Version DPC/3

EGT3
ENGINEERING TRIPOS PART IIB

Monday 18 April 2016   9.30 to 11

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) Define the threshold voltage for a MOSFET and explain its significance in terms of MOSFET operation. [20%]

(b) Calculate the threshold voltage for a silicon n-channel MOSFET at T=300 K with the following parameters:

gate oxide thickness	$d=5.0\times10^{-9}$ m
oxide dielectric constant	$\varepsilon_i=3.9\ \varepsilon_0$
semiconductor dielectric constant	$\varepsilon_S=11.9\ \varepsilon_0$
acceptor concentration	$N_A= 2.0\times10^{21}$ m^{-3}

Assume the device is ideal and V_{DS} is negligibly small. [40%]

(c) n-channel MOSFETs with the above parameters are fabricated and, due to a fault in the process, some fixed charge is present at the oxide/semiconductor interface.

From the I_D-V_{GS} data below, obtained for V_{DS}=0.001 V, determine the density and sign of the fixed charge.

V_{GS} (V)	I_D (A)
1.0	$1.43\text{x}10^{-6}$
1.4	$1.89\text{x}10^{-6}$
1.8	$2.35\text{x}10^{-6}$
2.2	$2.81\text{x}10^{-6}$
2.6	$3.27\text{x}10^{-6}$
3.0	$3.73\text{x}10^{-6}$

[40%]

State all assumptions and approximations made.

2 (a) With reference to the metal-insulator-silicon structure shown in Fig. 1, where the semiconductor is n-type, explain what is meant by

(i) depletion, and

(ii) inversion in the silicon.

Illustrate your answer with electron energy vs distance band diagrams. [20%]

(b) Explain how *small-signal* capacitance vs voltage measurements can be used to obtain information about the doping density in the semiconductor. Describe a possible experimental setup. Explain what is meant by *small-signal*. Derive an expression, in terms of easily measurable quantities, for the concentration of ionized impurities as a function of distance into the semiconductor from the insulator interface. [40%]

(c) The results of an experiment on a similar structure to that in Fig. 1 are (i) bias voltage to metal +3 V, capacitance 40 pF, and (ii) bias voltage to metal -3 V, capacitance 15 pF. When the measurement frequency was increased by a factor of ten, there was no change in the measured values of capacitance. The test device metal area is 2×10^{-1} m^2, the insulator has a relative permittivity 5, and the semiconductor has a relative permittivity 12. Calculate the insulator thickness and the depletion depth into the semiconductor. Assuming that the silicon is uniformly doped, calculate the doping density in the silicon, making reasonable estimates of any unknown quantities. [40%]

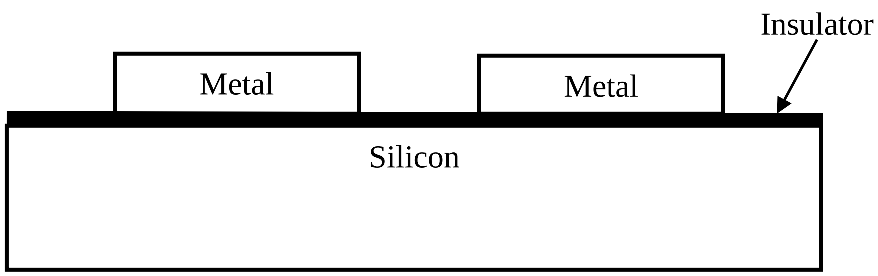

Fig. 1

State all assumptions and approximations made.

3 (a) With reference to ferroelectric materials, explain briefly

(i) what is meant by polarization and domains, and [10%]

(ii) how a ferroelectric thin film can be incorporated into a Field Effect Transistor (FET) type device to make a non-volatile memory cell and how it works. [20%]

(b) Using the partial cross section of a one-transistor one-capacitor (1T/1C) ferroelectric memory cell, as shown in Fig. 2,

(i) state the function of, and the type of material used for, the layers A, B, C, D and E, and [15%]

(ii) draw a circuit diagram (based on Fig. 2) and use it to explain how a cell can be addressed for a WRITE operation (include a sketch of the charge vs voltage diagram in the explanation). [15%]

