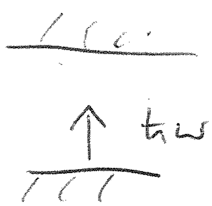
SS course fall 08

Conversion efficiency limits for solar cells:

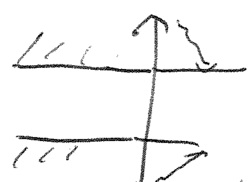
- Thermodynamic limit:

  Carnot efficiency $\eta_{carnot} = 1 - \frac{T_c}{T_s} \simeq 1 - \frac{300}{6000} = \underline{0.95}$

- Ultimate efficiency: for single p-n junction, single gap, $T=0$



$\hbar\omega < E_g$ lost



$\hbar\omega > E_g$

$\hbar\omega - E_g$ is lost

defin: $$Q(T) = \frac{2\pi}{c^2} \int_{E_g/h}^{\infty} \frac{\nu^2 d\nu}{e^{h\nu/kT} - 1}$$ ← Blackbody spectrum

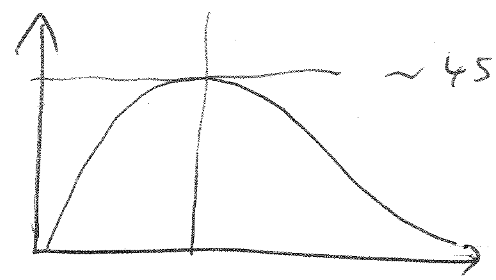
this is the # of photons with $h\nu > E_g$ / unit area / unit time for blackbody at T

$P_{out,ult.}$: output power $= E_g A\, Q(T_s)$

P_{in} = incident power $= A P_s$ $$P_s = \frac{2\pi h}{c^2} \int_0^{\infty} \frac{\nu^3 d\nu}{e^{h\nu/kT_s} - 1}$$

$$\eta_{ult} = \frac{P_{out,ult}}{P_{in}} = \frac{E_g\, Q(T_s)}{P_s} = \frac{x_g \int_{x_g}^{\infty} \frac{x^2\,dx}{e^x - 1}}{\int_0^{\infty} \frac{x^3\,dx}{e^x-1}}$$

with $x_g = \frac{E_g}{kT_s}$



ultimate efficiency can only be obtained if there is perfect absorption of blackbody radiation at $T = T_s$, and $T_c = 0$.

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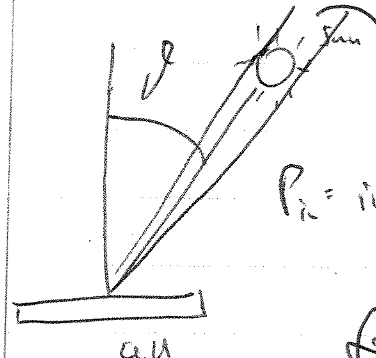
more realistic: finite T_C

need to consider carrier recombination

$\longrightarrow$ detailed balance limit



solid angle $d\Omega$

P_{in} = incident power $= A\, P_s\, d\Omega\, \frac{\cos\theta}{\pi}$

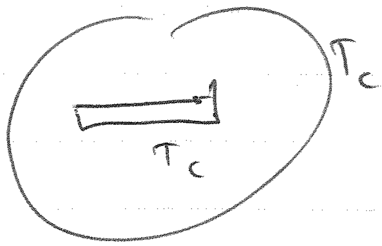
for $\theta = 0$ $\quad P_{in} = A P_s \frac{\Omega}{\pi}$ $\quad \frac{\Omega}{\pi} \approx 2.2 \times 10^{-5}$

# of photons absorbed = # of e-h pairs created.

$$F_s = A\, Q(T_s)\, \frac{\Omega}{\pi}$$

now consider solar cell at $T = T_c$

surrounded by temp. T_c:



(thermal equilibrium)

$$F_{c,0} = 2A\, Q(T_c)$$ = # of e-h pairs created

= # of radiation recombination events

$$\int_{\text{sphere}} \frac{d\Omega \cos\theta}{\pi} = 2$$ (both sides)

now calculate V_{oc} and I_{sh}

F_c = rec. rate = $F_c(V)$ ← voltage across cell

$F_c(0) = F_{co}$ (<u>detailed</u> <u>balance</u> <u>argument</u>)

