2007 IIB 4B6 Prof P Migliorato
pm@eng.cam.ac.uk

4B6 2007

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.

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.

$$\frac{d^2\psi}{dx^2} = -\frac{\rho(x)}{\varepsilon_s\varepsilon_0}$$

$$\rho(x) = -qN_A$$

$$\frac{d\psi}{dx} = \frac{qN_A}{\varepsilon_s\varepsilon_0}(w-x)$$

$$\psi_S = \frac{qN_A}{2\varepsilon_s\varepsilon_0}w^2$$

$$w = \left(\frac{2\varepsilon_s\varepsilon_0}{qN_A}\psi_S\right)^{\frac{1}{2}}$$

$$Q_S = Q_B = qN_A w$$

30%

which proves the required equation.

(b) $V_G = V_i + \psi_s$

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

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

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

20%

(c) $w = \left(\frac{2\varepsilon_s\varepsilon_0}{qN_A}\psi_S\right)^{\frac{1}{2}} = 2.29 \times 10^{-6}$ m

10%

(d)

$$1/C_{tot} = 1/C_D + 1/C_i = \frac{w}{\varepsilon_s\varepsilon_0} + \frac{d}{\varepsilon_{ox}}$$ **10%**

C_{tot}= 4.05 x 10^{-5} Farad m^{-2}

(e)
In deep depletion the depletion length w increases with the pulse voltage V, so the capacitance decreases until breakdown occurs.

When the inversion charge is formed, such charge, localized very close to the insulator - semiconductor interface, screens the bulk of the semiconductor, $\psi_S \approx 2\psi_B$ and the depletion region decreases.

At low frequency the inversion charge is modulated by the ac voltage. The total semiconductor capacitance is the parallel between the inversion charge capacitance and the depletion capacitance. The latter is constant, because ψ_S and therefore w are nearly constant, while the former increases with the amount of inversion charge. Eventually the inversion charge capacitance becomes much bigger than the insulator capacitance and $C_{tot}=C_i$.

At high frequencies the inversion charge cannot follow the ac voltage and therefore the semiconductor capacitance is C_D. So $C_{tot}= C_i//C_D=$ constant. **30%**

O.2

a) 30%

$$J_n = q\mu_n n F + q D_n \frac{dn}{dx}$$

$$n = N_c \exp\left(\frac{E_F - E_{C0} + q\psi}{kT}\right)$$

$$\frac{dn}{dx} = \frac{n}{kT}\left(\frac{dE_F}{dx} + q\frac{d\psi}{dx}\right)$$

$$D_n = \mu_n \frac{kT}{q}$$

$$F = -\frac{d\psi}{dx}$$

$$J_n = \mu_n n \frac{dE_F}{dx}$$

70% b) the I-V characteristic is obtained by integration

$$\int_0^L I_D\,dy = W\int_0^{V_{DS}} G(V_c)\,dV_c$$

$$I_D = \frac{W}{L}K\left[(V_{GS}-V_T)V_{DS}-\frac{V_{DS}^2}{2}\right]$$

$$F_y(L) = \left.\frac{dV_c}{dy}\right|_{y=L} = \frac{I_D}{W}\,\frac{1}{G(V_{DS})}$$

$$F_y(L) = \frac{1}{L}\,\frac{(V_{GS}-V_T)V_{DS}-\frac{V_{DS}^2}{2}}{V_{GS}-V_{DS}-V_T} = 3.10^5 \text{ V/m}$$

Q.3

(a)

