MODULE 4B6: Solid State Devices and Chemical/Biological Sensors
Example Paper2

Unless otherwise stated assume that:

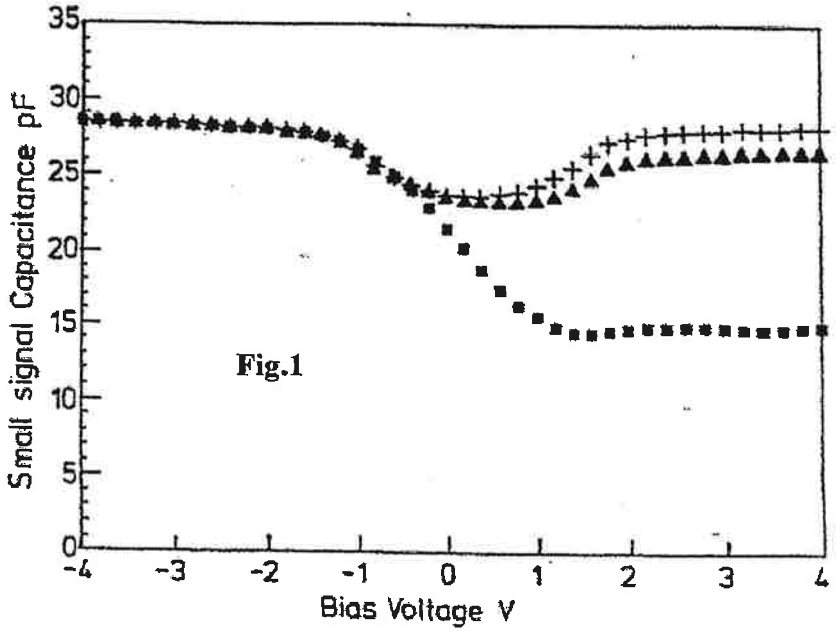
- **the semiconductor is silicon,**
- **the insulator is SiO_2**
- **the temperature is 300K,.**
- **the devices are ideal.**

1 (a) Consider a metal-insulator-semiconductor (MIS) structure in which the semiconductor is uniformly lightly doped n-type. Explain briefly why small-signal capacitance-voltage measurements are useful to obtain information about the insulator layer and about the doping density. Illustrate your answer with a sketch of the variation of the capacitance with the voltage measured with respect to the semiconductor.

(b) Make a corresponding capacitance-voltage sketch to part (a) for the case of a highly doped p-type semiconductor. Indicate on the diagram which voltage range corresponds to accumulation of carriers in the semiconductor. Is the measured capacitance dependent upon the measurement frequency in this region?

Draw the corresponding energy band sketch for a cross section through the structure in accumulation.

(c) Figure 1 shows the capacitance-voltage data from a partially characterized structure measured at three different frequencies. The insulator is 100 nm thick and has a relative permittivity of 4, and the relative permittivity of the semiconductor is 10. Make a lower-limit numerical estimate of the maximum extent of the depletion region into the semiconductor. Explain why it is a lower limit.



2. The following voltages are applied to an ideal silicon MOSFET, with $N_A = 10^{15}\text{cm}^{-3}$, $V_{DS} = 5V$, $V_{GS} = 10V$, $V_{BS} = 0V$. Under these conditions strong inversion occurs at every point y in the channel.

Calculate the depletion length at the drain (y=L) and at the source (y=0). (Use the appropriate formulas among those given at the end of the paper)

***3.** A MOSFET parameters are:

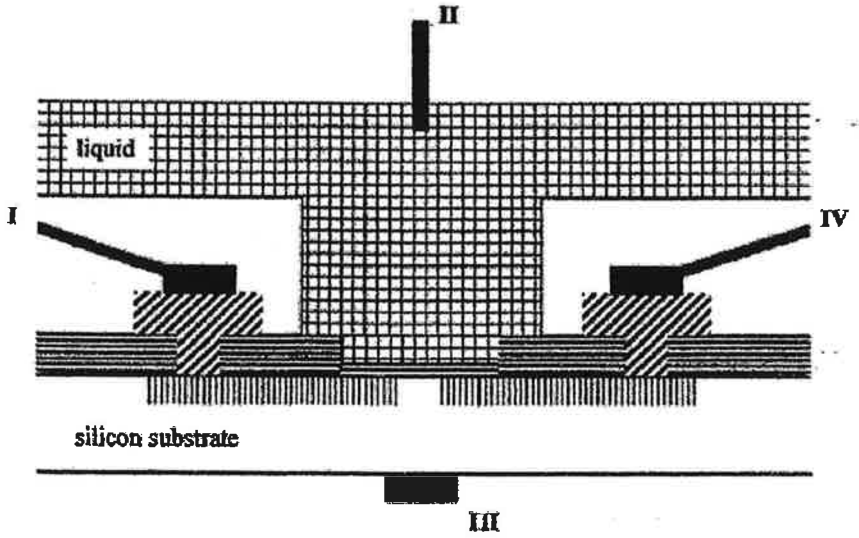
Oxide thickness: 30nm;
$W = 10\mu m$
$\mu_n = 1000\ \text{cm}^2 V^{-1} s^{-1}$
$N_A = 10^{15}\ \text{cm}^{-3}$

