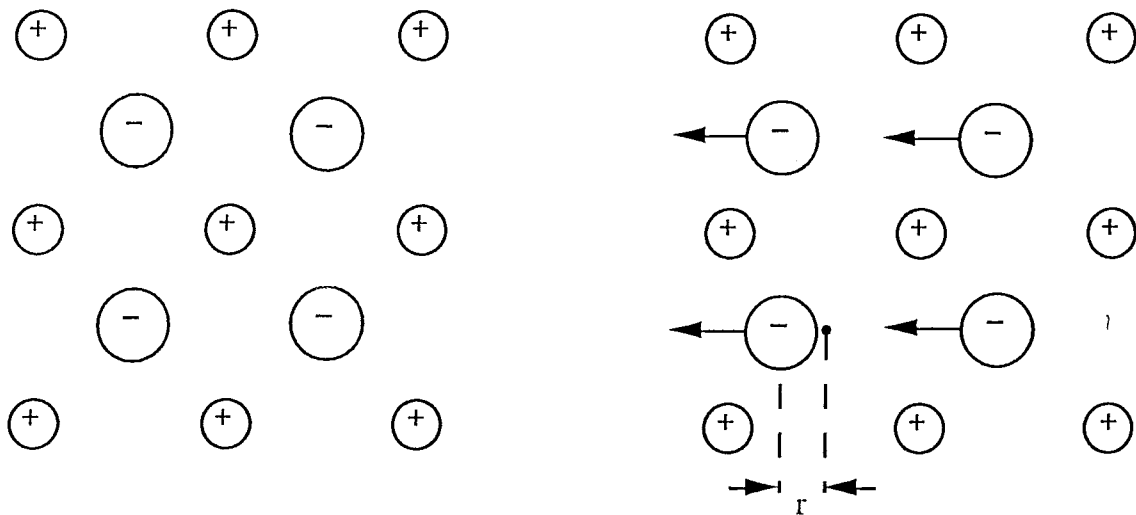


Module 4C3 : ELECTRICAL AND NANO MATERIALS SOLUTIONS

1(a)(i) The pyroelectric effect is the release of electric charge that occurs in pyroelectric materials as their temperature changes. Quantitatively this is described in terms of the pyroelectric coefficient, p , which is given by the rate of change of P_s , the spontaneous polarisation, with temperature, i.e. the gradient of the $P_s(T)$ curve ;

$$p = \frac{\Delta P_s}{\Delta T} = \frac{d P_s}{dT}$$

P_s occurs in polar dielectric materials whose structure contains a unique axis along which an electric dipole moment exists. Only a limited number of crystal structures exhibit polar properties (orthorhombic, tetragonal and triclinic, for example) and majority of these are ferroelectric. P_s originates from a structural transition which results in a displacement of the positive and negative centres of charge symmetry, i.e.;



Non-polar lattice

Polar lattice

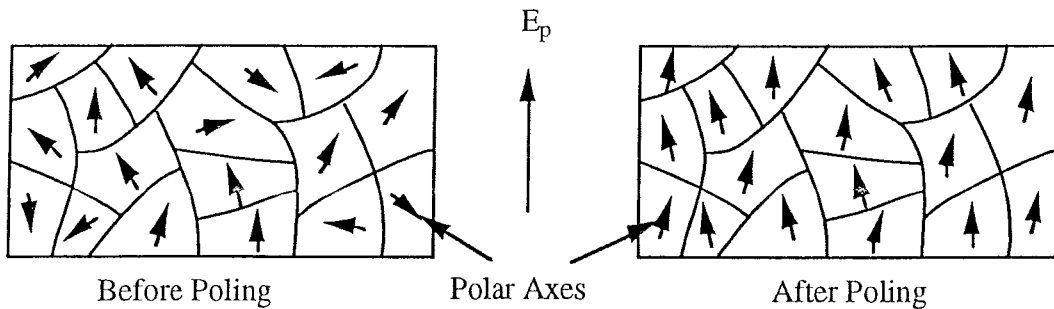
Electric dipole per unit cell = $q r$, hence P_s , is given by the total dipole moment per unit volume;

