1995

(b) Power output $= P = IV = V.I_o(e^{eV/kT}-1) - VI_L$

max. when $\frac{dP}{dV} = 0$, therefore

$$0 = 1.\,I_o(e^{eV_m/kT}-1) + V_m I_o.\frac{e}{kT}.e^{eV_m/kT} - I_L$$

$$I_o\left(1+\frac{eV_m}{kT}\right)e^{eV_m/kT} = I_o + I_L$$

$$\left(1+\frac{eV_m}{kT}\right)e^{eV_m/kT} = 1 + \frac{I_L}{I_o}, \quad \text{since } I_L = I_{sc}$$

$$\left(1+\frac{eV_m}{kT}\right)e^{V_m/kT} = 1 + \frac{I_{sc}}{I_o} \quad \text{is condition for max. power}$$

(c) If $I_{sc} \gg I_o$, $V_m \gg kT/e$, above equation becomes

$$\left(\frac{eV_m}{kT}\right)\exp(eV_m/kT) = I_{sc}/I_o, \quad \text{rearranging}$$

$$\left(\frac{eV_m}{kT}\right)\frac{I_o}{I_{sc}} = \exp(-eV_m/kT)$$

$$\ln\left(\frac{eV_m}{kT}\right) + \ln\left(\frac{I_o}{I_{sc}}\right) = -eV_m/kT$$

$$\ln\left(\frac{eV_m}{kT}\right) = \ln\left(\frac{I_{sc}}{I_o}\right) - eV_m/kT \quad \text{where } x = \frac{eV_m}{kT},\ c = \ln\frac{I_{sc}}{I_o}$$

(d) If kT/e at RT ≈ 25meV, use different values of V_m to satisfy the above equation. Best guess when $V_m = 0.4$, $I_o = 1$n $I_{sc} = 100$mA; $2.77 \pm 18.42 - 16 \approx 2.42$ so maximum power delivered at $V_m \approx 0.4$.

(e) For maximum power, need current at $V_m \approx 0.4$

$$I = I_o(e^{e0.4/kT}-1) - I_L = 10^{-9}(e^{16}-1) - 100\text{mA}$$

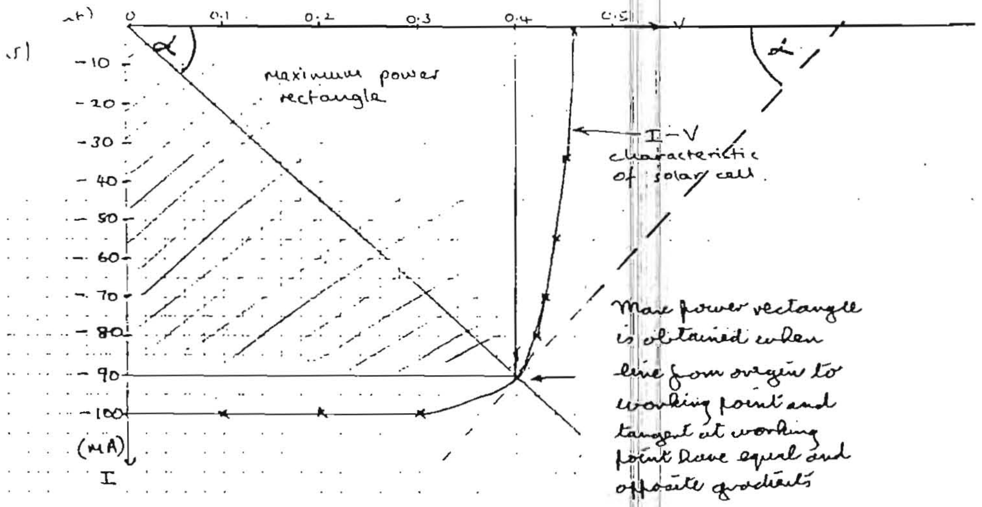
≈ 91mA, so max. power is

$$P = I_{max}V_{max} \approx 91\text{mA} \times 0.4\text{V} = 36.4\text{mW}$$

(f) I-V characteristic of cell is obtained by ~~solving~~

$$I = 10^{-9}(e^{eV/kT}-1) - 100\text{mA}$$

V	0	0.2	0.4	0.42	0.43	0.44	0.45	0.46	(V
-I	100	100	91	80	70	55	34	2	(mA



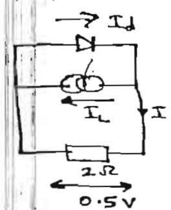
At the optimum operating point, V = 0.4V and I = 90mA, therefore power is VI = 36mW similar to that obtained in (e).