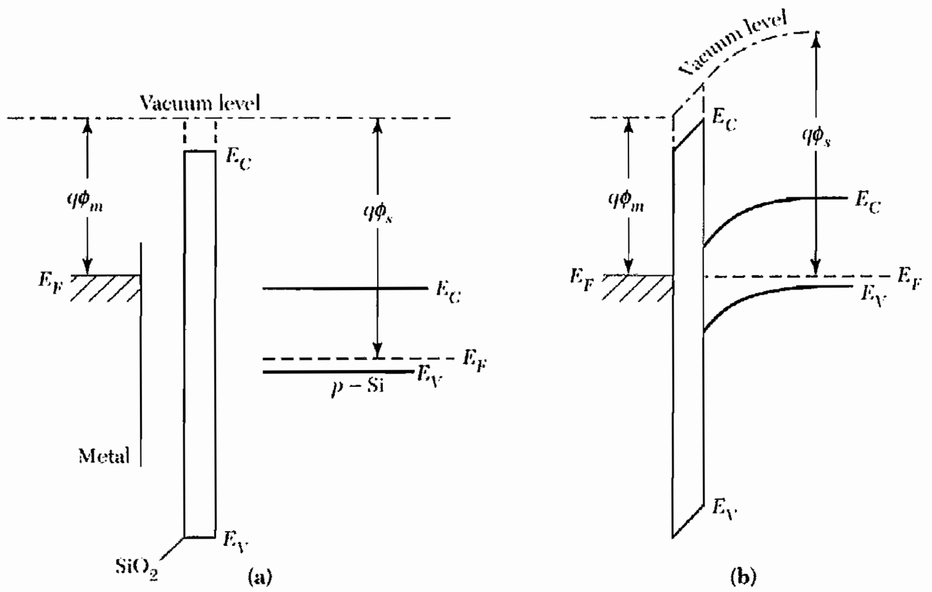
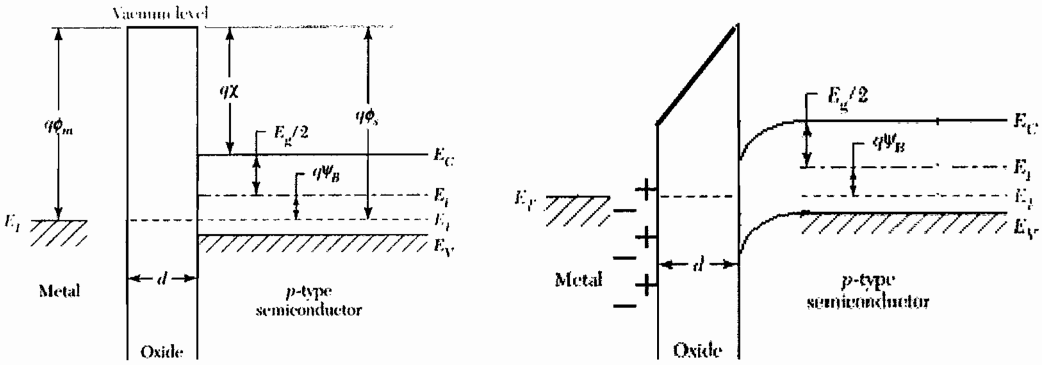


Fig. 9 (*a*) Energy band diagram of an isolated metal and an isolated semiconductor with an oxide layer between them. (*b*) Energy band diagram of an MOS diode in thermal equilibrium.

The result is a flat band shift $V_{FB} = \phi_m - \phi_s$

(b)



H_2 is adsorbed at interface and generates + charge
A dipole layer is formed

$$V_{FB} = -\psi_{int} \qquad \text{if } \phi_m = \phi_s$$

$$V_{FB} = \frac{\phi_m - \phi_s}{q} - \psi_{int} \qquad \text{if } \phi_m \neq \phi_s$$

