

Engineering Tripos Part IIB

Monday 28 April 2014

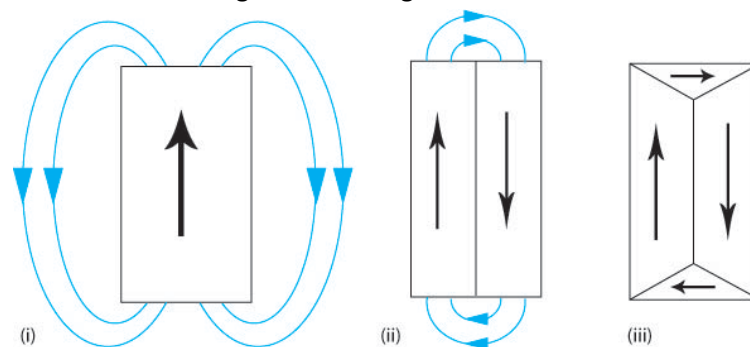
9.30 to 11

MODULE 4C3: Electrical and Nano Materials

Crib

1. a) Magnetisation in a magnetic material arises from the response of the dipoles within the material to an externally imposed field. These dipoles can align opposite to the applied field, in a diamagnetic material, or with the applied field, in the case of a paramagnetic material. In a soft ferromagnetic material the dipoles spontaneously align with each other and with any external field. The moments due to these dipoles give rise to a contribution to the magnetic field inside the material which is termed the material's magnetisation - $\mathbf{M} = \sum \mathbf{m} / V$. Magnetisation is a function of the magnetic field, \mathbf{H} , seen by the dipoles, we define \mathbf{M} having set $\mathbf{H} = \mathbf{H}_0$. Making this assumption the magnetic flux is given by the relationship $\mathbf{B} = \mu_0(\mathbf{M} + \mathbf{H}_0)$. [15%]

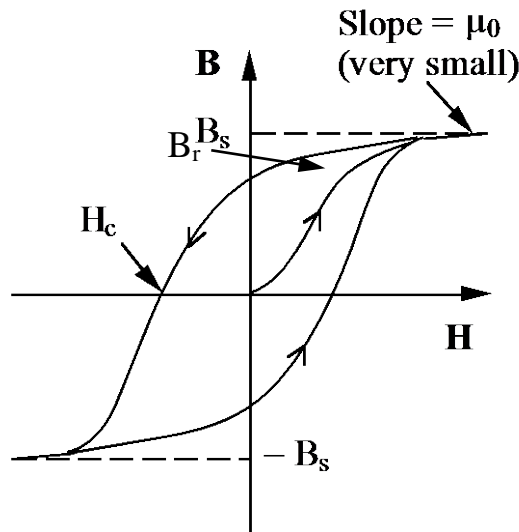
- b) The internal magnetic dipoles in both hard and soft magnetic materials will spontaneously align with each other. In both cases magnetic domains can form in the absence of an applied external field such that no net magnetisation is generated.



In a soft ferromagnetic material the domain walls move freely so with no external field the domain arrangement shown in (iii) above is always seen. In an externally applied field the domains align with the external field and the overall behaviour is, below the saturation field where all the domains are aligned, is that of a paramagnetic material with a very large susceptibility. Consequentially for the same H field, from a coil for example, a soft ferromagnetic material allows a much larger B field to be generated. Thus soft ferromagnetic materials are used in engineering for (for example) transformer cores, inductors, electromagnets, magnetic shielding. A non-ferromagnet cored transformer would have to be impractically large.

