4B6 Crib 2014
Prof D Chu
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 layer 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. [20%]

(b) $$V = V_i + \psi_s$$

$$V_i = -\frac{Q_B}{\varepsilon_i} d$$

$$Q_B = -(2\varepsilon_s q N_A \psi_s)^{1/2}$$

$$V = \frac{(2\varepsilon_s q N_A \psi_s)^{1/2} d}{\varepsilon_i} + \psi_s = 5.06\ \text{V}$$ [30%]

(c)

(i) When the output current I_D, for a given V_{GS}, increases linearly with V_{DS}, the MOSFET is said to be in linear regime.

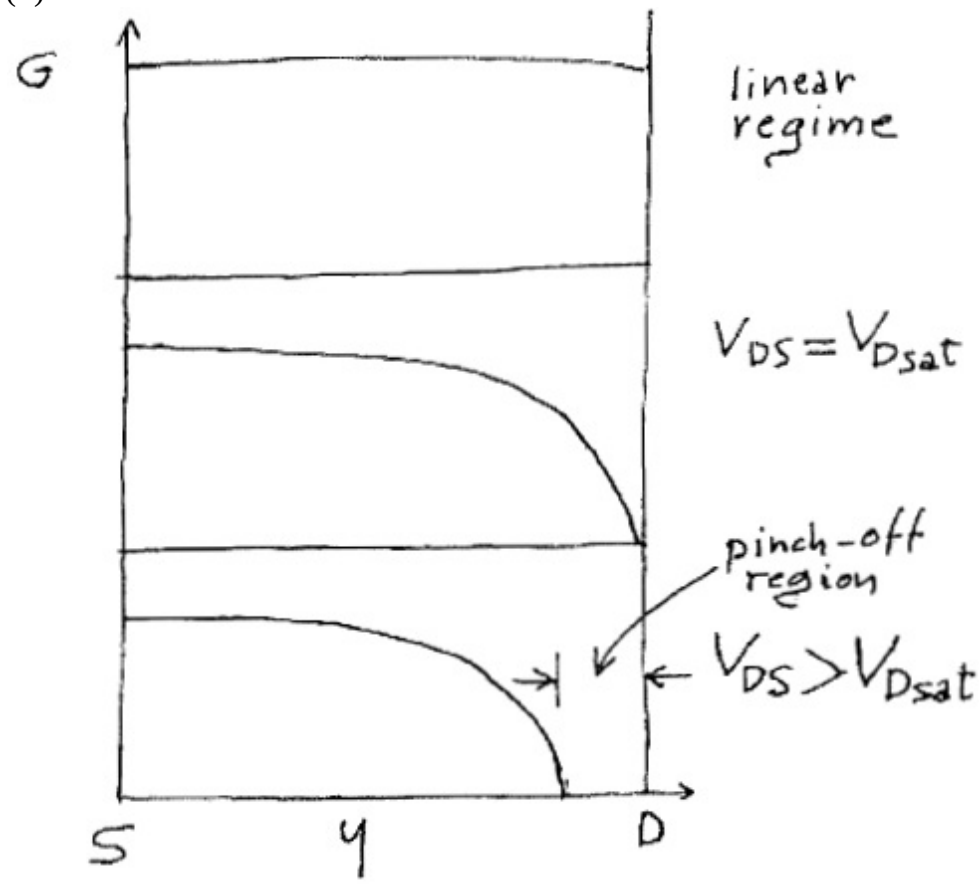
When the output current I_D, for a given V_{GS}, becomes constant with V_{DS}, the MOSFET is said to be in saturation.

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=0. [15%]

(ii)



[15%]

(d) The region where G=0 is called pinch-off region and the left hand boundary is the pinch-off point. At the pinch-off point $V=V_{Dsat}$.

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%]

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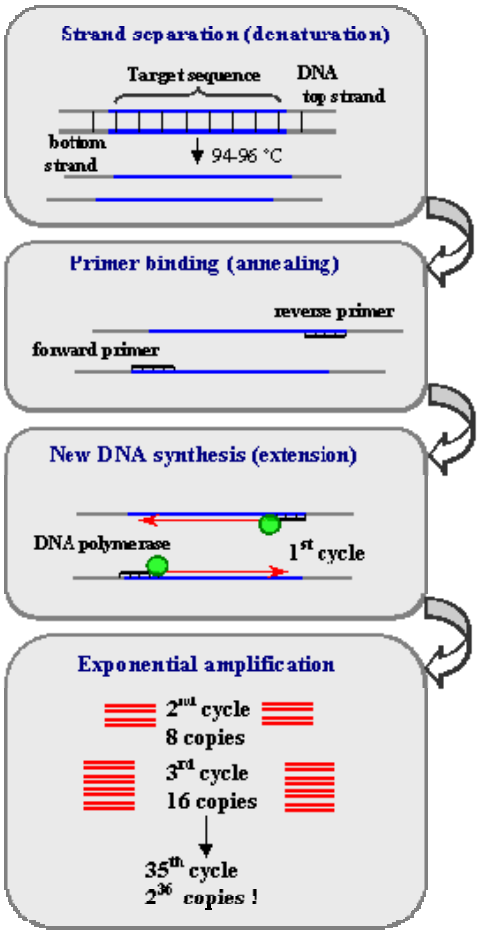
Q2