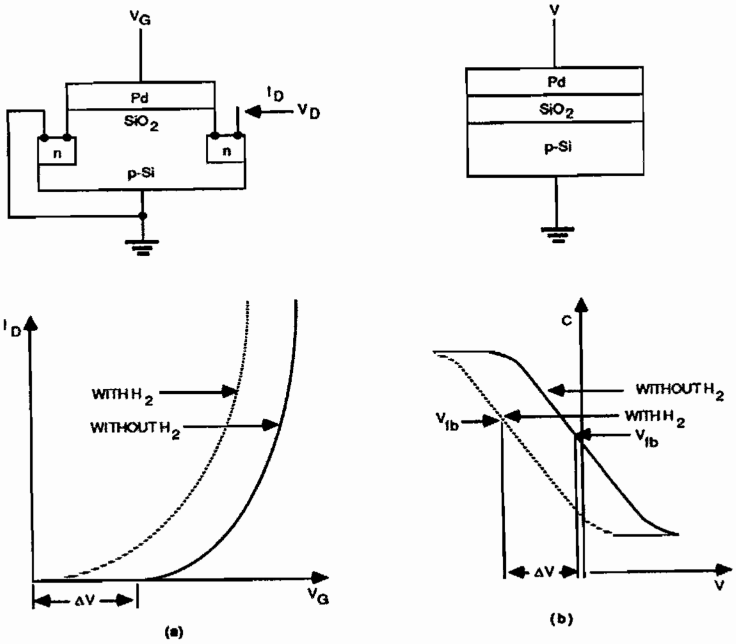


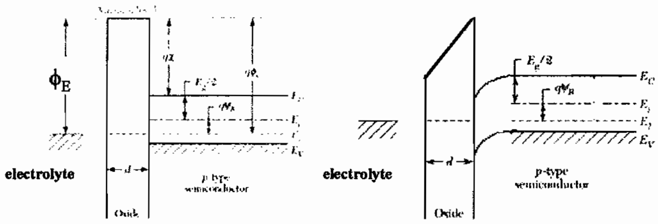
Figure 9.6 Schematic diagrams of hydrogen-sensitive MOS structures (a) a Pd MOS transistor and its $I_D(V_G)$ curve (b) a Pd MOS capacitor and its C-V curve (Ref. 10)

(c) Ion-Sensitive-Field-Effect Transistor (ISFET)

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

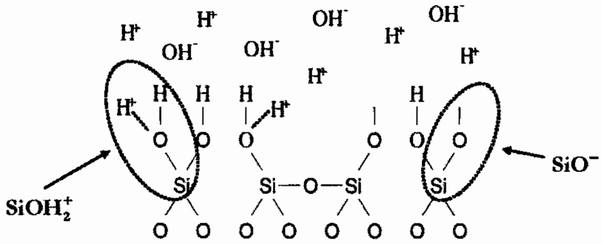
where: Q_{int} = Charge on insulator surface

C_{dl} = capacitance of the electrochemical double layer



$$V_{FB} = \phi_E - \phi_S - \Psi_L$$

3. Acidic / Basic Reactions at Surface:



$$SiOH \rightleftarrows SiO^- + H_s^+ \qquad K_a = \frac{[H_s^+][SiO^-]}{[SiOH]}$$

$$SiOH + H_s^+ \rightleftarrows SiOH_2^+ \qquad K_b = \frac{[SiOH_2^+]}{[H_s^+][SiOH]}$$

$[H_s^+]$ Concentration of H^+ in solution at the surface

$[SiO^-]$ Concentration of SiO^- on the insulator surface

$[SiOH_2^+]$ Concentration of $SiOH_2^+$ on the insulator surface

$$\frac{K_a}{K_b} = \frac{[H_s^+]^2[SiO^-]}{[SiOH_2^+]}$$

$$[H_s^+] = [H_b^+]\exp\left(-\frac{q\Psi_L}{kT}\right)$$ Boltzman relationship

$[H_b^+]$ Concentration of H^+ in the solution bulk

$$-\ln\left[H_b^+\right]+\ln\left(\frac{K_a}{K_b}\right)^{\frac{1}{2}}=-\frac{q\Psi_L}{kT}+\ln\left(\frac{\left[SiO^-\right]}{\left[SiOH_2^+\right]}\right)^{\frac{1}{2}}$$

$$-\ln\left[H_b^+\right]+\ln\left(\frac{K_a}{K_b}\right)^{\frac{1}{2}}\approx-\frac{q\Psi_L}{kT}$$

$$pH=-\log_{10}\left[H_b^+\right] \qquad pH_{pzc}=-\log_{10}\left(\frac{K_a}{K_b}\right)^{\frac{1}{2}}=\text{constant}$$

$$\Psi_L=2.303\frac{kT}{q}\left(pH_{pzc}-pH\right)$$

$$\Delta\psi_L=59\text{mV}/(\text{pH unit}) \quad \text{at } 300^\circ\text{K}$$

❖**An ISFET senses and amplifies the change in *double layer potential* $\Delta\psi_L$ due to the change in pH**

