Question 1
Part (a)

We assume:

(1) The junction is abrupt and all acceptors are ionised, so that in the p-type region $= N_A$. In the p-type region there is fixed charge due to ionised acceptors.
(2) The electric field exists only within the depletion region. There are no electric fields outside the depletion region, therefore:

$$\mu E \frac{\partial(\Delta n)}{\partial x} = 0$$

(3) We are in steady-state so the left hand side is zero.

$$\frac{\partial(\Delta n)}{\partial t} = 0$$

Therefore

$$D_e \frac{\partial^2(\Delta n)}{\partial x^2} = \frac{\Delta n}{\tau_e}$$

$$\therefore \frac{\partial^2(\Delta n)}{\partial x^2} = \frac{\Delta n}{{L_e}^2}$$

The general solution to this differential equation is

$$\Delta n = A \exp\left(\frac{-x}{L_e}\right) + B\exp\left(\frac{x}{L_e}\right)$$

We impose the condition that the minority carrier concentration can only decay away from the depletion edge.

$$\Delta n = A \exp\left(\frac{-x}{L_e}\right)$$

To find the constant A, we use the boundary condition that at x=0,

$$n = n(0) = \frac{n_i^2}{N_A} \exp\left(\frac{qV}{kT}\right)$$

And also note that $\Delta n = n - \frac{n_i^2}{N_A}$.

So,

$$\Delta n(0) = \frac{n_i^2}{N_A} \exp\left(\frac{qV}{kT}\right) - \frac{n_i^2}{N_A}.$$

This gives the solution

$$\Delta n = \frac{n_i^2}{N_A}\left[\exp\left(\frac{qV}{kT}\right) - 1\right]\exp\left(\frac{-x}{L_e}\right)$$

Also, we have assumed there is no net recombination or generation in the depletion region, and that the injected minority carrier concentration is much less than the majority carrier concentration (low injection). [35%]

Part (b)

As the n-doping is much higher than the p-doping, we can assume that the reverse saturation current is dominated by minority carrier electrons on the p-type side.

$$\begin{aligned} J_n &= qD_e\frac{dn}{dx} \\ &= -q\frac{D_e}{L_e}\frac{n_i^2}{N_A}\left[\exp\left(\frac{qV}{kT}\right) - 1\right]\exp\left(\frac{-x}{L_e}\right) \end{aligned}$$

Evaluating at x=0 gives

$$J_n = -q\frac{D_e}{L_e}\frac{n_i^2}{N_A}\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

And converting to net current gives

$$\begin{aligned} I &\approx q\frac{D_e}{L_e}\frac{n_i^2}{N_A}\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \\ &= I_s\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \end{aligned}$$

The reverse saturation current is therefore given by

$$\begin{aligned} I_s &= q\frac{D_e}{L_e}\frac{n_i^2}{N_A} \\ &= q\frac{L_e}{\tau_e}\frac{n_i^2}{N_A} \end{aligned}$$

$$\begin{aligned} I_s &= q\frac{L_e}{\tau_e}\frac{n_i^2}{N_A} \\ &= 1.0\times10^{-2}\times1.602\times10^{-19}\times\frac{100\times10^{-6}}{1.0\times10^{-6}}\times\frac{(10^{16})^2}{5\times10^{22}} \\ &= 3.20\times10^{-10}\text{A} \\ &= 320\text{ pA} \end{aligned}$$

[25%]

Part (c)
(i)

$$I_{sc} = I_s\left(\exp\left(\frac{qV_{oc}}{kT}\right) - 1\right)$$
$$= 327 \times 10^{-12} \times \left(\exp\left(\frac{0.6}{0.025861}\right) - 1\right)$$
$$= 3.44 \text{ A}$$

[20%]

(ii)

$$g_{opt} = \frac{I_{sc}}{qA(L_e + L_h)}$$

Assume L_h is negligible.

$$g_{opt} = \frac{3.44}{1.602 \times 10^{19} \times 10^{-2} \times (100 \times 10^{-6})} = 2.15 \times 10^{25} \text{m}^{-3}\text{s}^{-1}$$

[20%]

Comments: This question required the students to understand the derivations presented in the lecture notes and apply them to a new situation: a pn^+ solar cell. Part (a) was answered well by most students. Part (b) was also answered well, although some students neglected to derive the equation for I_s and simply recited it from memory. One student performed the derivation perfectly but neglected to calculate the final answer. Part (c) involved numerical calculations and was generally answered well.