(a) PCR is a simple and inexpensive method that a specific segment of DNA can be copied billions of time over. PCR reaction requires the following components:

1) DNA template: the sample DNA that contains the target sequence. At the beginning of the reaction, high temperature is applied to the original double stranded DNA molecule to separate the strands from each other (Denaturation).
2) DNA polymerase: enzyme that synthesizes new strands of DNA complementary to the target sequence.
3) Forward and reverse primers: short sequence of single-stranded DNAs that are complementary to the target sequence which allows you to define the segment of DNA to be amplified.
4) Nucleotides: single units of the bases A, T, G, and C which are the 'building blocks' for new DNA strands.



Step 1) Denaturation: High temperature (94-96 ^{o}C) is used to denature the sample DNA strand

Step 2) Annealing: the reaction temperature is lowered to 50 – 65 ^{o}C to allow the hybridization of the forward and reverse primer to the sample DNA template

Step 3) Extension: Depending on the type of polymerase used, a typical temperature would be around 70 ^{o}C. The DNA polymerase synthesizes a new DNA strand complementary to the DNA template strand by adding the single nucleotides

These three steps will be repeated depending on the amount of DNA needed to be amplified.

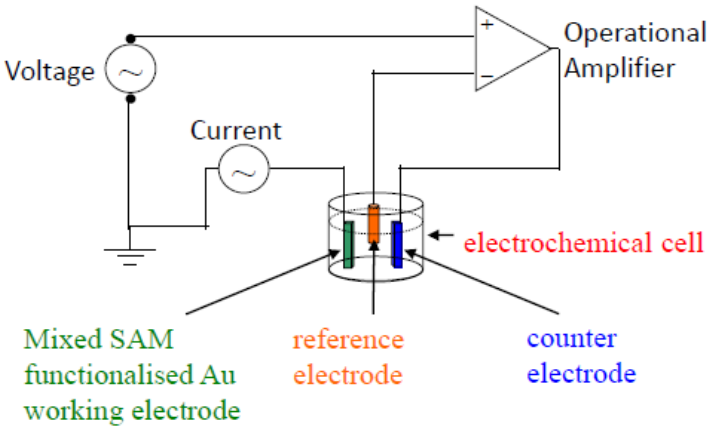
[40%]

(b) Ignoring the complexities of the first few steps of the amplification reaction, which produce longer products that eventually make an insignificant contribution to the total DNA amplified, this amount of product approximately doubles for every amplification step. Therefore

$$2n\ [2x300x330/(6x1023)] = \ 100x10\text{-}9$$
$$n=38.1$$

Thus only about 38 cycles of PCR amplification are sufficient to amplify DNA from a single molecule to a quantity that can be readily handled and anlyzed biochemnically. [20%]

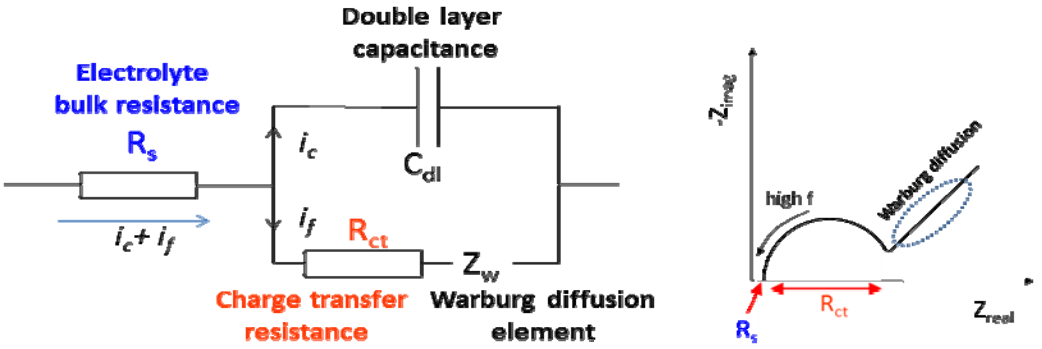
(c)



A standard three-electrode cell

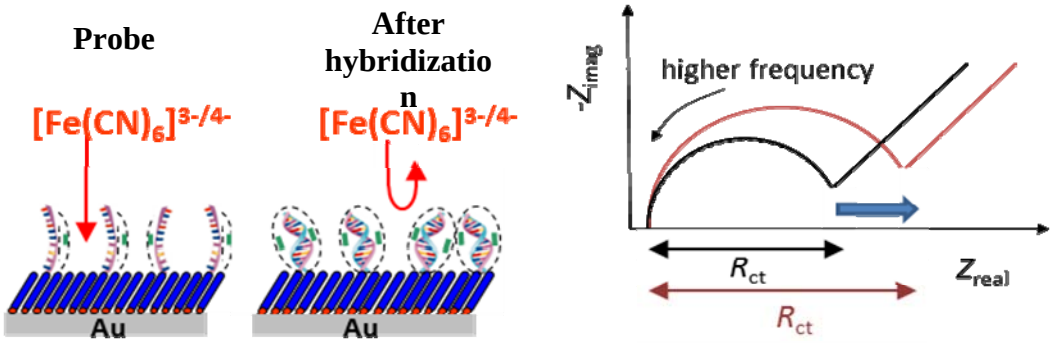
In general, an electrochemical cell can be considered simply an impedance to a small sinusoidal excitation, hence it is able to represent the system's performance by an equivalent circuit that pass current with the same amplitude and phase angle that the real cell does under a given excitation. A frequently used circuit, 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. 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 also plotted below.



