

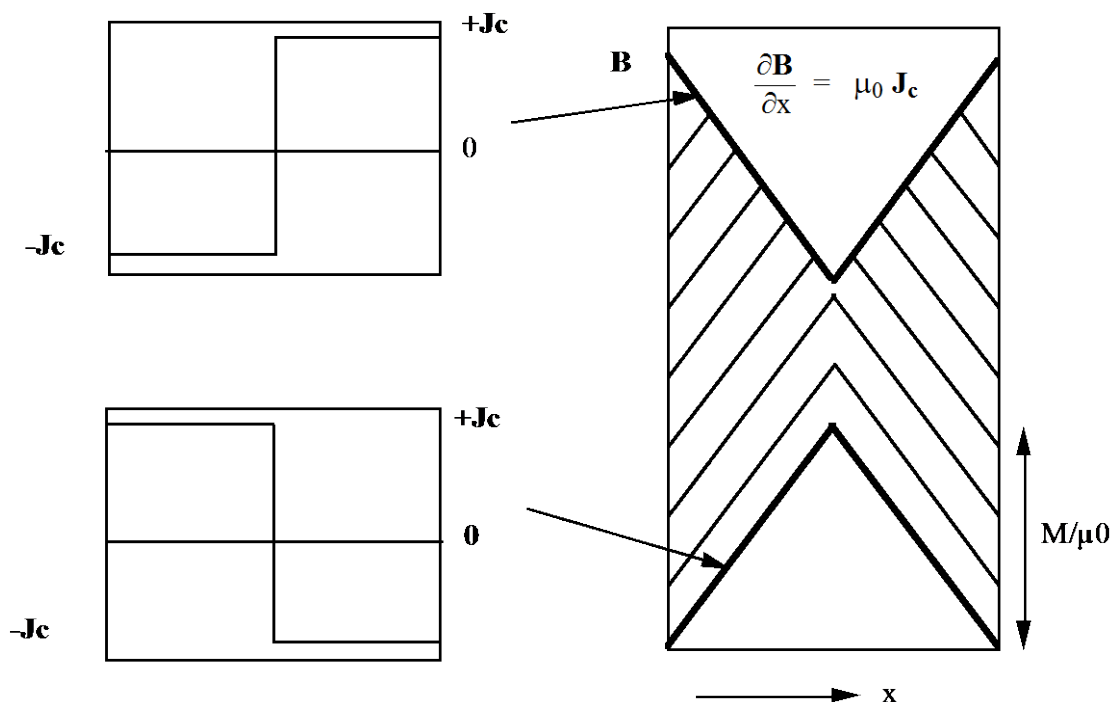
Engineering Tripos Part IIB  
 Friday 24 April 2015 9.30 to 11

**MODULE 4C3: Electrical and Nano Materials**

**Crib**

Q1) (a) The Bean model describes the flow of current and penetration of magnetic field into a bulk type II superconductor. It assumes that there are no local magnetic dipoles (i.e. unpaired spins) present in the material so the currents can be treated as in the free space case (i.e.  $B = \mu_0 H$ ) and that the current density flowing is either  $+J_c$  or  $-J_c$  where the field penetrates the material.  $J$  is zero elsewhere.

A bulk superconductor of slab geometry is magnetized by first cooling below its superconducting transition temperature, followed by the application and removal of a magnetic field (the zero field cooling magnetization process). It is necessary to apply approximately twice the penetration field to completely magnetise a bulk superconductor of slab geometry when the applied field is removed to achieve complete reversal of the induced current.



It is necessary to apply approximately twice the penetration field to completely magnetise a bulk superconductor of this geometry when the applied field is removed to achieve complete reversal of the induced current. Field penetrates or is removed only as lines of slope  $\mu_0 J_c$ .

Also accept – FC process where the superconductor is cooled in field equal to maximum trapped field.

