

Built in potential = 0.92 eV

$$V_{bi} = E_{Fn} - E_{Fp}$$

Assuming that all dopants are activated

$$n = N_D = N_C \exp\left(\frac{E_{Fn} - E_C}{RT}\right) \quad p = N_A = N_V \exp\left(\frac{E_V - E_{Fp}}{RT}\right)$$

$N_C = N_V$  Considering either the n or p semiconductor in equilibrium - i.e. far away from the junction depletion region.

$$n_i^2 = n_{nt} p_{np} = N_C N_V \exp\left(\frac{-E_g}{RT}\right) = N_V^2 \exp\left(\frac{-1.12 q}{RT}\right)$$

$k = 1.38 \times 10^{-23}$  (Boltzmann const)  $q = 1.602 \times 10^{-19}$  C (elementary charge)  
 $T = 300 \text{ K}$

$$\therefore N_V = n_i \exp\left(\frac{1.12q}{2kT}\right) = 2.88 \times 10^{25} \text{ cm}^{-3}$$

$\uparrow$   
 $10^{16}$

Considering the band energies of the junction above.

$$V_{bi} + (E_C - E_F) = E_g - (E_F - E_V)$$

$$\therefore (E_V - E_F) = V_{bi} + (E_C - E_F) - E_g$$

$$(E_C - E_F) = kT \ln \frac{N_C}{N_D} = 1.38 \times 10^{-23} \times 300 \times \ln\left(\frac{2.88}{2}\right)$$

$$= 1.51 \times 10^{-21} \text{ J}$$

$$\therefore (E_V - E_F) = (0.92 - 1.12)q + 1.51 \times 10^{-21}$$

$$= -3.053 \times 10^{-20} \text{ J}$$

$$\therefore p = N_V \exp\left(\frac{E_V - E_F}{kT}\right) = 2.88 \times 10^{25} \exp\left(\frac{-3.053 \times 10^{-20}}{1.38 \times 10^{-23} \times 300}\right)$$

$$p = N_A = 1.81 \times 10^{22} \text{ m}^{-3}$$


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$$(c) \quad I_S = qA \left( \frac{n_i^2 D_e}{N_A L_e} + \frac{n_i^2 D_h}{N_D L_h} \right)$$

$$\text{Also } \sqrt{D_e \tau_e} = L_e \quad \text{and} \quad \sqrt{D_h \tau_h} = L_h$$

$$\therefore I_S = qA \left( \frac{n_i^2 L_e}{N_A \tau_e} + \frac{n_i^2 L_h}{N_D \tau_h} \right)$$

(2)

substituting values from Table 1 and solution for  $N_A$

$$\bar{I}_S = 10^{-2} \times 1.662 \times 10^{-19} \left[ \frac{10^{32}}{1.81 \times 10^{22}} \times \frac{250}{5} + \frac{10^{32}}{2 \times 10^{25}} + \frac{1}{200} \right]$$

$$\bar{I}_S \approx 10^{-2} \times 1.662 \times 10^{-19} \left[ \frac{10^{32}}{1.81 \times 10^{22}} \times \frac{250}{5} \right]$$

$$\approx \underline{\underline{443 \times 10^{-12}}} = \underline{\underline{44.3 \text{ pA}}} \quad \underline{\underline{0.689 \text{ mV}}}$$

d)  $V_{oc} = \frac{kT}{q} \ln \left[ \frac{I_{sc}}{\bar{I}_S} + 1 \right]$

$$\bar{I}_S = \frac{I_{sc}}{\left( \exp \left( \frac{qV_{oc}}{kT} \right) - 1 \right)}$$

