

$$V_{bi} = E_{Fn} - E_{Fp} \quad \text{--- (1)}$$

$$n = N_c \exp\left(\frac{E_{Fn} - E_c}{RT}\right)$$

$$\therefore E_{Fn} = E_c + RT \ln\left(\frac{n}{N_c}\right) \quad \text{--- (2)}$$

$$p = N_v \exp\left(\frac{E_v - E_{Fp}}{RT}\right)$$

$$\therefore E_{Fp} = E_v - RT \ln\left(\frac{p}{N_v}\right) \quad \text{--- (3)}$$

$$\therefore E_{Fn} - E_{Fp} = E_c - E_v + RT \ln\left(\frac{np}{N_c N_v}\right)$$

$$0.91 = 1.12 + RT \ln\left(\frac{np}{N_c N_v}\right)$$

$$-0.21 = \frac{RT}{q} \ln\left(\frac{np}{N_c N_v}\right) \quad \text{--- (4)}$$

$$np = N_c N_v \exp\left(\frac{-0.21q}{RT}\right) \quad \text{--- (5)}$$

We can assume that

$$n = N_D$$

$$\text{and } p = N_A$$

$$\text{Also } N_c = N_v$$

Considering p-side of the junction away from the depletion edge:

$$\phi_{np} = n_i^2$$

$$N_v^2 = N_c \exp\left(\frac{E_{Fp} - E_c}{RT}\right)$$

$$\times N_v \exp\left(\frac{E_v - E_{Fp}}{RT}\right)$$

$$N_v^2 = N_c^2 \exp\left(\frac{E_v - E_c}{RT}\right) \quad \text{--- (6)}$$

$$N_c = n_i \exp\left(\frac{E_c - E_v}{2kT}\right) \quad \text{--- (6)}$$

Substituting (6) in (5) for $N_c N_v = N_c^2$

$$\frac{N_D}{N_A} = \frac{n_i^2}{N_c^2} \exp\left(\frac{0.91q}{RT}\right)$$

$$N_A = 3.2 \times 10^{22} \text{ m}^{-3}$$

(1)

$$b) n_0 = n_p(x_p) = n_n(-x_n) \exp\left(\frac{q(V - V_{bi})}{RT}\right)$$

$$n_0 = 5 \times 10^{24} \exp\left(\frac{0.4 - 0.91}{0.026}\right)$$

$$= 1.5 \times 10^{16} \text{ m}^{-3}$$

$$c) 1) V_a = \frac{kT}{q} \ln\left(\frac{I_{sc} + I_s}{I_s}\right)$$

$$\therefore 0.72 = 0.026 \ln\left(\frac{I_{sc} + I_s}{I_s}\right) \quad \boxed{I_{sc} = \left[\exp\left(\frac{0.60}{0.026}\right) - 1\right] I_s}$$

Need to calculate I_s

$$I_s = qA \left[\frac{n_i^2 D_e}{N_A L_e} + \frac{D_h n_i^2}{L_h N_D} \right]$$

Also $L = \sqrt{DE} \therefore D = L^2/E$

$$I_s = qA \left[\frac{n_i^2 L_e}{N_A E_e} + \frac{D_h n_i^2}{L_h N_D} \right]$$

$$= 3.76 \times 10^{-10} \text{ A}$$

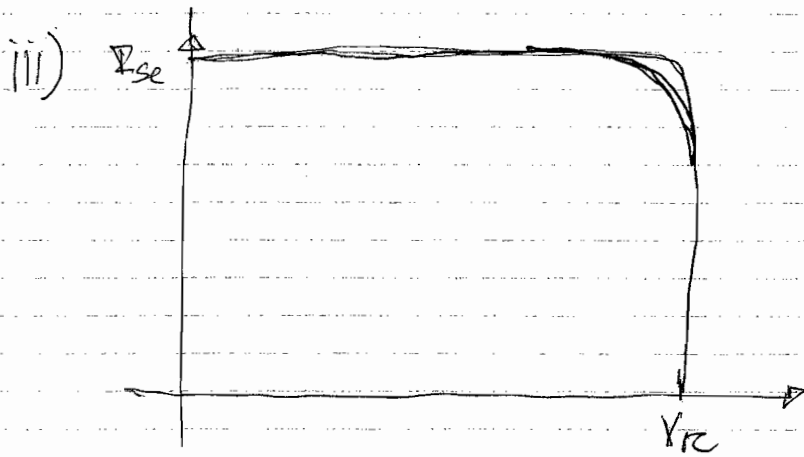
Substituting for I_s in expression above for I_{sc} gives

$$I_{sc} = \underline{\underline{3.96 \text{ A}}} \quad (\approx 4 \text{ A})$$

d) $I_{sc} = qA G L_e$ Assume only carriers generated in the p-type region contribute to the photocurrent.