*[A clear and coherent answer was required to score highly here. Some candidates wrote down a hodge-podge of correct facts but without clearly linking them]*

b) For a thin superconducting slab with a d.c. field (i.e.  $\frac{d\mathbf{D}}{dt} = 0$ ) applied parallel to the slab surface with the assumption of the Bean model (i.e.  $\mathbf{B} = \mu_0 \mathbf{H}$  and  $\mathbf{J} = \mathbf{J}_c$ ) :

$$\text{Curl } \mathbf{B} = \mu_0 \mathbf{J}_c$$

$$\text{Curl } \mathbf{B} = \nabla \wedge \mathbf{B} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ B_x & B_y & B_z \end{vmatrix} = \mu_0 \mathbf{J}_c$$

Assumptions;

1.  $\mathbf{B}$  is constant in the slab for constant  $y$  and constant  $z$ . Hence  $\frac{\partial}{\partial y} = \frac{\partial}{\partial z} = 0$ .

2.  $B_x = B_y = 0$ .

Therefore :

$$\text{Curl } \mathbf{B} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & 0 & 0 \\ 0 & 0 & B_z \end{vmatrix} = \mu_0 \mathbf{J}_c \quad \text{i.e. } \frac{\partial B_z}{\partial x} \mathbf{j} = \frac{\partial \mathbf{B}}{\partial x} \mathbf{j} = \mu_0 \mathbf{J}_c$$

$$\frac{\partial \mathbf{B}}{\partial x} = \mu_0 \mathbf{J}_c \quad \text{where } \mathbf{J}_c \text{ is parallel to } y.$$

$B$  is therefore  $\mu_0 J_c x$

ii) The result from the last question can be integrated to give the average magnetisation in the slab so  $M = J_c d / 4$ . (Peak  $B$  is  $\mu_0 J_c d / 2$ , average  $B$  is therefore  $\mu_0 J_c d / 4$  so  $M$  is  $J_c d / 4$ ).

If we can relate the Magnetisation to  $J_c$  this means we can measure the M-H loop of a superconductor and use this to determine its critical current.

*[Some candidates lost marks by doing the maths but not explaining why this can be used. Candidates were not penalised for being a factor of two out in their calculation of the average magnetisation, as this problem is often presented with a slab of thickness  $2a$ .]*

c) For the NdFeB the Magnetisation is  $B_{rem}/\mu_0$ . This is independent of sample thickness and is thus  $8 \times 10^5$  A/m in both cases. For the superconductor in the 4mm case the Magnetisation is  $8 \times 10^5$  A/m. However in the 8mm case the Magnetisation is  $1.6 \times 10^6$  A/m. The key observation here is that in a conventional permanent magnet material  $M$  is a materials parameter whereas in a superconductor it goes up linearly with the length over which the current loop is flowing.

*[The maths here was generally right although with some unit errors i.e. A/m<sup>2</sup> in place of A/m. Some candidates got confused and multiplied by  $\mu_0$ . Candidates were not penalised for being a factor of two out in their calculation of the average magnetisation as this problem is often presented with a slab of thickness  $2a$ .]*

Q2) (a) Full marks could be obtained for bullet point descriptions of these effects. Pyroelectric materials are sub-classes of dielectrics, and are characterised by an asymmetry in their crystallographic structure, which leads to polar properties. Pyroelectricity occurs in polar dielectrics whose structure contains at least one *axis* along which an electric dipole moment exists (in contrast to piezoelectrics, which are characterised by point symmetry). Only 10 of the 21 dielectric structures, therefore, exhibit pyroelectric properties (orthorhombic, tetragonal and triclinic, for example). A pyroelectric material is necessarily piezoelectric, although the converse is not true.