$$P_s = \frac{\sum_{\text{All unit cells}} q r}{V} \quad \text{Cm}^{-2}$$

(ii) The piezoelectric effect is the production of a change in dielectric polarisation by the application of a mechanical strain. Conversely, application of an electric field to a piezoelectric material will cause it to strain mechanically. The crystallographic structure of piezoelectric materials lacks a centre of symmetry, as is the case with pyroelectrics, but does not necessarily possess a polar axis (i.e. spontaneous polarisation). Hence, whereas all pyroelectrics are piezoelectric, the converse is not true. Of the 21 known structures which lack a centre of symmetry, 20 are piezoelectric - only 10 are pyroelectric. Pyroelectricity and

piezoelectricity are examples of an extrinsic variable such as E , temperature or stress, σ , coupling to an intrinsic variable such as D or strain, ϵ , via a material property.

Ferroelectrics are the most useful pyroelectric materials from an applications point of view since they can be fabricated in polycrystalline (ceramic) form and poled by the application of a large electric field ($E_p \sim 1 - 5 \text{ V}\mu\text{m}^{-1}$). This is technically much easier than fabricating polar materials in single crystal form to obtain a unique polar axis. The poling process of ferroelectrics aligns individual domains to yield a net overall polarisation.



[50%]

(b) Passive piezoelectric effect; applied stress gives a change in polarisation (direct piezoelectric effect). E.g. hydrophones, microphones and phonographic pick-ups.
Active piezoelectric effect; applied field gives a strain (converse piezoelectric effect). E.g. buzzers (watches), loudspeakers and depth-sounders.

Piezoelectric device in Fig. 1 operates under longitudinal mode (i.e. passive or direct piezoelectric effect). The change in polarisation along x_3 generated by a stress applied parallel to the x_1 axis is given by;

$$\Delta P_3 = d_{31} \sigma_1 \quad \Delta P = \frac{\Delta Q}{A} = d_{31} \frac{F}{a}$$

$$\underline{\Delta Q = \frac{d_{31} F A}{a}}$$

Effect of aspect ratio is to amplify charge in longitudinal mode. d_{31} is the piezoelectric coupling coefficient which relates the change in polarisation along x_3 to the stress applied parallel to the x_1 (material parameter).

[30%]

$$(c) \quad \Delta Q = \frac{d_{31} F A}{a} \quad \Delta V = \frac{\Delta Q}{C} \quad C = \frac{\epsilon_r \epsilon_0 A}{d}$$

$$\Delta V = \frac{d_{31} F A d}{\epsilon_0 \epsilon_r A a} = \frac{-274 \times 10^{-12} \times 0.01 \times 100 \times 10^{-6} \times 0.5 \times 10^{-3}}{8.85 \times 10^{-12} \times 3400 \times 100 \times 10^{-6} \times 0.5 \times 10 \times 10^{-6}}$$

$$\text{i.e. } \Delta V = 9.1 \text{ mV}$$

[20%]

