

1 (a)

$$V_{bi} = \frac{KT}{q} \ln \left[\frac{N_D N_A}{n_i^2} \right]$$

$$= 0.026 \ln \left[\frac{10^{25} \times 10^{23}}{25 \times 10^{32}} \right] = 0.87 \text{ V} \quad [15\%]$$

$$(b) I_s = qA \left[\frac{L_e}{\tau_e} \frac{n_i^2}{N_A} + \frac{L_h}{\tau_h} \frac{n_i^2}{N_D} \right]$$

$$= 1.602 \times 10^{19} \times 10^{-2} \left[\frac{1 \times 10^{-4}}{1 \times 10^{-6}} \times \frac{25 \times 10^{32}}{10^{23}} + \frac{10^{-7}}{1 \times 10^{-9}} \times \frac{25 \times 10^{32}}{10^{25}} \right]$$

$$\cong 1.602 \times 10^{-19} \times 25 \times 10^9$$

$$\cong 4 \text{ nA} \quad [15\%]$$

$$(c) I_F = I_s \left[\exp \left(\frac{qV_F}{KT} \right) - 1 \right]$$

$$V_F = \frac{KT}{q} \ln \left[\frac{I_F}{I_s} + 1 \right]$$

$$= 0.026 \ln \left[\frac{5}{4 \times 10^{-9}} + 1 \right] = 0.55 \text{ V} \quad [20\%]$$

$$(d) I_{opt} = g_{opt} qA [L_e + L_h] = 10^{25} \times 1.602 \times 10^{-9} \times 10^{-2} [10^{-4} + 10^{-7}] = 1.6 \text{ A}$$

But the optically generated current has the impact of increasing the effective reverse current.

$$\therefore I_{Fopt} = I_s \left(\exp \left(\frac{qV_F}{KT} \right) - 1 \right) - I_{opt}$$

$$\text{and } I_{Fopt} = 5 \text{ A} - 1.6 \text{ A} = 3.4 \text{ A} \quad [20\%]$$

(e) $I_{Fopt} = I_{SC}$ under open circuit conditions

$$I_{Fopt} = 0$$

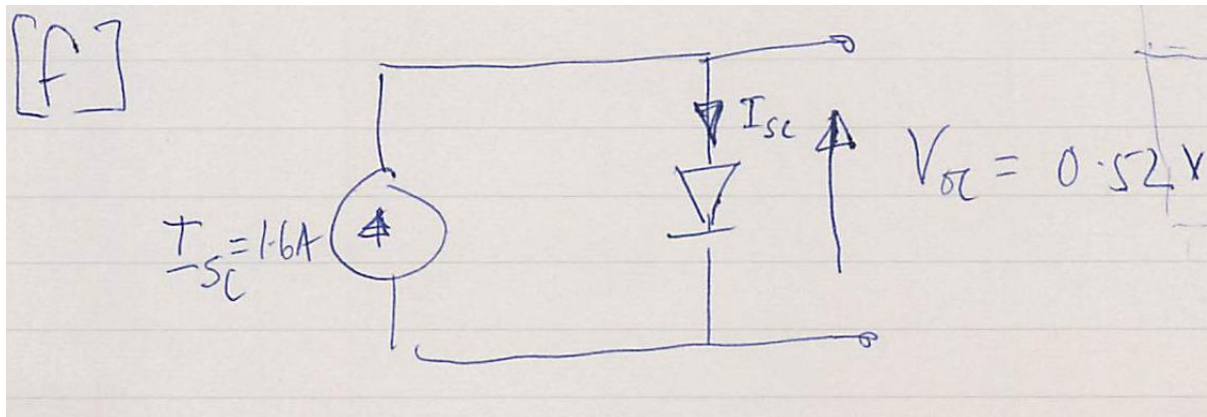
$$0 = I_S \left(\exp\left(\frac{qV_F}{KT}\right) - 1 \right) - I_{opt}$$

$$V_{OC} = \frac{KT}{q} \ln\left(\frac{I_{SC}}{I_S} + 1\right) = 0.026 \ln\left(\frac{1.6}{4 \times 10^{-9}} + 1\right)$$

$$\underline{V_{OC} = 0.52 \text{ V}}$$

[15%]