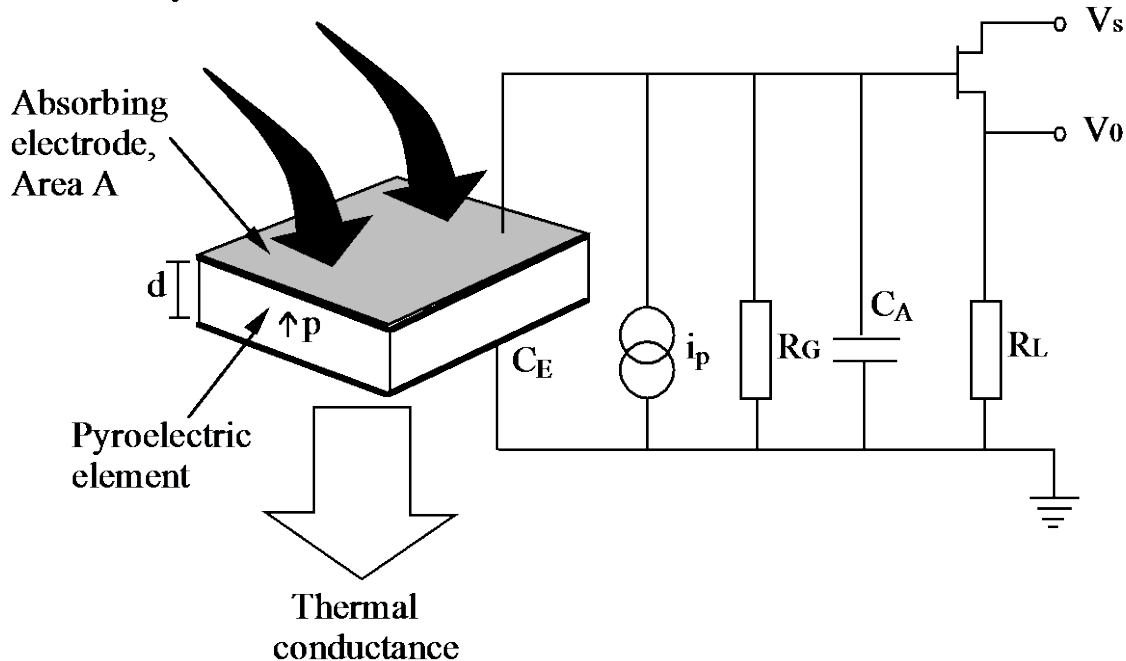
The pyroelectric effect arises due to the change in the asymmetry of the crystal lattice when the crystal lattice parameters change with heating of the crystal. If not read out this change in polarization soon disappears due to the leakage current back through the material.

b) Ferroelectrics are the most versatile form of pyroelectric materials for the manufacture of pyroelectric devices, although not all pyroelectrics are ferroelectric. Ferroelectrics are polar materials in which the direction of the spontaneous dipole moment can be changed by the application of an electric field due to the presence of a number of polar axes in the crystal structure (which is a particular feature of the perovskite lattice). As a result, ferroelectrics may be processed in the form of ceramics (polycrystalline materials), and polarised using an applied electric field. This is cheaper and easier than using non-ferroelectrics such as  $\text{LiTiO}_3$ , which has only one polar axis and, therefore, has to be processed in the form of a single crystal. This is both complex and expensive (although single crystals tend to have higher pyroelectric coefficients than polycrystalline materials). Ferroelectrics undergo a structural phase transformation to a lower crystal symmetry at the Curie temperature,  $T_c$ . This means that if heated above this temperature they will “depole” and the detector is likely to become useless. Consequently a ferroelectric with a sufficiently high Curie temperature must be chosen.

*[While candidates noted the multiple axes and consequent ability to pole in any direction, some missed the point that this means ferroelectric pyroelectric elements can be polycrystalline which is an important consideration.]*

c)

Incident radiation,  
sinusoidally modulated



The above is a very full diagram. In the case of a motion detector the modulation comes from the segmented fresnel lenses in front of the detector which turns the moving infra red source in front of the detector into something approximating to a sinusoid.

$d$  - element thickness,  $p$  - pyroelectric coefficient which leads to a voltage,  $C_E$  - element capacitance,  $i_p$  pyroelectric current,  $R_G$  - FET gate resistance,  $C_A$  capacitance of the amplifier,  $R_L$  load resistance

Incoming infra-red radiation is modulated and focused onto the pyroelectric element (which has been coated in a radiation-absorbing surface, such as platinum-black). This causes the temperature of the element to rise, and for its intrinsic polarisation to decrease. This, in turn, causes charge to be released from the element (which is effectively the dielectric filling in a capacitor), with the amount of charge being directly proportional to the temperature change. The signal is then amplified using a FET, which has high input impedance to take the signal from a high impedance source.

For a good response, a pyroelectric element should:

1. Absorb and retain as much heat as possible during charge release monitoring;
2. Have a low thermal capacity (for max. temperature rise for given heat input);
3. Retain the charge long enough for it to be amplified (long enough electrical time constant required).

