1) A) I) Soft magnetic materials exhibit a large magnetisation response to an external field but do not exhibit a large remanence as they have a small Hc. Hard magnetic materials exhibit strong pinning of domain walls which leads to hysteresis .

For example, the sketch below shows pure iron, a relatively soft material and SmCo a hard material. The real difference in Hc is larger than depicted below – values are 4 Am^{-1} for iron and 600 Am^{-1} for SmCo. Consequently, if plotted on the sma scale it is not unreasonable to depict the soft material as a straight line with almost no hysteresis. A soft material is thus, between saturation, like a paramagnet with orders of magnitude greater relative permeability.
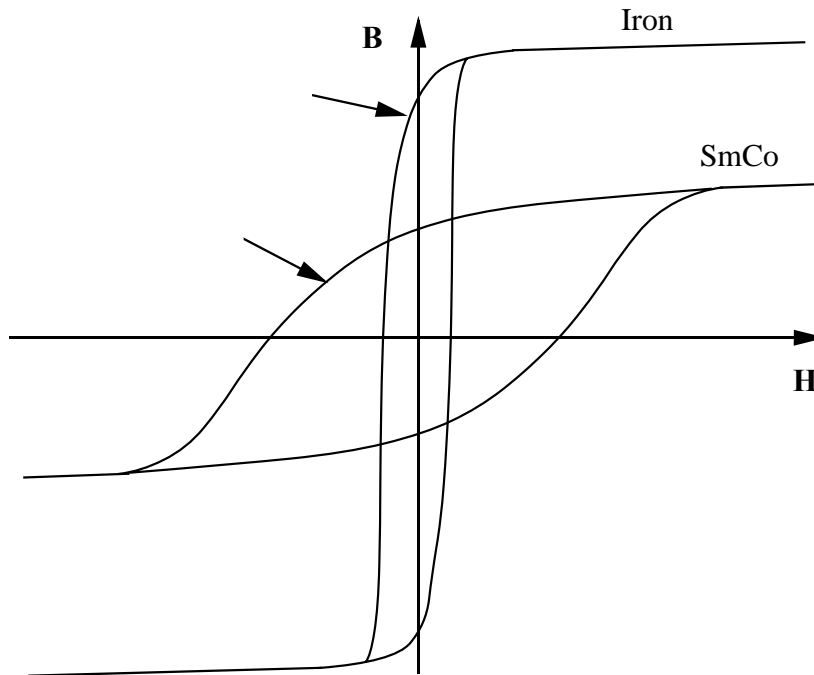
ii) Key paramters are the saturation magnetisation (which leads to saturation field) which is the field at which all the spins in the material is aligned, coercive field which is the field required to de-magnetise a magnetic material. Further properties include the Curie temperature above which magnetic ordering disappears and (BH)max which is the maximum energy density in the magnetic field achieveable when a permanent magnet is fabricated from a particular material.

Saturation field and Curie termperature are important in both cases. For a soft material the coercive field must be as small as possible whereas in a hard material it needs to be as large as possible. When making permanent magnets from a hard material the BH energy product is a key parameter.

iii) Any reasonable examples accepted here such as (soft) permalloy for magnetic recording heads, electrical steel for transformers , soft iron for the core of an electromagnetic in a scrap yard and ferrite in the core of a high frequency transformer in a switched mode power supply. For hard example materials include Alnico, SmCO and NdFeB and applications include motors, generators, fridge magnets, positioning and focussing electron beams.

b) The magnetisation from a conventional magnetic material is due to the alignment of the spin (both electron and orbital) associated with the atoms within the material. The number of Bohr magnetons available per volume is fundamentally limited and thus maximum Magnetisation is sample size independent. It depends on the material itself.