(f)



[15%]

2 (a) a-Si:H band-gap 1.8 – 1.5 eV

$$400 \text{ nm light energy} - h \times \frac{3 \times 10^8}{4 \times 10^7} = h \times \frac{3}{4} \times 10^{15}$$

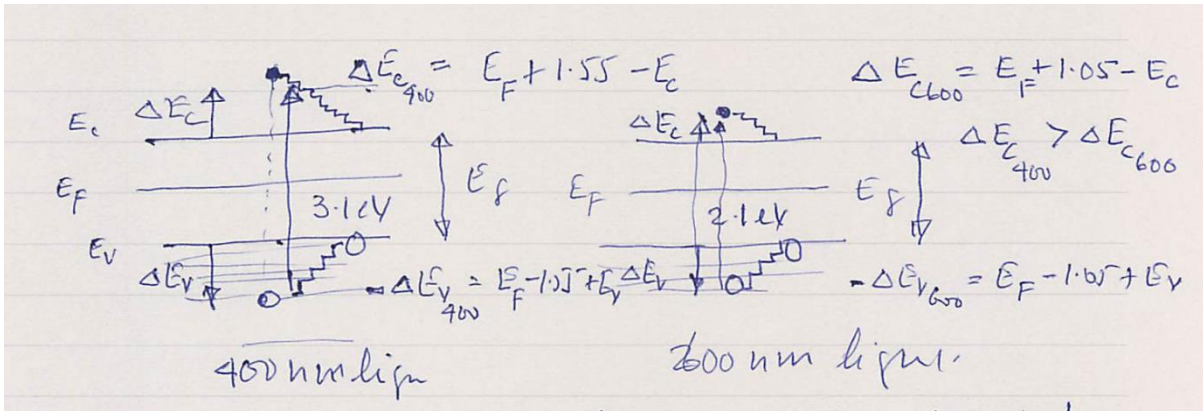
$$600 \text{ nm light energy} - h \times \frac{3}{6} \times 10^{15}$$

$$\text{In } eV(600nm) \frac{h}{q} \times 5 \times 10^{14} \text{ and } \frac{h}{q} \times 7.5 \times 10^{14} (400nm)$$

$$= 2.1 \text{ eV}$$

$$= 3.1 \text{ eV}$$

Assuming photon loses energy through absorption by a valence band electron which is excited symmetrically relative to the mid-gap Fermi level to the conduction band.



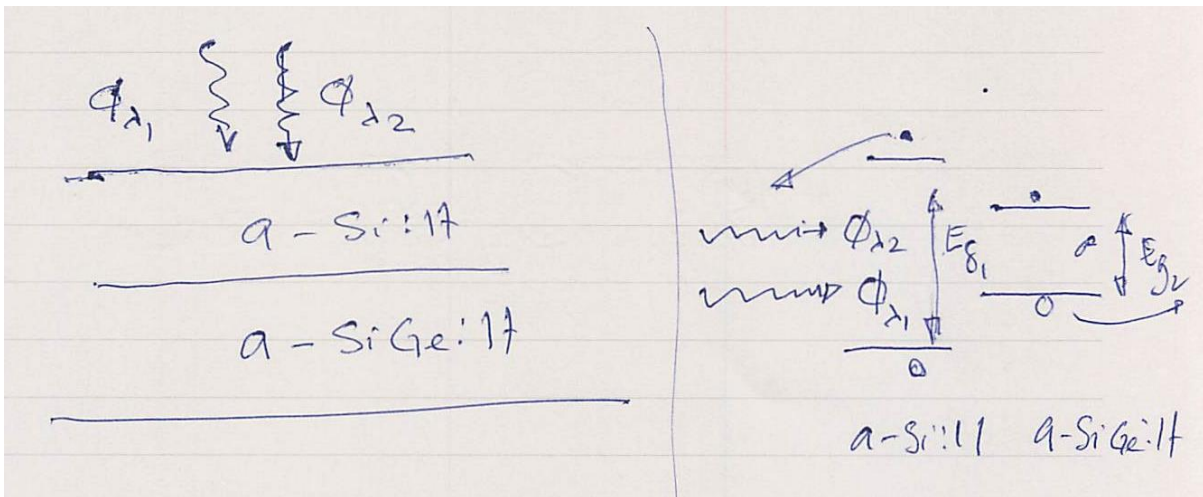
The shorter wave length light excites the valence electron to a higher energy state in the conduction band and generates a hole deeper in the valence band.