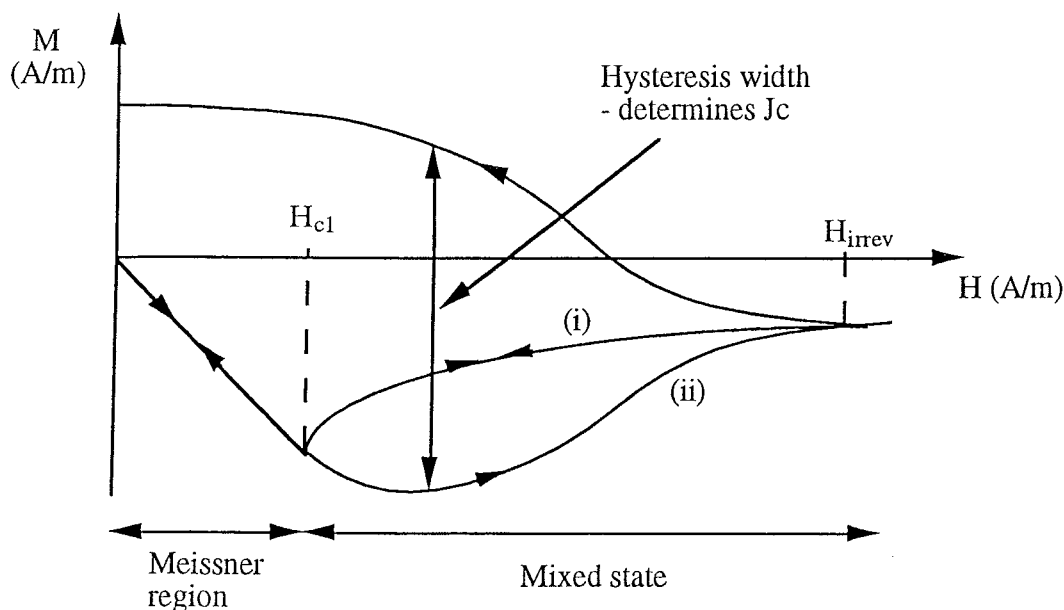
Assessor's comment

A popular and straightforward question, reasonably well-answered by most candidates. Common sources of lost marks were for confusing classification of materials with operating principles in part (a) and for not providing examples of active and passive operation in part (b).

2. (a) Magnetic flux density is generated in type II bulk superconductors by the Faraday effect. This involves applying a changing magnetic field to the superconductor, which induces an e.m.f., which causes an Eddy current to flow throughout the bulk material, which, in turn, generates magnetic flux. As a result, bulk superconductors generate fields in a way analogous to a wire-wound solenoid. The magnitude of the net magnetic moment depends on the magnitude of these induced currents and the area over which they flow. Hence the volume magnetisation, M (defined as the net magnetic moment per unit volume) increases in direct proportion to the cross sectional area of the sample, normal to the direction of applied magnetic field (i.e. in proportion to r). Critical current density is directly proportional to the number and strength of flux pinning centres in the bulk microstructure. Pinning centres impede the motion of flux lines, which leads to the formation of a gradient, dB/dz , in flux density through the thickness of slab geometry. According to the Bean model, J_c flows where field penetrates the bulk material, and is proportional to the magnitude of the local field gradient.

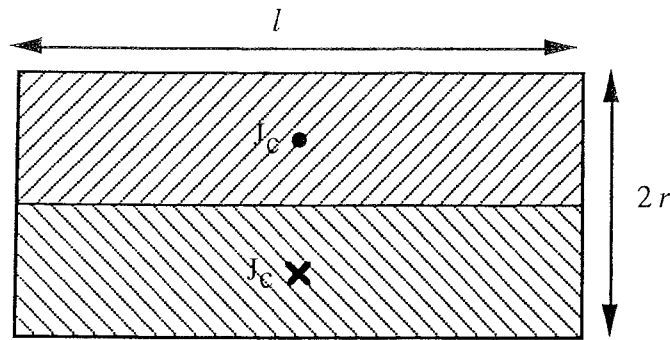
[30%]

(b) The variation of magnetisation with applied field at a given temperature for (i) an 'ideal' type II superconductor (no flux pinning) and (ii) a type II superconductor which contains magnetic flux pinning centres is as follows:



[25%]

(c) The flux density B at the centre of a long solenoid of N turns, length ℓ and carrying a current I is given by $B = \frac{\mu_0 N I}{\ell}$, where μ_0 is the permeability of free space. The analogy of the NI product of a solenoid in a long, solid superconducting cylinder is the total circumferential current. The current in one half of the cylinder determines the circumferential current:



Circumferential current = $J_c \times r \times \ell$

i.e. Flux density in the superconductor $B = \frac{\mu_0 J_c \times r \times \ell}{\ell}$

Therefore, $B = \mu_0 J_c r$

Flux density is proportional to the radius of the cylinder, as required.

