1. a) the threshold voltage corresponds to the condition (for a p-type semiconductor) n (at the surface) $= n_S = N_A$

$$n_S = n_0 \exp\left(\frac{q\psi_s}{kT}\right),$$ n_0 = conc. of electrons in the bulk

$$n_0 \simeq \frac{n_i^2}{N_A}$$

at threshold:

$$N_A^2 = n_i^2 \exp\left(\frac{q\psi_s}{kT}\right) \qquad \psi_s = 2\frac{kT}{q}\ln\frac{N_A}{n_i}$$

the threshold voltage is the voltage V_G to be applied to the gate to achieve the above surface potential ψ_s

b) $V_G = V_i + \psi_s \qquad \psi_s = 0.612 \text{ V}$

$$V_i = -\frac{Q_s}{C_{ox}} = -\frac{Q_B}{C_{ox}} = \frac{d}{\epsilon_i}(2q\epsilon_s N_A)^{1/2} = 1.177\text{V}$$

$V_G = 1.7897$ V

c) In this case the additional charge of the interface states Q_{it} must be included:

$$Q_{it} = -\int_{E_v}^{E_c} q D_{it} F(E)\,dE = -q D_{it}(E_{F_S} - E_v)$$

where E_{F_S} is the Fermi Level at the surface

$$E_{F_S} - E_V = E_{F(BULK)} - E_V + q\psi_s$$

$$E_{F(BULK)} - E_V \simeq kT \ln \frac{N_V}{N_A}$$

$$Q_{it} = -0.0013 \quad \text{Coulomb } m^{-2}$$

$$V_i = \frac{-Q_{it} - Q_B}{C_{ox}} = 9.16 \text{ V}$$

$$V_G = 9.77 \text{ V}$$

d) The Fermi Function is symmetric about the Fermi Level. So:

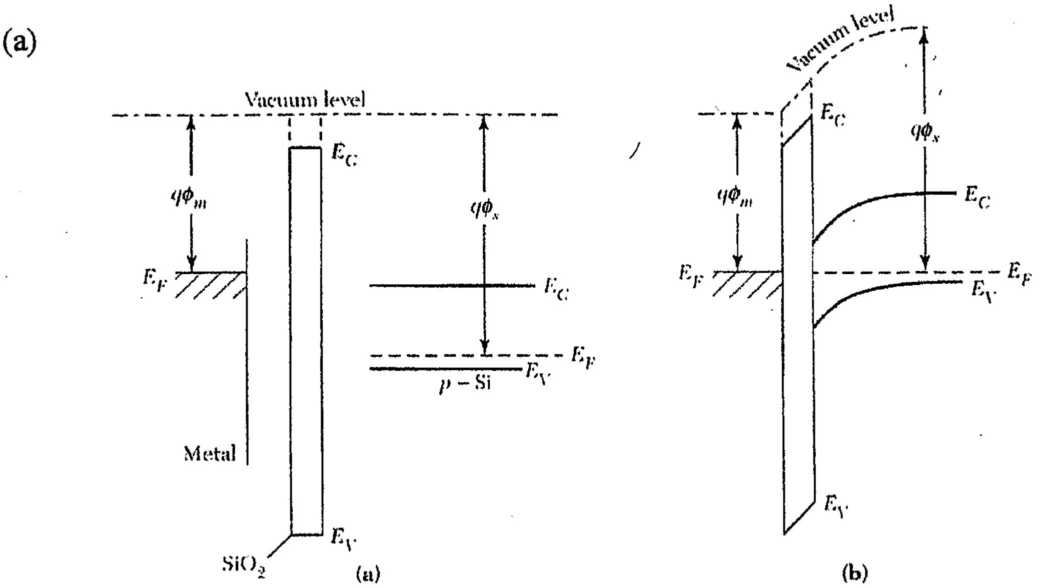
$$\int_{E_V}^{E_C} q D_{it} F(E) dE$$

does not change for D_{it} constant when the correct $F(E)$ is used.

