Centre de Thermique de Lyon CETHIL UMR 5008

Physics of the thermal behavior of photovoltaic cells

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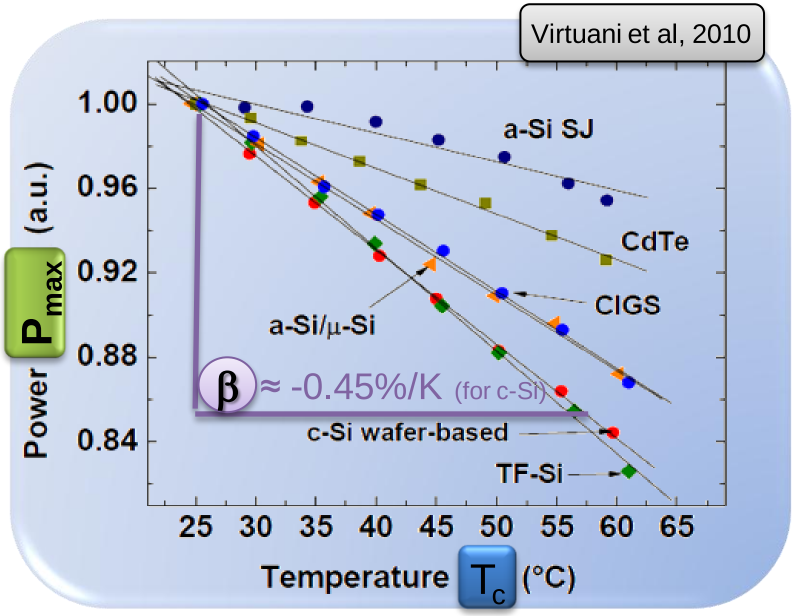
UNSW
June 2014, Sydney

Introduction



Virtuani et al, 2010

$$\eta_{PV} \propto T_c$$

?

Why are photovoltaic devices negatively affected by temperature? What are the parameters involved?

1

Fundamental losses in PV conversion

- Detailed balance principle (Shockley Queisser limit)
- Energy/Entropy balance (Thermodynamic limit)

2

Dependences of these losses on temperature

3

Additional losses in real PV cells

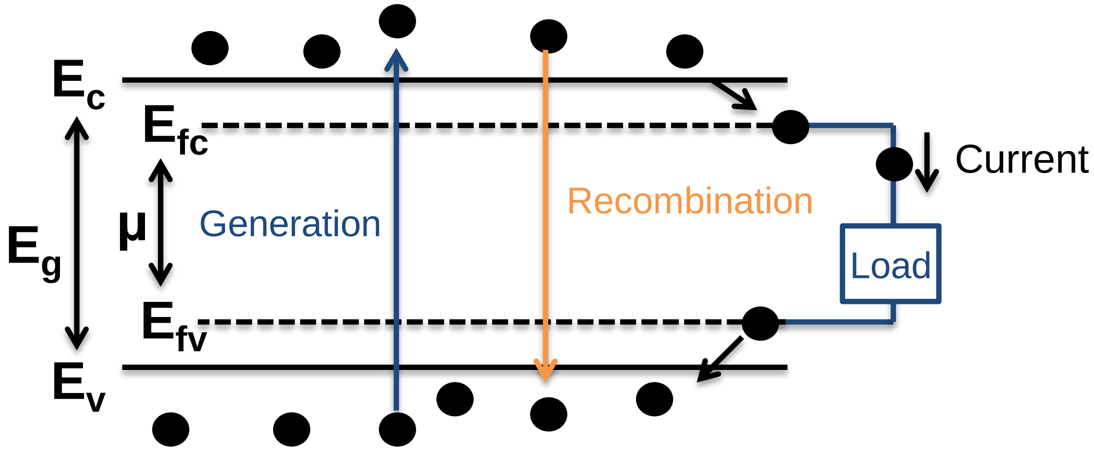
- External Radiative Efficiency
- Intrinsic temperature coefficient of silicon cells

4

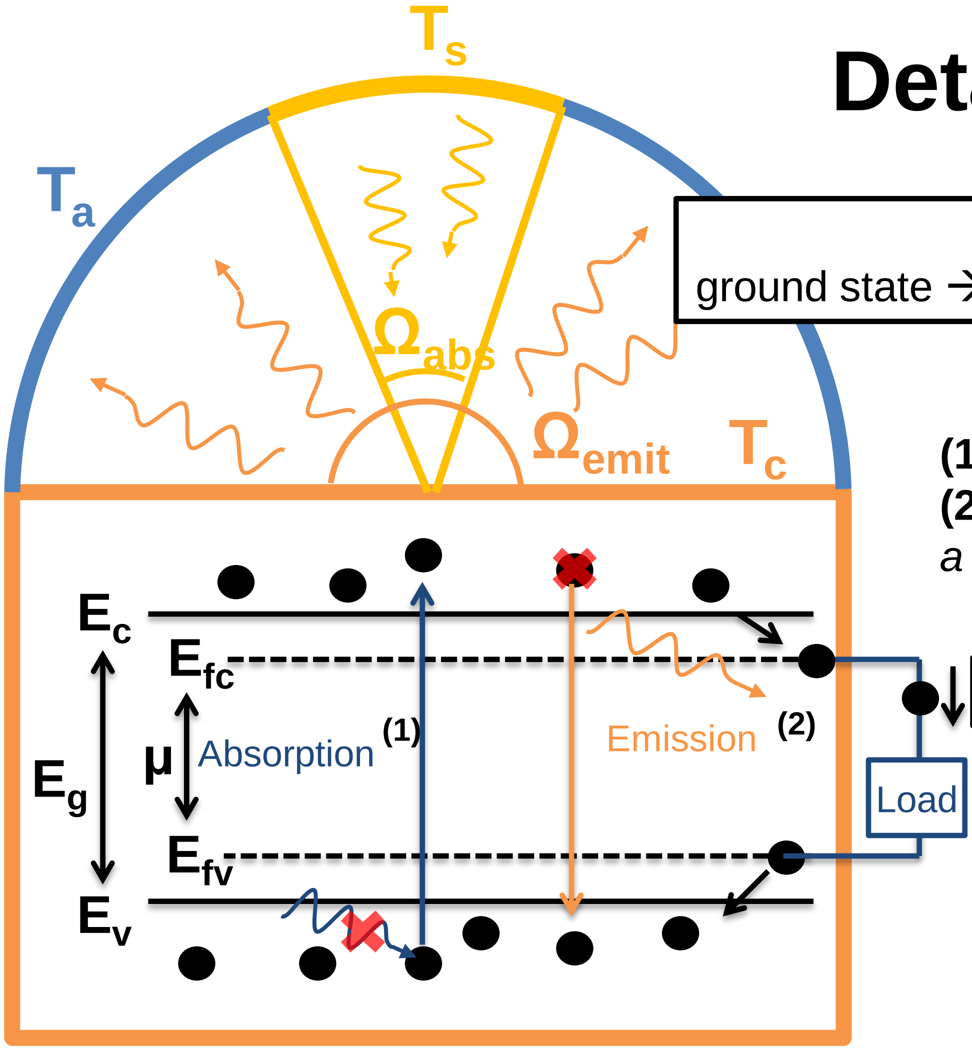
A thermal engineering view on PV performances

Detailed balance principle

Condition for an equilibrium:
ground state → excited state = excited state → ground state



Detailed balance principle



Condition for an equilibrium:
ground state → excited state = excited state → ground state

Shockley & Queisser assumptions:

(1) *1 photon excites only 1 electron*

(2) *All recombinations are radiative, i.e. generate a photon*

Current = q (Photons absorbed – Photons emitted)

Generalized Planck's equation → photon fluxes

$$\dot{N}(E_g,T,\mu,\Omega)=\frac{2\Omega}{c^2h^3}\int_{E_g}^{\infty}\frac{E^2}{e^{\frac{E-\mu}{kT}}-1}dE$$

(3)

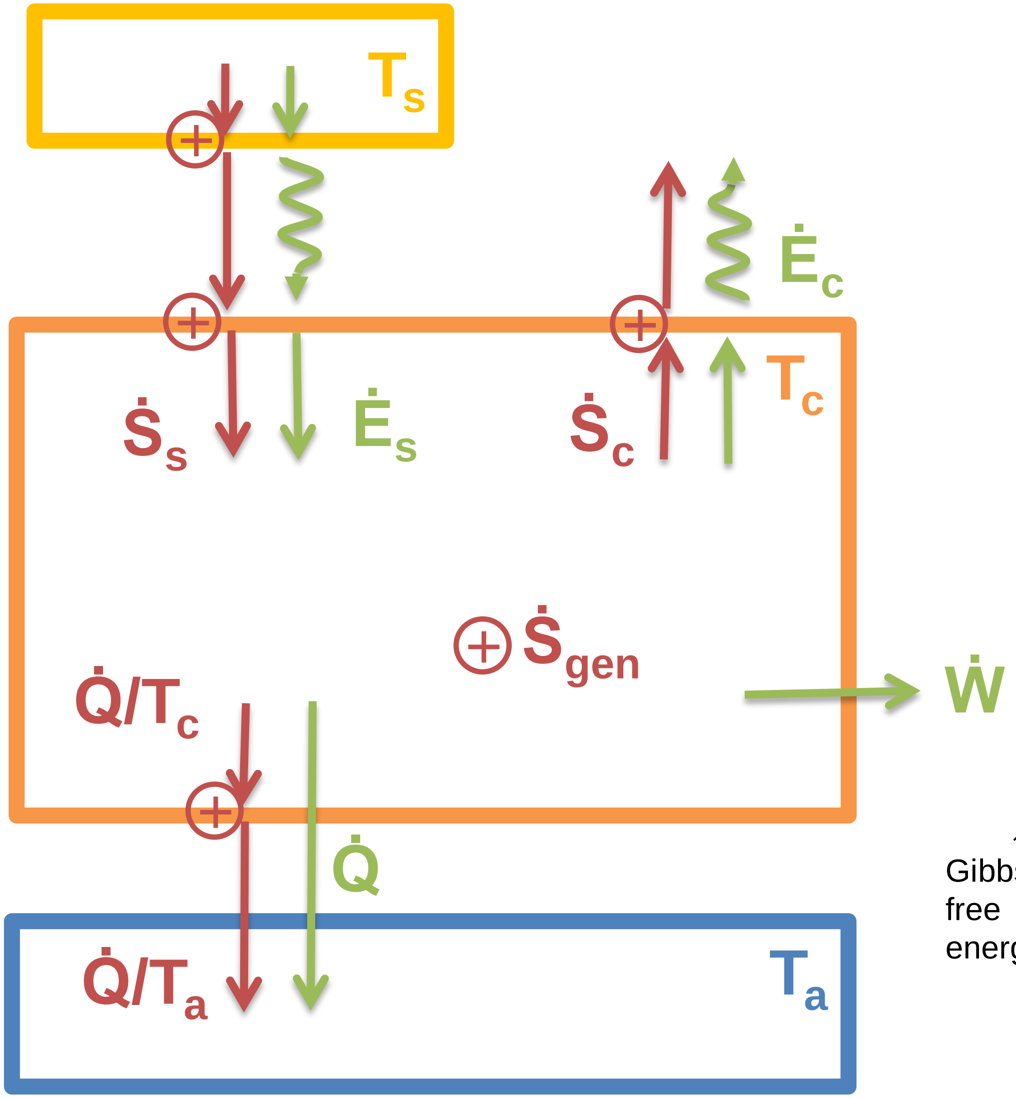
μ is the chemical potential of the radiation for the luminescent radiation from the cell: **(4)** $\boldsymbol{\mu = qV}$

(3) *Single gap: absorbs every photons with* $E \geq E_g$ *and none with* $E < E_g$

(4) *Assuming perfect charge transport*

$$\rightarrow \boxed{P_{elec}=q(\dot{N}_{abs}-\dot{N}_{emit})V}$$

Energy/Entropy balance



- Thermodynamics enables to evaluate the theoretical limits of energy conversion processes

- Different energy forms do not contain the same amount of **free energy (or exergy: energy that can be extracted to produce work)** because they contain different amount of entropy

