4B6 Crib 2016

Q1

(a) The threshold voltage V_T is defined as the voltage between gate and source, V_{GS}, such that the concentration of minority carriers at the surface equals the concentration of majority carriers in the bulk, for a negligible source and drain bias, V_{DS}. It corresponds to the transition point from weak inversion to strong inversion, the region in which a MOSFET is always used. [20%]

(b) In these conditions:

$$|E_F - E_i|_{surface} = |E_F - E_i|_{bulk} = q\psi_B$$

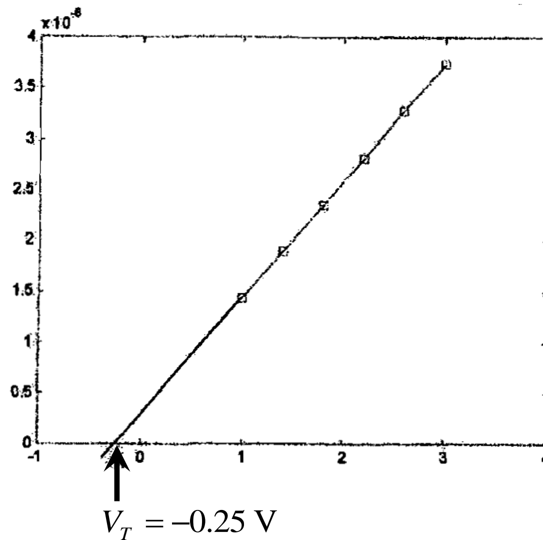
$$N_A \approx p = n_i \exp\frac{q\psi_B}{kT}$$

$$\psi_S = 2\psi_B = \frac{2kT}{q}\ln\frac{N_A}{n_i} = \frac{1.4\times10^{-23}\times300}{1.6\times10^{-19}}\ln\left(\frac{2\times10^{21}}{10^{16}}\right) = 0.64\text{ V}$$

$$Q_B = -(2\varepsilon_S q N_A \psi_S)^{\frac{1}{2}} = -(2\times11.9\times8.9\times10^{-12}\times1.6\times10^{-19}\times2\times10^{21}\times0.64)^{\frac{1}{2}}$$
$$= -2.0\times10^{-4}\text{ C m}^{-2}$$

$$V_T = \psi_S + \frac{d}{\varepsilon_i}|Q_B| = 0.64 + \frac{5\times10^{-9}}{3.8\times8.9\times10^{-12}}\times2.0\times10^{-4} = 0.68 + 0.03 = 0.67\text{ V}$$ [40%]

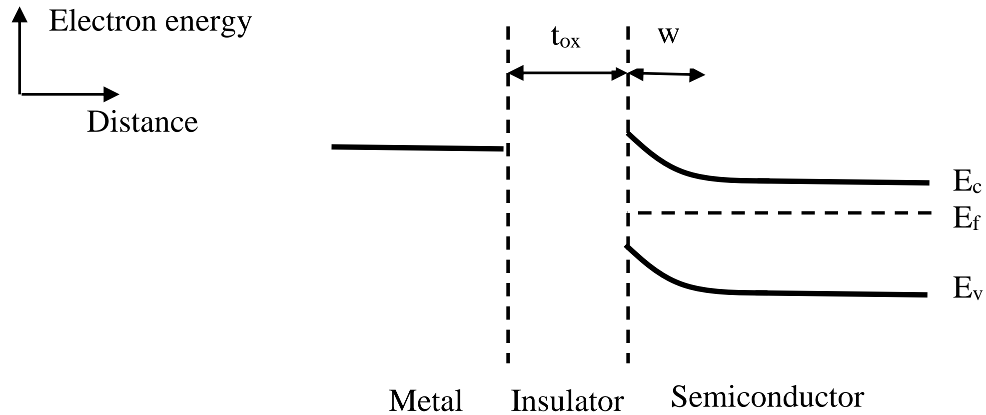
(c)