$$I_{sc} = \bar{I}_S \left( \exp \left( \frac{qV_{oc}}{kT} \right) - 1 \right)$$

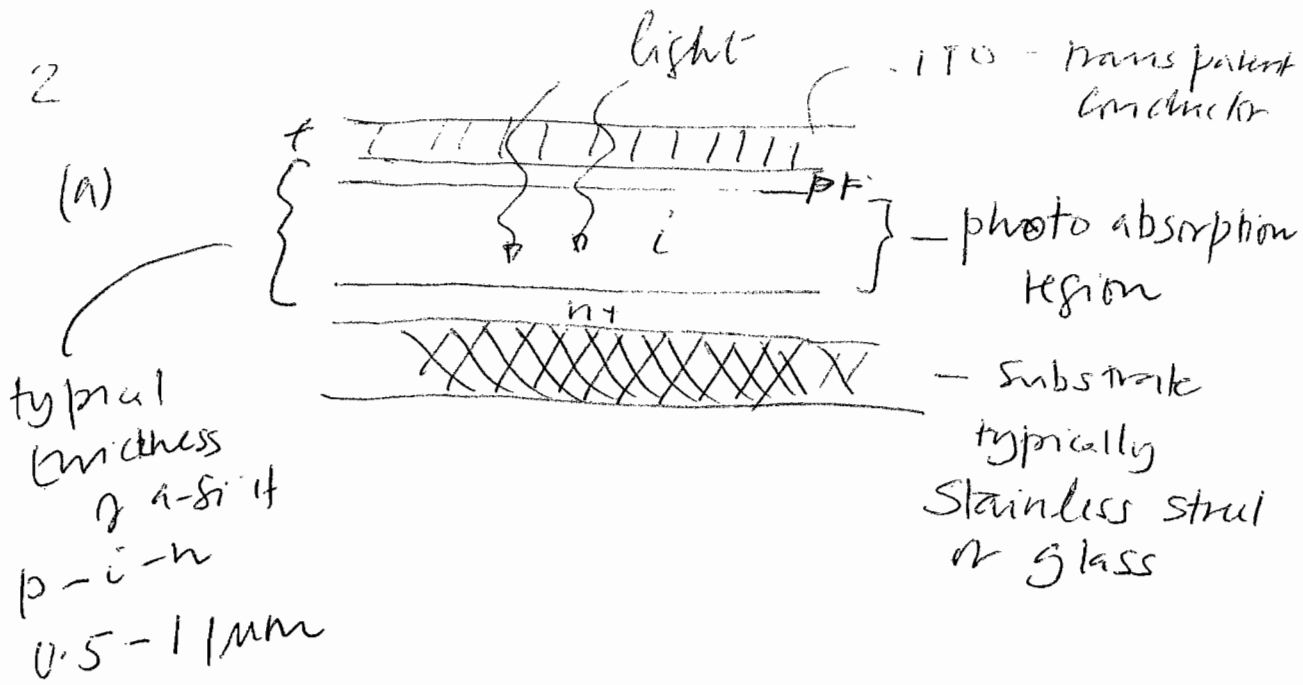
$$I_{sc} = \underline{\underline{443 \times 10^{-12}}} \left[ \exp \left( \frac{1.662 \times 10^{-19} \times 0.65}{1.81 \times 10^{-23} \times 300} \right) - 1 \right]$$

Short Circuit Current  $I_{sc} = \underline{\underline{3.71 \text{ A}}} \quad 47 \text{ A}$

e)  $I_{sc} = qA S_{opt} [L_e + L_h]$

$$S_{opt} = \frac{I_{sc}}{qA [L_e + L_h]} = \frac{3.71}{1.662 \times 10^{-19} \times 10^{-2} \times \frac{250}{2} \times 2 \times 10^{-6}} = 9.26 \times 10^5 \text{ cm}^{-3}$$

(3)

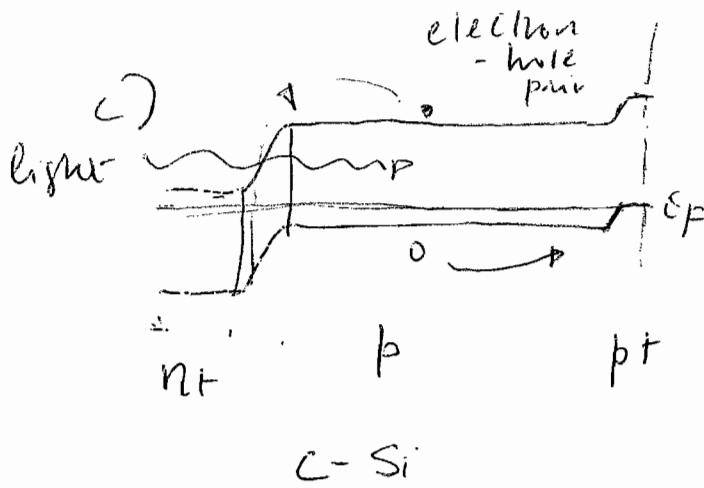


(b) Crystalline Si is an indirect band-gap material. This means that absorption of a photon to create an electron-hole pair must be accompanied by the absorption/generation of a phonon (unit of lattice vibrational energy) to preserve momentum of the excited electron. It is not possible in crystalline-Si to have the excitation of electrons from the valence band edge to the conduction band edge purely through absorption of a photon for the energy transition. This makes photon absorption inefficient and a large volume/path length is required for light to be absorbed. (4)

Hence the requirement for a bulk semiconductor absorber region below the junction depletion region. The ~~photo generated absorber~~ carriers diffuse to the junction for separation.

In amorphous Si - a-Si:H, the requirement for momentum conservation of excited carriers is removed. This is because by definition there is no crystal structure and the momentum and energy relationships which has to exist in a crystal is removed.

This makes a-Si:H a pseudo-direct band-gap material. This means that it can absorb light much more efficiently - i.e. smaller volume/path length. This makes it possible to have a thin film (approx 100-1000  $\mu\text{m}$ ) solar cell.

