4B14 Cribs 2015

Q1

(a) $V_{bi} = \frac{kT}{q} ln\left[\frac{N_D N_A}{n_i^2}\right] = 0.026\ ln\left[\frac{10^{24} \times 10^{23}}{10^{32}}\right] = \ 0.898\ eV = 0.90\ eV$ [15%]

(b) $I_s = qA\left[\frac{L_e}{\tau_e}\frac{n_i^2}{N_A} + \frac{L_h}{\tau_h}\frac{n_i^2}{N_D}\right] = 1.602 \times 10^{19} \times 10^{-3} \times \left[\frac{120\times10^{-6}\times10^{32}}{1\times10^{-6}\times10^{23}} + \frac{0.4\times10^{-6}\times10^{32}}{1\times10^{-9}\times10^{24}}\right] = 25.6\ pA$ [15%]

(c) $x_p = \left[\frac{\epsilon V_{bi} 2 N_D}{q N_A (N_A + N_D)}\right]^{1/2} = \left[\frac{11.9\times8.85\times10^{-12}\times0.90\times2\times10^{24}}{1.602\times10^{-19}\times10^{23}(10^{23}+10^{24})}\right]^{1/2}$ =104 nm [20%]

(d) $n_0 = N_D exp\left(\frac{q(V_A - V_{bi})}{kT}\right) + \frac{N_A}{n_i^2} = 10^{24} \times exp\left(\frac{(0.5-0.898)}{0.026}\right) + \frac{10^{23}}{10^{32}} = 2.25 \times 10^{17} m^{-3} = 2.25 \times 10^{11} cm^{-3}$ [20%]

(e) $I_{sc} = I_s\left(exp\left(\frac{V_{oc}}{kT}\right) - 1\right) = 2.56 \times 10^{-11} \times \left(exp\left(\frac{0.6}{0.026}\right) - 1\right)$ =0.27 A

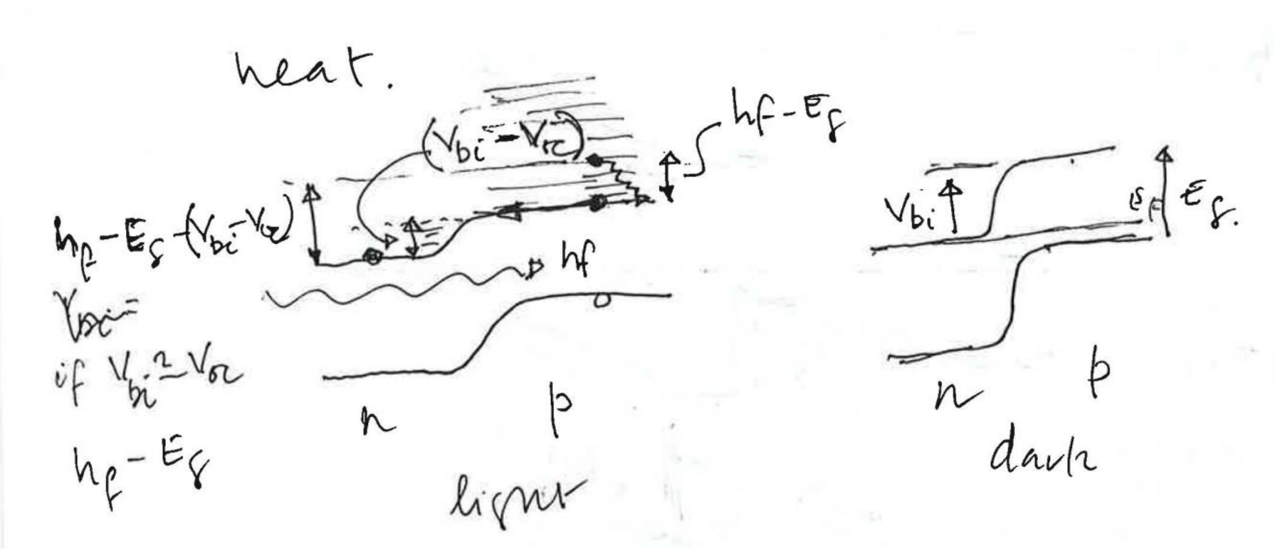
$$g_{opt} = \frac{I_{sc}}{qA(L_e + L_h)} = \frac{0.27}{1.602 \times 10^{19} \times 10^{-3}(120 \times 10^{-6} + 0.4 \times 10^{-6})} = 1.4 \times 10^{25} \mathrm{m}^{-3}\mathrm{s}^{-1}$$

