Version DPC/4 + List of Answers

EGT3
ENGINEERING TRIPOS PART IIB

Friday 1 May 2015 2 to 3.30

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)

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) Figure 1 shows the double layer sheet capacitance of mercury in contact with NaF solution as a function of ionic strength. Explain the origin of electrical double layer capacitance and give examples using the model used to describe it. [25%]

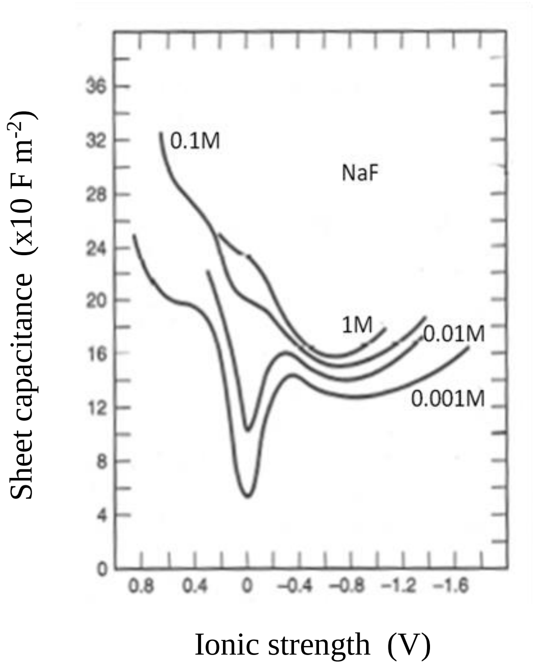
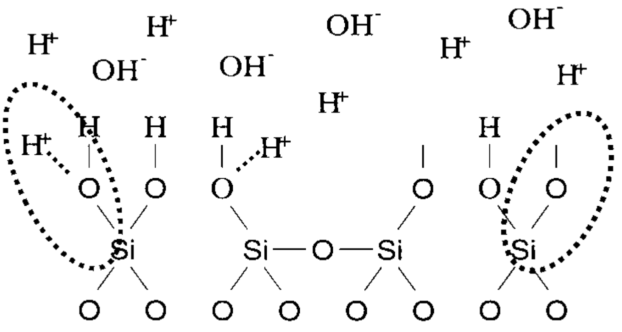


Fig. 1

(b) (i) Ion Sensitive Field Effect Transistor (ISFET) is used as a pH sensor by measuring the change in the double layer potential ψ_L. With reference to the acidic/basic reactions at the surface in Fig. 2, write down the equations for the equilibrium constant K_b and K_a. H_s^+ is the H^+ at the surface in the solution side. [15%]



$$\mathbf{SiOH + H_s^+ \xrightarrow{K_b} SiOH_2^+} \qquad \mathbf{SiOH \xrightarrow{K_a} SiO^- + H_s^+}$$

Fig. 2

(ii) Express the concentration of H_s^+ at the surface in terms of K_b, K_a, the concentrations of $SiOH_2^+$ and SiO^-. [25%]

(iii) With the Boltzmann relationship shown below, express the double layer potential ψ_L in terms of K_b, K_a and concentration of hydrogen ions in the bulk solution, H_b^+. [35%]

$$[\mathrm{H}_s^+] = [\mathrm{H}_b^+] \exp\left(-\frac{q\psi_L}{kT}\right)$$

State all assumptions and approximations made.

2 (a) For the ferroelectric thin film material shown in Fig. 3, find the values of:

(i) Remnant Polarisation. [10%]

(ii) Coercive field. [10%]

(iii) Energy density consumed in a full switching cycle. [10%]

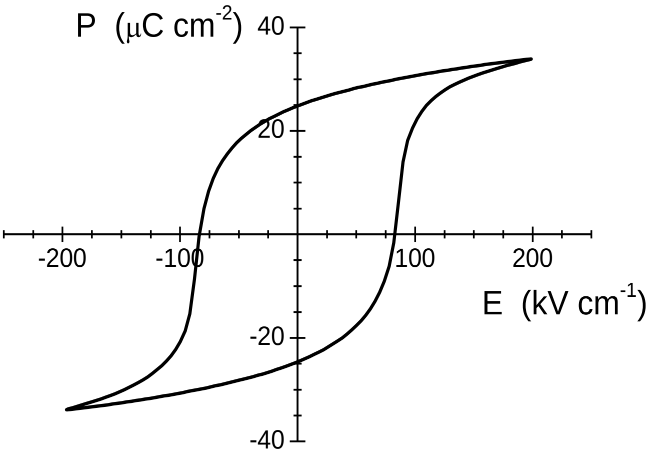


Fig. 3

(b) A ferroelectric thin film capacitor in a Ferroelectric Random Access Memory (FRAM) cell is made of the ferroelectric material shown in Fig. 3 with dimensions of 150 nm in thickness and 0.18 μm by 0.18 μm square in size.

