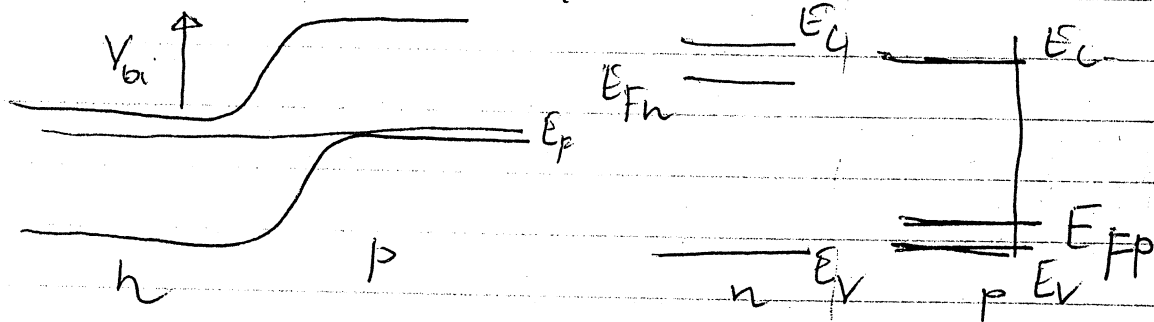


2005

CRIB FOR MODULE 4B14

SEMI-CONDUCTOR PHYSICS
GENERATION & DISTRIBUTION

Q1
a)



Fermi level in n-side.

From

$$n = N_c \exp\left(\frac{E_{Fn} - E_C}{kT}\right) \quad \text{--- (1)}$$

$$E_{Fn} = E_C + kT \ln\left(\frac{n}{N_c}\right)$$

$$p = N_v \exp\left(\frac{E_V - E_{Fp}}{kT}\right) \quad \text{--- (2)}$$

$$E_{Fp} = E_V - kT \ln\left(\frac{p}{N_v}\right)$$

Substit in potential

$$E_{Fn} - E_{Fp} = E_C - E_V + kT \ln\left(\frac{np}{N_c N_v}\right)$$

In volts

$$\underbrace{E_{Fn} - E_{Fp}}_{\downarrow} = \underbrace{E_C - E_V}_{\downarrow} + \underbrace{kT \ln\left(\frac{np}{N_c N_v}\right)}_{\downarrow} \quad \text{--- (3)}$$

Need to calculate N_c (or N_v) to solve (3)

Consider either n or p material for hom junction in equilibrium.

For p:

$$p n_p = n_i^2$$

where n_p is minority carrier conc. (electrons) in p material.

①

$$\therefore n_i^2 = N_V \exp\left(\frac{E_V - E_{FP}}{kT}\right) \cdot N_C \exp\left(\frac{E_{FP} - E_C}{kT}\right)$$

$$\therefore n_i^2 = N_C N_V \exp\left(\frac{E_V - E_C}{kT}\right)$$

$$N_C = N_V$$

$$n_i = N_C \exp\left(\frac{E_V - E_C}{2kT}\right) = N_C \exp\left(\frac{-1.12q}{2kT}\right)$$

$$N_C = \frac{1.6 \times 10^{16}}{\exp\left(\frac{-1.12q}{2kT}\right)} = \frac{1.6 \times 10^{16}}{\exp\left(\frac{-0.56}{0.026}\right)}$$

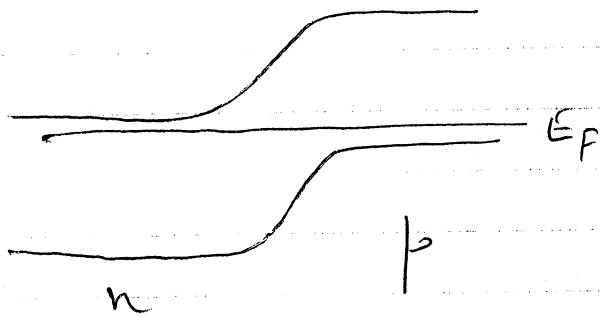
at 300K $\frac{kT}{q} = 0.026$

$$N_C = 3.62 \times 10^{25} \text{ m}^{-3} \quad \text{--- (4)}$$

Substituting (4) into (3) and taking $N_C = N_V$

$$\begin{aligned} \frac{E_{FN} - E_{FP}}{q} &= 1.12 + 0.026 \ln\left(\frac{5 \times 10^{47}}{3.62^2 \times 10^{58}}\right) \\ &= 1.12 + 0.026 \times -7.87 \\ &= \underline{\underline{0.92 \text{ V}}} \end{aligned}$$