But the electron and hole can only be extracted at the band edge energies E_C and E_V respectively.

Hence the excess energies ΔE_C and ΔE_V of the photo generated electron and hole respectively are lost through thermal excitation of atomic vibrations in the a-Si:H. This excess energy cannot be recovered.

Since there is more excess energy ($E_g - E_{\text{photon}}$) generated for 400 nm light, the conversion efficiency will be greater for 600 nm light. [20%]

(b)



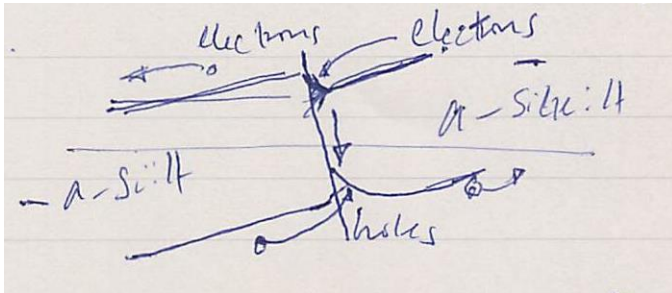
Consider two photons $\phi_{\lambda_1}(E) \gg E_{g1-a-Si:H}$ $\phi_{\lambda_2}(E) < E_{g2-a-Si:H}$

$\phi_{\lambda_1}(E) \gg \phi_{\lambda_2}(E) \gg E_{g-a-Si:H}$

The a-Si:H can absorb the shorter wavelength photons while the a-SiGe:H can absorb the longer wavelength photons which would not be absorbed by the a-Si:H. The a-SiGe:H can in principle absorb both photons, but both the electron and hole generated by the more energetic

photon would have a large energy loss. By having the a-Si:H, for example to collect electrons from, the energy loss from the more energetic photons would be reduced.

Only photogenerated holes in the a-SiGe:H can be collected. This is because the way the energy band diagrams are aligned, electrons from the a-SiGe:H face a barrier to cross into the a-Si:H. Photogenerated electrons in the a-SiGe:H accumulate at the interface and recombine in the holes entering the a-SiGe:H from the a-Si:H (there is a valence band potential difference which allows hole transfer at the interface). There is therefore a recombination current at the interface of the two materials.



[25%]

(c) When delivering power, it is important that all currents (electron, hole and recombination) are matched. In essence we have two solar cells in series. Therefore the electron-hole generation and collection/recombination have to be matched. Hence the layer thicknesses need to be specified carefully taking into consideration their absorption characteristics over the solar spectrum. In addition, the contact resistance between the two layers also needs to be minimised.

[20%]

(d) (i) The purpose of the layer is to minimise light reflected from the solar cell surface. It is termed an anti-reflection coating.

[10%]

(ii) With reference to the Formulae and Constants sheet, considering the transparent insulating layer on the a Si surface.

R (reflection) minimum $2\theta = \pi$

$$\therefore \frac{\pi}{2} = \frac{2\pi n_2 d}{\lambda} \quad \text{Note that reflection is only minimised to zero for a single wavelength.}$$

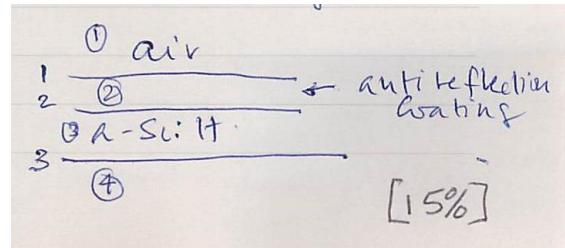
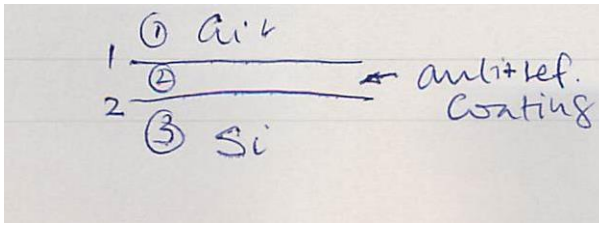
Normally chosen to be at the solar spectrum maximum i.e. 600 nm.