We consider here the gas of excited electron-hole pairs :

$$F = \mu N = E - \boxed{T_c S} + pV$$

Gibbs free energy

Electrochemical energy

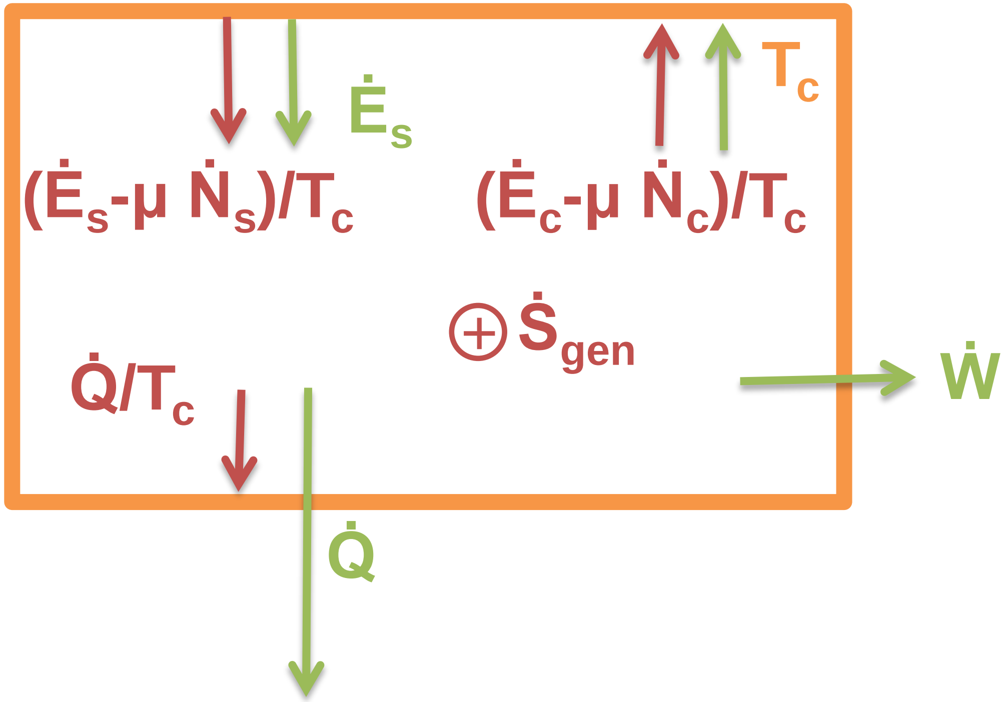
Number of e-h pairs

Internal energy

Entropy

“disordered energy” ultimately converted into heat

Energy/Entropy balance



Irreversible thermodynamics → entropy fluxes

$$\dot S = \frac{\dot E - \mu \dot N}{T}$$

$$\begin{cases} \dot W = \dot E_s - \dot E_c - \dot Q \\ \dfrac{\dot Q}{T_c} = \dfrac{\dot E_s - \mu \dot N_s}{T_c} - \dfrac{\dot E_c - \mu \dot N_c}{T_c} + \dot S_{gen} T_c \end{cases}$$

$$\dot W = \mu(\dot N_s - \dot N_c) - \dot S_{gen} T_c$$

(1) 1 photon creates excites only 1 electron
(2) All recombinations are radiative
(3) *Single gap: absorbs every photons with $E \geq E_g$ and none with $E < E_g$*
(4) Assuming perfect charge transport

$$\dot S_{gen} = 0 \quad \text{and} \quad \mu = qV$$

$$\rightarrow \boxed{\dot W = q(\dot N_s - \dot N_c)V}$$

Analytical solution

$$\boxed{P_{elec} = q(\dot{N}_{abs} - \dot{N}_{emit})V}$$

$$\begin{array}{cc} \swarrow & \searrow \\ f(E_g,T_s,\Omega_{abs}) & f(E_g,T_c,V,\Omega_{emit}) \end{array}$$

$$\left.\begin{array}{ll} \textbf{(1)} & \left(\dfrac{\partial P_{elec}}{\partial E_g}\right)_V = 0 \\[2ex] \textbf{(2)} & \left(\dfrac{\partial P_{elec}}{\partial V}\right)_{E_g} = 0 \end{array}\right\} P_{max}$$

Boltzmann approximation $\dot{N}(E_g,T,\mu,\Omega) \approx \dfrac{2\Omega}{c^2h^3}\displaystyle\int_{E_g}^{\infty} \dfrac{E^2}{e^{\frac{E-\mu}{kT}} - \cancel{1}}\,dE$ → analytical solution of **(1)**

$$qV_{opt} = E_g\boxed{(1-\frac{T_c}{T_s})} - \boxed{kT_c\ln(\frac{\Omega_{emit}}{\Omega_{abs}})}$$

: relates the optimal operating voltage and E_g **(*)**

Carnot efficiency **Angle mismatch loss**

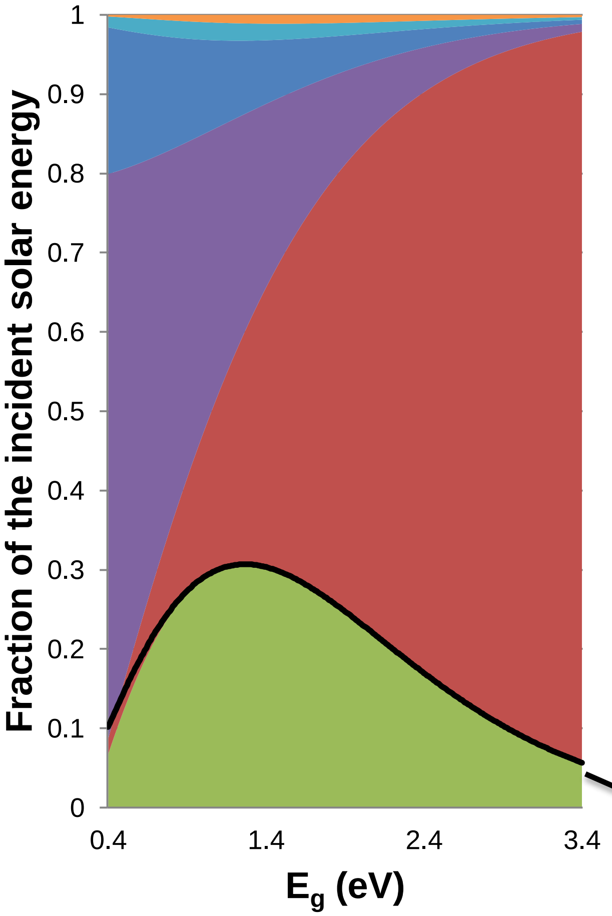
(*) only correct when E_g=E_g(max) but stays a good approximation for any E_g

$$P_{max} = J_{opt}V_{opt} = q(\dot{N}_{abs} - \dot{N}_{emit}(V_{opt}))(E_g - Carnot_{loss} - Angle\,mismatch_{loss})$$

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)

Losses = f(Eg)

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)



Similarly to an heat engine, the work that can be extracted is ultimately limited by the temperature difference between the sun and the cell

+

The radiation emitted by cell is lost

+

A standard PV cell emits in more directions than it absorbs light coming directly from the sun

+

A single gap absorber can not efficiently use the broad solar spectrum

Photons with insufficient energies

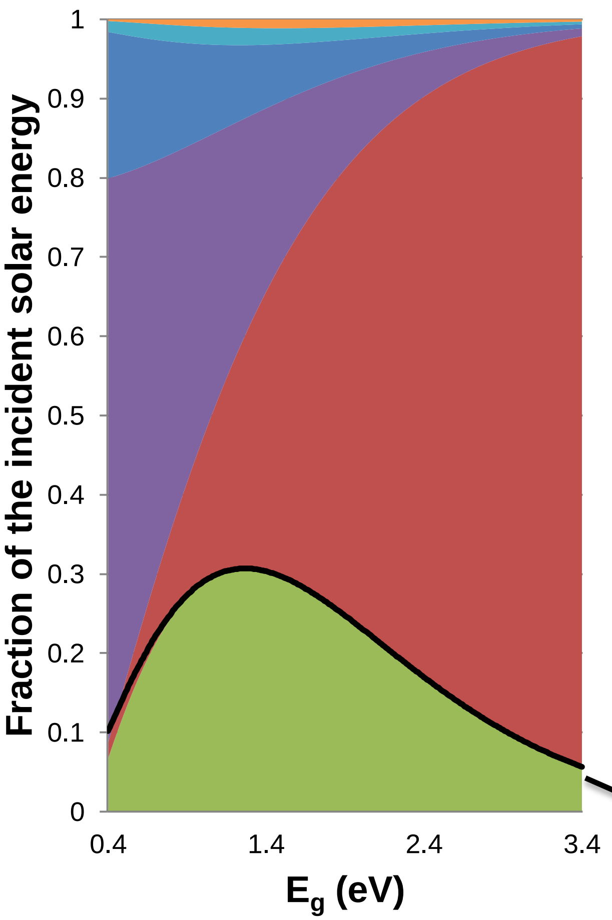
Photons too energetic

=

Shockley Queisser limit
(numerical)

3^{rd} gen PV > Shockley-Queisser limit

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)



Solar TPV,
Thermophotonics

Hot carriers,
Down conversion
/ Multiple Excitons Generation

Impurity PV,
Up conversion

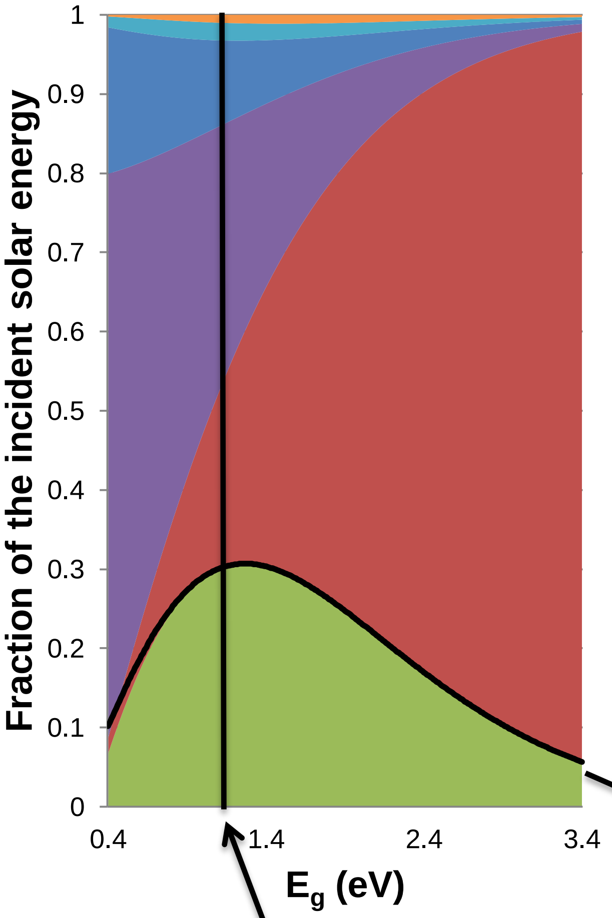
Multi-junctions,
Spectral splitting

Concentration,
Limited angle emission

Shockley Queisser limit

3rd gen PV > Shockley-Queisser limit

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)