Alternative method for built in potential



Under equilibrium $J=0$ $J_n=0$ $J_p=0$

\therefore If we consider electron current

$$J_n = q n \mu_n E + q D_n \frac{dn}{dx} = 0 \quad \text{--- (1)}$$

$$\therefore E = - \frac{D_n}{\mu_n} \cdot \frac{1}{n} \frac{dn}{dx}$$

where E is the electric field across junction
 n = electron concentration

Noting that

$$E = - \frac{dV}{dx}$$

then

$$- \int_{-\infty}^{+\infty} E dx = V = V_{bi}$$

Since there is no applied voltage, E must be due to the gradient of the built in potential.

$$\therefore \frac{D_e}{\mu_e} \int_{-\infty}^{\infty} \frac{1}{n} dn = V_{bi}$$

$$\frac{D_e}{\mu_e} \ln[n] \Big|_{-\infty}^{\infty} = V_{bi}$$

taking $-\infty$ to be edge of n region
and $+\infty$ to be edge of p region

$$V_{bi} = \frac{D_e}{\mu_e} \left[\ln \left[\frac{n_i^2}{N_A} \right] - \ln [N_D] \right]$$

$$= \frac{D_e}{\mu_e} \ln \left[\frac{n_i^2}{N_D N_A} \right] = \frac{kT}{q} \ln \left[\frac{n_i^2}{N_D N_A} \right]$$

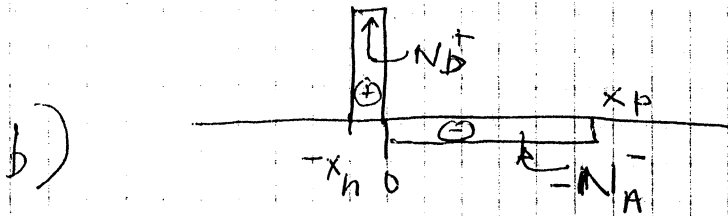
$$= 0.026 \ln \left[\frac{1.6^2 \times 10^{32}}{5 \times 10^{17}} \right] = -0.92V$$

Note neg sign as this the barrier for electrons seen from n side to p.

For holes barrier is 0.92V.

\therefore Generally ok to quote $|V_{bi}| = \underline{\underline{0.92}}$

$$\text{or } V_{bi} = \frac{kT}{q} \ln \left[\frac{N_D N_A}{n_i^2} \right]$$



charge balance across depletion region

$$\therefore N_D x_n = N_A x_p \quad \text{--- (1)}$$

From Poisson's eqn $\frac{dE}{dx} = \frac{q}{\epsilon} (N_D^+ - N_A^- + p - n)$

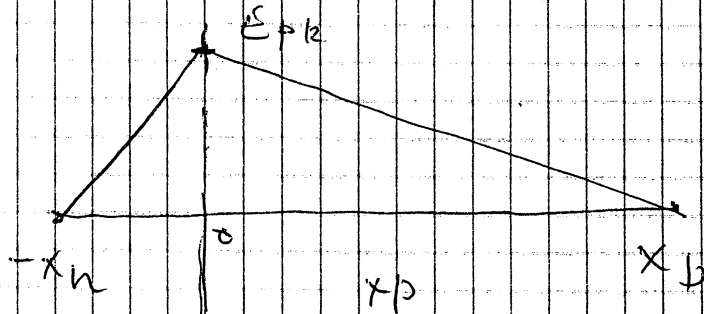
and applying depletion approximation

(no net charge outside depletion region and that $-x_n \leq x \leq 0$ has only N_D^+ and $0 < x \leq x_p$ only has N_A^-)

$$\epsilon \int_{-x_n}^{x_p} \frac{dE}{dx} dx = \int_{-x_n}^0 N_D^+ dx = \int_0^{x_p} N_A^- dx$$

$$\frac{\epsilon E}{q} = \left[N_D x \right]_{-x_n}^0 - \left[N_A x \right]_0^{x_p}$$