$$n_2 = 2.2 \quad \lambda = 600\text{nm}$$

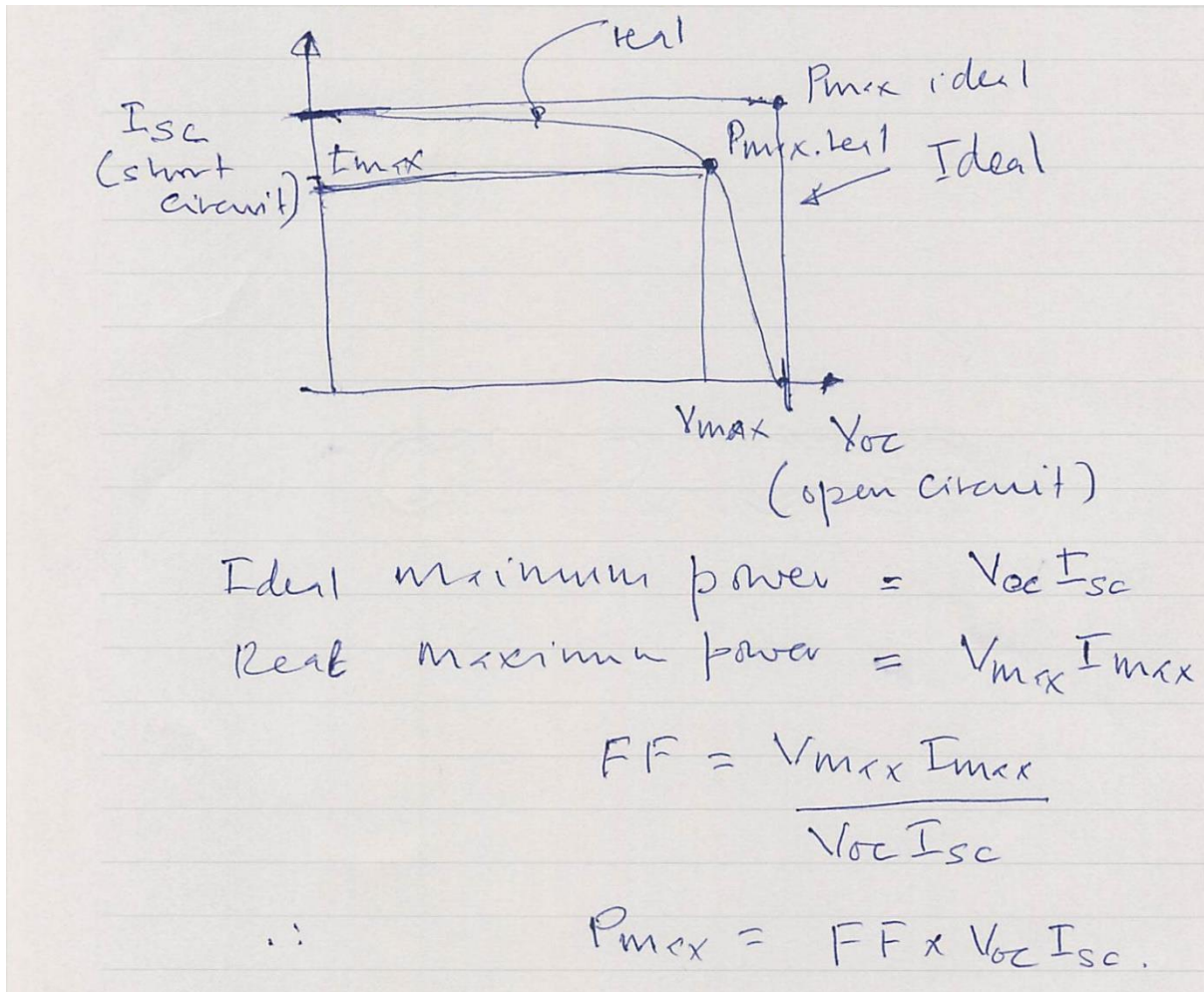
$$\therefore d = \frac{\lambda}{4n_2} = \frac{600}{2.2 \times 4} = 68\text{nm}$$

[10%]

(iii) Since the solar cell made from amorphous semiconductors have thin film absorbers, extra reflection interfaces have to be considered when calculating the reflection minimum.



