Version JHD/4 - with numerical answers

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 30 April 2026   14.00 to 15.40

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.

You may not remove any stationery from the Examination Room.

1 (a) Figure 1 shows the schematic band structure of a crystalline semiconductor.

(i) Estimate the bandgap energy (to two significant figures) from the diagram and state whether this is a direct or indirect bandgap semiconductor. Justify your answer. [15%]

(ii) Based on the curvature of the bands shown in Fig. 1, determine whether the electron or hole effective mass is lower. Consequently, state whether you would expect the electron or hole mobility to be higher in this material. [15%]

(iii) If this material were used to fabricate a p-n junction for an LED, discuss two specific benefits this material would offer over silicon regarding efficiency and the range of applications. [10%]

(iv) Estimate the emission wavelength if this material were used as the active region in a light emitting diode and state the corresponding colour of the emitted light. [10%]

(b) It is desired to use this material to emit light at a photon energy of 2.0 eV by fabricating it into quantum dots.

(i) Explain the principle of quantum confinement and how it modifies the electronic density of states compared to the bulk material. [15%]

(ii) The energy levels for a single particle of mass m^* in a 3D cubic box of side D are given by:

$$E_{n_x,n_y,n_z} = \frac{h^2}{8m^*D^2}(n_x^2 + n_y^2 + n_z^2).$$

If the electron effective mass is $0.1\, m_e$ for the material above, estimate the size of quantum dot required to achieve this 2.0 eV emission, stating any assumptions made. [20%]

(c) Explain how the bandgap energy of a semiconductor typically changes with increasing temperature. Why is this dependency a specific challenge for the operation of laser diodes in telecommunications? [15%]

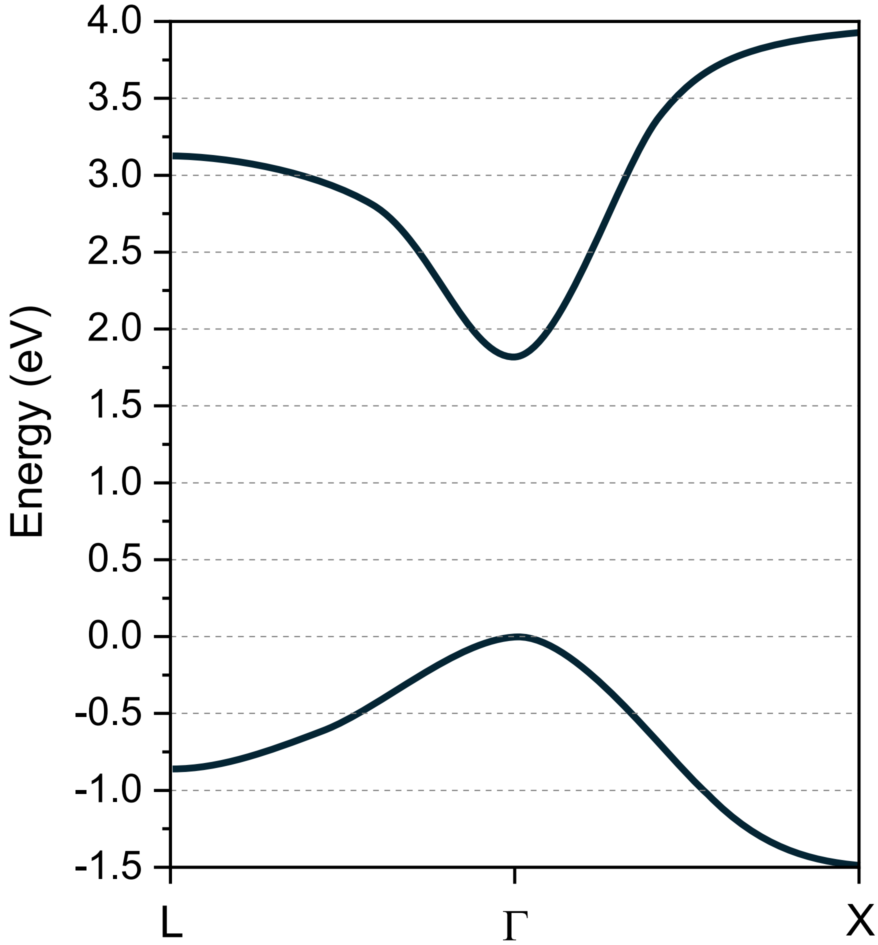

Fig. 1

(TURN OVER

2 (a) Table 1 lists the properties of two semiconductors.