[30%]

There was some uncertainty amongst some candidates on calculating the depletion region width and minority carrier injection across the junction.

Q2

(a) Photons which have energy in excess of the band-gap energy of the semiconductor can be absorbed and contribute to the PV energy conversion process. But the energy at which the photo generated electron and hole can be extracted is at maximum the band-gap energy of the semiconductor. In practice at 300 K the open circuit voltage of Si p-n junction is $\cong 0.7V$ whereas the band-gap energy is 1.12 eV. Therefore the energy at which carriers are extracted is in fact even below the band-gap energy. The excess energy of a photon $h_f > E_g$ and $E_g > V_{OC}$. The photo excited carriers have to be swept across the junction to reach the electrodes. There is therefore a further energy loss (V_{bi}-V_{OC}) in crossing the junction. Strictly speaking it is (V_{bi}-V_{op}) where V_{op} is the operational terminal voltage, but ok to assume $V_{OC} \cong V_{op}$. Total energy lost is therefore hf-E_g-(V_{bi}-V_{OC})



[20%]

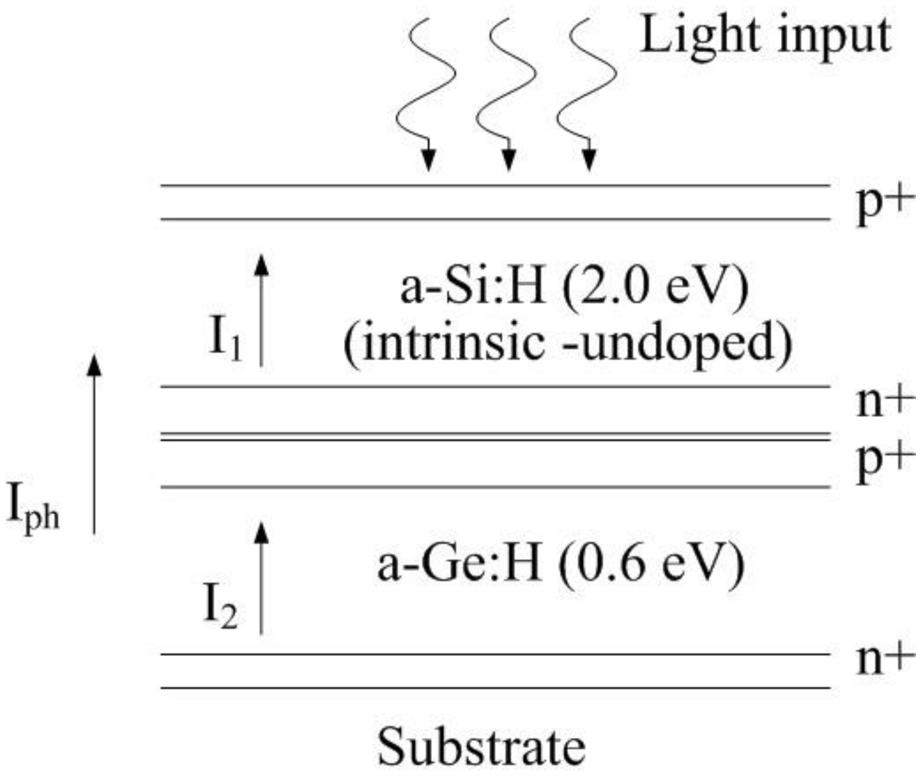
(b) From the above, 800 nm light has less energy in excess of the band-gap energy.

