2008 IIB 4B6 SOLID STATE DEVICES AND CHEMICAL\BIOLOGICAL SENSORS

PROF P. MIGLIORATO

4b6 Crib 2008

Q1

a) If we apply a positive (negative) voltage step to a p-type (n-type) MOS capacitor, which is sufficient to generate an inversion larger at equilibrium, there is a time interval, after the step, when no free electrons (holes) are present at the interface. This is due to the fact that the inversion charge must be thermally generated and this requires a finite time. 20%

During such a time interval, the MOS is said to be in 'deep depletion' and the only charge present in the semiconductor is the depletion charge.

b) $V_G = V_i + \psi_s$

$$V_i = \frac{Q_B}{\epsilon_i} d$$ 30%

$$Q_B = - [2\, \epsilon_s\, q\, N_A\, \psi_s]^{1/2}$$

$$V_G = \frac{[2\epsilon_s\, q\, N_A\, \psi_s]^{1/2} d}{\epsilon_i} + \psi_s = 5.06\text{V}$$

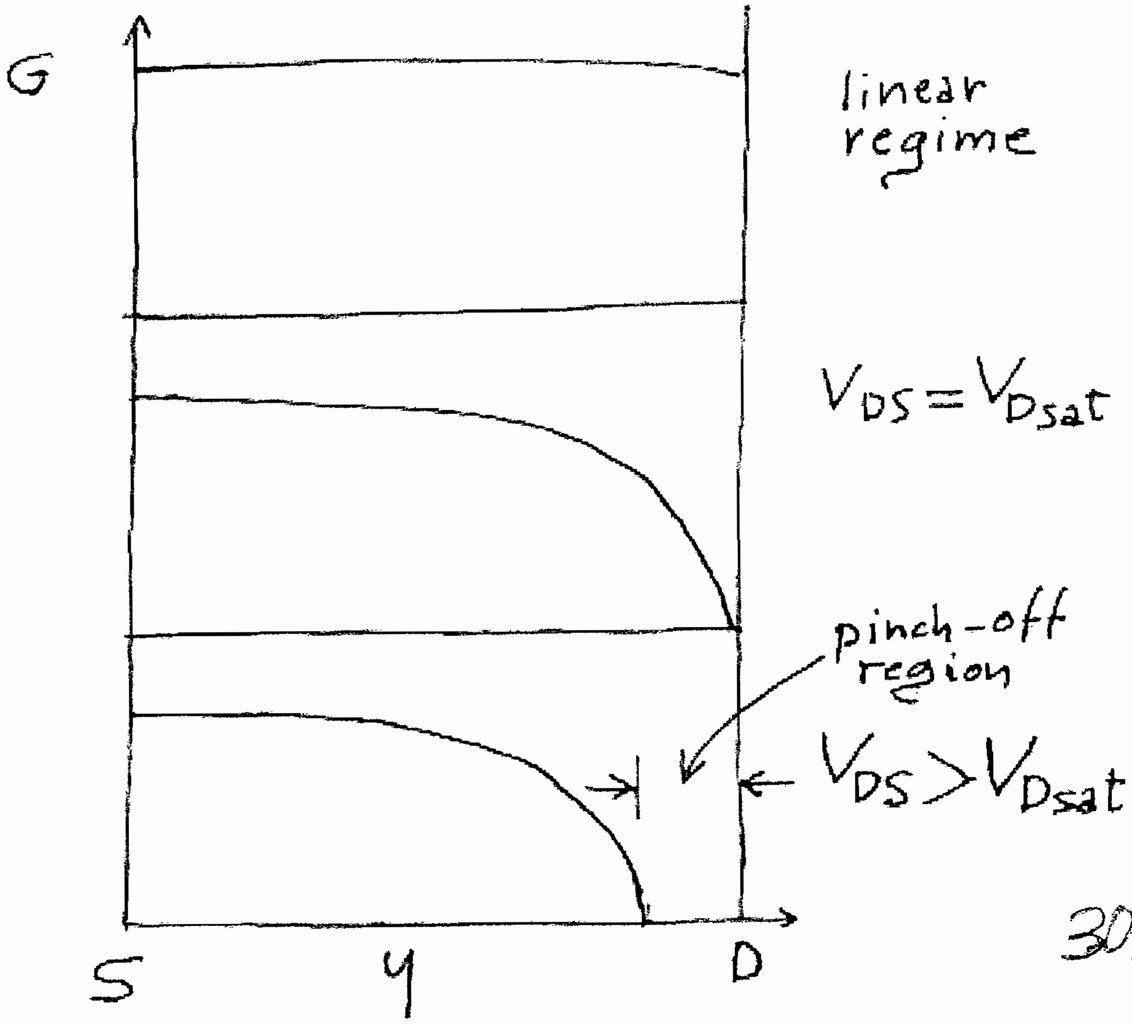
c)

When the output current I_D, for a given V_{GS}, becomes constant with V_{DS}, the MOSFET is said to be in ***saturation***.

