what energies do the states related to hydrogen lie? [10%]

END OF PAPER

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Answers

3(a) Five horses