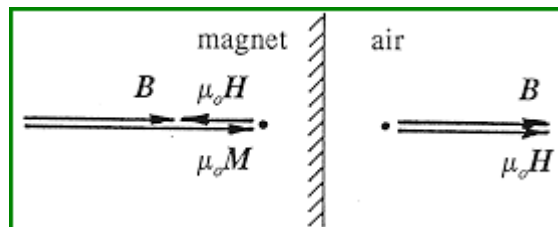
Conversely hard ferromagnetic materials exhibit strong "pinning" of domain walls, often through the deliberate production of a dense granular microstructure. This leads to hysteretic behaviour where the magnetisation is no longer a simple function of \mathbf{H} but instead depends on the history of the external field seen by the ferromagnetic. From a practical standpoint the fact that domains in hard ferromagnets are difficult to rearrange leads to the

useful property of remanent magnetisation, that is they exhibit a magnetisation even once the external field has been removed i.e. permanent magnets. Permanent magnets are used in small, powerful electric motors, in fixings, latches, torque drives, magnetic separators, loudspeakers, generators, eddy current braking, magnetrons, klystrons, electron lenses, alternators etc. etc. etc.



[35%]

c) A permanent magnet generates a reverse field that acts to demagnetise *itself*. This is called the “self-demagnetising” or “demagnetising” field.



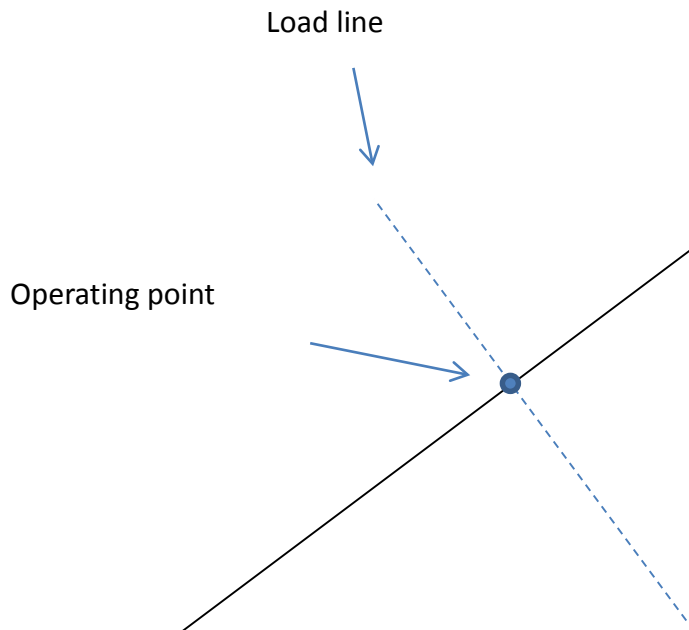
This demagnetising field H_m is given by $-NM$ where M is the magnetisation of the magnet and N is a shape dependent “demagnetisation factor”. From $\mathbf{B}=\mu_0(\mathbf{M}+\mathbf{H}_0)$ we can then write that $\mathbf{B}_{op}=\mu_0(\mathbf{M}-\mathbf{M}N)$ or $\mathbf{B}=\mu_0\mathbf{M}(1-N)$. 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:

$$\frac{B_{op}}{H_m} = -\mu_0 \frac{(1-N)}{N}$$

Where this load line intersects with the BH plot is the operating point.



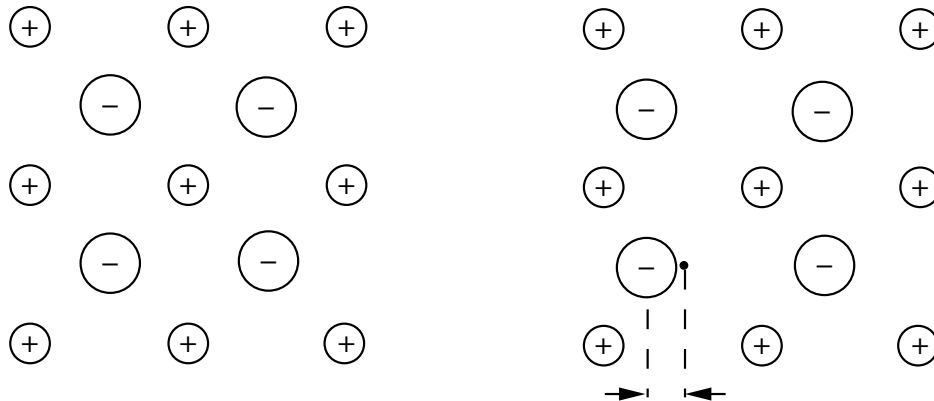
If the operating point falls near or past the coercive field of the material a magnet made in such a shape would spontaneously demagnetise. [35%]