However for any other D_{it} it will change. In particular if D_{it} increases exponentially towards the conduction band minimum the difference could be quite substantial

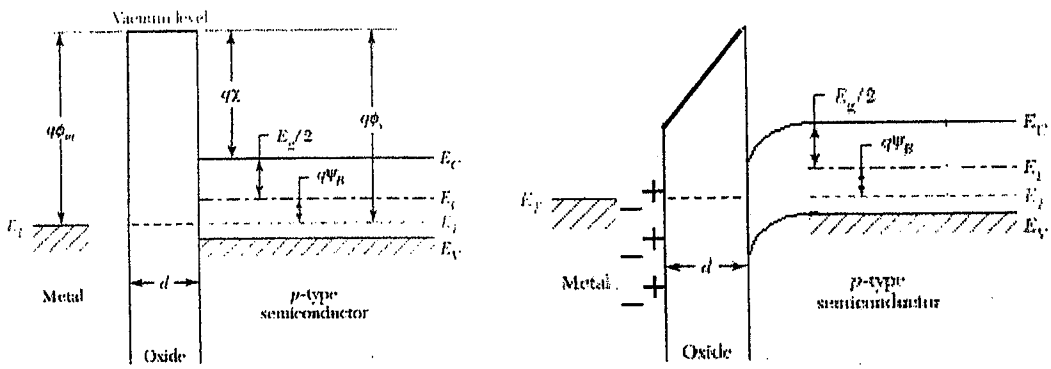
4B6 Q2 Crib 2011

(a)



(*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 $V_{FB} = \phi_m - \phi_s$

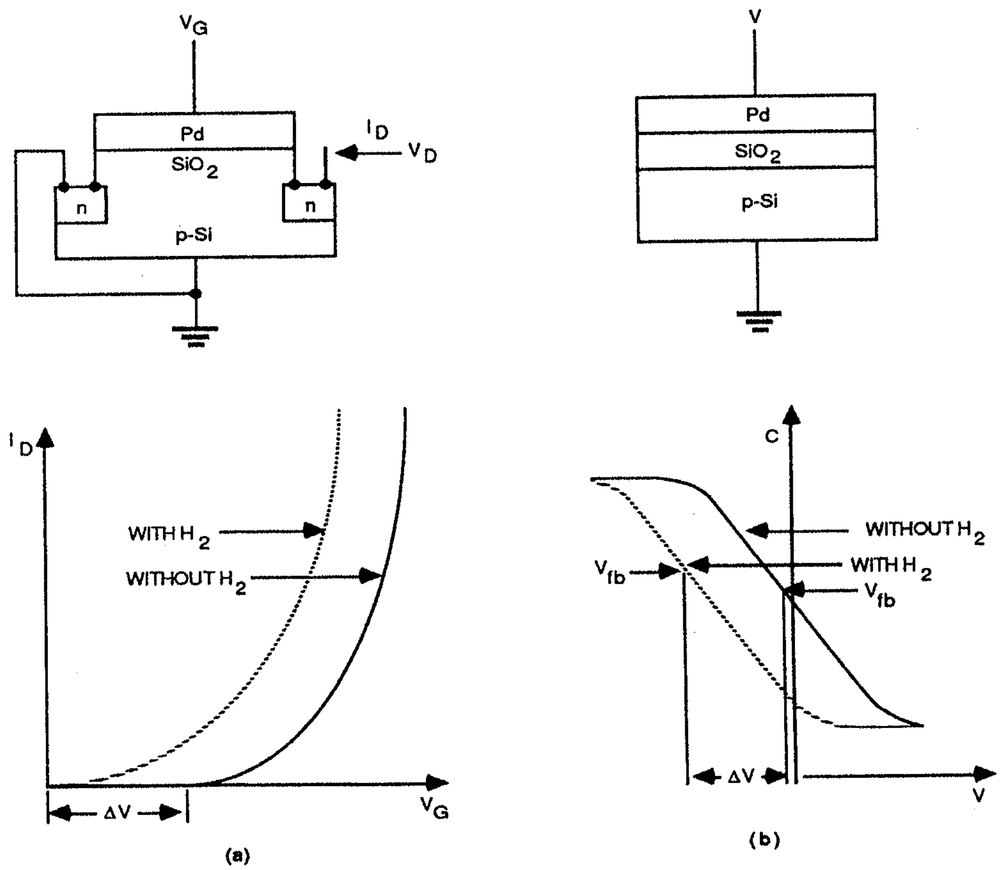


H_2 is adsorbed at interface and generate positive charge.