$F_c(V) \propto np$ ← hole density

electron density

at $V = 0$ $np = n_i^2$ n_i = intrinsic carrier density

$$\Rightarrow F_c(V) = F_{co} \frac{np}{n_i^2}$$

$$\frac{np}{n_i^2} = e^{\frac{qV}{kT_c}}$$ (from Fermi function)

($E_g \gg kT_c$)

$$F_c(V) = F_{co}\, e^{\frac{qV}{kT_c}}$$

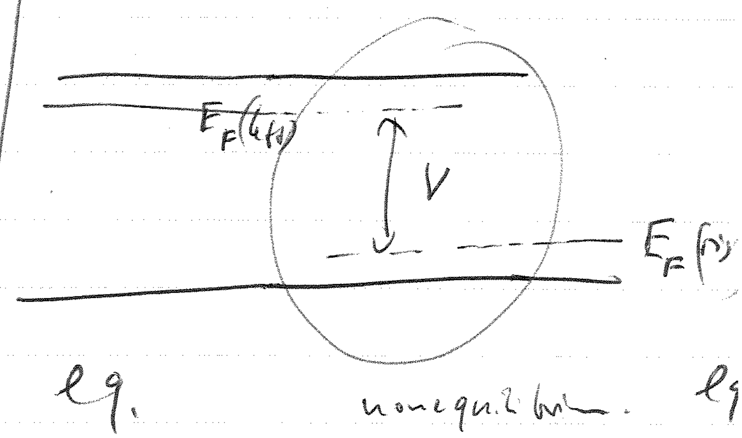


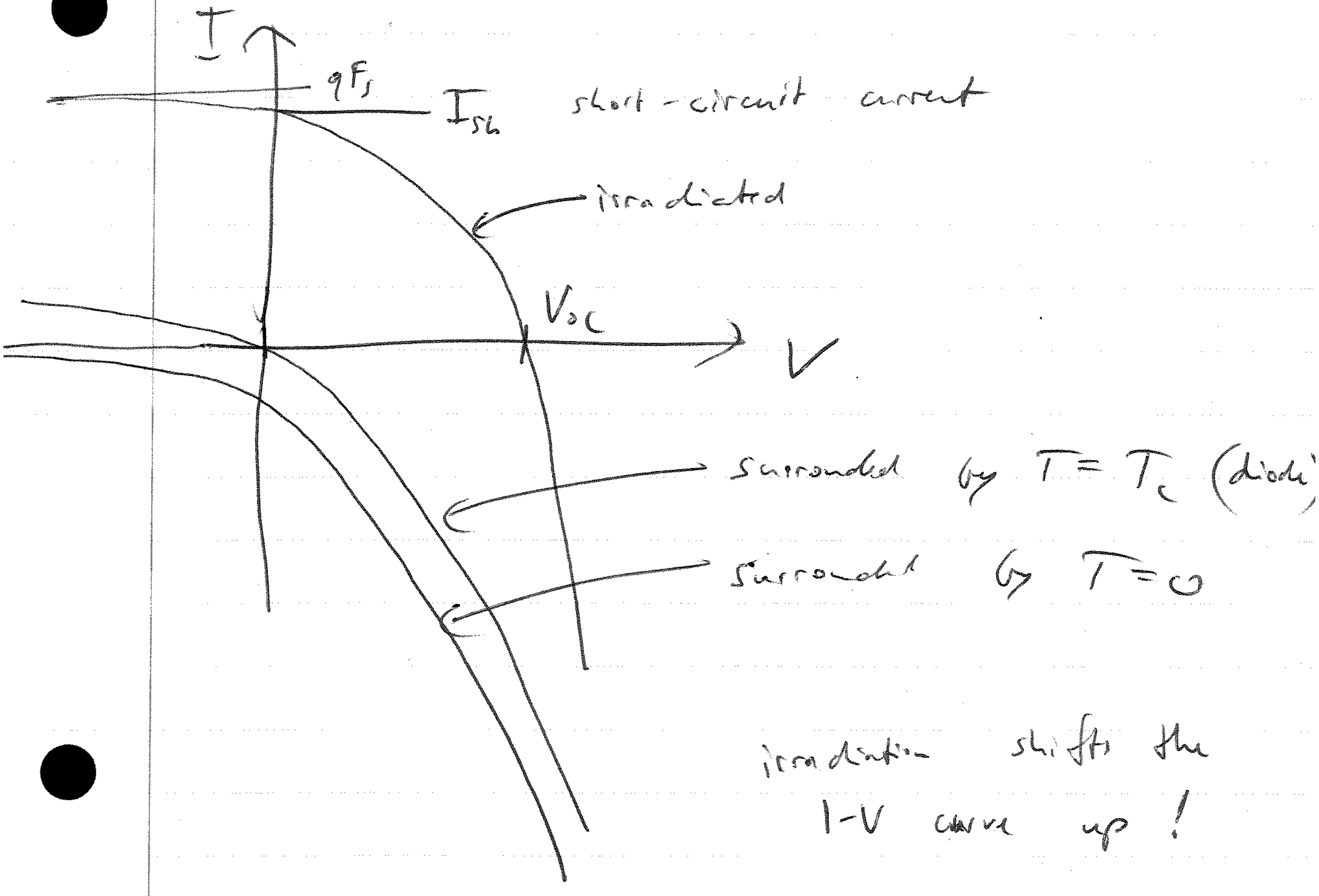
photo current: $I = q\left(F_s - F_c(V)\right)$

