Version JHD/7 with numerical answers

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 28 April 2021 9 to 10.40

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 and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
You are allowed access to the electronic version of the Engineering Data Books.

10 minutes reading time is allowed for this paper at the start of the exam.

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 (a) Steel can been used both as a *hard* and as a *soft* magnetic material. Provide explanations for this observation. [20%]

(b) A pure sine waveform is applied to one side of a transformer and the output voltage measured with an oscilloscope. It is noted that the output waveform is distorted. Explain how the magnetic properties of the core material can give rise to this effect. [20%]

(c) For a permanent magnet of a specified shape fabricated from a given magnetic material explain how the magnitude of the magnetic B-field at the poles and the energy product (BH) can be determined. [20%]

(d) In pre-1918 internal combustion motors the spark required for ignition was typically provided by a *magneto*. This was a high voltage generator in which a copper coil was rotated within the magnetic field provided by a horseshoe shaped permanent magnet (an example is shown in Fig. 1) providing a field of roughly 0.02–0.03 T. In magnetos of this age, it is observed that the strength of the spark generated declines with time, and that the simple removal and replacement of the horseshoe magnets would cause them to demagnetise.

(i) Account for the observed decline in performance with time of these magnetos and suggest, with reasons, what magnetic material could have been used for the permanent magnets in these systems. [15%]

(ii) Explain how the magnets could be removed and replaced without demagnetising them. [10%]

(iii) Suggest and justify a suitable modern material to use in the permanent magnet. What changes to the design could be enabled by modern magnetic materials? [15%]

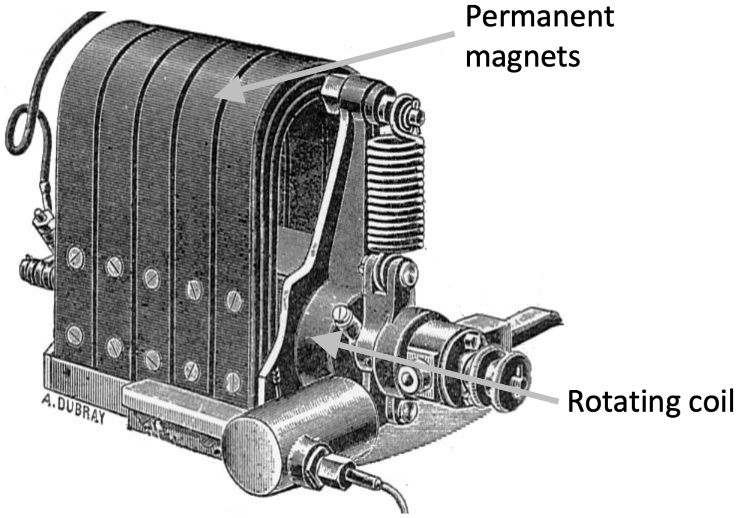

Fig. 1

2 (a) (i) Explain why a real capacitor should be modelled as an ideal capacitor in series with a resistance. Why can't this resistance be characterised by measuring the DC resistance of a capacitor? [15%]

(ii) Discuss the possible advantages and disadvantages to using a ferroelectric material as the dielectric in a capacitor. [20%]

(b) (i) Only three coefficients, d_{15}, d_{33} and d_{31}, are normally required to specify the piezo-electric behaviour of a material. Explain why each of the three coefficients is identified with a specific *mode* of operation in a piezoelectric device. Comment on why different modes find different applications. [10%]

(ii) Sketch a device that exploits d_{15}, indicating relevant dimensions, the direction of applied force and position of electrical contacts. Derive the equation which relates charge appearing on the element's surface to force applied. [15%]

(c) A gas ignitor is designed to generate a spark in a 2 mm gap using a lead titanate piezoelectric element of area 2 mm^2 and thickness 1 mm. The piezoelectric element has coefficients d_{15}= 30 pC N^{-1}, d_{31}= -4 pC N^{-1} and d_{33}=51 pC N^{-1}, and has a relative permittivity ε= 170. The breakdown voltage of air may be taken to be 30 kV cm^{-1}. The electric constant, ε_0, equals 8.85×10^{-12} F m^{-1}.