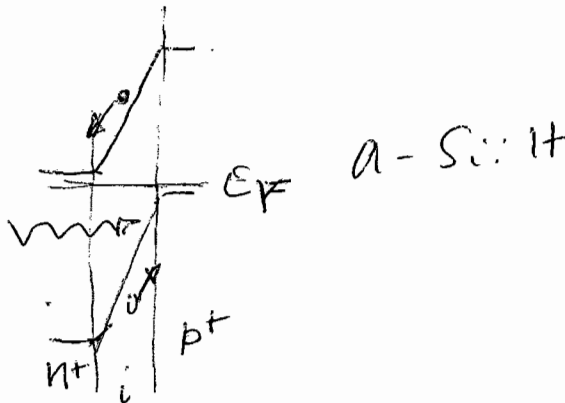


Dominant in a-Si:H  
Dominant in C-Si

$$I_e = qA \left[ \mu_n n E + D_n \frac{dn}{dx} \right]$$

$$I_h = qA \left[ \mu_p p E - D_p \frac{dp}{dx} \right]$$

$$I = I_e + I_h$$



The major difference is that in amorphous Si all <sup>photo-generated</sup> carriers are generated in the i-layer, which corresponds to the depletion layer in the C-Si junction. In the C-Si junction e-h pairs are created far from the junction, and then diffuse to the front (n-p) and back (p-p<sup>+</sup>) junctions for separation to the electrodes.

In a-Si:H there is no practical diffusion. This is because it is amorphous and there are many defects ~~with~~ through which the carriers can recombine.

(6)

Therefore in a-Si:H the carriers have to be subject to the built in field between the  $n^+$ - $p^+$  region in order to separate carriers before they recombine. Therefore in a-Si:H the photogenerated current is determined by the rate of drift in the intrinsic layer. Because of the good photoabsorption, all the light can be absorbed within the electric field region. In the c-Si cell the photogenerated current is diffusion limited.

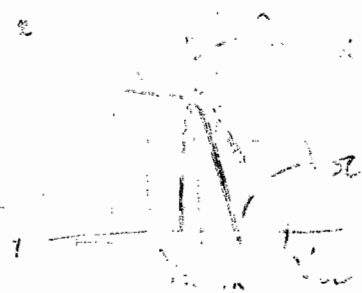
a-Si:H also has a larger band-gap than c-Si. This helps in establishing a larger built in field across the  $i$ -layer.

d)

$$i) \quad 0.1 = \frac{V_{oc} I_{sc} \cdot FF}{P_{in}}$$

$$\therefore I_{sc} = \frac{100 \times 10^{-2}}{0.6} = \underline{\underline{1.66 \text{ A}}}$$

ii) Solar cell output



10% is about  
 10% efficiency for  
 4th a-Si:H cell  
 Assume  $V_{max} \approx V_{oc}$

⑥

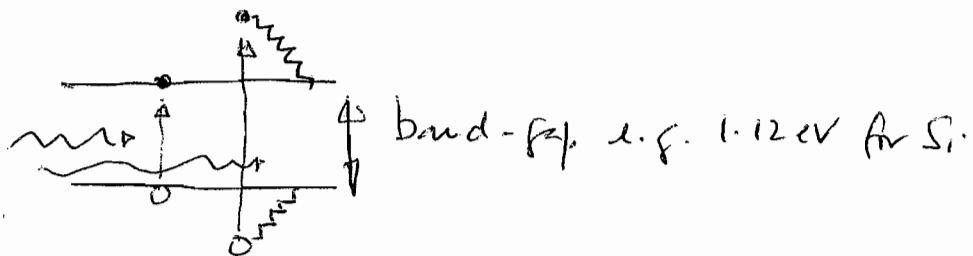
3 a)



Solar spectrum

← energy above band-gap.

All energies above the band-gap energy can be absorbed by a semiconductor.



I ideally, a photon should have energy just above that of the band-gap. In that case all the energy of the photon can be transformed into the separating potential of the electron hole-pair across the band-gap.

For photons which have energy above the band-gap energy electron hole-pairs will be created with separating energy above that of the band-gap potential. But this cannot be maintained. The electron-hole pair will relax to the lowest possible energy separation. ⑦



within the semiconductor - which is the band-gap energy. During this ~~relaxation~~ relaxation the electron-hole pair loses energy to the semiconductor lattice as heat.

Since the solar spectrum has energies above the band-gap energy of the absorbing semiconductor, heat generation is inevitable. The ideal semiconductor would have a band-gap close to that of the peak of the solar spectrum at  $530\text{ nm}$ . This will allow the maximum number of photons to be absorbed with the least heating.

There is always a trade-off between open-circuit voltage, <sup>proportional to the</sup> ~~the~~ maximum separating voltage for an electron hole pair, i.e. band-gap and short circuit current. The latter is larger with a small band-gap material as a larger number of total photons can be absorbed from the solar spectrum.

b) The open circuit voltage is the parameter which is most effected through heating. In a solar cell the separating electric field is supplied by the built-in potential <sup>across</sup> ~~separating~~ the p and n regions of the junction. The open circuit voltage is related to this built-in potential, but is ultimately related to the energy barrier for electron and hole flow across the junction. There is always the probability of carrier excitation over the barrier. This varies exponentially with carrier energy. This means that as carriers acquire energy through heating, ~~to reduce~~ the effective built-in potential across the junction falls.