Determine the current (I_d) for which the maximum drift velocity would be equal to 1/10 of the thermal velocity (thermal velocity = 10^7 cm/s), when $V_{GS} = 5V$, $V_{DS} = 2V$.

4. Describe the physical origin of gap states (or traps) in a-Si and polysilicon thin-film transistors and the effect they have on the transistor operation.

5 (a) Discuss briefly what is meant by a MOS based chemical sensor, taking a hydrogen ChemFET as an example. Explain what material is used as the gate electrode and make a sketch of the electrical characteristics showing the effect when hydrogen is detected

(b) Explain the use of pH in describing hydrogen ion concentration. Describe the operation of an ion-sensitive field effect transistor (ISFET) as a biosensor and the relevance of pH. With reference to the partially completed diagram showing the cross section of an ISFET identify the functions of the connections I - IV and the electrical functions of the various layers in the device.



6. (a) Explain briefly how ferroelectric materials can be used in ferroelectric random access memory (FRAM) devices for silicon-based integrated circuit technology.

(b) With reference to the partially completed device cross section in Figure 3 explain how a one-transistor one-capacitor (1T/1C) ferroelectric memory cell operates, and the electric function of the layers I - IV in Figure 3 Outline briefly a possible device fabrication process, identifying the most critical steps.

(c) Discuss the present status of FRAM technology, the performance relative to competing technologies, and likely future developments.

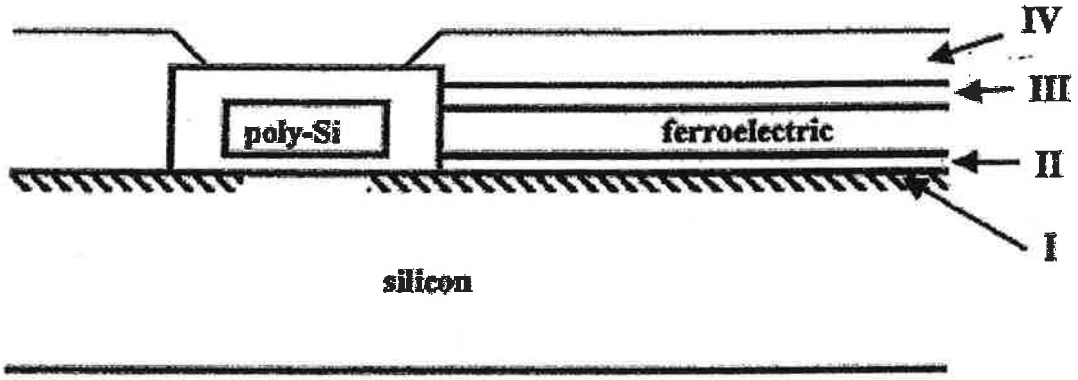


Fig.3

Formulas and constants

$\varepsilon_0 = 8.85\ 10^{-12}$ farad/m permittivity in vacuum
$k=1.38\ 10^{-23}$Joules $^0K^{-1}=8.625\ 10^{-5}$ eV $^0K^{-1}$ Boltzman constant
$kT/q = 0.025V$ at $T=300K$

$N_c=2.8\ 10^{25}m^{-3}$
$N_v=1.04\ 10^{25}m^{-3}$
Eg(silicon)=1.12eV
ε_i (silicon dioxide) = $3.9\varepsilon_0$
ε_s (silicon)= $11.9\varepsilon_0$

$n=N_C \exp((E_F-E_C)/kT))$
$p=N_V \exp((E_V-E_F)/kT))$

$(np)^{0.5} = n_i=6.6\ 10^{15}m^{-3}$

Fixed charge in the depletion region:

$$Q_B = -\left[2\ \varepsilon_S\ q\ N_A\ \psi_S\right]^{\frac{1}{2}}$$

Channel Conductance as a function of position y in the channel:

$$G(y) = \mu_n \frac{\varepsilon_i}{d}[\ V_{GS} - (\psi_s(y) - Q_B(y)\frac{d}{\varepsilon_i})\ ]$$

Current:

$$I_D = W \frac{d\ V_C}{d\ y} G\ (y)$$

where V_C is the channel potential