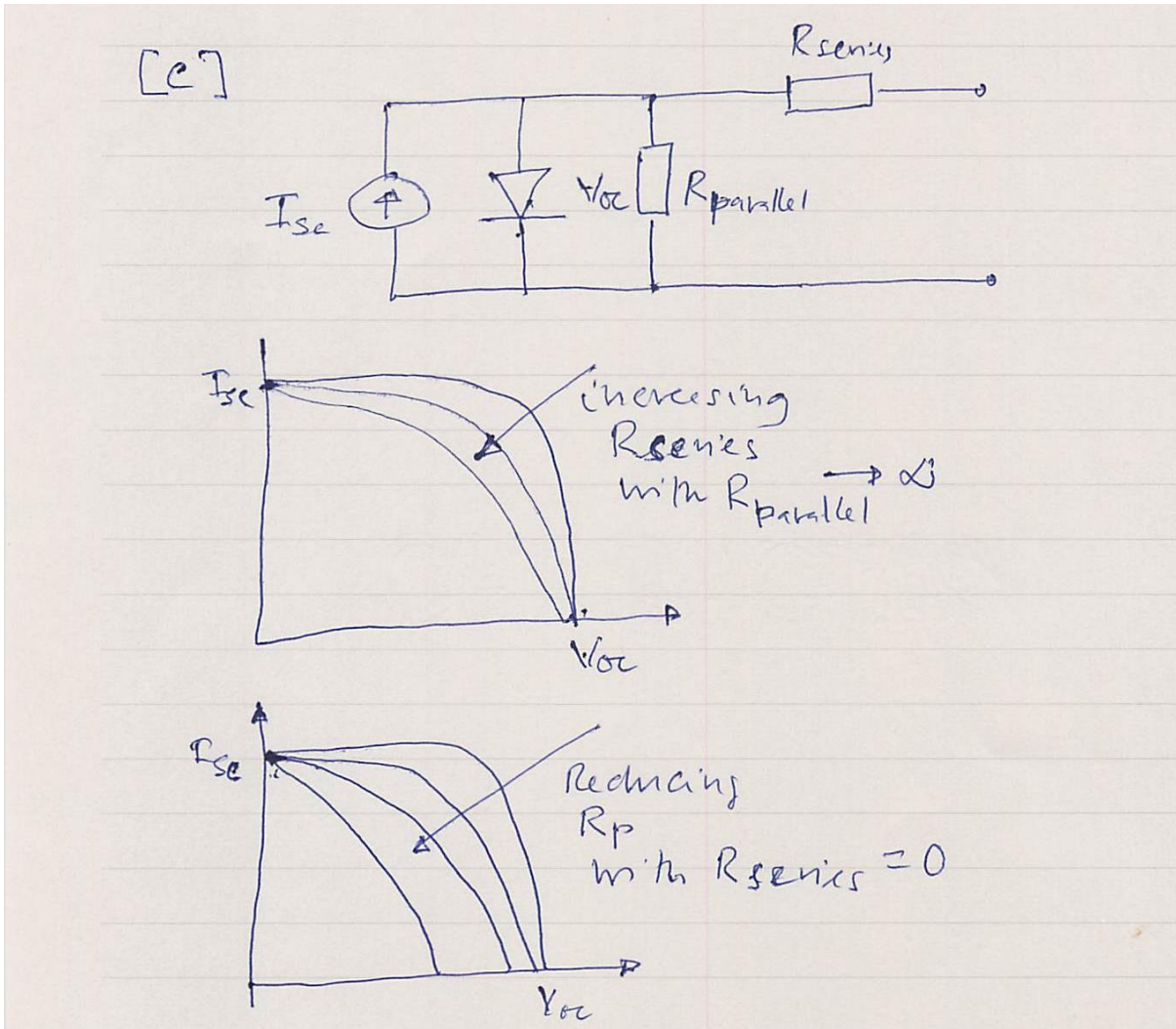
3 (a) The *Fill Factor* (FF) signifies how close the current-voltage output characteristics of a solar cell approach an ideal rectangle based on constant maximum current and maximum voltage.



