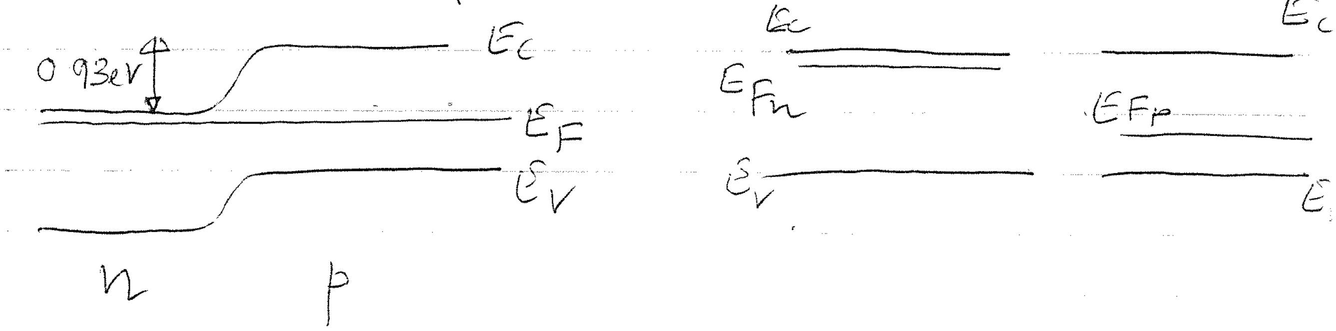
Solutions to Tripos paper D14 - IIB - 04

Q1 - Built in potential $0.93V = V_{bi}$

a)



$$V_{bi} = E_{Fn} - E_{Fp}$$

$$n = N_D = N_c \exp\left(\frac{E_F - E_c}{KT}\right), \quad p = N_A = N_V \exp\left(\frac{E_V - E_F}{KT}\right)$$

Also we are told $N_c = N_V$ and

$$n_i^2 = N_c N_V \exp\left(\frac{-E_g}{KT}\right) = N_V^2 \exp\left(\frac{-1.12q}{KT}\right)$$

$k = 1.38 \times 10^{-23}$ $T = 300K$ $q = 1.602 \times 10^{-19}$ C

$n_i = 2 \times 10^{16}$

$$\therefore \quad 4 \times 10^{32} \exp\left(\frac{-1.12}{0.026}\right) = N_V^2$$

$$N_V = 4.52 \times 10^{25} = N_c$$

From band alignments

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

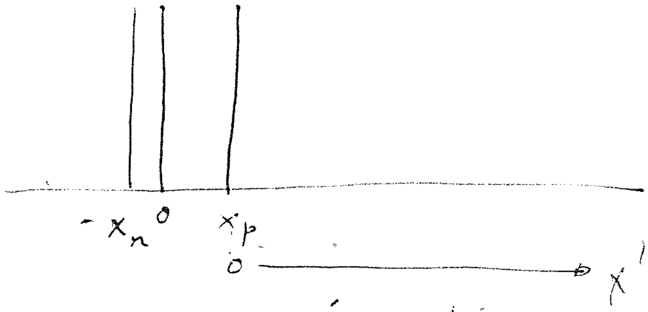
$$(E_c - E_F) = E_g + 0.026 \ln\left(\frac{10^{23}}{4.52 \times 10^{25}}\right) - 0.93$$

$$= 0.03$$

$$\therefore \quad n = 4.52 \times 10^{25} \exp\left(\frac{-0.03}{0.026}\right)$$

$$\underline{\underline{n = 1.43 \times 10^{25}\ m^{-3} = N_D}}$$

b)



In a p-n junction, on the p-side at the edge of the depletion region, $x' = 0$

Under equilibriums at $x'' = 0$

$$p_{p0} = N_A \qquad n_{p0} = \frac{n_i^2}{N_A} = N_D \exp\left(-\frac{qV_{bi}}{kT}\right)$$

When a forward voltage V is applied.

