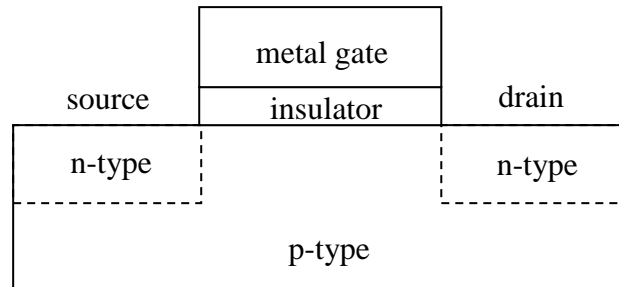


Q1

- (a) Sketch of the cross-section of an FET based MIS structure



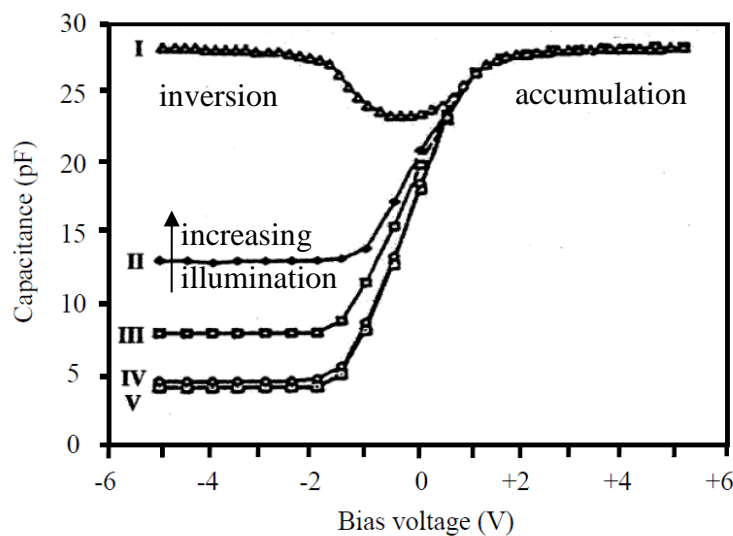
Transistor operation is achieved by applying positive voltage to the gate to invert the channel above threshold and switch on conduction of electrons from the source to the drain.

The switch is fast when the source-drain separation is made as small as the fabrication technology allows.

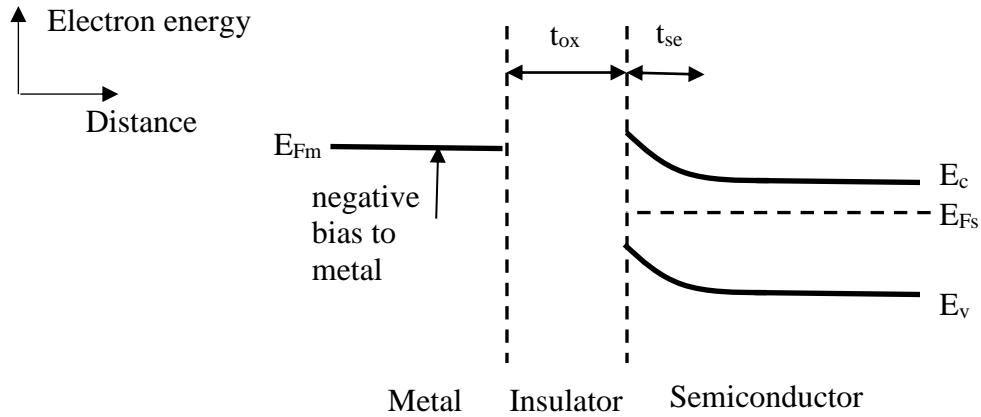
[30%]

- (b) To take the data a small ac signal, e.g. 0.5 V peak-to-peak, is applied on top of a dc bias which is varied from -5 to +5 V in this case. The size of the ac determines the minimum voltage range of the C-V curve structure that can be resolved reliably, i.e. independent of the size itself. In this case, small would be ≤ 0.1 V.

The semiconductor is n-type because applying a negative bias voltage results in inversion with holes at the surface of the semiconductor.



When the semiconductor is inverted the semiconductor is depleted to a depth t_{se} and the effective capacitor plate separation is $t_{ox} + t_{se}$ for high frequency ac measurements.