d) To get maximum energy we need to maximise the BH product. Take the derivative of B times H which is $\mu_0(M-MN)$ times $-MN$. The derivative is $\mu_0M^2(2N-1)$ 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.

In terms of practical magnetic materials only NdFeB and SmCo have coercive fields large enough that they can be fabricated into such a shape without demagnetising. Indeed the coercive field of NdFeB is so large that it can be made into *any* shape. [15%]

2 a) 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.

Both these materials exhibit spontaneous polarisation, P_s , This arises microscopically from a structural transition which breaks the symmetry of the positive and negative charges.



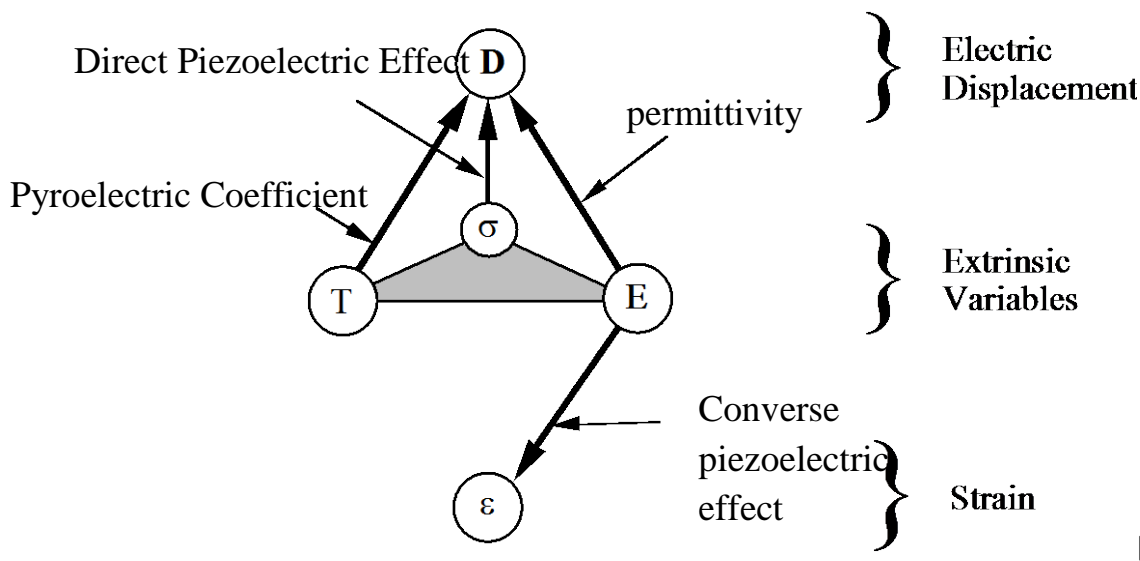
Non-polar lattice

Polar lattice

Pyroelectricity arises from a change in the spontaneous polarisation with temperature. This is quantified as the pyroelectric coefficient, p , which is the rate of change of P_s with temperature.

In a similar manner the piezoelectric effect arises from the change in the polarisation caused by an applied stress distorting the crystal structure.

From a practical point of view most piezo and pyro electric materials used in applications are ferroelectrics, materials which exhibit remanent polarisation since they are easy to pole and have multiple axes along which they exhibit pyro/piezo electrical properties.