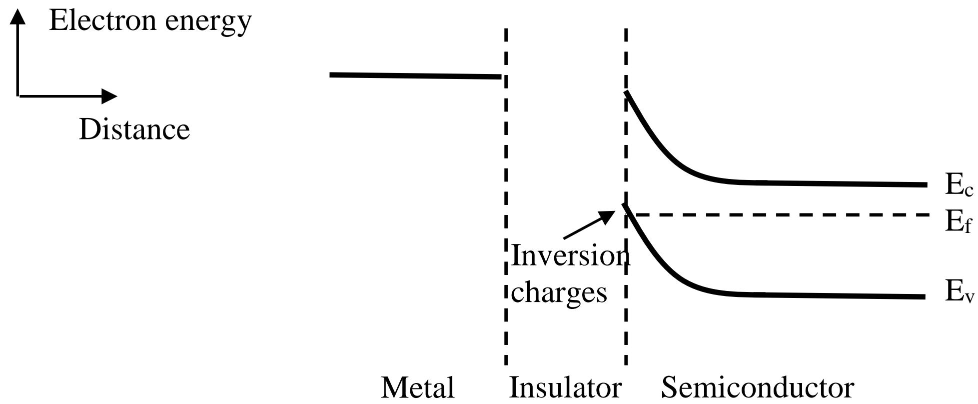
$$Q_F = \frac{\varepsilon_i}{d}\Delta V_T = \frac{3.8\times8.9\times10^{-12}}{5\times10^{-9}}[0.67 - (-0.25)] = 6.2\times10^{-3}\text{ C m}^{-2}$$ [40%]

Q2

(a) When a negative voltage is applied to the metal with respect to the gate then the bands are bent in the semiconductor which is depletion of charge carriers (conduction band electrons) to a depth into semiconductor.



Inversion occurs when a large voltage (d.c.) is applied to the metal and holes are induced at the interface.



[20%]

(b) In the semiconductor is depleted to a depth x and the applied voltage is made more negative, the depth increases by dx

$$\frac{1}{C_{total}} = \frac{1}{C_{ox}} + \frac{1}{C_s}$$

Per unit area

$$\frac{1}{C} = \frac{t_{ox}}{\varepsilon_0 \varepsilon_{ox}} + \frac{x}{\varepsilon_0 \varepsilon_s}$$

Differentiate with respect to voltage

$$-\frac{1}{C^2}\frac{dC}{dV} = \frac{1}{\varepsilon_0\varepsilon_s}\frac{dx}{dV}$$

When the depth increases by dx the charge incurred is qNdx, but for a simple capacitor dQ = CdV.

Hence CdV = qNdx, and

$$\frac{dx}{dV} = \frac{C}{qN}$$

Substitute into the previous expression

$$-\frac{1}{C^2}\frac{dC}{dV} = \frac{1}{\varepsilon_0\varepsilon_s}\frac{C}{qN}$$

It gives

$$N = -\frac{1}{\varepsilon_0\varepsilon_s}\frac{C^3}{q\frac{dC}{dV}}$$

A *small signal* is used to obtain the differential quantity dC/dV from the measured C-V curve as capacitance per unit area of MIS. [40%]

(c)

$$C_{ox} = \varepsilon_0\varepsilon_{ox}\frac{A}{t_{ox}}$$

$A\varepsilon_0\ \varepsilon_{ox} = 2\text{x}10^{-8}\ \text{x}\ 8.9\text{x}10^{-12}\ \text{x}\ 5 = 89\ \text{x}10^{-20}$

$$C_s = \varepsilon_0\varepsilon_s\frac{A}{w}$$

$A\varepsilon_0\ \varepsilon_s = 2\text{x}10^{-8}\ \text{x}\ 8.9\text{x}10^{-12}\ \text{x}\ 12 = 214\ \text{x}10^{-20}$

The measured 40 pF at +3 V corresponds to oxide only, therefore

$$t_{ox} = \varepsilon_0\varepsilon_{ox}\frac{A}{C_{ox}} = \frac{89\times10^{-20}}{40\times10^{-12}} = 2.23\times10^{-9}\ \text{m}$$