This is a linear variation of E of the form



Also noting $|V_{bi}| = \int_{-x_n}^{x_p} E dx = E_{pk} [x_n + x_p]$ (5)

$$E_{pk} = q \cdot \frac{N_D x_n}{\epsilon}$$

$$V_{bi} = \frac{N_D x_n [x_n + x_p]}{2\epsilon} \quad (\text{area of triangle})$$

but from ① $N_D x_n = N_A x_p$ and $x_n = \frac{N_A x_p}{N_D}$

$$\therefore V_{bi} = \frac{q N_A x_p}{2\epsilon} \left[\frac{N_A x_p}{N_D} + x_p \right]$$

$$\therefore x_p = \left[\frac{\epsilon 2 N_D V_{bi}}{q N_A [N_A + N_D]} \right]^{1/2}$$

$$= \left[\frac{2 \times 0.92 \times 10^{25}}{5 \times 10^{22} [5 \times 10^{22} + 10^{25}]} \cdot \frac{\epsilon}{q} \right]^{1/2}$$

$$\approx \left[\frac{2 \times 0.92}{5 \times 10^{22}} \cdot \frac{8.85 \times 10^{-12}}{1.602 \times 10^{-19}} \right]^{1/2} = \underline{\underline{44 \text{ nm}}}$$

⑥

(c)

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

3

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

$$V = \frac{kT}{q} \ln\left(\frac{10^{21}}{10^{23}}\right) + V_{bi}$$

$$= 0.8 \text{ V}$$

d)

$$I_{sc} = \frac{q}{q_{ph}} q A (L_e + L_h)$$

$$A = \frac{q_{ph}}{q} \times 1.6 \times 10^{-19} \times 10^{-2} (80 + 0.5) \times 10^{-6}$$

$$q_{ph} = \frac{4 \times 10^{-27}}{1.6 \times 85} = \underline{\underline{3.0 \times 10^{-25} \text{ m}^{-3}}}$$

e)

The built in potential gives the condition for no net current flow under dark conditions. When exposed to light

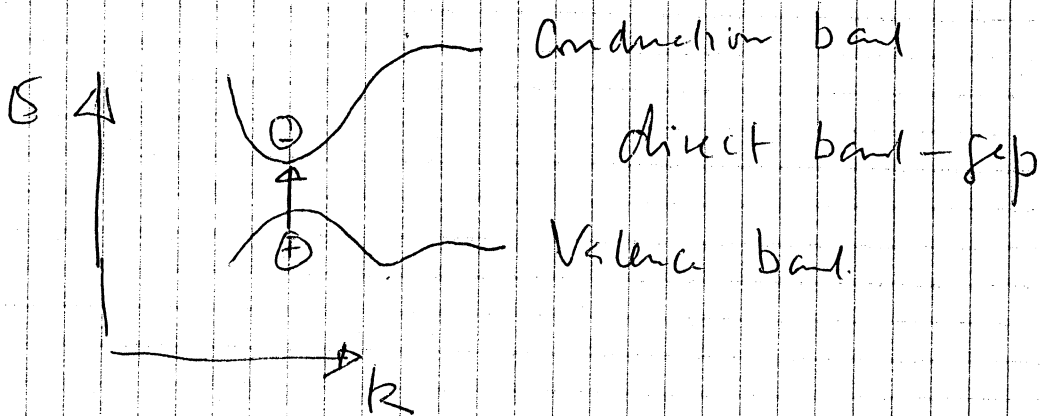
(7)

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The Fermi level of the semiconductors are no longer at their equilibrium values. Consider the p-side, where most of the light is absorbed. There will be a constant generation of ~~minority carriers~~ electron hole pairs. This will mean that the minority carrier electron concentration in the p-region will be very much higher than that under equilibrium conditions. One way of looking at it as if the intrinsic carrier concentration (n_i) in the p-semiconductor has increased by many orders of magnitude. An implication of this is that one needs to consider a separate Fermi level for holes and electrons in the p-semiconductor (denoted the quasi-Fermi levels), under non-equilibrium conditions when exposed to light. It is then the condition of no net current flow ($J_n = 0$ $J_p = 0$ $J = 0$) under based on alignment of the quasi-Fermi levels which determines the open circuit voltage.