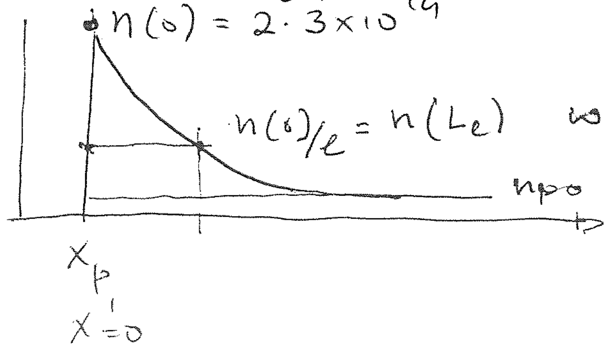
$$n(0) = N_D \exp\left(-\frac{q(V_{bi}-V)}{kT}\right) = N_D \exp\left(-\frac{qV_{bi}}{kT}\right)\exp\left(\frac{qV}{kT}\right)$$

$$n(0) = n_{p0}\exp\left(\frac{qV}{kT}\right) = \frac{4\cdot 10^{32}}{10^{23}}\exp\left(\frac{0.5}{0.026}\right) = 9.2\times 10^{1}\ m$$

The <u>excess</u> amount of minority carriers in the ~~p~~ region at $x' = 0$ is:

$(n(0) - n_{p0})$, and this excess charge decays as x' increases due to recombination with holes in the ~~pn~~ p-region. The characteristic life time is τ_e. This gives rise to a diffusion current/flow of minority carriers away from the junction. The diffusion relationship is:

$$D_e \frac{d(n-n_{p0})}{dx^2} = \frac{n-n_{p0}}{\tau_e} \rightarrow (n-n_{p0}) = (n(0)-n_{p0})\cdot\exp\left(-\frac{x}{\sqrt{D\tau_e}}\right)$$



where $L_e = \sqrt{D_e\tau_e}$.

d) Under optical conditions

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

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

$$\therefore I_{opt} = I_s\left[\exp\left(\frac{0.6q}{kT}\right) - 1\right]$$

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

$$= 10^{-3}\left(\frac{200\times10^{-6}}{1\times10^{-6}}\cdot\frac{4\times10^{32}}{10^{23}} + \frac{0.5\times10^{-6}}{1\times10^{-9}}\times\frac{4\times10^{32}}{1.4\times10^{25}}\right)$$

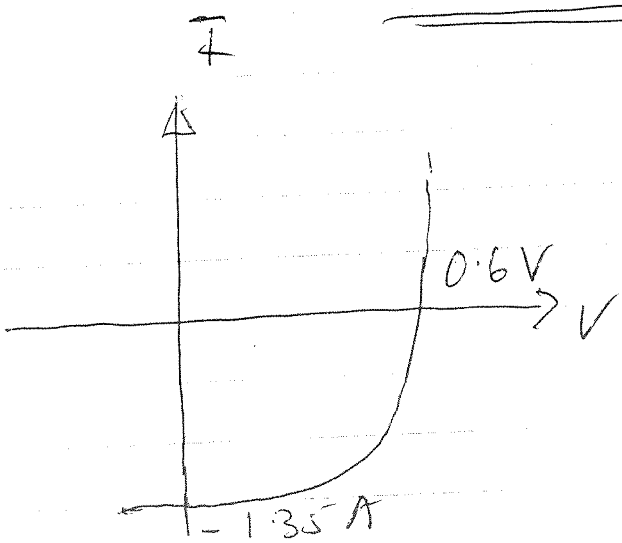
$$= 128\,pA$$

$$\therefore I_{opt} = 1.28\times10^{-12}\left[\exp\left(\frac{0.6}{0.026}\right) - 1\right]$$

$$= \underline{\underline{1.35\,A}}$$

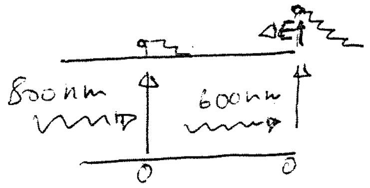
$$g_{opt} = \frac{I_{opt}}{qAL_e} = \frac{1.35}{1.602\times10^{-19}\times10^{-3}\times200\times10^{-6}}$$

$$= \underline{\underline{4.25\times10^{-25}\,m^{-3}s^{-1}}}$$



I-V characteristic for Solar Cell.

2. (a) Efficiency higher for 800nm light.



$\Delta E = E_{photon} - E_{band\text{-}gap}$.

The ΔE is excess energy of the photon above the band-gap energy. This energy is lost as heat. The maximum potential energy that can be stored in a separated electron and hole within the semiconductor is the built in potential. A minimum of E_g is required to generate an electron hole pair. Since $V_{bi} \leq E_g$, there is always an ~~lower~~ upper limit to conversion efficiency. The upper limit is

$$\eta = \frac{E_g I_{opt}}{(E_{photon} - E_g) I_{opt}}$$

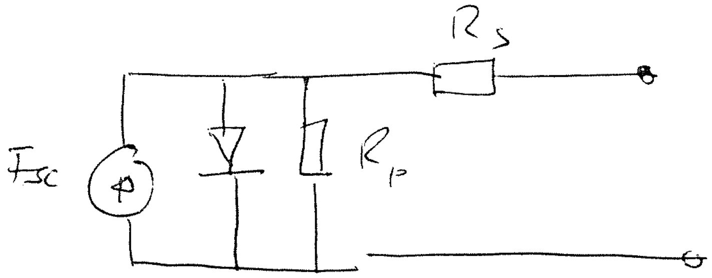
assuming that all the available photons generate electron hole pairs.

