Version JHD/4 with numerical answers

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 26 April 2023   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.

You may not remove any stationery from the Examination Room.

1 (a) Explain why, although there are 27 piezoelectric coefficients in total, in practice only d_{33}, $d_{31} = d_{32}$ and $d_{15} = d_{24}$ are of interest in engineering applications. Identify which "mode" of operation corresponds to each of these coefficients and sketch one. [15%]

(b) Explain why it is, in practice, convenient to use a ferroelectric material where piezoelectric properties are required in an engineering application. [10%]

(c) Figure 1(a) shows a commercially available piezoelectric actuator chip operating using the converse piezoelectric effect. It consists of alternating layers of a polycrystalline ferroelectric ceramic and electrodes as shown in cross section in Fig. 1(b). Each of the ten piezo elements is 0.1 mm high and 3 mm long on each side. The manufacturer specifies a maximum voltage of 100 V which provides a total vertical displacement of the end plate of 0.5 μm. The total capacitance of the actuator is 10 nF.

[The direct piezoelectric effect relates the piezoelectric coefficients of a material, d_{ij}, to polarisation, $\boldsymbol{P}$, and stress, $\boldsymbol{\sigma}$, as $P_i = d_{ij}\sigma_j$. The converse effect relates d_{ij} to strain, $\boldsymbol{S}$, and electric field, $\boldsymbol{E}$, as $S_i = d_{ij}E_j$.]

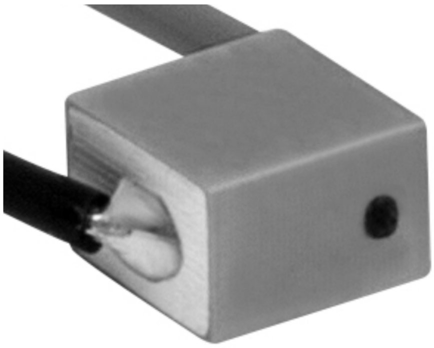
(i) Identify which mode of piezoelectric operation is being exploited in this device and state which piezoelectric coefficient determines the performance of the device in this mode. [15%]

(ii) Explain how the manufacturer ensures that applying a voltage to the marked terminals results in an overall net strain in the indicated direction. [10%]

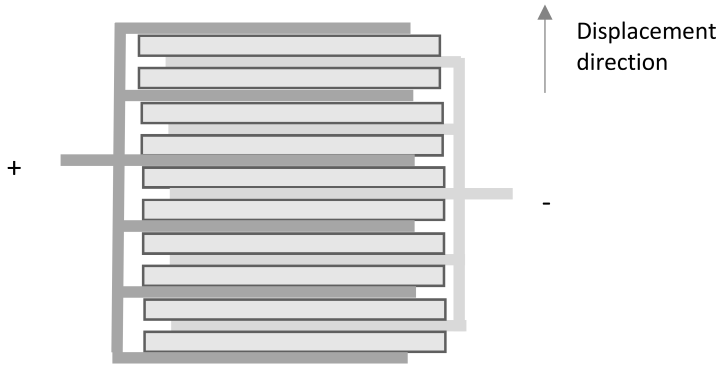
(iii) Estimate the piezoelectric coefficient for the mode you specified in your answer to (i). Specify any assumptions you make and carefully show your working. [20%]

(iv) If the element was employed to instead exploit the direct piezoelectric effect, calculate what force would need to be applied to the actuator in order to achieve a potential of 100 V between the terminals. Carefully explain your working. [20%]

(v) Explain how the same arrangement of electrodes and piezo elements could be used to give a sideways displacement of the top plate of the actuator. What would the manufacturer need to change in order to achieve this? Identify the mode of operation involved. [10%]



(a)



(b)

Fig. 1

2 (a) The lifetime of an excited state of an atom is about $\Delta t = 10^{-8}$ s. Using Heisenberg's energy-time uncertainty principle, estimate the uncertainty in frequency Δf of emitted photons. Compare Δf to the average frequency of emitted photons of $f = 7 \times 10^{14}$ Hz from this state. [15%]

(b) ZnSe is a wide-bandgap semiconductor that is used in lasing applications. Nitrogen can be used to p-type dope ZnSe.