For a p-n junction with optical excitation under open-circuit.

$$0 = I_S \left[ \exp\left(\frac{qV_{oc}}{kT}\right) - 1 \right] = I_{opt}$$

$$V_{oc} = \frac{kT}{q} \ln \left[ \frac{I_{opt}}{I_S} + 1 \right]$$

$$\frac{dV_{oc}}{dT} = \frac{k}{q} \ln \left[ \frac{I_{opt}}{I_S} + 1 \right] - \frac{kT}{q} \cdot \frac{1}{I_S} \cdot \frac{1}{\ln \left[ \frac{I_{opt}}{I_S} + 1 \right]} \cdot \frac{dI_S}{dT}$$

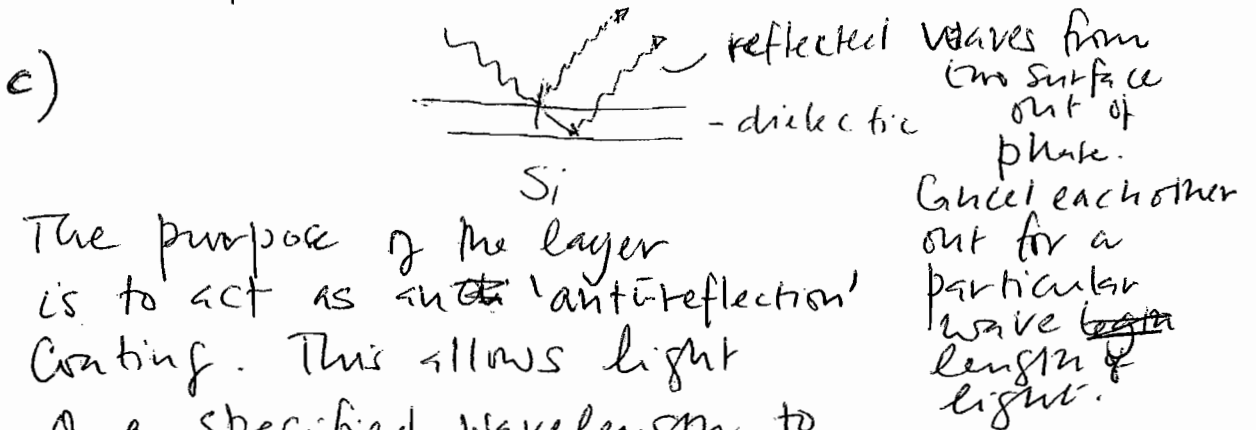
$$\frac{dI_{opt}}{dT} \approx 0$$

(9)

$$\frac{dV_{02}}{dT} = \frac{V_{02}}{T} - \left(\frac{kT}{q}\right)^2 \frac{1}{I_s^2} \frac{1}{V_{02}} \frac{dI_s}{dT}$$

The second term in the expression above is negative and proportional to  $\frac{dI_s}{dT}$ .

Therefore it is the growth of reverse saturation current with temperature which gives rise to a negative rate of change in  $V_{02}$  with rise in temperature.



i) The purpose of the layer is to act as an 'anti-reflection' coating. This allows light of a specified wavelength to have minimum reflection. Hence, maximum transmittance into the semiconductor. Typically, the wavelength is chosen to be that of the solar spectrum at which energy is at a peak (550-600 nm).

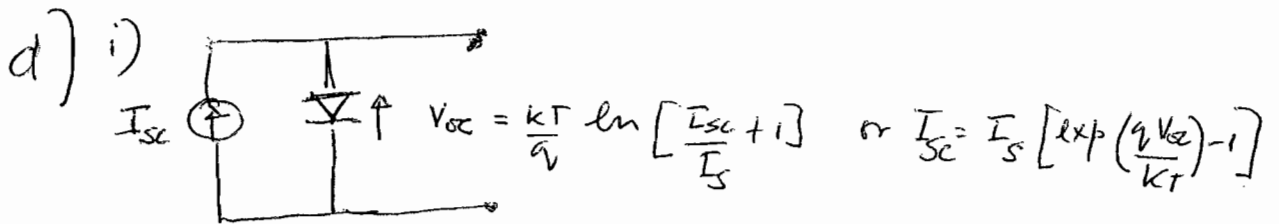
ii) From formula sheet, Reflection is a minimum when

$$\theta = \pi/2 \quad \theta = \frac{2\pi n_2 d}{\lambda}$$

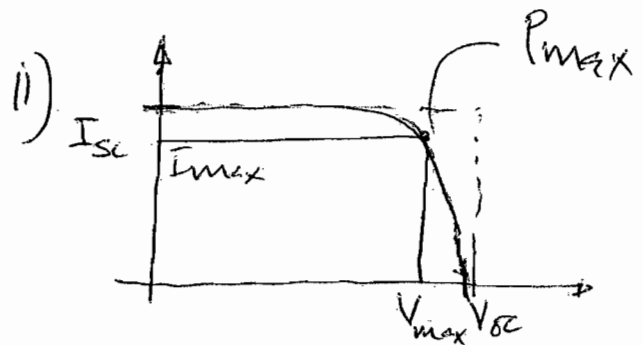
$n_2$  is the refractive index of the dielectric layer, of its thickness

i) Taking the wavelength at which the reflection is minimised to be  $\lambda = 600 \text{ nm}$  and  $n = 2.5$

$$d = \frac{\lambda}{4n} = \frac{600 \text{ nm}}{10\pi} = 19.1 \text{ nm} \approx \underline{\underline{19 \text{ nm}}}$$



A current source  $I_{sc}$  with an internal impedance which is  $\ll$  forward biased diode.



