1 (a)



J axis (vertical), V axis (horizontal), curves labelled "dark" and "illuminated", circle labelled "operation region"
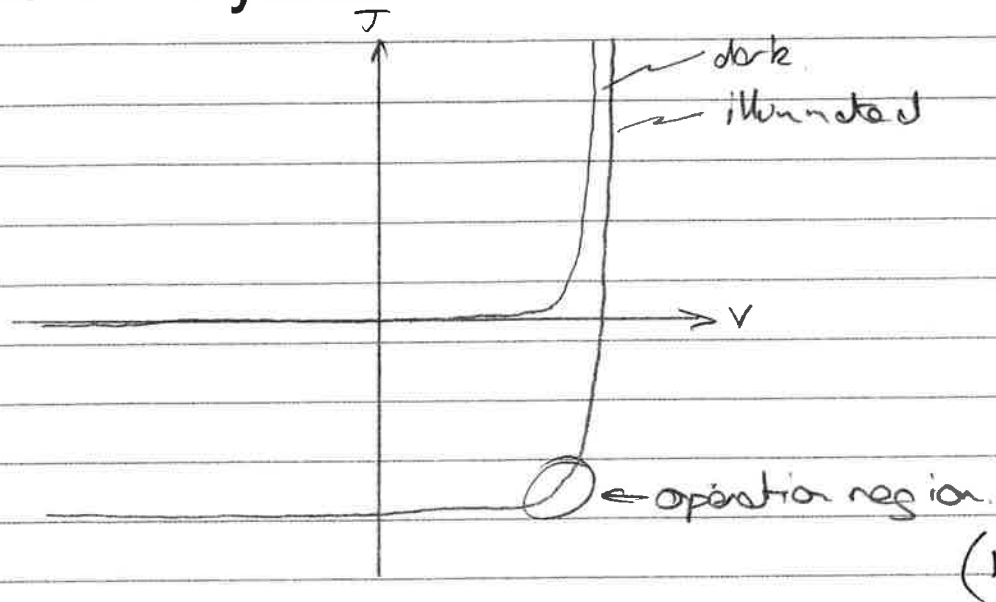
(10%)

(b) (i) Let $\dfrac{e L_e n_{p_0}}{\tau_e} = a = \dfrac{1.602 \times 10^{-19} \times 0.5 \times 10^{-6} \times 10^{14}}{10 \times 10^{-6}} = 8 \times 10^{-7}$

Hence, at $V_{oc}$, when $J = 0$,

$$e g_{op} (L_e + L_h) = \alpha \left( e^{c V_{oc}/k_T} - 1 \right)$$

$$g_{op} = \frac{\alpha \left( e^{e V_{oc}/k_T} - 1 \right)}{e (L_e + L_h)}$$

$$= \frac{8 \times 10^{-7} \left( e^{0.52/0.862 \times 10^{-4} \cdot 298} - 1 \right)}{1.602 \times 10^{-19} \cdot 1 \times 10^{-6}}$$

$$\therefore g_{op} = 3.1 \times 10^{27} \, n^{-3} s^{-1}$$

(20%)

(ii) $J_{sc}$ is when $V = 0$, so

$$J_{sc} = 1.602 \times 10^{-19} \times 3.1 \times 10^{27} \times 1 \times 10^{-6}$$

$$J_{sc} = 495 \, A n^{-2}$$

(10%)

(iii)
$$-J_m = \alpha\left(e^{eV_m/kT} - 1\right) - J_{sc}$$
$$= 8 \times 10^{-7}\left(e^{0.45/0.862 \times 10^{-4} \times 298} - 1\right) - 495$$
$$\underline{J_m = -463 \text{ Am}^{-2}}$$

$$\therefore FF = \frac{V_m J_m}{V_{oc} J_{sc}}$$
$$= \frac{0.45 \times 463}{0.52 \times 495}$$
$$\underline{FF = 0.81}$$