$$E_{ph-800} = h\frac{c}{800\times10^{-9}} \qquad E_{ph-600} = h\frac{c}{600\times10^{-9}}$$

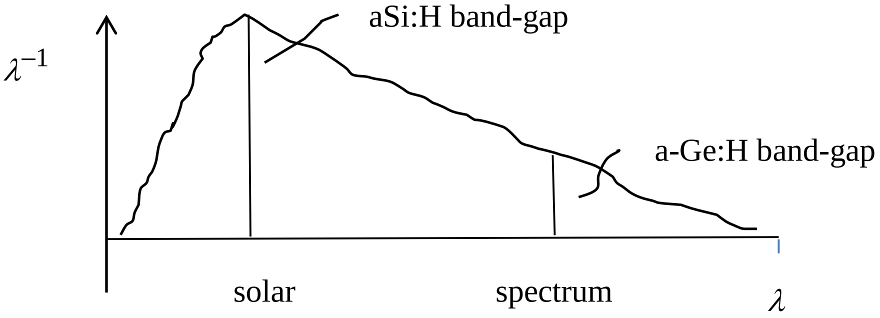
$\therefore E_g - E_{ph-800} < \langle E_g - E_{ph-600}$

So less heat generated by absorbing 800 nm light and therefore conversion of 800 nm light is more efficient than converting 600 nm light. [20%]

(c) A-Si:H has a band-gap of $\cong 1.8 - 2.0\ eV$, well matched to the peak of the solar spectrum at 550-600 nm. But all photons with energy less than $E_{ph} = \dfrac{hc}{(\lambda \rangle 600\,nm)}$ are not absorbed. A-Si:Ge has a band-gap of $\cong 0.6\ eV$. Therefore all the lower enegy photons in the $0.6eV \langle E_{ph} \langle 2.0\ eV$ energy range can be absorbed by the a-Si:Ge and contribute to the photo current. The V_{OC} developed will also be larger $V_{OC} \cong V_{OC-aSi:H} + V_{OC-aGe:H}$. [30%]



This is equivalent to two cells connected in series. Hence the current condition is $I_1=I_2=I_{ph}$. I_1 and I_2 are generated in the two different absorber layers from different parts of the solar spectrum, where the energy flux (photon flux) is different for different wavelengths



Therefore important that the two semiconductor absorber layers are matched for their respective parts of the spectrum to ensure equal numbers of photons are absorbed. After this, still challenges exist to ensure electrical transport properties are matched. The internal n+/p+ interface/contact between the two cells acts as a recombination zone. Electrons from the wide band-gap material recombine with holes from the narrow band-gap material. The external electrodes therefore collect holes from the wide band-gap material and electrons from the narrow band-gap material. As the two layers are in series, the affect of the extra carriers is to increase open circuit voltage and hence the voltage at which current is extracted. [30%]

An understanding the finer details of energy dissipation within the semiconductor and across the junction when collected was absent in all answers. In the tandem solar cell the candidates exclusively concentrated on the more efficient photon absorption aspect without taking that onto explain the increase in effective open circuit voltage

Q3

(a) $$V_{OC} = \frac{\eta kT}{q} \ell n\left(\frac{I_{SC}}{I_s} + 1\right)$$

$$\therefore I_{SC} = I_s \exp\left(\frac{qV_{OC}}{\eta KT}\right) - I_s$$

$$I_{SC} = 2.89\ A$$ [20%]

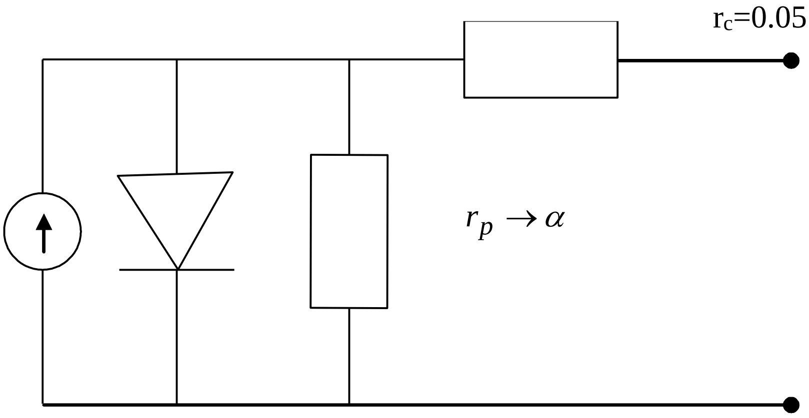
(b) Efficiency = $$\frac{FF_O V_{OC} I_{SC}}{10^3 \times 10^{-2}}$$