The saturation regime begins when the conductance G (bottom figure) is approximately zero at the drain (y=L), that is when

$$V_{DS} = V_{GS} - V_T = V_{Dsat}$$

where V_T is the threshold voltage. Further increase of V_{DS} will result in a wider region where $G \approx 0$



30%

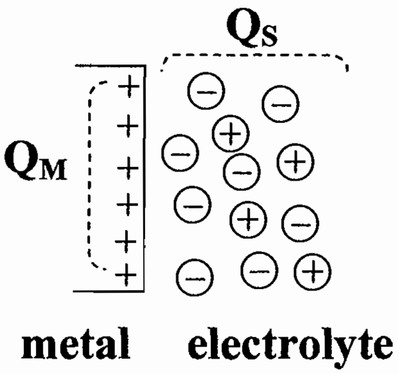
d) The region where $G \approx 0$ is called ***pinch-off region*** and its left hand boundary is the ***pinch-off point***. At the pinch-off point $V_C = V_{Dsat}$.

It should be pointed out that in the pinch-off region the conductance is small but not exactly zero. The current flow is sustained by the high electric field

20%

Q2

a)



50%

As indicated in the figure, when a metal is in contact with an electrolyte, a surface charge Q_M arises on the metal, due to excess or defect (this is the case of the 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 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. The system Q_M-Q_S is referred to as Electrochemical Double Layer and the potential drop as the Double Layer Potential.

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 strands 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.

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 ISFETs.

b) Assumptions:

- The solution is modeled as point ions embedded in a dielectric continuum representing the solvent;

20%

- The metal electrode is considered as a perfect conductor;

- The distribution of the ions near the interface is calculated from electrostatics and statistical mechanics.

- To be specific we consider a planar electrode in contact with a
- solution of a z - z electrolyte (i.e., cations of charge number +z and anions of charge number -z).

4B6-2008 Crib Q3

(a) (i) Remnant polarisation: $P_r \sim 25\ \mu C\ cm^{-2}$ [10%]

(ii) Coercive field: $E_c \sim 80\ kV\ cm^{-1}$ [10%]

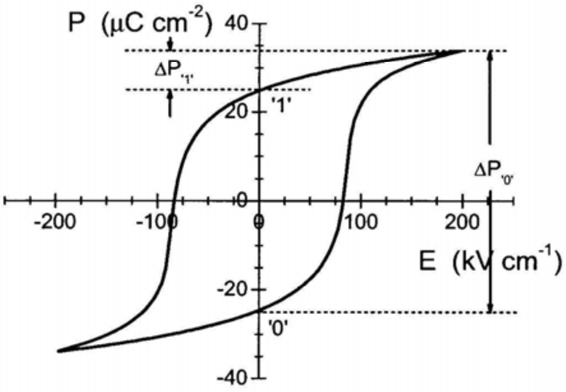
(iii) Energy density consumed in a full switching cycle: [10%]

$$E \sim 2Pr*2Ec \sim 2\ J\ cm^{-3} = 2x10^{6}\ J\ m^{-3}$$

(b) (i) $\Delta Q = \Delta P*\text{Area} = (0.18\mu m*0.18\mu m)\ \Delta P = 3.24x10^{-10}\ cm^2 * \Delta P$ [15%]

$$\Delta Q_{'1'} = 3.24x10^{-10}\ cm^2 * \Delta P_{'1'} = 3.24x10^{-10}\ cm^2 * (34-25)\ \mu C\ cm^{-2} = 2.9x10^{-15}\ C = 2.9\ fC$$

$$\Delta Q_{'0'} = 3.24x10^{-10}\ cm^2 * \Delta P_{'0'} = 3.24x10^{-10}\ cm^2 * (34+25)\ \mu C\ cm^{-2} = 19x10^{-15}\ C = 19\ fC$$