$$\eta = \frac{V_m J_m}{P}$$
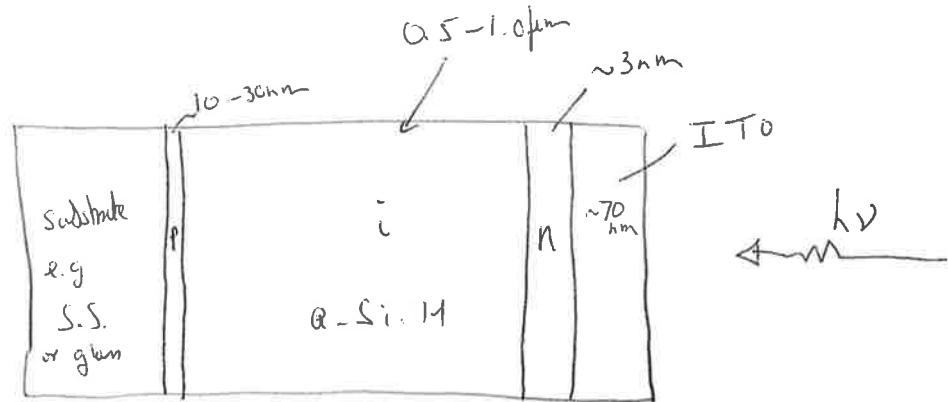$$= \frac{0.45 \times 463}{1000}$$

$\left(35\%\right)$

$$\underline{\eta = 20.8\%}$$

(iv) Reducing the illumination will cause the voltage at maximum power to also drop. Therefore, this point varies as a solar cells illumination changes due to varying cloud cover, or the varying shading (eg on a vehicle). Therefore, the effective load needs to be dynamically changed so that the cell is always being operated at $V_m$.

$\left(25\%\right)$

2 (a)

basic    structure

Substrate e.g S.S. or glass

$p$ — 10-30nm

i    a-Si:H — 0.5-1.0μm

$n$ — ~3nm    ~70 nm
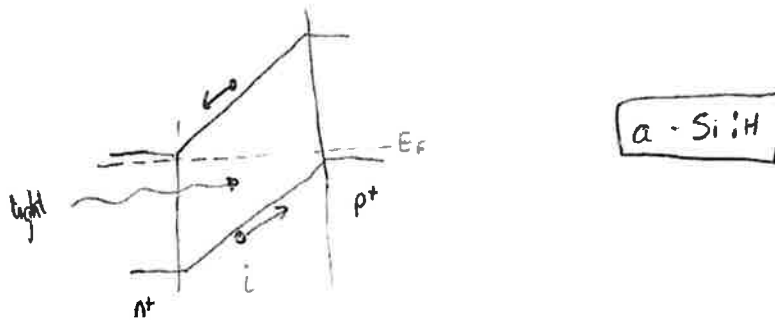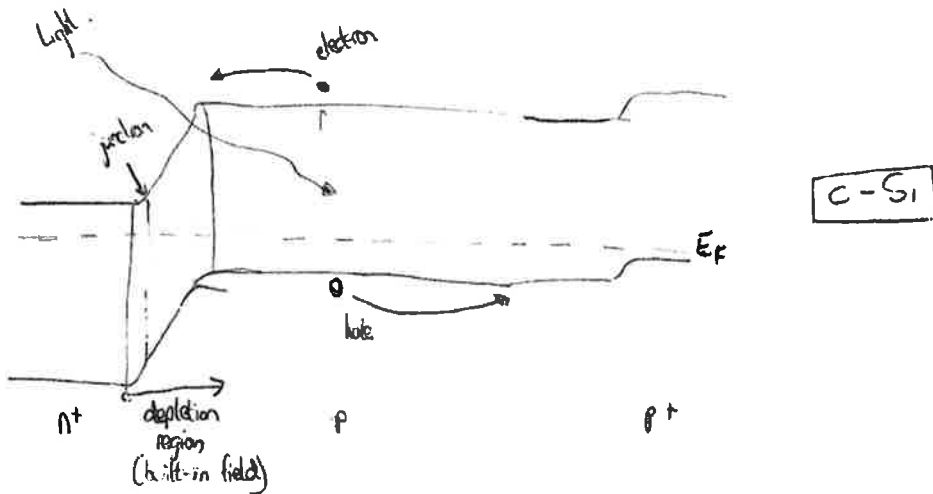
ITO

$h\nu$

better than having $n-i-p$ as lower absorption
in "$n$" layer than in "$p$"                    (20%)

alternative could have

a $p$-type a-SiC:H as the window layer
but this is not what is expected.