FF from Formulae and Constants sheet

$$\frac{qV_{OC}}{\eta KT} = 20.9 \qquad \therefore FF_O = \frac{20.9 - (\ell n(20.9 - 0.72))}{21.9} = 0.82$$

$$\therefore \text{Efficiency} = \frac{0.82 \times 0.6 \times 2.89}{10} = 14.2\,\%$$ [20%]

(c) Taking into account only the series resistance $r_C (r \to \alpha)$



$$r_O = \frac{V_{OC}}{I_{SC}} = \frac{0.6}{2.94} = 0.205$$

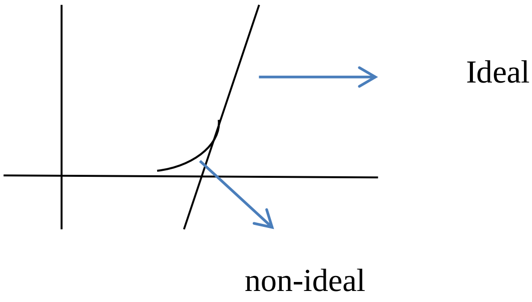
$$FF_1 = FF_O(1 - r_C / r_O) = 0.82\left(1 - \frac{0.05}{0.205}\right)$$

$$FF_1 = 0.62$$

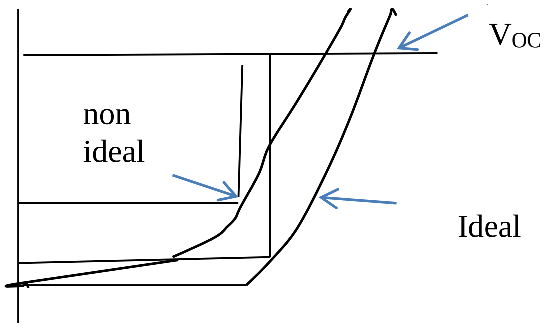
$\therefore$ Better estimate of efficiency is:

$$\frac{14.4\times 0.62}{0.82}=10.89\,\%$$ [30%]

(d) Ideality factor represents the exponential turn-on response of the solar cell as a p–n junction under dark conditions. The 'sharper' the turn-on more ideal and when non-ideal there is a softer turn-on.



When operating as a solar cell the softer turn-on is seen as a loss of V_{OC}.