A dipole layer is formed

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

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

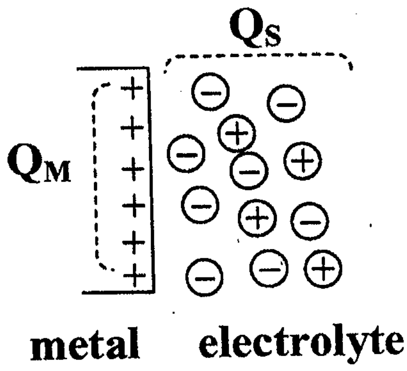


Schematic diagrams of hydrogen-sensitive MOS structures (a) a Pd MOS transistor and its $I_D(V_G)$ curve (b) a Pd MOS capacitor and its C-V curve

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

Q2

c)



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.

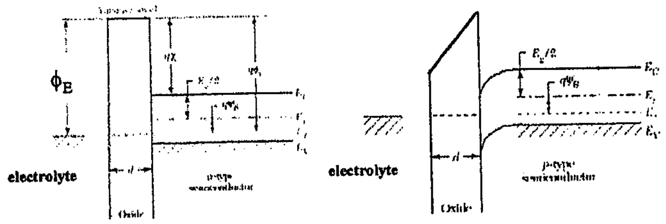
Since the charge is affected by chemical reactions at the interface, modification of the surface with suitable receptors enables detection of chemical/biological reactions through a change in the double layer potential. An example of this is the detection of DNA hybridization. DNA carries a negative 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.

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

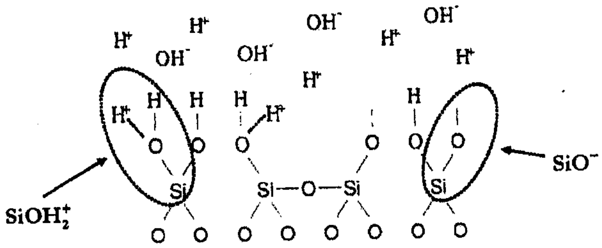
$$\psi_L = \frac{Q_{int}}{C_{dl}}$$ where: Q_{int} = Charge on insulator surface

C_{dl} = capacitance of the electrochemical double layer



$$V_{FB} = \phi_E - \phi_s - \psi_L$$

Acid-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

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

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

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

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

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

❖**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**

Answer for Question 3 on FRAM:

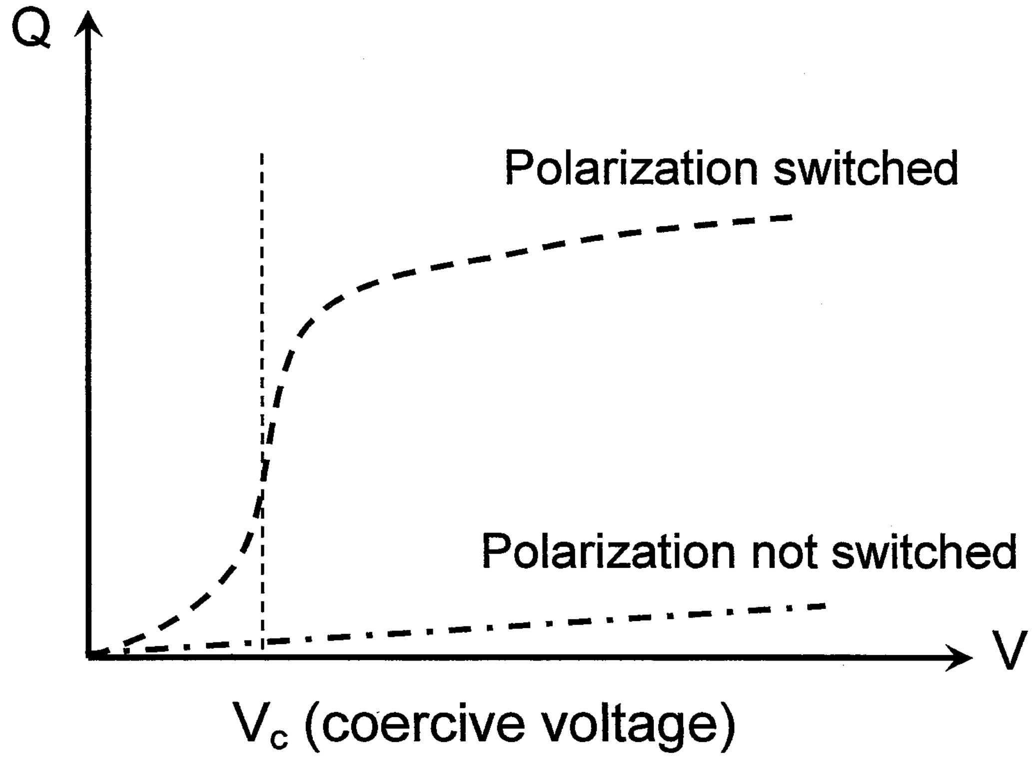
(1) Ferroelectric material is a kind of material which exhibits spontaneous polarization. The polarization consists of electrical dipoles which originate from asymmetric spatial separation of the positive and negative ionic charges in each atomic unit cell. Polarization domain is an area within which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