(i) Which mode of operation would require the least force to produce sufficient voltage for the ignitor to operate? [15%]

(ii) For your chosen mode of operation calculate the force required on the element to generate the spark. [25%]

3 (a) Explain the concept of orbital hybridisation and use the tight binding approximation to outline the origin of the energy band gap for the diamond phase of carbon (C). Support your answer by sketching the relevant energy levels in the transition from atomic C to a bulk diamond crystal. [20%]

(b) Outline the origin of Si surface states and indicate them in a band diagram. Explain how such surface states can be passivated by oxidation and hence why the SiO_2:Si interface has an important role in the semiconductor industry. [20%]

(c) Explain the term 2D materials, and the advantages of so-called van-der-Waals heterostructures. Give a 2D material, including a sketch of its unit cell, that can be used as a dielectric. [20%]

(d) Carbon nanotubes (CNTs) are used as new material for optically transparent electrodes and as channel material for thin film transistors as part of a future range of flexible displays. Discuss the specific CNT material requirements for both applications and, with reference to currently used standard materials for these applications, outline the advantages that CNTs could bring. [25%]

(e) CNT arrays are also considered as potential material for scaled interconnects. Outline a suitable choice of material to isolate such interconnects from each other. [15%]

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4 (a) Figure 2 shows the band diagram of monolayer tungsten disulphide (WS_2). Is this a direct or indirect bandgap material? Justify your answer. Estimate the photon wave length emitted from this material. [15%]

(b) Explain the hydrogenic model of substitutional doping of a semiconductor using the example of p-type doping of crystalline gallium nitride (GaN). Give a suitable acceptor material and estimate the ionisation energy assuming the effective mass of holes in GaN is 1.2 and the relative permittivity of GaN is 8.9. Comment on the effectiveness of such doping based on your result. [25%]

(c) Scattering by ionised impurities such as dopants is a significant cause of mobility limitation. Explain how this can be reduced by transfer doping and sketch a band diagram of an appropriate semiconductor heterostructure. Explain what limits the choice of materials for such heterostructure design. [25%]

(d) Explain why historically, following the 8-N rule, it was thought that substitutional doping would not work for amorphous semiconductors. Use the example of phosphorus doping of amorphous silicon. [10%]

(e) Outline how the hybridisation of carbon is linked to the electrical properties of organic semiconductors. Explain what an exciton is and why much of the optoelectronic properties of organic semiconductors are dominated by processes involving excitons. [15%]

(f) Discuss the significance of excitonic effects in monolayer WS_2 and give an example of how such effects would manifest themselves with respect to your answer in (a). [10%]

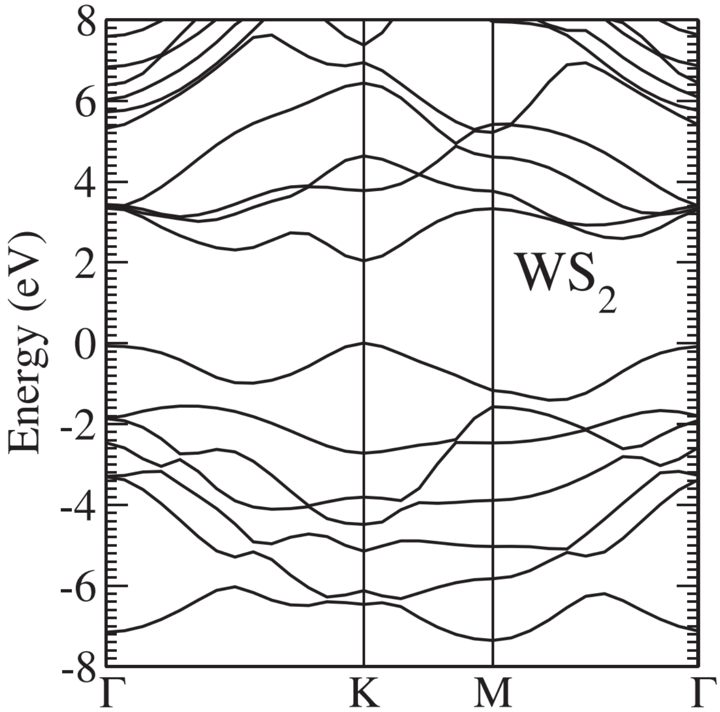

Fig. 2

Version JHD/7 with numerical answers

Numerical answers:

Q2. (c) ii) 354 N

Q4. (a) 590 nm. (b) 206 meV.

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