$$\therefore G = \frac{I_{sc}}{qA L_e}$$

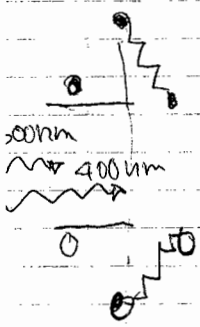
$$= 1.65 \times 10^{25} \text{ m}^{-3} \text{ s}^{-1}$$



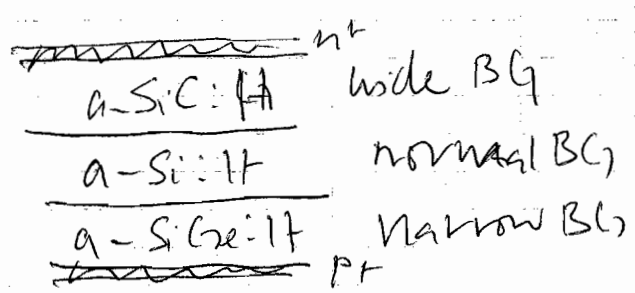
For a C-Si solar cell the characteristic is quite square. (Full marks if the 0.72V and one kT/q information are used to estimate the Fill Factor as well from the Formulae and Constants Sheet).

2

a) A 400 nm photon has energy which is significantly above the band-gap a-Si:H. Whereas the 600 nm photon has an energy closer to the band-gap. Therefore the energy separation of an electron-hole pair created with absorption of 600 nm light can be better maintained (the maximum energy separation has to be equal to the band-gap). The excess energy, above the band-gap separation, is converted to heat within the semiconductor. Hence, the a-Si:H cell would be hotter when converting 400 nm light compared to 600 nm light.



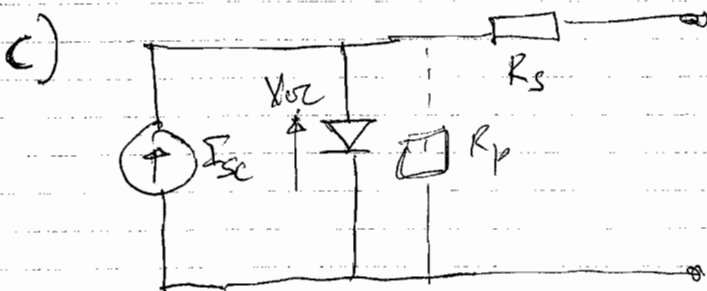
b) Light which has energy significantly above the band-gap energy is absorbed near the surface and generates heat (as per discussion in a) above). On the other hand light which has energy below the band-gap is transmitted through the cell without being absorbed. So the best structure is:



In effect it is like having ^{individual} ~~the~~ cells to absorb the high energy, medium energy and low energy parts of the solar spectrum.

These cells in turn are connected in series with each other, hence the use of the term 'tandem' solar cells' to describe such three layer cells.

These cells will have a higher efficiency because they will have a higher open circuit voltage (~~having~~ ~~each layer acting in series~~) by allowing for a higher ^{maximum} separation voltage for electrons and holes compared to a-Si:H alone. They can in principle also generate more current through absorption of more photons from the solar spectrum - specifically the below band-gap element.



R_p can be ignored.

Consider only the amorphous Si:H layer absorbing light through limiting the spectrum of light. In this event, the a-SiC:H and a-SiGe:H layers will appear as series resistance

with the photoabsorbing layer. Hence R_s will be excessive and the cell performance will degrade (low fill factor). So it is very important that each part of the cell independently generate an I_{sc} which is close to each other for optimum performance. This requires the thicknesses and band-gaps to be carefully optimised. Otherwise each of the series layers can appear as an internal 'load' to the ~~cell~~ ^{layer} generating the ~~the~~ highest I_{sc} .

a) Advantages

- 1) low cost through lower temperature (hence energy) required for production.
- 2) Can be easily scaled to be manufactured over large areas.
- 3) Can easily design modules by connecting strips of a-Si:H on the same substrate in series ~~and~~ to set desired voltage and scale area of each strip to achieve desired current.
- 4) Has lower energy pay back time. That is it has to operate for less time (typically 2 years) before it has generated the equivalent energy ~~to~~ that which was consumed in its manufacture.
- 5) Can be incorporated as an integral part of a building or glass components easily.