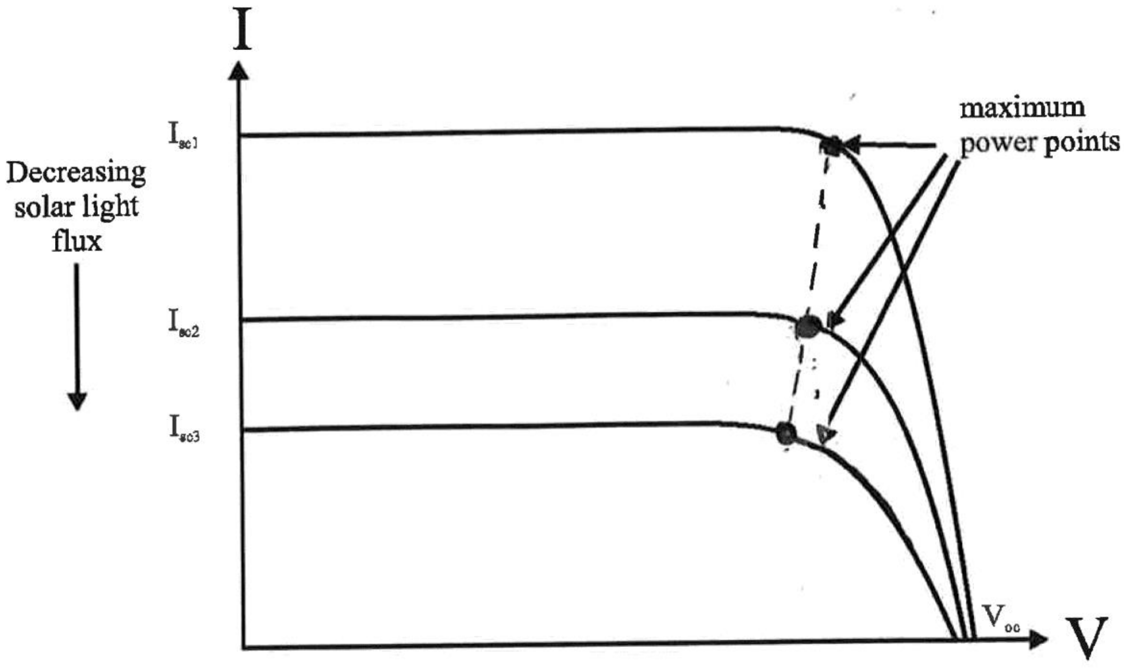
Also the Fill Factor will reduce.

The cause of non-ideality is recombination of photo generated carriers in the depletion layer of the p–n junction and at the n^+ surface close to the junction. Manufacturing of the cell more cautiously to reduce surface recombination and defects at the metallurgical junction between n+ and p substrate is the best way to improve ideality $\rightarrow$ enhance V_{OC} $\rightarrow$ enhance efficiency. *[30%]*

Some candidates did not take through the non-ideality factor into the calculation of the fill factor and hence overestimated the cell efficiencies under the two conditions considered.

Q4

(a) (i)



As the solar light flux changes due to weather conditions and time of day, the maximum power available from a solar installation will change. It is not possible to analytically predict the maximum power point by measuring the short circuit current of the power plant.

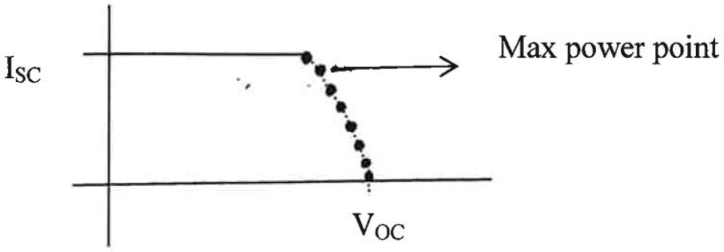
- cannot short circuit a plant connected to the grid in practical terms in any case.

It is therefore necessary to have method of detecting and evaluatng the maximum power point, as the requirement is to extract maximum power, by sampling over time. [10%]

(ii) Two common methods

a) Perturb and Observe
b) Incremental Conductance

Peturb and Observe



Initially on turn-on $I_o = 0$. Then I increases to $I_1 = I_o + \Delta I$ and V reduces such that $V_1 < V_o = V_{OC}$. The power at the current operating point is determined from V_1 and I_1, P_1. If $P_1 > P_0$ (as it must be initially at $I_0 = 0$) then $I_2 = I_1 + \Delta I$ is taken as the new operating point. This process is repeated as long as $P_{n+1} \rangle P_n$. When $P_{n+1} \langle P_n$, then the previous operating point P_n is taken as the max power point.

The process is then repeated periodically, typically every 10 secs – 1 min, i.e. the current operation point is changed to determine if $P_{n+1} > P_n$. Two trials have to be made after the initial max power point is chosen P_{n+1}^{i} at $I_n + \Delta I$ and P_{n+1}^{ii} at $I_n - \Delta I$. I is either reduced or increased depending on the P_{n+1}. If both directions of $P_{n+1}^{i,ii}$ are $\langle P_n$, then the current operating point is maintained.