[40%]

b) As

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

$\frac{dT}{dt} = \frac{\eta i\omega W_0 e^{i\omega t}}{G_T + i\omega H}$ combining with the fact that $i_p = A p \frac{dT}{dt}$ we can write an expression for the current responsivity (current per incident power) (as $H = \tau_T G_T$)

$$\begin{aligned} R_i &= \frac{i_p}{W_0} = \frac{A p \eta i\omega e^{i\omega t}}{G_T (1 + i\omega \tau_T)} \\ &= \frac{A p \eta i\omega e^{i\omega t} (1 - i\omega \tau_T)}{G_T (1 + \omega^2 \tau_T^2)} \end{aligned}$$

Taking the modulus

$$\begin{aligned} |R_i| &= \left| \frac{A p \eta \omega e^{i\omega t} (i + \omega \tau_T)}{G_T (1 + \omega^2 \tau_T^2)} \right| \\ &= \frac{A p \eta \omega \sqrt{1 + \omega^2 \tau_T^2}}{G_T (1 + \omega^2 \tau_T^2)} = \frac{A p \eta \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2}} \end{aligned}$$

As required.

[30%]

c) At low frequencies heat has time to leak of the detector and R_i is linearly proportional to ω . At high frequencies the equation for the current responsivity tends to $A p \eta / H$ as $H = cdA$ where d is the detector thickness and c the volume specific heat this becomes $p \eta / cd$ – constant. It is therefore better to operate at frequencies much greater than $1/\tau_T$

[10%]

d) For the example of PVDF given the current responsivity is $(27 \times 10^{-6} \times 0.95) / (500 \times 10^{-9} \times 2.6 \times 10^6)$ which is roughly $2 \times 10^{-5} \text{ A/W}$

[20%]

3 (a) In the sputtering process ions from the gas phase are accelerated towards a target where they knock out (sputter) target species and the flux of target species is then used to deposit the thin film (see lecture notes). In the semiconductor industry typically glow discharge plasmas are used to ionise Ar gas which then are accelerated towards the sputter target. In order to maintain a plasma a certain pressure range is required (typically 10-100 mTorr). Sputter yield is mainly dependent on target material, ion type, energy and angle of incidence. Unlike to evaporation (for which the vapour pressure between the elements greatly varies), sputtering is well suited for alloy deposition. Sputtering is possible for most materials, also composite targets and polymers. The large area of the sputter target leads to improved uniformity relative to evaporation. Due to the higher gas pressure for sputtering (compared to evaporation), the mean free path is shorter and step coverage is improved. Also the sputtered atoms are energetic which improves film adhesion.

[20%]

(b) The thickness of the silicon dioxide can be determined by eg ellipsometry, for which the change in light polarization upon reflection from film/substrate interfaces is measured. Given that the optical properties of the Si and its oxide are known, the oxide thickness can be determined. Alternatively, light interference allows an estimate of the oxide thickness simply by looking at its colour (step gauges).

[10%]

(c) The impingement flux J , ie the number of water molecules that hit the silicon oxide surface per unit area per unit time is (see lecture notes) is given by:

$$J = \frac{1}{4} n \bar{v} = \frac{p}{\sqrt{2\pi mkT}}$$

The number of atoms in a monolayer N_{mono} is approx. $1/d^2$, and it will take time $t_{\text{mono}} = N_{\text{mono}}/J$ for monolayer coverage of substrate.

Assuming a water molecule diameter of $d=0.5$ nm, $N_{\text{mono}} \approx 1/d^2 = 4 \times 10^{18} \text{ m}^{-2}$; $t_{\text{mono}} \geq 10\text{s}$,

$$J = \frac{N_{\text{mono}}}{t_{\text{mono}}} = \frac{p}{\sqrt{2\pi mkT}}$$

which at RT and for $m=18u$, gives a required background pressure of $p \leq 10^{-5}$ Pa

[25%]

(d) Carbon nanotube can be catalytically grown by chemical vapour deposition (CVD) from the Ni film. Based on its higher surface energy, the Ni film dewets upon heating and Ni nanoparticles are formed. The heated Ni nanoparticles are then exposed to a carbon containing gas and the gas species catalytically dissociate on the nanoparticle surfaces. The resulting carbon forms a graphitic lattice, which envelopes the particle and eventually "lifts-off" and forms a carbon nanotube.