Disadvantages

- 1) It has lower efficiency $\approx 10\%$ compared to $\approx 20\%$. As a result of the area c-Si . This means more area is required to generate the same power, hence adding to installation cost.
- 2) Life time is limited. a-Si:H cells degrade with time on exposure to light. Therefore an a-Si:H solar plant will only operate for 8-10 years before cells need to be replaced. With c-Si 25 year life times are typical.

$$3) a) V_{oc} = \eta \frac{kT}{q} \ln\left(\frac{I_{sc}}{I_s} + 1\right)$$

$$\therefore I_s = \frac{I_{sc}}{\left[\exp\left(\frac{qV_{oc}}{\eta kT}\right) + 1\right]} = \frac{3}{\left[\exp\left(\frac{1.602 \times 10^{-19} \times 0.6}{1.1 \times k \times 330} + 1\right)\right]}$$

Under reverse bias in the dark.

$$I = I_s \left[\exp\left(\frac{q(V - V_{bc})}{\eta kT}\right) - 1 \right]$$

V will be negative

$$\therefore I \rightarrow -I_s \quad \text{from above } I_s = 5.12 \times 10^{-9} \text{ A}$$

$$b) \Rightarrow \text{Efficiency} = \frac{V_{oc} I_{sc} \times FF}{P_{in}}$$

$$FF \text{ is the fill factor. } FF = \frac{FF_1 \cdot FF_2}{FF_0}$$

FF_0 is the intrinsic fill factor for a Si p-n junction.

This calculated using the open circuit voltage and the operating temperature using the expression given in the formulae and constants data sheet.

FF_1 and FF_2 are fill factors adjusted for the series resistance in the cell and shunt current loss (parallel resistance R_p across junction) in the cell. $FF_2 \rightarrow FF_0$ when $R_p \rightarrow \infty$

$$\therefore FF = FF_1 = FF_0 (1 - r_s) \quad \text{where } r_s = \frac{R_{series}}{R_0}$$

$$R_0 = V_{oc}/I_{sc} = 0.2 \Omega \quad R_{series} = 0.02 \Omega$$

(8)

$$\therefore FF_1 = FF_0 \left(1 - \frac{0.02}{0.2}\right) = 0.9 FF_0$$

FF_0 (using $\frac{9 \times 0.6}{K330}$) from the Formulae sheet

is 0.815 $\therefore FF_1 = 0.733$

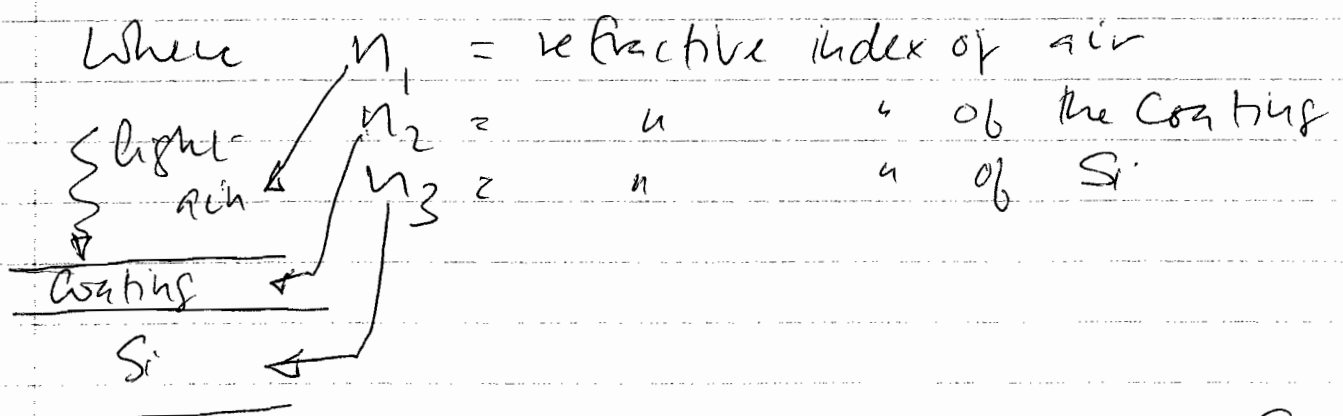
$$\text{Efficiency } \eta = \frac{0.6 \times 3 \times 0.733}{10} = 0.132 \text{ or } \underline{\underline{13.2\%}}$$

c) The layer acts as an anti-reflection coating. It can be designed to give zero reflection for a single wavelength. It is best to make the zero reflectance wavelength match that which corresponds to the peak of the solar spectrum. This is a 600 nm.