In ~~the~~ terrestrial power generation the relative intensity of the solar spectrum at each wavelength governs $I_{opt}(E_{photon})$. This spectrum intensity must be convoluted ~~the~~ with the $(E_{photon} - E_g)$ term to get a measure of how much of the solar spectrum can be absorbed by a semiconductor of gap E_g.

(b) — V_{oc} — loss due to recombination in the depletion region.
— Leads to an ideality factor $\eta > 1$.
(explain in detail).

— I_{sc} — loss due to surface recombination.
- Assumption of both surfaces of the cell being a very long way away (5× diffusion length) not true. ∴ Enhanced recombination in the diffusion region gives lower current.
— On the p-side of the junction, absorption of light very far away from the junction does not contribute to I_{sc}. The photogenerated e-h pair recombine before they are separated.

(c)



I_{sc} = Optically generated short circuit current

Diode which gives $I_{sc} = I_s\left(\exp\left(\frac{qV_{oc}}{kT}\right) - 1\right)$.

$R_s \rightarrow$ Series contact resistance
$R_p \rightarrow$ Junction leakage current at edges of the cell.

(d) Refer to attached sheet of formulae.

Reflection of an air-coating-Si system can be made lower than that of a air-Si surface. ∴ Thin layer used as an Anti-reflection coating.

R min when $2\theta = \pi$

$\therefore \frac{4\pi n d}{\lambda} = \pi$ $\qquad d = \frac{\lambda}{4n}.$

Choose $\lambda = 600$ nm on the basis that this where the solar spectrum peaks.

$\therefore \quad d = \frac{600 \text{ nm}}{8} = \underline{\underline{75 \text{ nm}}}$

when $\theta = \pi/2$ $\qquad$ 1 (giv)

$$R_{min} = \left(\frac{n_2^2 - n_1 n_3}{n_2^2 + n_1 n_3} \right)$$

$\leftarrow$ Can be memorised or calculate from the formulae sheet. $\qquad$ 2 $\quad$ 3

$n_1 = 1 \qquad n_3 \approx \sqrt{11.9} = 3.45$

$R_{min} = 0 \qquad$ if $\quad n_2^2 - n_3 = 0.$

$n_2 = \sqrt{3.45} = \underline{\underline{1.86}}$

$\approx \underline{\underline{1.9}}$

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3 (a) $\quad 0.55 = \frac{1.2kT}{q} \ln\left(\frac{2}{I_s} + 1 \right)$

$\therefore \quad I_s = \frac{2}{\left(\exp\left(\frac{0.55}{1.2 \times 0.026} \right) - 1 \right)} = \underline{\underline{44 \text{ nA}}}$

b) Efficiency $\quad$ From formulae sheet using $V_{oc} = 0.55$, $\frac{kT}{q} = 0.026$

$$\eta = \frac{FF_0 V_{oc} I_{sc}}{P_{in}} = \frac{0.815 \times 0.55 \times 2}{10} = \underline{\underline{0.09}}$$

$\underline{\underline{9\%}}$

c) $FF = FF_0 \left(1 - \frac{0.05}{(V_{oc}/I_{sc})}\right) = 0.815\left(1 - \frac{0.05}{0.275}\right)$

$= 0.667$

$\therefore \eta' = 0.09 \times \frac{0.667}{0.815} = 0.074$

$\therefore$ 7.4 %

d) I_s (reverse saturation current) is the main parameter effected by temperature. As the temperature increases more carriers can be thermally excited across the potential barrier V_{bi} at the p-n junction. This gives a larger leakage current term.

remember $I_s = Aq\left(\sqrt{\frac{D_e}{\tau_e}}\, n_{po} + \sqrt{\frac{D_h}{\tau_h}}\, p_{no}\right)$.

$n_{po} = N_D \exp\left(\frac{-q V_{bi}}{kT}\right)$ and $p_{no} = N_A \exp\left(\frac{-q V_{bi}}{kT}\right)$

$\therefore$ An increase in temp gives rise to higher n_{po} and p_{no}. The I_s dependency, however, is not quite exponential with Temp. because D_e (and D_h) and τ_e reduces as temp increases.

Generally $I_s = CT^{\gamma} \exp\left(\frac{-E_g}{kT}\right)$

For temp rise of 30K, V_{oc} drops by 60mV.