However light absorbed in the depletion region produces electron-hole pairs which separate in the electric field and produce an inversion charge which stays near to the equilibrium charge at each point in the applied ac cycles.

Hence the capacitor plates are effectively separated by t_{ox} , the capacitance is large under illumination compared with in the dark.

Using a reduced ac frequency in moderate light would also result in an increase capacitance being measured.

[30%]

(c) In accumulation region

$$C_{ox} = \epsilon_0 \epsilon_{ox} \frac{A}{t_{ox}}$$

$$t_{ox} = \epsilon_0 \epsilon_{ox} \frac{A}{C_{ox}} = \frac{8.9 \times 10^{-12} \times 5 \times 2 \times 10^{-8}}{28 \times 10^{-12}} = 3.2 \times 10^{-8} \text{ m}$$

In inversion region

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

$$\frac{1}{4 \times 10^{-12}} = \frac{1}{28 \times 10^{-12}} + \frac{1}{C_{se}}$$

$$\therefore C_{se} = 4.7 \text{ pF}$$

As above

$$C_{se} = \epsilon_0 \epsilon_{se} \frac{A}{t_{se}}$$

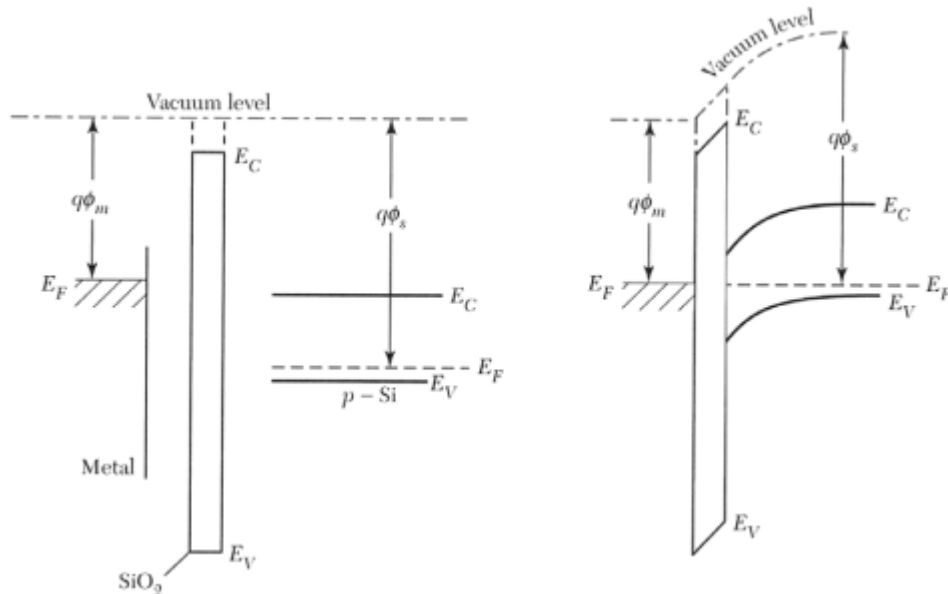
$$t_{se} = \epsilon_0 \epsilon_{se} \frac{A}{C_{se}} = \frac{8.9 \times 10^{-12} \times 10 \times 2 \times 10^{-8}}{4.7 \times 10^{-12}} = 3.8 \times 10^{-7} \text{ m}$$

With short pulse dc measurement, the deep depletion regions can be probed.

[40%]

