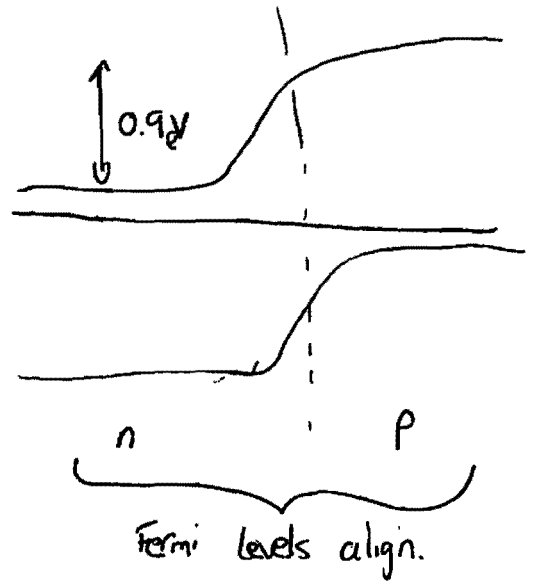
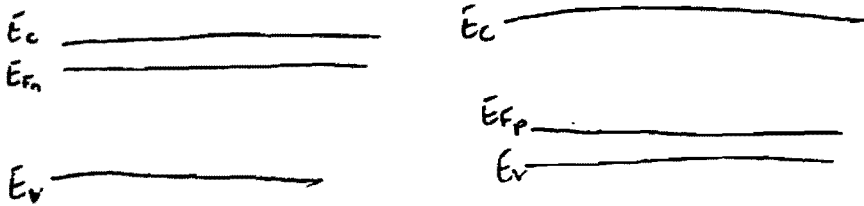


CRIBS 4B14 2012

SOLAR ELECTRONIC POWER; GENERATION & DISTRIBUTION

(Q1)

(a) Built in potential,  $V_{bi} = 0.9V$



$$V_{bi} = E_{F_n} - E_{F_p}$$

$$n = N_D = N_C \exp\left(\frac{E_F - E_C}{kT}\right) \quad p = N_A = N_V \exp\left(\frac{E_V - E_F}{kT}\right)$$

Note  $N_C = N_V$  (ie. available states at the band edges are equal)

$$n_i^2 = pn \quad n_i^2 = N_C N_V \exp\left(\frac{-E_g}{kT}\right) = N_V^2 \exp\left(\frac{-1.12q}{kT}\right)$$

$$n_i = 1.5 \times 10^{16} \text{ m}^{-3}; \quad k = 1.38 \times 10^{-23}; \quad T = 300 \text{ K}; \quad q = 1.602 \times 10^{-19} \text{ C}$$

$$\Rightarrow 2.25 \times 10^{32} \exp\left(\frac{1.12}{0.026}\right) = N_V^2$$

$$N_V = N_C = 3.39 \times 10^{25}$$

From band alignments:

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

$$(E_C - E_F) = E_g + 0.026 \ln\left(\frac{10^{22}}{3.39 \times 10^{25}}\right) - 0.9 = 8.657 \times 10^{-3}$$

$$n = 3.39 \times 10^{25} \exp\left(\frac{8.657 \times 10^{-3}}{0.026}\right)$$

$$n = N_D = 2.43 \times 10^{25} \text{ m}^{-3}$$

$$N_A = 10^{16} \text{ cm}^{-3} = 10^{22} \text{ m}^{-3}$$

(b) Under optical conditions

$$I = I_s \left[ \exp\left(\frac{qV}{kT}\right) - 1 \right] - I_{opt}$$

Under open circuit,  $I = 0$   $V = V_{oc}$

$$\therefore I_{opt} = I_s \left[ \exp\left(\frac{0.52q}{kT}\right) - 1 \right]$$