In a superconductor however, the Magnetisation depends on a current loop and thus depends on the size of the sample as well as the maximum critical current available.

c) i) The Magnetisation leads to a magnetic field in the magnetic material that acts back through the material itself – hence the term demagnetisation.
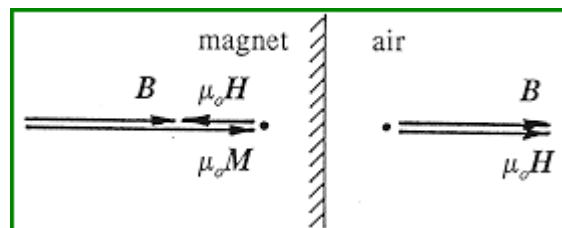

The magnitude of this field is given by -NM where N is the demagnetising factor of the shape of the magnet. For an infinite rod no field returns through the material so N is 0 for a flat plate all field returns so it is 1.

ii) From $B=\mu_0(M+H_0)$ we can then write that $B_{op}=\mu_0(M-MN)$ or $B=\mu_0 M(1-N)$. However $M=H/-N$ so we obtain the required result $B=\mu_0 (1-N)/N$
This is a line on a BH plot through the origin with gradient:

$$\frac{B_{op}}{H_m} = \mu_0 \frac{M - NM}{-NM}$$

Rearranging we obtain the required result. If this is plotted on the BH characteristic for the magnetic material in question the intersection defines the operating point of the magnet. At that point the values of B and H give the energy product.

Load line

Operating point
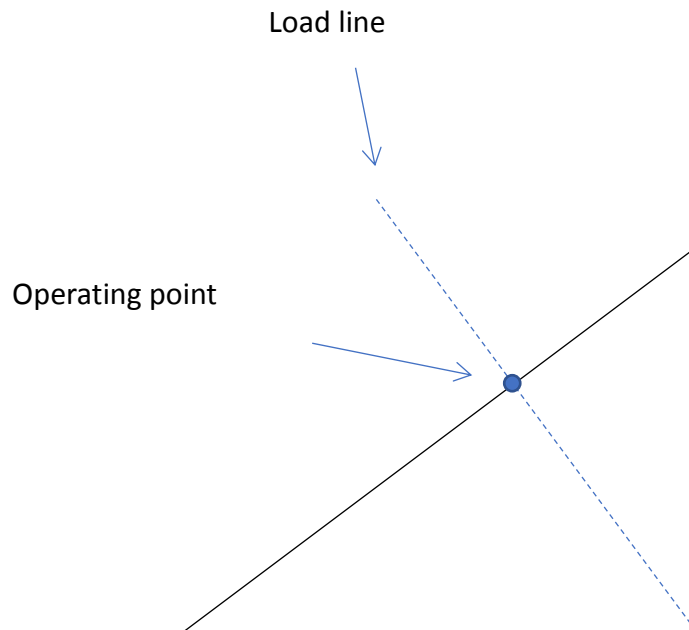
iii) To get maximum energy we need to maximise the BH product. Take the derivative of B times H which is μ_0(M-MN) times $-M N$. The derivative is μ_oM2(2N-1) so N=1/2 is the optimum demag factor to get the most energy in the field. A squat cylinder of height equal to radius has N roughly equal to 0.5.

This question was very well answered for the most part. Candidates lost marks by simply providing equations in response to questions rather than an actual explanation as required. Part (b) which required candidates to appreciate the difference between magnetisation due to intrinsic spin in a ferromagnet and magnetisation due to a circulating current in a superconductor was the least well answered part with some incomplete or irrelevant answers.

2) I) Both pyroelectric and piezoelectric materials are sub-classes of dielectric materials. Their electrical properties arise from asymmetry in their crystal structure. Many dielectric materials are piezoelectric (20 of 21). Pyroelectric materials need to have an axis with a dipole moment along it, consequently fewer dielectric structures exhibit pyroelectric properties (10 of 21). All pyroelectrics are piezoelectric.