[15%]

(b) The FF is reduced by any hindrance to the junction I_{SC} and V_{OC} appearing at external terminals of the cell. In general any series resistance will reduce the operational voltage when delivering power. Similarly any resistance in parallel with the junction will reduce the operational current.

[15%]



[20%]

(d) Referring to the Formulae and Constants sheet,

$$FF_O = \frac{\frac{V_{OC}}{0.026} - \ln\left(\frac{V_{OC}}{0.026} + 0.72\right)}{\frac{V_{OC}}{0.026} + 1}$$

[20%]

This is an empirical relationship. An estimate for V_{OC} requires trial and error substitution.

If $V_{OC} = 0.7$

$$FF_O = 0.83 \text{ given } \frac{\frac{0.7}{0.026} - \ln\left(\frac{0.7}{0.026} + 0.72\right)}{\frac{0.7}{0.026} + 1} = 0.964 - 0.119 = 0.85$$

$$\text{If } V_{OC} = 0.6 \quad \frac{\frac{0.6}{0.026} - \ln\left(\frac{0.6}{0.026} + 0.72\right)}{\frac{0.6}{0.026} + 1}$$

$$= 0.828 = 0.83$$

∴ Estimate is $V_{OC} = 0.6$ V [20%]

(e) $0.18 = FF_O \times V_{OC} \times I_{SC} / 10^{-2} \times 10^3$

$$\therefore I_{SC} = \frac{0.18}{0.83 \times 0.6} \times 10 = 3.6 \text{ A} \quad [15\%]$$

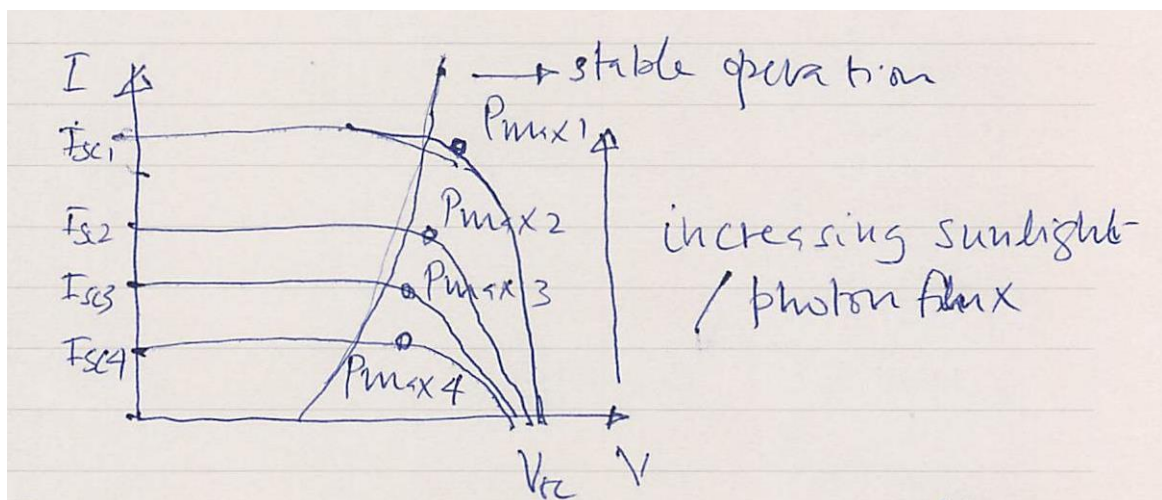
(f) $FF = FF_O(1 - r_c)$ where $r_c = \frac{0.06}{(0.6/3.6)} \rightarrow r_o$

$$= FF_O(0.64) = 0.53 \quad r_c = 0.36$$

$$\therefore \text{efficiency} = 0.18 \times \frac{0.53}{0.83}$$

$$= 0.115$$

Or 11.5% [15%]



4 (a)

As the light conditions change, the effective operational $I - V$ curve of solar cells/plant changes. It is therefore important to trace the maximum power point (MPP). If this is not done when light changes, there is the possibility of the operation point lying outside the stable region and the output collapsing.

