Version SH/4

EGT3
ENGINEERING TRIPOS PART IIB

Friday 26 April 2019   9.30 to 11.10

Module 4C3

ADVANCED FUNCTIONAL MATERIALS AND DEVICES

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) With reference to crystal structure, explain the observation that all materials which exhibit pyro-electric behaviour are piezo-electric, but that the converse is not true. [25%]

(b) A pyro-electric element is used in an occupation detector in an office. A plastic lens focusses infrared radiation coming from different directions onto the detection element. A simplified version of the detection element and circuit is shown in Fig. 1.

(i) Given that pyroelectric detectors are sensitive to modulation of the incident flux, explain how the system can detect if someone is in the office. Discuss potential disadvantages of these detectors in this context. [15%]

(ii) Explain, with reasons, if you would expect this sensor to operate in current mode or voltage mode. Provide an equation for the relevant time constant(s). [15%]

(iii) Responsivity is defined as the ratio of current or voltage to incident power. For the mode chosen in (ii), derive an equation for the responsivity of the system in Fig. 1 at large angular frequency ω. Note that

$$\theta = \frac{\eta W_o}{G_T + i\omega H} e^{i\omega t} \quad \text{and} \quad i_p = pA\frac{dT}{dt},$$

where W_o is the amplitude of the assumed sinusoidal incident radiation, η is the emissivity of the surface of the detector, and θ is the difference between the temperature T of the element and ambient. [30%]

(iv) What other factors may need to be considered when choosing a pyro-electric material for such an application? [15%]

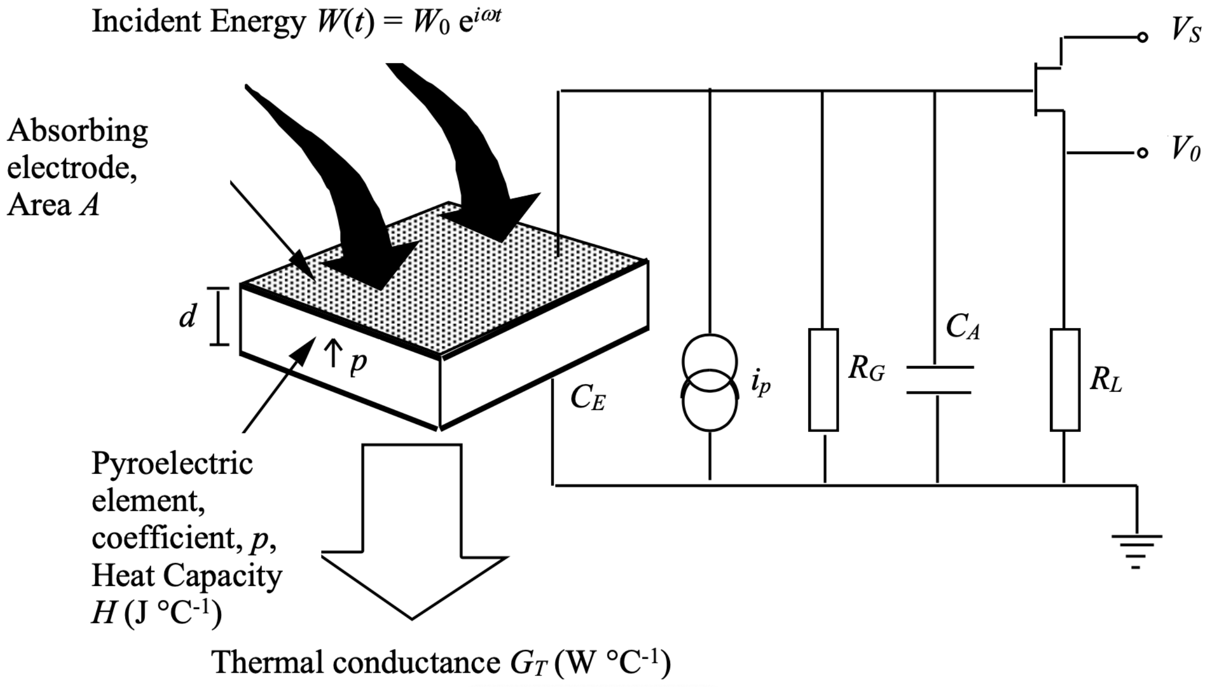

Fig. 1

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2 (a) (i) Sketch the expected M-H curves for *Type-I* and *Type-II* superconductors with no flux pinning, and a *Type-II* superconductor which exhibits flux pinning. Provide an explanation for the difference in the observed magnetic behaviour in these three types of superconductor. [25%]