[20%]

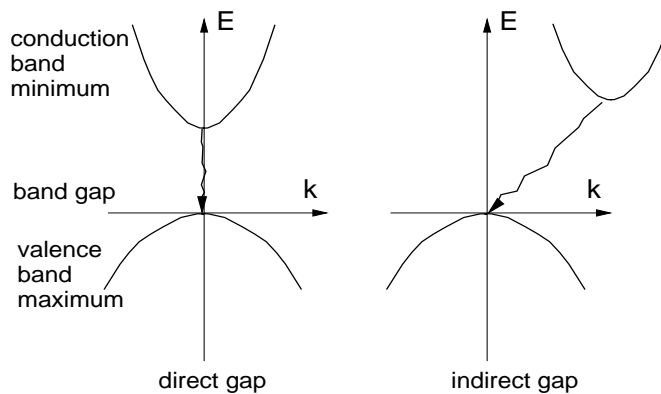
(e) The as-grown carbon nanotube can be characterised eg by scanning electron microscopy, where a primary electron beam scanned across the sample surface induces the emission of secondary electrons. The emission of these secondary electrons reflects the sample surface (see lecture notes).

[15%]

(f) The titanium dioxide film can be deposited by atomic layer deposition (ALD). ALD is a CVD-based technique which allows atomic level thickness control by breaking the CVD process into two self-limiting (half)reactions. For CVD using binary reactions, the A and B reactants are present at the same time and form the product film continuously on the substrate. In ALD, the substrate is exposed to the A and B reactants individually and the product film is formed in a stepwise and digital fashion.

[10%]

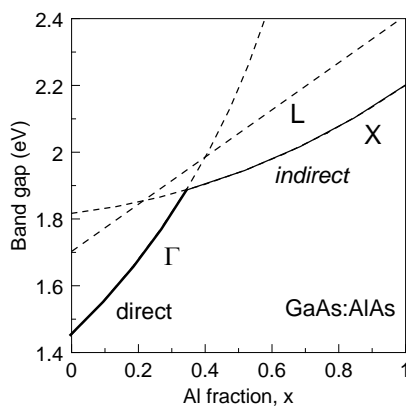
4(a)



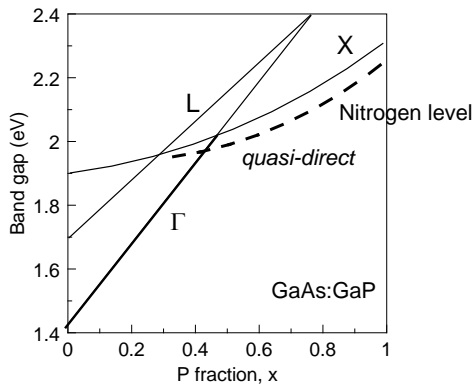
In a direct gap semiconductor, the VB maximum and CB minimum are at the same k point (which does not have to be a Gamma). In an indirect gap semiconductor, the VB max and CB min are at different k points. Vertical transitions in k space (at same k point) do not require phonon participation to conserve momentum, and so have a high probability, but indirect transitions need phonons, and so have low probability. This direct semiconductors are much better for optoelectronic devices.

[15%]

(b) alloy GaAs with wider gap material like AlAs.



Alloy with GaP and introduce deep impurity like N which has localised transitions.



[10%]

c) While the electron mass in free space is a universal constant, in a solid the effective mass m^* is a variable. m^* is derived from the ratio of the kinetic energy of the electron, and the k vector of the electron, from

$$E = (\hbar k)^2/2m^*$$

A standard band structure plots E versus k , thus m^* is proportional to $1/\text{curvature}$ of bands at an extremum. A sharper extremum = lower mass.