The output characteristic from the equiv-cct in i) has the form.

An ideal power supply with an open circuit voltage of  $V_{oc}$  and short circuit current of  $I_s$  would have a power output

$P = V_{oc} I_s$ , A ~~square~~ rectangular area on the output characteristic.

In a solar cell, the maximum power

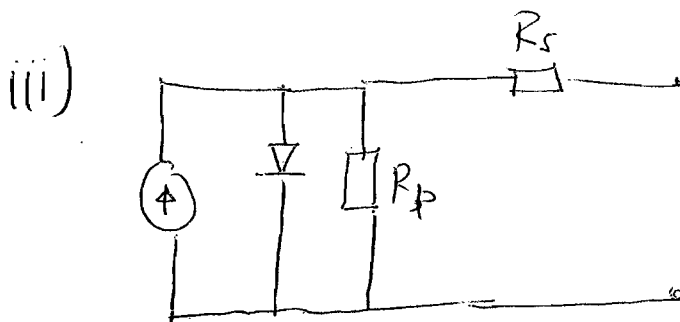
(11)

output is obtained at some current and voltage  $I_{max}$ ,  $V_{max}$  where  $I_{max} < I_{sc}$  and  $V_{max} < V_{oc}$  as shown. Therefore

the fill factor is defined as

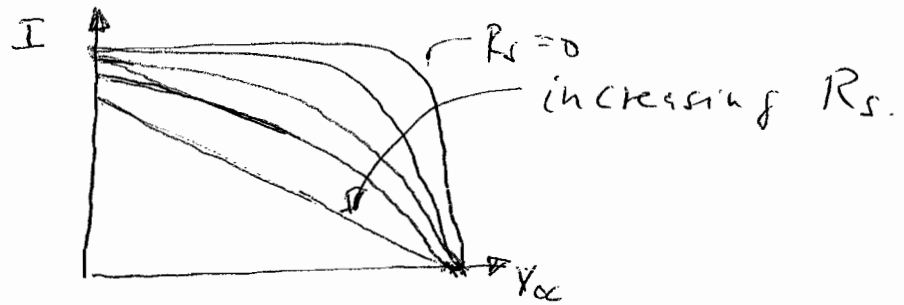
$$FF = \frac{V_{max} I_{max}}{V_{oc} I_{sc}}$$

It is a relative measure of how 'ideal' a solar cell is as a power supply, the best solar cells approach a FF of 0.9.

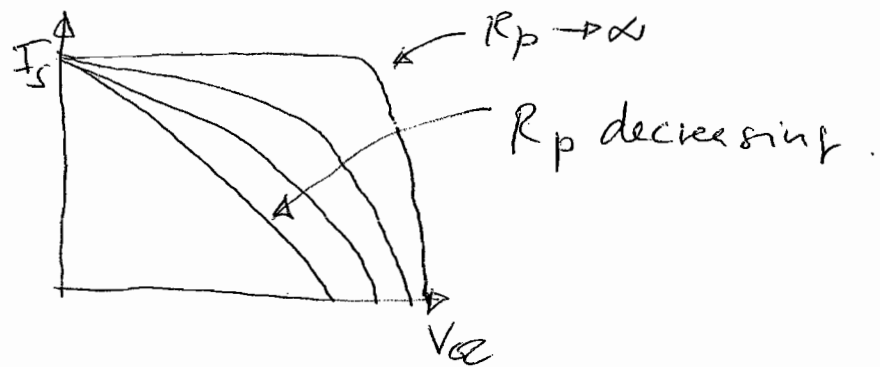


$R_s$  ~~and  $R_p$~~  represents the influence of series resistance within the p-n junction. This arises due to the resistance of the bulk semiconductor and the contacts.  $R_p$  represents the photo-generated current which leaks around the perimeter of the solar cell without being collected by the contacts. Ideally  $R_p \rightarrow \infty$  as the cell size becomes large.

Both Increasing  $R_s$  leads to loss in Fill factor.