1996

(a) – (c) book work/notes

(d) $I = I_o(e^{eV/kT}-1) - I_L$

$I_o = 2\times10^{-10}$A, $V = 0.5$V, $\frac{kT}{e} = 0.025$V



$$I = -\frac{V}{R} = -\frac{0.5}{2} = -0.25\text{A}$$

substituting this into above eqn.

$$I_L = 2\times10^{-10}(e^{e0.5/kT}-1) + 0.25$$
$$\approx 2\times10^{-10}.e^{20} + 0.25 = 0.347\text{ A}$$

$$V_{oc} = \frac{kT}{e}\ln\left(\frac{I_L}{I_o}+1\right) \approx \frac{kT}{e}\ln\left(\frac{I_L}{I_o}\right) = 0.025\,.\,21.27$$
$$= 0.532\text{ V}$$

Power $= V.I = 0.5\,.\,0.25 = 0.125$ W

$V_{oc}.I_{sc} = 0.532\,.\,0.347 = 0.184$ W

fill factor $= \frac{\text{Power}}{V_{oc}I_{sc}} = \frac{0.125}{0.184} = 0.68$

This is a reasonable value for f.factor, therefore the 2Ω load is close to optimum.

1997 (a) notes

(b) $E_g = 1.8\text{eV}$, for absorption $\lambda \leq \frac{hc}{E_g}$

$$\lambda \leq \frac{6.62\times10^{-34} \times 3\times10^{8}}{1.8 \times 1.6\times10^{-19}} \leq 690\,\text{nm}$$

Wavelength λ below 690nm will be absorbed, and λ above 690nm will be transmitted.
λ below 690nm is in the visible part of the spectrum while λ above 690nm is in the near infra-red part of the spectrum.

1997 (cont) (c) notes

(d) $V_{oc} = 0.5\,\text{V}$, $I_o = 2\times10^{-10}\,\text{A}$

$$V_{oc} = \frac{kT}{e} \ln\left(\frac{I_L}{I_o}+1\right), \quad \frac{kT}{e} \approx 0.025\text{V at RT}$$

so by substituting into above, $I_L \approx 97\text{mA}$

Load current $I = I_d - I_L = I_o(e^{eV/kT}-1) - I_L$

I at $V = 0.45$ therefore given by

$$I = 2\times10^{-10}(e^{e0.45/kT}-1) - 0.097 = 0.013 - 0.097$$
$$= 84\,\text{mA}$$

Power $= VI = 0.45 \times 0.084 = 37.8\text{mW}$

Efficiency $= P_{out}/P_{in} \times 100\%$

P_{in} = area of cell $\times$ 1KW

$$\text{Efficiency} = \frac{37.8\text{mW}}{25\times25\times10^{-6}\times1000} \times 100 = 6\%$$

(e) notes

1998

$\lambda_c = hc/E_g = 1.24/E_g(\text{eV})$

For AlGaAs, $\lambda_c = 1.24/1.8 = 0.69\,\mu\text{m}$ is maximum λ

For Ge, $\lambda_c = 1.24/0.66 = 1.88\,\mu\text{m}$ is maximum λ.

Calculations: First need dark current I_o for each cell.

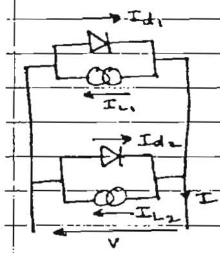
From open circuit voltage equation

$V_{oc} = 0.7 = kT/e \log_e(1.4/I_o + 1)$ for Si cell

Assuming $kT/e = 25\text{meV}$ at room temperature,

$I_o = 9.68\times10^{-13}\,\text{A}$ for Si cell

Similarly, $I_o = 5.52\times10^{-18}\,\text{A}$ for AlGaAs cell



For array, under short circuit conditions, $V = 0$, so $I_{sc} = -1.4 - 1.3 = -2.7\text{A}$