Piezo electric materials have a symmetry such that strain causes a separation of charge centres. In a pyro electric material it is further the case that the change in lattice paramters occasioned by change in temperature also leads to a change in charge centre position.
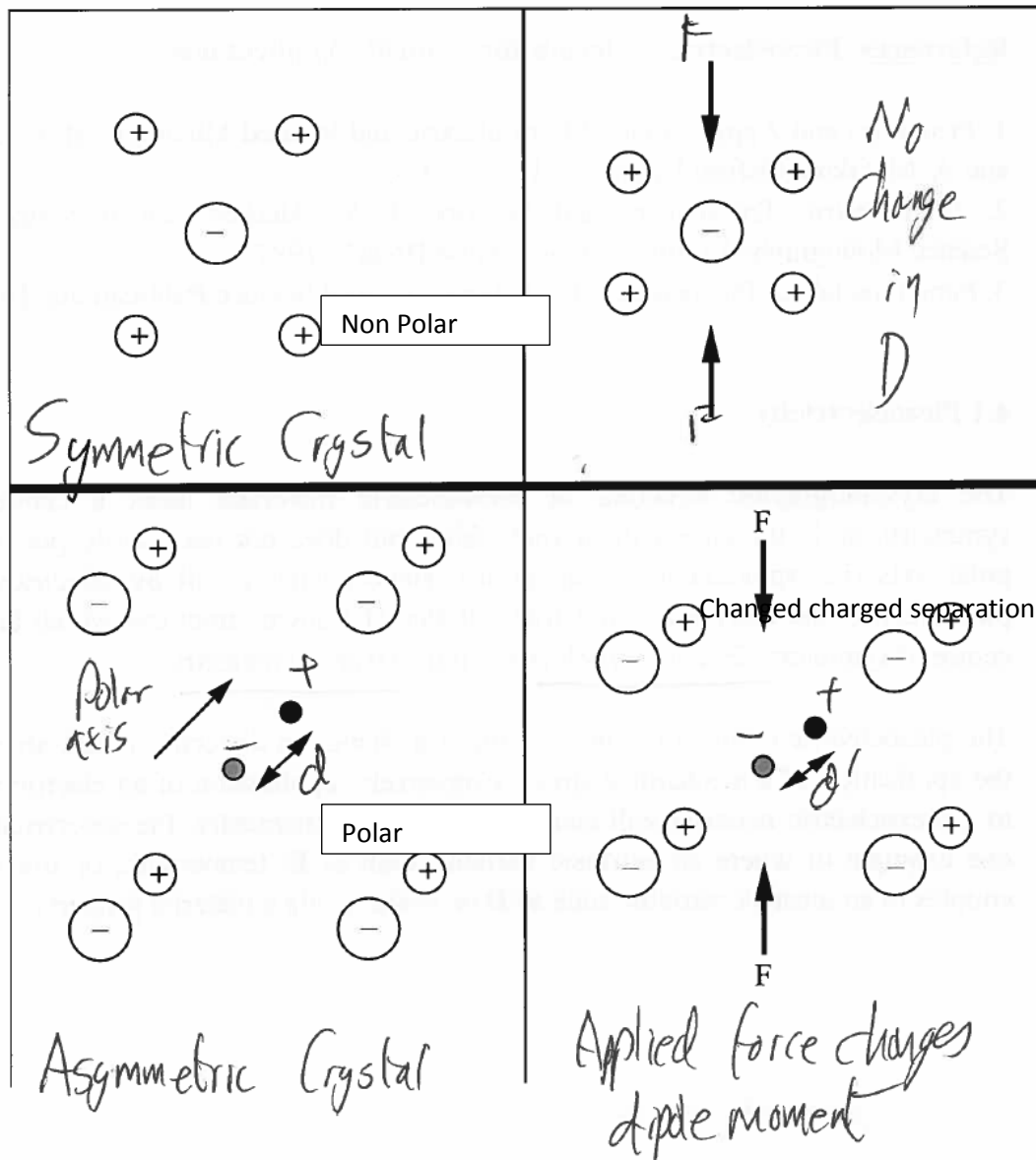
ii) From a practical point of view most piezo and pyro electric materials used in applications are ferroelectrics, materials which exhibit remnant polarisation since they are easy to pole and have multiple axes along which they exhibit pyro/piezo electrical properties so the

direction of operation can be defined with a large electrical field. It also means that polycrystalline materials can be used .

iii) Electric dipole per unit cell =qr

where q is the charge on each ion and **r** is the displacement between positive and negative charge centres, measured from + to −.