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

$$= q \cdot 10^{-2} \left( \frac{180 \times 10^{-6}}{1 \times 10^{-5}} \cdot \frac{2.25 \times 10^{32}}{10^{22}} + \frac{0.5 \times 10^{-6}}{0.5 \times 10^{-9}} \cdot \frac{2.25 \times 10^{32}}{2.43 \times 10^{25}} \right)$$

$$= 6.50 \times 10^{-9} \text{ A}$$

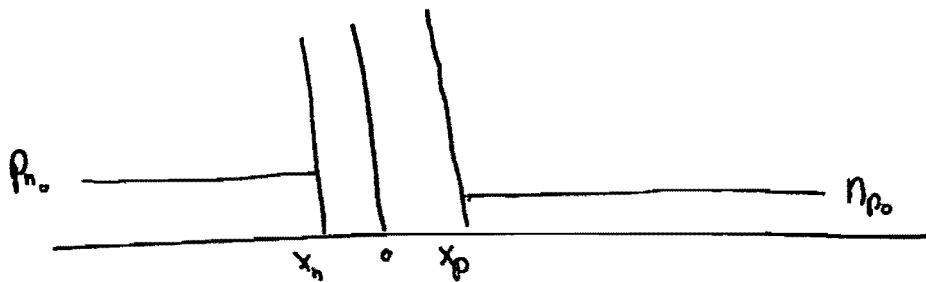
$$\Rightarrow I_{opt} = 6.5 \times 10^{-9} \left[ \exp\left(\frac{0.52}{0.026}\right) - 1 \right] = \underline{\underline{3.15 \text{ A}}}$$

(c) Assumptions:

- Assuming all dopants are activated, i.e.  $N_D = n$  and  $N_A = p$
- At the point where the semiconductor is in equilibrium, i.e. far away from the junction depletion region  $n_i^2 = n_{n,p} p_{n,p}$
- All the voltage drop occurs within the depletion region  
 $\Rightarrow$  There is a much larger number of free carriers outside the depletion region than inside

(d) At equilibrium, minority carrier concentration on eg the p side is given by:

$$n_{p0} = N_D \exp\left(\frac{-V_{bi} q}{kT}\right)$$

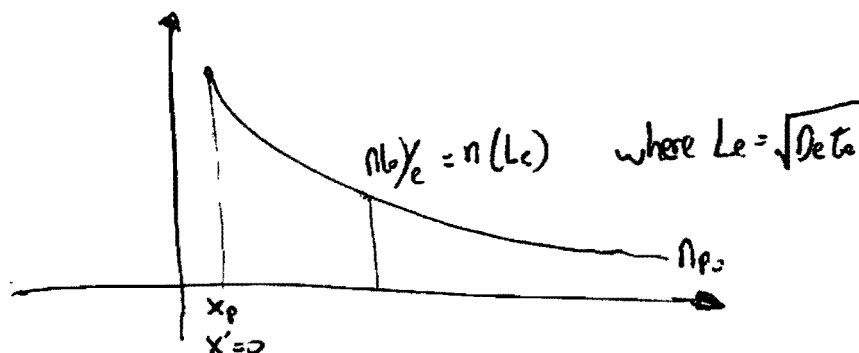


When a forward voltage is applied, at the edge of the depletion region, the excess amount of minority carriers in the p region is:

$$(n(x) - n_{p0})$$

The excess charge decays as  $x$  increases due to recombination with holes in the p-region. The characteristic lifetime is  $\tau_c$ . This gives rise to a diffusion/current flow of minority carriers away from the junction. The diffusion relationship is:

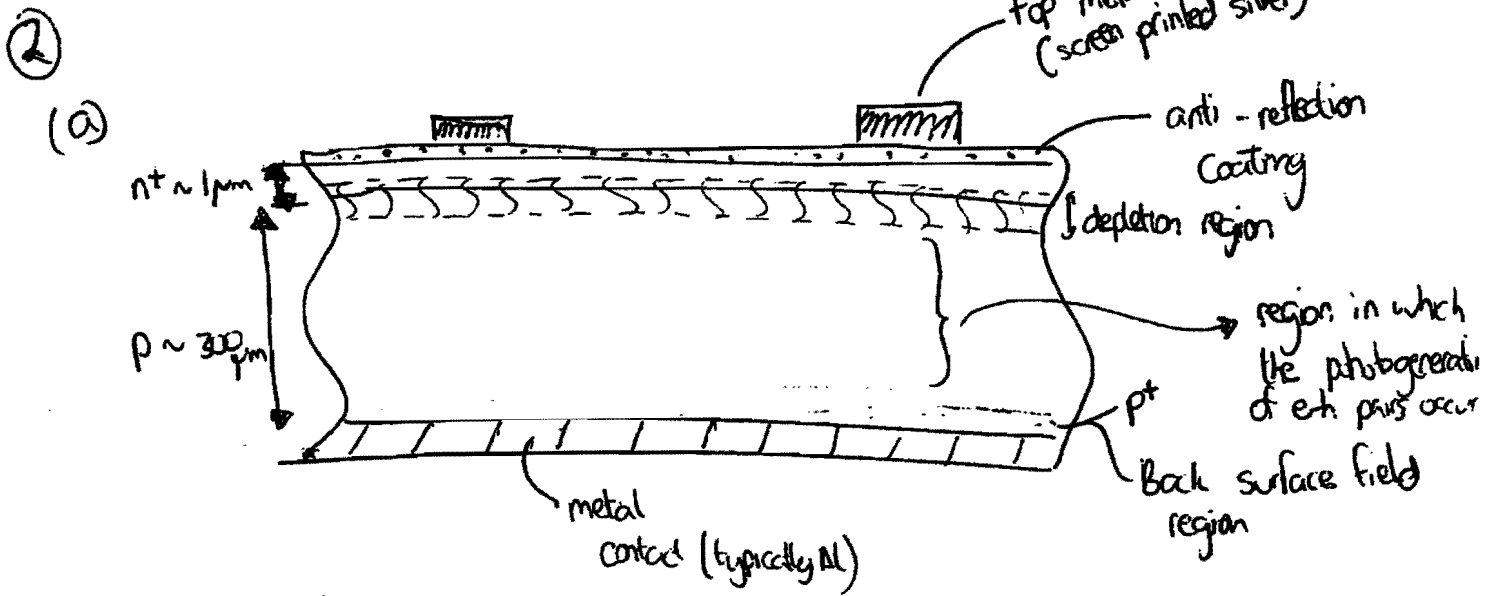
$$D_c \frac{d^2(n - n_{p0})}{dx^2} = \frac{n - n_{p0}}{\tau_c}$$



(e) If the furnace temperature is increased during phosphorus doping, a higher n-type doping density would result. If this doping is not excessive, assumption of all dopants being activated can still be made.

In n-type doping is higher:

- (i) depletion width in the n region would reduce.
- (ii) The Fermi level in the n region would increase, thereby increasing the  $V_{bi}$ .
- (iii) Although conductivity in the region would be higher, a larger doping density also implies more defects and more recombination.



(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 (quantum of lattice vibrational energy) to preserve momentum of the excited electron. It is not possible in crystalline-Si to have 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. Hence the requirement for bulk semiconductor absorber region below the junction depletion region. The photogenerated carriers diffuse to the junction for separation.

In a-Si:H the requirement for momentum conservation is removed. This is because ~~by~~ there is no crystal structure, and as a result the energy and momentum relationship which has to exist in a crystal is removed.

This makes a-Si:H a pseudo-direct bandgap material. This in turn 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 100-1000x thinner) solar cell.

- There would be no benefit in making thicker a-Si:H solar cells. In fact it would be detrimental. Most of the light is absorbed within  $\sim 1\mu\text{m}$  thick a-Si. Its amorphous nature also means that mobility is reduced ~~and~~ as is charge carrier lifetime and diffusion length. Hence having a much thicker cell would lead to an excessive recombination, and a highly reduced amount of <sup>collected</sup> charge carriers.

- 2) (c) The peak of the solar spectrum is at 550nm, and hence in sunlight, more charge carriers would result from 550nm light.