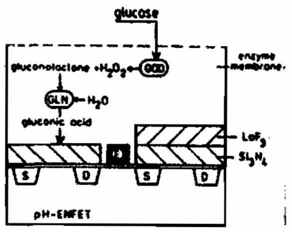
❖**pH measurements are important (blood pH)**

❖**By functionalising the gate insulator organic/bio/inorganic compounds can be detected**

Technique: ENFET
(Bioreceptor: <u>En</u>zyme, Transducer: IS<u>FET</u>)

Bioreceptors: Glucose oxidase (GOD) + Gluconolactonase (GLN)
Transducer: pH-ISFET (gate oxide: Si_3N_4)
Buffer Solution: Water (H_2O)
Reactions:

$$\text{glucose} + O_2 \xrightarrow{GOD} H_2O_2 + \text{gluconolactone}$$
$$\text{gluconolactone} + H_2O \xrightarrow{GLN} \text{Gluconic acid}$$



Question 4:

(1) Explain what is (i) ferroelectric material, (ii) polarization and (iii) domains. [10%]

(2) Describe the structure and the principle of operation of a ferroelectric field-effect transistor (F-FET). [20%]

(3) With reference to the circuit diagram of Figure 1, explain how a one-transistor one-capacitor (1T/1C) ferroelectric memory cell operates for its WRITE and READ operation. Include a sketch of the sensed charge vs applied voltage curve for the READ operation. [40%]

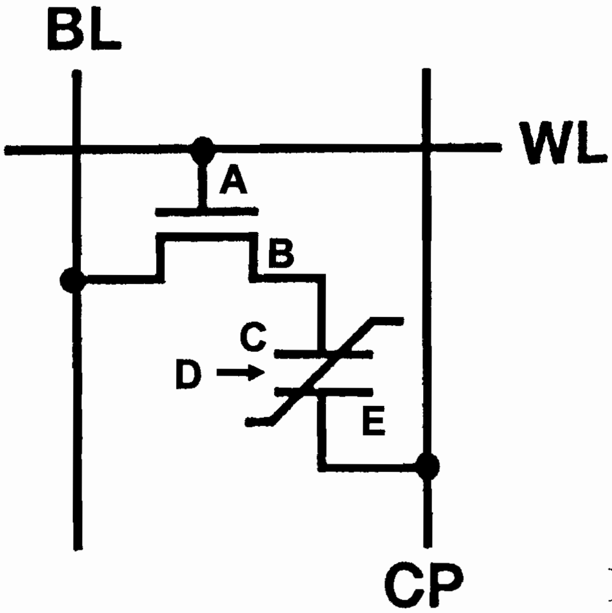
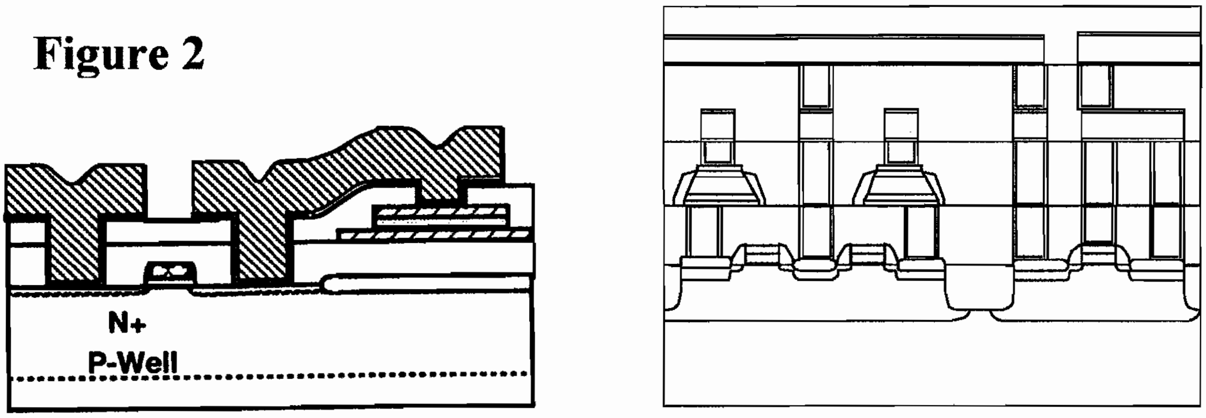