(i) Using the hydrogenic model, estimate the ionization energy for a shallow donor dopant in both materials. Based on your result, explain which material is more difficult to dope n-type at room temperature. [20%]

(ii) Suggest a suitable element to use as a substitutional n-type dopant for InAs, assuming it substitutes for the In site. Briefly explain your choice with reference to the periodic table. [15%]

(b) (i) Explain what an exciton is and how the exciton binding energy influences the emission spectrum of an LED. [15%]

(ii) Use the hydrogenic model with the reduced effective mass

$$m_{eff} = \frac{m_e^* m_h^*}{m_e^* + m_h^*}$$

to calculate the exciton binding energy for both ZnO and InAs. Determine in which of these materials excitonic effects are relevant for room temperature operation. [20%]

(c) For a modern CMOS transistor, fabricated using a process node smaller than 14 nm, explain how the physical structure of the device and the selection and properties of the gate-dielectric material are engineered to enhance electrostatic coupling efficiency. [15%]

(d) You are tasked with designing a field-effect transistor entirely from 2D layered materials. Propose a specific material for each of the components of the transistor. Explain why the properties of your chosen materials make each suitable for their respective application. [15%]

	ZnO	InAs
Bandgap E_g	3.37 eV	0.36 eV
Relative Permittivity ε_r	7.0	15.0
Effective electron mass m_e^*	0.24 m_e	0.023 m_e
Effective hole mass m_h^*	0.59 m_e	0.41 m_e

Table 1

3 (a) Explain the classification of pyroelectric and piezoelectric materials in terms of the polar properties of the crystallographic lattice in these classes of materials. [20%]

(b) Figure 2 shows the cross section of a piezoelectric element used as a microphone of dimensions 0.5 × 20 × 20 mm. The electrodes, of area A, cover the whole top and bottom surfaces. The element is arranged so that the force from incident sound on a diaphragm is applied to area a in the x_1 direction.

(i) Give the mode of operation, and state which piezoelectric constant determines the performance of the device. [10%]

(ii) Derive an equation that relates the charge, Q, generated for an instantaneous force applied to the element in the x_1 direction. [15%]

(iii) For the lead zirconate titanate derived piezoelectric material, PZT-5 (ε_r=3400, d_{33}=592 pC/N and d_{31}=−274 pC/N), determine the voltage that would appear between the electrodes if a force of 0.02 N is applied to the element. [20%]

(c) The manufacturer wishes to replace PZT-5 with the piezoelectric polymer polyvinylidene fluoride (PVDF).

(i) Determine the voltage generated for the same incident force if the PZT-5 element is replaced with an identically dimensioned PVDF (ε_r=14, d_{33}=25 pC/N, d_{31}=−25 pC/N) element. [15%]

(ii) Comment on the advantages and disadvantages of this substitution. Suggest any changes to the design of the transducer that might be appropriate to better exploit the properties of PVDF. [20%]

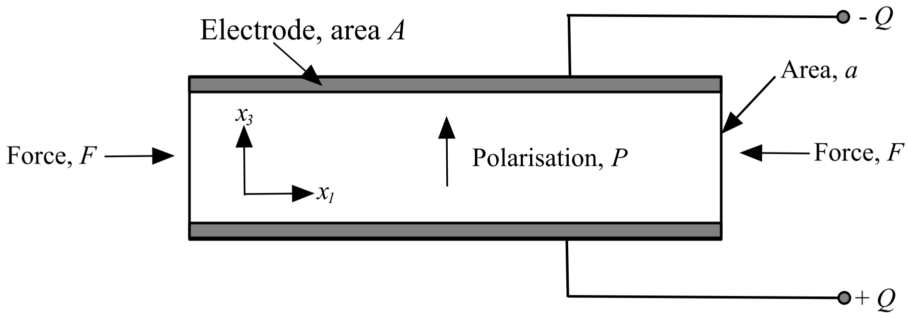

Fig. 2

4 (a) Explain why the maximum trapped magnetic field obtainable in a conventional ferromagnet is ultimately limited by choice of material, whereas in a bulk superconductor the maximum trapped field depends on sample size. [15%]

(b) Practical ferromagnetic materials are divided into two broad categories depending on the magnitude of the coercive field.

(i) Explain, using a sketch, the difference in the response to an external magnetic field of ferromagnets with small coercive fields (soft) and those with large coercive fields (hard). [15%]

(ii) Give four examples of key magnetic properties of materials and discuss how these vary between soft and hard magnetic materials. [10%]

(iii) Give one example each, with justification, of where in an electric motor a soft and a hard magnetic material might be employed. [10%]

(c) Consider the case of a permanent magnet.

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

(ii) Briefly account for the existence of the demagnetisation field. [10%]

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

$$\boldsymbol{B} = \mu_0 \boldsymbol{H_m} \left(\frac{N-1}{N} \right),$$

and with the aid of a sketch explain how this relation can be used to determine the operating point, and the energy product. [20%]

(iv) Explain, giving an example, how suitable choice of shape can be used to optimise the energy product in a permanent magnet. [10%]

END OF PAPER

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Numerical Answers

1(a)(i)1.8 eV (iv) 689nm - Red (b)(ii) 10.6 nm

2(a)(i) ZnO - 67 meV InAs - 1.4 meV (b)(ii) ZnO - 47 meV InAs - 1.3 meV

3(b)(iii) 9.1 mV (c)(i) 200 mV