(b)



Diagram labelled c-Si showing junction, electron, hole, $E_F$, depletion region (built-in field), regions $n^+$, $p$, $p^+$, and light.



Diagram labelled a-Si:H showing light, regions $p^+$, $i$, $n^+$, $p$, and $E_F$.

|  Drift term. | Diffusion term. |
| Dominant in a-Si:H | Dominant in c-Si |

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

$$I_h = q A \left[ \mu_h p E - D_n \frac{dp}{dx} \right]$$

$$I = I_e + I_h$$

The major difference is that **c-Si cells are diffusion dominated** while **a-Si:H cells are principally drift cells**. In amorphous Si, all photogenerated carriers are generated in the i-layer, which corresponds to the depletion layer in the c-Si junction. In a-Si:H there is no practical diffusion. This is because it is amorphous and there are many defects through which the carriers can recombine (diffusion length is very small).

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.

pv237

In the c-Si junction, photoabsorption is low, resulting in a much thicker cell to achieve the same absorption. However, crystalline quality is high, resulting in lower recombination and higher diffusion length. Most e-h pairs are created far from the junction, in the bulk of the cell, and then diffuse to the front ($n^+$-p) and back (p-$p^+$) junctions for separation to the electrodes. 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 filed across the i-layer.

$\left(30\%\right)$

(c)
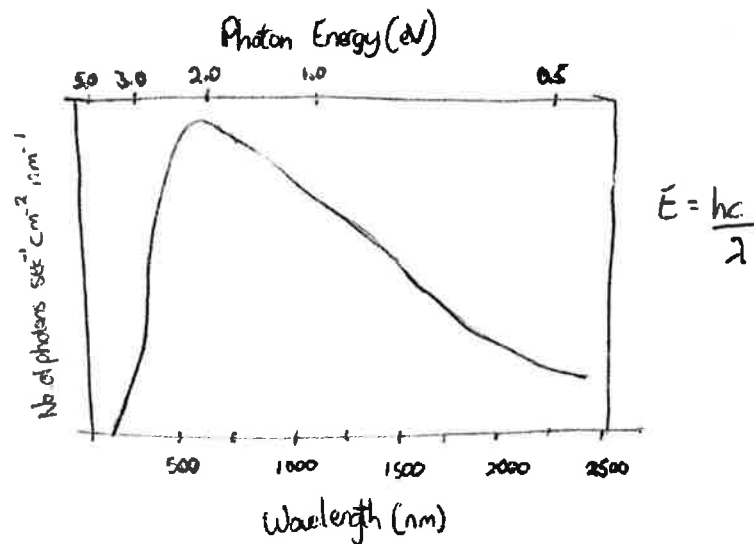


The figure above shows an approximation to the photon density at different energies from the solar spectrum (AM 1.5). Only the photons which have an energy greater than the bandgap (towards the left in the figure) contribute to generating electron-hole pairs. Therefore the smaller the bandgap, the larger the number of photons which contribute to generate electron-hole pairs, resulting in larger optically generated currents and hence $J_{sc}$. Small deviations from this trend, e.g. with poly-Si having a lower Jsc than c-Si are a result of other factors coming into play, in this case the reduction in current due to recombination resulting from larger number of defects and grain boundaries in poly-Si.

The open circuit voltage ($V_{oc}$) increases as the band gap increases. The maximum possible Voc would be equal to the built in field which results on the formation of the pn junction. In an ideal device the $V_{OC}$ is limited by radiative recombination. The $V_{OC}$ increases with bandgap as the recombination current falls.

There is therefore an optimum for the $V_{oc}I_{sc}$ product and hence conversion efficiency as a function of the band-gap of the semiconductor material used for solar cells. When absorbing a photon with energy greater than the band-gap, the excess energy above the bandgap separation is eventually relaxed and lost to the semiconductor lattice as heat.