(ii) $V_{sense} = \Delta Q / C_{sense}$ [15%]

$$V_{sense,'1'} = \Delta Q_{'1'} / C_{sense} = 2.9\ fC / 2\ pF = 1.5\ mV$$

$$V_{sense,'0'} = \Delta Q_{'0'} / C_{sense} = 19\ fC / 2\ pF = 9.5\ mV$$

(iii) $\min(\text{Area}) = \min(V_{sense})*C_{sense} / \max(\Delta P) = 1mV*2pF/[(34+25)\mu C\ cm^{-2}]$ [20%]

$$= 2x10^{-15}/59x10^{-6}\ cm^2$$

$$= 3.38x10^{-11}\ cm^2 = 3.38x10^{-3}\ \mu m^2$$

$$= 58nm\ x\ 58\ nm$$

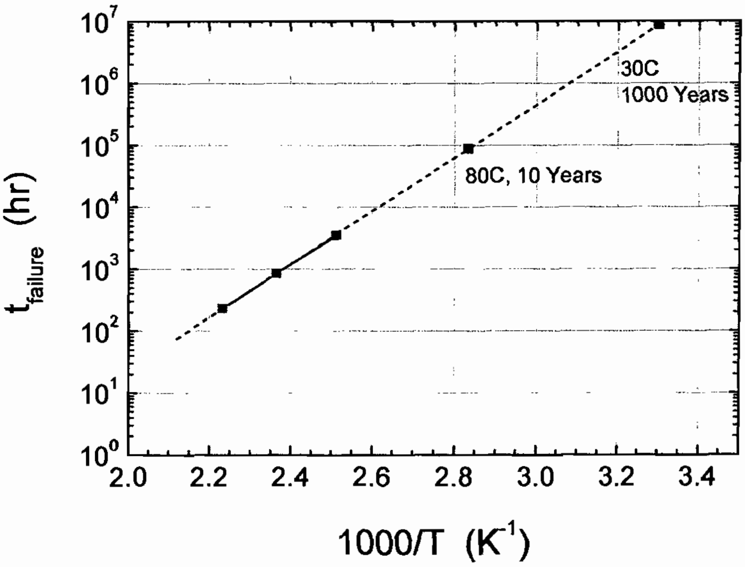
Answer for Question 3 on FRAM: (continued)

(c) 80°C → 1000/T = 1000/(80+273) = 2.83 (K^{-1}) [20%]

30°C → 1000/T = 1000/(30+273) = 3.30 (K^{-1})

$9x10^4$ hrs = $9x10^4/(24*365)$ yrs = 10.27 yrs ~ 10 yrs

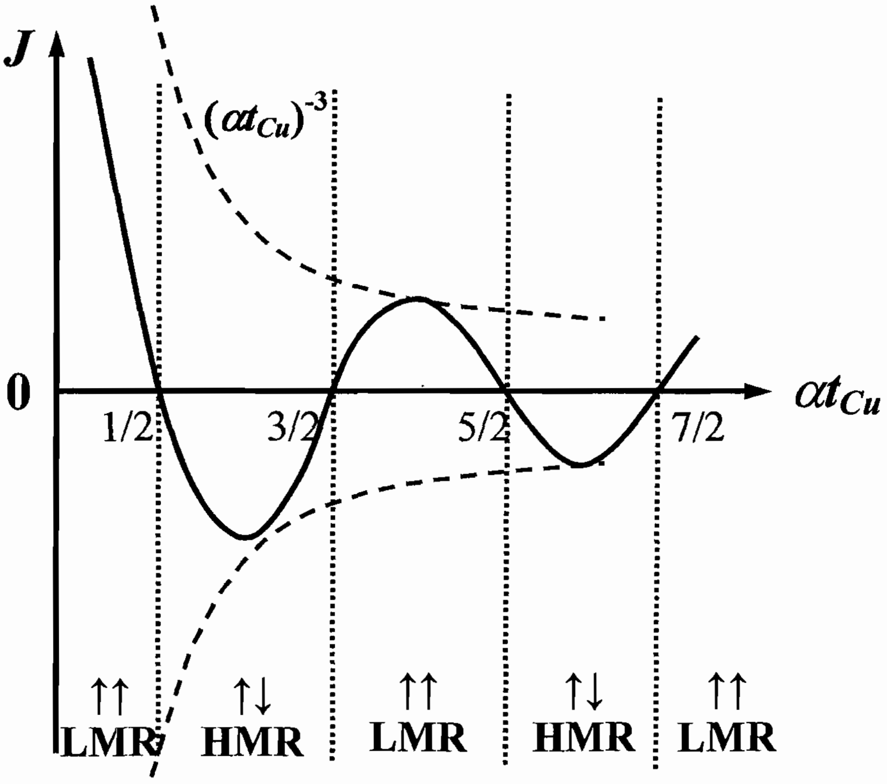
$9x10^6$ hrs = $9x10^6/(24*365)$ yrs = 1027 yrs ~ 1,000 yrs