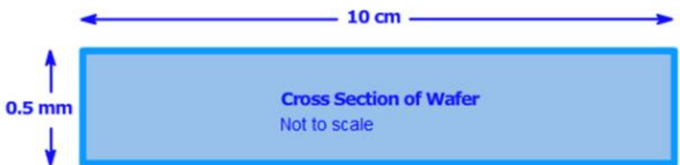
2 (a) Crystalline Si has to be thick because it is not an efficient optical absorber. It has an indirect band-gap, which for a material with a crystal structure, means than an energy gain alone will not allow a carrier (electron) in the valance band to be excited to the conduction band. Hence, the absorption of photons (light) alone cannot take place. This is because in a crystal, electrons have both allowed energy and momentum states. In Si the transition of an electron from the valance band to the conduction band requires both an energy and momentum transition. As photons have no momentum a transition across the band which absorbs a photon requires an accompanying momentum gain/loss through absorption/loss of a phonon (crystal vibration). In direct band-gap materials the crystal structure is such that an energy transition across the band-gap without requiring a change in momentum is allowed.

In amorphous Si there is no crystal structure. It has the characteristic bond angles and bond distances between Si atoms as in the crystal, but no periodic order in the location of the Si atoms. This allows relaxation of the conditions required for momentum conservation in exciting electrons across the band-gap. a-Si:H is therefore a pseudo direct band-gap material and an efficient optical absorber. Hence it requires much less thickness to absorb the photons from the solar spectrum which can lead to energy transitions across the band gap. [15%]

2 (b) Solar cell fabrication process below. [30%]

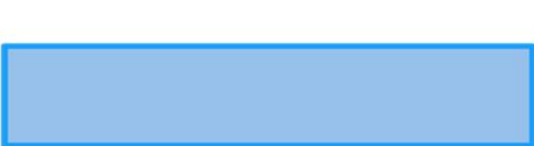
Starting Wafer

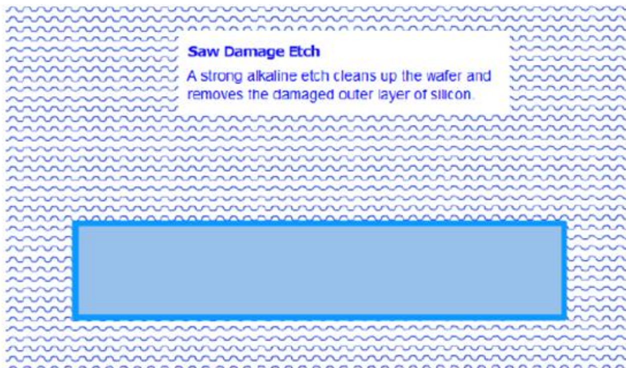
The starting wafer is about 0.5mm thick and 10 x 10 cm2 in size. The wafer is typically P-type doped with small amounts of boron (1e16 atoms/cm3)