Q2

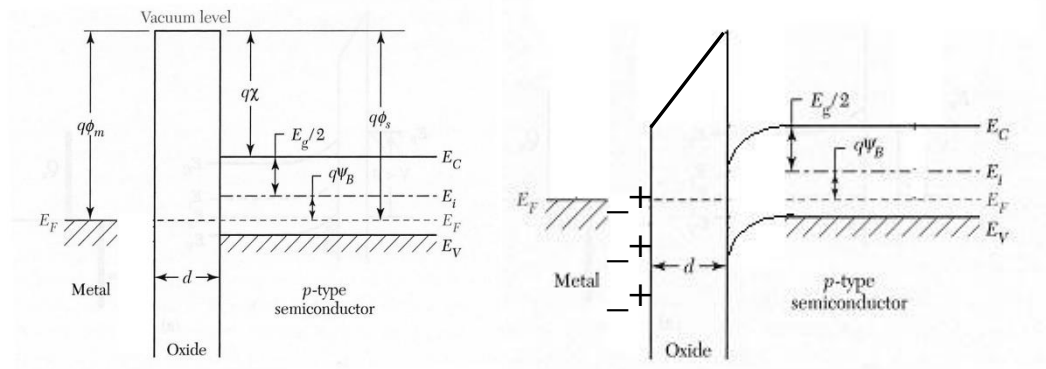
- (a) (left) The energy band diagram of an isolated metal of a work function ϕ_m and an isolated semiconductor of a work function ϕ_s with an oxide layer between them; (right) the energy band diagram of an MOS diode in thermal equilibrium.



The result is a flat band shift, $\Delta V_{FB} = \phi_m - \phi_s$, in the MOFET.

[20%]

- (b) When H_2 is adsorbed at the interface and generate “+” charges, a dipole layer is formed to create an interface potential Ψ_{int} .

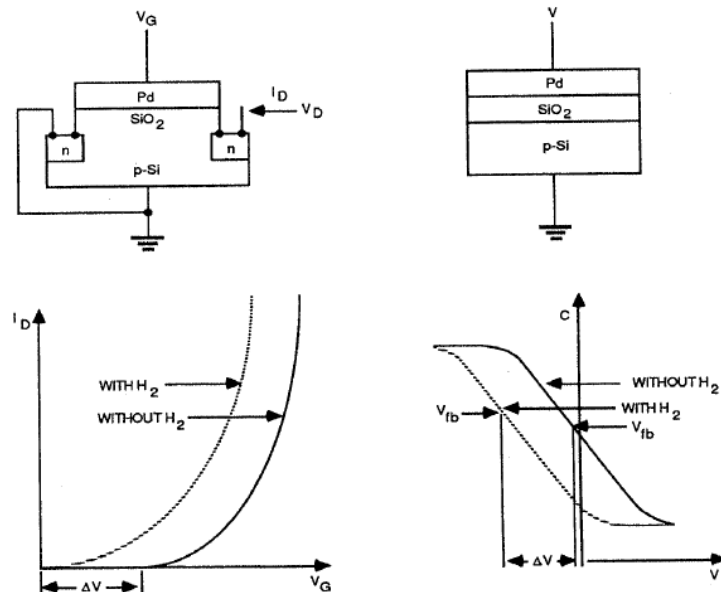


The flat band voltage is:

$$V_{FB} = -\Psi_{int} \quad \text{if } \phi_m = \phi_s$$

$$V_{FB} = (\phi_m - \phi_s) - \Psi_{int} \quad \text{if } \phi_m \neq \phi_s$$

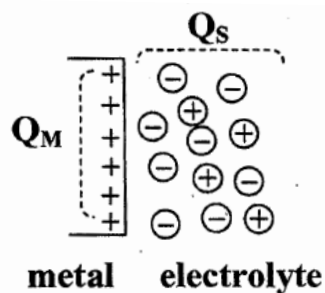
Schematic diagrams of (left) a hydrogen-sensitive MOS transistor and its I_D - V_G curve and (right) a hydrogen-sensitive MOS capacitor and its C - V curve.



Other gases which can be detected by this principle include H_2S , NH_3 , CO , etc.

[20%]

- (c) (i) When a metal is in contact with an electrolyte, a surface charge Q_M arises on the metal, due to excess or defect (in the case of the following figure) of electrons. This charge can be due to chemical reactions or simply to the differences in electron affinity. The metal charge must be balanced by an ionic charge Q_S of opposite sign in the electrolyte. The latter is not in general confined on the surface, but is distributed across a certain distance from the interface. Therefore there will be a potential drop across such a distance. This system Q_M - Q_S is referred to as Electrochemical Double Layer and the potential drop as the Double Layer Potential.



charge neutrality requires:

$$Q_M = -Q_S$$

[10%]

- (ii) A double layer exists also at an insulator/electrolyte interface. In this case the charge on the insulator is not due to mobile electrons, but to fixed charge resulting from ionic exchange with the electrolyte. One case of great practical importance is the protonation-deprotonation of the surface of Si_3N_4 , which is the basis for the operation of ion-sensitive field effect transistors (ISFETs).