The ideal semiconductor to minimize heat production would have a band-gap close to that of the peak of the solar spectrum at ~550nm, which would allow the maximum number of photons to be absorbed with the least heating.
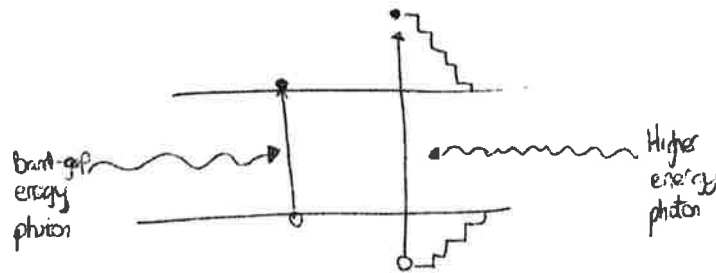


$\left(30\%\right)$

(d) The ideal solar cell model assumes that carriers do not recombine within the junction depletion region when being swept across. In practice this assumption breaks down due to the possibility of electrons and holes recombining via the residual trap energy levels in the semiconductor band-gap. There are two major types of non-radiative recombination: Direct recombination of electrons and holes (Auger recombination) and recombination via one (or more) states in the energy gap (Schockley-Read-Hall-SRH).  This latter mechanism is dominant in the depletion region.

The effect of this recombination in the depletion region is to introduce an extra term into the diode current equation, such that:

$$I = I_s\left(\exp\left(\frac{eV}{kT}\right) - 1\right) + I_w\left(\exp\left(\frac{eV}{2kT}\right) - 1\right)$$

Which can be expressed as:

$$I = I^*_s\left(\exp\left(\frac{eV}{\eta\, kT}\right) - 1\right) \qquad \text{where } I^*_S = I_S + I_W$$

η is termed the ideality factor and takes a value between 1 and 2. η = 1 without depletion region combination. With a large amount of recombination in the depletion region, η →2. The effect of the depletion region recombination is to give the diode a "softer" turn-on characteristic.  Under light illumination, when the diode I-V curve is shifted into the 4$^{th}$ quadrant, this gives rise to a lower Voc.

$\left(20\%\right)$

DARK CONDITIONS

UNDER ILLUMINATION
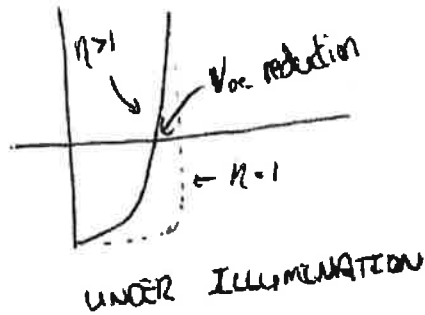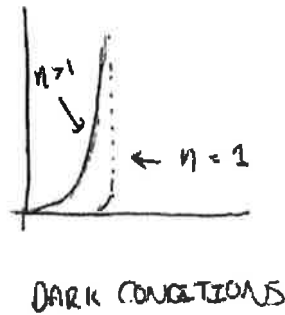
3. (a) Consider a 10 *micron* thick layer of particles with a diameter of 20 nm and a porosity of 50% spread on a 1 cm² flat electrode

Area of Sphere = $A = 4\pi r^2$

Volume of Sphere = $V = 4/3\ \pi r^3$

Volume occupied by spheres is $0.5 \times 10^{-3}$ cm³

Since $A/V = 3/r$

$A = 3V/r = 3 \times 0.5 \times 10^{-3} / 10^{-6} = 1500$ cm²

The internal area is 1500 times higher than the geometric area. The actual value will be a little below this as some of the surface area of the particles will be lost in interparticle contact.

This provides a very high surface area for i) dye monolayer absorption ii) solid-liquid interface for charge separation.

Given in the dye-sensitised solar cell, the dye determines the absorption (TiO$_2$ only absorbs in the UV), a much higher amount of dye in the same projected surface area implies a higher absorption of sunlight. Note the dye coating on the TiO$_2$ is only about a monolayer to allow efficient charge extraction once light is absorbed and the exciton is created. Also, the large solid-liquid area interface provides many more sites for reaction with the electrolyte, hence further improving charge extraction.

(20%)

(b) **Advantages**

- Simple , low cost fabrication process

- Wide variety of available dyes = high tunability

- TiO$_2$ is a low cost material

- Multiple semitransparent and varying colour possibilities for situations where aesthetics are important (e.g building integrated PV)

**Limitations**

- Contains liquid electrolyte, opening some stability and packaging issues

- Most efficient modules are comparable to a-Si efficiencies, however only on a rigid form factor. Lower permissible processing temperatures for flexible substrates (plastics) do not permit the proper fusing of the $TiO_2$ nanoparticles, resulting in lower efficiencies for the flexible version.