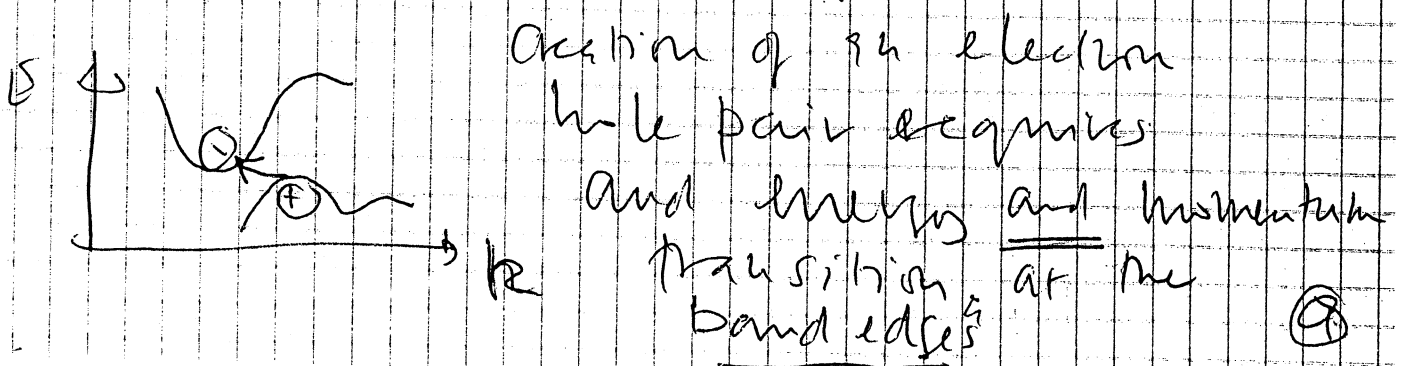
2

a) In a direct band semiconductor a photon can be converted to an electron hole pair with absorption of energy $\hbar\nu$ at the band edges.



This is important as it is the absorption at the band-edges which is most efficient as there is minimum conversion of energy into heat when the electron hole pairs are separated.

In an indirect band gap semiconductor



Photons do not have any momentum - only energy. Therefore for absorption of the photon to create an e-h pair, momentum transfer has to take place through an auxiliary mechanism - phonon generation/absorption, usually mediated by heat. The photon absorption process is therefore ~~more~~ less probable in an indirect band-gap semiconductor compared to a direct band-gap semiconductor. This requires the effective thickness of the absorption region to be much thicker in an indirect band-gap semiconductor. Si is an indirect band-gap material. GaAs is a direct band-gap material.

b) In amorphous - Si the momentum conservation requirement is ~~relaxed~~ ^{easier to} satisfied compared to Si as the momentum of an electron at a given energy level can have a wide spectrum of values. This is due to the absence of crystalline atomic structure in a-Si. It is however ordered (10)

in as much as all atoms have a characteristic bond-length and bond angle within a 'random' network.

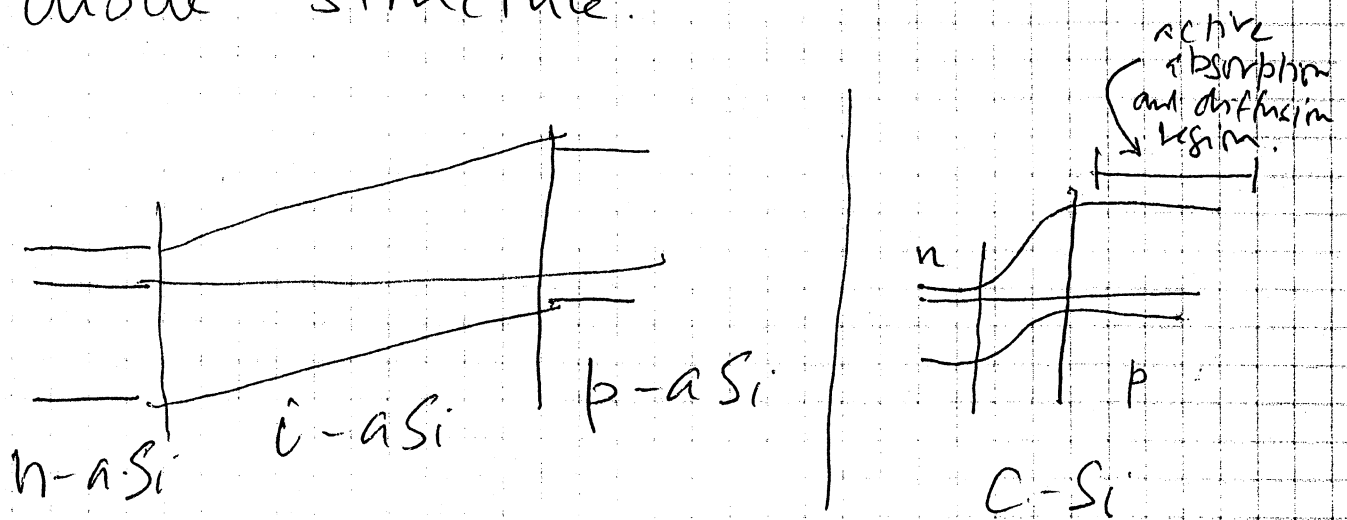
The relaxation of ~~the conservation~~ momentum selectivity means that a-Si appears like ~~a~~ a direct band-gap semiconductor for absorption of photons.