(i) If we apply a voltage across it in the form of a positive step function with a height of +3V, what will be the switching charge if the initial information stored in this memory cell was of State ‘1’ (positively polarised) or State ‘0’ (negative polarised), respectively? [20%]

(ii) If the bit line parasitic capacitance, which is utilised as a sensing capacitor, is 2 pF, what are the sensed voltage levels for State ‘1’ and State ‘0’, respectively? [20%]

(iii) Theoretically, how small in size can this ferroelectric capacitor be in order to maintain its original function as a memory cell, given that the Read-out sense amplifier has a resolution of 1 mV? [10%]

(c) Figure 4 shows the results of an accelerated reliability test for the above memory cell. What are the projected life times of this device at 80 °C and 30 °C, respectively? (Hint: assume $t_{\text{failure}} \sim \exp(+\Delta E/kT)$, where ΔE is a constant and k the Boltzmann constant.) [20%]

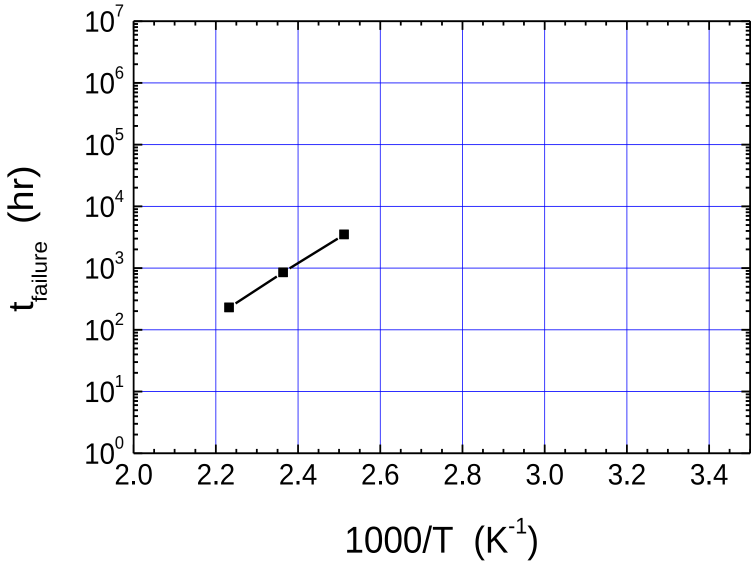


Fig. 4

State all assumptions and approximations made.

3 (a) Explain:

(i) How a Magnetic Tunnel Junction (MTJ) works in the Current-Perpendicular-to-Plane (CPP) and Current-In-Plane (CIP) configurations, as shown in Fig. 5. [20%]

(ii) Whether the lower Co layer, which is not in contact in the CIP configuration, has any impact on the measured current and why. [20%]

(iii) How a bit of information is stored and which physical quantities are readout. [10%]