For the two capacitors in series is the 15 pF measured at -3 V

$$\frac{1}{C_{total}} = \frac{1}{C_{ox}} + \frac{1}{C_s}$$

$$\therefore \quad \frac{1}{15 \times 10^{-12}} = \frac{1}{40 \times 10^{-12}} + \frac{1}{C_s}$$

Therefore, C_s = 24 pF, and

$$w = \varepsilon_0 \varepsilon_s \frac{A}{C_s} = \frac{214 \times 10^{-20}}{24 \times 10^{-12}} = 8.9 \times 10^{-8} \text{ m}$$

In the depleted region, Poisson's equation gives

$$\varepsilon_0 \varepsilon_s \frac{d^2 V}{dx^2} = qN$$
$$\therefore V = \frac{1}{2} qN \frac{w^2}{\varepsilon_0 \varepsilon_s}$$

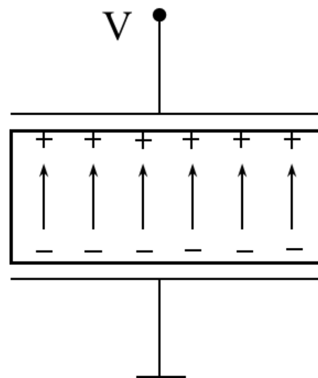
If the band gap of silicon is ~1 V, take the band bending to be a maximum of ~0.8 V, then

$$N = \frac{2\,\varepsilon_0 \varepsilon_s V}{q w^2} = \frac{2 \times 8.9 \times 10^{-12} \times 12 \times 0.8}{1.6 \times 10^{-19} \times (8.9 \times 10^{-8})^2} = 1.2 \times 10^{23} \text{ m}^{-3}$$

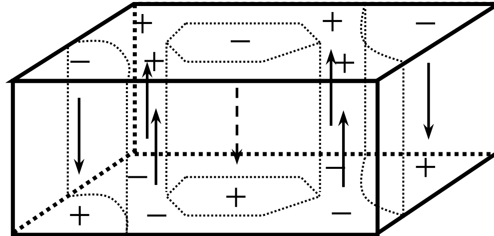
[40%]

Q3

(a) (i) The polarization of a ferroelectric material is the spontaneous alignment of the electronic dipoles, which can be switched by applying a sufficiently strong external electric field.



A macroscopic sample of ferroelectric thin film is typically not uniformly polarized but breaks up into domains of opposite polarizations, which corresponds to a lower energy state. The application of a sufficiently strong external field aligns the domains. [10%]

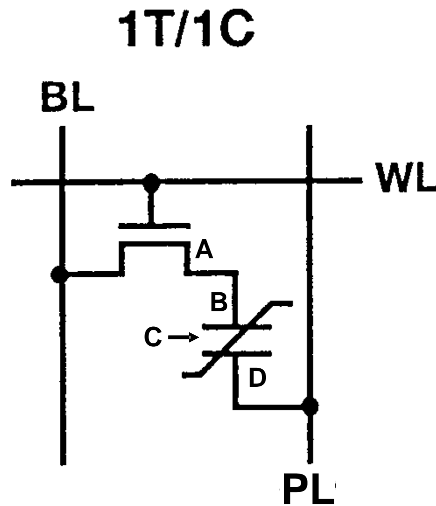


(ii) A ferroelectric non-volatile memory cell can be constructed by putting a thin film ferroelectric material under the gate electrode of a field effect transistor (FET), in place of the normal gate dielectric materials.

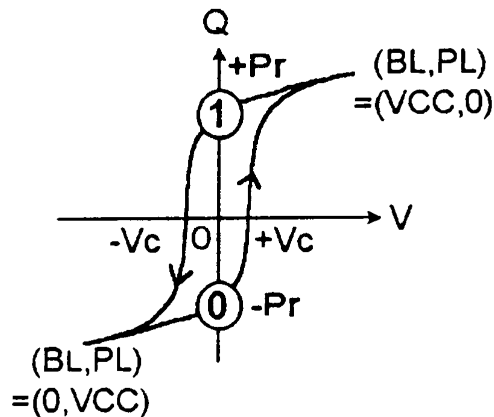
Such an FET-like ferroelectric non-volatile memory device can be operated with the readout via
the charge approach: $\Delta Q = A\ \Delta P$, or
the field approach: $E \sim P$ [20%]