(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 according to the switch of polarization direction).

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

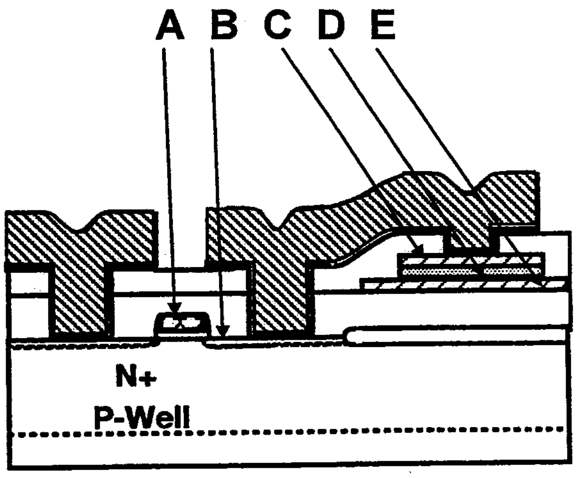
WRITE: Set WL to high to switch the transistor to ON state;
Set BL to high (low) and CP to low (high) to write '1' (or '0').

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.

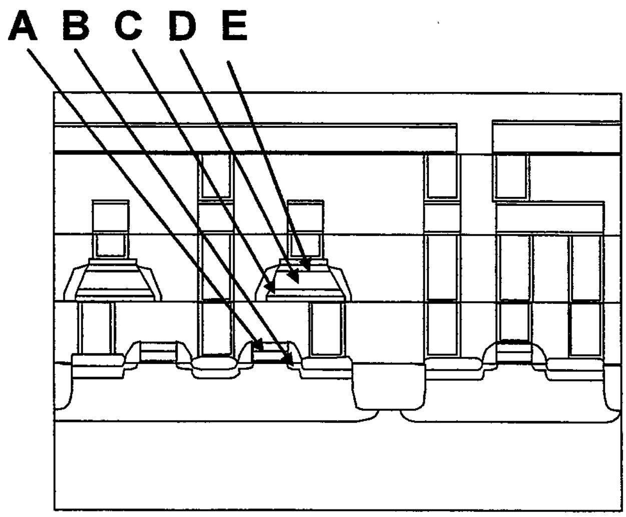


Answer for Question 3 on FRAM (continued)