[10%]

- (d) (i) Since the charge is affected by chemical reactions at the interface, modification of the surface with suitable receptors enables detection of chemical/biological reactions through a change in the double layer potential. An example of this is the detection of DNA hybridization. DNA carries a negative charge in a pH neutral solution, due to the de-protonation of the phosphate backbone. When a strand of DNA, immobilized on a gold surface is exposed to its complementary, the negative charge on the metal increases affecting the double layer potential and the event can be detected.

[10%]

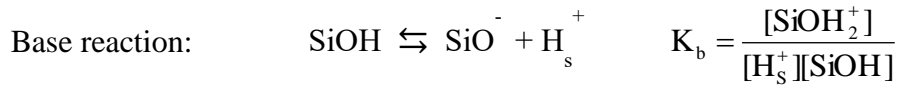
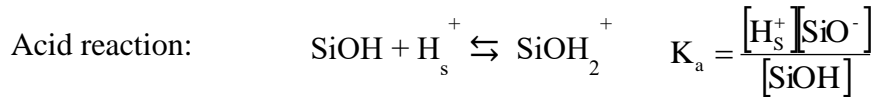
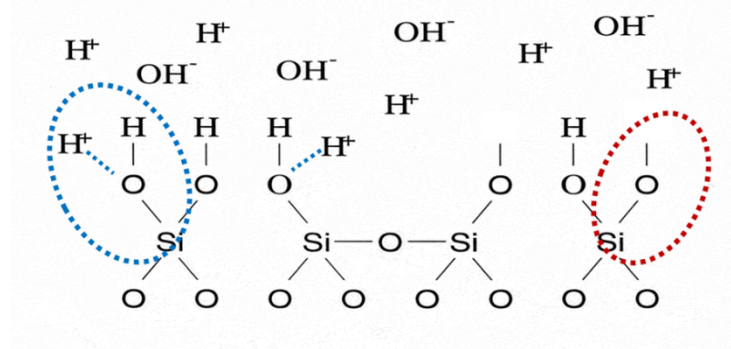
- (ii) For a pH sensor, the interface potential is replaced by a double layer potential Ψ_L and the flat band voltage becomes:

$$V_{FB} = (\phi_m - \phi_s) - \Psi_L$$

$$\Psi_L = \frac{Q_{int}}{C_{dl}}$$

where $\Psi_L = Q_{\text{int}} / C_{\text{dl}}$ and Q_{int} is the charge at the insulator interface and C_{dl} the capacitance of the electrochemical double layer.

Q_{int} is due to surface adsorption / desorption for SiO_2 . In the case of acidic / basic reaction at the interface, they are:



Thus:

$$\frac{K_a}{K_b} = \frac{[\text{H}_s^+]^2 [\text{SiO}^-]}{[\text{SiOH}_2^+]} \quad \therefore [\text{H}_s^+] = \sqrt{\frac{K_a [\text{SiOH}_2^+]}{K_b [\text{SiO}^-]}}$$

$[\text{H}_s^+]$ is the concentration of H^+ at the interface;

$[\text{SiO}^-]$ is the concentration of SiO^- at the interface;

$[\text{SiOH}_2^+]$ is the concentration of SiOH_2^+ at the interface.

pH value is defined as: $\text{pH} = -\log_{10} ([\text{H}_b^+])$
and $\text{pH}_{\text{PZC}} = -\log_{10} (K_a / K_b)^{1/2}$

$[\text{H}_b^+]$ is the concentration of H^+ in the solution bulk.