[20%]

(d) The equation for the solenoid is only valid in the limit of a long solenoid, however, so the above equation only applies for superconducting cylinders of length greater than their radius, which is clearly the case here. As a result, the length of the cylinder is not required in the calculation. Also, we assume that J_c is independent of magnetic field. With these assumptions:

$$B = 4\pi \times 10^{-7} \text{ (H/m)} \times 5 \times 10^8 \text{ (A/m}^2\text{)} \times 0.5 \times 10^{-2} \text{ (m)}$$

$$= 3.1 \text{ T}$$

Applied field = 0, hence $B = \mu_0 M$ i.e. $M = \frac{B}{\mu_0}$

$$M = \frac{3.1}{4\pi \times 10^{-7}} \approx 2.5 \times 10^6 \text{ A/m}$$

[25%]

Assessor's comment:

An reasonably popular question. Very few candidates correlated J_c with flux pinning in part (a), and the proof by analogy with a solenoid in part (c) wa generally answered poorly. Only one student was able to calculate the magnetization in part (d).

3 (a) (i) The evaporation rate R_{evap} is given by (see lecture notes)

$$R_{\text{evap}} = \sqrt{\frac{m_{\text{Al}}}{2\pi k \rho_{\text{Al}}^2}} \times \frac{P_{\text{vapourAl}}}{\sqrt{T}} \times \frac{\pi r_{\text{crucible}}^2}{4\pi r_{\text{planetary}}^2}$$

inserting $m_{\text{Al}}=27u$, $\rho_{\text{Al}}=2700 \text{ kg/m}^3$, $p_{\text{vapourAl}}=1 \text{ Pa}$, $T=1473\text{K}$, $r_{\text{crucible}}=0.02 \text{ m}$ and $r_{\text{planetary}}=0.35 \text{ m}$

gives $R_{\text{evap}}=1.8 \times 10^{-10} \text{ m/s}=1.8 \text{ \AA/s}$

[15%]

(ii) The arrival rate of Al atoms is

$$J_{\text{Al}}=R_{\text{evap}} \times \rho_{\text{Al}}/m_{\text{Al}}= 1.1 \times 10^{19} \text{ atoms/m}^2\text{s}$$

The arrival rate of water $J_{\text{H}_2\text{O}}$ is given by

$$J_{\text{H}_2\text{O}} = \frac{P_{\text{H}_2\text{O}}}{\sqrt{2\pi m_{\text{H}_2\text{O}} kT}}$$

which has to be $J_{\text{Al}}/10$.

$$\text{Hence } p_{\text{H}_2\text{O}} = \frac{J_{\text{Al}}}{10} \times \sqrt{2\pi m_{\text{H}_2\text{O}} kT} = \frac{J_{\text{Al}}}{10} \times \sqrt{2\pi \cdot 18u \cdot k \cdot 293\text{K}} = 3 \times 10^{-5} \text{ Pa}$$

[15%]

(iii) An appropriate pumping scheme consists of a kinetic vacuum pump (e.g. turbo molecular pump or diffusion pump) backed by a mechanical, positive displacement pump (see lecture notes). The kinetic pump is directly connected to the chamber via a gate valve. The mechanical pump is connected via a backing valve between the outlet of the kinetic pump and the exhaust line. For pumping down the chamber, the mechanical pump typically also has an additional direct connection to the chamber via a roughing valve.

A positive displacement pump is a vacuum pump in which a volume filled with gas is cyclically isolated from the inlet, the gas being then transferred to an outlet. A rotary vane pump, for instance, contains an eccentrically mounted rotor with spring loaded vanes, which slide in and out within the cylindrical interior of the pump, enabling a quantity of gas to be confined, compressed and discharged through an exhaust line.

A kinetic pump imparts momentum to the gas (either via rotating vanes for a turbo molecular pump or via an oil vapour jet for a diffusion pump) in such a way that the gas is transferred continuously from the pump inlet to the outlet. Kinetic pumps require a certain minimum mean free path, hence require a fore/backing pump to operate.

[20%]

(iv) Evaporating Al getters water vapour and residual oxygen, hence pressure decreases.

[10%]

(b) (i) Figure 2(a) shows the carbon nanofibre array imaged with a secondary electron detector. Secondary electrons (SE), i.e. sample atom electrons that have been ejected by inelastic interactions with the primary beam, have a

typical kinetic energy of less than 50 eV. Hence SE have a short mean free path (~nm) within the sample, i.e. can escape only from the sample surface, and the SE emission is strongly dependent on sample topography.

