Version JHD/3-post with numeric answers

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 1 May 2025   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 variation of band gap and position of conduction band minimum for Phosphorus alloying of GaAs. The valence band maximum remains at the Γ point.

(i) Calculate the minimum wavelength of light that can be efficiently created from that alloy. What visible colour does this correspond to? [10%]

(ii) Indicate how this wavelength range can be extended and efficient light emission be achieved for GaP. Sketch such a light emission process in a band diagram, indicating valance and conduction band structure and how energy and momentum are conserved. [15%]

(iii) Assuming that GaP and GaAs show type 1 (straddling) interfacial band alignment, sketch a device structure to enable efficient lasing. Give the expected laser wavelength. [15%]

(iv) Indicate a major material constraint of heterojunction engineering such as in part (a)(iii). Give a class of emerging nanomaterials which can overcome this constraint. [10%]

(b) GaP quantum dots with diameter D are produced as a colour conversion material for light emitting diodes.

(i) Explain the concept of exciton Bohr radius and its significance in the context of expected size dependent electronic properties. Indicate the order of magnitude of the exciton Bohr radius for a conventional semiconductor like GaP. [10%]

(ii) Considering only confinement effects in a simple infinite potential well model, derive an expression of how the GaP quantum dot bandgap will vary with D. State all assumptions made. [30%]

(iii) Outline a simple experimental set-up to measure D. [10%]

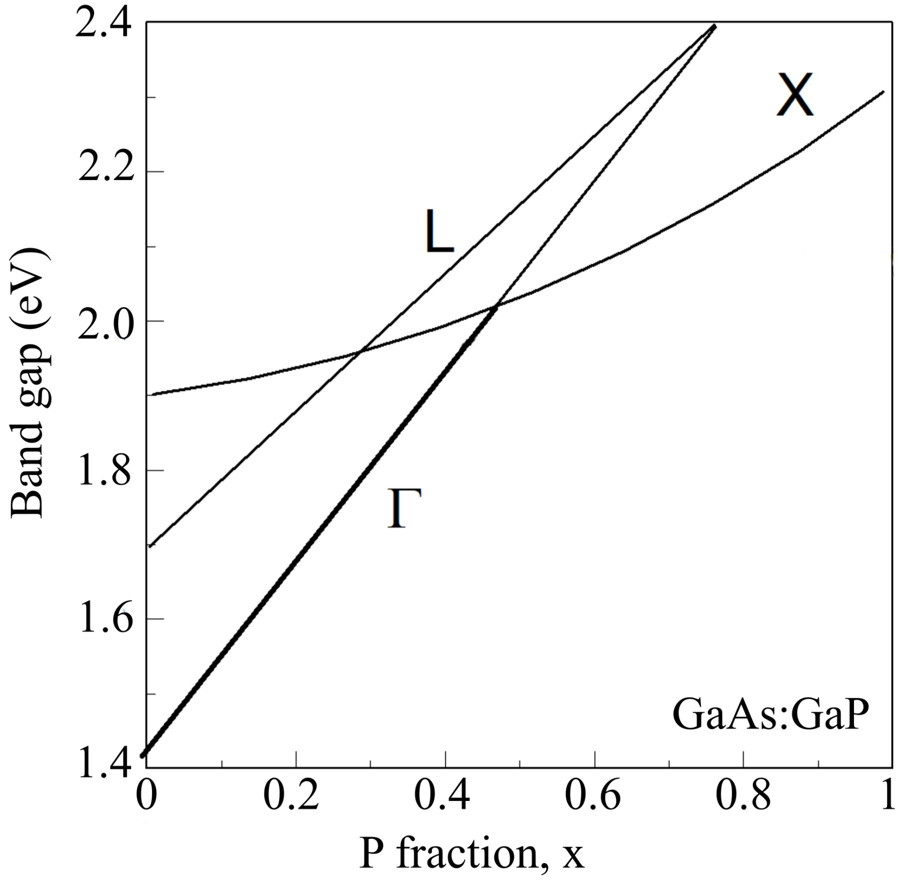

2.4
2.2
2.0
1.8
1.6
1.4
Band gap (eV)
0
0.2
0.4
0.6
0.8
1
P fraction, x
L
X
Γ
GaAs:GaP

Fig. 1

2 (a) Figure 2 shows simplified valence band structures of unstrained Si and Si under uniaxial compression.