$\therefore V_{oc}' = 0.55 - 0.06 = 0.49\,V.$, $\frac{dI_s}{dT} \simeq 0$

$\therefore$ Substituting into working in (a)

$$I_s' = \frac{2}{\left(\exp\left(\frac{0.49}{1.2 \times 0.026 \times \frac{11}{10}}\right) - 1\right)} = \underline{\underline{1.03\,\mu A}}$$

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4. (a) Consider two cells connected in series. In the extreme case, a short circuit can be applied across the terminals. Then,

$$V = V_{cell1} + V_{cell2} = 0.$$

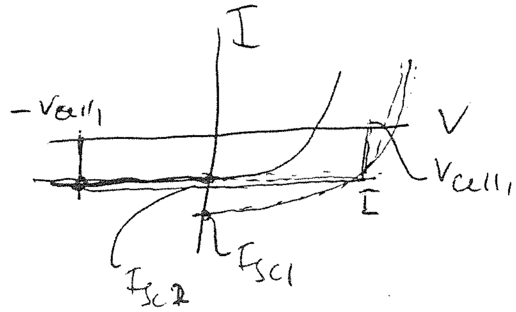
$$\therefore V_{cell1} = -V_{cell2}$$

The current through both cells the same.

$$\therefore I = I_s\left[\exp\left(\frac{qV_{cell1}}{kT}\right) - 1\right] - I_{sc1} = I_s\left[\exp\left(\frac{-qV_{cell1}}{kT}\right) - 1\right] - I_{sc2}$$

$\therefore$ One of the cells has the equivalent voltage of the other cell applied as a <u>reverse</u> bias.

$\therefore$ Therefore in the diode characteristic it operates in 3rd quadrant



$-I \times -V_{cell1} = IV_{cell1}$ (power dissipated)

For the other cell

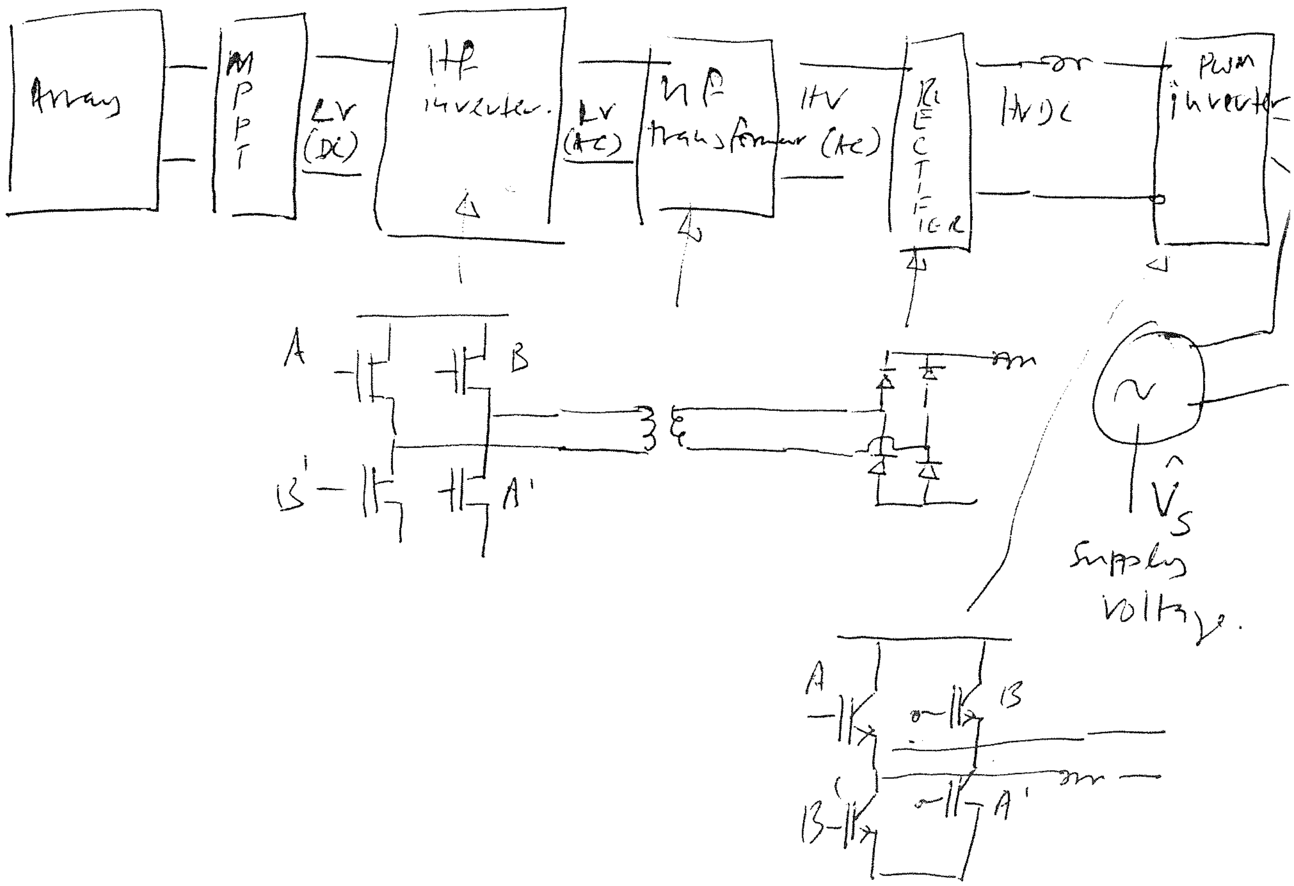
$-I \times V_{cell2} = -IV_{cell1}$ (power generation)