- Solid electrolytes are under development, but as of yet, result in lower efficiencies due to the low conductivity of the electrolyte

- Not as well understood as Silicon

- High number of interfaces (between $TiO_2$ nanoparticles) results in a higher recombination than Si (although lower than would be expected for the number of existing interfaces)

(20%)

(c) The dyes shown on the paper have absorption spectra which progressively starts absorbing at longer wavelengths from (1) to (8). The absorption spectra is determined by the band-gap of the dye. Shifting this spectrum has an effect in both performance and aesthetics of the solar cell. All photons with energy higher (lower wavelength) than that at which the dye commences absorption, will contribute to the photocurrent. Hence the resulting photocurrent of those dyes in a cell, assuming all other properties are the same should increase from (1) to (8).

The absorption also determines what light will be transmitted though the cell (or reflected I case of a metal back contact) which in turn determine the colour of solar cells which use that dye. I.e. from dyes (1) to (8) the resulting colour of the cell would change from greenish (1)(550nm-600nm) towards redish (5)(700 nm) towards dark blackish when most of the visual spectrum is absorbed. Note other components of the solar cell such as the glass, ITO and $TiO_2$ only absorbed in the UV region and are considered transparent in the visual range.

(20%)

(d) **The cost effectiveness of PV Today**

The economics situation of photovoltaic technology is at a very dramatic and rapidly changing situation today. Crystalline Si module prices have dropped from over 4\$/Wp in 2008 to less than 0.60\$/Wp from some of the Chinese made panels today. The reasons for this drop is of debate, and is a result partially due to scaling and process improvements and partially artificial due to the current oversupply of panels in the market. Nevertheless, this has vast consequences on the PV industry and the economic viability of PV installations. A technology considered and expensive green alternative is now starting to face situations where it is and economically attractive option.

Whether PV is cost effective for any particular location, depends on a number of factors, mainly including cost of generation, insolation and energy usage profiles. It is important to understand the cost of traditional grid connected electricity is not a fixed cost, but is a scales as a function of cumulative operating capacity. E.g. coal can provide a certain base production,

but peaks in demand would be satisfied typically by gas, oil and diesel which get increasingly expensive. Hence, if peak demand matches peak sunlight availability, that is an attractive scenario for PV. A good example would be demand resulting from air conditioning usage in hot countries (e.g. Spain).

Of course the amount of energy generated by a particular installation is directly correlated to the available solar insolation in the area, and will determine the rate of return of investment. For instance, with current numbers, without subsidies, PV investments in the UK reach breakeven somewhere about 15-25 years, while in some areas in southern Spain it can be 5-7 years, without any artificial subsidies.

Finally, the access to natural resources is more difficult in certain parts of the world (e.g. Sri Lanka), which rely on import of these resources. This makes traditional coal and oil powered generation relatively expensive.

The combination of these factors, already provides a certain number of uses and countries where PV power generation is the most economically attractive option today. This could be expanded quite quickly if the problem of storage and on demand use was solved, but that is another question............

(40%)

