Version JHD/6 w numerical answers

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 25 April 2024   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) A common element in intruder alarm systems is a pyroelectric detector situated behind a multi-element Fresnel lens. Such a lens and the field of view of each of the elements is shown in Fig. 1.

(i) Explain why practical pyroelectric detectors are sensitive only to a time varying incident flux of infra-red radiation. [15%]

(ii) Explain how, in this application, the lens arrangement gives rise to a time varying incident flux on the detector. [15%]

(iii) Suggest two ways in which an intruder could avoid detection by such a device. Explain your answers carefully with reference to the operation of the detector and amplifier. [20%]

(iv) Would movement of an object which is colder than the surrounding environment trigger such a detector? Explain your reasoning. [10%]

(b) The detection element of a pyroelectric intruder detector uses a FET amplifier stage and operates in voltage mode. The amplifier stage has a capacitance C_A and gate resistance R_G. The pyroelectric element has an emissivity of η, relative permittivity ε_r, area A, pyroelectric coefficient p and capacitance C_E. The element has a heat capacity H and thermal conductance to surroundings of G_T. The incident radiation power is modulated with angular frequency ω and is described by $W(t) = W_0 e^{i\omega t}$ and the difference in temperature between the element and surroundings is given by

$$\Delta T = \frac{\eta W_0 e^{i\omega t}}{G_T + i\omega H}$$

(Recall that the thermal time constant is H/G_T and the electrical time constant is CR_G where $C = C_E + C_A$.)

(i) Define the voltage responsivity of the detector in terms of the admittance of the amplifier $Y = (1/R_G) + i\omega C$, the pyroelectric current i_p and the input power amplitude W_0. [10%]

(ii) Derive an expression relating the magnitude of the voltage responsivity to the detector's thermal and electrical time constants, η, A, R_G, G_T, p and ω. [20%]

(iii) At high values of ω compared to the electrical and thermal time constants deduce how the voltage responsivity varies with ω. [10%]

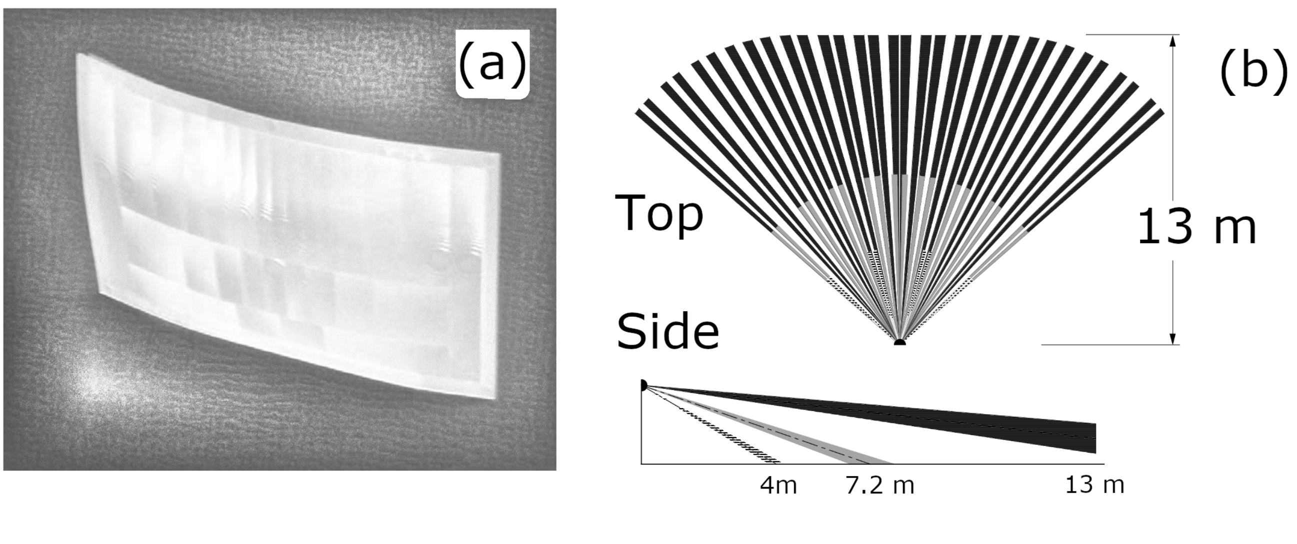

Fig. 1

2 (a) Figure 2 shows a calculated band diagram of monolayer NbS_2. Is this material an insulator, semiconductor or metal? Explain your answer. [10%]

(b) Graphene is a mono-layer crystal in which the band structure may be engineered in numerous ways.