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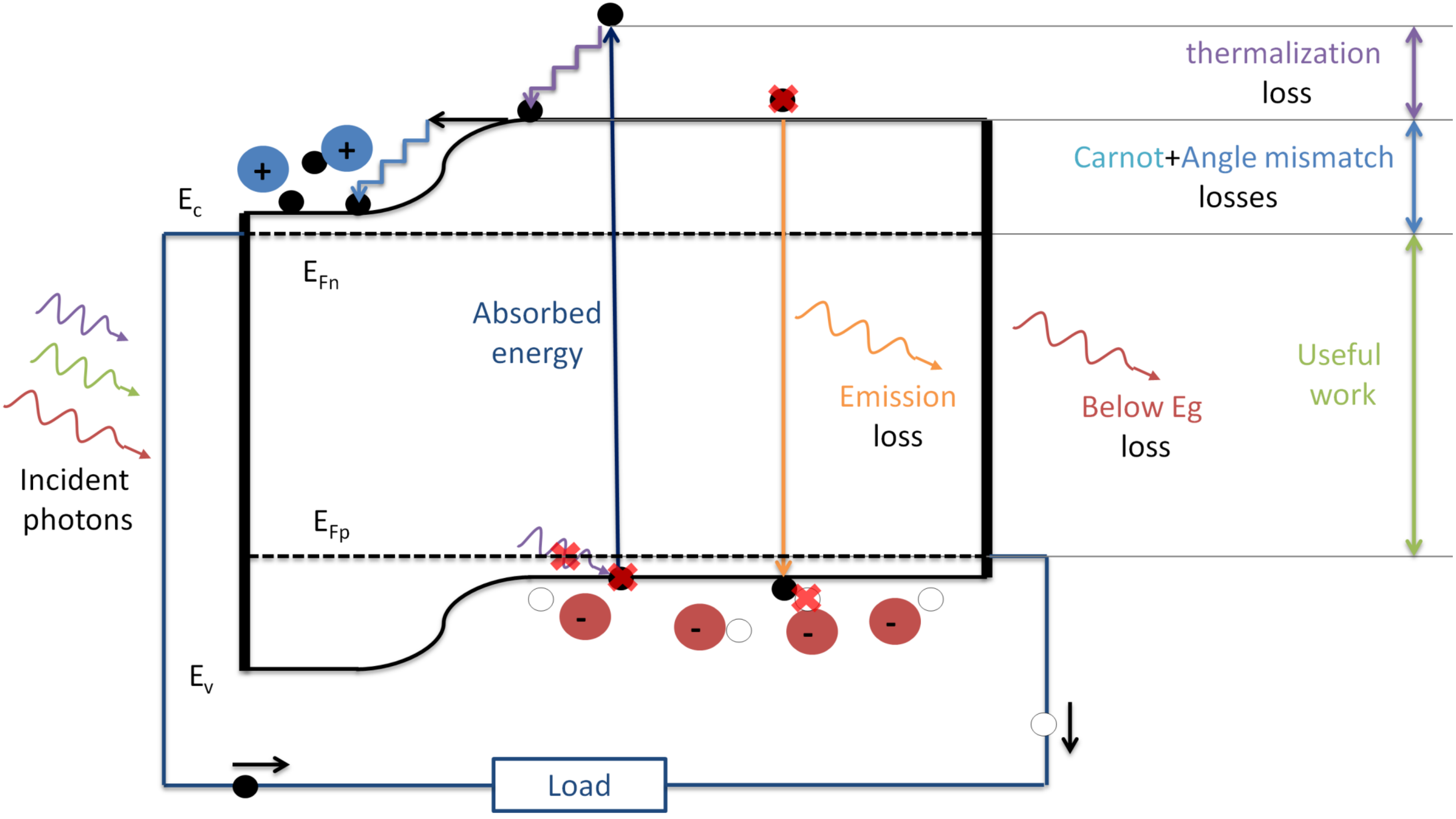
Shockley Queisser limit

E_g (Si at 300K) ≈ 1.12 eV

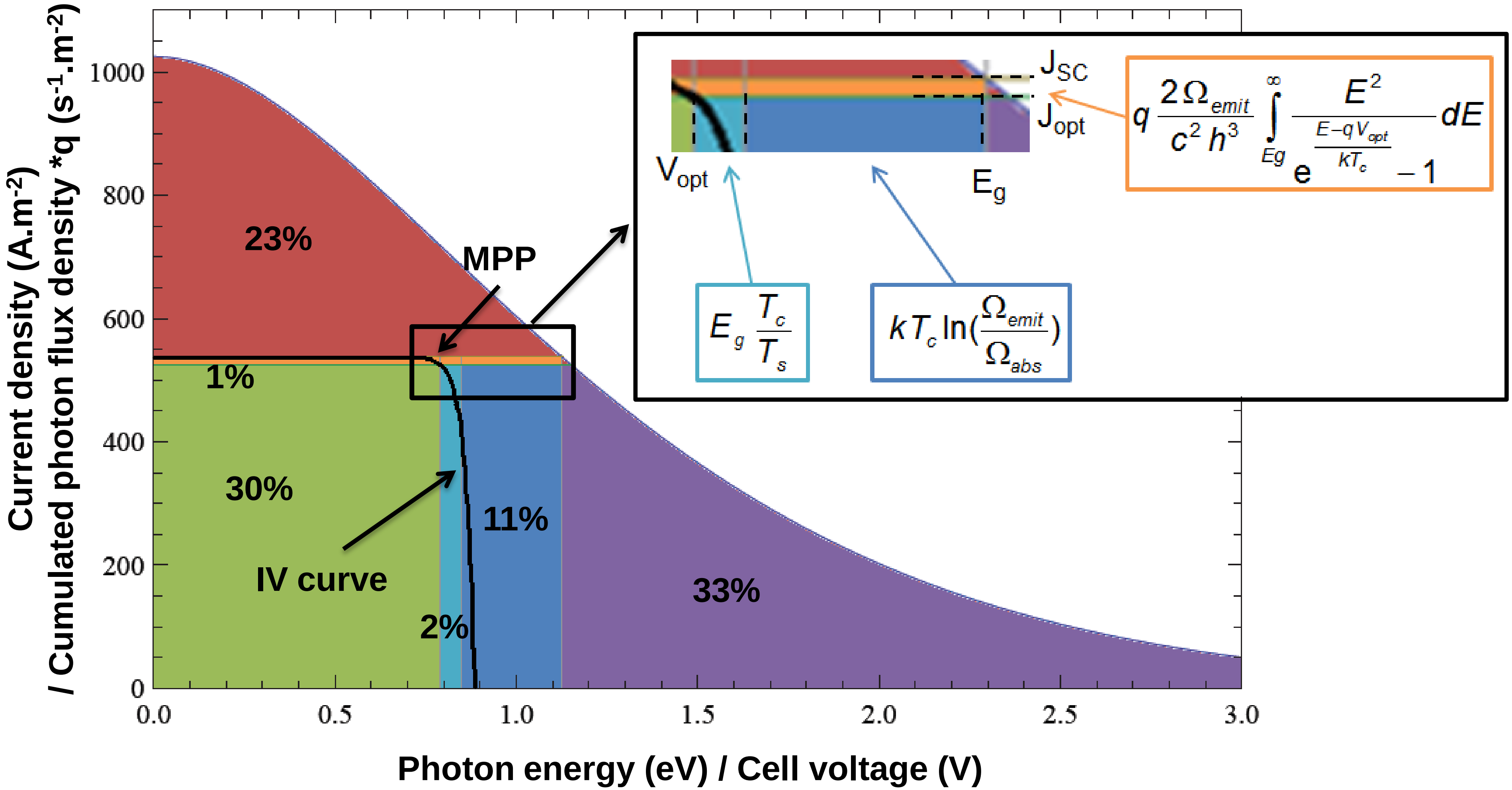
Band diagram of an ideal Si cell at MPP

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)



IV curve of an ideal Silicon cell

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)

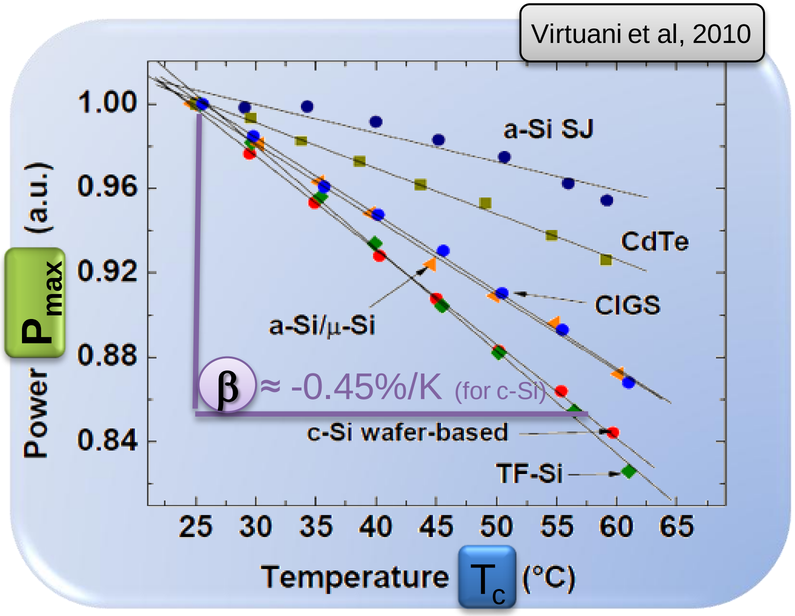


$$q\frac{2\Omega_{emit}}{c^2h^3}\int_{Eg}^{\infty}\frac{E^2}{e^{\frac{E-qV_{opt}}{kT_c}}-1}dE$$

$$E_g\frac{T_c}{T_s}$$

$$kT_c\ln(\frac{\Omega_{emit}}{\Omega_{abs}})$$

Overview


Virtuani et al, 2010

$\eta_{PV} \propto T_c$

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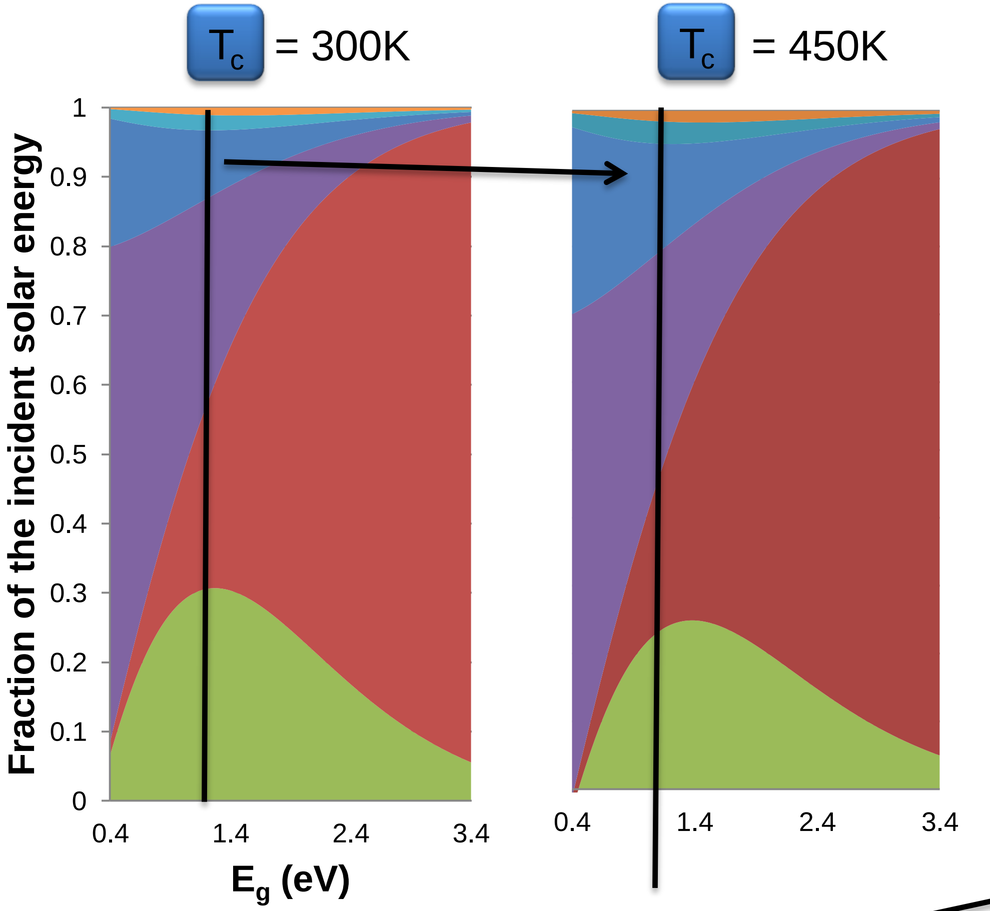
4 **A thermal engineering view on PV performances**

Some losses = f(T_c)

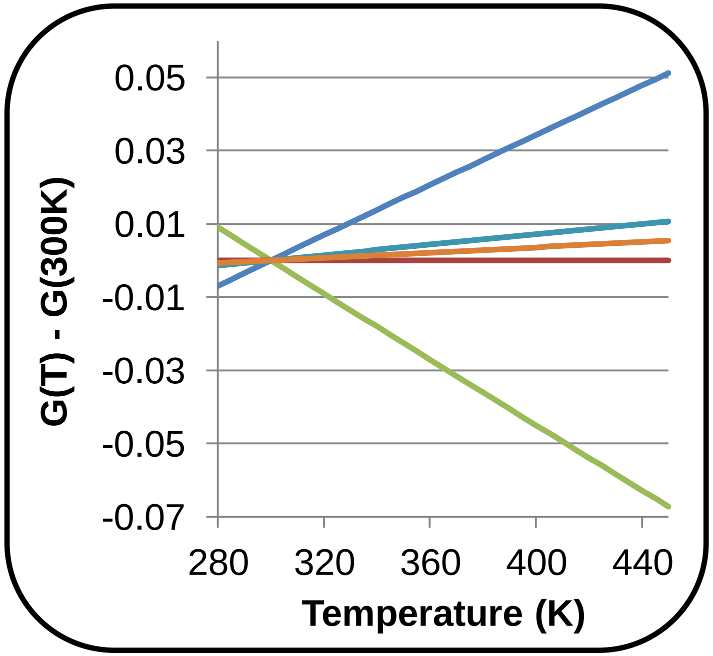
Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)

∝ T_c **∝ T_c** **∝ T_c**



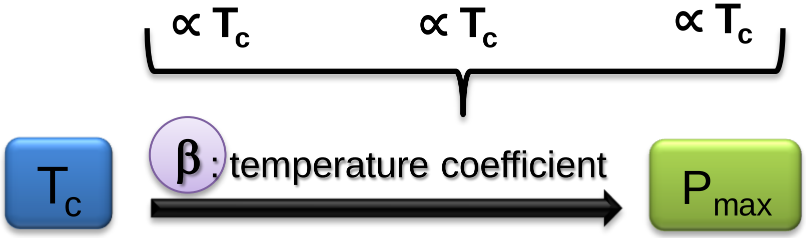
E_g(Si)=1.12 eV

- The **emission** rate increases with **T_c** so the **angle mismatch** loss increases as well.
- Also, $\Delta T = T_{sun} - T_{cell}$ decreases with **T_c** so the **Carnot** loss increases.