Boltzmann relationship gives: $[\text{H}_s^+] = [\text{H}_b^+] \exp (-q \Psi_L / k_B T)$

$$\begin{aligned}
 -\ln [H^+] + \ln \left(\frac{K_a}{K_b} \right)^{\frac{1}{2}} &= -\frac{q\psi_L}{kT} + \ln \left(\frac{[SiO^-]}{[SiOH^+]_2} \right)^{\frac{1}{2}} \\
 -\ln [H^+] + \ln \left(\frac{K_a}{K_b} \right)^{\frac{1}{2}} &\approx -\frac{q\psi_L}{kT} \quad \underbrace{\ln \left(\frac{[SiO^-]}{[SiOH^+]_2} \right)^{\frac{1}{2}}}_{\text{negligible}}
 \end{aligned}$$

which leads to:

$$\begin{aligned}
 \psi_L &= 2.303 \frac{kT}{q} (\text{pH}_{\text{pzc}} - \text{pH}) \\
 \Delta\psi_L &= 59\text{mV}/(\text{pH unit}) \quad \text{at } 300^\circ\text{K} \quad [30\%]
 \end{aligned}$$

Q3

- (a) Ferroelectric material is a kind of material which exhibits spontaneous polarization.

The polarization consists of electrical dipoles which originate from asymmetric spatial separation of the positive and negative ionic charges in atomic unit cells.

Polarization domain is a volume within which the polarization of each unit cell is in the same direction.

[10%]

- (b) Ferroelectric material can be incorporated into a FET to replace or as part of its gate dielectric material to form a ferroelectric-FET (F-FET).

The difference of the surface charge induced at the interface between the ferroelectric material and the semiconductor channel material for the opposite polarization directions will create a shift in the FET's threshold voltage.

Such a shift is non-volatile as it depends only on the direction of which the ferroelectric material is polarized, and it can be used to represent a bit of information (for example, the status of a F-FET at a given gate voltage can be changed between ON and OFF according to the switch of polarization direction).

[20%]

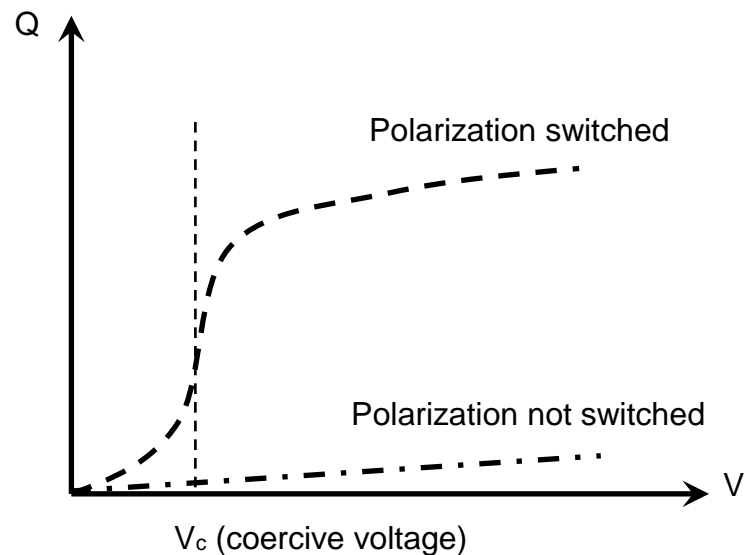
- (c) WRITE and READ operation in a 1T/1C FRAM cell:

WRITE: Set WL to High to switch the transistor to ON state;
 Set BL to High and CP to Low to write '1'.

(or Set BL to Low and CP to High to write '0'.)

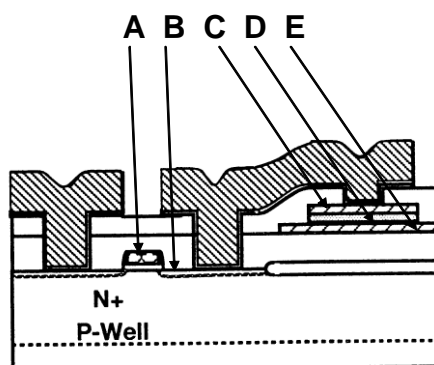
READ: Set WL to High;
Set BL to a fixed state (either High or Low);
Sense the amount of charge flowing out CP
(for example: when BL is set to a fixed High,
The high or low amount of charge being sensed will
indicate the stored information is of '0' or '1' state);
Write back the information if it has been altered.