[20%]

(d) 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}.



To improve the sensitivity, one can: i) optimize the mixing ratio of the DNA probe and Mercaptohexanol; ii) optimize the measurement buffer ionic strength; iii) use peptide nucleic acid probe (neutral) rather than DNA probe (negatively charged).

[20%]

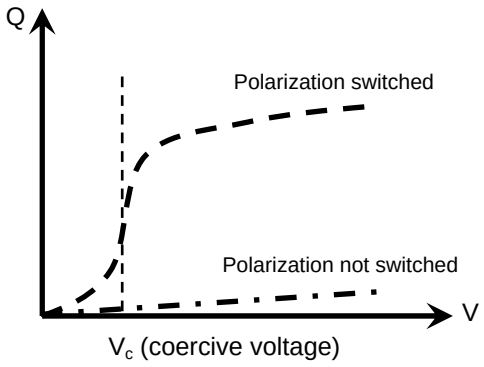
(a) Ferroelectric material is a sub-group of piezoelectric material which exhibits spontaneous polarization, i.e. a net dipole moment with no external electric field applied. The polarization is consisted of electrical dipoles which originate from asymmetric spatial separation of the positive and negative 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%]

(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 binary digit of information. Therefore, an F-FET at a given gate voltage can be in the ON or OFF state according to the polarization direction. This can be used as non-destructive readout of the stored data. [20%]

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

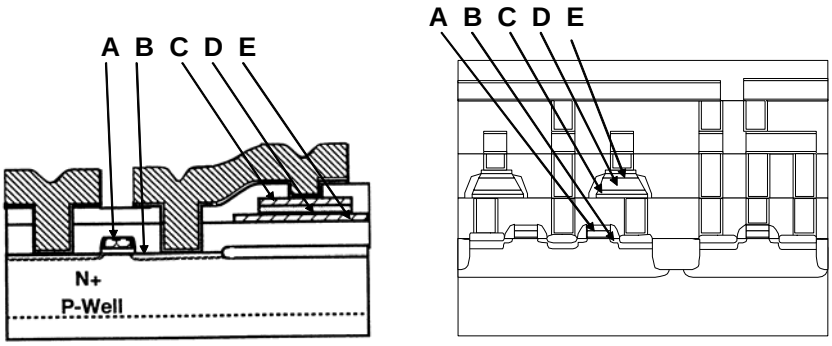
WRITE: Set WL to high to switch the transistor to ON state;
Set BL to high (low) and CP to low (high) to write '1' (or '0').

READ: Set WL to high;
Set CP to high;
Set BL to low and sense the amount of charge flowing out BL as an indication of the original polarisation state, i.e. the stored data (for example: high /low charge indicates '0' /'1' state); (Alternatively, set BL to float and sense BL voltage as a result of charging BL parasitic capacitance.)
Write back the information if it has been altered.



[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).

A planar structure has the advantage of being simple to fabricate hence low costs and the disadvantage of being large in footprint so that it is difficult to achieve high memory density.

The main advantage of stacked 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. [30%]

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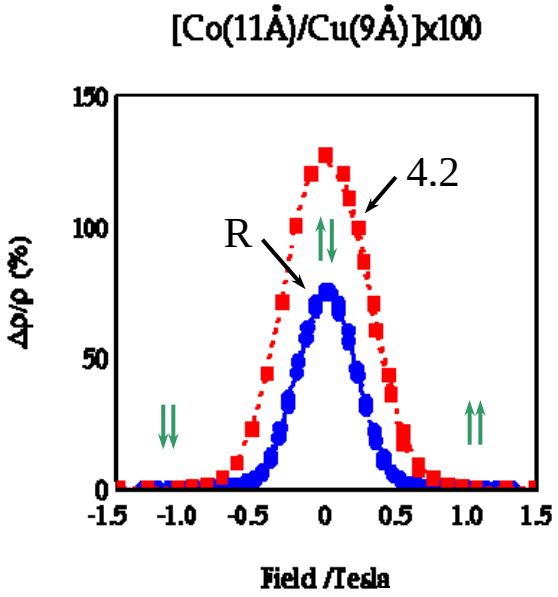
Q4

(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 used to ensure the initial magnetisation in the FM layers is anti-parallel. [30%]

(b) 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.



The magneto-resistance MR% is defined as:

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

where R(AP) and R(P) are the resistance at anti-parallel and 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). [40%]

(c) 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 while the direction of magnetisation in the soft layer is often used to assist data read-out. 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%]