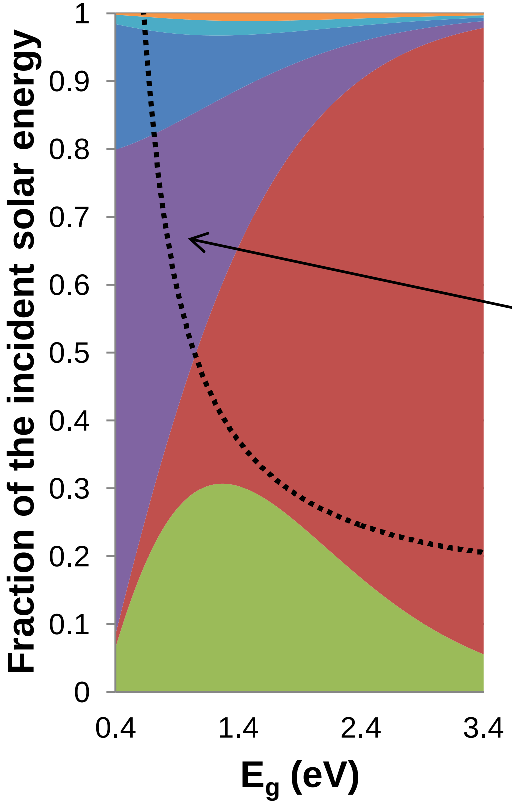
Temperature coefficient β

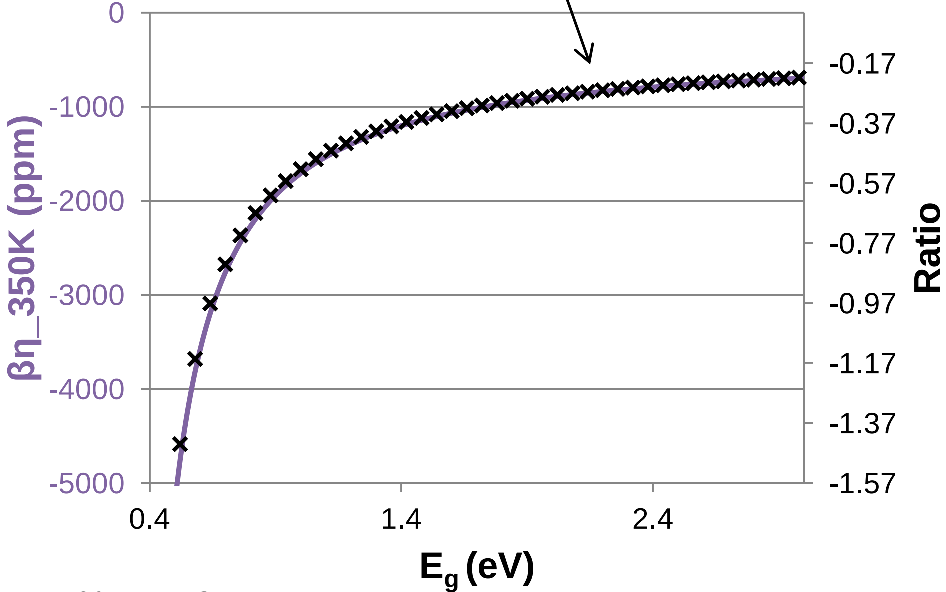
Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)



$$\beta(T)=\frac{1}{\eta(298.15\mathrm{K})}\frac{\eta(T)-\eta(298.15\mathrm{K})}{T-298.15}$$

$$\beta = f\left(\frac{\text{Carnot} + \text{Angle mismatch} + \text{Emission}}{\text{Output power}}\right) = f(E_g)$$





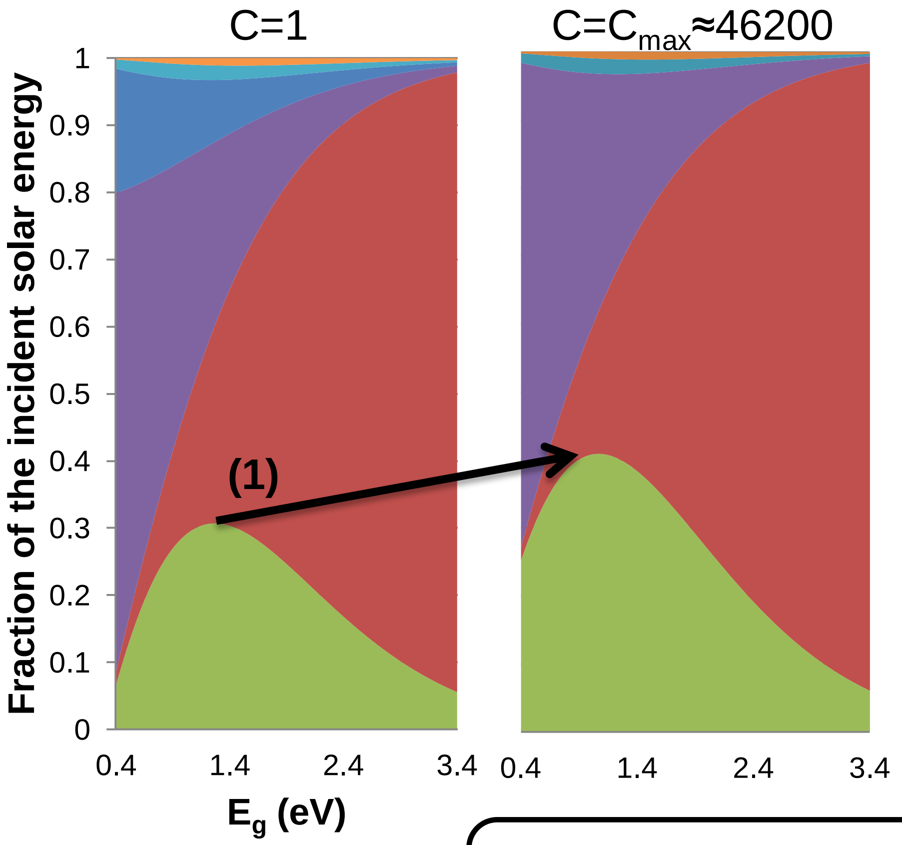
→ **Reducing certain losses also improves β**

O. Dupré, June 2014, UNSW

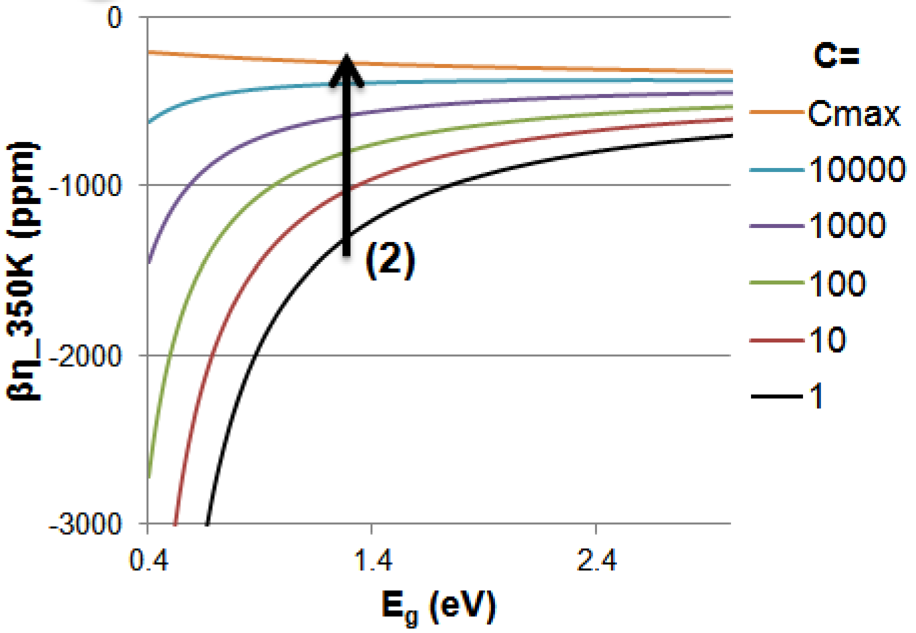
Temperature coefficient = f(Concentration)

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)

$$C = \frac{\Omega_{abs}}{\Omega_{abs}(1sun)} \qquad C_{max} = \frac{\Omega_{emit}}{\Omega_{abs}(1sun)} \qquad \textit{Angle mismatch} = \frac{\Omega_{abs}}{\Omega_{emit}} = C\,\frac{\Omega_{abs}(1sun)}{\Omega_{emit}}$$



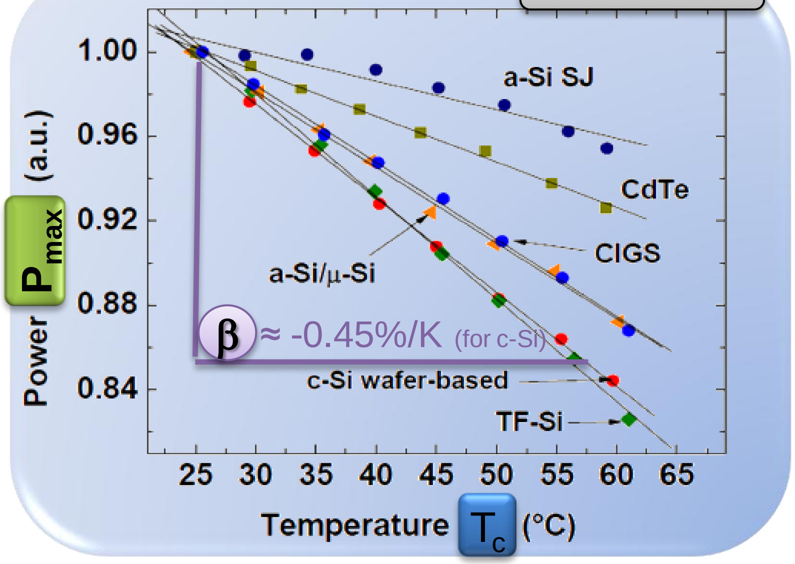
$\beta = f(\textit{Angle mismatch} / \textit{Concentration})$



Minimizing the **angle mismatch**:

(1) Improves P_{max} **(2) AND** improves β

Overview



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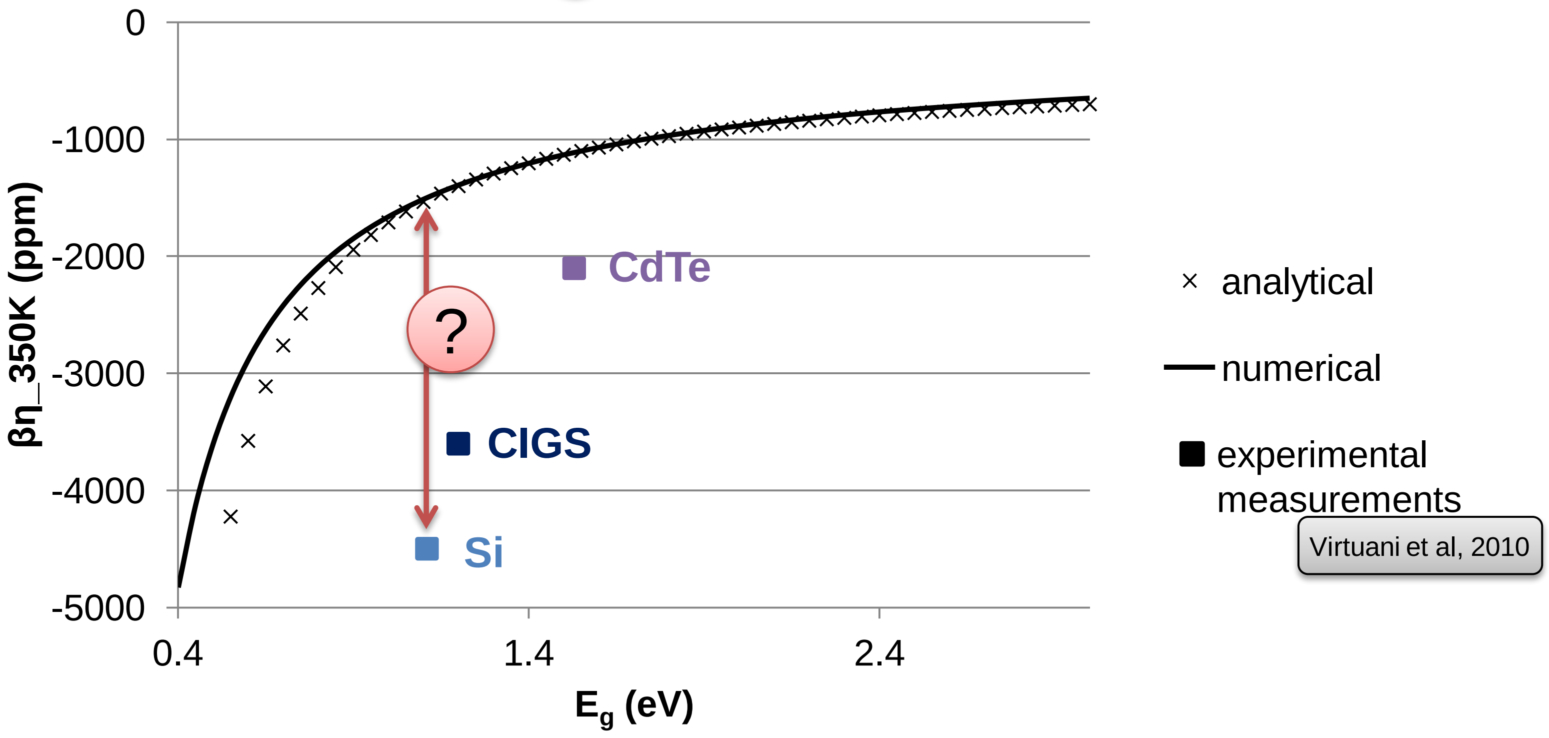
A thermal engineering view on PV performances

UNSW
AUSTRALIA

Additional losses in real devices

$$\beta = f(E_g)$$

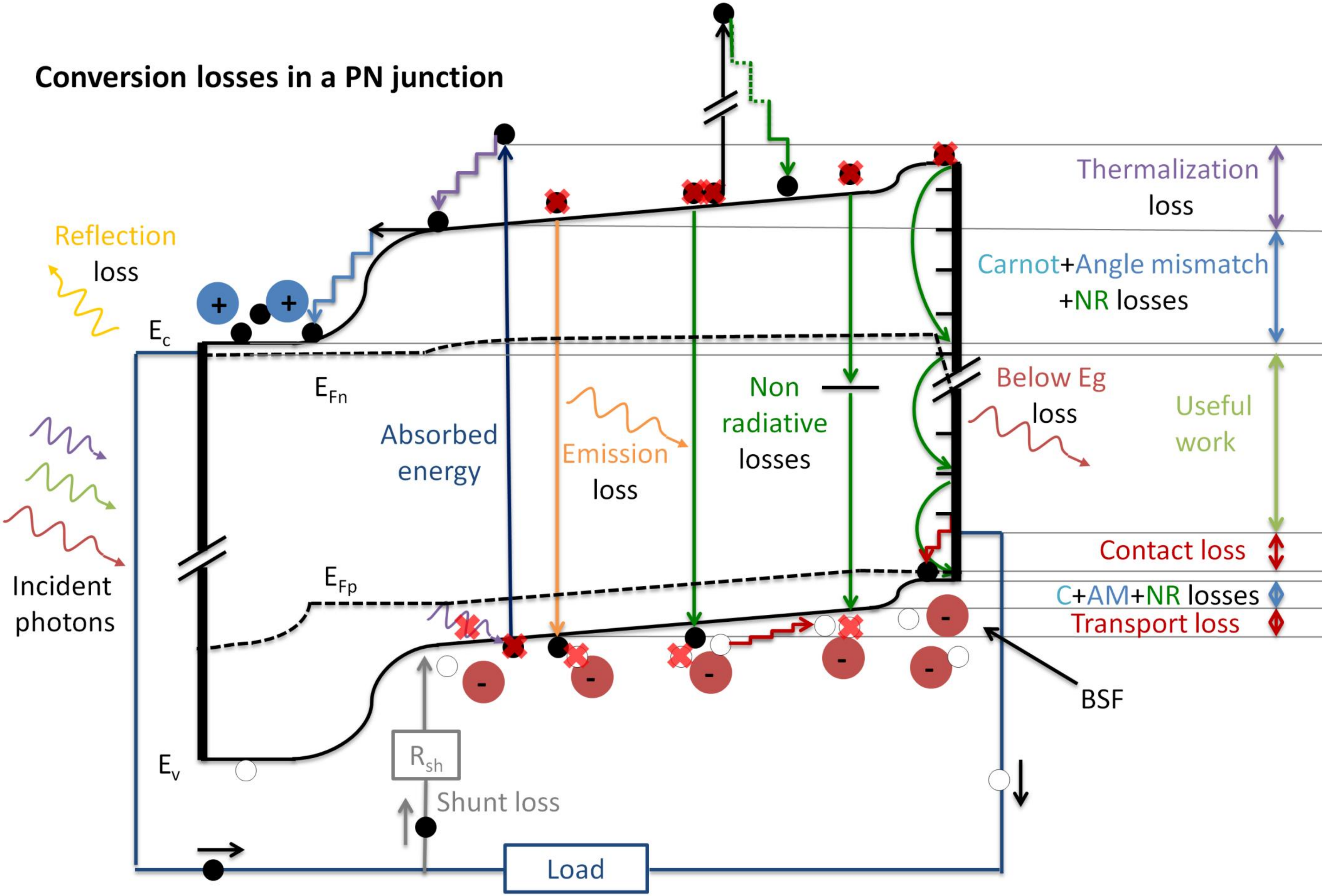


Virtuani et al, 2010

? Why do real PV devices have worse β than predicted before?

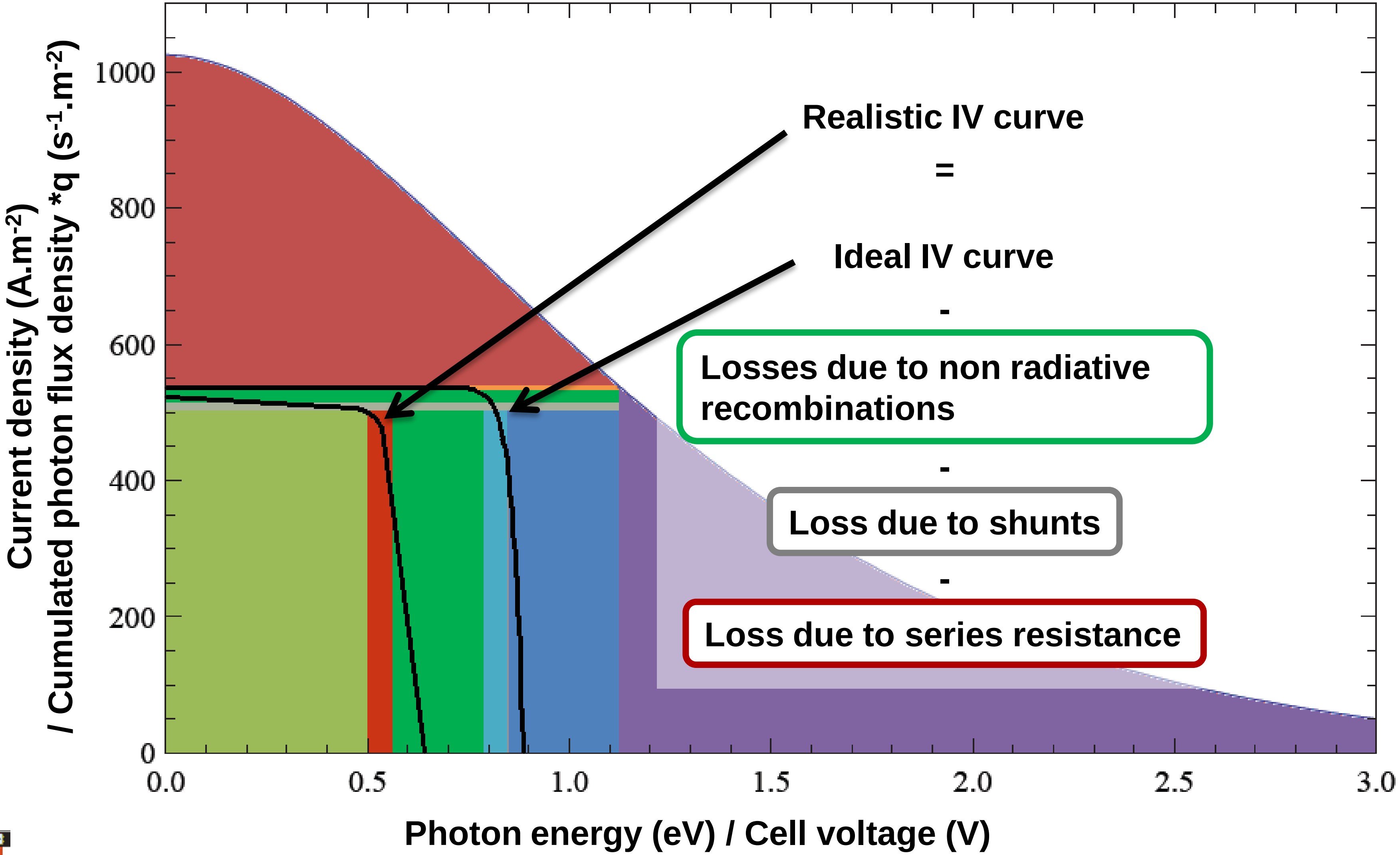
O. Dupré, June 2014, UNSW

Additional losses in real devices



IV curve of a commercial Silicon cell

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission + Non radiative recombination + Series + Shunt)



Realistic IV curve

=

Ideal IV curve

-

Losses due to non radiative recombinations

-

Loss due to shunts

-

Loss due to series resistance

External Radiative Efficiency: ERE

$$J(V) = J_{light} - J_{rec\_dark}(V)$$

(superposition principle)

Green, 2012

$$ERE = \frac{photon\ emission}{total\ dark\ current\ recombination} = \frac{\dot{N}_{emit}\, q}{J_{rec\_dark}}$$

- similar to EQE of a LED: *how many electrons need to be excited to emit one photon?*
- different from $IRE = \frac{R_{rad}}{R_{tot}}$

because of photon recycling

$$J = q\left(\dot{N}_{abs} - \frac{1}{ERE}\dot{N}_{emit}\right)$$

Using Boltzmann approximation → analytical solution:

$$qV_{MPP} = E_g \boxed{\left(1 - \frac{T_c}{T_s}\right)} - \boxed{kT_c \ln\left(\frac{\Omega_{emit}}{\Omega_{abs}}\right)} - \boxed{kT_c \ln\left(\frac{1}{ERE_{MPP}}\right)}$$

