EPSRC Centre for Doctoral Training in New and Sustainable Photovoltaics

Fundamentals of Photovoltaics: Problems on the lectures

October / November 2018

USEFUL INFORMATION

k_B = 1.38 x 10^{-23} m^2 Kg $s^{-2}K^{-1}$	Boltzmann's constant
c = 3 x 10^8 ms^{-1}	speed of light in vacuum
e = 1.602 x 10^{-19} C	charge on an electron
h = 6.63 x 10^{-34} m^2 kg s^{-1}	Planck's constant
$P_{AM1.5}$ = 1000 Wm^{-2}	Normalised power of AM1.5 solar spectrum

Unless stated explicitly, assume room temperature to be T = 300 K

These problems are highly relevant to the test that you will sit on Tuesday 6th November. Work through them and make sure you have a good understanding of their solutions. Please do work collaboratively to answer the problems. You are encouraged to use #cdtpvC5 to raise points/queries and to post links to your solutions. The rest of your cohort will benefit greatly from your contributions so share them if you can.

Lecture 1. Solar spectrum and basic device operation.

Group discussion questions

a) What impurity would you add to silicon to make it n- or p-type?

b) What impurity would you add to GaAs to make it n- or p-type?

c) What is meant by the AM1.5 standard?

d) What are the main physical contributions to the spectrum shape of solar radiation at the Earth's surface?

e) What happens physically to CO_2 molecules when they absorb light? Why?

Lecture 1. Basic device response

1. The current-voltage response of a solar cell, measured under standard conditions, is given by

$$J(V) = J_{sc} - J_o\left(\exp\frac{eV}{nk_BT} - 1\right)$$

(a) For a cell with values of $J_o = 10^{-8}$ mAcm^{-2}, $n = 2$ and $J_{sc} = 28$ mAcm^{-2}, calculate the open circuit voltage. Derive any formula that you use.

(b) The cell has a fill factor of 80%. What is its conversion efficiency?

(c) If the cell's area is 1 cm^2 what area would be needed to generate a power of 1 kW?

(d) Sketch the ideal $J - V$ response for the cell and show the effects of parasitic series, R_s, and shunt, R_{sh}, resistances.

(e) In the case of high R_s and high R_{sh} show that $1/R_s$ is proportional to the slope of the $J - V$ curve in the vicinity of $J = 0$.

(f) In the case of low R_s and low R_{sh} show that $1/R_{sh}$ is proportional to the slope of the $J - V$ curve in the vicinity of $V = 0$.

2. Two ideal solar cells have an open circuit voltage of 0.8 V and the same short circuit current under an AM1.5 solar spectrum. One has an ideality factor of 1, the other has an ideality factor of 2. What is the relative difference in the efficiencies of the two cells?

Problem 2 above is for discussion only. How would you solve it?

3. For a solar cell with a V_{oc} of 0.65V, a Jsc of 12 mAcm^{-2}, a Fill Factor of 0.6 and a J_{MPP} value of 10 mAcm^{-2}, calculate the voltage at the maximum power point.

Lecture 2: Detailed balance

a) The peak power output of a solar module, under AM1.5 illumination, is 1kW. What would be its peak power output on Mars? State your assumptions.

b) For an ideal two level system, explain qualitatively how the band gap determines the upper limit of conversion efficiency.

c) List the key requirements for an ideal solar cell.

d) List and describe three separate strategies for beating the Shockley-Queisser limit.

Lecture 3: Semiconductors

A p-type direct gap semiconductor has an acceptor density of $N_A = 10^{20}$ m^{-3}. Its recombination coefficient is 5 x 10^{-12} m^{-3}s^{-1} and the intrinsic carrier concentration is $n_i = 10^{16}$ m^{-3}

If light causes an excess generation of 10^{22} pairs m^{-3}s^{-1} find:

a) The minority carrier lifetime.

b) The equilibrium generation rate.

c) The electron and hole number densities under illumination.

Lecture 4: Junctions

Group discussion questions

What is the origin of the electric field in a photovoltaic solar cell?

1. The direct band gap of $Al_xGa_{1-x}As$ is given empirically by

$E_G = 1.4702 + 1.155x + 0.37x^2$ eV

For a GaAs-AlGaAs heterojunction, the direct band gap difference ΔE_G is accommodated approximately $\frac{2}{3}$ in the conduction band and $\frac{1}{3}$ valence band for an Al composition of 0.3.

Sketch the band diagrams for the following cases:

a) N+-$Al_{0.3}Ga_{0.7}As$ on n-GaAs
b) N+-$Al_{0.3}Ga_{0.7}As$ on p-GaAs.