The spontaneous polarisation, **P**$_s$, is then given by the total dipole moment per unit volume, V:

$$P_s = \frac{\sum_{all} q \cdot r}{V} \quad (Cm^{-2})$$

b i) Tensor equations arise when a change in one variable in one direction causes a change in a second variable in a different direction. There are 3×3 possible applied stresses.

This would require a tensor of order 3 to relate P to σ:

$$P_i = d_{ijk}\,\sigma_{jk}$$

It is possible to use reduced suffix notation when the indices i and j are interchangeable (i.e. when $\sigma_{23} = \sigma_{32}$, etc.), which is the case here by symmetry.
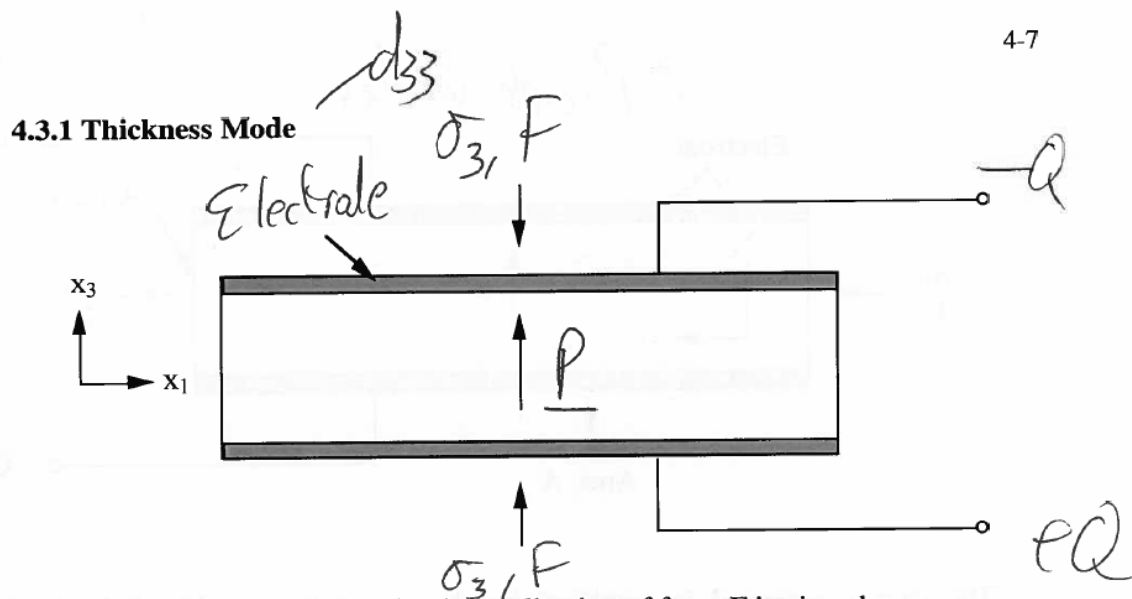
Hence $\sigma_{jk} \rightarrow \sigma_j$ (j = 1 to 6). These represent the three uniaxial (σ_1 to σ_3) and three shear (σ_4 to σ_6) stresses (compressive forces are negative, by convention).

This leads to a simplified matrix form for P

$$\begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{pmatrix}$$

ii) Piezoelectric materials are practically used in the form of thin plates so strain or large field is only developed in one direction. In this geometry therefore E_1, E_2 or σ_1, σ_2 are zero. Consequently only $d_{31}=d_{23}$, d_{33} and $d_{15}=d_{24}$ are non-zero.

iii) The three operating modes are therefore the longitudinal, thickness and shear modes of operation corresponding to $d_{31}=d_{23}$, d_{33} and $d_{15}=d_{24}$ respectively.

c) $P = \chi\, E + d\, \sigma$ hence $\left(\dfrac{\partial P}{\partial \sigma}\right)_E = d$, $\Delta P = d\, \Delta \sigma$

$\Delta P = \Delta Q/A$, $\Delta\sigma = \Delta F/A$, $\Delta Q = C\,\Delta V$, $C = \dfrac{\varepsilon_0\, \varepsilon\, A}{t}$

i.e. $\Delta P = \dfrac{\Delta Q}{A} = d\,\dfrac{\Delta F}{A}$ so $\Delta Q = d\,\Delta F = C\,\Delta V$

Thus:

$$\Delta V = \frac{d\, t\, \Delta F}{\varepsilon_0\, \varepsilon\, A} = \frac{t\, \Delta F}{\varepsilon_0\, A} \times \frac{d}{\varepsilon}$$

This question was, in general, well answered. Candidates lost marks for the most part for deficient explanations that failed to cover key points. Many sketches used in explanations were sufficiently rough to hinder the examiner in understanding them.