(b) (i) In Fig.2,
A is an n-type doped region in the p-type silicon substrate forms the source or drain region of the access transistor and forms one electrode of the ferroelectric storage capacitor;
B is a diffusion barrier such a Pt/Ti to avoid the possibility of interaction between the silicon and the ferroelectrics;
C is the ferroelectric layer;
D is the top electrode of the capacitor;
E is an insulator which also provides a hermetic seal. [15%]

(ii) Circuit diagram of a 1T/1C ferroelectric memory cell:



With reference to the illustrate 1T/1C cell, a WRITE operation is performed by set WL to High and
set BL to Vcc and PL to 0, for State “1” (positively polarized), or
set BL to 0 and PL to Vcc, for State “0” (negatively polarized). [15%]



(c) (i) From Fig. 4,

Remnant polarisation: Pr = 23 μC cm^{-2}

Coercive field: Ec = 150 kV cm^{-1} [10%]

(ii) The corresponding electric field for +5V is
+500 kV cm^{-2} (= +5V / 100nm).

Resulting charge is:
$\Delta Q = \Delta P$*Area = (0.25μm*0.25μm) $\Delta P = 6.25\text{x}10^{-10}$ cm^2 * ΔP

For the intitial State "1" (positively polarised) with +5V applied,
$\Delta Q_{\text{"1"}} = 6.25\text{x}10^{-10}$ cm^2 * $\Delta P_{\text{"1"}} = 6.25\text{x}10^{-10}$ cm^2 * (38-23) μC cm^{-2}
= $9.4\text{x}10^{-15}$ C = 9.4 fC

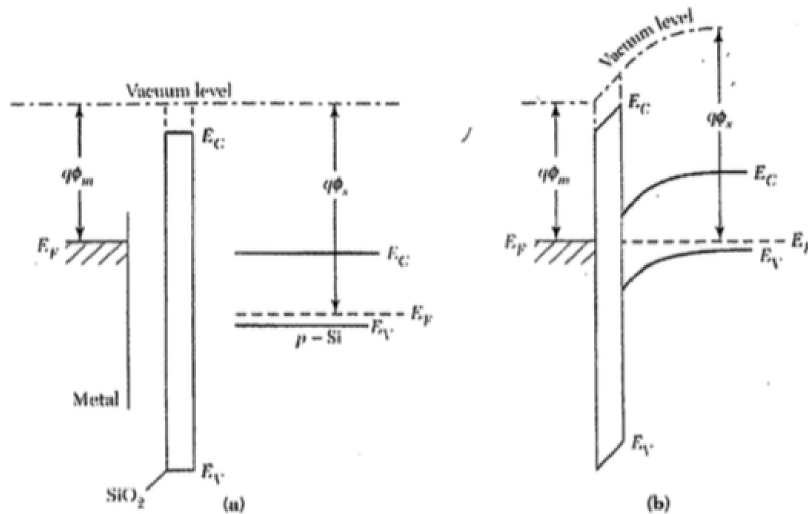
$\Delta Q_{\text{"1"}} = 6.25\text{x}10^{-10}$ cm^2 * $\Delta P_{\text{"1"}} = 6.25\text{x}10^{-10}$ cm^2 * (38+23) μC cm^{-2}
= $38\text{x}10^{-15}$ C = 38 fC

For the initial State "0" (negatively polarised) with +5V applied,
$\Delta Q_{\text{"0"}} = 6.25\text{x}10^{-10}$ cm^2 * $\Delta P_{\text{"0"}} = 6.25\text{x}10^{-10}$ cm^2 * (38+23) μC cm^{-2}
= $38\text{x}10^{-15}$ C = 38 fC [20%]