Figure 1

(4) Mark the parts A, B, C, D and E in Figure 2 at the corresponding places for both planar and stacked structures. Describe the function and possible materials for each part. Give a brief comparison for the advantages and disadvantages for these two structures. [30%]

Figure 2



Planar structure

Stacked structure

Question 5:

(1) What is the giant magneto-resistance (GMR) effect? (including its principle, basic elements and their functions) [30%]

(2) Explain the performance of a GRM unit, based on the experimental results shown in Figure 3. How could the $\Delta\rho/\rho > 100\%$? [40%]

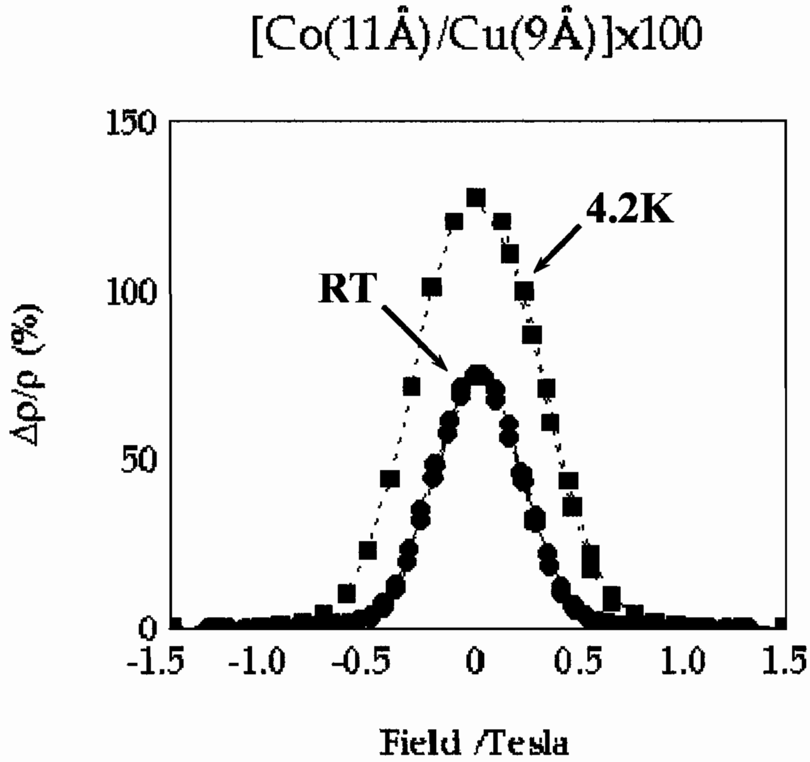
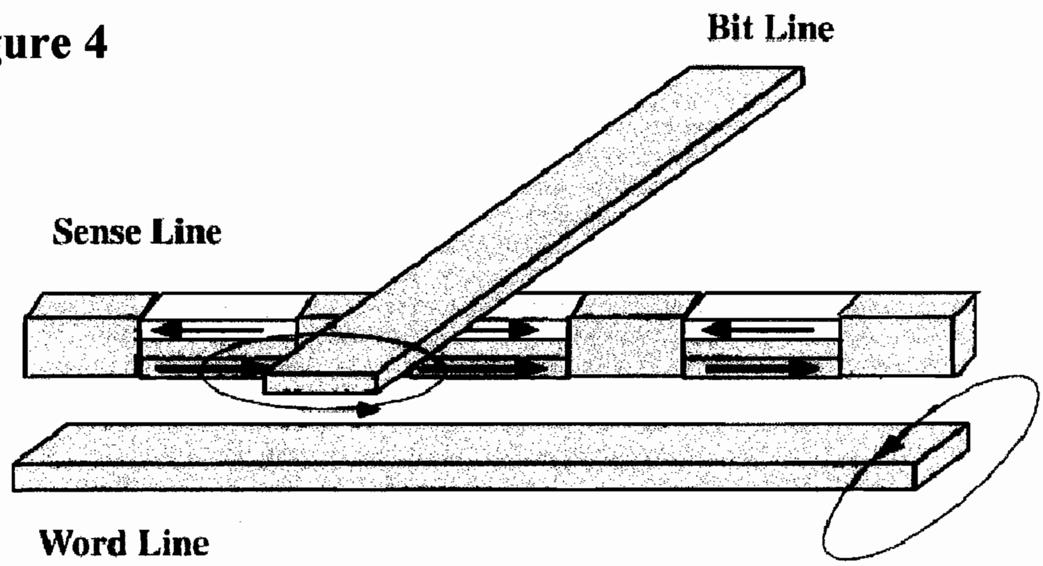