This means that a thin-layer of a-Si can absorb as much light as a much thicker layer of crystalline Si. Typically a $1\mu\text{m}$ thick layer of a-Si can absorb much light as a $200\mu\text{m}$ thick layer of crystalline Si.

In a-Si there is almost no diffusion current due to the life-time of minority carriers being extremely small compared to Si. This means that separation of photo-generated electron-hole pairs can only occur under the action of an electric field. Therefore in a a-Si solar cell it is only the carriers generated

in the ~~deplete~~ depletion region which can contribute to a photo current.

As stated in a) a thin layer ($\approx 1 \mu\text{m}$) of $n\text{-Si}$ can absorb light very effectively. Therefore the best structure is to create a built-in field across a thin layer of undoped (intrinsic) ~~absorbers~~ $i\text{-Si}$. This is the p-i-n diode structure.



In crystalline Si all photons absorbed within a diffusion length of the p-n junction are swept across and contribute to the photo current. Therefore the active absorption region is ~~around~~ ^{around} up to $100 \mu\text{m}$ away from the junction depletion region.

c)

The solar spectrum has a peak at 530 - 600 nm. In converting solar light to electricity it is therefore important to capture the peak of the spectrum and all wavelengths between ~~above~~ below it. This can be achieved with any semiconductor which has a band-gap below that of the solar spectrum. All wavelengths below the band-gap energy can then contribute to electron-hole generation and hence a photocurrent (I_{sc}).

But the energy, hence voltage, which can be preserved by absorbing a photon is limited ~~to the~~ by the band-gap of the semiconductor. It can never exceed the band gap. This therefore limits the V_{oc} available from smaller band gap semiconductor. For preserving

V_{oc} it is best to match the band-gap to the peak of the solar spectrum (550-600nm).
 But this would mean that the photo current available from the spectrum below the peak energy is not accessible.

These considerations limit the maximum theoretical conversion efficiency from a ~~single~~ single semiconductor ~~material~~ material to about $\approx 40\%$. The theoretical maximum achievable from Si is about $\approx 25\%$.

d) By ~~having~~ having a variable i) band-gap it is possible to absorb different part of the solar spectrum in a 'tuned' manner. That is absorb more of the spectrum while maintaining the optimum energy available (V_{oc}) from that part of the spectrum. Short wavelength light is absorbed first with a wide band gap material. long

wave length light passes through to be absorbed by narrow band-gap semiconductors. The voltages of the different absorption regions add up in series to provide the combined V_{oc} of the solar cell.

ii) The major disadvantage with series connection is that the photocurrent is limited by that of the cell generating the smallest current. In tandem cell the current will be limited by the cell absorbing the lower intensity long wavelength part of the spectrum. If not correctly balanced, this could lead to power dissipation within the cells which are absorbing the high intensity part of the spectrum.