Under open circuit conditions, $I = 0$

$$2.7 = 5.52\times10^{-18}[\exp(eV_o/kT)-1] + 9.68\times10^{-13}[\exp(eV_o/kT) - 1]$$

$$2.7 \approx 9.68\times10^{-13}[\exp(eV_o/kT)-1]$$
$$V_o = 0.716\,\text{V}$$

I-V of array is therefore

$$I = [9.68\times10^{-13} + 5.52\times10^{-18}][\exp(eV/kT)-1] - 2.7 \text{ A}$$

Power $= V \times I$

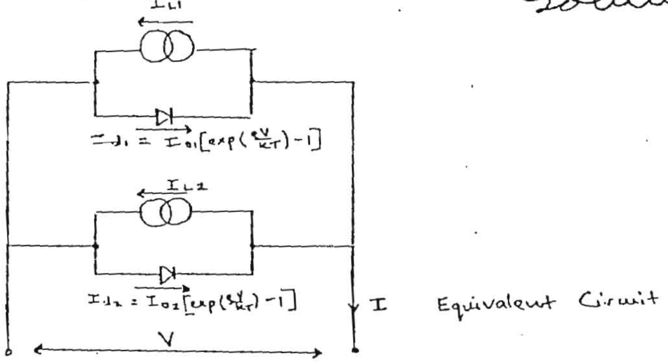
V(V)	0	0.2	0.4	0.5	0.55	0.6	0.65	0.7
I(A)	2.7	2.7	2.7	2.7	2.7	2.68	2.51	1.3
Power(W)	0	0.54	1.08	1.35	1.485	1.608	1.631	0.91

Maximum power is $\sim$ 1.631 W

Fill factor = Maximum power $/(V_{oc}.I_{oc})$

$= 1.631/(0.716 \times 2.7) = 0.84$

1999 (eL000-p00) Solar Cell Solutions (1)



Equivalent Circuit (2)

$$I = I_{01}\left[\exp\left(\frac{eV}{kT}\right)-1\right] - I_{L1} + I_{02}\left[\exp\left(\frac{eV}{kT}\right)-1\right] - I_{L2}$$

(3)

$$I = \left[I_{01}+I_{02}\right]\left[\exp\left(\frac{eV}{kT}\right)-1\right] - \left(I_{L1}+I_{L2}\right) \qquad (1)$$

Voc when I=0, therefore from eqn. (1)

$$\left[I_{01}+I_{02}\right]\left[\exp\left(\frac{eV_{oc}}{kT}\right)-1\right] = \left(I_{L1}+I_{L2}\right)$$

$$V_{oc} = \frac{kT}{e}\ln\left(\frac{I_{L1}+I_{L2}}{I_{o1}+I_{o2}}+1\right) \qquad (2)$$

Isc when V=0, therefore from eqn. (1)

$$I_{sc} = -\left(I_{L1}+I_{L2}\right) \qquad (3)$$

(2)

Calculation:
Assume kT/e = 25meV for 300K
$I_{o1} = 4 \times 10^{-11}$ A, $I_{o2} = 5 \times 10^{-10}$ A, $I_{L1} = 0.25$A, $I_{L2} = 0.1$A

Substitute values into eqn.(1)

$$I = \left(5.4\times10^{-10}\right)\left[\exp\left(\frac{V}{0.025}\right)-1\right] - 0.35\,A$$

V	0	0.2	0.4	0.42	0.44	0.46	0.48
-I	0.35	0.35	0.345	0.339	0.326	0.297	0.232
Power = V x I	0	0.07	0.138	0.142	0.143	0.137	0.115

Maximum power obtainable from the array is 143mW. (3)
This occurs at 0.44V when a current of 0.326A flows, so the optimum load resistor is,
R=0.44/0.326 = 1.35 ohms (2)
From eqns. (2) & (3),

$$V_{oc} \cong 0.025\ln\left(\frac{0.35}{5.4\times10^{-10}}\right) = 0.507$$

$I_{sc} = -0.35$A

Fill factor of cell = $(V_{opt} I_{opt})/(V_{oc} I_{sc}) = 0.805$ (2)

For series combination,

$$I = I_{01}\left[\exp\left(\frac{eV_1}{kT}\right)-1\right] - I_{L1} \qquad (4)$$

$$I = I_{02}\left[\exp\left(\frac{eV_2}{kT}\right)-1\right] - I_{L2} \qquad (5)$$

$$I_{01}\left[\exp\left(\frac{eV_1}{kT}\right)-1\right] - I_{L1} = I_{02}\left[\exp\left(\frac{eV_2}{kT}\right)-1\right] - I_{L2}$$

$$I_{01}\exp\left(\frac{eV_1}{kT}\right) - I_{02}\exp\left(\frac{eV_2}{kT}\right) = I_{L1} + I_{01} - I_{L2} - I_{02} \qquad (6)$$

(1)