The effective mass or hydrogenic model of dopant energy level notes that the carrier moves in the $1/r$ Coulombic potential of the ionised dopant. This is equivalent to the potential of the electron in a hydrogen atom, so that the binding energy is given by the Rydberg;

$$R_0 = \frac{e^4 m}{32\pi^2 \epsilon^2 \hbar^2}$$

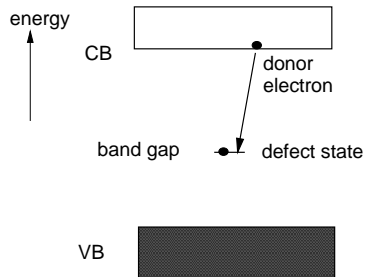
As it is in a solid, we replace m with m^* , and ϵ_0 with $\epsilon_0 \epsilon_r$. Thus $R' = R_0 m^*/\epsilon_r^2$

To ionise a dopant, we need a small R' and thus small m^* and large ϵ .

[30%]

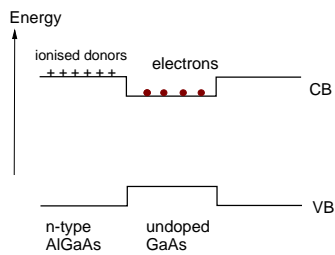
(d) Three problems:

1. low impurity solubility
2. high effective mass of bands, and low dielectric constant, makes large Rydberg, so that the dopant states do not ionise.
3. donors or acceptors get compensated by intrinsic defects which absorb the carriers being generated.



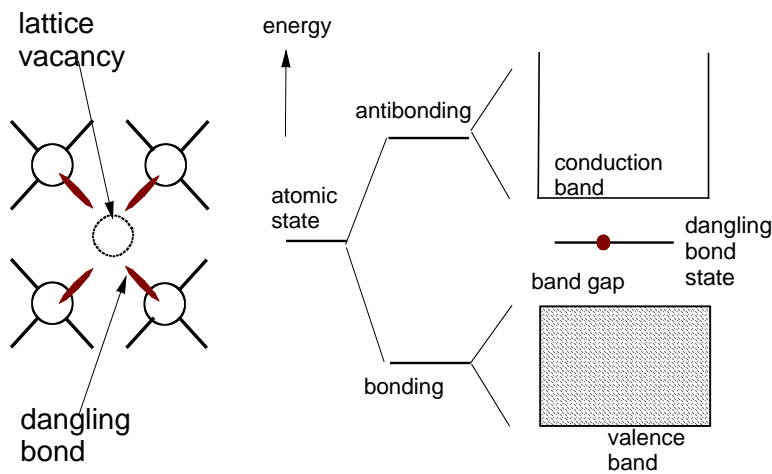
[25%]

(e) Modulation doping has dopants in wide gap region. Carriers transfer to lower gap region, adjacent. Absence of ionised dopant scattering centres in this region means that the carriers have much higher mobility. See notes for density of mismatch calculation.



[20%]

5(a)

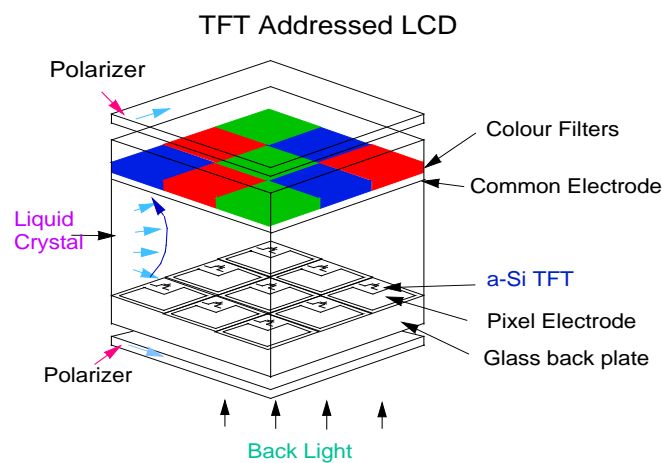


As defect states (dangling bonds) are not forming a bond, their states form energy levels which lie at the energy of the *unbonded state*. These lie between bonding and antibonding levels. Hence they lie in the middle of the band gap. [25%]

(b) Defect states due to dangling bonds are monovalent. They are passivated by monovalent elements like hydrogen or F. They form Si-H bonds, whose states lie well outside the band gap.