4. (a)
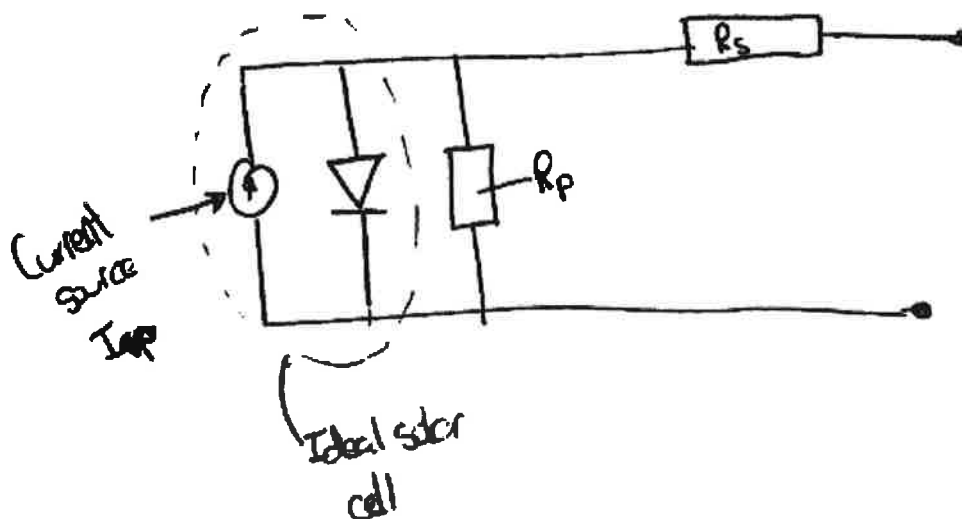


The current source and diode represent the ideal solar cell.

$$I_{sc} = I_s \left[ e^{\frac{qV_{oc}}{kT}} - 1 \right]$$

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 the current $I_{sc}$ from the source bypasses the diode.

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

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

(20%)

(b) The output characteristic of a typical solar cell has the form below:
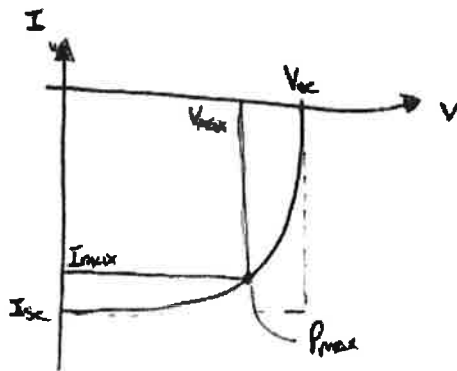


An ideal power supply with a $V_{oc}$ and $I_{sc}$ would have a power output $P = V_{oc}I_{sc}$, and a rectangular area on the output characteristic.

In a solar cell, the maximum power output is obtained at some current and voltage $I_{max}$, $V_{max}$, where $I_{max} < I_{sc}$ and $V_{max} < V_{oc}$ as in the diagram. The fill factor is defined as the ratio of the maximum power rectangle and the ideal power rectangle.

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

It is a relative measure of how 'ideal' a solar cell is as a power supply. Typical solar cell fill factors range from 0.6 (poor) to 0.9 (best).

Increasing the series resistance, $R_s$, leads to loss in fill factor and reduction in the $I_{sc}$. $V_{oc}$ remains constant as at open circuit conditions, there is no current flowing through Rs, hence no voltage drop occurs through it.

Rp should ideally be as large as possible (minimising leakage). Decreasing $R_p$ leads to loss in fill factor, and a decrease in the $V_{oc}$, as current would flow through $R_p$. $I_{sc}$ remains constant.
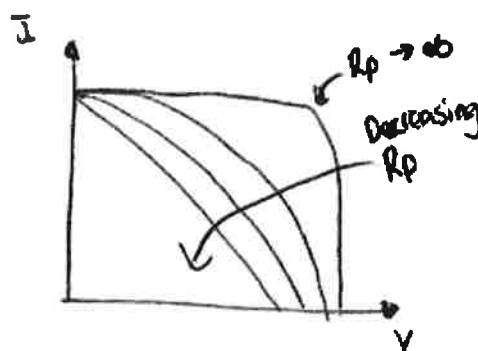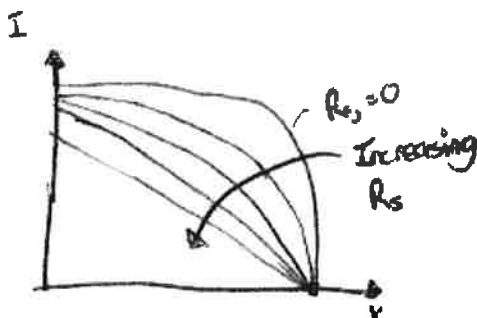


(30%)

(c)