3)

$$\begin{aligned}
 a) \quad V_{oc} &= \eta \frac{kT}{q} \ln \left[\frac{I_{sc}}{I_s} + 1 \right] \\
 &= 1.1 \times 0.026 \times \ln \left[\frac{2 \times 10^9}{58} + 1 \right] \\
 &= \underline{\underline{0.5V}}
 \end{aligned}$$

$$\begin{aligned}
 b) \quad \eta &= \frac{V_{oc} I_{sc} FF_0}{P_{in}} \\
 P_{in} &= 1 \times 10^{-3} \times 10^{-2} = 10W
 \end{aligned}$$

FF can be calculated from relationship given in the formulae sheet.

$$\frac{qV_{oc}}{kT} = \frac{0.5}{0.026} = 19.2$$

$$FF_0 = \frac{19.2 - \ln[19.2 + 0.72]}{19.2 + 1} = 0.8$$

$$\therefore \eta = \frac{0.5 \times 2 \times 0.8}{10} = 0.08$$

8% efficient

c) From formulae sheet:

$$i) \quad \theta = \frac{2\pi n_2 d}{\lambda}$$

necessary to make
 $\cos \theta = \pi/2$

(16)

$$\therefore \frac{n_2 d}{\lambda} = \frac{1}{4}$$

Choose λ to be matched to the peak of the solar spectrum at 600 nm - This is an assumption

$$\therefore d = \frac{600 \text{ nm}}{4 \times 2.2} = 68.18 \text{ nm} \approx \underline{\underline{70 \text{ nm}}}$$

ii) From formulae sheet,

$$\text{When } \theta = \pi/2$$

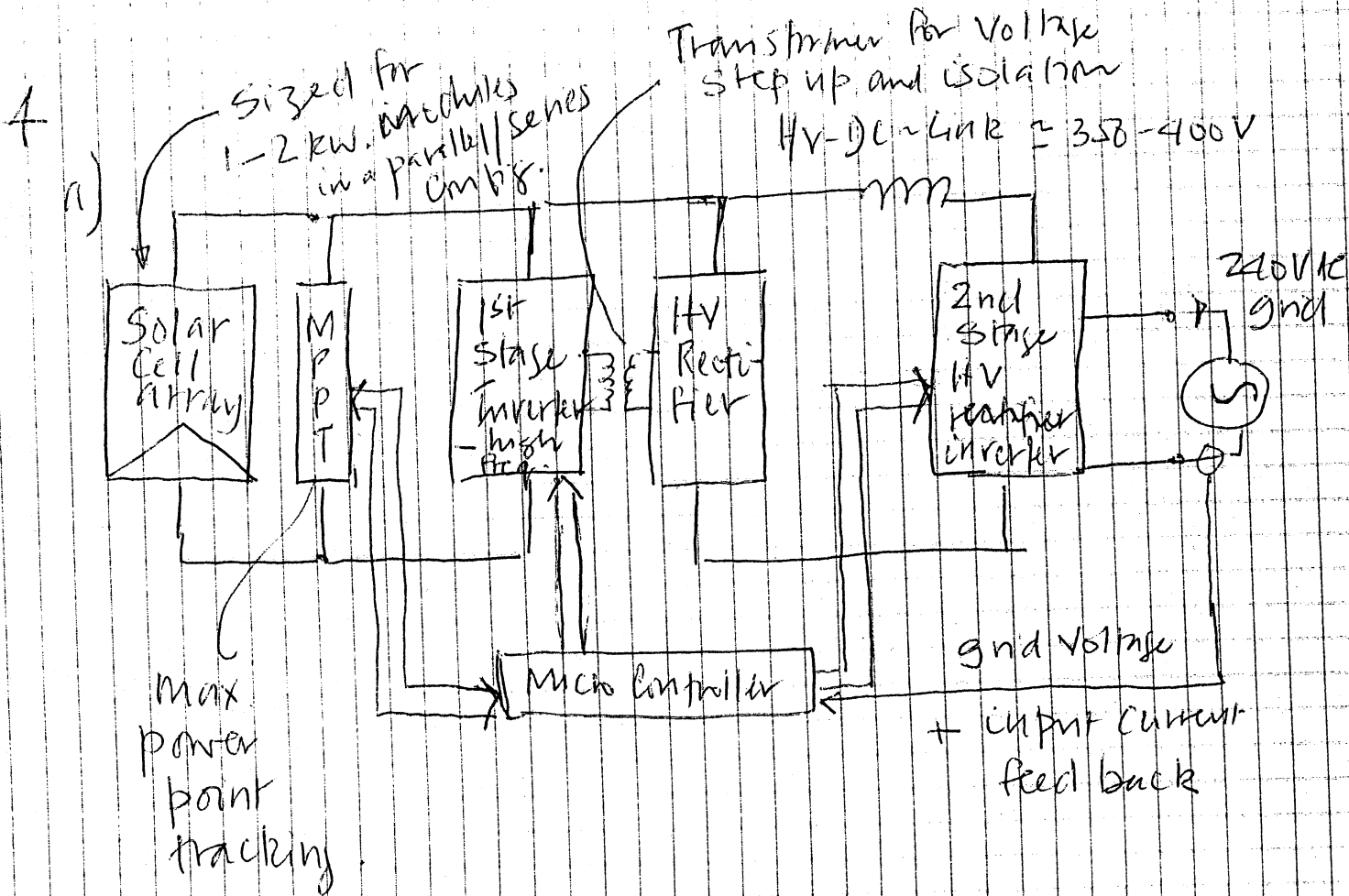
$$R(\lambda)_{\min} = \left(\frac{n_2^2 - n_1 n_3}{n_2^2 + n_1 n_3} \right)^2$$

