EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 3 May 2017   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) Outline a suitable deposition technique for each of the following cases, stating for each case the principles of operation:

(i) 1 μm thick amorphous Si layer for a solar cell; [10%]

(ii) 100 nm thick Au layer for an electrical contact; [10%]

(iii) 1 nm thick Hf oxide layer as transistor dielectric. [10%]

(b) Outline a non-contact characterisation technique, including its principle of detection, with which the film thickness of case (a)(iii) can be measured. [10%]

(c) Al is deposited at a rate of 0.3 nm/s in a vacuum chamber with a background pressure of 10^{-6} torr of mainly water vapour. Determine the ratio of the arrival rates of Al atoms and H_2O molecules at the substrate. Assume an Al film density of 2700 kg/m^3 and state all other assumptions made. [20%]

(d) Figure 1 shows a scanning electron microscopy (SEM) image of a 1 nm Ni film on Si oxide substrate that was heated to 500°C.

(i) Explain why the Ni film splits into small islands upon heating. [10%]

(ii) Figure 1 was recorded with a standard secondary electron detector. Explain the contrast mechanism. [20%]

(iii) Discuss how contrast and resolution would change if a back scatter electron detector had been used. [10%]

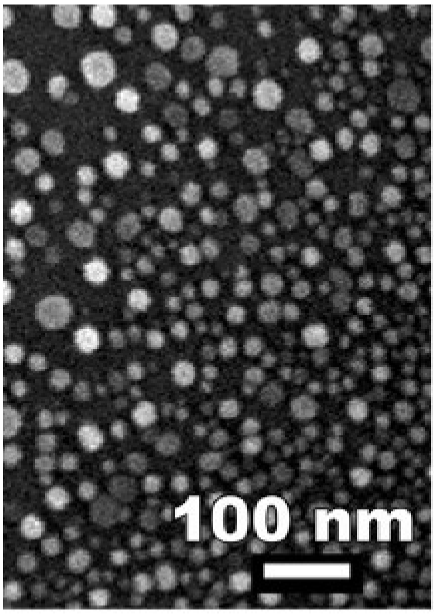

Fig. 1

2 (a) Explain the origin of surface states on Si and then explain in terms of a bonding model how SiO_2 passivates them. [35%]

(b) Explain how semiconductors have become more important recently, in terms of lighting sources. Explain which semiconductors are used and describe the competing technologies. Explain how an inorganic light emitting diode can be act as a white light source. [25%]

(c) Explain with the aid of bond and band diagrams how conduction occurs in organic semiconductors. [15%]

(d) Describe how organic semiconductors can act in organic light emitting diodes, using a band diagram. How are band edge carriers provided? [25%]

3 (a) Describe the hydrogenic model of doping in semiconductors. [25%]

(b) Explain the three phenomena which can limit the doping of semiconductors. [20%]

(c) Given the relationships between conductivity and mobility and effective mass, and noting part (b), explain the benefits of a low effective mass for semiconductors. [20%]

(d) Draw a labelled diagram of a CMOS FET showing the channel, gate oxide, metallic lines and the passivation insulator. Using a bullet point format, give examples of new materials being used for these components and the reasons behind these substitutions. [35%]

4 (a) Sketch the ***M-H*** (magnetisation vs magnetic field) curve for a Type-I and a Type-II superconductor. Label the key features. [20%]

(b) Provide a qualitative explanation for the difference in the ***M-H*** response of Type-I and Type-II superconductors sketched in part (i). [20%]

(c) The relationship between the magnetic induction, ***B***, the electric displacement field, ***D***, and the current density, ***J***, flowing in a conductor is given by

$$\mathrm{curl}\,\boldsymbol{B} = \mu_0\left(\boldsymbol{J} + \frac{d\boldsymbol{D}}{dt}\right) .$$

A large thin flat slab of a Type-II superconductor of thickness $2d$ is shown in Fig. 2.