Multiply LHS & RHS of eqn.(6) by $\exp\left(\frac{eV_2}{kT}\right)$

$$I_{01}\exp\left(\frac{eV_1+eV_2}{kT}\right) - I_{02}\exp\left(\frac{2eV_2}{kT}\right) = \exp\left(\frac{eV_2}{kT}\right)\left(I_{L1}+I_{01}-I_{L2}-I_{02}\right) \qquad (7)$$

Let Va = $V_1 + V_2$ and Ic = $I_{L1} + I_{01} - I_{L2} - I_{02}$ and rearrange (7)

$$I_{02}\exp\left(\frac{2eV_2}{kT}\right) + I_c\exp\left(\frac{eV_2}{kT}\right) - I_{01}\exp\left(\frac{eV_a}{kT}\right) = 0$$

(2)

Solving this quadratic gives,

$$\exp\left(\frac{eV_2}{kT}\right) = \frac{-I_c \pm \left[I_c^2 + 4I_{o1}I_{o2}\exp\left(\frac{eV_a}{kT}\right)\right]^{1/2}}{2I_{o2}} \qquad (8)$$

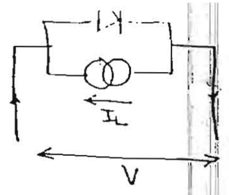
only positive value is real, so substituting eqn.(8) into eqn.(5) gives,

$$I = \frac{-I_c + \left[I_c^2 + 4I_{o1}I_{o2}\exp\left(\frac{eV_a}{kT}\right)\right]^{1/2}}{2} - I_{o2} - I_{L2}$$

$$I = \left[I_{o1}I_{o2}\exp\left(\frac{eV_a}{kT}\right) + \frac{1}{4}\left(I_{L1}+I_{01}-I_{L2}-I_{02}\right)^2\right]^{1/2} - \left(\frac{I_{L1}+I_{01}-I_{L2}-I_{02}}{2}\right) - I_{L2} - I_{02}$$

$$I = \left[I_{o1}I_{o2}\exp\left(\frac{eV_a}{kT}\right) + \frac{1}{4}\left(I_{L1}+I_{01}-I_{L2}-I_{02}\right)^2\right]^{1/2} - \frac{1}{2}\left(I_{L1}+I_{01}+I_{L2}+I_{02}\right)$$

(2)



Solution to Solar Cell Question 2000 (1)

$$I = I_d - I_L = I_o\left(e^{eV/kT} - 1\right) - I_L$$

when open cct., $I = 0$, $V = V_{oc}$

$$0 = I_o\left(e^{eV/kT} - 1\right) - I_L$$

$$V = V_{oc} = \frac{kT}{e}\ln\left(\frac{I_L}{I_o} + 1\right)$$ (1)

when short cct., $V = 0$

$$I = I_{sc} = -I_L$$ (1)

$$I = I_o\left(e^{eV/kT} - 1\right) - I_L$$

$$\text{Power} = V.I = V I_o\left(e^{eV/kT} - 1\right) - V I_L$$

[M]aximum in power occurs when $\frac{dP}{dV} = 0$ and $V = V_m$ (2)

$$0 = 1.I_o\left(e^{eV_m/kT} - 1\right) + V_m I_o \, e/kT \, . \, e^{eV_m/kT} - I_L$$

$$I_o\left(1 + \frac{eV_m}{kT}\right)e^{eV_m/kT} = I_o + I_L$$

$$\left(1 + \frac{eV_m}{kT}\right)e^{eV_m/kT} = 1 + \frac{I_L}{I_o}$$

Since $V_m \gg kT/e$ and $\frac{I_L}{I_o} \gg 1$ and $I_L = I_{sc}$

$$\left(\frac{eV_m}{kT}\right)e^{eV_m/kT} = \frac{I_{sc}}{I_o}$$

$$\ln\left(\frac{eV_m}{kT}\right) + \frac{eV_m}{kT} = \ln\left(\frac{I_{sc}}{I_o}\right)$$

$$\ln\left(\frac{eV_m}{kT}\right) = \ln\left(\frac{I_{sc}}{I_o}\right) - \frac{eV_m}{kT}$$ (4)

$I_o = 10^{-10}$ A, $I_{sc} = 50$ mA

(c) $$\ln\left(\frac{eV_m}{kT}\right) + \frac{eV_m}{kT} = \ln\left(\frac{I_{sc}}{I_o}\right) = 20.03$$