(i) Using the hydrogenic model, estimate the acceptor binding energy. Assume an effective hole mass m* of 0.75 and a dielectric constant ε_r of 9 for ZnSe. Does N occupy the Zn or the Se lattice site? [20%]

(ii) It is found that such p-type doping is not easy, and that the effective acceptor concentration is limited. Limited N solubility can be excluded as a reason for this. Give an alternative reason and discuss this. [15%]

(c) Figure 2 shows the band diagram of monolayer black phosphorus. Discuss why and how the bandgap varies with layer number and sketch the band diagram of AB stacked bilayer black phosphorus. [20%]

(d) A new flexible, ultrathin field effect device design uses monolayer black phosphorus as the channel material. The device body is meant to have high optical transparency. Suggest suitable materials for the dielectric and gate contact. Explain how the stack can be fabricated. [15%]

(e) Figure 3 schematically shows the optical absorption in a 2D semiconductor like black phosphorus. Explain the origin of the spectral features below the bandgap E_g. Why are they labelled 1s and 2s? [15%]

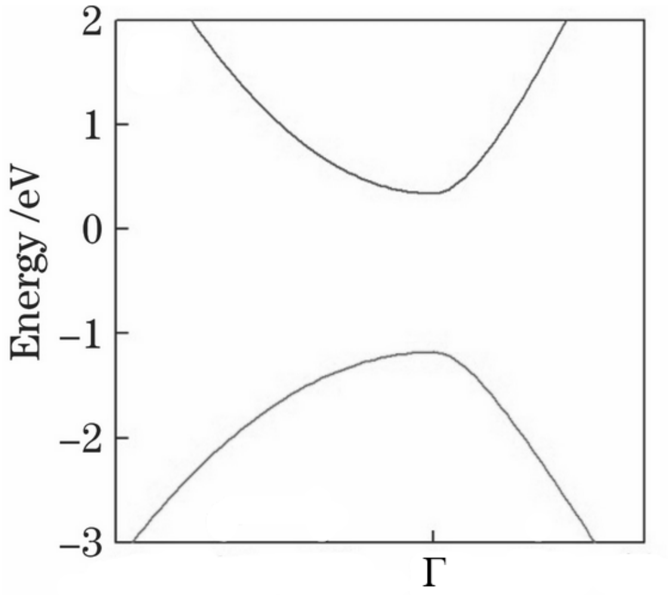


Fig. 2

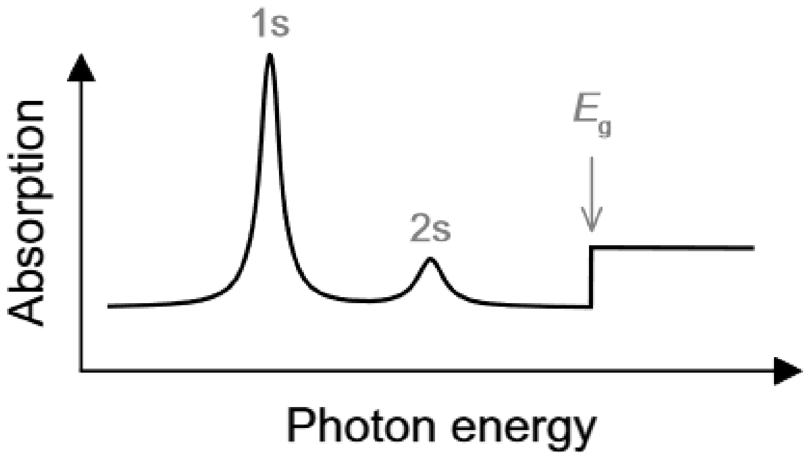


Fig. 3

3 (a) For each of the different methods of generating a magnetic field listed below (i-iii), explain how the magnetic field arises and how materials properties limit the achievable magnetic field:

(i) a copper solenoid carrying a transport current, [10%]

(ii) a magnetised disc of bulk superconductor, [10%]

(iii) a magnetised disc of NdFeB. [10%]

(b) (i) Using Ampere's law in the form $\nabla \times \boldsymbol{H} = \boldsymbol{J} + d\boldsymbol{D}/dt$, or otherwise, derive an equation that relates the maximum field B^* that may be trapped in the superconducting slab shown in Fig. 4 to its critical current J_c and thickness $2d$. [15%]

(ii) Using a sketch of magnetic field vs distance through the cross-section of the slab explain why, in order to achieve the maximum possible trapped field, the slab needs to be subject to an externally imposed field of magnitude $2B^*$ if the slab is cooled below T_c in zero field. [15%]

(c) A thin slab of MgB_2 of thickness 1 mm, width 10 mm and length 20 mm was cooled to 20 K in an external magnetic field and that field was then removed. The magnetic field used was large enough to ensure that the sample was in the critical state. The magnetic moment of the slab in the z-direction was subsequently measured to be 2.5×10^{-1} Am^2. You may assume that the slab's behaviour is described by the Bean model. Explaining your method carefully in each case, determine:

(i) the average magnetisation, [15%]

(ii) the peak trapped field in the slab, [10%]