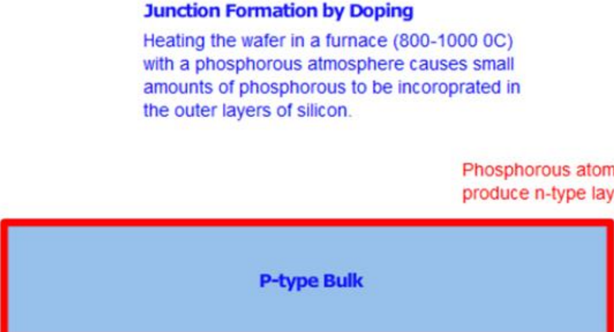


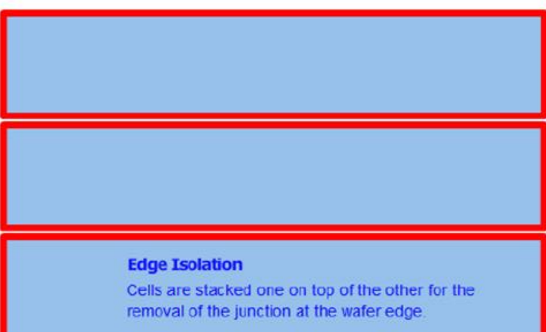
Saw Damage

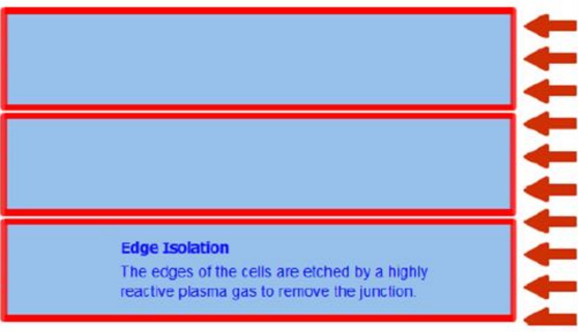
The starting wafer is uneven due to saw damage and is coated in cutting fluid.











Edge Isolation

After plasma etching, the front junction is no longer in contact with the rear of the cell.

Screen Printing the Rear Contact

A screen is lowered onto the rear of the cell along with metal paste.

Metal Paste

Rear of Cell

(wafer is upside down)

Screen Printing the Rear Contact

A squeegee drags across the screen forcing the metal paste through holes in the screen print mask.

A grid of silver is cheaper but doesn't produce a back surface field (BSF). Aluminium paste produces a higher performance cell with a BSF but requires a second print of silver paste for a solderable contact.

Screen Printing the Rear Contact

The paste is dried in an oven to drive off the organic solvents and binders.

Firing the Rear Contact

The cell is placed in a second furnace at a much higher temperature to fire the metal contact into contact with the silicon.

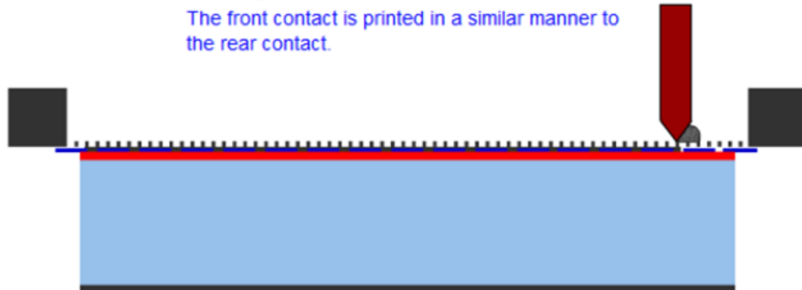
Firing the Rear Contact

The firing process destroyes the rear n-layer so the metal makes contact with the p-type bulk.

The cell is flipped over for printing on the front.

Printing the Front Contact

The front contact is printed in a similar manner to the rear contact.