Value of $V_m = \underline{\underline{0.45\text{ V}}}$ gives 20.89 . so close enough. (4)

(d) $$I_{max} = I_o\left(e^{\frac{e0.45}{kT}} - 1\right) - I_L = 10^{-10}\left(e^{18} - 1\right) - 0.05 = 43.44\text{ mA}$$

Power = $V_m I_{max}$ = 19.5 mW

Choose this operating point by selecting the load resistor (4)

$$V_{oc} = \frac{kT}{e}\ln\left(\frac{I_L}{I_o} + 1\right) = 0.025\ln\left(5\times10^{8}\right) = 0.5\text{ V}$$

$I_{sc} \cdot V_{oc}$ = 25 mW

(e) Fill factor = $\frac{19.5}{25}$ = 0.78

i.e. a good high value. (3)

2001 Solar Cell Questions Solution

Answers: Question 6

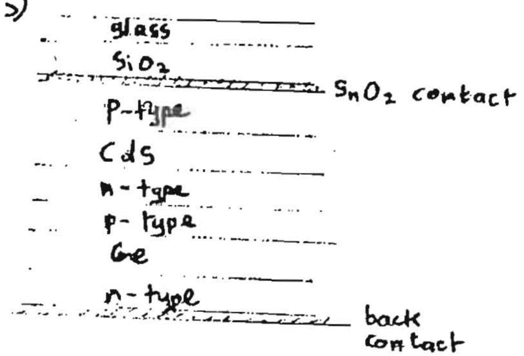
a) Maximum wavelength for electron-hole generation is:

(i) for Ge $\lambda_{max} = \frac{1.24}{0.66} \mu m = 1.88 \mu m$

(ii) for CdS $\lambda_{max} = \frac{1.24}{2.3} \mu m = 0.54 \mu m$

1.88μm is in the infra-red and 0.54μm is in the visible part of the spectrum.

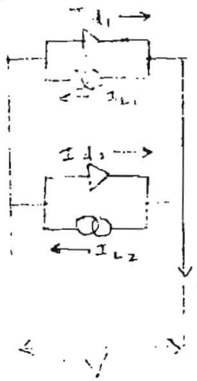
b)



c) Advantage of multi-junction solar cells is that their total efficiency can be very high. Disadvantages are that they are complicated to make, hence expensive and that the short circuit current is determined by the worst cell.

Question 7:

a) Two cells in parallel may be represented as follows:



illumination

$I = I_{d1} - I_{L1} + I_{d2} - I_{L2}$

The voltage across both cells have to be identical and using the diode equation;

$I = I_{o1}\left(\exp{}^{eV}/_{kT} - 1\right) - I_{L1} + I_{o2}\left(\exp{}^{eV}/_{kT} - 1\right) - I_{L2}$

$I = \left(I_{o1} + I_{o2}\right)\left(\exp{}^{eV}/_{kT} - 1\right) - \left(I_{L1} + I_{L2}\right)$

Under open circuit, I=0 and exponential term will be >> 1, so expression can be rewritten as

$$\exp\left({}^{eV_{OC}}/_{kT}\right) \approx \frac{I_L}{I_O}$$

$$V_{OC} \approx \frac{kT}{e} \ln\left(\frac{I_L}{I_O}\right)$$

b) i) Under short circuit, V=0, $I_L = -\left(I_{L1} + I_{L2}\right) = -2.8A$

We need to determine I_{o1} & I_{o2} for each cell:

Cell 1: $0.6 \approx \frac{kT}{e} \ln\left(\frac{1.5}{I_{o1}}\right)$, rearranging this gives $I_{o1} = 5.66 \times 10^{-11}$A

Cell 2 $1.2 \approx \frac{kT}{e} \ln\left(\frac{1.3}{I_{o2}}\right)$, rearranging this gives $I_{o2} = 1.85 \times 10^{-21}$A

Therefore $V_{OC} \approx \frac{kT}{e} \ln\left(\frac{2.8}{5.66x10^{-11}}\right) = 0.615V$

ii) The equation for the array is:

$$I = \left(5.66x10^{-11}\right)\left(\exp{}^{eV}/_{kT} - 1\right) - 2.8$$

V(V)	0.1	0.2	0.3	0.4	0.45	0.5	0.53	0.55	0.6
I(A)	2.8	2.8	2.8	2.8	2.79	2.77	2.71	2.60	1:3
Power(W)	0.2.8	0.56	0.84	1.12	1.26	1.39	1.44	1.43	0.78

Maximum power =1.44W