EGT3
ENGINEERING TRIPOS PART IIB

Monday 24 April 2017 14.00 to 15.30

Module 4B6

SOLID STATE DEVICES AND CHEMICAL/BIOLOGICAL SENSORS

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
Attachment: 4B6 formulae and constants sheet (1 page)
Reproduction of Fig.3 of Question 3 (1 page)

10 minutes reading time is allowed for this paper.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 (a) Sketch how a Metal-Insulator-Semiconductor (MIS) structure is used in a Field Effect Transistor (FET) device and explain briefly the FET operation. Outline the requirements to make a high-performance device with a fast switching speed. [30%]

(b) Figure 1 shows the small-signal capacitance versus voltage curves for a partially characterised MIS structure with curves V to I corresponding to various intensity levels of increasing illumination by white light. The x-axis is the voltage applied to the metal with respect to the semiconductor. What does the phrase "small-signal" mean in this context and what is the condition with which it can be treated as a small signal? Explain whether the semiconductor is n-type or p-type, and use energy-band diagrams to explain why the MIS structure is most sensitive to light in certain bias voltage ranges. Would the measured capacitance depend on the ac measurement frequency? [30%]

(c) Taking the relative permittivity (ε_r) of the insulator to be 5 and the MIS capacitance area to be 2×10^{-8} m^2, use the data in Figure 1 to calculate the insulator thickness. If the relative permittivity of the semiconductor is 10, estimate the maximum depth of the depletion region. Can the semiconductor be depleted to a greater depth? [40%]

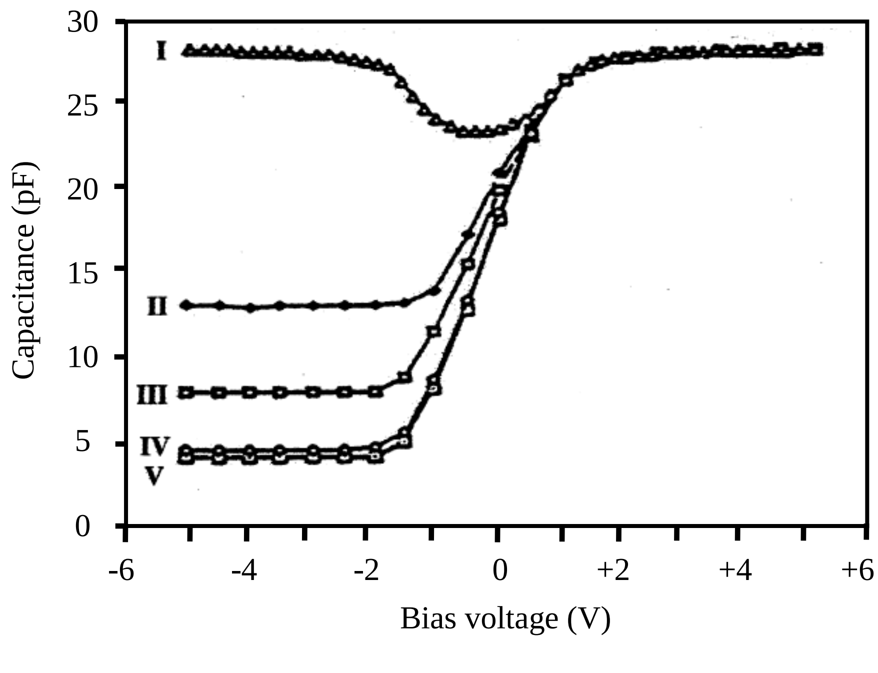


Figure 1

State all assumptions and approximations made.

2 (a) With the aid of a band diagram, discuss the effect of the work function difference between metal gate and semiconductor in a Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET). [20%]

(b) With the aid of band diagrams, explain how a MOSFET can be used as a hydrogen gas sensor and sketch the principle of detection of a hydrogen sensitive Metal-Oxide-Semiconductor (MOS) transistor and a hydrogen sensitive MOS capacitor. [20%]

(c) Explain the formation of the electrochemical double layer:

(i) at the interface between a metal and an electrolyte; [10%]

(ii) at the interface between an insulator such as SiO_2 and an electrolyte. [10%]

(d) Explain how the electrochemical double layer

(i) as described in (c)(i) can be used to detect DNA hybridization; [10%]

(ii) as described in (c)(ii) can be used as a pH sensor. [30%]

State all assumptions and approximations made.

3 (a) Explain the meaning of ferroelectric material, polarization, and polarization domain. [10%]

(b) Describe the structure and the principle of operation of a Ferroelectric Field-Effect Transistor (F-FET). [20%]

(c) With reference to the circuit diagram of Figure 2, explain how a one-transistor one-capacitor ferroelectric memory cell operates for its WRITE and READ operation. Include a sketch of the sensed charge versus applied voltage curve for the READ operation. [40%]

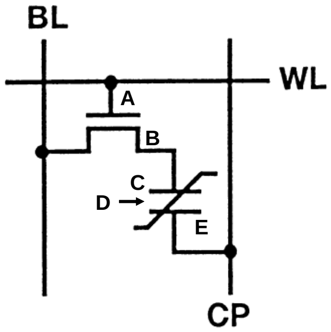
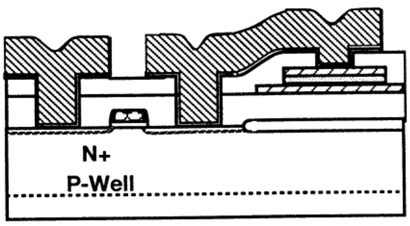