- General method is empirical. Perturb and observe. At intervals of seconds (adequate for terrestrial solar light variation) the operation point is 'perturbed' to $I + \Delta I$. Then power $P_{n+1} = V_{n+1}(I + \Delta I)$ is compared to P_n . If $P_{n+1} > P_n$ then the process continues until

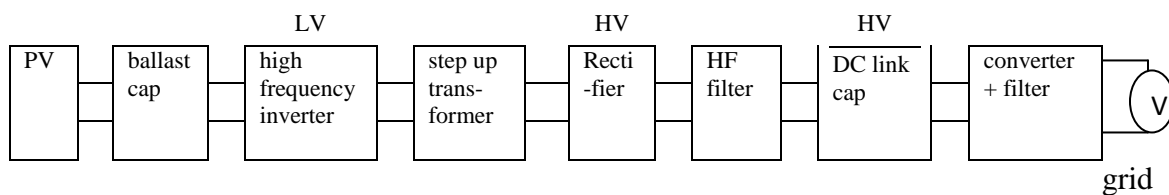
$P_{n+1} < P_n$, and the P_n point is chosen. Otherwise $P_{n+1} = V_{n+1}(I - \Delta I)$ is implemented and the same process followed until $P_{n+1} < P_n$.

- Alternatively the mathematical model $P = VI \quad \frac{dP}{dV} = I + V \frac{dI}{dV} = 0$ at P_{\max}

$$\therefore \frac{dI}{dV} = \frac{-I}{V} \text{ is used.}$$

This requires the gradient $\frac{\Delta I}{\Delta V}$ to be calculated and matched to $\left| \frac{I}{V} \right|$ at the maximum power point. This is termed the incremental inductance method.

(b)



[20%]

- (c) - The price of electricity varies during the day depending on demand.
- In many cities the high-demand is in the daytime when offices and factories are operating.
 - During the day peak demand can be when the sun is at most intense, e.g. air conditioning loads in the mid-day period.
 - Solar plant output is also at maximum when demand peaks.
 - Peak demand electricity is priced much higher than the average electricity price.
 - Many utilities maintain a 'spinning reserve' to meet peak demand.
 - Solar can replace the 'spinning reserve' and have the electricity generated priced at the peak-demand level. It is also when solar output is maximum. [30%]
- (d) - Solar PV cells require energy to manufacture them. For Si cells this energy is high as there is a metallurgical process to convert sand (SiO_2) to pure-crystalline/polycrystalline Si. This requires high temperature to melt SiO_2 (glass). Following this there is actual manufacture of the solar cell which also requires dopant diffusion and oxidation steps at temperatures of 900 – 1100°C.
- A crystalline Si all needs to operate in a sunny climate for about 3-5 years to generate the equivalent energy consumed in its manufacture. In the UK it could be as high as 7 years
 - However, the operational life of c-Si cells is 20-25 years. So there is a 'green energy' profit over its lifetime if output levels can be maintained. This requires maintenance to remove dust, fouling etc. from the solar panel surface. This may be difficult in some installations.
 - Recently there has been evidence to show that at end of life (25 years) solar panels can be disassembled and the cells taken out. These cells can be reprocessed and recycled at an energy cost approaching 1/3rd of what would be required to make new solar cells. This has the potential of reducing the lifetime energy footprint of solar cells significantly and enhancing their sustainability.
 - The cost of solar cells are directly related to the energy used in their manufacture.

- Low cost solar cells use less energy but have lower efficiency and life time. Low cost solar cells therefore need to have more area to generate the same power.
- Low cost solar cells are a-Si:H, and CdTe, and CIGS thin film varieties. They use less material per generated watt of power and are therefore more sustainable in one aspect.
- The energy pay back period (generated energy = energy to manufacture) is 1-2 years.
- Taken as a whole PV is a sustainable technology. But it is important to consider the entire life cycle including potential recyclability. [30%]