(i) Explain the concept of effective mass. Replot the E-k diagram for the unstrained Si and label the so-called heavy holes. [15%]

(ii) Give an expression for how hole mobility depends on effective mass. Explain how hole mobility changes for Si under compression. [15%]

(b) The semiconductor industry has seen so-called high-k and low-k materials replacing SiO_2.

(i) Discuss what advantage high-k materials offer for scaled transistor design. Name two high-k oxides and outline how ultrathin films of such oxides are commercially produced. [20%]

(ii) Outline the need for low-k materials. Outline a possible design strategy to achieve low k. [20%]

(c) Carbon nanotubes continue to be on the semiconductor industry materials roadmap. Give a specific example where carbon nanotubes can outperform conventional materials currently used in the semiconductor industry. For this example, discuss what type of carbon nanotube structure is desired and what the main integration challenges are. [15%]

(d) For next generation consumer electronics new solutions to transistor design are sought that enable mechanical flexibility and high optical transparency across the visible range. Outline a possible transistor design, including materials choices for the semiconductor, dielectric and contacts. [15%]

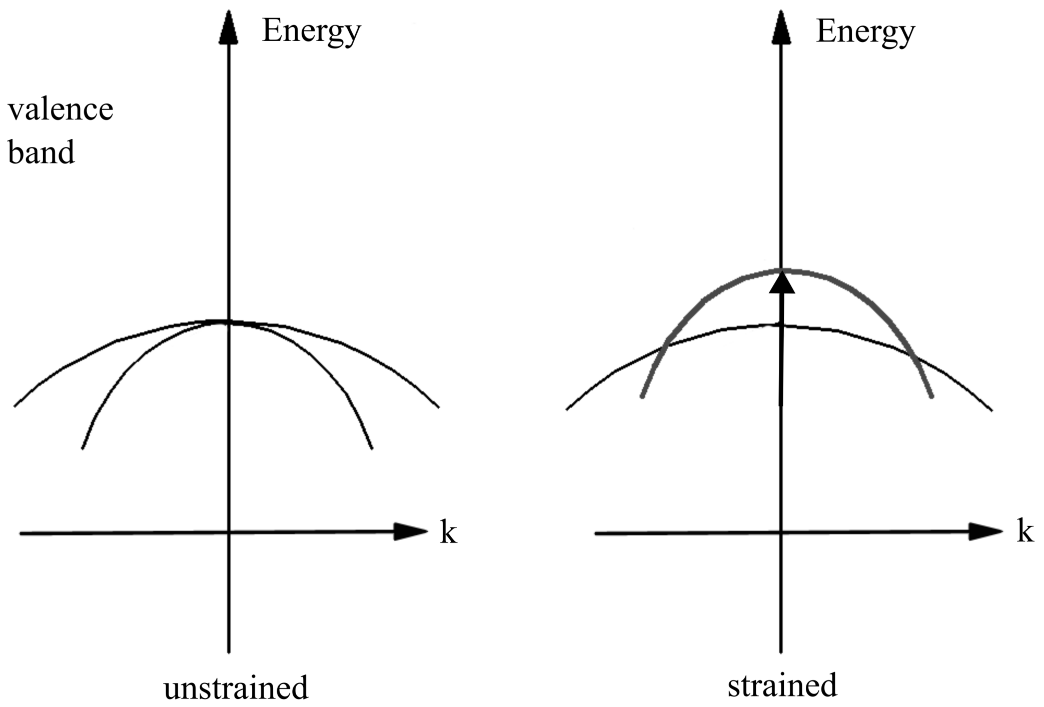


Fig. 2

3 (a) With reference to crystal structure, carefully account for the observation that all materials which exhibit pyro-electric behaviour are piezo-electric, but that the converse is not true. [15%]

(b) The state equation for the change in polarisation P due to the operation of the Piezoelectric effect is sometimes written terms of stress σ and a piezoelectric coefficient d as $P = d\sigma$ (in the absence of an external electric field).