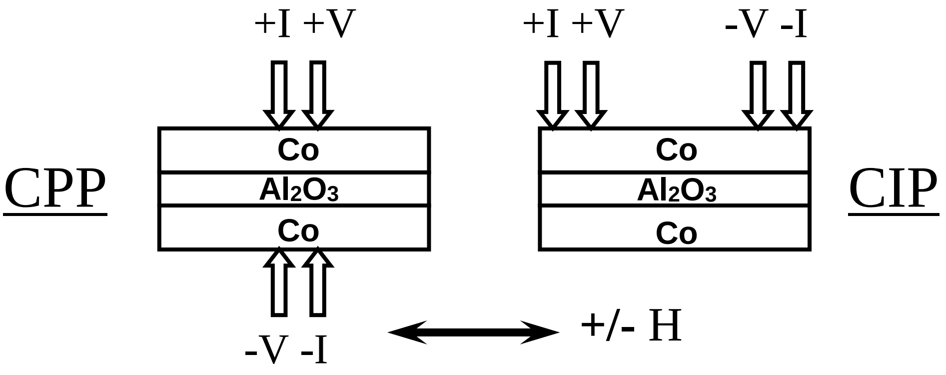


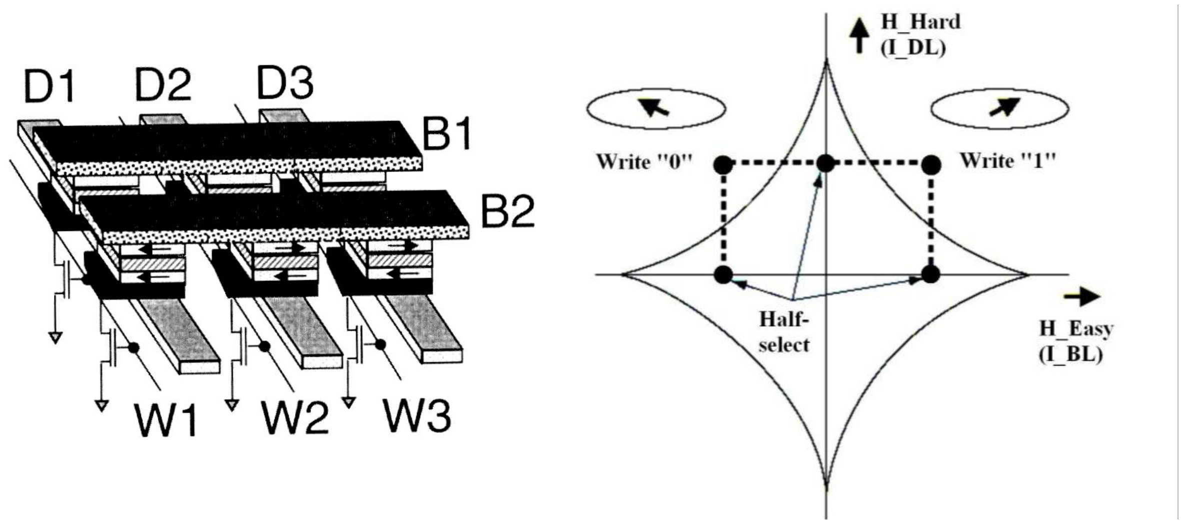
Fig.5

(b) A sketch of a Magnetic Random Access Memory (MRAM) array is shown in Fig. 6(a). For a given cell (say B2-W2), explain without reproducing Fig. 6(a):

(i) How to write a bit of information into the cell, with reference to Fig. 6(b). [30%]

(ii) How to read the stored information. [10%]

(iii) The importance of the physical geometry of the device. [10%]



(a) (b)

Fig. 6

State all assumptions and approximations made.

4 (a) Define the threshold voltage for a Metal-Oxide-Semiconductor (MOS) capacitor. [10%]

(b) An ideal p-type silicon MOS capacitor has the following parameters:

oxide thickness	$d = 2.0\times10^{-7}$ m
oxide dielectric constant	$\varepsilon_i = 3.9\varepsilon_0$
semiconductor dielectric constant	$\varepsilon_S = 11.9\varepsilon_0$
intrinsic carrier concentration	$n_i = 1.45\times10^{16}$ m^{-3}
acceptor concentration	$N_A = 2.0\times10^{21}$ m^{-3}
effective Density of States in Conduction Band	$N_C = 2.08\times10^{25}$ m^{-3}
effective Density of States in Valence Band	$N_V = 1.04\times10^{25}$ m^{-3}

Calculate the threshold voltage of this device at room temperature. [30%]

(c) A MOS capacitor with the above parameters contains interface states at the silicon/SiO_2 interface. These states are acceptor-like, that is each state carries a charge $q = -1.6\times10^{-19}$ C when occupied, and are neutral when empty. Their density, D_{it}, is constant throughout the bandgap: $D_{it} = 10^{16}$ m^{-2} eV^{-1}.

Assume that the Fermi function F(E) can be approximated as a step function:

$$F(E) = 1 \quad \text{for } E \leq E_F$$
$$F(E) = 0 \quad \text{for } E > E_F.$$

Calculate the threshold voltage at room temperature in this case. [30%]

(d) Discuss whether the result of the calculation in (c) would change, if the correct Fermi function is employed:

(i) For the D_{it} above.

(ii) For any D_{it}. [30%]

State all assumptions and approximations made.

END OF PAPER

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ENGINEERING TRIPOS PART IIB

Module 4B6

SOLID STATE DEVICES AND CHEMICAL/BIOLOGICAL SENSORS

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

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ENGINEERING TRIPOS PART IIB

Module 4B6

SOLID STATE DEVICES AND CHEMICAL/BIOLOGICAL SENSORS

List of Answers

1. (b) (i)

$$K_b = \frac{[SiOH_2^+]}{[H_S^+][SiOH]} \qquad K_a = \frac{[H_S^+][SiO^-]}{[SiOH]}$$

(ii)

$$\frac{K_a}{K_b} = \frac{[H_S^+]^2[SiO^-]}{[SiOH_2^+]} \qquad \therefore [H_S^+] = \sqrt{\frac{K_a}{K_b}\frac{[SiOH_2^+]}{[SiO^-]}}$$

(iii)

$$-\ln[H_b^+] + \ln\left(\frac{K_a}{K_b}\right)^{\frac{1}{2}} = -\frac{q\psi_L}{kT} + \underbrace{\ln\left(\frac{[SiO^-]}{[SiOH_2^+]}\right)^{\frac{1}{2}}}_{\text{negligible}}$$

$$-\ln[H_b^+] + \ln\left(\frac{K_a}{K_b}\right)^{\frac{1}{2}} \approx -\frac{q\psi_L}{kT}$$

2. (a) (i) 25 μC cm^{-2}; (ii) 80 kV cm^{-1}; (iii) $8x10^6$ J m^{-3}

   (b) (i) 2.9 fC for ‘1’, 19 fC for ‘2’; (ii) 1.5 mV for ‘1’, 9.5 mV for ‘0’;
   (iii) 58 nm x 58 nm

   (c) ~10 yrs at 80ºC, ~1,000 yrs at 30ºC

3.

4. (b) 1.79 V; (c) 9.99 V