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



Planar structure



Stacked structure

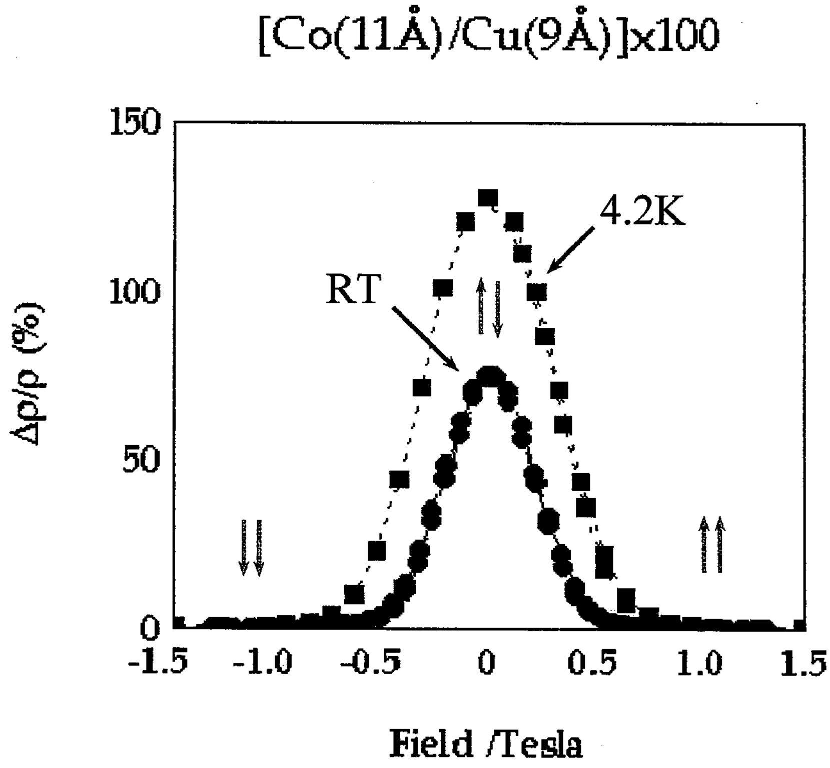
A: Gate of FET; conductive material/metal (Cu, Al, etc)
B: Drain of FET; doped semiconductor material (p- or n-type Si);
C: Electrode of ferroelectric capacitor; conductive material/metal (Pt, Ir, etc);
D: Ferroelectric material; ferroelectrics – insulating type (PZT, SBT, etc);
E: Electrode of ferroelectric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

Answer for Question 4 on MRAM:

(1) GMR effect is how 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 metal 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.

(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, $\Delta\rho/\rho$ 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 of anti-parallel alignment at the low temperature. The symmetric behaviour of $\Delta\rho/\rho$ for the positive and negative external magnetic field is due to equivalence of the system when fully magnetised in the opposite directions.



The magneto-resistance MR% is defined as:

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

Answer for Question 4 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 represent the information stored in the cell. The Write is achieved by magnetising the hard layer in the desired direction. To avoid mis-write due to 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.

2011 4B6 Answers to numerical questions

Q1 b: 1.79V
c: 9.77V

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[20%]

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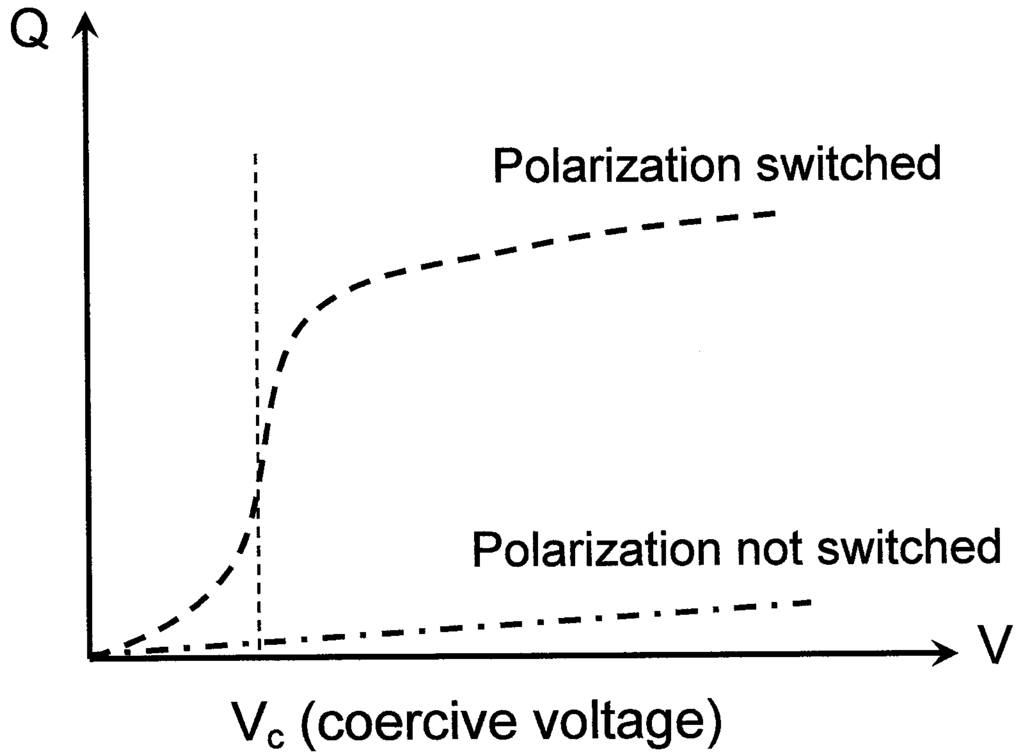