(i) Sketch the band diagram of isolated graphene around the so-called K-point. [10%]

(ii) Differently twisted bilayer graphene samples are placed on a Si/SiO_2 substrate. In optical microscopy the samples exhibit distinctly different colours. Explain this finding. [20%]

(iii) Explain how a band gap can be opened when graphene is patterned into nanoribbons. Sketch a band diagram for such a graphene nanoribbon. Indicate the size of band gap that can be achieved and discuss how the mobility will vary with ribbon width. [20%]

(c) A new flexible, low-cost device for surface disinfection is being developed using UV-C light emitting diode (LED) technology.

(i) The device requires a conducting layer with a sheet resistance below 1 kOhm/sq and UV transparency. Give a possible materials design solution. Discuss how combined high conductivity and transparency could be achieved in this system. [20%]

(ii) The device also requires an efficient UV emitter design. Give a possible materials design solution that can be combined with your solution to (c)(i). [20%]

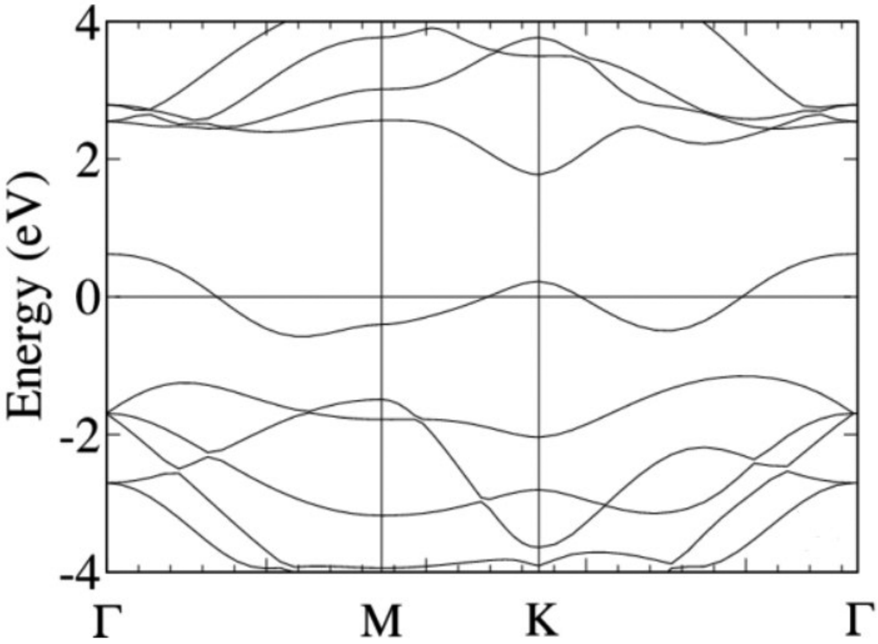

Fig. 2

3 (a) A layer of arsenic (As) is deposited onto a germanium (Ge) wafer. The wafer is then briefly annealed. Ge has a dielectric constant ε_r of 16 and average effective masses of electrons and holes of 0.55 and 0.37, respectively.

(i) Discuss what type of doping this will result in for the Ge. [10%]

(ii) Estimate the dopant level with respect to the corresponding band edge using the hydrogenic model. Sketch the Ge band diagram and indicate the dopant energy level. Will the As dopants be ionised at room temperature? [20%]

(iii) The Ge is found to have a number of point defects, particularly vacancies. Discuss where the energy level of these defect states will lie in the context of the Ge band diagram, and why these defects are electronically detrimental. [15%]

(iv) Discuss why Si and not Ge became the dominant material for CMOS technology. [10%]

(b) A p-n junction is formed using Ge as the semiconductor. Discuss the effectiveness of such a junction for outdoor photovoltaic applications. Suggest a better material for this application and indicate the maximum solar conversion efficiency that can be achieved. [20%]

(c) Figure 3 shows a band diagram of germanene, which is a 2D phase of Ge that has been recently demonstrated.