(i) Explain why this is a simplification and provide a state equation that better represents the behaviour of a real material. [15%]

(ii) From this, explain qualitatively why piezoelectric materials are often used in the form of thin sheets and why there are three modes of operation. [10%]

(c) Figure 3(a) shows a commercially available piezoelectric actuator which consists of a stack of ferroelectric layers with an electrode between each layer. Figure 3(b) shows how the electrodes are connected. When an electric field is applied to the stack with the bottom face fixed in place, the top layer of the stack moves sideways by a distance which depends on the applied voltage. Each of the twelve piezo elements is square with sides of 3 mm and a thickness of 0.5 mm. The manufacturer specifies a maximum service voltage of +/- 250 V, which provides a sideways displacement of the top plate of +/- 1.5 μm with respect to the bottom plate. The capacitance of each element is 0.125 nF.

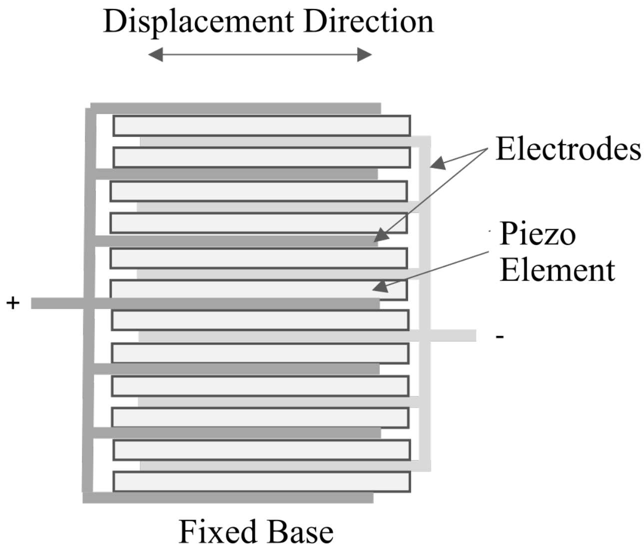
(i) Identify the mode of piezo-electric operation that is being exploited and the direction of polarisation of the ferroelectric layers. [10%]

(ii) Calculate, specifying any assumptions you make and carefully showing your working, what the piezoelectric coefficient is, for the actuator material for the mode you specified in your answer to part (c)(i). [20%]

(iii) If the element was used as a transducer, rather than as an actuator, calculate what sideways force would need to be applied to the top plate in order to achieve a potential of 250 V at the terminals. [20%]

(iv) How would you expect the mechanical response of the device to change with respect to applied voltage if it is first accidentally subject to a large over-voltage of a few kV. Assume that the device is not mechanically damaged. [10%]


1 mm


Displacement Direction
Electrodes
Piezo
Element
+
-
Fixed Base

(a) (b)

Fig. 3

4 (a) Using appropriate sketches of magnetisation vs applied field explain the difference between *hard* and *soft* magnetic materials and outline the applications of each type. [15%]

(b) Steel and steel alloys are often used in applications that call for a *soft* magnetic material.

(i) Outline how *electrical steels* intended for such applications differ from mild steel in processing and composition and how these differences improve their suitability for this application. [15%]

(ii) Explain why steel based *soft* magnetic materials are commonly used in 50 Hz applications but are not used at kHz frequencies. Outline which materials are suitable for such applications, giving your reasons. [10%]

(c) A *hard* ferromagnetic material is to be fabricated into a squat disc-shaped magnet, with height equal to radius, for use in an industrial application.

(i) This shape has a demagnetising factor N of approximately 0.5. Show that the energy stored in a magnet is maximised when $N = 0.5$. Recall that the demagnetising field is given by the expression $H_d = -NM$ where M is magnetisation. [20%]

(ii) Explain why iron could not be used to make a permanent magnet with such a shape. [10%]

(iii) Give two examples of materials whose properties are shown in the databook that would allow a shape factor of 0.5 to be achieved. Justify your choices. [10%]

(iv) Using information in the databook estimate the largest practical shape factor possible in a magnet fabricated from the Alcomax III grade of Alnico. [20%]

END OF PAPER

Numeric Answers:

Q 1(a)(i) 620 nm, (iii) 886nm, (b)(i)5-10nm,

Q 3 (c)(ii) 500pC/N, (iii) 62.5N

Q4 (c)(iv) 0.05