Figure 2(b) shows the carbon nanofibre array imaged with a backscattered electron (BSE) detector. BSE are those primary beam electrons that escape the sample surface through multiple electron-atom interactions (Rutherford scattering). BSE usually retain a large fraction of their original energy, hence have a larger sample interaction volume and give a lower spatial resolution compared to SE imaging. The BSE yield (number of BSE/number of primary e-) increases monotonically with Z of the specimen.

[15%]

(ii) Carbon nanofibre growth is generally mediated by catalytic metal nanoparticles (typically Fe, Co or Ni), which in the case of Figure 2 remain at the tip of the as-grown nanofibres. The Z contrast of the BSE image shows them as bright spots.

[10%]

(iii) Energy dispersive X-ray spectroscopy (EDS) or wavelength dispersive spectroscopy (WDS) [e.g. in a scanning electron microscope (SEM)] can be used to analyse the chemical elements present within a given spot size. Through excitation by the incident e-beam, electron vacancies are created in the atomic core levels of the sample. Electrons from outer core level shells can fill these holes, and the energy freed for each transition is emitted as characteristic X-ray. The X-ray energies and intensities allow an elemental fingerprinting. For SEM-based EDS it is difficult to reduce the sampling volume to less than $1 \mu\text{m}^3$, the minimum detectable concentration for most elements is ~0.1%. Hence, the presence of for instance Fe, Co or Ni as carbon nanofibre catalyst can be confirmed, but probing the chemical composition for a tip of an individual nanofibre is not realistic.

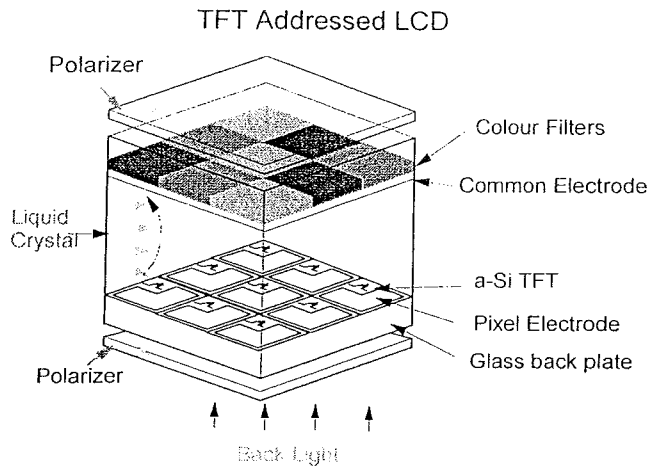
X-ray photoemission spectroscopy (XPS) or Auger electron spectroscopy (AES) are other suitable non-destructive characterisation techniques (see lecture notes) for the sample shown in Figure 2. The lateral probe size for XPS is in the order of 0.1 mm^2 , hence no individual nanofibres can be mapped. XPS is extremely surface-sensitive (due to low escape depth of photoelectrons), detectable concentration by XPS is ~0.1%. The narrow XPS linewidths allow chemical shifts to be resolved, i.e. not only the presence of Fe, Co or Ni can be confirmed for the sample but also the detailed chemical state of the nanofibre catalyst.

[15%]

Assessor's comment:

A third of the candidates attempted this question. Part (a)(i) and (ii) was poorly answered, only one candidate was able to determine the relative arrival rates in part (a)(ii). Most candidates could outline pumping scheme, but failed to consider Al gettering in part (a)(iv). Most candidates were able to distinguish between the SE and BSE image and to list probing technique for catalyst tip in part (b), but common sources of lost marks were for not explaining the basic contrast mechanisms or principles/limits of detection.