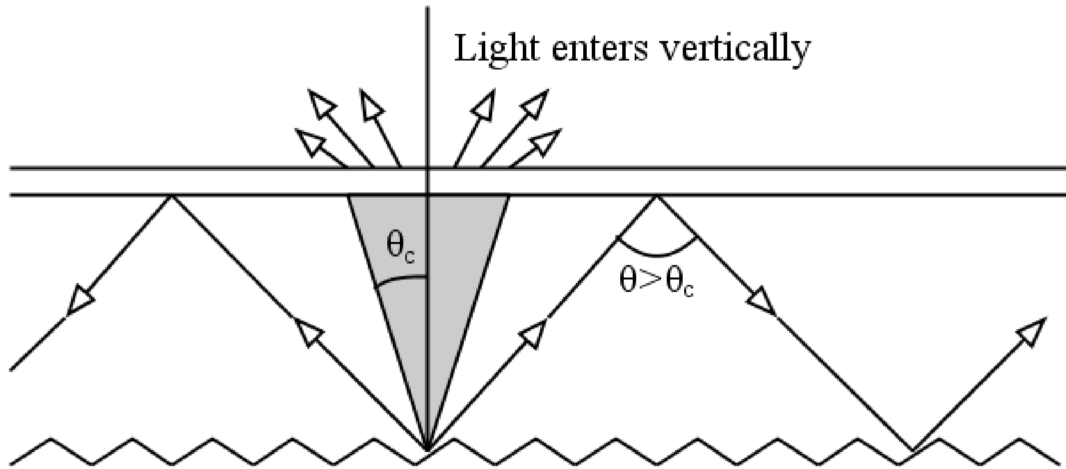
Printing the Front Contact

A pattern of the lines is used to prevent shading of the cell.

Firing the Contacts

A furnace heats the cell to a high temperature to fire the metal paste into the silicon.

2 (c) One way to do this is to change the direction of the light path within the cell to become lateral after it enters the cell vertically. Once this is achieved, as the Si has higher density than air, light will be ‘trapped’ in the Si through total internal reflection the same as it occurs in an optical wave guide/fibre. This allows there to be a long optical path (laterally) for effective absorption of photons while having a thin cross section vertically.



All light reflected within the Lambertia cone with an angle equal to the critical angle for total internal reflection can exit the Si. All other light is ‘trapped’ through total internal reflection

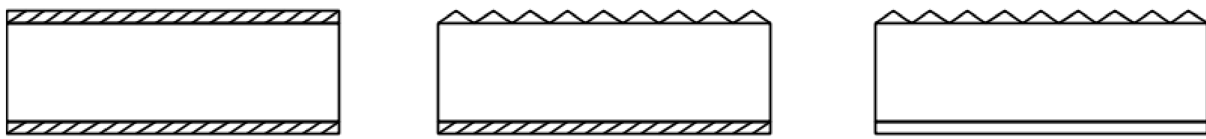
Back surface roughened to randomize direction of reflection from back surface

$$\theta_c = \sin^{-1}\left(\frac{n_{air}}{n_{si}}\right) = 16°$$

[35%]

2(d) The starting Si would be a 0.05mm (50 μm) foil rather than a 0.5mm wafer.

The manufacturing process would be the same as that for the conventional cell except for an additional back surface roughening step. This can be done after the edge isolation step, before the screen printing of the rear contact.



Edge isolation	Back surface roughening. This can be done through chemical etching while protecting the front surface or by plasma etching back surface only.	Screen printing back metal. Ideally the etch depth will be close to that of the sacrificial n-layer at the back. The printed metal layer thickness is much larger than etch depth

[20%]

Comments: This was the least popular question of the examination. For part (a), most students were able to explain that amorphous Si has a pseudo-direct bandgap and therefore absorbs light more efficiently that crystalline Si. However, one student got very lost and only described the effect of diffusion length. Most students also accurately described the manufacturing process for crystalline Si solar cells in part (b). Answers to part (c) were strong, with most candidates describing back-texturing to improve the efficiency of c-Si solar cells. Some candidates listed additional strategies (anti-reflection coatings, finger contacts) that would not strictly achieve the increase in optical path length required for increased photon absorption in an ultrathin c-Si solar cell. Part (d) was answered well by those candidates who answered part (c) correctly.

