EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 26 April 2016 2 to 3.30

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.

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

1 (a) Sketch magnetisation vs. magnetic field (M-H) curves for a diamagnetic, paramagnetic, soft ferromagnetic and a hard ferromagnetic material, indicating key features and typical values for each case. Provide, with reasons, an example of a practical application for two of these types of magnetic materials. [30%]

(b) Describe qualitatively the origin of the remanent magnetic field generated in the following materials when first magnetised by the application and removal of a large external magnetic field. In each case, identify what aspects of the material control the magnitude of the remanent magnetic field and how that field changes with sample size.

(i) A disc of hard ferromagnetic material. [20%]

(ii) A disc of a superconducting material cooled below its critical temperature. [20%]

(c) A hard ferromagnetic material is to be fabricated into a disc-shaped magnet with height equal to radius.

(i) Show that this shape which has a demagnetising factor, N, of ½ maximises the energy stored in the magnet. [20%]

(ii) Explain why pure iron could not be used to make a permanent magnet with such a shape. Suggest, with reasons, two materials from which a magnet of this shape could be made.

[10%]

2 (a) Describe briefly the classification of dielectric materials as piezoelectric, pyroelectric or ferroelectric. Give a potential application for each class of material. [25%]

(b) Explain, with the aid of sketches, the crystallographic origin of the piezoelectric and pyroelectric effects. Give an equation which relates the overall spontaneous polarisation $\boldsymbol{P_s}$ to the dipole moment of each unit cell. [20%]

(c) In the absence of an external electric field, the state equation for the change in polarisation, $\boldsymbol{P}$, due to the operation of the piezoelectric effect is sometimes written in terms of stress, $\boldsymbol{\sigma}$, and a piezoelectric coefficient, d, as $\boldsymbol{P} = d\boldsymbol{\sigma}$.

(i) Explain why this is a simplification and provide a state equation that better represents the behaviour of a real material. [20%]

(ii) Explain qualitatively why piezoelectric materials are often used in the form of thin sheets and list the three common modes of operation. [15%]

(iii) Provide a labelled sketch of a piezoelectric transducer operating in one of these common modes and give a potential application of that mode. [20%]

3 (a) Outline the basic principles of chemical vapour deposition (CVD) as widely used in the semiconductor industry for thin film deposition. Sketch the temperature dependence of the CVD deposition rate and discuss the two main rate-limiting processes that are typically observed. [20%]

(b) Explain why low pressure operation can be beneficial for CVD. [10%]

(c) In order to fabricate a graphene-based field effect transistor an extremely thin Al_2O_3 film needs to be deposited on the graphene.

(i) Explain how atomic layer thickness control for the Al_2O_3 film can be achieved with a CVD-type process. [15%]

(ii) Explain why achieving a 1nm thin, continuous Al_2O_3 film on graphene is challenging on the basis of thin film nucleation theory. [15%]

(d) X-ray photoelectron spectroscopy (XPS) is used to characterise a 20nm thick, continuous Al_2O_3 film on graphene. Explain what information can be gained about the Al_2O_3 film and why XPS is extremely surface sensitive. [15%]

(e) Contact patterns on the graphene device are formed by electron beam lithography, whereby the sample is covered by an electron-sensitive polymer film. Exposure to a focused electron beam changes the solubility of the polymer, so that the exposed area can be selectively etched by immersing it in a solvent. Fig. 1 shows an etched cross-section of the polymer surface after a test exposure to a static electron beam.

(i) Explain the characteristic pear shape of this cross-section based on the fundamental electron-matter interactions that occur. [15%]

(ii) A polymer layer of much higher effective average atomic number relative to that of Fig. 1 is now exposed to the electron beam. Explain and sketch the expected cross-sectional shape of the etched polymer layer. [10%]

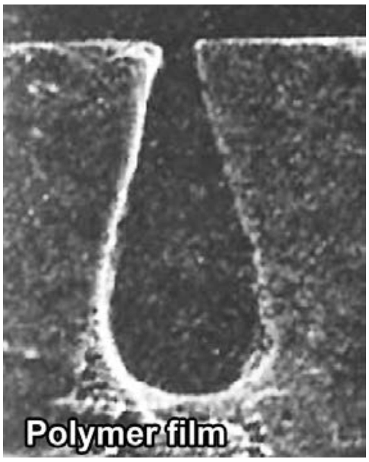

Fig. 1

(TURN OVER

4 (a) Explain the origin of surface states on a covalent semiconductor. Why can these surface states degrade transistor performance? [20%]

(b) Explain how the surface states are passivated in a planar Field-Effect Transistor (FET), using both schematic bonding and band diagrams. [20%]

(c) Assume a FET has an interface state density of 5×10^{24} m^{-3} over a thickness of 5 nm with a local relative dielectric constant of 5. Calculate the shift in the gate threshold voltage of the FET using Gauss' theorem or otherwise. [25%]

(d) Explain the origin of the band gap in amorphous Si in the absence of a crystal structure. [20%]

(e) Explain the origin of the types of gap states in amorphous Si and how some of them can be passivated by hydrogen. [15%]

5 (a) Explain how Moore's law scaling has been implemented for Field-Effect Transistors (FETs) from 1965-2000, and its effect on the relevant FET properties. Explain how scaling today differs from this, and give examples of the materials and FET functions involved. [30%]

(b) Describe two typical conduction mechanisms in insulators. [15%]

(c) Describe the device structure of a Flash memory, and how the write and erase processes work. Explain the critical function of SiO_2 in these two processes. [35%]

(d) Explain how the Flash memory read process is carried out in terms of the charge trapped in the floating gate. [20%]

END OF PAPER

Numerical Solutions: Q4 c) 0.22 V