$\therefore$ Therefore some intermediate point where, if the ~~state~~ series current through

~~As~~ a string of series connected cells, exceeds the I_{sc} of one of the cells, then that cell will have power dissipated within it.

(b) Control strategy to ensure that
- the array as a whole operates at its Maximum Power Point – MPP tracking.
- Explain "dithering" method for MPPT.
- No, a separate control units for each face of the building is required at minimum. This is because the sun will not fall equally on all faces of the building throughout the day. So the MPP will be different for each array (I_{sc} – varies on each face).

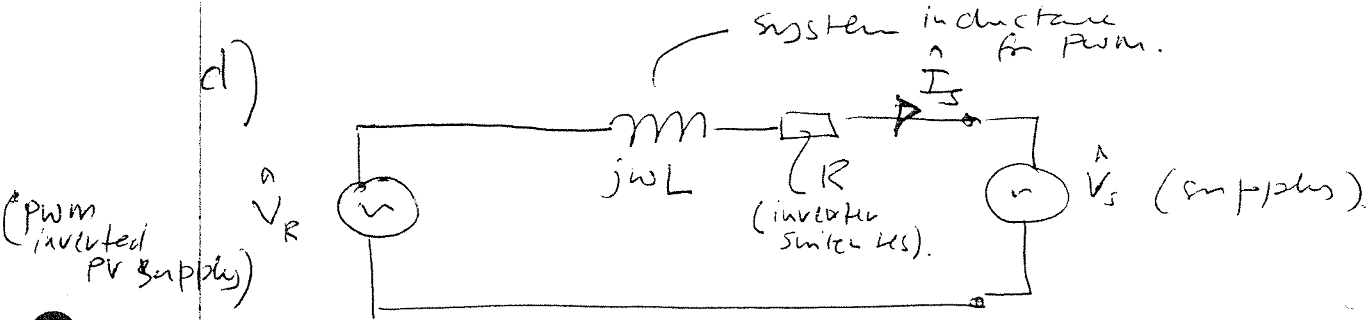
(c)

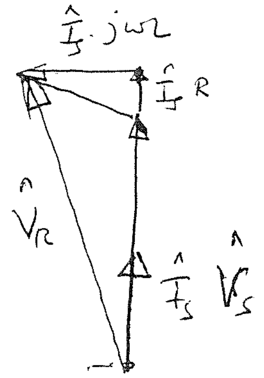


1st HF stage of DC power ~~stage~~ switching important to get step up in voltage using a <u>small</u> transformer. Due to the problems of series connecting solar cells, large strings of series connected cells to achieve HV not feasible.

The second HF inversion stage v. important to generate a sinusoidal wave form with low harmonic pollution. This is required because the grid is sinusoidal AC. Typically the PWM method is used. This requires switching at f_c/f, where f_c is the current switching frequency and f is the frequency of the sinusoidal wave form. $f_c/f \simeq 15$.

d)





- This is the same phasor diagram as for an <u>overexcited</u> synchronous generator. ($|\hat{V}_R| > |\hat{V}_s|$)

- We also assume that p.f. = 1. i.e. $\hat{V}_s$ and $\hat{I}_s$ always kept in phase.

The inherent assumptions are:

(i) That inverter ω can always be identical to supply ω

(ii) $|\hat{V}_R| > |\hat{V}_s|$, (iii) Sophisticated enough control to ensure p.f. = 1, even when $|\hat{I}_s|$ changes rapidly due to changes in sunlight.