2. An ideal Si p-n junction has $N_A = 10^{18}$ cm^{-3} and $N_D = 10^{15}$ cm^{-3} in the p and n regions respectively at 300K.

   a. Calculate the built-in potential.
   b. Calculate the width of the depletion in the *p* and *n* regions.
   c. Calculate fractional change in total width of the depletion region under biases of +0.7 V and −0.7 V.

3. The parameters of an ideal Si *p* − *n* junction are:

$$N_A = 5x10^{16} cm^{-3},\ N_D = 10^{16}\ cm^{-3}$$

$$D_n = 21\ cm^2/s,\ D_p = 10\ cm^2/s,$$

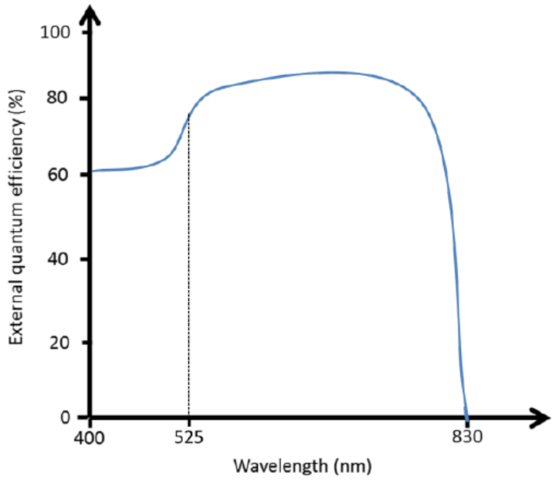
$$\tau_p = \tau_n = 5 \times 10^{-7} s$$

a) Sketch the band diagram for this junction.
b) Calculate the reverse saturation current density.
c) Estimate the junction's V_{OC} under AM1.5 illumination. State the assumptions that you have made.
d) Assuming a fill factor of 80%, estimate the conversion efficiency.
e) Sketch the *JV* response of the junction in dark and light conditions.

Lecture 5 Junction characterisation

(a) The figure below shows an external quantum efficiency (*EQE*) curve for a solar cell. Using the information in the plot, determine:

i. The approximate band gap of the p-type absorber layer in eV
ii. The approximate band gap of the n-type window layer in eV
iii. The type of solar cell you believe this may be



(b) The figures that follow are EQE curves for cells of the same type but which have lower efficiency than the high efficiency cell in Figure 1. For each curve identify a likely cause for the reduced performance of the cell.

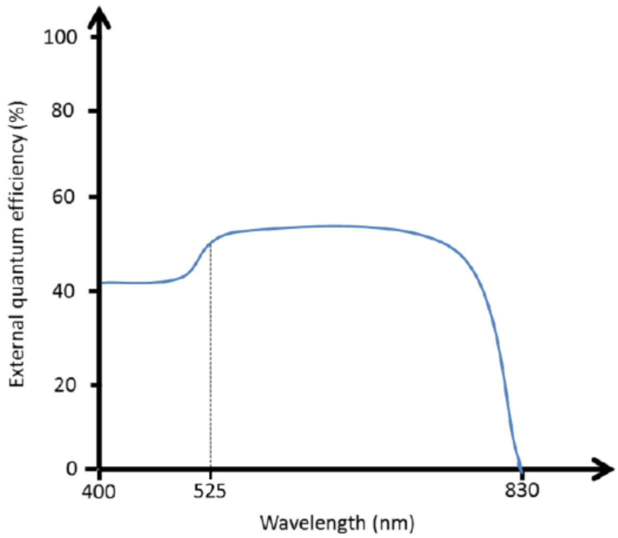


Fig 5b (i)

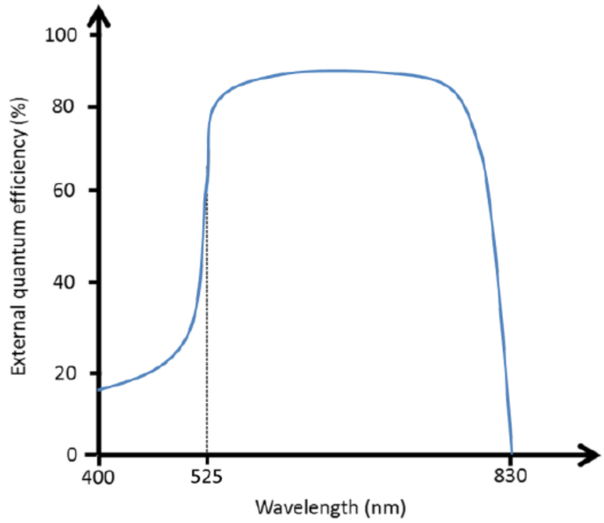


Fig 5b (ii)