The detector will operate under (i) current mode at low frequencies ( $\sim 10$  Hz - current has time to flow) and (ii) voltage mode at high frequencies ( $\sim$ kHz - current does not have time to flow).

d)

$$\Delta T = \frac{\eta W_0 e^{i\omega t}}{G_T + i\omega H}$$

Substitute  $Y = \frac{1}{R_G} + i\omega C$  ( $C = C_E + C_A$ ) and  $H = \tau_T G_T$ ;

$$i_p = A p \frac{dT}{dt} = \frac{\eta p A i \omega W_0 e^{i\omega t}}{G_T + i\omega H}$$

$$R_V = \frac{i_p}{Y W_0} = \frac{\eta p A i \omega e^{i\omega t}}{G_T (1 + i\omega \tau_T) \left(\frac{1}{R_G} + i\omega C\right)}$$

But  $C = \tau_E/R_G$  hence ;

$$R_V = \frac{\eta R_G p A i \omega e^{i\omega t}}{G_T (1 + i\omega \tau_T) (1 + i\omega \tau_E)} = \frac{\eta R_G p A i \omega e^{i\omega t} (1 - i\omega \tau_T) (1 - i\omega \tau_E)}{G_T (1 + \omega^2 \tau_T^2) (1 + \omega^2 \tau_E^2)}$$

The modulus of the Responsivity is therefore (recall that  $|z|^2 = zz^*$ ):

$$|R_V| = \frac{R_G \eta p A \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2} \sqrt{1 + \omega^2 \tau_E^2}}$$

ii) Substitution of the given value for omega into the derived equation leads to

$$R_v(\max) = \eta p A \frac{R_G}{G_T} \left( \frac{1}{(\tau_T + \tau_E)} \right)$$

In an imaging system there must be a chopper element to modulate the incoming infrared light. The chopper speed needs to be adjusted so that the modulation frequency of the incoming light  $\omega$  is  $1/\sqrt{\tau_E \tau_T}$ .

*[Some candidates talked about changing the pyroelectric material, although the questions states this is fixed.]*

3 (a)(i) Evaporation method relies on heating source material high enough for vapour pressure to become significant and material to evaporate (or sublime from solid state) onto target substrate (details see lecture notes). Low vacuum pressure gives higher evaporation rate and clean conditions. [15%]

(ii) Evaporating Al getters water vapour and residual oxygen, hence pressure reduces. [10%]

(iii) Basic expression for mean free path:

$$\lambda_{mfp} = \frac{1}{\sigma n} = \frac{1}{\pi d^2 n}$$

Assume ideal gas:  $p = nkT$

Hence

$$\lambda_{mfp} = \frac{kT}{\pi d^2 p}$$

Take estimate for cross section, order of  $d \approx 0.5$  nm. With  $p = 10^{-5}$  Pa,  $T = 298$ K:

$$\lambda_{mfp} \approx 0.5 \text{ km}$$

Hence evaporation is in “line-of-sight”, resulting in shadow effects and poor step coverage. [20%]

(iv) Step coverage can be improved by sample rotation and heating the substrate to activate diffusion of evaporated species. [10%]

(b) (i) The fact that graphene is actual monolayer can be inferred from interference contrast in optical microscope. This relies on interference effects from beams of light reflected from the various interfaces of the graphene/oxide/Si trilayer system, eg of oxide/Si, graphene/oxide interfaces, and can be easily seen under white light illumination in reflection. [15%]

(ii) A method to highlight that graphene is made up only of carbon is X-ray photoelectron spectroscopy (XPS). In XPS, the sample is irradiated with (relatively low energy) X-rays and the absorption of these photons results in the ejection of electrons via the photoelectric effect. The kinetic energy of the emitted photoelectrons is given by  $E_{kin} = hc/\lambda - E_b$ , where  $E_{kin}$ ,  $hc/\lambda$  and  $E_b$  are energies for ejected  $e^-$ , incident photon and involved bound electron state, respectively. Since values of the binding energy are element specific, atomic identification and characterisation of elemental composition is possible through measurement of photoelectron energies and number of photoelectrons. [15%]

(c) In a simple model, thin film nucleation can be described in terms of classical thermodynamics, where overall system then strives to minimize Gibbs free energy. The force equilibrium at three phase boundary can be expressed as

$$\gamma_{sv} = \gamma_{fs} + \gamma_{fv} \cos \theta$$

where subscripts f, s, v represent film, substrate and vapour, respectively (analogous to wetting for water droplets).