Surface states come from the dangling /broken bonds on the surface. They are usually passivated by oxidation. This turns the DBs into Si-O bonds. The states of the Si-O bonds lie well outside the band gap, so it passivates them. [20%]

(c)

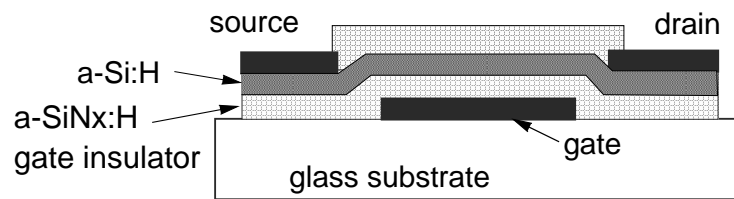


Light from back light passes through a polariser. It then passes through the liquid crystal which can rotate the plane of polarisation, depending on the voltage across it. The light then passes through a crossed polariser. Only if light is rotated does light come through. Hence this behaves as a voltage controlled light valve. A-Si TFTs control voltage on the electrode and so field across the LC. Colour filters for each pixel.

The back light of AM-LCD is always on, whereas OLEDs are emissive displays, thus OLEDs are more efficient. OLEDs can be thinner, and simpler and cheaper in principle.

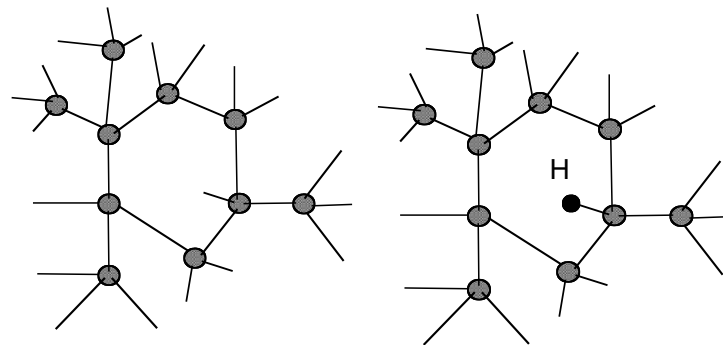
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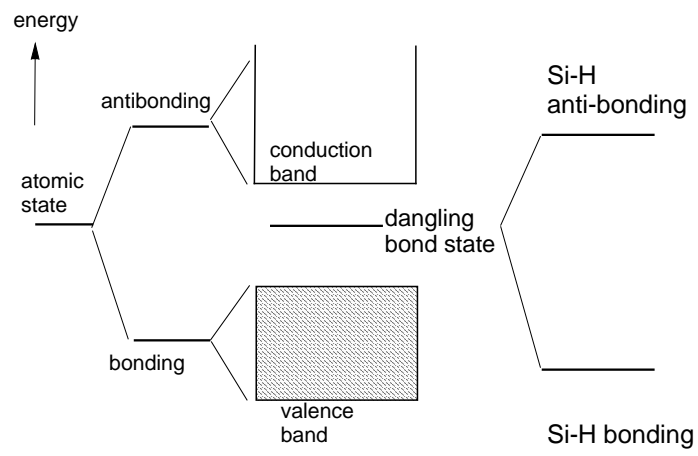
(d)



TFT = gate electrode a bottom, gate insulator (silicon nitride not SiO_2), conductive a-Si layer (instead of c-Si), followed by source and drain electrodes (Cr). A-Si is much cheaper than c-Si

Defect passivation in a-Si:H by hydrogen passivating Si dangling bonds. H is monovalent, and Si-H bonds have states outside the gap.





[30%]