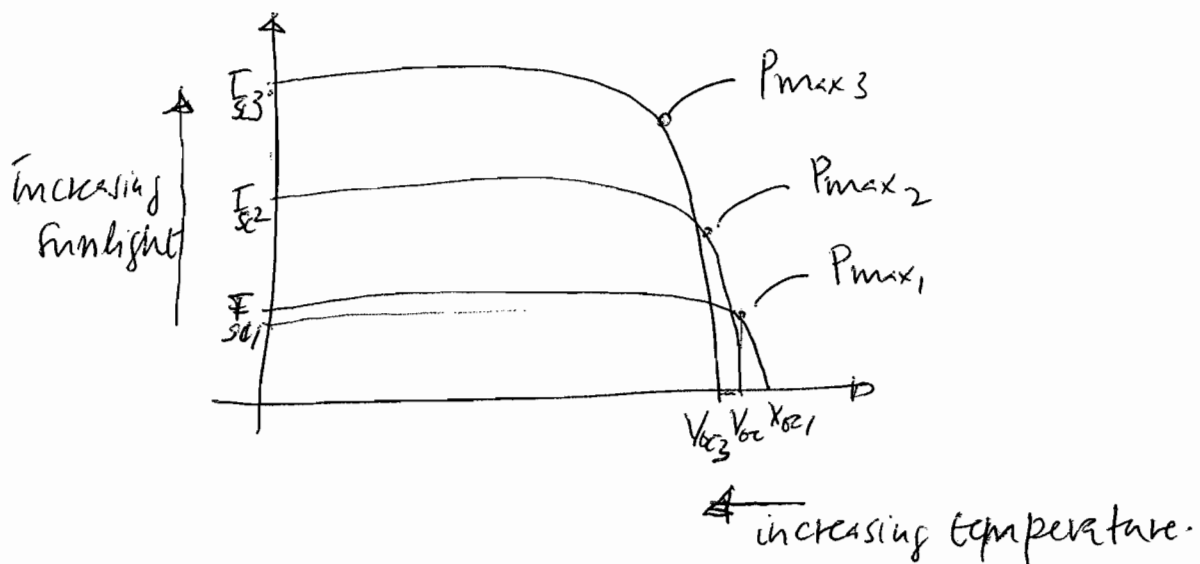


Decreasing  $R_p$  leads to loss in Fill factor.



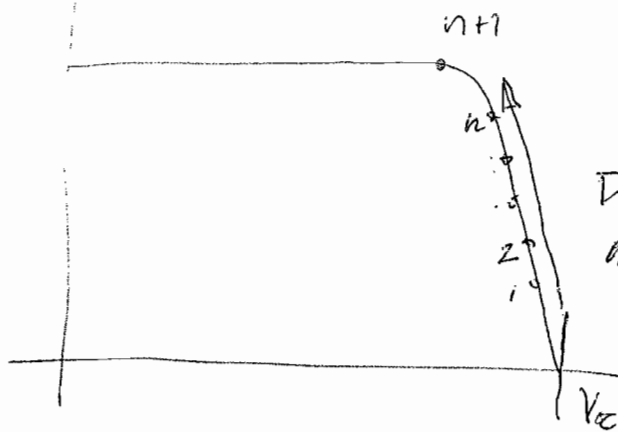
4)

a) MPPT is necessary because as the ~~sun~~ intensity of sunlight changes the output characteristics of the solar cell also changes. Also, as the environmental temperature changes power output changes. In terms of cell parameters this is seen as changes to  $I_{sc}$  and  $V_{oc}$ . When operating a solar plant it is important to always aim for maximum power output. The voltage and current at which max power is obtained changes as the irradiation from the sun varies. Hence MPPT is required for the operation of a solar power plant.



(14)

b) Empirical



Increase of current as long as  $I_n \times V_n = P_n$  is increasing.

When  $I_n \times V_n > I_{n+1} \times V_{n+1}$  Previous point taken as max power point.

Once the initial point is found, an empirical or mathematical ~~method~~ method can be followed to maintain the MPP.

Empirical.

Every second the current is decreased as a trial to see whether power is increased.

If so reduction continues until  $P_{n+1} < P_n$  and  $P_n$  chosen as new  $P_{max}$  (MPP)

If  $P_i < P_o$ , then the current is increased. The current increase continues until  $P_{n+1} < P_n$ .

$P_n$  then chosen as new MPP.

This is implemented via the power conversion controller at 1sec intervals (typically) to track the operating point. The sampling frequency ~~must~~ must be much faster than the typical times over which solar conditions vary.

(15)



This method is usually termed 'dithering' about an operating point.

### Mathematical

Alternatively by sampling the  $I, V$  the MPP point can be calculated.

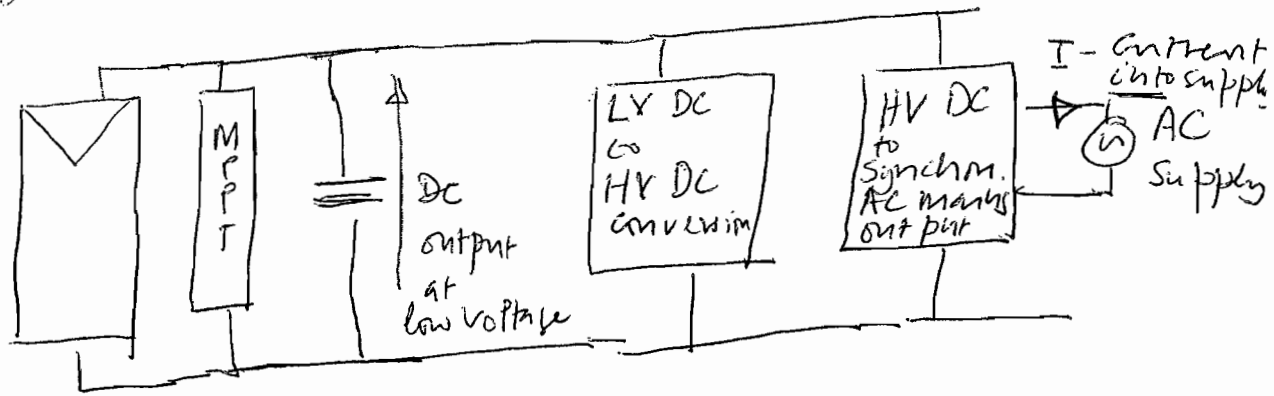
$$P = IV \quad \text{at} \quad P_{\max} = \frac{dP}{dV} \quad \text{or} \quad \frac{dP}{dI} = 0$$

$$\therefore \frac{dP_{\max}}{dV} = I + V \frac{dI}{dV} \quad \therefore \frac{dI}{dV} = -\frac{I}{V}$$

In this method the controller changes the operating point while monitoring  $I$  and  $V$  and calculating  $\frac{dI}{dV}$ . The  $I, V$  point is set when the closest match between  $\frac{dI}{dV}$  and  $-\frac{I}{V}$  is found.