3 (a) $F = \pi r^2 \times \Delta p = \pi\,(0.25)^2 \times (10^5 - 1\, Pa) = 20000\, N$

Assume weight of horse 500 kg, i.e. force per horse = 500 × 9.81 N = 4900 N. So 5 horses required.
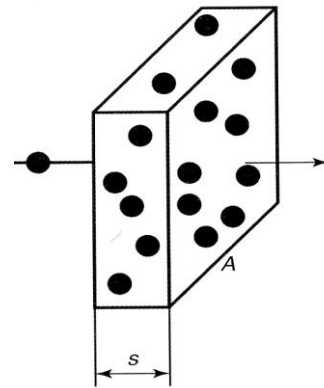
(b) Derivation of mean free path λ (see lecture notes)

effective cross section   σ= πd^2
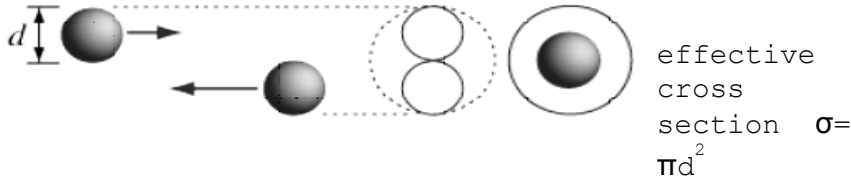
total collision area = N×σ = n×A×s×σ,

where n is number density of gas, σ is effective cross section and V=A×s is volume.

If total collision area equals A, then s=λ, hence
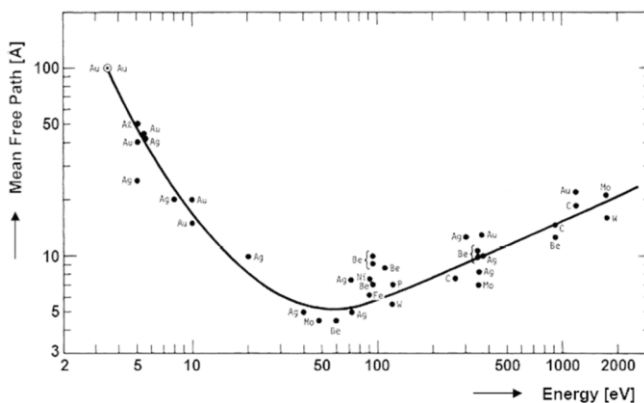
$$\lambda = \frac{1}{\sigma n} = \frac{1}{\pi d^2 n}$$

Taking relative velocities for a homogeneous Maxwellian gas into account, this value for λ reduces by a factor of √2

Assume von Guericke achieved pressure of 1 Pa:
λ at RT: d=0.5 nm, use ideal gas approximation: n=p/kT

$$\lambda = \frac{kT}{\pi d^2 p} \cong 5mm$$

(c) (i) Universal curve:

(ii) In XPS X-ray absorption results in the creation of photo-electrons, the energy of which is characteristic of the elements in the sample and their chemical state (see lecture notes for more detailed description). The escape depth of photo-electrons relates to the inelastic mean free path of electrons in solids, i.e. the universal curve of (i). This escape depth and hence the XPS surface sensitivity can be tuned by either changing the X-ray energy [hence changing the kinetic electron

energy, which affects the electron mean free path as plotted in (i)], or by changing the emission angle by tilting the sample (i.e. changing the geometric path length). Collecting at a more grazing emission angle for instance will lead to increased surface sensitivity by increasing path length of photo electrons by cos of the tilting angle.