\therefore From the reflectance expression in the Formulae and Constants sheet:

$$R = \frac{n_2^2 (n_1 - n_3)^2 \cos^2 \theta + (n_1 n_3 - n_2^2)^2 \sin^2 \theta}{n_2^2 (n_1 + n_3)^2 \cos^2 \theta + (n_1 n_3 + n_2^2)^2 \sin^2 \theta}$$

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



\therefore When $\theta = \pi/2$ $\cos^2 \theta$ terms are eliminated.

$$\therefore \text{Require } \frac{\pi}{2} = \frac{2\pi n_2 d}{\lambda}$$
$$\frac{\lambda}{4} = n_2 d$$

Also if $n_1 n_3 - n_2^2 = 0$ the numerator of the expression for $R \rightarrow 0$

$$\therefore n_2 = \sqrt{n_1 n_3} = \sqrt{n_3} = 1.86$$

Take $\lambda = 600 \text{ nm}$ $n_3 = 11.9^{0.5}$ from data sheet
 $n_1 = 1$ (for air)

$$\therefore d = \frac{150}{n_2} = \frac{150}{\sqrt{n_3}} = \frac{150}{1.86} = 80.65 \text{ nm}$$

~ 80 nm

Therefore the optimum antireflective coating on Si^{at 600nm} would be 80 nm thick and have a refractive index of 1.86.

4 a) An 'Ac module solar panel' is a single PV panel which has built into it an inverter circuit which allows the panel to be connected directly into the mains supply.

A PV panel has a ^{max} power rating of 100 - 200W typically. Therefore the AC module inverter has to be capable of transferring small amounts of power (down to 10-15W) in AC form suitable for the mains at high efficiency. The AC module allows a mains connected solar installation to be built up from a single PV panel.

b) The advantages are:

(i) The whole installation does not have to be built at the same time in a unit of 1kW. The 1kW minimum is now common due to the fact that the grid connection through an inverter can only be scaled down to 1kW. With AC modules, the system can be built up module at a time using different panel types.

(ii) Since each panel has its own AC connection, the power conversion is optimised for each panel. With a centralized system, panels are connected in series to increase connection voltage on the DC bus which is input-
(11)

the inverter. If one of the panels malfunctions or is not very closely matched to the others, power output from all the panels are compromised (equal photocurrent has to be sustained in all panels in a series connection). With the Module AC approach this is overcome. There is also minimal system loss due to shading of panel due the parallel nature of the AC Module connection.

