EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 27 April 2022 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, with sketches, how the piezoelectric effect arises in a crystal. Outline why pyroelectric materials are piezoelectric while not all piezoelectric materials are pyroelectric. [10%]

(b) A cross-section of an infrared sensor, designed as an intruder detector, is shown in Fig. 1. The detector has two detection zones separated by a shield, the detector is placed behind a multi-segment Fresnel lens. Each zone contains two identical lithium tantalate pyroelectric elements, one with a high emissivity black coating and one with a low emissivity gold reflective coating. The elements are supported at one edge so as to make minimal thermal contact with the package. The detector operates in voltage mode.

(i) Suggest how the gold-coated elements might provide immunity to false triggering. [10%]

(ii) Suggest how the dual detection zones might provide immunity to false triggering. [10%]

(iii) All four elements are connected to a high input impedance FET amplifier, sketch how the elements should be connected so as to maximise resistance to false triggering and explain how your proposed configuration achieves this aim. [15%]

(iv) If the detection elements were thermally anchored to the package how would this affect the response of the detector. [15%]

(c) A pyroelectric element has a thermal time constant of $\tau_T = H/G_T$ where H is its heat capacity and G_T thermal conductance to its surroundings. The temperature difference between element and surroundings is given by $\theta = \frac{\eta W_0}{G_T + i\omega H} e^{i\omega t}$ and charge release in the element by $i_p = Ap\frac{\mathrm{dT}}{\mathrm{dt}}$ where T is temperature, η emissivity, A area and p the pyroelectric coefficient. The incoming radiation is of power $W(t) = W_0 e^{i\omega t}$, where t is time.

(i) Explain carefully how to deduce the relationship between current responsivity, pyroelectric constant, volume specific heat and element thickness assuming that the incoming infra-red radiation varies sinusoidally with a short period compared to the thermal time constant. [20%]

(ii) What advantages and disadvantages are there to using polyvinylidene fluoride (PVDF) as the pyroelectric material in a pyroelectric element used in current mode, instead of 40 μm thick lithium tantalate? If $LiTaO_3$ is replaced with PVDF what changes need to be made to the configuration of the detector elements to retain the same current responsivity? [$LiTaO_3$ has a volumetric heat capacity of 3.2 MJ m^{-3} K^{-1} and a pyroelectric constant of 230 μC m^{-2} K^{-1}. PVDF has a volumetric heat capacity of 2.6 MJ m^{-3} K^{-1} and a pyroelectric constant of 27 μC m^{-2} K^{-1}.] [20%]

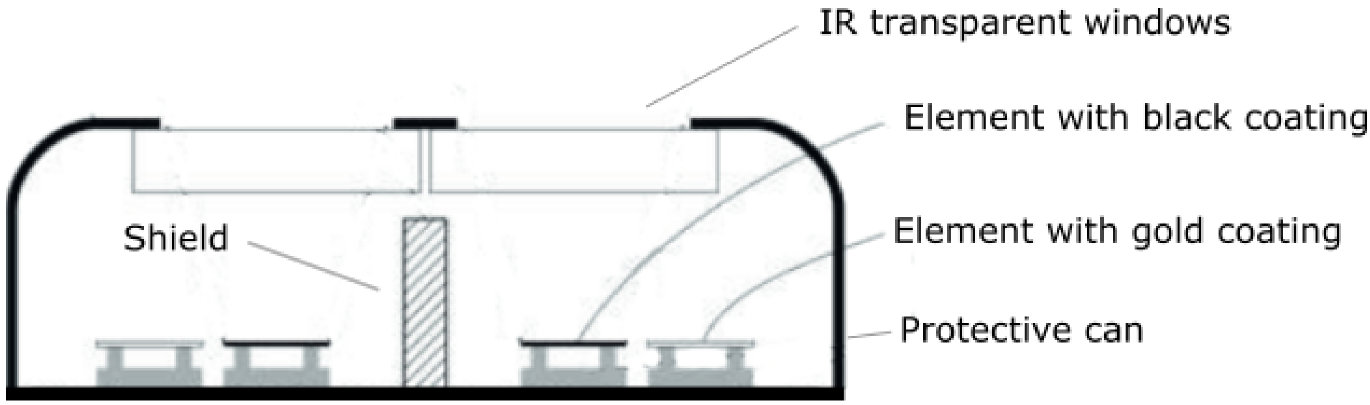
IR transparent windows
Element with black coating
Shield
Element with gold coating
Protective can

Fig. 1

2 (a) Figure 2 shows a schematic band diagram of GaP. Using Heisenberg's uncertainty relationship, explain how efficient light emission can be achieved in this material. Sketch the light emission process, indicating how energy and momentum are conserved. [10%]

(b) Poly(p-phenylene vinylene) (PPV) is a conjugated polymer.