Figure 3

(3) With reference to Figure 4, explain the WRITE operation of a pseudo spin valve (PSV) magnetic random access memory (MRAM) array. [30%]

Figure 4



Answer for Question 4 on FRAM:

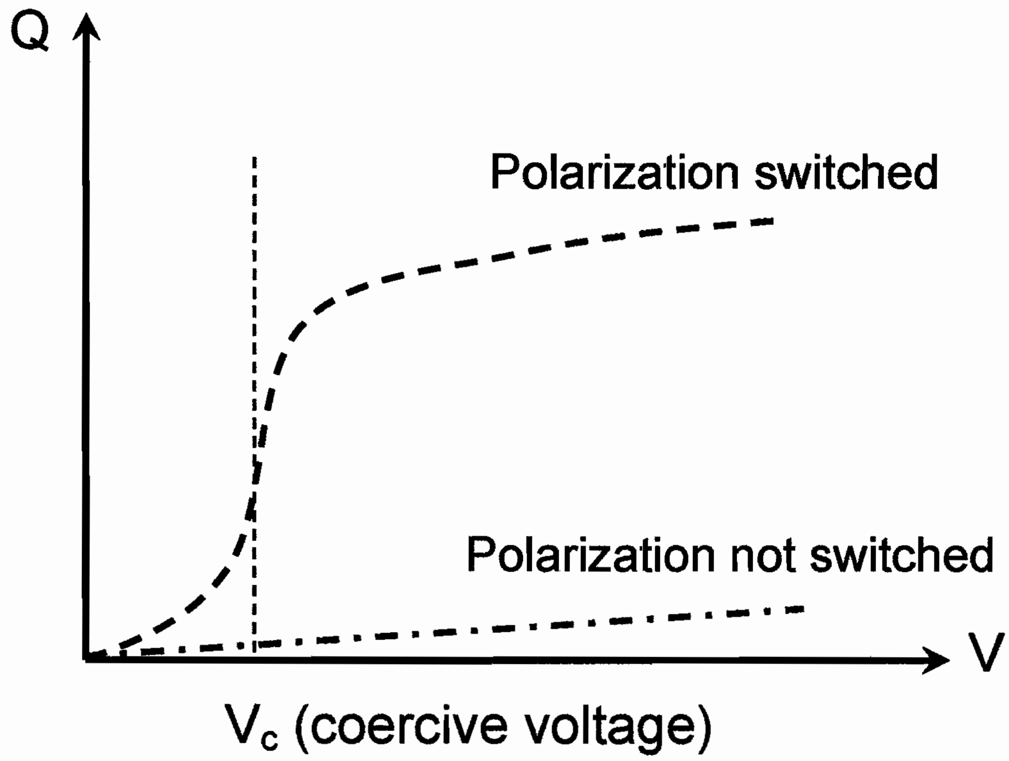
(1) Ferroelectric material is a kind of material which exhibits spontaneous polarization. The polarization is consisted of electrical dipoles which originate from asymmetric spatial separation of the positive and negative ionic charges in each atomic unit cell. Polarization domain is an area within which the polarization of each unit cell is in the same direction. [10%]