4(a)

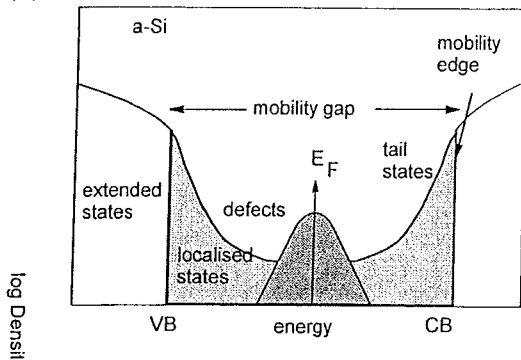


LCD acts as light switch, on or off. Light from back-light passes through polarisers which normally prevent light passage. Voltage applied to top electrode rotates polarisation plane of the light passing through the LCD so that it now comes through the top polariser.

The voltage on the top electrode is controlled by an a-Si thin film transistor (TFT)

[20%]

(b)



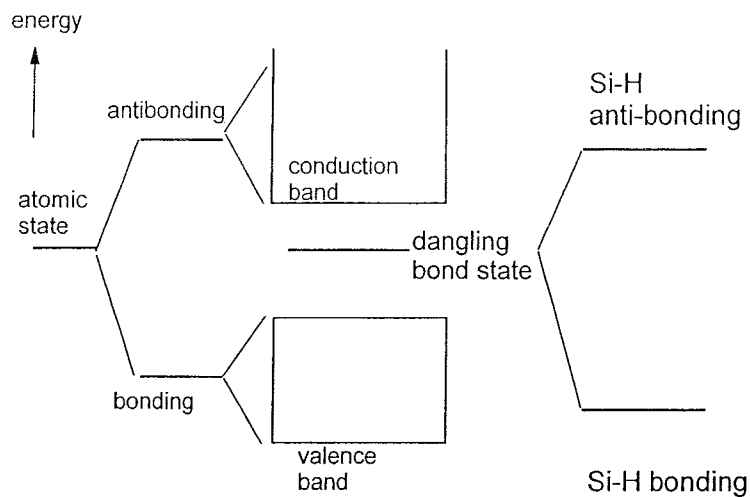
The density of states of a-Si is based on that of c-Si, with a valence band and conduction band. In same energy ranges. There is still a band gap. The disorder causes broadening of CB and VB states into the gap – the band tails. There are also defect states in the middle of the gap.

The main band states are extended, and can conduct electricity at 0 K. Those in gap and the defect states are localised, and do not conduct electricity, except under high fields or above 0 K.

Mobility of a-Si $\sim 1 \text{ cm}^2/\text{Vs}$

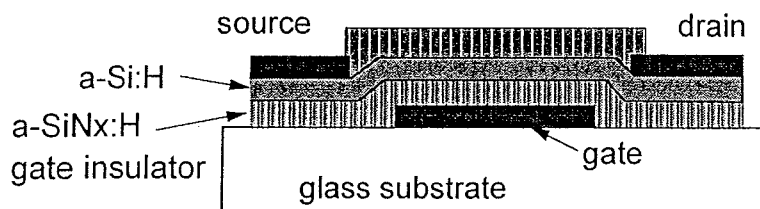
[30%]

(c) (i) The defect is the Si dangling bond, which appears in the band structure as follows;



(ii) Role of hydrogen. H is used to passivate the defects – remove the gap states in a-Si. The midgap states are due to dangling bonds, and the H makes Si-H bonds, thereby removing them. The H also sits in weak Si-Si bonds, thereby sharpening up the band tails. This reduces defect density from $1E20$ to $1E16$ cm^{-3} and improves mobility. [25%]

(d)



The typical TFT has a channel of a-Si, a gate insulator of a-SiN_x. It is 'bottom gate'. It is staggered – source/drain on opposite sides than gate. Gate voltage induces charge in the channel, which then flows under influence of V_{ds} to drain. [25%]

Assessor's comment:

A question about amorphous Si, displays and thin film transistors that had not been asked before. Four attempts were good, one was poor. The four good attempts gave good answers to all sections on the question, but lacked some detail where they lost marks. The candidates failed to give values for things like defect densities and mobility of a-Si.