Carnot efficiency **Angle mismatch loss** **Non radiative recombination loss**

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission + Non radiative recombination)

Temperature coefficient = f(ERE)

Commercial Si cell

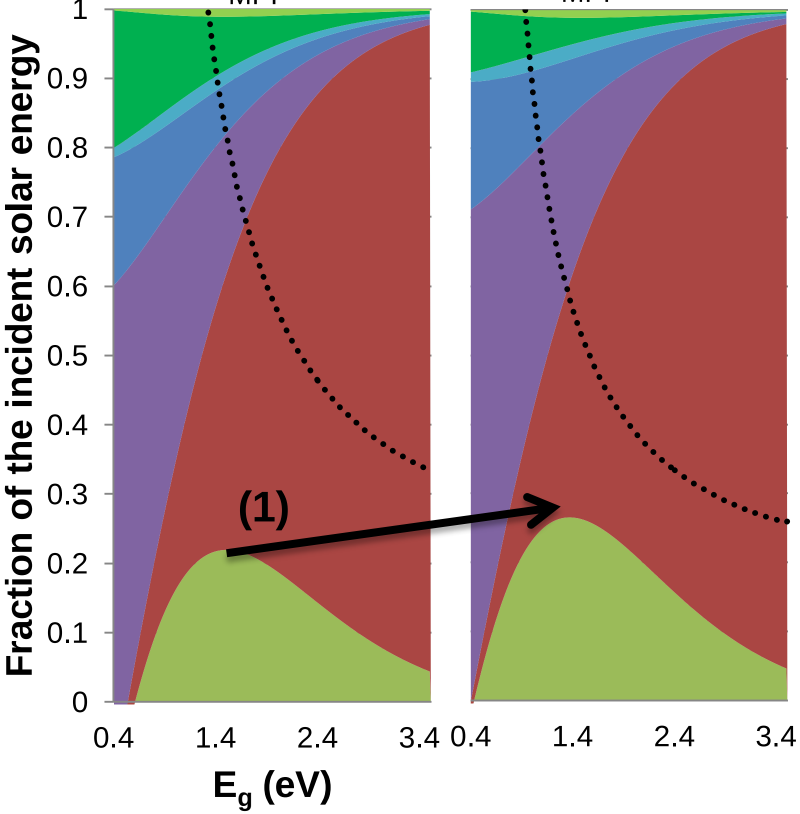
V_{oc}=580 mV

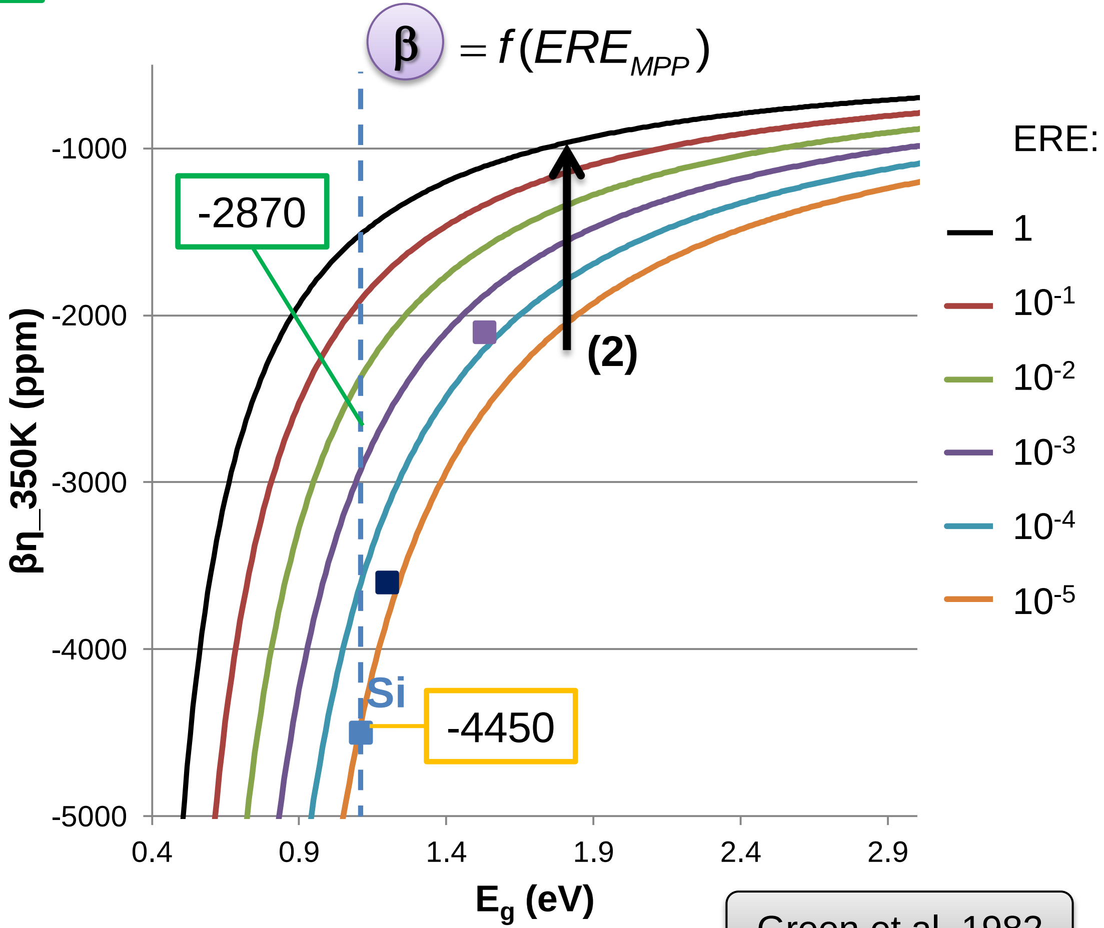
$ERE_{MPP}=10^{-5}$

State of the art Si cell

V_{oc}=710 mV

$ERE_{MPP}=1.5\ 10^{-3}$





Green et al, 1982

Minimizing the **non radiative losses**:

(1) Improves P_{max} **(2) AND** improves β

"As the open-circuit voltage of silicon solar cells continues to improve, one resulting advantage, **not widely appreciated**, is reduced temperature sensitivity of device performance"

Temperature coefficient = f(T_c)

$$\beta = f(ERE_{MPP})$$

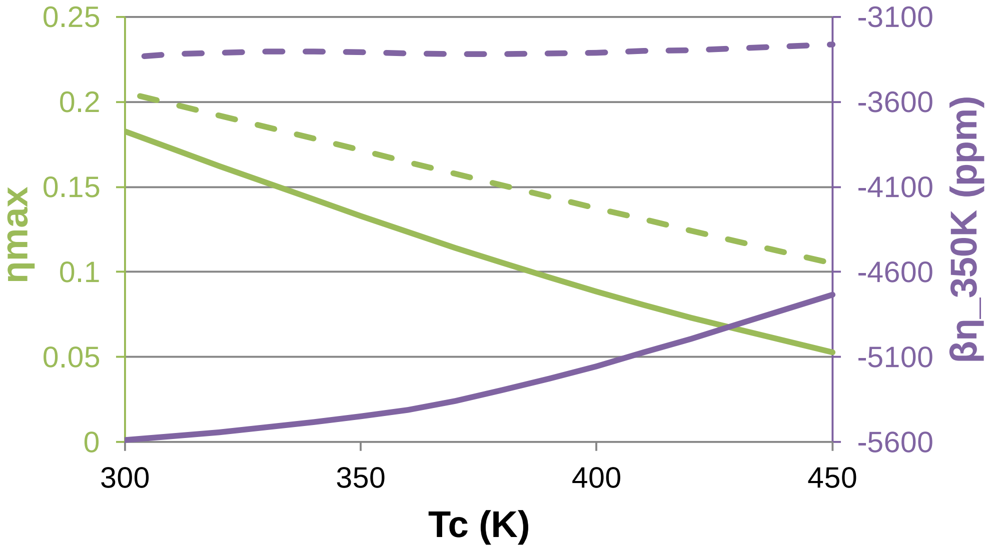
BUT

Radiative and non radiative recombination mechanisms have different temperature and voltage dependences (and V_{MPP}=f(T_c))

$\rightarrow$ $ERE_{MPP} = f(T_c)$

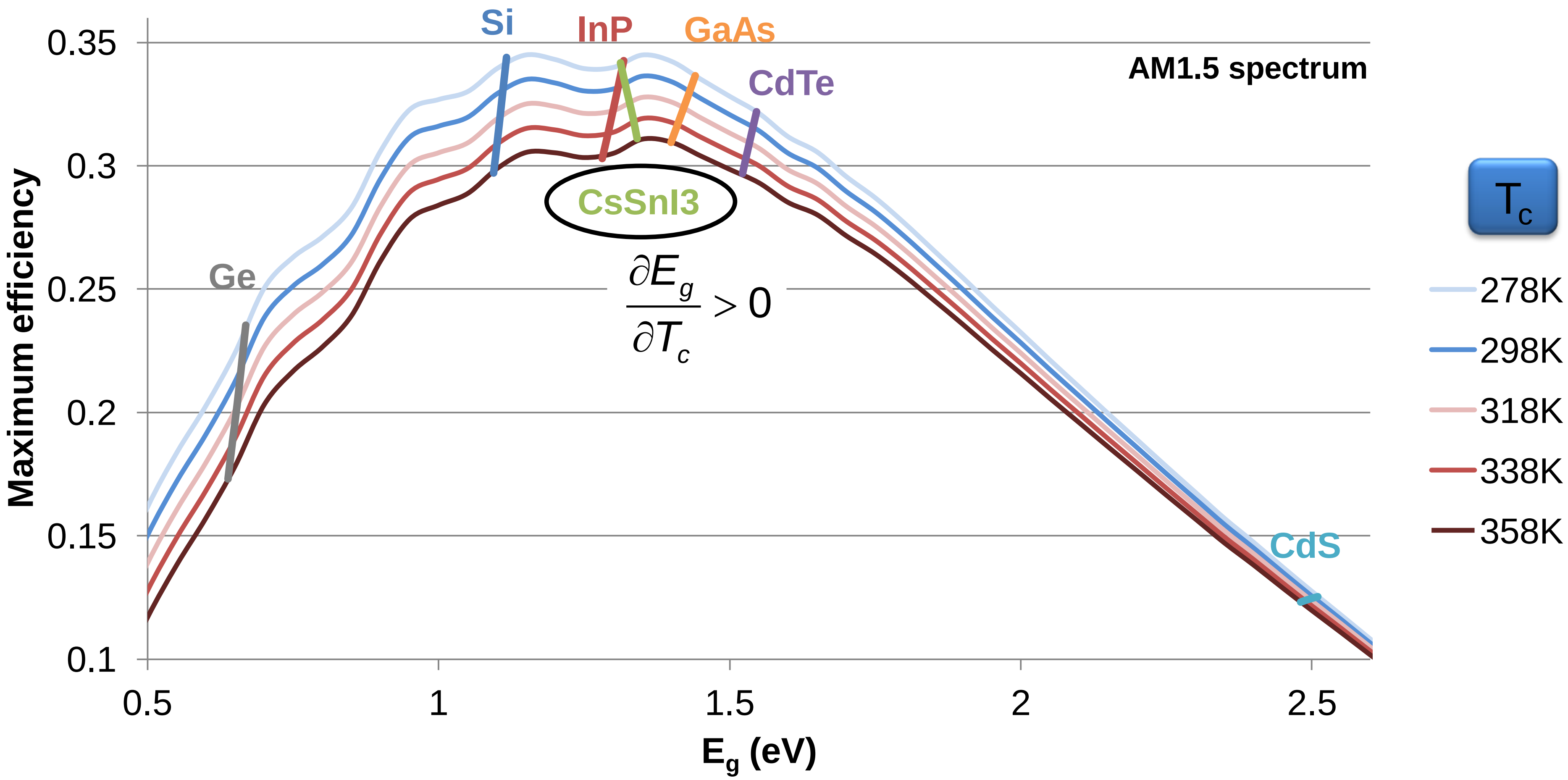
$\rightarrow$ $\beta = f(T_c)$

Example:
SRH recombination theory using 2 different **trap energies E_t**:
- - - - E_c-E_t=0.26
—— E_c-E_t=0.43



ALSO Series and shunt losses = f(T_c) → impact on β ?