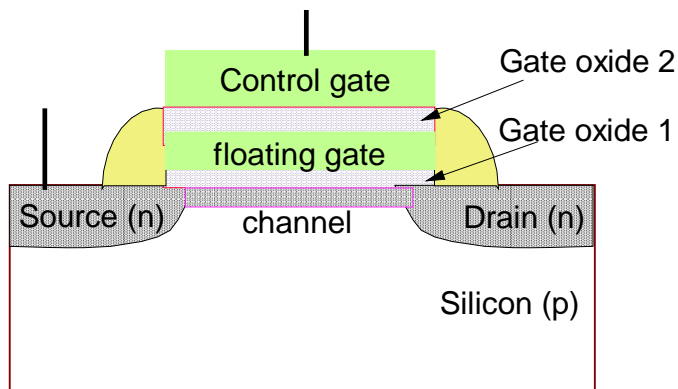
For  $\gamma_{sv} < \gamma_{fs} + \gamma_{fv}$

an island nucleation mode, called Volmer Weber growth mode, results. This can be expected for graphene support, as it does not like to be “wetted”. One could argue graphene is so thin that it shows “wetting transparency”, but same is expected for Al evaporation on SiO<sub>2</sub>. [15%]

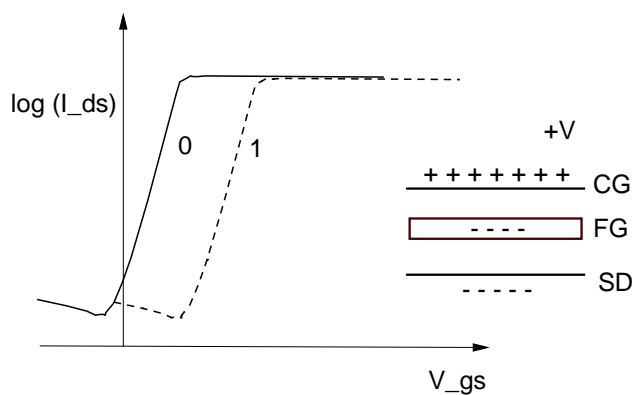
*[Question generally answered well, but descriptive parts often lacked clarity or failed to cover all parts of the question. A number of mistakes were made on the numerical part of (a)(iii), although derivation of mean free path was presented well, often even incl. correction factor from Maxwell statistics. But simple estimate did not have to include that.]*

4 (a) Non-volatile = Data is retained if supply voltage is turned off. Volatile = data is lost if supply voltage is turned off. Data is retained by periodic refreshment.

(b)



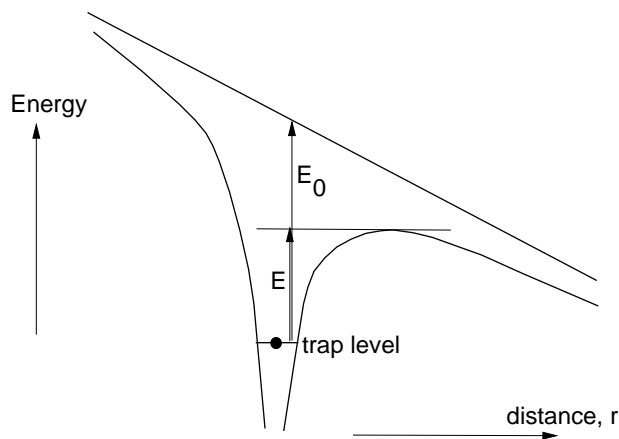
(c)