(i) Explain how you would expect its band gap to vary with polymer chain length. [15%]

(ii) Assuming a dielectric constant of 2 and an average effective mass of 0.1, estimate the expected exciton binding energy for PPV. Comment on how this affects the design of light emitting devices which use PPV. [15%]

(iii) Sketch and compare typical light emitting diode device structures for PPV and GaP. [20%]

(c) Fabrication of monolayer sp2-bonded amorphous carbon films has been demonstrated. Outline what electronic properties can be expected from this amorphous 2D material as compared to graphene. Suggest a potential application area for such amorphous films. [20%]

(d) Sketch the unit cell of an "armchair" graphene nanoribbon that has a width equal to 4 dimer (two carbon sites) lines. Explain what electronic band structure can be expected from such ribbons, and why they are pursued for applications in nanoelectronics. [20%]

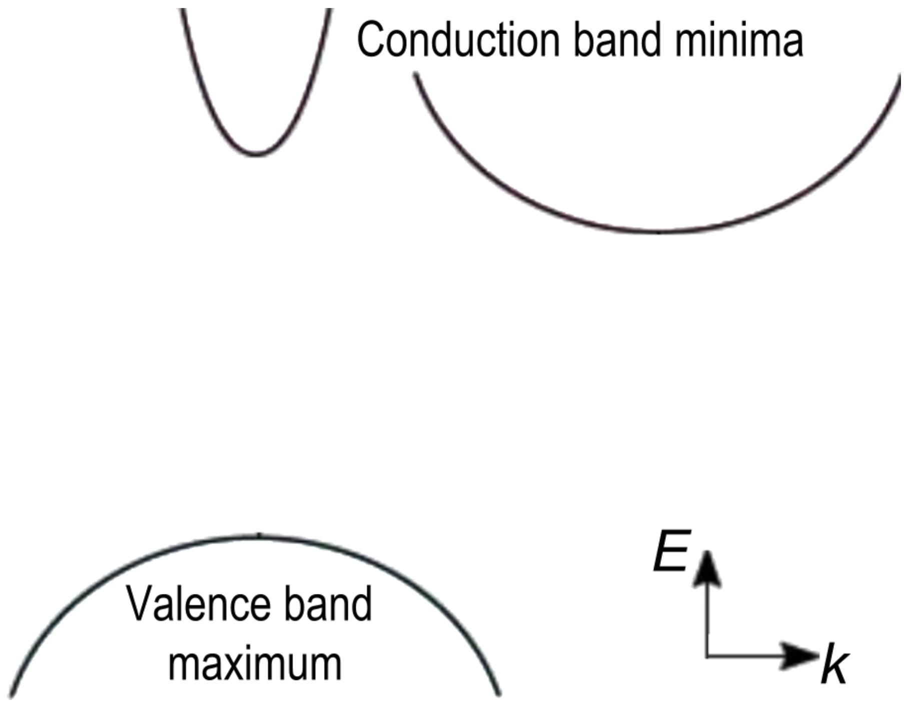

Fig. 2

3 (a) Figure 3 shows a schematic E-k diagram of a semiconductor.

(i) Explain what is meant by light and heavy holes. Replot the valence band part of the E-k diagram and label your plot accordingly. [15%]

(ii) Give two reasons why small effective masses are desirable in semiconductors. Outline how and why the effective mass can vary with temperature. [15%]

(b) Outline the basic crystal structure of methylammonium lead tri-iodide ($MAPbI_3$) and explain what properties make this class of hybrid material highly suitable for photovoltaic applications. [15%]

(c) Using band diagrams, give a possible explanation why $MAPbI_3$ shows a high defect tolerance compared to GaAs. [15%]

(d) Explain why and how the band gap changes if methylammonium is changed to formamidinium (FA), i.e. comparing $MAPbI_3$ and $FAPbI_3$. Note that FA represents an organic cation with a larger ionic radius. [10%]

(e) Starting with the model of an infinite potential well, and considering only simple confinement effects, derive an expression which describes how the band gap of $MAPbI_3$ will change if it is in the form of quantum dots instead of a film. Comment as to how this affects optical emission. State all assumptions made. [30%]