(iii) Energy consumed due to switching of polarisation from negative to positive direction can be approximated in the order of:
ΔE ~ 2*Pr*Ec*Volume = 2*Pr*Ec*Area*Thickness
= 2*23 μC cm^{-2} * 150 kV cm^{-1}
* $6.25\text{x}10^{-10}$ cm^2 * $100\text{x}10^{-7}$ cm
= $4\text{x}10^{-14}$ J = 40 fJ [10%]

Q4

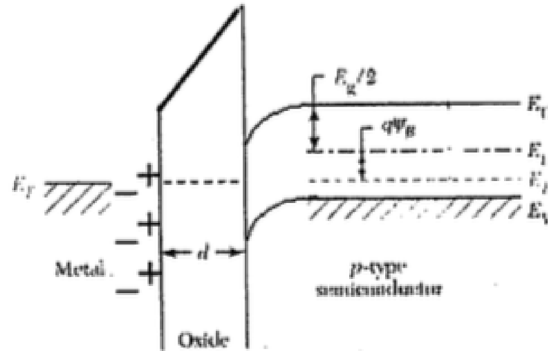
(a)



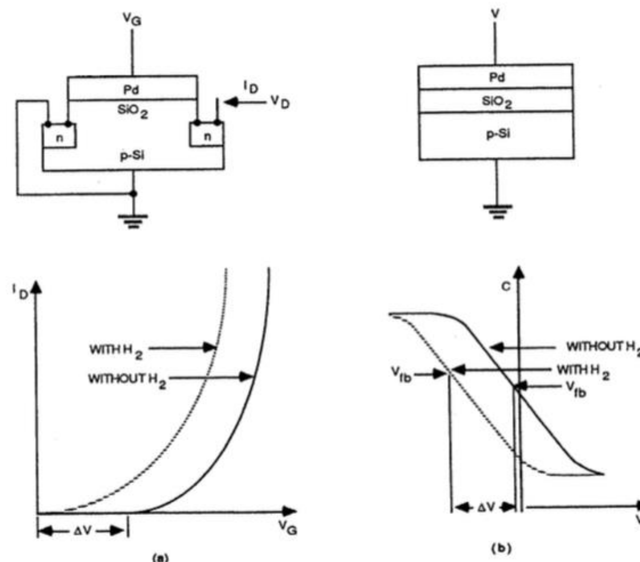
The flat band voltage $V_{FB} = \phi_m - \phi_s$

H_2 is adsorbed at the interface and generate positive charge. A dipole layer is formed, ψ_{int}.

Now the flat band voltage has changed to: $V_{FB} = \phi_m - \phi_s - \psi_{int}$



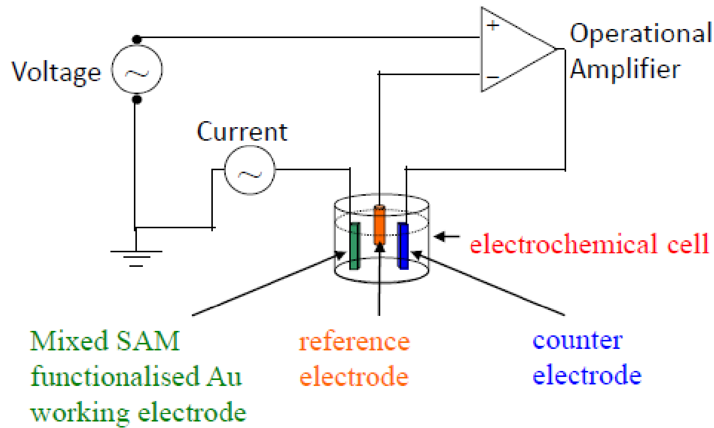
Therefore I-V curve of a p-type MOSFET shifts negatively; the Capacitance vs Voltage curve of a MOS structure also shifts negatively.