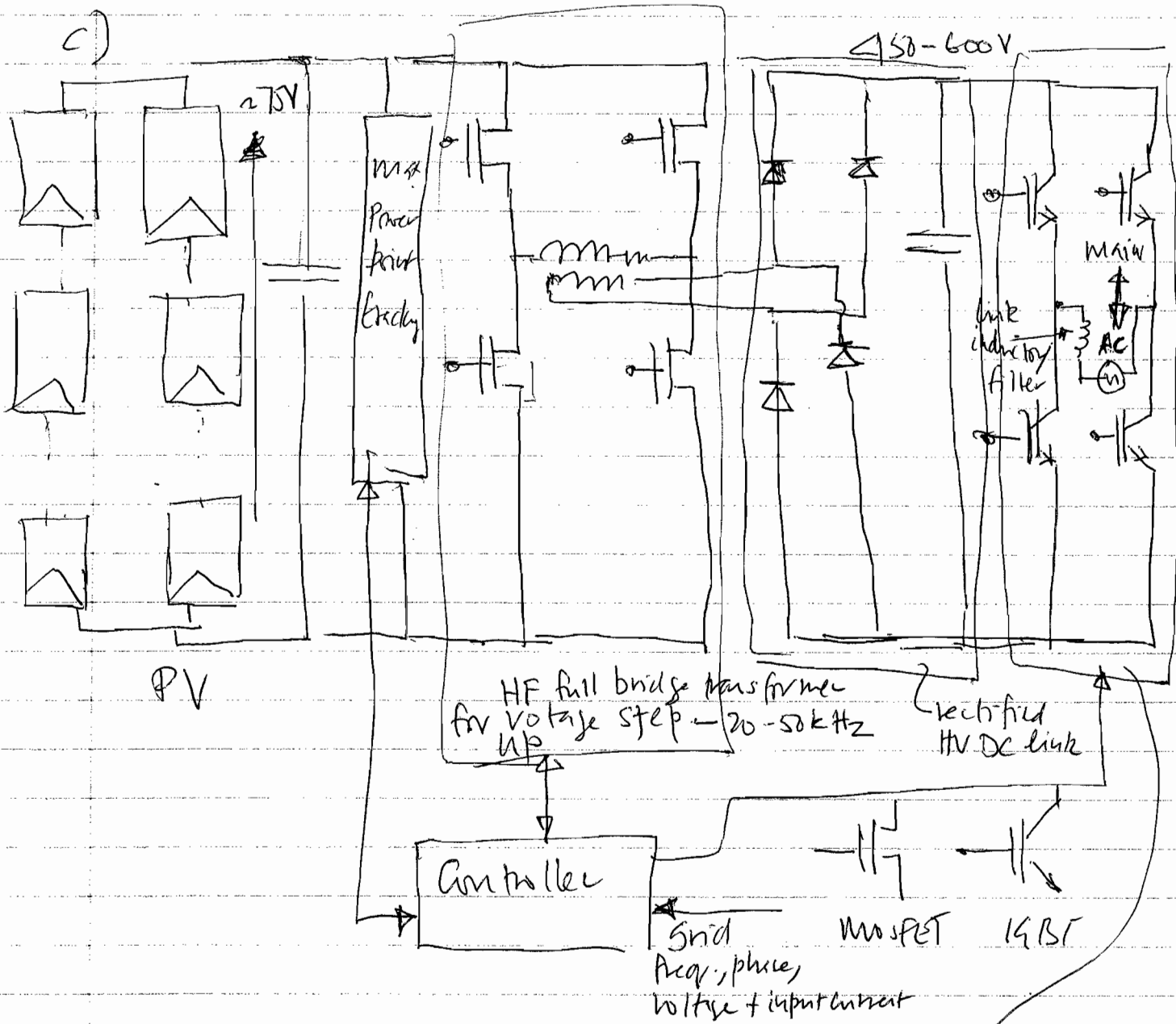
iii) No HV DC bus connection is required on the roof. This is a main safety concern in PV installations and requires electricians with special DC wiring accreditation to service / install.

Disadvantages
ii) Inverter failure (main cause for unreliability) does not lead to the whole installation being lost.

i) Since each panel has an inverter the electronic content of the installation is increased. Each of the electronic components consume energy and the efficiency of low power conversion is not as good as high power conversion. Therefore total system losses due to power conditions can be higher.

ii) The inverters may be more unreliable if they are on the roof with the panels and exposed to extreme temperature and humidity.

iii) Maintenance in the event of failure will require access to the roof and make repairs difficult/costly.



Controller matches DC power output from PV to AC power into the grid on an 'instantaneous' basis. It also adjusts PV operating point to maximize DC power out.

Sine wave current output to grid with harmonic distortion < 5%.

PWM inverter which is grid synchronized to transfer power with a power factor of 1.

d)

i) Points to cover.

- European public becoming increasingly aware of carbon emissions and climate change.
- Life style contribution to carbon emissions something individuals can influence.
- In the context of the above, increasing awareness of individuals wanting to mitigate their carbon footprint.
- The AC module solar panel is a 100-200W 'green generator' which can be plugged in directly into the domestic electricity supply.
- Because the unit of power available for connection is small, equivalent to that consumed by domestic appliances, its cost is affordable (£200 - £300).
- A consumer could offset their power consumption partially (perhaps completely by ^{for} washing machine, dishwasher + the generator) by installing a single solar panel.
- AC module allows 'green generation' to be a consumer choice driven by lifestyle, just as with other consumer electronics and electrical products.

ii) ~~Germany~~ Germany is an example of a country where legislation on pricing for 'green' electricity has driven market expansion. This has led to solar PV, to be adopted even though it is a relatively small volume industry and therefore expensive.

In Germany electricity companies are ^{legally} bound to buy power at ^{up to} 5 times the price at which they sell it from domestic 'green' generators. The cost is borne by all the other consumers who pay a price for electricity which absorbs the PV subsidy. It is therefore only possible under democratic terms when most of the power consumers agree to subsidise green technologies. This model is being widely adopted across Europe (Switzerland, Austria, Netherlands, Greece)

In countries such as Japan (and the UK on a ~~very~~ limited scale) no subsidy is given for power buy back. But up to a 50% subsidy is given on initial capital expenditure. This comes from 'green taxes' imposed on public consumption (e.g. petrol)

As for example in the case of safety technologies in cars and planes, legislation plays a key role in their widespread adoption. The consumer has no choice but to pay for it. But legislation cannot be passed in the first place without widespread public acceptance. (15)