Incremental Conductance

Again V_n and I_n are sampled. Then using the relationship

$P = VI \ \therefore \dfrac{dP}{dI} = \dfrac{dV}{dI} I + V$ and at max power $\dfrac{dP}{dI} = 0 \therefore \dfrac{dV}{dI} = \dfrac{V}{I}$

$I_{n+1} = I_n + \Delta I$ is carried out until $\dfrac{\Delta I}{\Delta V} = \left| \dfrac{I}{V} \right|$.

The current operating point needs to be changed, as in perturb and observe, periodically. [10%]

(b) Advantages

- More specific energy by using a smaller area of semiconductor junction. Therefore there is potential for reducing cost per watt of the solar cell.
- This cost advantage can be used to manufacture more complex solar cells and to use more expensive semiconductor materials which can yield higher efficiency. For example, in GaAs/A1GaAs hetero junctions are used in space and yield >35% efficiency but are uneconomic to use on earth for generating power compared to Si. But by concentrating light to greater light intensity than natural sunlight, typically 10X, high efficiency GaAs/A1GaAs cells can become economic.
- By ultra concentration, 100Xsun, small highly engineered solar cell structures, for example superlattices which can absorb efficiently across the solar spectrum, can

become economic.

Disadvantages

- The optics required for concentration, typically flat Fresnel lenses, as used in light houses but in reverse with the solar cells replacing the light source, make module construction more complex and therefore more costly. The modules are also more bulky (more weight). Installation costs go up.
- When solar light is concentrated the entire spectrum is concentrated. This means that the long wavelength light which is not absorbed is also concentrated into the module and generates heat through absorption on the back substrate and module housing.
- With more intense light more heat is also dissipated per unit area of solar cell. Heating in turn can degrade PV performance of the cell.
- Thermal management in concentrated PV systems is a crucial issue. If active cooling, such as pumped fluid is used, then the complexity and cost of the concentrated PV system further increases. [30%]

(c)

- Feed in tariffs and subsidies have enabled solar and other ‘green’ generation technologies on the basis that it is investment in non CO_2 emission routes to generation.
- The level of tariff needs to reflect market size for solar. As market size increases costs come down due to economies of scale.
- If tariffs do not track cost reduction, market distortion can take place, e.g. farmers in Germany generating solar power rather than growing wheat.
- As the number of solar installations become significant, then the amount of power demanded from traditional generators is reduced and their sale price has to rise to cover costs.
- However, a fail safe electric power system is a major requirement for modern society.
- Additionally, at present there is no energy storage with solar installations. This requires all excess power generated on a site to be distributed to other users via the grid.
- Therefore the utility companies, not only suffer from reduced demand but also in maintaining the grid to enable solar power plants to distribute power to other users and further reduce demand.

- So, who pays for the grid as utility companies see a rapid non-linear drop in demand as solar (and wind power) generation increases to a significant proportion of the power capacity of the grid?
- One possibility is for there to be a charge for solar generators to access the grid. Thereby sharing the cost of maintaining the grid infrastructure.
- If there are 'green obligations' which demand that utilities purchase green power such as solar on a nett metering or higher price than they sell electricity, then the cost of electricity has to rise for other consumers in order for the utility companies to cover costs and make a profit.
- As unit electricity costs go up, the incentive to install solar power also increases and the utility companies get further squeezed.
- The price of electricity also rises as the reserve power generation required for a secure and stable power supply rises as a proportion of the total power generated by utilities.
- If the utility companies are allowed to charge for use of the grid to domestic and business customers who are also solar generators, then the effective cost of solar generation rises. While this may alleviate commercial pressure on the utilities it may also stop the advance of the CO_2 emitting generation technologies.
- In principle it is possible to envisage non grid connected solar sites when energy storage technology becomes more cost effective. If large users of electric power opt for such a solution in response to charges to access the grid, then the economic viability of the utilities and the grid becomes an issue.
- The mobile phone vs landline analogy does not apply as mobile phones also rely on a grid (network) for connection and distribution of information – the wireless transmission/receive towers. [50%]

There were a range of opinions and views all of which were reasonable and well argued!