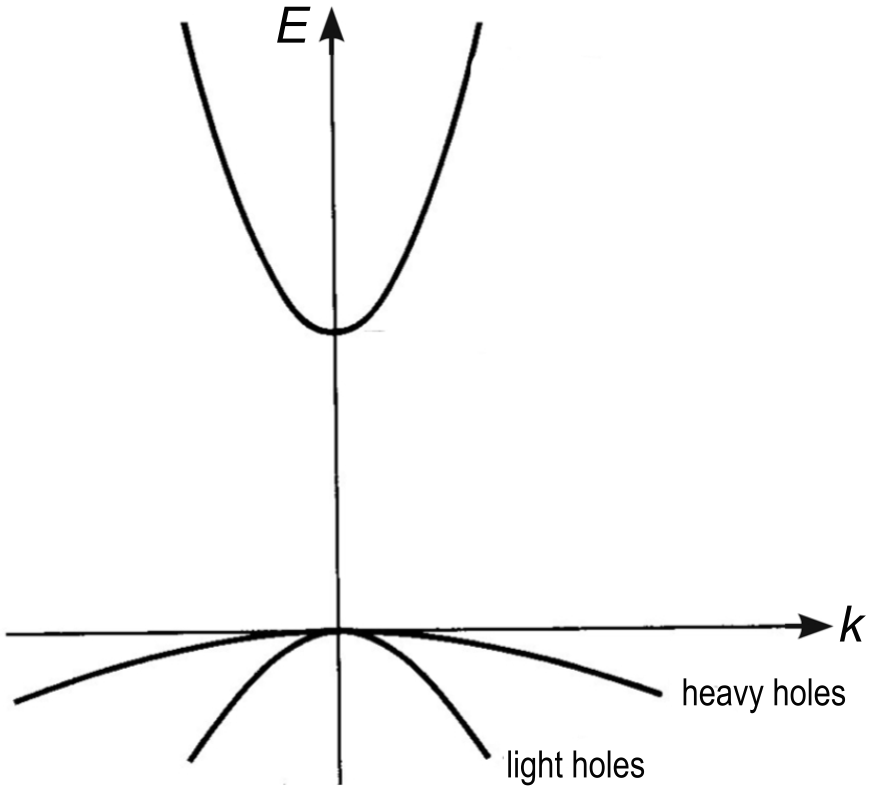

Fig. 3

4 (a) Explain why some ferromagnetic materials exhibit appreciable hysteresis and some do not, with reference to material properties. For each type give one example of how materials processing can be used to optimise magnetic properties. [15%]

(b) Descriptions of three permanent magnets are given below. For each one suggest which ferromagnetic material the permanent magnet consists of. Include detailed justifications.

(i) A horseshoe-shaped magnet intended as a child's toy. Magnetic field at poles measured to be 0.05 T. Observed to spontaneously demagnetise if a keeper is not used. [10%]

(ii) A squat disc magnet used as part of a compact permanent magnet motor operating at 120 °C. Field at surface measured to be 0.3 T. Magnet has a dull dark appearance. [10%]

(iii) A spherical magnet used as part of a kitchen door catch. Field at surface measured to be 0.3 T. Magnet has a bright metallic finish. [10%]

(c) Two permanent magnets are fabricated in the same shape and fully magnetised. One is fabricated from "Ferrite 8" and the other from 35% cobalt steel. The magnet's shape corresponds to a demagnetisation factor, N, of 0.1. Their B-H characteristics are shown in the electrical databook.

(i) Using a suitable load line, or otherwise, estimate the expected B-field at the surface of each of the two magnets immediately after magnetisation. [Remember that the demagnetisation field $H_d = -MN$ and $B = \mu_0(M + H)$, where M is magnetisation and μ_0 is the permeability of free space.] [20 %]

(ii) State, with reasons, if you would expect the magnets to remain magnetised in use. [15 %]

(iii) Determine, explaining your assumptions and reasoning, the maximum achievable (BH) energy product achievable in a permanent magnet fabricated from each of these materials if their shape can be freely altered. [20 %]

END OF PAPER

Numerical Answers:
4 c (i) Ferrite 8 $\approx$ 0.2 T Co-Steel $\approx$ 0.37 T
4 c (iii) Ferrite 8 $\approx$ 31.8 kJ/m^3 Co-Steel $\approx$ 7 kJ/m^3