(d) (i) see lecture notes:
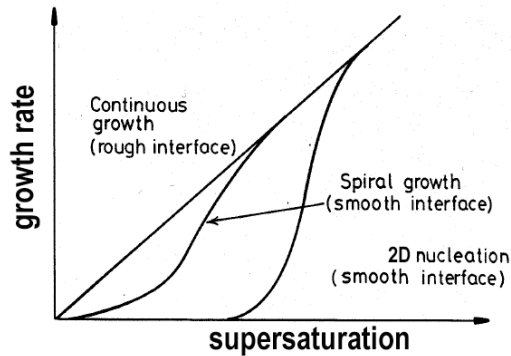
(ii) Typical Si nanowire CVD uses a transition metal catalyst nanoparticle, such as Au, that selectively (compared to say a SiO_2 support layer) reacts with the gaseous precursor (for instance silane) at elevated temperature. At temperatures above the Au-Si eutectic, this leads to the liquefaction of the nanoparticle and upon Si supersaturation to the nucleation of a Si crystal. This is often described in terms of the so-called vapour-liquid-solid growth model. The Si nanowire then grows in a 2D nucleation regime, that is layer-by-layer, at the liquid-solid interface between the Si crystal and the AuSi nanoparticle that wets the emerging crystal and rides at its tip.

(e) The native oxide layer on a Si nanowire could be analysed by transmission electron microscopy (TEM), which offers the required spatial resolution as well as allows analytical modes (such as electron-energy loss spectroscopy) to map the level of oxidation.

While most candidates could give expression for mean free path and outline some XPS and CVD principles, the parts that required deeper understanding incl. discussion of inelastic mean free path and supersaturation could only be answered by the better students. The 2D nucleation part in d(i) was not well answered, and some candidates got mixed up and discussed mass-transfer and surface reaction-controlled regimes. Also part d)(ii) mainly attracted generic comments on CVD, and only one candidate discussed actual catalytic nanowire growth.

Q4.(a)
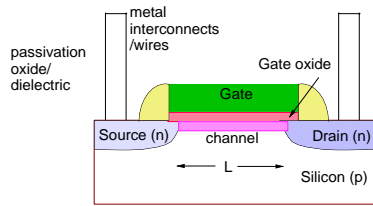
(b)   gate electrode. Changed from heavily doped poly-Si to TiN or other metal, to give higher conductivity.

Gate oxide. Changed from SiO2 to a thicker layer of a high K oxide such as HfO2, to stop tunnelling conduction through the gate oxide.

Interconnects. Al has changed to Cu to increase conductivity

Inter-wire dielectric. Has change from SiO2 to low K dielectric such as SiOF and then polymer SiCHO.

(c)
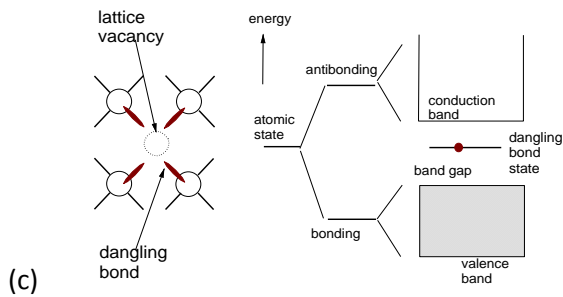
(d) The dangling bond state in the gap come from broken bonds at vacancies, surfaces etc. Their energy is at the original sp3 bond energy, so they lie in midgap.

   Defect states can also come from dopants which have deep levels due to small dielectric constant or high effective mass of the semiconductor.

   (e)   passivation is the removal of gap states from the gap, often by a chemical reaction with a passivant. Typical passivants are SiO2 or hydrogen.
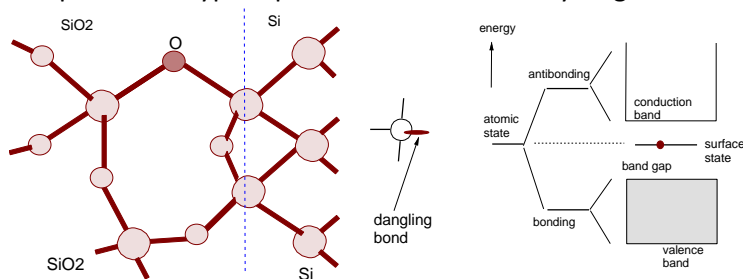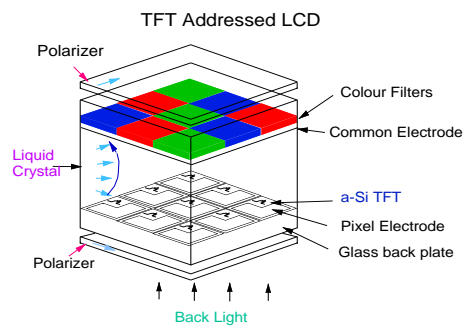