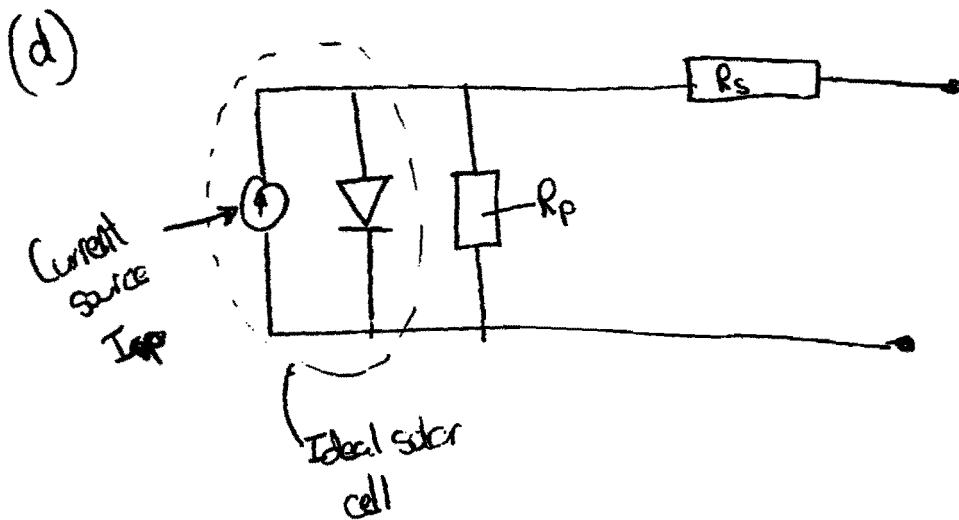
However,

$$E = \frac{hc}{\lambda}$$

Bandgap of Si corresponds to  $\sim 1100\text{nm}$

$\Rightarrow$  Therefore 800nm light would be more efficient because it has an energy closer to that of the bandgap. Of the energy that comes with each photon the excess energy beyond that of the bandgap is wasted as heat.

The 550nm photon, although containing more energy, has a greater portion wasted as heat.



The current source and diode represent the ideal solar cell

$$I_{sc} = I_0 \left[ \exp\left(\frac{eV_{oc}}{kT}\right) - 1 \right]$$

The circuit gives the condition that when the load terminals are open circuit, all the current flows across the diode. The voltage across the diode is  $V_{oc}$

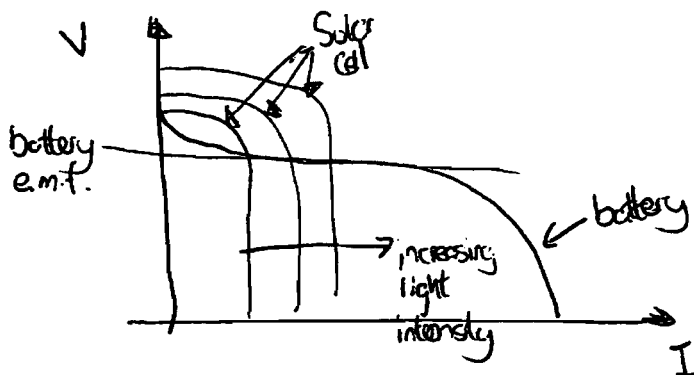
Upon short circuiting output terminals, all current  $I_x$  from the source bypasses the diode.

$R_s$  is added for real cells to account for bulk-resistance of the p-n ~~junction~~ semiconductor region through which the photo-generated current has to flow before being collected. It also includes the contact resistance resulting from contact with the metal.

$R_p$  represents the leakage current before it flows to the terminals, caused by leakage at physical perimeter of the Si wafer.

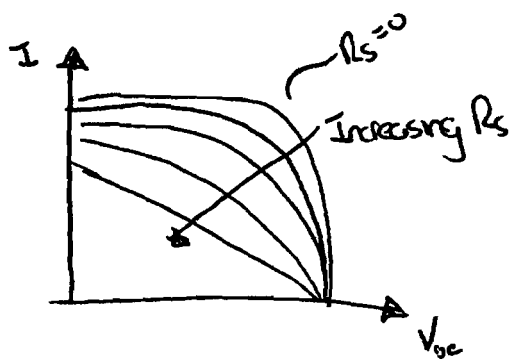
(c) The battery is modelled electrically as a voltage generator, characterised by its e.m.f.

The solar cell is better modelled as a current generator and its characteristics depend entirely on the nature of the illuminating source.