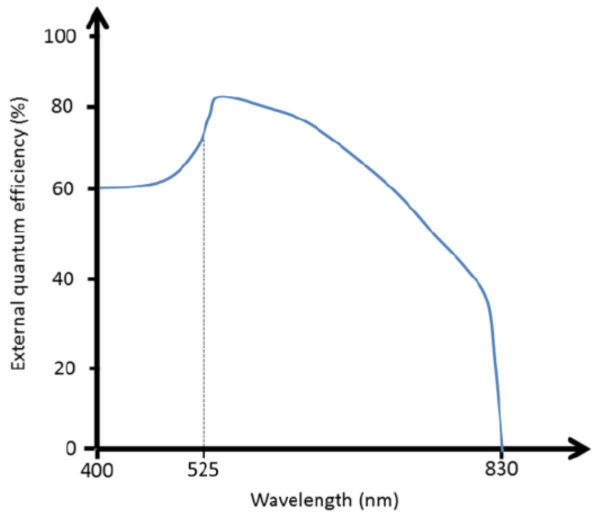


Fig 5b (iv)

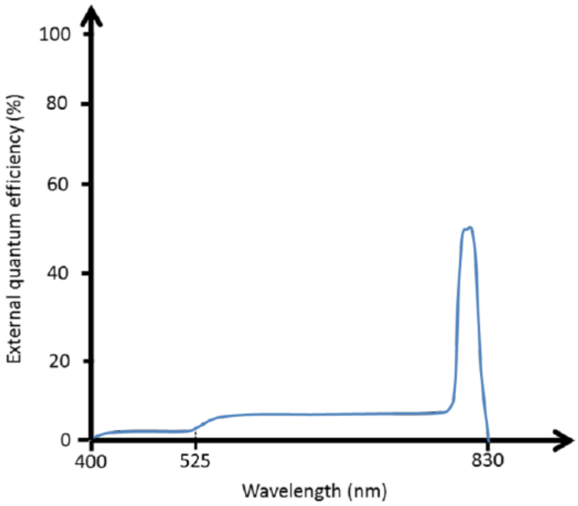


Fig 5b (v)

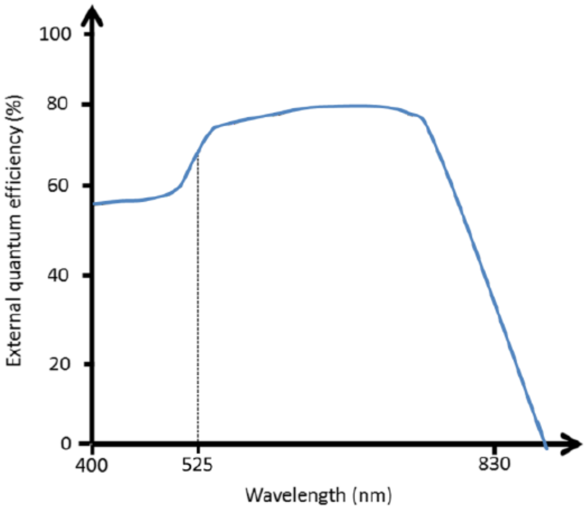


Fig 5b (vi)

Lecture 6 Optical properties of semiconductors

1. The absorption edge of a particular semiconductor is well described by:

$$\alpha\,(E_{phot}) = 2 \times 10^4 (E_{phot} - E_g)^{1/2}$$

Where α is the absorption coefficient in cm^{-1} and E_{phot} and E_g are the photon energy and band gap respectively in eV.

(a) Does this semiconductor have a direct or indirect band gap?
(b) What function of α would you plot against hν to obtain linear data from which to estimate the band gap?
(c) If the band gap found from the plot in (b) was 1.2 eV, from the above equation, calculate α at 0.1, 0.5 and 2.0 eV above the band gap
(d) Calculate the thickness of PV absorber material, in nm, required to absorb 60%, 95% and 99% of incident photons at a wavelength for which the absorption coefficient is 10^5 cm^{-1}.

2. Calculate the thickness of PV absorber material, in nm, required to absorb 50, 90 and 99% of the incident photons at a wavelength for which the absorption coefficient is 10^5 cm^{-1}.

Lecture 7 Solid state reactions and phase diagrams

For the Pb-Sn phase diagram in the figure below consider points A, B and C

For each point, state:

(a) The phases present
(b) Their compositions
(c) Their amounts, and
(d) Sketch the microstructure that you would expect at equilibrium