Answer for Question 4 on MRAM:

(a) Since the free energy $E = -J\overrightarrow{M}_{Co,1} \cdot \overrightarrow{M}_{Co,2}$ and $J \sim \cos(2\pi\alpha t_{Cu})/(2\pi\alpha t_{Cu})^3$, [50%]

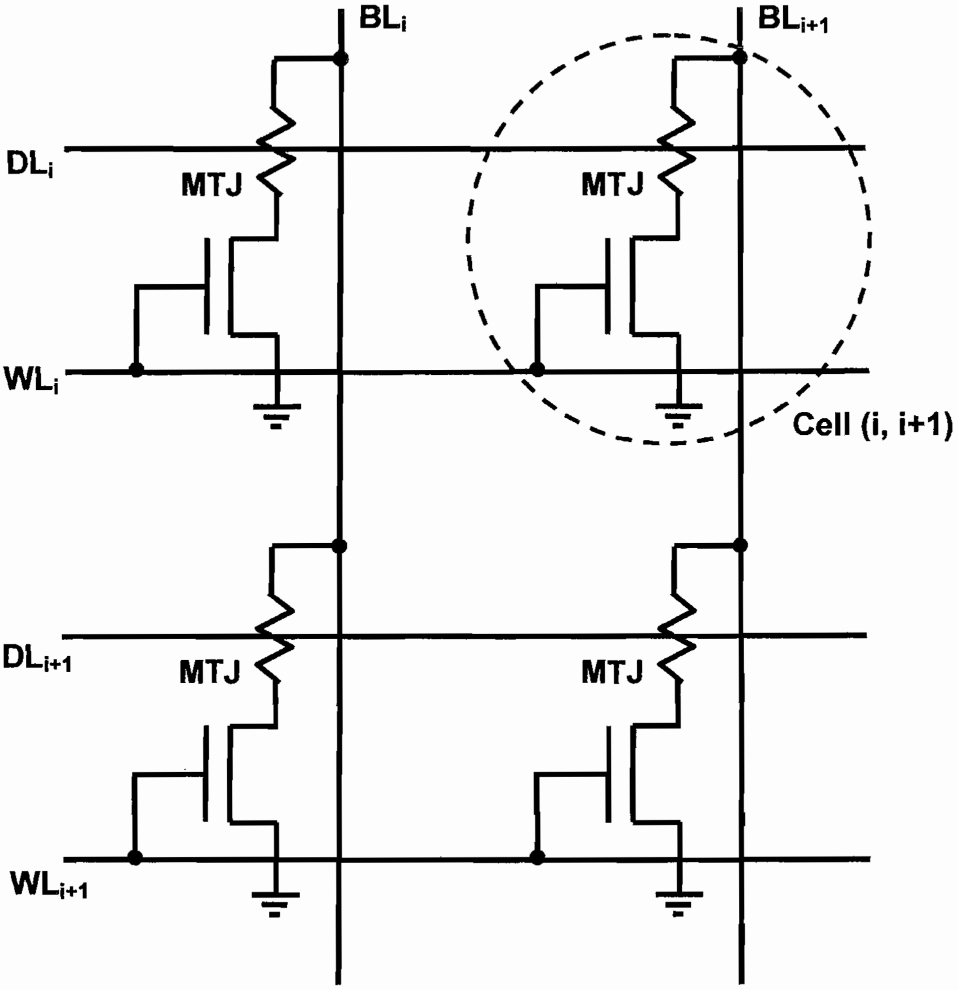
the in-plane magnetisations in the two Co layers, $\overrightarrow{M}_{Co,1}$ and , $\overrightarrow{M}_{Co,2}$ are in parallel and anti-parallel directions when $J > 0$ and $J < 0$, respectively. The zero field magneto-resistance in the CPP configuration is low LMR (high HMR) when the magnetisations are parallel (anti-parallel).



Answer for Question 4 on MRAM: (continued)

(b) (i) Memory matrix as shown here: [20%]

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



(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 the combined magnetic field induced switches the magnetisations of the two magnetic layers of the MTJ in the chosen cell to the desired parallel or anti-parallel configuration, which represents the bit of information to be stored there. [15%]

Read: Set WL_i to High and all the rest WLs to Low; [15%]
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.)