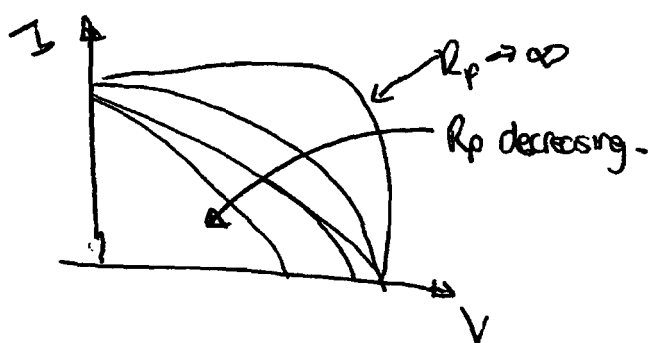




②(f) Increasing  $R_s$  leads to a reduction in  $I_{sc}$  and a loss in fill factor.



Decreasing  $R_p$  leads to loss in fill factor and decrease in  $V_{oc}$



③ (a) 50% of rooftop =  $225 \text{ m}^2$

$$225 \text{ m}^2 / 1.5 = 150 \text{ modules}$$

$$\text{Installation output power (rated)} = 37500 \text{ W}$$

Canary Islands insolation:  $2075 \text{ kWh/m}^2$

$$2075 \times 225 = 466875 \text{ kWh}$$

$$\text{@ } 15\% \text{ Eff} \approx 70031 \text{ kWh}$$

Assumption → Inverter efficiency  $\approx 97\% = 67930 \text{ kWh}$

UK Insolation:  $1100 \text{ kWh/m}^2 \times 225 = 247500 \text{ kWh}$

$$\text{@ } 15\% \text{ Eff} \rightarrow \text{Generates} \approx 37125 \text{ kWh}$$

$$\text{Inverter Efficiency} \approx 97\% = 36011 \text{ kWh}$$

$$\Rightarrow \text{Annual return: Canary Islands} \cdot \text{€ } 20,379 \quad (67930 \times 0.30)$$

$$\text{Cambridge} \cdot 36011 \times 0.40 = \text{€ } 14,404$$

$$\begin{array}{r} \text{Total Cost} = 150 \times 375 \quad (\text{module}) \\ + 25000 \quad (\text{inverter}) \\ + 22000 \quad (\text{installation}) \\ \hline \text{€ } 103,250 \end{array}$$

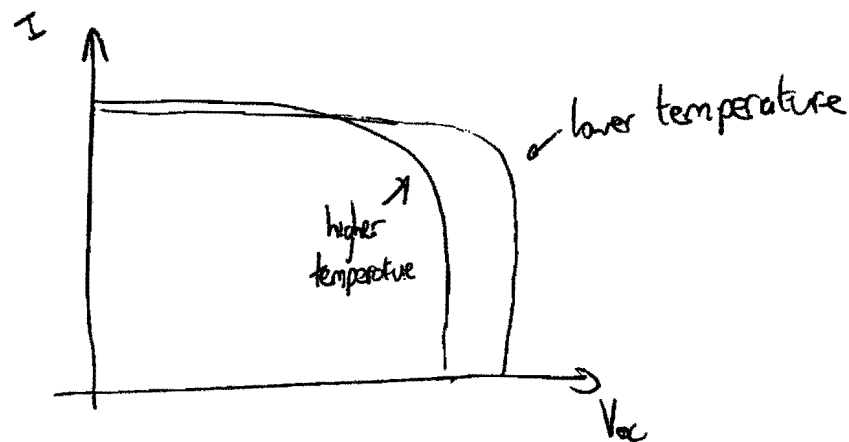
$$\text{Payback time: Canary Islands} \approx 5 \text{ years}$$

$$\text{Cambridge} \approx 7.2 \text{ years}$$

- Assumptions:
- Panels are placed at optimal tilt angle for each location.
  - The system continually operates at maximum efficiency (not realistic)

(b) The fundamental difference in both locations is temperature. The temperature difference between the two locations would result in the UK cells somewhat overperforming the calculated values while the cells in the Canary Islands would slightly underperform.

On operation, temperature affects the  $V_{oc}$  of the photovoltaic cell:



- Temperature reduces the bandgap of the material by affecting its lattice constants.