$$R(600 \text{ nm}) = \left(\frac{2.2^2 - (11.9)^{1/2}}{2.2^2 + (11.9)^{1/2}} \right)^2 = 0.028 \approx \underline{\underline{0.03}}$$

iii) From lecture notes - bare Si reflects about 30% light over spectrum of interest. With AR coating ~~average~~ average between 0 and 20%. So 20% more light coupled. (7)

Amplified in. This means - approximately -
efficiency improved by 20% due
to a 20% increase in I_{sc} .

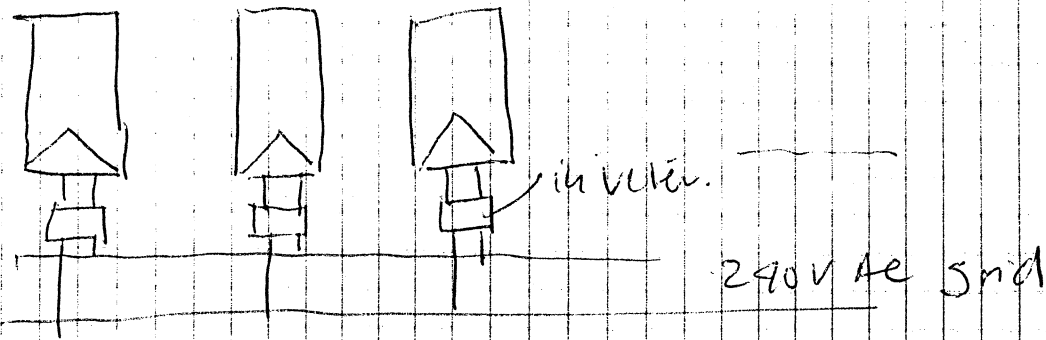
$$\begin{aligned} \therefore \text{Efficiency} & \approx 1.2 \times 0.08 = 0.096 \\ & \approx \underline{\underline{10\%}} \end{aligned}$$



b) In a solar generating system, the solar cells are guaranteed for 25 years (c-Si or 10 years for a-Si). However, the electronics in the inverter stage is at best guaranteed for 5 years (more typically 3 years). This means that in a \$10K solar installation, if the inverter stage fails, the whole system is incapacitated.

In calculating cost of ownership, the cost of inverter replacement must be factored in over the life time of the solar installation. The inverter costs are typically 10-15% of the overall installation cost. This means that it is quite likely that the true capitalized cost of a grid connected solar installation could double over its operating life time in order to maintain maximum amount of kWh generation.

One possible way to reduce risk of entire system failure is to split the solar module array between many inverter stages. At one extreme, it is possible that each 24V solar module has its own low power inverter stage, with all the ~~up~~ modules feeding the grid in parallel. This is the AC Module concept.