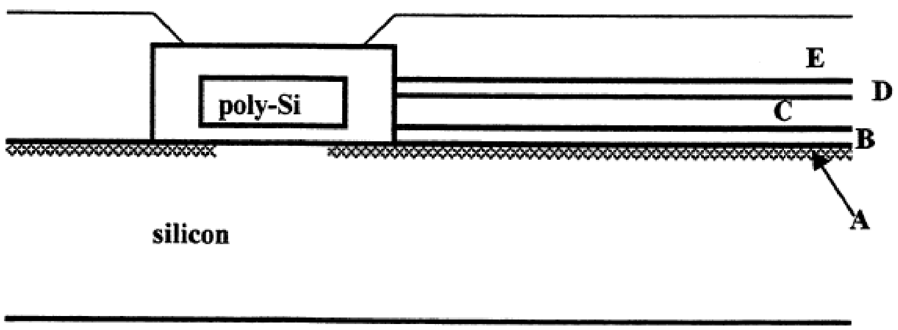

Fig. 2

(c) The ferroelectric capacitor in Fig. 2 is made of a ferroelectric material and its hysteresis curve is shown in Fig. 3. It has dimensions of 100 nm in thickness and 250 nm by 250 nm in area. Estimate:

(i) the remnant polarisation and coercive field of the material; [10%]

(ii) the amount of switching charge during a READ operation with a +5 V applied on the ferroelectric capacitor, when the initial information stored in this memory cell is State “1” (positively polarised) and State “0” (negatively polarised), respectively; [20%]

(iii) the energy consumed by the ferroelectric capacitor due to a single polarisation switching. [10%]

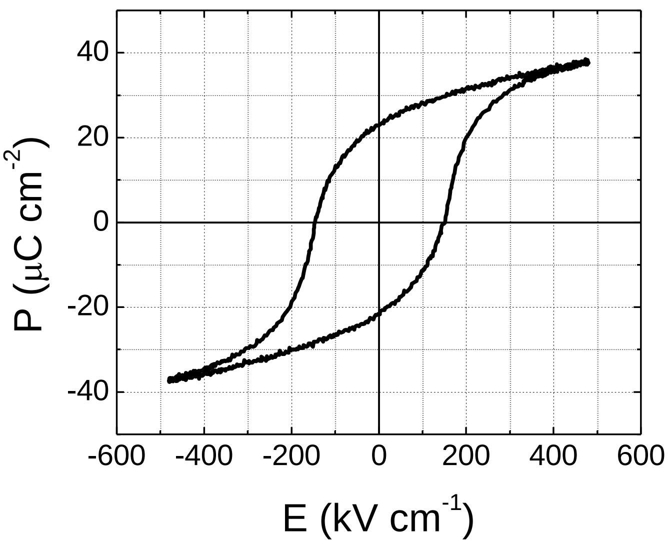

Fig. 3

State all assumptions and approximations made.

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4 (a) With the aid of band diagrams and schematic MOS structures, explain the ways which a MOSFET can be used as a hydrogen gas sensor and what other gases can also be detected. [30%]

(b) Electrochemical Impedance Spectroscopy (EIS) is proposed for DNA detection. Draw a standard three-electrode cell that is suitable for such an application. [10%]

(c) Figure 4 shows a self-assembled single-stranded DNA probe and Mercaptohexanol co-immobilized on to a gold electrode. The buffer solution used in the cell has a redox couple Ferricyanide $[Fe(CN)_6]^{3-}$ and Ferrocyanide $[Fe(CN)_6]^{4-}$.

(i) Construct an equivalent electrical circuit model to estimate the impedance of the system, and comment on each component. [20%]

(ii) Describe the frequency response of the equivalent electrical circuit and sketch the Nyquist plot. [20%]

(iii) Explain the change in the Nyquist plot if the target DNA is hybridised with the DNA probe. [20%]

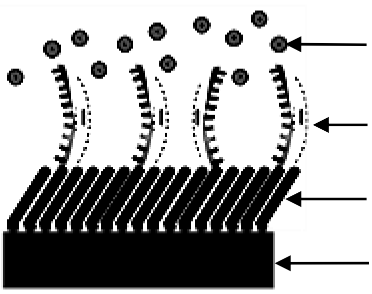

Fig. 4

State all assumptions and approximations made.

END OF PAPER

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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

Bulk charge in the depletion region:

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