The disadvantage is that the controller must have arithmetic capability to carry out division rapidly and accurately. OK for large power plants, but may be unsuitable for small installations where computing power is limited.

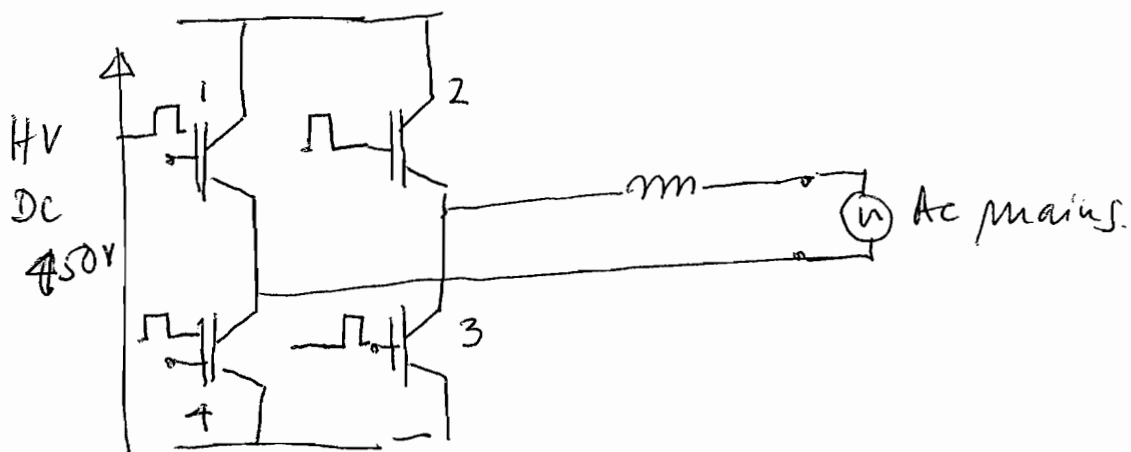
c)



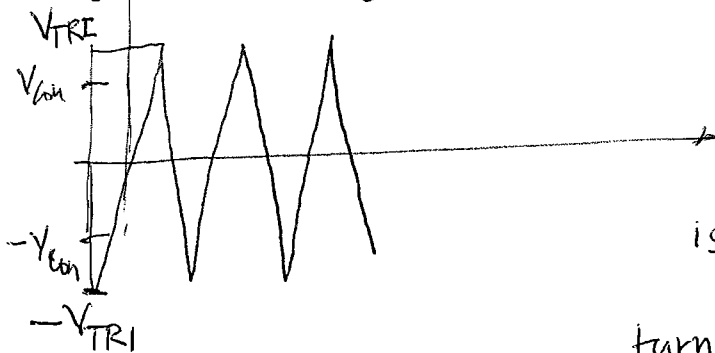
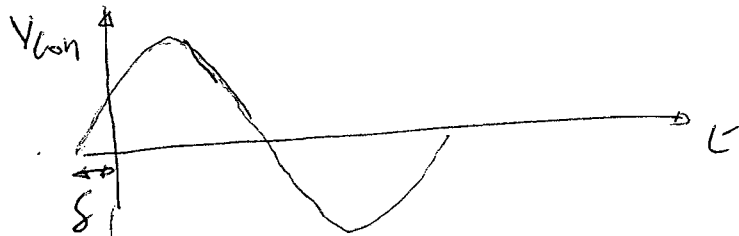
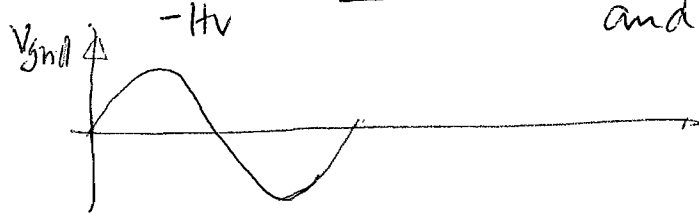
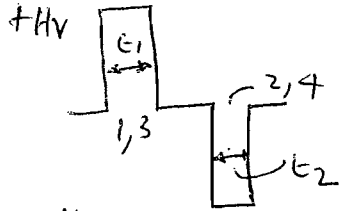
Solar plant

The main blocks for DC solar power conversion to AC mains input is shown above.

PWM is used in the first stage to generate an AC sine wave output which is synchronised to the grid voltage and power is transferred with controlled phase - power factor.



For the HV DC to AC conversion power electronic switches (usually IGBT's as shown) 1 and 3 or 1 and 4 are turned on alternatively. This gives alternate cycles of +HV or -HV pulses at the output.