Bandgap = f(T_c), influence of the spectrum

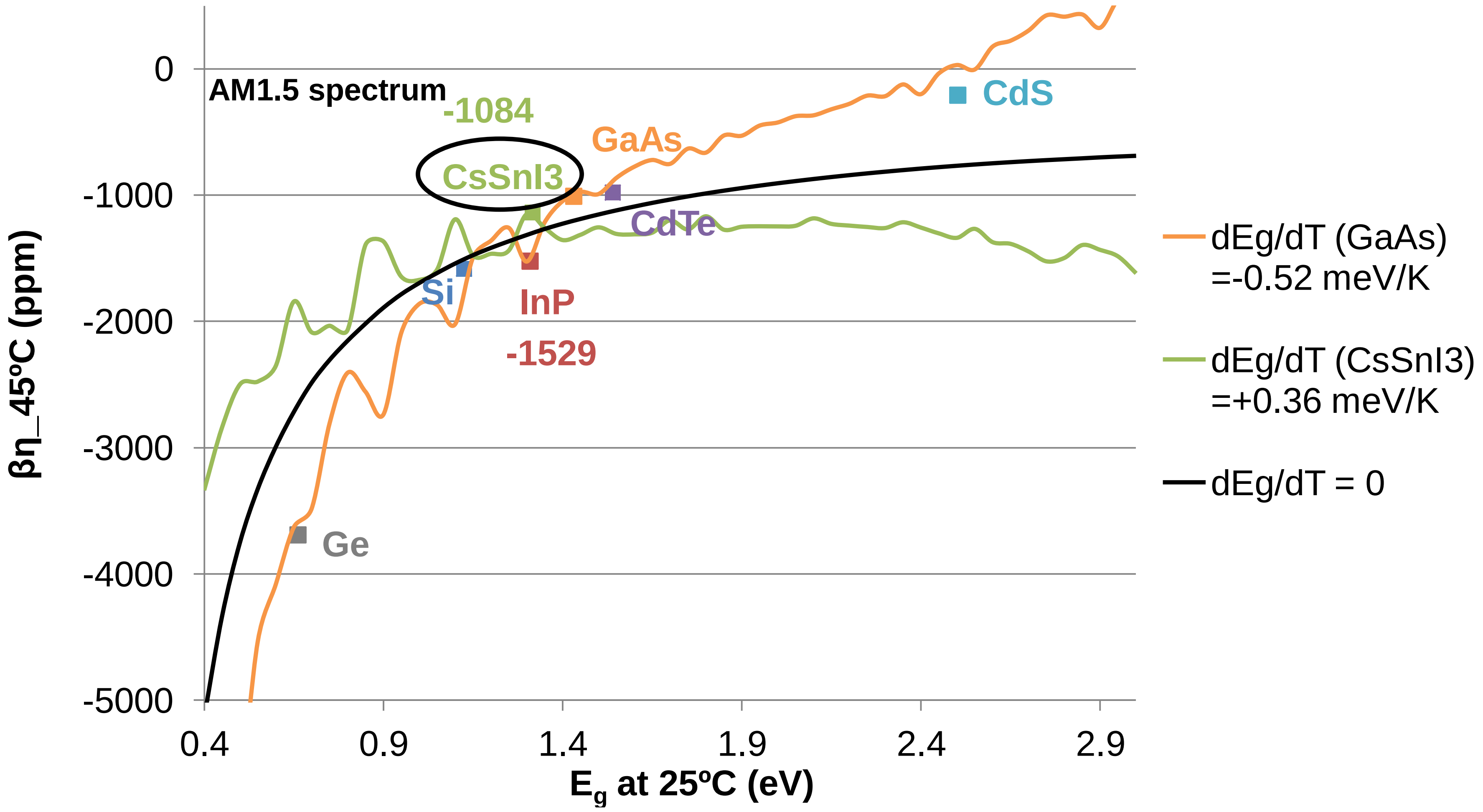


$$\frac{\partial E_g}{\partial T_c} > 0$$

→ $$\beta = f(Eg, \frac{\partial E_g}{\partial T_c}, incident\ spectrum)$$

→ Perovskite compound (**CsSnI3**) interesting $(Eg, \frac{\partial E_g}{\partial T_c})$

Bandgap = f(T_c), influence of the spectrum



→ $$\beta = f(Eg, \frac{\partial E_g}{\partial T_c}, incident\ \ spectrum)$$

→ Perovskite compound (CsSnI3) interesting $(Eg, \frac{\partial E_g}{\partial T_c})$

Intrinsic β of silicon cells

Using the state-of-the-art parameters* and considering carefully their **temperature dependences**, we derived the temperature coefficient of the limiting efficiency of crystalline silicon solar cells

$\eta(298.15K) = 29.6\%$

Intrinsic β of crystalline silicon cells = -2380 ppm/K

This is obviously not a minimum but as silicon cells improve towards their limiting efficiencies, their temperature sensitivity is expected to converge toward this value

(SQ limit with AM1.5)

< 33.4%

< -1582 ppm/K

Differences with the SQ assumptions:

- Auger recombination
- Realistic absorbance of silicon with Free Carrier Absorption and assuming a Lambertian light trapping scheme

$$A_{bb}(E) = \frac{\alpha_{bb}(E)}{\alpha_{bb}(E) + \alpha_{FCA}(E) + \frac{1}{4n_r^2 W}}$$

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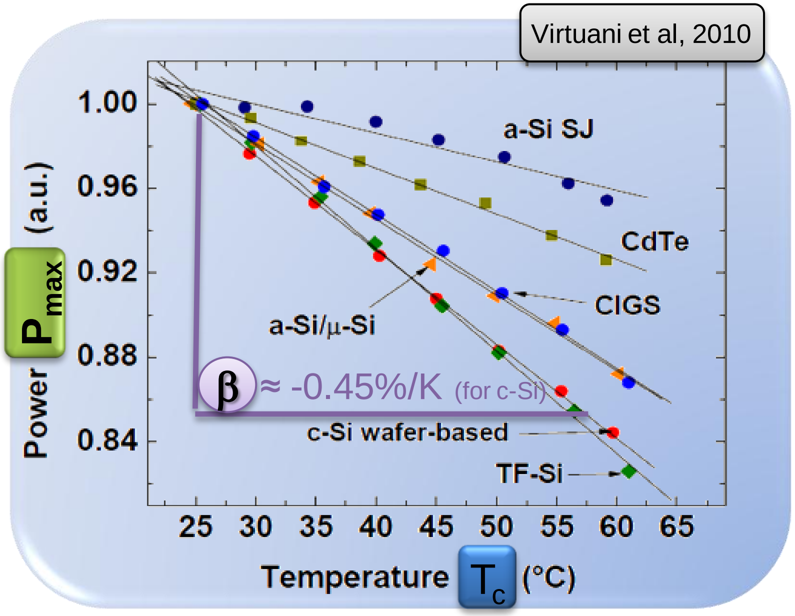
* Richter et al, 2013

Overview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A thermal engineering view on PV performances

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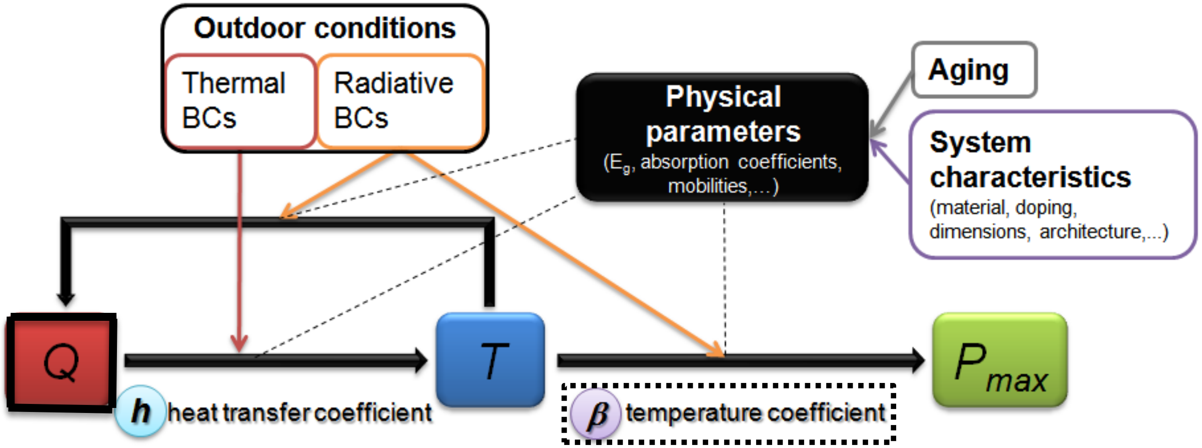


Outdoor conditions

Thermal BCs

Radiative BCs

Physical parameters

(E_g, absorption coefficients, mobilities,…)

Aging

System characteristics

(material, doping, dimensions, architecture,…)