- Also,  $V_{oc} = \frac{kT}{e} \ln \left( \frac{I_{sc}}{I_s} + 1 \right)$

where  $I_s$  is a function of  $n_i^2$

$$I_s = eA \left( \frac{D_e n_i^2}{L_e N_n} + \frac{D_h n_i^2}{L_h N_p} \right)$$

$$n_i^2 = B T^3 \exp \left( \frac{-E_g}{kT} \right)$$

~~10~~

3c

## Advantages

- Microinverters allow the optimum power available from each module to be connected to the AC grid. Maximum power point tracking individually for each module.
- There are no by-pass diodes. Each module is in effect parallel connected to the grid.  
This allows more energy harvest over time.
- Additionally, feedback for the performance of each individual panel can be provided, making it easier to find faults.

## Disadvantages

- Because each module is handling smaller power, the efficiency is slightly lower. String inverters have a 1kW min rating.
- Higher number of modules means higher cost/W.
- 

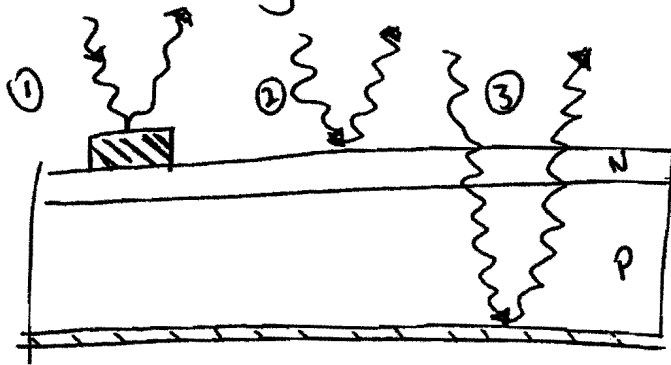
(d) Main points to consider:

- Human energy consumption rising, with limited resources = higher energy cost
- Feed-in tariffs and resulting high demand have led to larger scale module manufacturing, driving the cost of PV modules down.
- The very low price at the moment is somewhat unreal due to the sudden lowering in demand and the great over production.
- Nevertheless, increased pressure to lower costs will likely bring further reductions with time.
- Current module prices already approaching \$1/W
- Installation costs are a significant part of initial investment.

Ways of reducing this will certainly be valuable.

- In the short term, some form of government incentive (possibly diminishing) may be necessary to sustain demand.

④ (c) Fundamentally due to reflective losses.

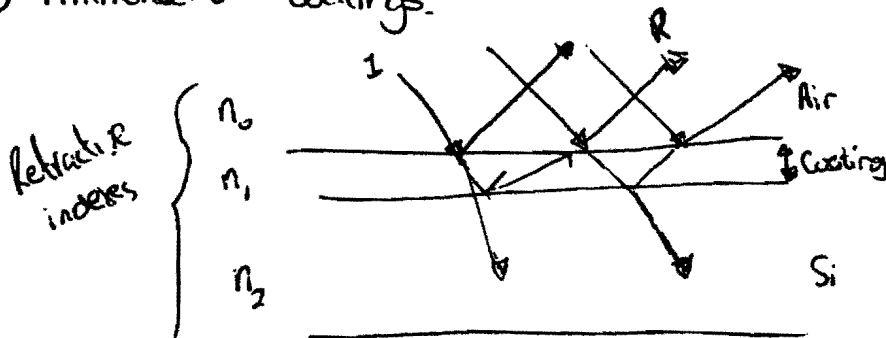


① Shading by top contact coverage

② Surface reflection

③ Reflection from the rear metal contact. → (This actually doubles the light's path length through the silicon, which is good, but light will still be lost when it reaches the top interface below the critical angle)

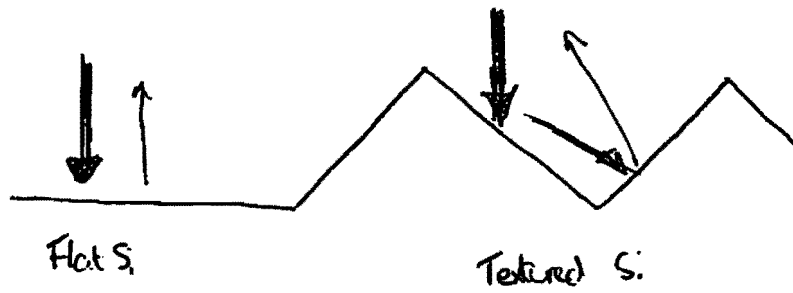
(b) ① Antireflection coatings.