   H converts Si DBs into Si-H bonds whose states lie outside the Si band gap energy range.

   SiO2 converts Si DBs into Si-O bonds, whose states also lie outside the Si band gap energy range.

Generally high scoring question. Most people knew 4B. Answers noticeably less good when it came to 4E.

Q5(a)

TFT Addressed LCD

polariser polarises light from the lights at bottom. This passes through the liquid crystal layer. The LC layer can rotate the plane of polarisation so that the light can no longer pass through the second polariser layer at the top. A voltage applied between the top transparent electrode and the bottom electrode changes the polarisation of the LC layer, and so allows the light to pass through. The display is divided into pixels of the 3 primary colours, and this makes up the full display.

(b)
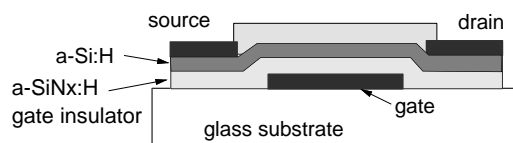
This is a bottom gated staggered structure. The current flows from source to drain, passing across the a-Si layer to the bottom of that layer. The gate dielectric is a-SiNx:H. The gate is a metal. Positive voltage on this electrode creates electron density in the a-Si:H channel above the gate, and current flows.

Differences to standard CMOS are a-Si:H channel, a-SiNx:H gate dielectric instead of SiO2 or HfO2, staggered structure instead of top gate, enhancement mode instead of inversion mode conduction.

(c)
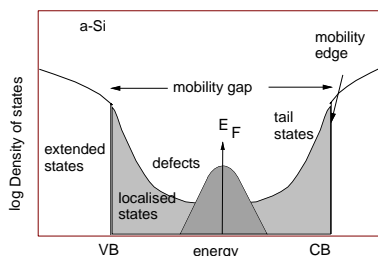
Extended states conduct electricity at 0^0K, like the band states in a crystal.

Localised states of band tail are created by the disorder. They do not conduct electricity at 0^0K. Conduction for these occurs by hopping from 1 state to the next (tunnelling) or by thermal activation to the extended states.

(d) Substitutional doping does work in a-Si:H, but not very well/efficiently. It can be doped and used in solar cells and thin film transistors. As in c-Si, P is a donor and B is an acceptor. Doping is carried out by adding PH_3 or B_2H_6 to gas mixture used to deposit the film. The doping is quite inefficient compared to in c-Si, as most dopant atoms introduced do not lead to free carriers.

We nonetheless use a-Si as:

1/ cheap, by factor 100,000
2/ made over large areas, 4m x 6m.
3/ made at much lower temperatures, 250C instead of 1000C.

(e)
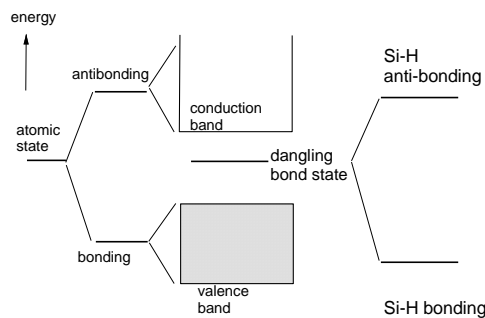
Hydrogen converts Si DB states into Si-H bonds, whose states lie within the valence or conduction band, out of the a-Si:H band gap, as in diagram.

This question was answered moderately well. Answers to parts C-E were not good, partly because candidates appeared to have run out of time.