(i) Derive, for the approximations used for the Bean model, the one dimensional relationship between the magnetic field, the critical current density $\boldsymbol{J_c}$ and distance, x, inside the slab. Consequently, deduce an expression for the relationship between maximum magnetisation and critical current. [15%]

(ii) The slab is cooled to a temperature below the transition temperature in zero applied magnetic field. With the aid of sketches explain why the Bean model predicts that an external magnetic field of twice the magnitude of the peak trappable magnetic field is required for full charging of the superconductor. [25%]

(iii) Deduce an expression for the relationship between magnetisation and critical current for the fully penetrated state in part (ii). [20%]

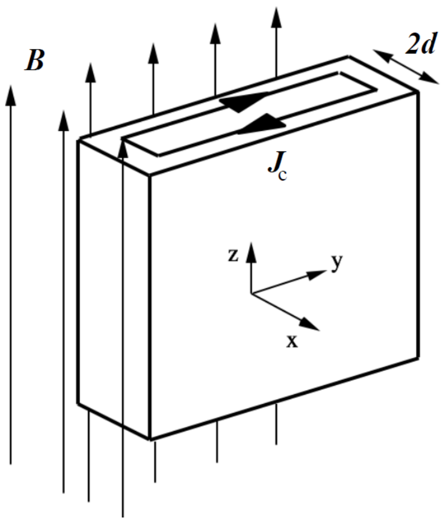

Fig. 2

5 (a) Sketch a circuit for a practical pyroelectric detector circuit employing a FET source follower. Explain qualitatively the origin of the thermal and electrical time constants associated with such a system.

Explain under what conditions, and why, the detector circuit operates in 'voltage' mode or 'current' mode. [35%]

(b) At high frequencies and where element capacitance dominates, the voltage responsivity R_V can be written as

$$R_v = \frac{\eta\rho}{c\varepsilon_r\varepsilon_0 A\omega}$$

where η is the emissivity of the detector, p the pyroelectric coefficient, c the volume specific heat capacity, A the element area, ω the modulation frequency of the incident radiation and ε_r and ε_0 are the relative permittivity of the element and the permittivity of free space respectively. Write a figure of merit, F_V, that relates voltage responsivity to material properties. [15%]

(c) If the element capacitance C_E dominates, the Johnson noise V_J can be written as:

$$\Delta V_J = \sqrt{4kT\frac{\tan\delta}{C_E}}\sqrt{\frac{1}{\omega}}$$

where tan δ is the loss tangent, T is the temperature and k is Boltzman's constant. Derive a second figure of merit F_D that allows the signal to noise performance of pyroelectric materials to be compared in terms of their material properties. [25%]

(d) Table 1 shows the properties of a number of common pyroelectric materials. Identify the best and worst performing materials in terms of F_V and F_D. Explain why the material with the worst F_V and F_D properties is nonetheless a popular materials choice in engineering applications. [25%]

Material	**T_c** °C	***p*** $\mu Cm^{-2}K^{-1}$	***ε_r***	**tan δ** 10^{-3}	***c*** $MJm^{-3}K^{-1}$
Polyvinylidene fluoride (PVDF)	80	27	12	15	2.6
$LiTaO_3$	665	230	47	0.1	3.2
$Sr_{0.5}Ba_{0.5}Nb_2O_6$ (SBN-50)	121	550	400	3	2.3
$Pb(Zr_{0.58}Fe_{0.2}Nb_{0.2}Ti_{0.02})_{0.994}U_{0.006}O_3$ (PZFNTU)	230	380	290	10	2.5
$Pb_5Ge_3O_{11}$ (PGO)	178	110	40	0.5	2.0

Table 1

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2017, 4C3 exam Numerical answers

Q1 water molecule flux = 3.6 x 10^{18} /m^2s

Al atom flux = 1.8 x 10^{19} /m^2s

Ratio Al/water = 5