(2) 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 states according to the switch of polarization direction). [20%]

(3) WRITE and READ operation in a 1T/1C FRAM cell: [30%]

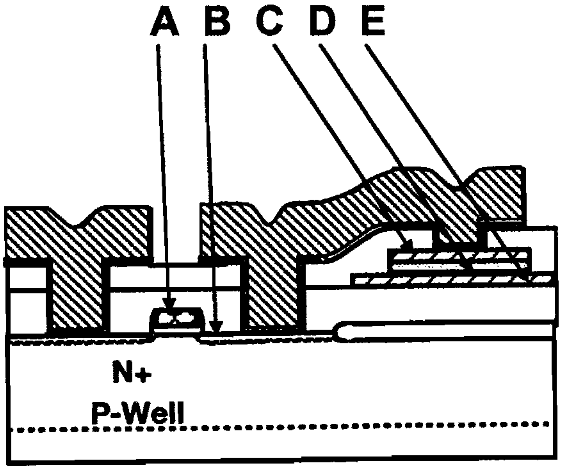
WRITE: Set WL to high to switch the transistor to ON state;
Set BL to high (low) and CP to low (high) to write '1' (or '0').

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: BL is high, high /low charge gives '0' /'1' state);
Write back the information if it has been altered.

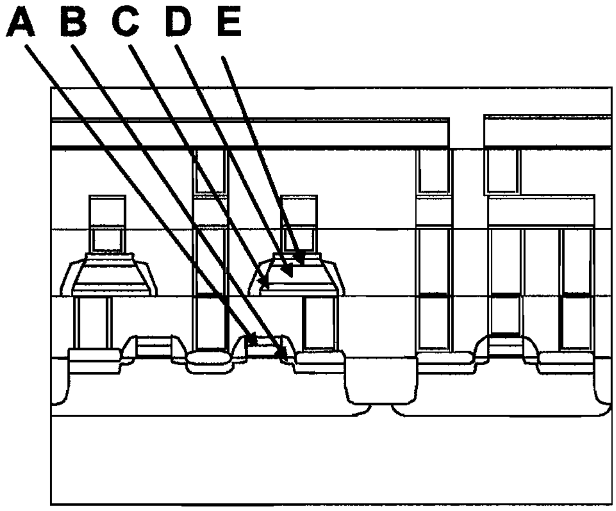


Answer for Question 4 on FRAM (continued)

(4) The parts of A, B, C, D and E: [40%]