(width)

The duration of the pulses  $t_1$  and  $t_2$  are controlled using the following procedure.

A sinusoidal wave form,  $V_{con}$ , is generated at the same frequency as  $V_{grid}$  (50/60 Hz). It is not in phase with  $V_{grid}$ .

Another high frequency triangular wave form with  $\pm V_{TRI}$  amplitude is also generated.

$$\pm V_{TRI} > \pm V_{con-pk}$$

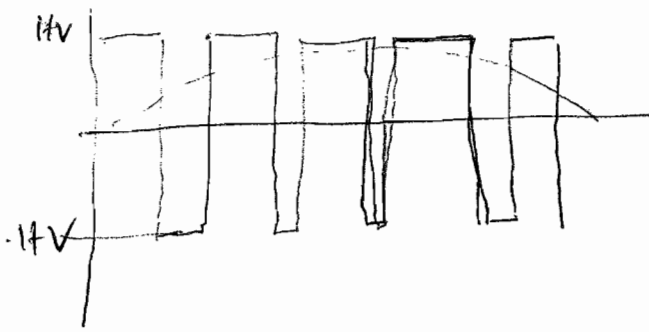
turn-on

The switching pulses to switches 1,3 when

$V_{TRI} > V_{con}$ . To turn-on switch 2,4 when

$V_{TRI} < V_{con}$ .

This gives an output pulse train which has its on times modulated by the convolution of  $V_{TRI}$  and  $V_{con}$ .



The Fourier spectrum of this signal is



-1 If  $f_{TR1} \gg f_{con}$  can easily low pass filter

pulse train to obtain only the  $f_{con}$  sine wave signal.  $f_{con} = f_{grid}$ .  $M_f = \frac{f_{TR1}}{f_{con}}$

The amplitude of the sine wave output is set dynamically according the ratio

$M_a = \frac{V_{con-pk}}{V_{TR1}}$  The output is amplitude is  $M_a \times HV$  (The

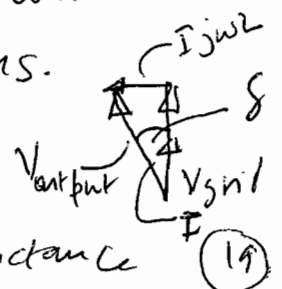
DC voltage)

$M_f$  and  $M_a$  are the frequency and amplitude modulation ratios

The phase  $\delta$  between the output 50/60Hz voltage with sine wave amplitude  $M_a \times HV$  is controlled to allow power transfer with power factor  $\Delta$ . In phasor terms.

$$V_{output} \angle \delta = I L \omega \cdot j \omega L + V_{grid} \angle 0$$

$\uparrow$  low pass filter inductance (19)



d)

i) Relative importance of reducing carbon emissions versus rising oil and gas prices in driving ~~the~~ rapid growth of the solar power sector

- Points to sought.

① Carbon emissions contribute to greenhouse gases and need to be reduced. Electricity generation contributes to  $\approx 30\%$  of greenhouse gas emission. In absolute terms will rise as more electricity generation occurs in developing countries. Also true for developed countries to sustain economic growth.

② Incentives for adoption of solar power generation in order to reduce carbon emissions associated with electricity generation.

- Description of incentives (Feed-in tariff, Capital grant, preferential credit rates).

③ Incentives ~~are less~~ become less significant in cost projections if the cost of generating electricity from oil and gas increase at the rates they have over the past 5 years

- This is driven by demand for oil and gas as world economy expands (India, China etc.)

This adoption of solar power increases.

Ⓟ But - Energy must be consumed to manufacture solar cells. Therefore the rising cost of oil and gas must also be reflected in a rise in solar cell costs at some point. At present solar cell prices are coming down as exponential growth in demand has brought in more and more manufacturing capacity. But this is not as rapid as expected due to demand outstripping supply and manufacturing (energy) costs going up.

Ⓟ The main advantage for solar cells is that once manufactured, ~~the~~ ~~their~~ energy generating costs are frozen over their life time ( $\approx 25$  years). Also true for other renewable technologies.

ii) The ~~the~~ expansion of nuclear power generation will not suppress adoption of solar power in the UK.

- points to cover

Ⓟ Nuclear power currently provides 20% of UK electricity. Its expansion and renewal may increase this to 30%. ~~The main~~

⑥ The main driver is that it is a non-carbon emitting technology (like solar). It is therefore likely to have more impact on the expansion and replacement of alternative carbon emitting generation technologies such as gas and coal.

⑦ Solar presently is negligible fraction of UK power generation. Many incentives for small scale domestic/urban power generation using solar as a means to reducing carbon footprint.

⑧ Scale of unit deployment with solar is at the other ~~spectr~~ end of the spectrum from nuclear (micro vs mega)

⑨ Availability or otherwise of nuclear generated electricity on the main ballasting power grid will have very little impact on the adoption of renewable power generation technologies.

⑩ Nuclear only has the advantage of not emitting carbon. The waste it produces and the storage required for many centuries is polluting. It is therefore unlikely to be accepted as a long term solution for all power generation.