At the optimum doping concentration of ~$10^{17}$ cm$^{-3}$, minority carrier life time is approx. 1 µs. This gives a diffusion length Le in the order of 50 µm. However, Si solar cell thicknesses typically exceed 200 µm, to allow for the absorption of long wavelength light. This means that minority carrier electrons created deep in the Si by absorption of long wavelength light cannot be readily swept across the junction to contribute to the photogenerated current. This problem can be partially solved by creating an additional built-in potential at the back contact to the solar cell. The built-in potential at the back will have the effect of creating an electric field which "pushes" electrons away from the back contact towards the upper junction.
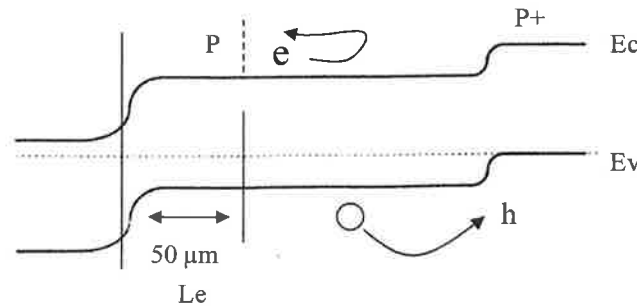


This Back Surface Field (BSF) is introduced by having a very heavily doped p$^+$ region at the back of the cell. The back contact is formed by alloying metal to the p$^+$ region. Overall, this has the effect of increasing the probability of collection for minority carriers generated deeper within the cell.



Cross section of a solar cell with BSF
(back surface field)
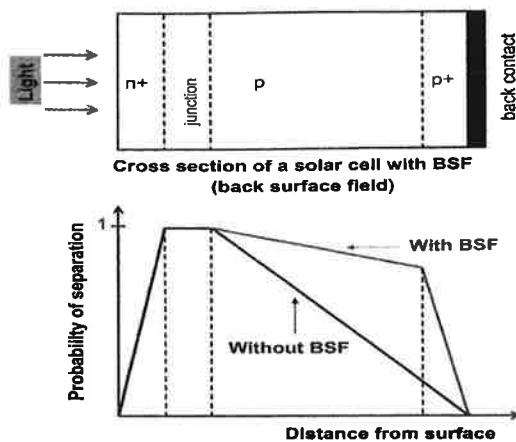
$(25\%)$

(d) The PERL cell has a number of design aspects which have led to significant performance improvements over the basic pn junction cell. Fundamentally all the improvements made consist of efforts to increase light absorption and to reduce charge carrier recombination:

a) Thinner, buried top metal fingers. A key feature of the buried contact is that the metal is buried in a laser-formed groove inside the silicon solar cell. This allows for a large metal height-to-width aspect ratio. A large metal contact aspect ratio in turn allows a large volume of metal to be used in the contact finger, without having a wide strip of metal on the top surface. Therefore, a high metal aspect ratio allows a large number of closely spaced metal fingers, while still retaining a high transparency. For example, on

a large area device, a screen printed solar cell may have shading losses as high as 10 to 15%, while in a buried contact structure, the shading losses will only be 2 to 3%. These lower shading losses therefore result in higher short-circuit currents. In addition, the buried contact also allows low parasitic resistance losses due to its high metal aspect ratio, its fine finger spacing and its plated metal for the contacts. The contact resistance of a buried contact solar cell is lower than that in screen printed solar cells due to the large metal-silicon contact area. Overall, these reduced resistive losses result in higher FFs.

b) Inverted pyramids – The inverted pyramid structure of the solar cell surface, formed by chemical etching significantly increases the light path in the solar cell (by up to 50x) by increasing the number of total internal reflections.

c) Double layer antireflection coating - a DLAR coating on the PERL cells further contributes to reduce the surface reflection loss. By choosing the right thickness and dielectric constant, reflections can be minimised in the visible region.

d) The first layer of the DLAR, consists of a thin, thermally grown oxide on the surface of the Si. This oxide layer is present both in the front and the back of the cell and serves to passivate the surface, reducing the number of dangling bonds and as a result, reducing recombination at the surfaces of the cell.

e) Heavy doping at the surface of the silicon beneath the top metal contact to minimise recombination;

f) A passivated rear surface with regular openings for the metal contact reduces the contact area with the metal, resulting in fewer sites for recombination. The density of the contacts is kept sufficient to not adversely affect collection probability. This reduced the total recombination at the contact, likely contributes to a higher Voc in the device.

g) Highly doped p+ region at back contacts creating a BSF

It should be noted some of these changes are very laborious, costly or currently have a low yield and hence are not always used in production environments.

$(25\%)$