3 (a) Efficiency $= \dfrac{V_{OC} I_{SC} FF_o}{P_{ch}}$

$$= \frac{0.65 \times 1.5 \times F_o}{1 \times 10^3 \times 50 \times 10^{-4}}$$

FF_o from formulae and constants sheet

$$FF_o = \frac{\frac{qV_{OC}}{kT} - \ln\left(\frac{qV_a}{kT} + 0.72\right)}{\frac{qV_{OC}}{kT} + 1}$$

$$\frac{qV_{oc}}{kT} = \frac{1.602 \times 10^{-19} \times 0.65}{1.38 \times 10^{-23} \times 300} = 25.152$$

$$FF_o = \frac{25.152 - \ln(25.152 + 0.72)}{26.152}$$

=0.84

$$\therefore \text{ Efficiency} = \frac{0.65 \times 1.5 \times 0.84}{5}$$

= 16.4%

[20%]

(b)(i) $V_{OC} = \frac{\eta kT}{q} \ln\left(\frac{I_{SC}}{I_S} + 1\right)$

$$I_S = \frac{I_{SC}}{\exp\left(\frac{qV_{OC}}{\eta kT}\right) - 1} = \frac{1.5}{\exp\left(\frac{25.152}{1.05}\right) - 1}$$

$$= \frac{1.5}{2.53 \times 10^{10}}$$

$$= 6.05 \times 10^{-11} A$$

[20%]

(ii) New FF_o

$$= \frac{\frac{25.152}{1.05} - \ln\left(\frac{25.152}{1.05} + 0.72\right)}{\frac{25.152}{1.05} + 1}$$

$$= \frac{23.954 - 3.146}{24.954} = 0.83$$

[30%]

(iii) Taking into account series resistance

$FF_1 = FF_0(1 - V_c)$ where $V_c = 0.025 / r_o$

$$r_6 = V_{OC} / I_{SC} = \frac{0.65}{1.5} = 0.43$$

$r_c = 0.058$

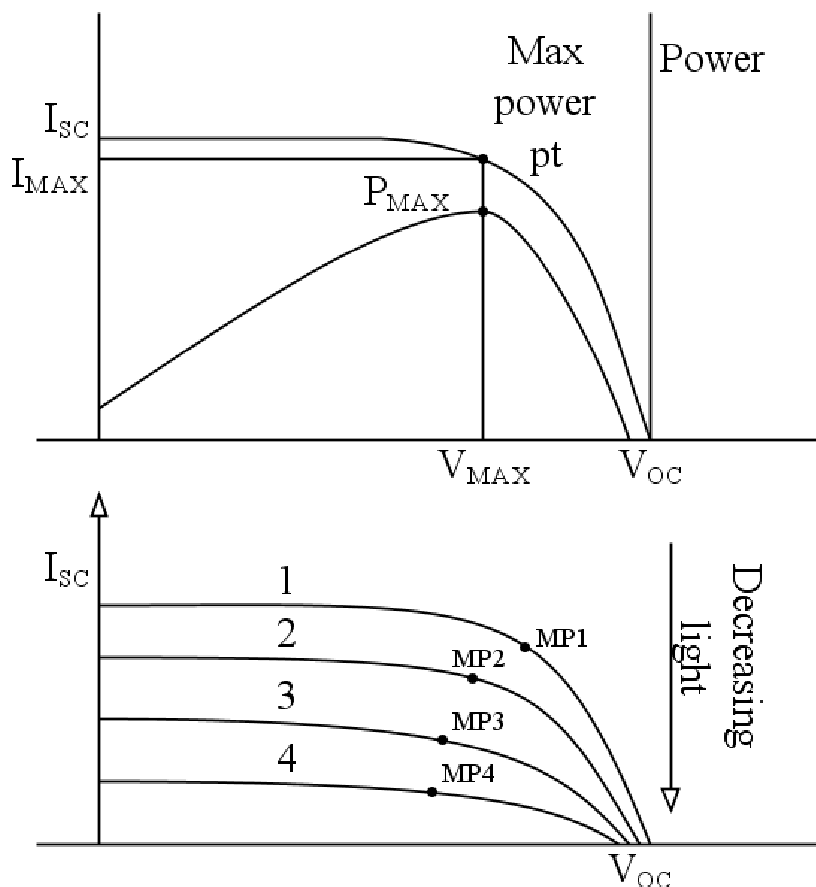
$FF_1 = 0.83 \times 0.94 = 0.78$

$\therefore$ better estimate for efficiency is

$\frac{16.4}{0.84} \times 0.78 = 15.2\%$ [30%]