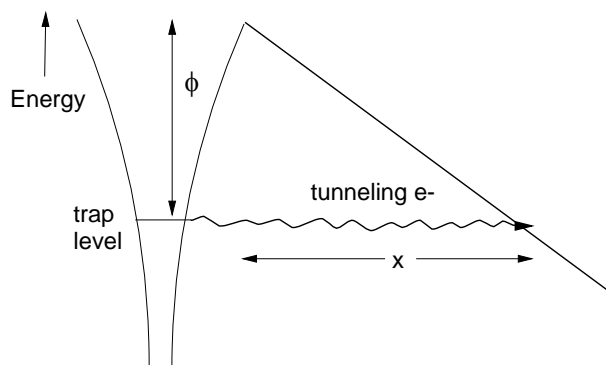
For an n-type channel, the gate threshold voltage where the transistor turns on is about  $V_g = 0$ . It is on for  $V_g > 0$  (full line). When  $V_g > 0$ , positive charge accumulates in the control gate (CG) and this induces the mobile negative charge in the channel.

When negative charge has been trapped in the floating gate (FG), then the first part of the positive charge on CG goes to balance the negative charge on FG. Only at higher positive  $V_g$ 's does this induce negative mobile charge in the channel. Thus, the gate threshold voltage is now positive, as shown by dashed line.

(d) There are 2 main conduction mechanisms in insulators, Poole-Frenkel hopping from defects (traps), or Fowler-Nordheim tunnelling over barriers.



PF



FN.

Charge and discharge of FG in NAND Flash occurs by **tunnelling** from source-drain to the FG, like FN. In NOR Flash, charging occurs by hot carrier injection instead.

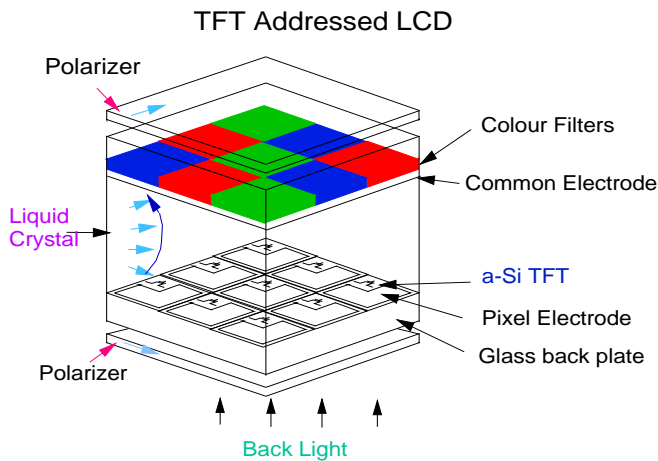
(e) To scale to higher memory density, use high K dielectrics, and smaller device sizes. However, limit to how far you can go. Will use 3-D device structures.



[Question was generally answered well. Most candidates got section (a) and (b) fully correct. They did not answer (c) so well, on how stored charge shifts the  $V_t$ , despite the hint to use Gauss' law, may be because it was not directly mentioned in the lecture notes.]

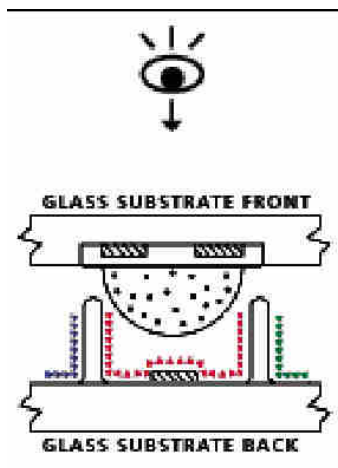
5(a)

3 display technologies. LCD, plasma, OLED.

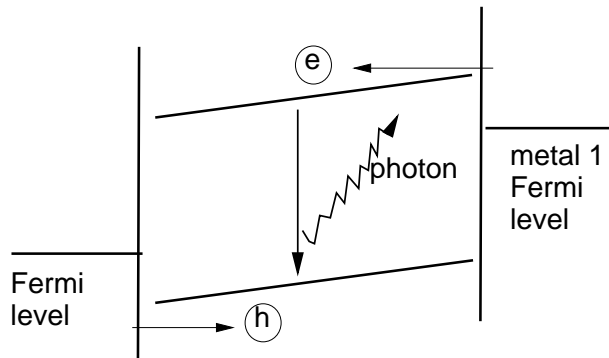


Liquid crystals (LC) are materials whose transmission of polarised light depends on their molecular orientation. Applying a voltage across them changes this orientation. Polarized light is formed by the bottom polarizer, its polarisation is varied by the LC, and then the overall transmission is determined by whether this polarisation plane corresponds to the top polarizer. Thus, the device acts as a 'light valve'.