(iii) the critical current of the sample of MgB_2. [15%]

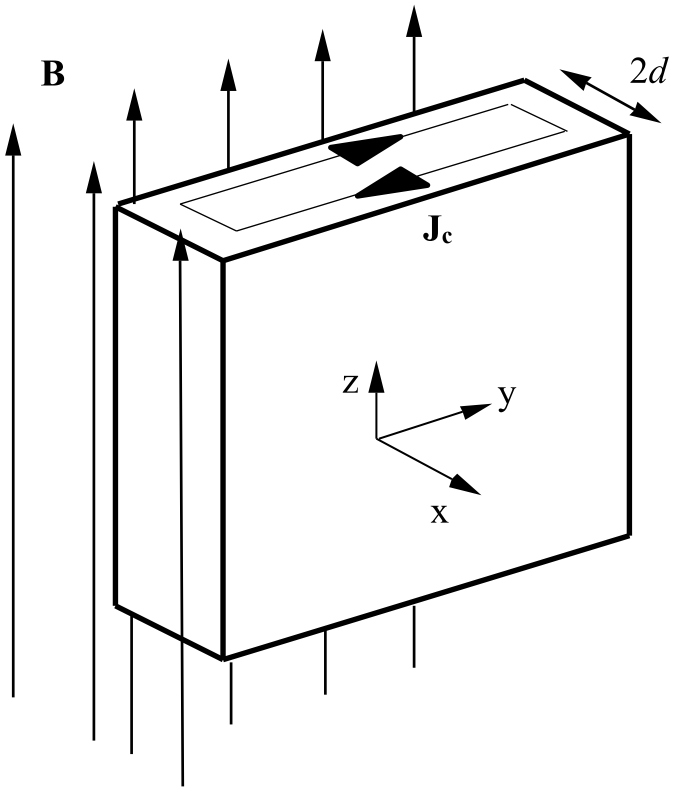


Fig. 4

4 (a) Figure 5 shows a band diagram of a crystalline semiconductor.

(i) Explain how the band dispersion links to carrier mobility, and state if this semiconductor has a higher electron or hole mobility. [15%]

(ii) Sketch the optical absorption coefficient versus photon energy for this semiconductor. [15%]

(iii) In order to lower cost, the same semiconductor material is deposited as amorphous film. Sketch the density of states versus energy for this amorphous film and label the salient features. Estimate the resulting mobility gap. [20%]

(iv) In comparison to (ii), sketch the optical absorption coefficient versus photon energy for the amorphous film. [15%]

(b) Suggest a material that would be superior to the semiconductor of part (a) for outdoor photovoltaic applications, and discuss why. [15%]

(c) A front bike light, emitting white light, is to be fabricated based on a light emitting diode device structure. Discuss if the semiconductor of part (a) is suitable for this. Suggest, giving your reasons for this choice, a material that is superior for this application. Outline the principle of white light creation. [20%]

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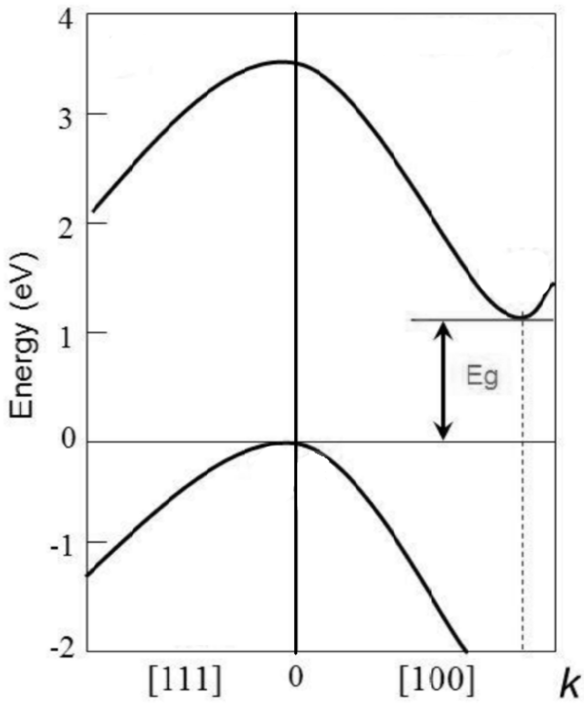

Fig. 5

Numerical Answers

Q1) c) iii) 500 pCN^{-1} iv) 200N

Q2 a) Δf = 8 x 10^6 Hz b) i) 0.13 eV above valence band edge

Q3 c) i) 1.25 x 10^{6} Am^{-1} ii) 3.14 T iii) $5x10^9$ Am^{-2}

Q4 a) iii) a-Si 1.7 eV

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