ENGINEERING TRIPOS PART IIB

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3 May 2013 09:30 - 11:00

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.*

Attachment: Formulae and Constants sheet (1 page)

STATIONERY REQUIREMENTS	SPECIAL REQUIREMENTS
Single-sided script paper	Engineering Data Book
	CUED approved calculator allowed

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

1 An ideal p-type silicon MOS capacitor has the following parameters:

gate oxide thickness	$d=1.0\times10^{-7}$ m
oxide dielectric permittivity	$\varepsilon_i=3.9\ \varepsilon_0$
semiconductor dielectric permittivity	$\varepsilon_s=11.9\ \varepsilon_0$
acceptor concentration	$N_A= 1.0\times10^{21}\ m^{-3}$

A voltage pulse of amplitude V is applied to the capacitor, resulting in a surface potential $\psi_s = 4\,\text{V}$, before any appreciable inversion charge is generated (i.e. in deep depletion).

(a) Starting from Poisson's equation:

$$\frac{d^2\psi}{dx^2} = -\frac{\rho(x)}{\varepsilon_s}$$

Prove that the total change per unit surface in the semiconductor is given by

$$Q_B = -(2\varepsilon_S q N_A \psi_S)^{\frac{1}{2}}$$ [30%]

(b) Calculate V. [20%]

(c) Calculate the length of the depletion region. [10%]

(d) Calculate the device capacitance per unit area under these conditions. [10%]

(e) Explain the behaviour of the capacitance as a function of V:

(i) in deep depletion; [10%]

(ii) after the formation of the inversion layer, when the frequency of the AC voltage employed to measure the capacitance is low (~1 Hz) and when it is high (~100 kHz). [20%]

2 (a) Draw the circuit diagram of a MOSFET inverting voltage amplifier and explain the Miller effect in such a circuit. [30%]

(b) If an inverting voltage amplifier has a gain A and Miller capacitance C_{GD}, write the expressions for:

(i) the input current due to the Miller capacitance; [10%]

(ii) the effective input capacitance; [10%]

(iii) the ratio of the amplifier's upper 3dB frequencies with and without the Miller capacitance. [20%]

(c) Discuss why it is important to minimize the Miller effect and how to do so at the device level. [30%]

3 (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 of the model used to describe it. [20%]

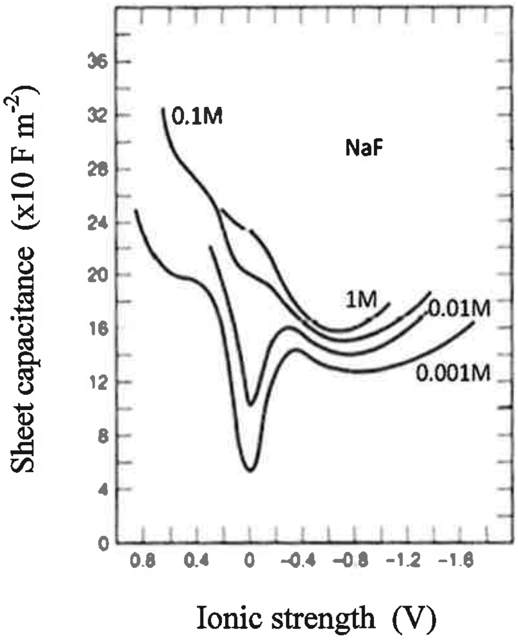

Fig. 1

(b) Electrochemical Impedance Spectroscopy is proposed in an application for DNA detection. The experimental setup is shown in Figure 2a. The measurement cell consists of the reference electrode, the counter electrode and the gold working electrode. The buffer solution has a redox couple Ferricyanide $[Fe(CN)_6]^{3-}$ and Ferrocyanide $[Fe(CN)_6]^{4-}$. Figure 2b shows the self-assembled single-stranded DNA probe and Mercaptohexanol co-immobilized on to the gold working electrode. Including the double layer capacitance, C_{dl}, work out an equivalent electrical circuit model to estimate the impedance between the working electrode and the reference electrode. Comment on each term. Sketch the frequency response (Nyquist plot) of the equivalent electrical circuit. [40%]

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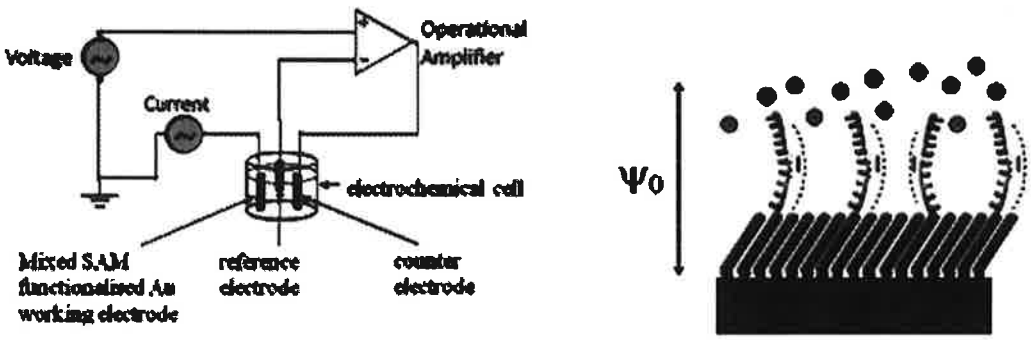

(a) (b)

Fig. 2

(c) Explain how single-strand target DNA can be detected with Electrochemical Impedance Spectroscopy, with reference to the equivalent electrical circuit model. [30%]

(d) Comment on ways to improve the sensitivity of the detection technique. [10%]

4 (a) 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 3. 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 $\vec{M}C_{o,2}$ 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. [50%]

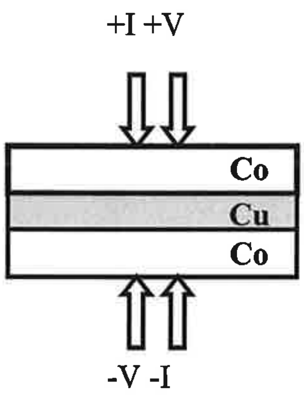

Fig. 3

(b) The circuit representation of an MRAM cell is shown in Figure 4. 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%]

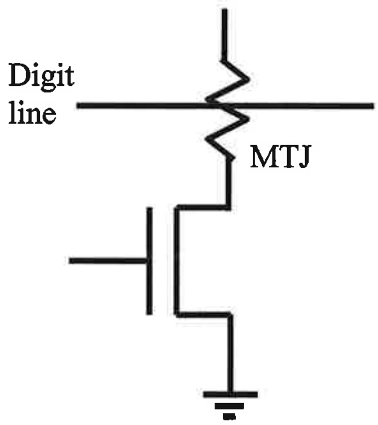

Fig. 4

END OF PAPER

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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

4B6, 2013 Numerical Answers

Q1(b) 5.06 V

Q1(c) 2.29×10^{-6} m

Q1(d) 4.05×10^{-5} Farad m-^{2}