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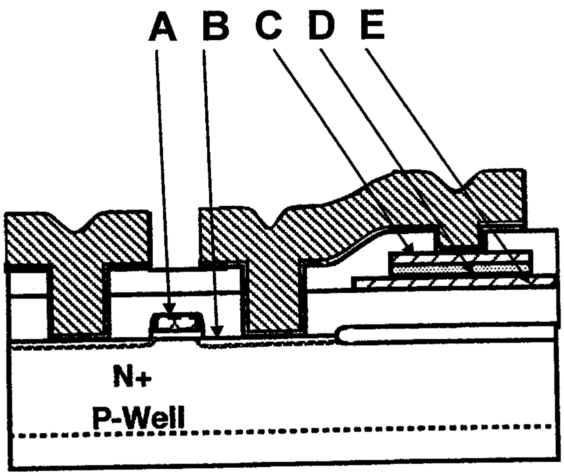

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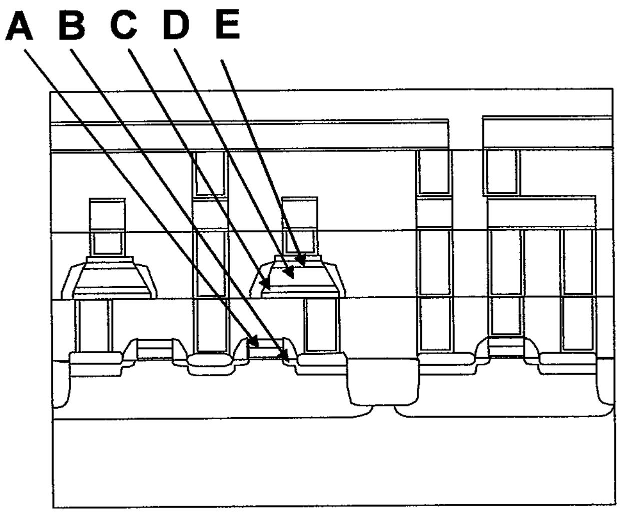

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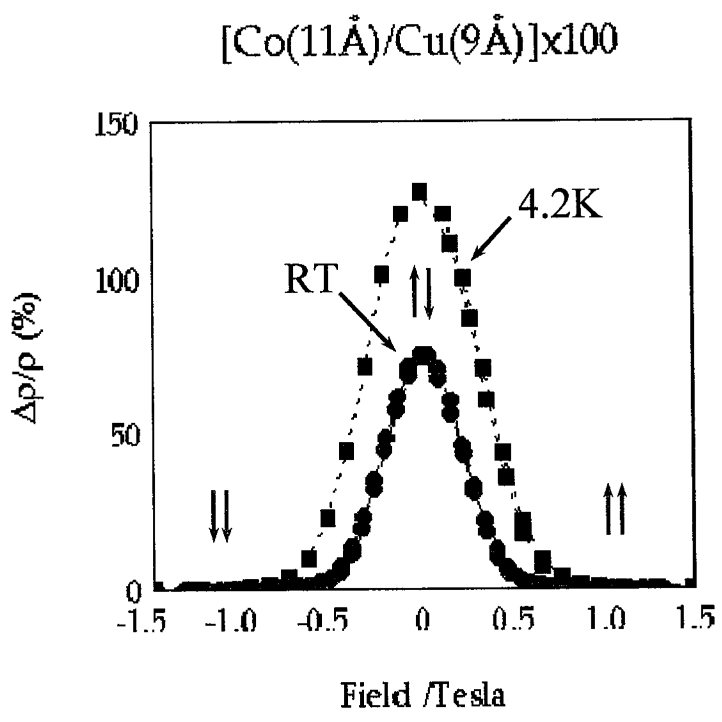

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