(ii) Derive an equation for the maximum current carrying capacity, I_c, of a wire of a *Type-I* superconductor with a critical field of H_c and a radius of r. [20%]

(b) A field of 15 T is desired in a superconducting solenoid cooled by liquid helium to 4.2 K. Fig. 2 shows critical current values vs operating magnetic field for a number of the practical superconductors discussed in the course.

(i) Discuss which of the materials in Fig. 2 would be most appropriate for this application, taking into account cost as well as ease of manufacture and use. [25%]

(ii) Calculate the number of turns of wire per metre length, n, required if a current, I, of 100 A in the solenoid generates a 15 T field. Assume the solenoid can be treated as being "long". Given the critical current of the superconductor chosen in (b)(i), determine the minimum cross-sectional area of the required wire. Is it feasible to construct the desired solenoid from this material? What other considerations affect the wire cross-section? Note that for a long solenoid $B = \mu_0 n I$. [30%]

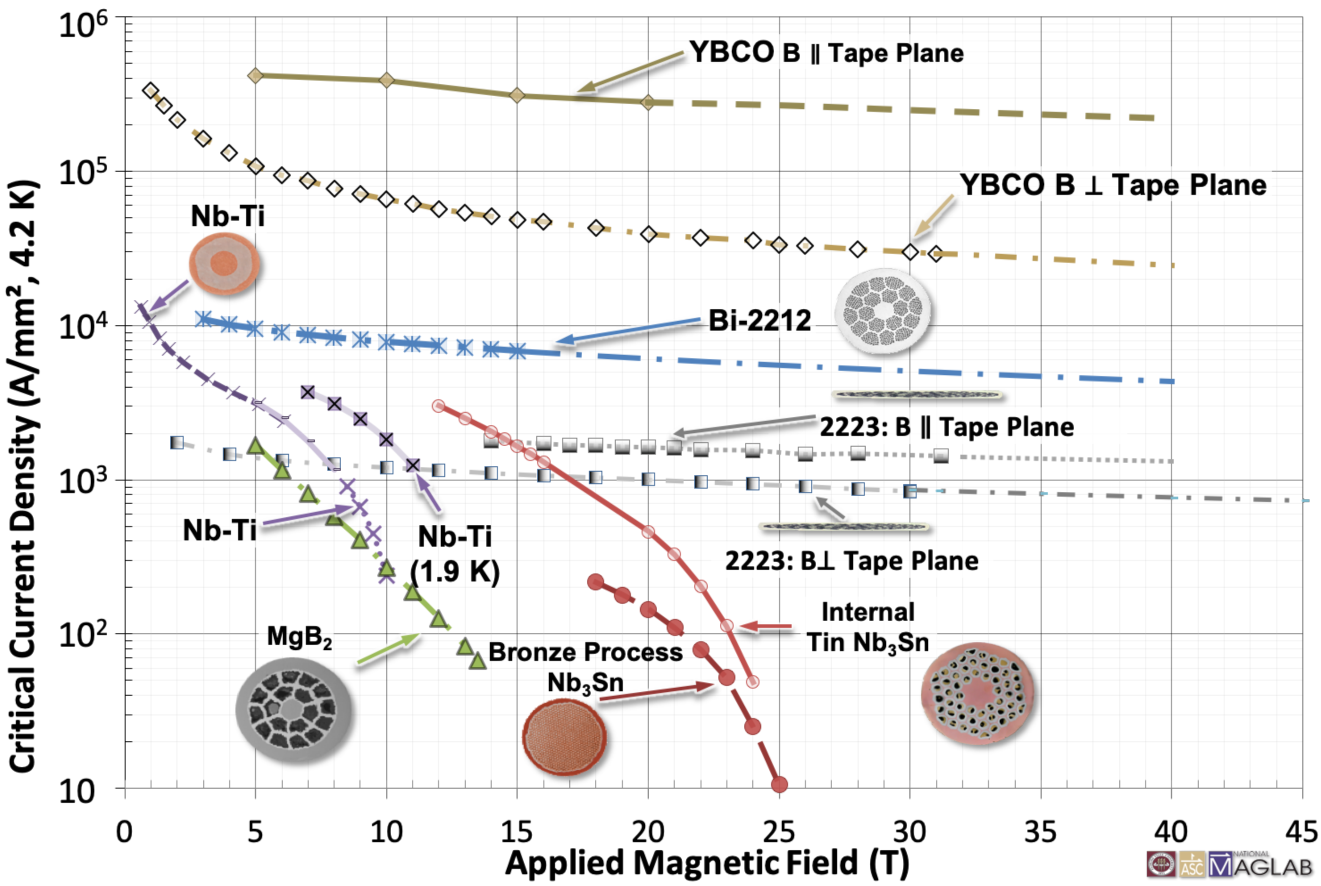

Fig. 2
Source: P. Lee, NHMFL/FSU Tallahasee.

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3 (a) Quantum dots are widely used in modern opto-electronic devices and biomedical imaging. Explain the concept of exciton Bohr radius and use it to define what a quantum dot is. [10%]

(b) Derive an expression for the electronic energy levels of a quantum dot of diameter D via a simple confinement approximation starting from a one dimensional infinite potential well. Sketch the possible electronic wavefunctions for the one dimensional infinite potential well according to the basic principles of quantum mechanics. Assume a cubic quantum dot shape and state all other assumptions. [25%]

(c) Derive the minimum kinetic energy of an electron inside a quantum dot of diameter D using Heisenberg's Uncertainty Principle. State all assumptions made. Estimate this energy for $D = 3\,\text{nm}$. Comment on how this compares to the ground state energy derived in part (b). [15%]