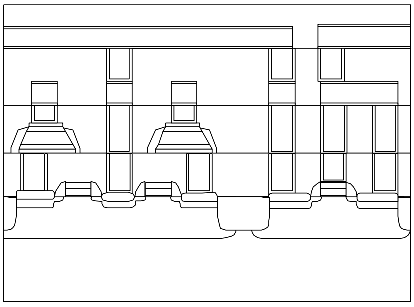
Figure 2

(c) Mark the parts A, B, C, D and E shown in Figure 2 at the corresponding places for both planar and stacked structures in Figure 3(i) and (ii) on the separated attachment page supplied. Describe the function and possible materials for each part. Give a brief comparison for the advantages and disadvantages of these two structures. [30%]



Planar structure

(i)



Stacked structure

(ii)

Figure 3

State all assumptions and approximations made.

4 (a) Explain what is the Giant Magneto-Resistance (GMR) effect, including its principle, the basic elements of a GMR device and their functions. [20%]

(b) A Magnetic Tunnel Junction (MTJ) is operating in Current-Perpendicular-to-Plane (CPP) configuration. It consists of two magnetic layers made of Co, separated by a thin non-magnetic layer made of Cu, with a thickness t_{Cu}, as shown in Figure 4. The free energy of magnetic interaction, E, between these two Co layers can be described in the form of $E = -J\vec{M}_{Co,1} \cdot \vec{M}_{Co,2}$ where $\vec{M}_{Co,1}$ and $\vec{M}_{Co,2}$ are the in-plane magnetisations of the two Co layers, respectively, and J the exchange integral. Assume that the exchange integral is of RKKY-type interaction, i.e. $J \sim \cos(2\pi a t_{Cu})/(2\pi a t_{Cu})^3$ where a is a constant. Sketch the exchange integral vs t_{Cu} and mark the regions of High and Low Magneto-Resistance (HMR and LMR) when the external magnetic field is zero. [30%]

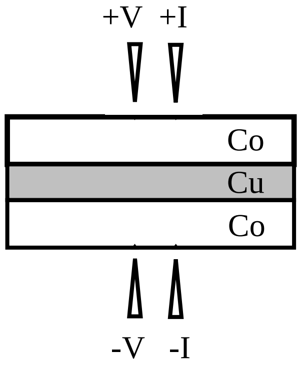


Figure 4

(c) The circuit representation of an MRAM cell is shown in Figure 5. Use it to:

(i) draw a memory matrix linked by Bit-line, Word-line and Digit-line; [25%]

(ii) describe how to Read and Write a bit of information to and from a chosen cell, respectively. [25%]

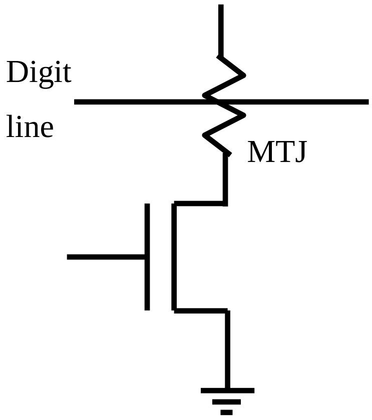


Figure 5

State all assumptions and approximations made.

END OF PAPER

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ENGINEERING TRIPOS PART IIB

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Formulae and constants

$\varepsilon_0 = 8.85 \times 10^{-12}$ Farad m^{-1} permittivity in vacuum

$k = 1.38 \times 10^{-23}$ Joules K^{-1} Boltzmann's constant

Bulk charge in the depletion region:

$$Q_B = -\left(2\varepsilon_S \, q \, N_A \, \psi_S\right)^{\frac{1}{2}}$$

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ENGINEERING TRIPOS PART IIB

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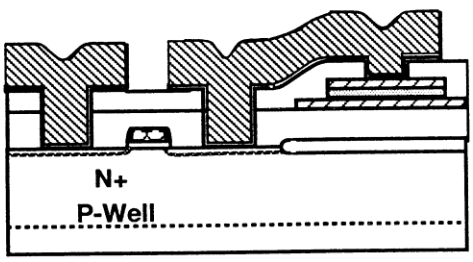
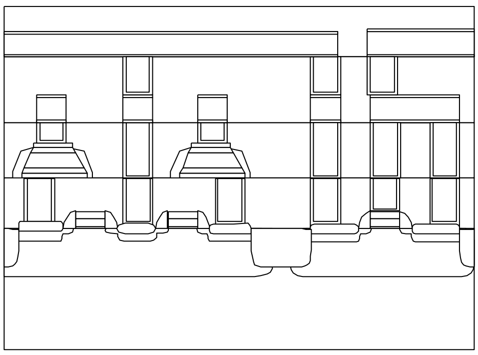
Reproduction of Fig. 3 of Question 3

Question 3



Planar structure

(i)



Stacked structure

(ii)

Figure 3

Assessor's comment:

Q1 MIS capacitor
Least popular question taken by only 8 candidates. Majority of them did well, showing a good understanding of the principles.

Q2 Bio-/Chemical sensors
A question answered reasonably well by the candidates. No problem in describing the underlying principles, but there is a difference on covering different aspects of a specific process.

Q3 FRAM
Joint most popular question, taken by everyone. Straightforward calculations. Many of the candidates did very well, but some did not mention how the sensing of switch charges is done.

Q4 GMR/MRAM
The other joint most popular question. It appears not easy to cover all the points to get a perfect answer, such as mentioning not only three elements in a GMR device but also their detailed functions.