Sketch of the sensed charge versus applied voltage curve for the READ operation

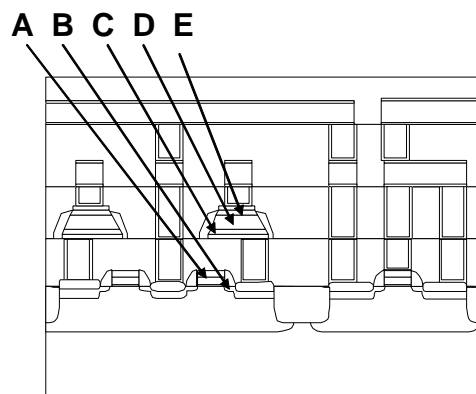


[40%]

(d) The parts of A, B, C, D and E:



Planar structure



Stacked structure

- A: Gate of FET; conductive material/metal (Cu, Al, etc)
- B: Drain of FET; doped semiconductor material (p- or n-type Si);
- C: Electrode of ferroelectric capacitor; conductive material/metal (Pt, Ir, etc);
- D: Ferroelectric material; ferroelectrics – insulating type (PZT, SBT, etc);
- E: Electrode of ferroelectric capacitor; conductive material/metal (Pt, Ir, etc).

The main advantage of a stacked structure over a planar structure is that each cell (1T/1C) of a stacked structure occupies a smaller area than that of a planar structure, hence, it is suitable for high density integration. The main disadvantage is that there are more layers/masks used in the case of a stacked structure, resulting in a more complicated fabrication process and hence higher cost.

[30%]

Q4

- (a) GMR effect is the phenomena that the magneto-resistance of a system can normally vary more than 50% in an external magnetic field. It is the result of a significant increase of spin-related scattering of the injected electronics, if their spin direction is anti-parallel rather than parallel to that of the electrons in the system.

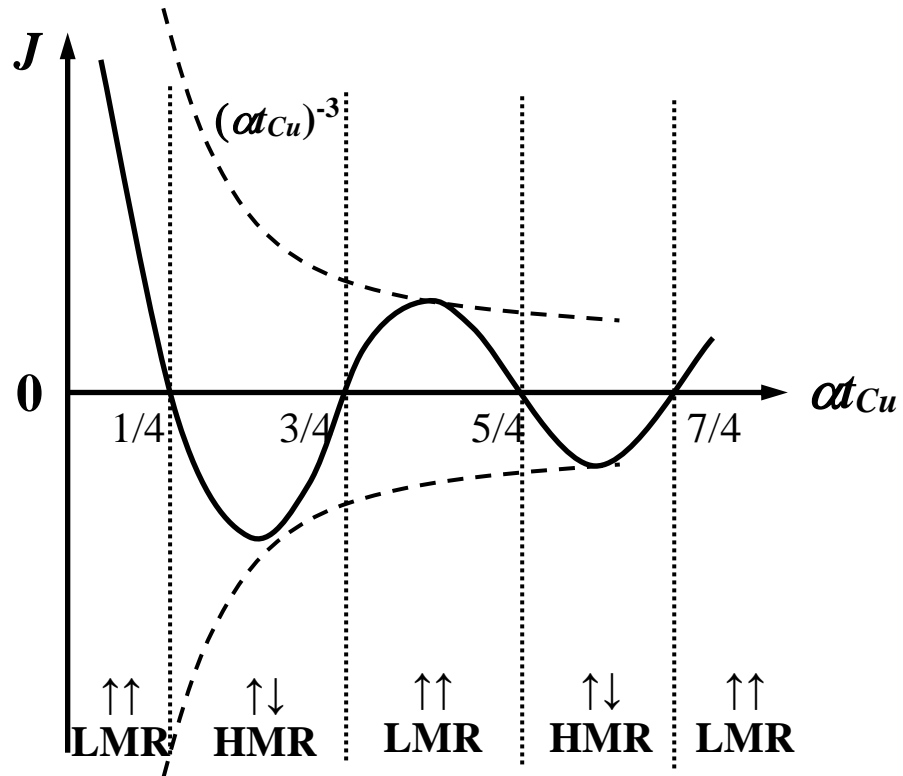
A GMR unit consists of three basic elements: two metallic FM layers and a non-magnetic layer sandwiched in between. In a metallic FM layer, majority of the spins of the conduction electrons is aligned in the same direction of its magnetisation. As the electrons flow from one FM layer to the other one, they experience different degrees of scattering, depending on the configuration of magnetisation. Such a spin-related scattering, hence the resistance, is maximum/minimum when the directions of magnetisation are parallel/anti-parallel in the two FM layers. The non-magnetic layer, known as spacer, is to modulate the couple of magnetic moments between the two FM layers and it is often used to ensure the initial magnetisation in the FM layers is anti-parallel, hence the high resistance state at the absence of an external magnetic field.