(d) Give an example of a typical material used for photoluminescent quantum dots. Assuming that for a given D the emission is around 520 nm, explain how for the same material the emission can be tuned into the blue wavelength regime. [10%]

(e) Sketch the structure of an organic light emitting diode, and use a band diagram to explain its operation. Comment on the key advantage of a heterostructure design. Given that current blue luminescent organic materials degrade quicker than those used for other colours, outline the design of a full colour organic light emitting display where such different aging is avoided. [30%]

(f) Discuss why quantum dots can be superior to organic luminescent materials in display applications, and sketch a quantum dot based emitter structure. [10%]

4 (a) Sketch the band structure of graphene. Explain how it differs from that of a standard semiconductor such as Si, and use it to outline why single-walled carbon nanotubes can be semiconducting or metallic. [15%]

(b) Outline the device structure of a field emission display and its principle of operation. Explain why carbon nanotubes are particularly suitable for this application. Give two other application areas, other than displays, where carbon nanotube field emitter arrays can outperform existing technology. [30%]

(c) Describe the principal features of the electronic structure of amorphous Si. How do its band gap and mobility differ from crystalline Si. [20%]

(d) Draw a schematic of a thin-film transistor typically used in active matrix display pixel control. Outline why an amorphous semiconductor is used as the channel material and which materials can outperform amorphous Si in this application. [20%]

(e) Transparent electrodes are required for an increasing range of applications. Explain, for the current standard material, how transparency and conductivity are achieved. Explain how this alternatively can be achieved with graphene or carbon nanotubes, and what advantages these new materials offer. [15%]

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4C3 2019 – Numerical Answers

Q2(b)(ii) 120000 turns per metre length. Cross-sectional area 0.05-0.1 mm^2.

Q3(c) Min. kin E = 12 meV