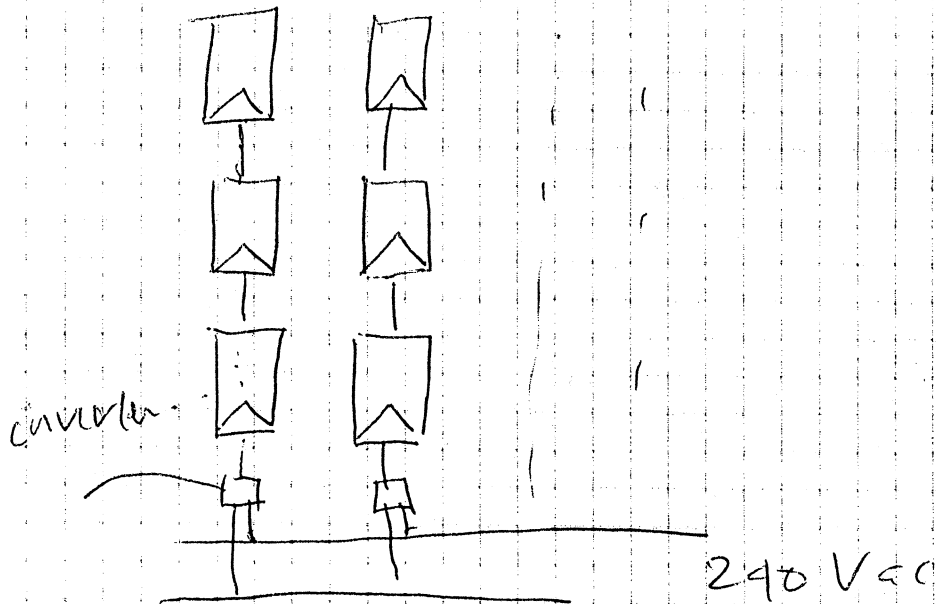
This has the advantage of increasing reliability in the electronics as each inverter is operating at lower powers. The overall system performance is also improved as the failure of one inverter does not incapacitate the whole system.

The disadvantage is that if a module inverter fails, then replacement cost may be higher as roof access ~~is~~ could be required.

One way of solving this is to have a central junction box with all the inverters located together. However, this has to be balanced against losses in the cables when transmitting low power at low voltage from each module. i.e.

Overall system efficiency ~~will~~ will be lower. The other disadvantage is that the costs associated with many small inverters is still larger than a single large inverter.

A compromise solution is the string inverter.



Here the modules are connected in series to have higher voltage, and then converted. Once several series (string) stages are connected in parallel to make up the entire system. Here there is improved performance of the entire system with larger power inverter stages. On the other hand the relative loss in output power with the loss of an inverter stage is larger than in an AC module installation. The major disadvantage with the string inverter is the series connection.

The current from a string is limited by the ~~max~~ lowest current available from a module in the string. This requires the modules in a string to be subject to the same ~~factor~~ insulation, limiting the ability to distribute modules over curved surfaces etc.

c) i) Points to be covered:

- Environmental concerns raising public awareness for need for non-CO₂ emitting power generation. This is reflected in Govt. expenditure.
- European govts. and EU ~~being~~ putting in place many incentives for capital costs and for preferential pricing on solar power (green) generation.
- Germany, Netherlands and Switzerland have already shown that incorporation of solar on a large scale in housing is possible.

- Solar technology mature to the point of being a mature building integrated system.
- In new housing the cost of the solar installation can be offset against the cost of the roof (in Capital and labour).
- With regulation to encourage new housing to have environmental sustainability, solar can become a standard feature on any new house in Europe. It is akin to all new housing being built with double glazing to improve energy efficiency in heating.

ii) Points to be covered.

- The economics of volume production, as in consumer electronic products, can apply to solar. Both for the cells and the inverters.
- The solar market has been growing at 30% annually since 1996. (24)

This has been driven by

- a) Environmental concerns in the US, Europe and Japan which have started to factor in the environmental cost of electric power generation. This means that the cost of solar is relatively much lower than before. In addition, the fuel costs are likely to rise over the next 10 years, again making fossil fuel generation significantly more expensive than at present.
- b) In developing countries, major financing initiatives from the World Bank to have rural electrification. Electricity a precursor to economic development as improved health and quality of life. Huge demand for current solar cell output due to these programmes.

Demand for solar has grown, but capacity for cell production has not increased at the same rate. This has meant that prices have stayed high. With time,

Market dynamics will ensure new capacity comes on stream to meet increasing demand. This will ~~not~~ result in a steady decline in cost of solar.

• Major considerations are therefore:

- Cost solar will decrease as in consumer electronics as demand increases. The latter is occurring due to reasons above.
- The pricing of other (non-renewable) technologies are being driven upwards by environmental pricing and increasing costs of fossil fuels due to limited supply.