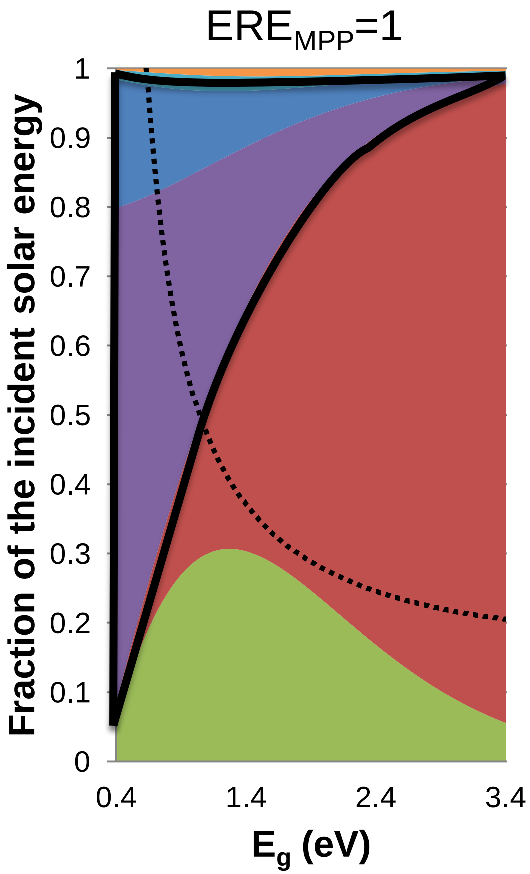
Q

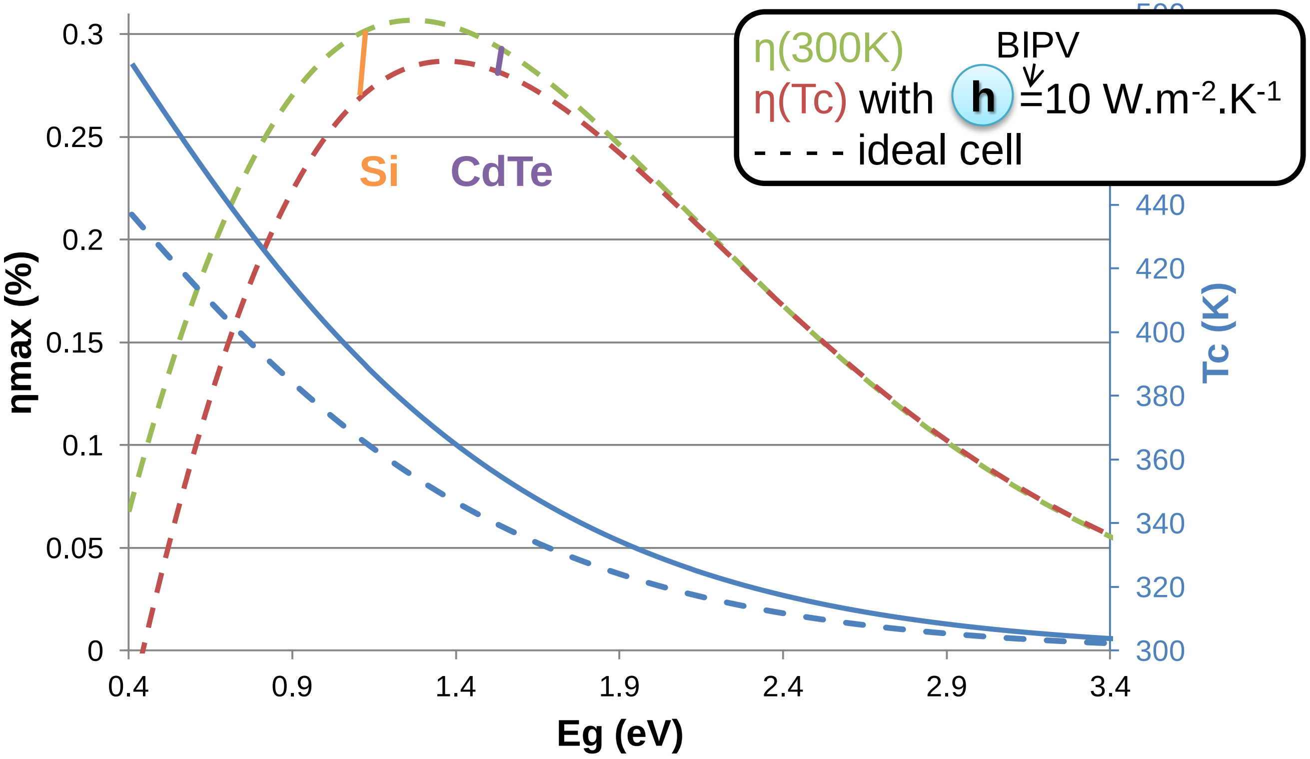
h heat transfer coefficient

T

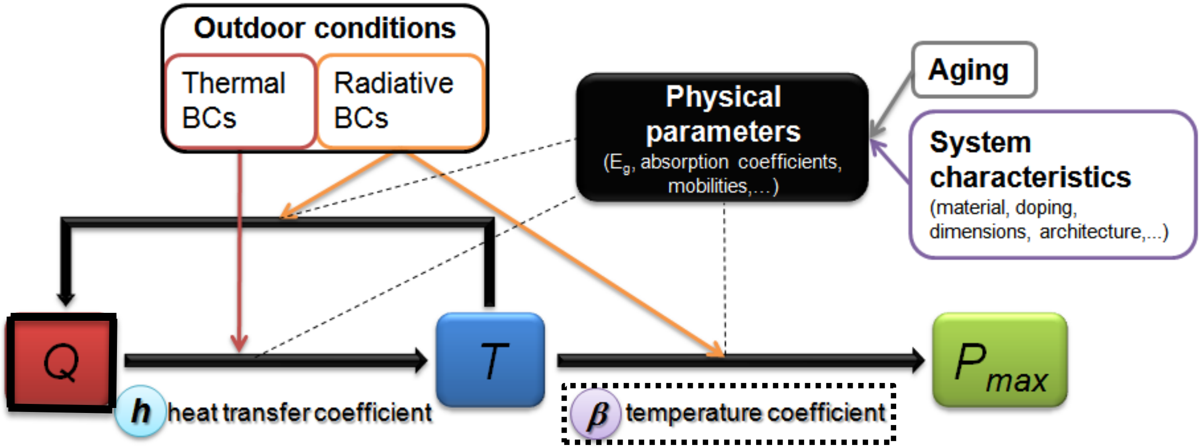
β temperature coefficient

P_{max}





A thermal engineering view on PV performances



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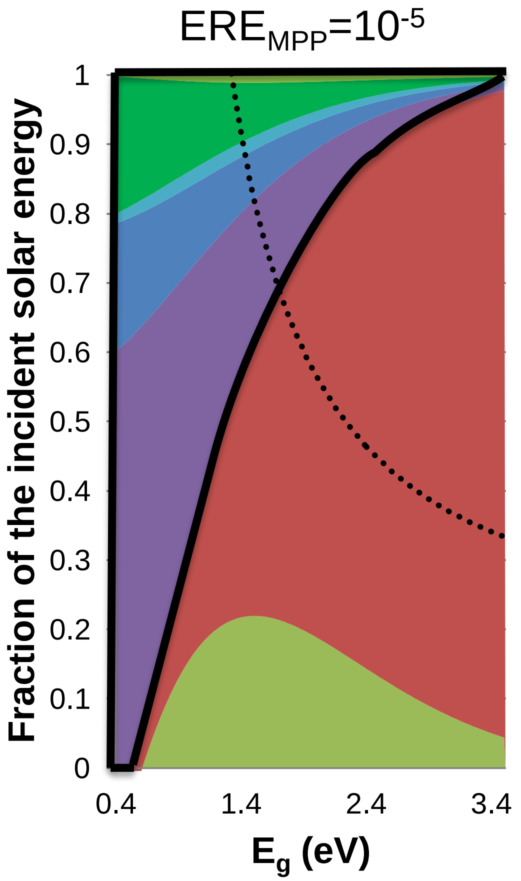
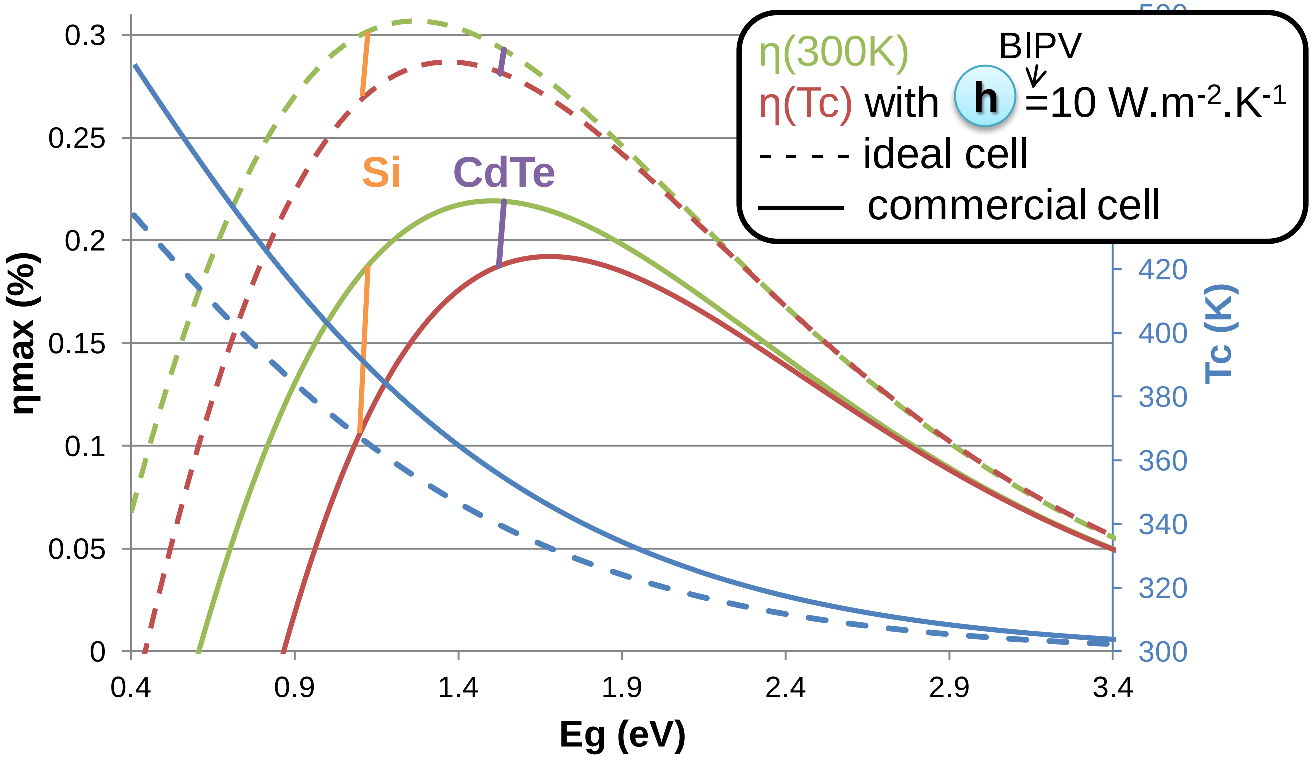




O. Dupré, June 2014, UNSW

Conclusions and future work

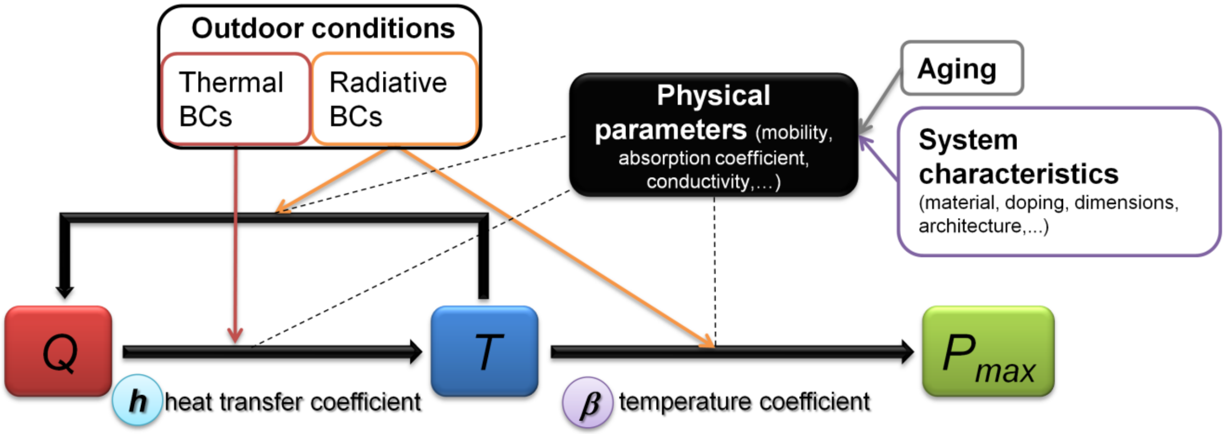
Reducing Angle mismatch or Non Radiative losses improves efficiencies AND temperature coefficients of PV cells

At one sun, β is principally a function of the cell bandgap (Eg) and quality (ERE)

$$\beta = f\left(E_g, ERE, C, \frac{\partial ERE}{\partial T_c}, \frac{\partial E_g}{\partial T_c}, \text{incident spectrum}, \frac{\partial \text{contact loss}}{\partial T_c}, \frac{\partial \text{shunt loss}}{\partial T_c} \ldots\right)$$

Investigate the impact of these parameters to be able to predict β of different technologies

Intrinsic β of crystalline silicon cells = -2380 ppm/K



Outdoor conditions

Thermal BCs

Radiative BCs

Physical parameters (mobility, absorption coefficient, conductivity,...)

Aging

System characteristics (material, doping, dimensions, architecture,...)

Q

T

P_{max}

h heat transfer coefficient

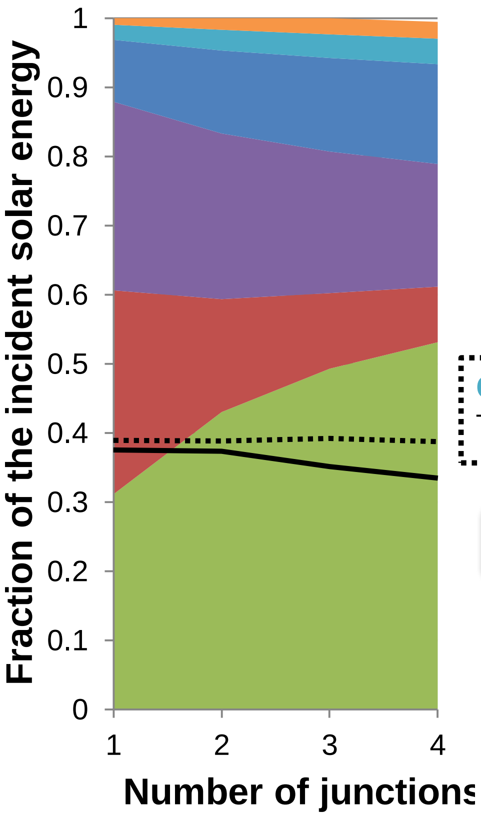
β temperature coefficient

Assess different PV strategies (TPV, BIPV, CPV, multi-junctions, ...) with this thermal approach

Thank you for your attention

Temperature coefficient of multi-junctions

Output power = Input power – Losses (BelowEg + Thermalization + Carnot + Angle mismatch + Emission)



$$\frac{\text{Carnot} + \text{Angle mismatch} + \text{Emission}}{\text{Output power}} \rightarrow \boxed{\beta \approx \text{cst} \approx 1260\ \text{ppm/K}}$$

Q ≈ cst → T_c ≈ cst