Planar structure



Stacked structure

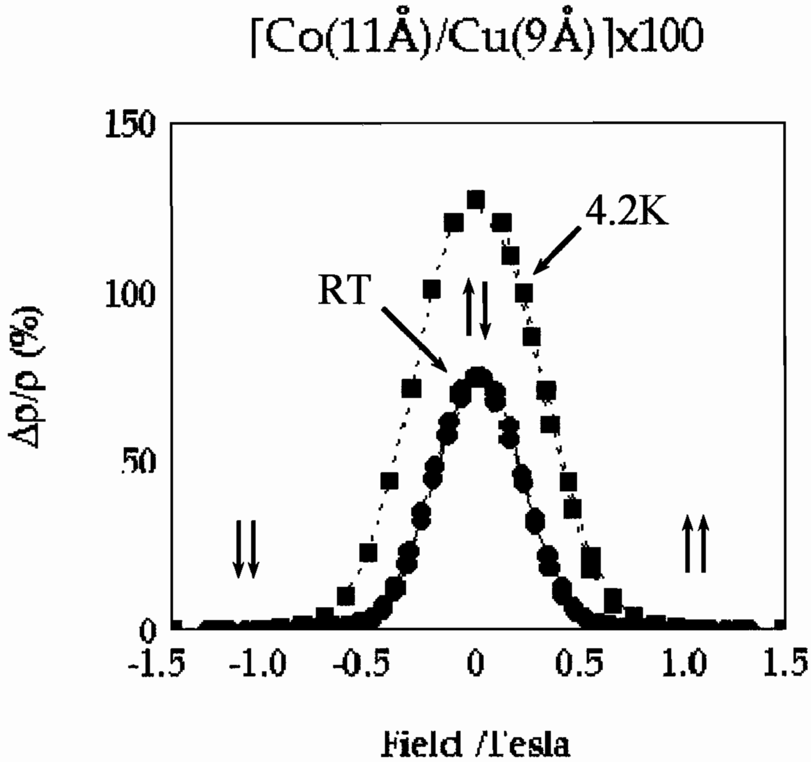
A: Gate of FET; conductive material/metal (Cu, Al, etc)
B: Drain of FET; doped semiconductor material (p- or n-type Si);
C: Electrode of ferroelectric capacitor; conductive material/metal (Pt, Ir, etc);
D: Ferroelectric material; ferroelectrics – insulating type (PZT, SBT, etc);
E: Electrode of ferroelectric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

The main advantage of stacked structure over 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 stacked structure, resulting in a more complicated fabrication process and hence higher cost.

Answer for Question 5 on MRAM:

(1) 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 significant spin-related scattering. 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 used to ensure the initial magnetisation in the FM layers is anti-parallel. [30%]

(2) The magnetisation in the FM layers is anti-parallel when the external magnetic field is zero. The $\Delta\rho/\rho$ reaches its maximum value in this situation. As the strength of the external field increases, the magnetisation opposite to the external field is reduced, hence the $\Delta\rho/\rho$. When the magnetisation of the FM layers is nearly parallel, the $\Delta\rho/\rho$ approaches its minimum. The maximum $\Delta\rho/\rho$ shall increase when the temperature is reduced from room temperature (RT) to 4.2K because of the higher degree anti-parallel alignment at the low temperature. The symmetric behaviour of the $\Delta\rho/\rho$ for the positive and negative external magnetic field is due to equivalence of the system when fully magnetised in the opposite directions. [40%]



The magneto-resistance MR% is defined as:

$$MR\% = \frac{R(\mathrm{AP}) - R(\mathrm{P})}{R(\mathrm{P})} \times 100 = \frac{\Delta R}{R}(\%) = \frac{\Delta\rho}{\rho}(\%)$$

Answer for Question 2 on MRAM (continued)

where R(AP) and R(P) are the resistance at parallel and anti-parallel situations, respectively. Since R(AP) is always larger than R(P), the MR% can be more than 100% if R(AP)>2*R(P).

(3) PSV consists of two FM layers: one 'soft' layer and one 'hard' layer. The direction of magnetisation in the hard layer is more difficult to switch than in the soft layer, and it is used to represents the information stored in the cell. The Write is achieved by magnetising the hard layer in the desired direction. To avoid the mis-write due to the half-selection, we need to go through two steps: (a) send a current pulse to the word line, switching the magnetisation nearly half way in all the half-selected cells; (b) send another current pulse of either positive or negative sign to the bit line to finally switch the selected cell to the desired direction. Only the combined field is strong enough to switch the hard layer of the selected cell, while the half-selected cells remain unchanged. [30%]