(i) Discuss potential applications for germanene based on electronic properties that you can see from the band diagram. [15%]

(ii) Si also has an analogous 2D phase called silicene. Sketch the band diagram of silicene around the so-called K-point. [10%]

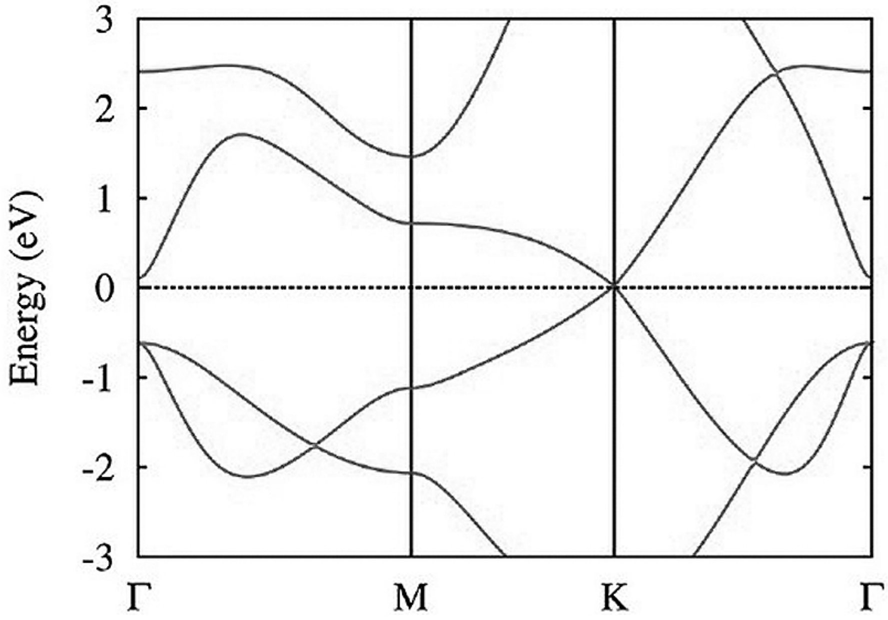

Fig. 3

4 (a) (i) Explain why a permanent magnet in the form of a disc with height equal to radius and consisting of cobalt steel will not remain magnetised while one composed of $SmCo_5$ will remain magnetised. [10%]

(ii) The demagnetising field in a permanent magnet not subject to an external magnetic field is given by $H_d = -MN$, where N is the demagnetising factor. Derive an equation which describes the relation between B and H which must be satisfied for a permanent magnet with a particular shape. [20%]

(iii) Explain how the equation derived in (ii) can be used to determine a load line which can be superimposed onto a plot of a material's B–H behaviour in order to graphically determine the operating point of a permanent magnet made from that material. [20%]

(iv) For a permanent magnet material with a sufficiently high coercive field show that the largest energy product is given by a magnet shaped so as to give a demagnetisation factor of 0.5. [15%]

(b) A hypothetical room temperature superconductor LZ-99 is found to exhibit a critical current density of 1×10^8 A/m^2 at 25 °C and a critical temperature of 30 °C.

(i) For a thin long slab of width 6 mm magnetised along its length (N=0) at 25 °C calculate the maximum achievable magnetisation for each of the cases of the slab consisting of the permanent magnet material N44H (see databook) and the superconductor LZ-99. [20%]

(ii) Based on your result from (i) and the stated properties of LZ-99 discuss what effect the discovery of such a room temperature superconductor would have on common uses of permanent magnets. [15%]

END OF PAPER

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Numerical Answers

3 a (ii) 29 meV

4 b (i) Sucon - 1.5×10^5 A/m N44H - 1×10^6 A/m