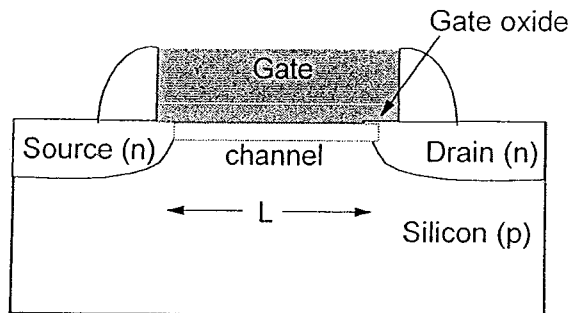
5 (a) Moore's law describes the 'scaling' of transistor dimensions in integrated circuits, and how these reduce by some factor each year. Example; size reduces by factor of 2 every 2 years. Scaling typically occurs at constant electric field, so this allows other parameters to be fixed. [15%]

(b) The surface of a semiconductor has dangling bonds. These create midgap states, which will act as recombination centres and traps. These will degrade device performance.

If you put SiO_2 onto the surface, the Si DBS now form Si-O bonds, and this converts Si DBS into Si-O bonds, whose states lie outside the Si band gap, so there is no recombination.

[10%]

(c)



[15%]

(d) SiO_2 is used for four main purposes;

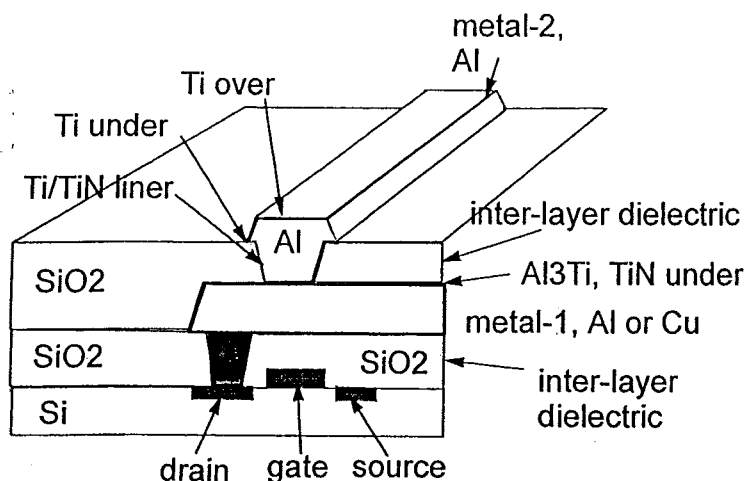
1. The gate dielectric;
2. The surround /intermetal dielectric;
3. The passivant;
4. The ion implantation/dopant mask.

Gate oxide -> high K oxide. Increases capacitance.

Intermetal dielectric -> low K dielectric to reduce capacitance, reduce RC time delay.

[20%]

(e) The components of a MOSFET are as follows;



The following changes would result in improved performance;

1. Channel -> high mobility channel - GaAs or Ge (mobility)

This would increase the mobility of the carriers and therefore increase the transconductance of the MOSFET.

2. Gate oxide -> high K oxide (raise C)

This would increase the gate-channel capacitance. So, for a given voltage, a larger charge density is induced in the channel, which would increase the drain current in proportion.

3. Intermetal dielectric -> low K oxide (lower C)

This would reduce the capacitance between the wires in the IC, so for a fixed R in the wires, the RC time constant is reduced, which reduces delays in signal transmission.

4. Interconnects, Al -> Cu -> carbon nanotubes (raise current density)

Al will carry a higher maximum current density, which would allow a large current density to flow between different FET devices.

5. Contact metals -> silicides (compatibility)

The use of silicon would reduce the resistance of the source and drain contacts and their Schottky barrier heights, so lowering the overall resistance of the circuit. This would reduce power loss and RC delays.

6. Gate electrodes, doped poly -Si -> gate metals (conductivity, depletion length)

This would reduce the gate depletion depth, so increasing the gate capacitance (see point 2 above). [40%]

Assessor's comment:

Question about scaling and the materials used in CMOS. The most popular question, perhaps because this is the core of this part of the course, and some variant is likely to appear most years. All except 2 candidates made good attempts on the question. The top candidate of 4C3 made an excellent attempt. For the good attempts, candidates lost marks mainly for lack of detail, rather than from incorrect answers or misunderstanding.