[20%]

- (b) Since the free energy $E = -J \vec{M}_{Co,1} \cdot \vec{M}_{Co,2}$ and the RKKY coupling is $J \sim \cos(2\pi at_{Cu}) / (2\pi at_{Cu})^3$.

The in-plane magnetisations in the two Co layers, $\vec{M}_{Co,1}$ and $\vec{M}_{Co,2}$ are in parallel and anti-parallel directions when $J > 0$ and $J < 0$, respectively.

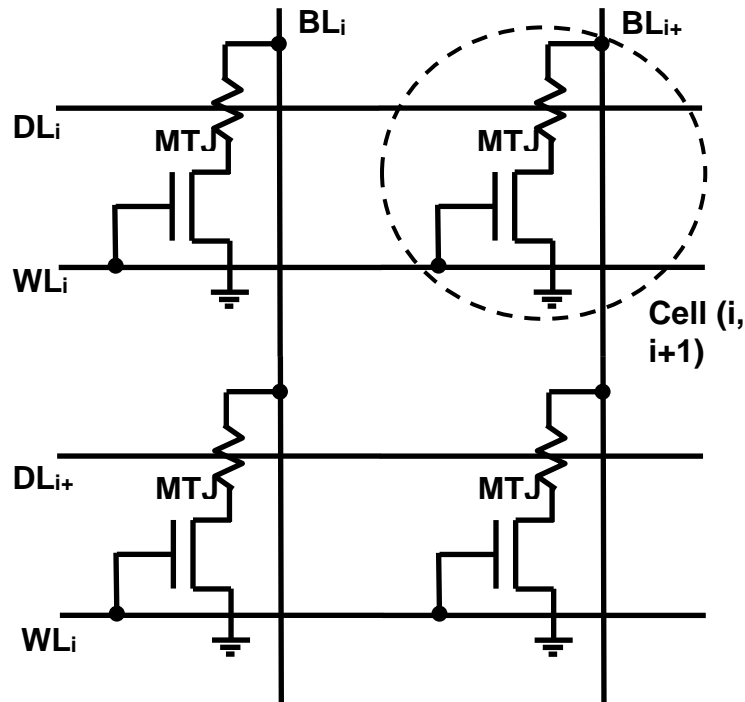
The zero field magneto-resistance in the CPP configuration is low LMR (high HMR) when the magnetisations are parallel (anti-parallel).



[30%]

(d) (i) Memory matrix as shown here:

BL / DL / WL ↔ Bit Line / Digit Line / Word Line



[25%]

(ii) Assume the position of the chosen cell is (i, i+1) as shown in the above sketch:

Write: Supply suitable current in DL_i and BL_{i+1}, so that each of them separately can only half-switch (tilt) the magnetisation of the free layer of the MTJ in the chosen cell but the combined magnetic field will be able to switch it to the desired parallel or anti-parallel configuration, which represents the bit of information to be stored there.

Read: Set WL_i to High and all the rest WLs to Low;
Set BL_{i+1} to High and all the rest BLs to Low;
Sense the current level on BL_{i+1} to find out that Cell (i, i+1) is in a high/low magneto-resistance state, in order to determine the stored bit of information.

(NB: the Read operation is non-destructive.)

[25%]

Assessor's comment:

Q1 MIS capacitor

Least popular question taken by only 8 candidates. Majority of them did well, showing a good understanding of the principles.

Q2 Bio-/Chemical sensors

A question answered reasonably well by the candidates. No problem in describing the underlying principles, but there is a difference on covering different aspects of a specific process.

Q3 FRAM

Joint most popular question, taken by everyone. Straightforward calculations. Many of the candidates did very well, but some did not mention how the sensing of switch charges is done.

Q4 GMR/MRAM

The other joint most popular question. It appears not easy to cover all the points to get a perfect answer, such as mentioning not only three elements in a GMR device but also their detailed functions.