By placing another interface in between the cell and the atmosphere, ~~the reflective in~~ another set of reflections are created at the new boundary. If the refractive index and the thickness are chosen such that the interference between the wave reflected from the anti-reflection coating top surface and that reflected from the semiconductor surface is out of phase, the waves destructively interfere, resulting in zero net reflected energy.

The coatings are usually optimised for the peak wavelength in the solar spectrum.

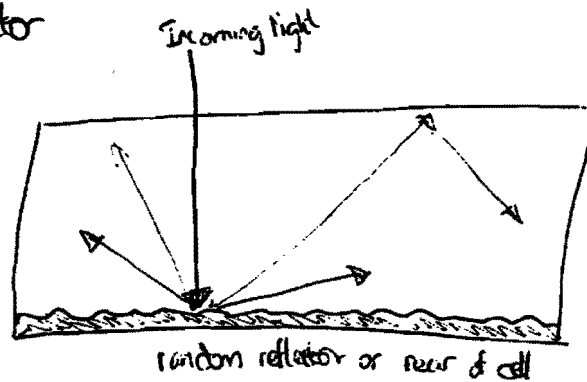
## ② Surface Texturing



Texturing the surface of Si increases the total number of reflections and hence the path length of light in the Si, resulting in a higher absorbed amount.

For Si, light trapping increases the path length by a factor of  $\sim 50$ .

## ③ Random Rear Reflector



A rear reflector with a rough texture randomises the direction of light reflected from the back contact, again allowing the light to have an increased path length in the cell, even permitting some to gain sufficient angle to be totally internally reflected back.

④ (c) From the formula sheet:

$$R = \frac{r_1^2 + r_2^2 + 2r_1r_2 \cos \theta}{1 + r_1^2 r_2^2 + 2r_1r_2 \cos \theta}$$

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

$R$  is minimum when  $\cos \theta = 0$

i.e. when  $\theta = \pi/2$

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

$n_2$  = refractive index of AR coating  
 $d$  = thickness " " "

If we take  $\lambda$  to be 550 nm (max intensity of solar spectrum)

$$d = \frac{\lambda}{4n_2} = \frac{550}{4(2.2)} = \underline{62.5 \text{ nm}}$$

(d) The best place to place the junction is close to the surface.

This comes <sup>from</sup> the probability of incoming photons generating electron-hole pairs being associated with how strongly they are absorbed within the semiconductor. The absorption for a given  $\lambda$  is:

$$I = I_0 \exp(-\alpha x) \quad \text{where } I_0 = \text{incident intensity} \\ \text{and } \alpha = \text{absorption coefficient.}$$

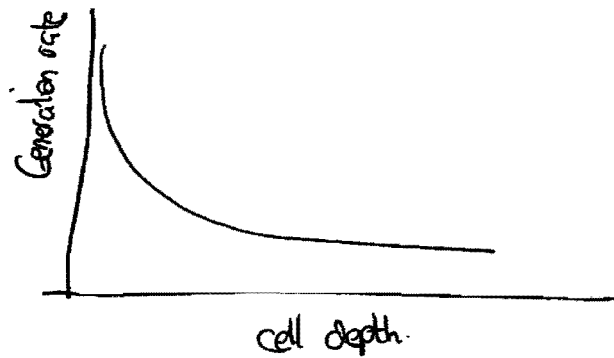
The generation rate at any given point in the cell is given by:

$$g(x, \lambda) = (1 - R(\lambda)) \Phi(\lambda) \alpha(\lambda) \exp(-\lambda x)$$

$\Phi$  = is photon flux



In a practical spectrum and cell, generation rate of e-h pairs in Si as a function of distance from surface looks like:



i.e.  $\Rightarrow$  the maximum number of electron-hole pairs are generated close to the surface.

+ The probability of a photogenerated minority carrier being swept across a p-n junction is highest when situated within a diffusion length from the edge of the depletion region.

Problems:

- (i) Surface recombination - higher recombination rate at the surface
- (ii) Series resistance - thin n layer increases the resistance to carry charge carriers to the top contact stripes.