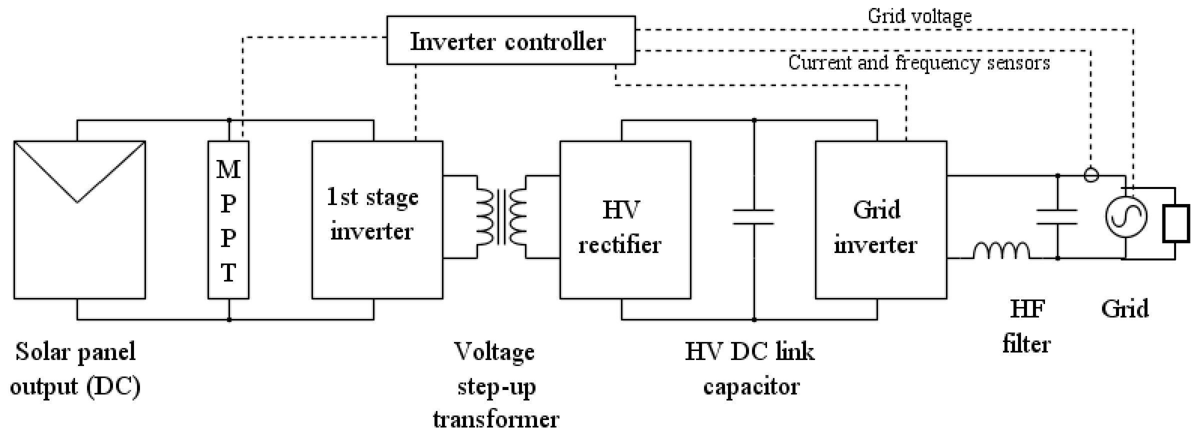
Comments: This question was attempted by all candidates. Many candidates answered all parts correctly. Some candidates misunderstood that the current is resistively limited above 1A, and took 1A to mean the operating point of the solar cell. Some candidates also neglected to use the ideality factor in their calculations of FF_0 in part (b-ii). Most candidates were able to calculate a better estimate of the efficiency in part (b-iii) based on the FF_0 calculated in part (b-ii) and the limiting resistance.

4 (a) In a solar power plant the optimum operating point is that at which maximum power is extracted. However, this optimum point changes as the solar intensity and temperature changes. Therefore it is necessary to have maximum point tracking.



[20%]

(b)



[30%]

(c) Points which need to be addressed.

(i) Solar power is cheaper now than any time before.

(ii) The cost of solar cells is directly related to the energy cost of its production. Therefore if fossil fuel prices drop, solar cell prices should also drop.

(iii) Grid parity, that is the cost of solar electricity without feed-in tariffs matching cost of grid power from other sources, is desirable but not essential.

(iv) (iii) applies as solar power is 'clean' and does not emit CO_2 emissions. As all countries are committed to reduce CO_2 emissions, continuing to generate with fossil fuels even at current levels is not possible. Hence solar will continue to grow even without subsidy. [50%]

Comments: This was also a popular question. I was pleased the students understood the concept of maximum power point tracking and how temperature and illumination conditions change the maximum power point. Most included diagrams showing how the IV curve and power depend on illumination conditions. In part (b), the answers generally showed good understanding of an inverter's operation and function. In part (c), most candidates wrote comprehensive essays, although none mentioned that the cost of solar cells is directly related to the energy cost of their production.