Schematic diagrams of hydrogen-sensitive MOS structures (a) a Pd MOS transistor and its $I_D(V_G)$ curve (b) a Pd MOS capacitor and its C-V curve

Other gases which can be detected by this principle include H_2S, NH_3 and CO. [30%]

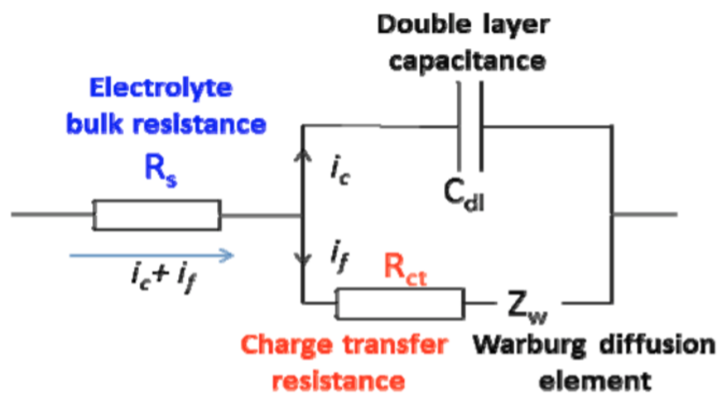
(b) A standard three-electrode cell:



[10%]

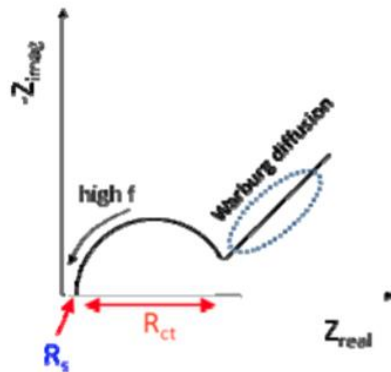
(c)

(i) In general, an electrochemical cell can be considered simply an impedance to a small sinusoidal excitation, hence it is able to represent the system's performance by an equivalent circuit that pass current with the same amplitude and phase angle that the real cell does under a given excitation. A frequently used circuit is called the *Randles equivalent circuit*, is shown below. The parallel elements are introduced because the total current through the working interface is the sum of distinct contributions from the faradaic process, i_f, and double-layer charging, i_c. The faradaic impedance is a series combination of the charge transfer resistance, R_{ct}, and the Warburg diffusion element. The charge transfer resistance represents the resistance for the redox molecules in buffer to exchange electrons with the metal electrode. The Warburg diffusion element represents a resistance to mass transfer/diffusion. The Warburg impedance depends on the frequency of the potential perturbation.



[20%]

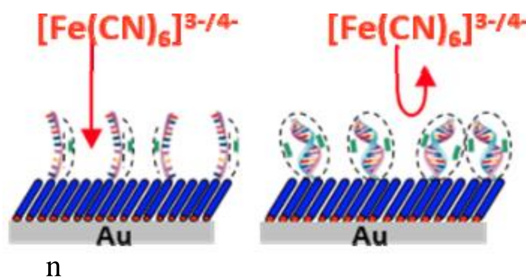
(ii) At high frequencies, it is small since diffusing reactants (redox molecules in buffer) do not need to move very far. At low frequencies, the reactants have to diffuse further, increasing the Warburg-impedance. It is a constant phase element and appears as a diagonal line with a slop of 45^0 on the Nyquist plot. R_S is the solution resistance between the reference electrode and the working electrode. It depends on the ionic concentration, type of ions, temperature and the geometry of the area in which current is carried. The Nyquist diagram of the system is plotted below.



[20%]

(iii)DNA biosensors with EIS measurement is based upon detection of the intrinsic negative charge of the target DNA. Hybridization with the immobilized probe single-stranded DNA causes an increased in the electrostastic barrier for the negatively charged redox molecules Ferricyanide $[Fe(CN)_6]^{3-}$ and Ferrocyanide $[Fe(CN)_6]^{4-}$ to exchange electrons with the Au electrode, resulting in an increase in charge transfer resistance R_{ct}.

Before Hybridisation *After Hybridisation*



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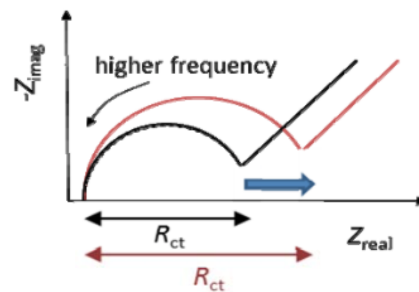

[20%]