The overall display consists of a series of pixels which build up the image, and one pixel for each of the three colours, red, blue and green. The LC for each pixel is controlled by its own thin film transistor (TFT).

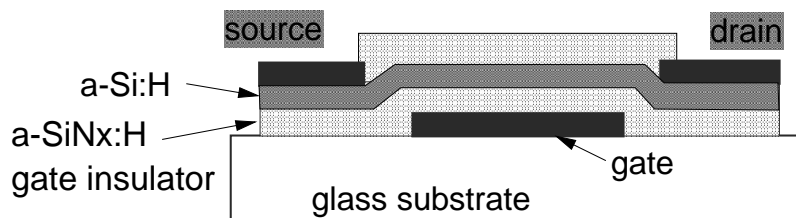


Plasma displays consist of 2 glass panels with many channels built up on the back panel. The image is built up from pixels again in the form of these channels. The channels are filled with gas. A high voltage (1000V) applied across the gas creates an ionised plasma, and the ions excite the phosphor on the front panel to form the image.



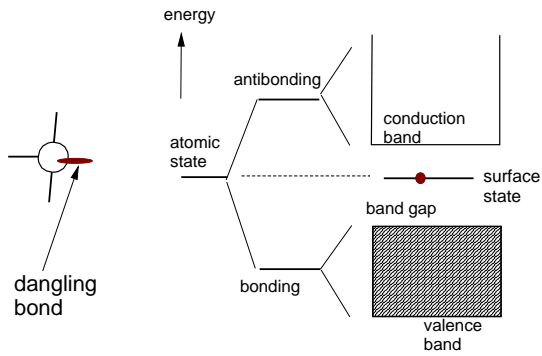
The OLED is essentially the same as the GaAs LED, but built out of large area organic films conductors instead of GaAs, so it is much cheaper. Electrons injected into CB by one electrode, holes injected into VB by other electrode. They recombine to give light out.

(b)

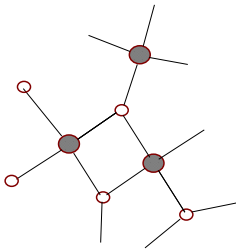


The TFT consists of a gate electrode on the glass substrate. Then a gate insulator, a-SiNx. An undoped a-Si:H layer is about 50 nm thick. Then source and drain metal contacts are applied on top of the a-Si layer. The main a-Si:H channel layer is not doped. The FET operates in enhancement mode, the field of the gate induced electrons into the a-Si:H channel.

(c) Defects give states in the band gap. Passivation bonds to the defect, converting this dangling bond like state into bonding and antibonding states that lie in the bands.

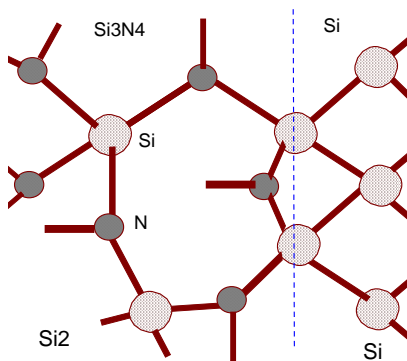


(d) (i)



Si<sub>3</sub>N<sub>4</sub>. Si is 4-valent, N is 3-valent. Network like SiO<sub>2</sub> but with 3-fold N not 2-fold O.

(ii) The Si<sub>3</sub>N<sub>4</sub> should tie up the surfaced DBs, just like SiO<sub>2</sub> did. Show a picture like this-



Hydrogen can tie up any remaining DBs.

(e) To increase s-d current, increase the channel mobility, for fixed geometry. Thus, for amorphous material, use metal oxide, or for crystalline material, use laser recrystallised poly-Si

*[Question was generally well answered, but the band diagram for passivation at the Si/SiO<sub>2</sub> surface proved challenging, as well as the bond diagram in part (d), because few candidates considered that the N atoms have 3 bonds in Si<sub>3</sub>N<sub>4</sub>].*