$$= q\left(F_s - F_{c0}\, e^{\frac{qV}{kT_c}}\right)$$

F_s: # of e-h pairs created

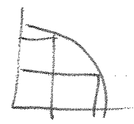
$F_{c0}\, e^{\frac{qV}{kT_c}}$: recombination rate

graph:



irradiation shifts the I-V curve up!

~~absorbed power~~ $= \cancel{A P_s \frac{\Omega}{\pi}} = \cancel{\frac{I_{sh}}{\eta_{ult}} \frac{E_g}{q}}$



$$\text{power} = IV = q\left(F_s - F_{c,0}\, e^{\frac{qV}{kT_c}}\right) V$$

max power: $\frac{d(IV)}{dV} = 0$

$$F_s - F_{c0}\, e^{\frac{qV_{max}}{kT_c}} - V_{max} F_{c0} \frac{q}{kT_c} e^{\frac{qV_{max}}{kT_c}} = 0$$

solve numerically for V_{max}

$P_{max} = I(V_{max}) V_{max}$ $\qquad \eta_{max} = \frac{P_{max}}{P_{abs}}$ $\qquad P_{abs} = A P_s$

$$\eta_{max} = \frac{I(V_{max}) V_{max}}{A P_s \frac{\Omega}{\pi}}$$

~~use~~

in terms of η_{ult}:

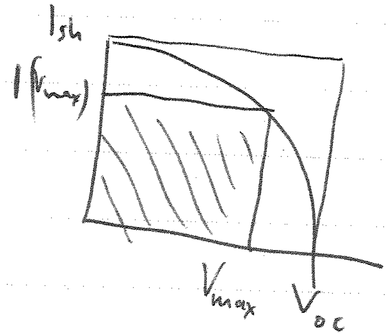
use $\eta_{ult} = \frac{P_{out,ult}}{P_{abs}} = \frac{I_{sh} E_g / q}{P_{abs}}$

$P_{abs} = \frac{I_{sh} E_s}{q\, \eta_{ult}}$ $\qquad I_{sh} = I(0) = q(F_s - F_{co})$

$\approx q F_s$

$\cancel{\eta_{max} = \frac{I(V_{max}) V_{max}\, q}{I_{sh} E_g} \eta_{ult}}$

$$\eta_{max} = \eta_{ult} \underbrace{\frac{qV_{oc}}{E_g}} \underbrace{\frac{V_{max}}{V_{oc}} \frac{I(V_{max})}{I_{sh}}}_{\text{"fill factor"}}$$



reduction of V_{oc} from E_g/q due to recombination

"detailed balance limit"

$$\lim_{T_c \to 0} \eta_{max} = \eta_{ult}$$ (Shockley & Queisser 1961)

[in actuality $\eta < \eta_{max}$ due to nonradiative recombination, contact resistance (dissipation), absorption and reflection losses, etc.]

What is $\cancel{X}$ V_{oc} ?

$$\cancel{I_{sc}} \quad I(V) = q\left(F_s - F_{co}\, e^{\frac{qV}{kT_s}}\right)$$

set $I = 0$

$$F_s = F_{co}\, e^{\frac{qV}{kT_s}}$$ solve for V

$$V_{oc} = \frac{kT_c}{q} \ln \frac{F_s}{F_{co}} = \frac{kT_c}{q} \ln\left(\frac{\Omega}{2\pi} \frac{Q(T_s)}{Q(T_c)}\right)$$