Solar cell efficiency

Overview

- Solar cell efficiency revisited
- Calculation of theoretical efficiency limits
  - 1st approach: Two-band systems
  - 2nd approach: The Shockley-Queisser limit
  - Examples of calculated efficiency limits
- Real solar cell efficiencies
- Beyond the Shockley-Queisser limit
  - 3rd generation solar cells

Clever student question:

”What is efficiency anyway?”

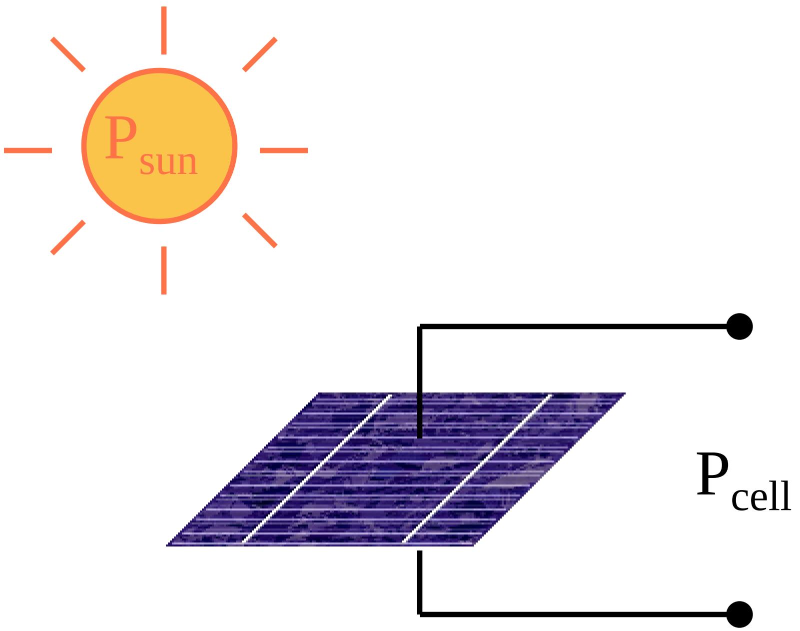
Solar cell efficiency revisited

- The efficiency (η) of a solar cell is defined as the ratio between the maximum electrical power delivered by the cell and the power of the light falling upon it:

$$\eta = P_{cell} / P_{sun}$$

- P_{cell} is given by

$$P_{cell} = I \cdot V$$

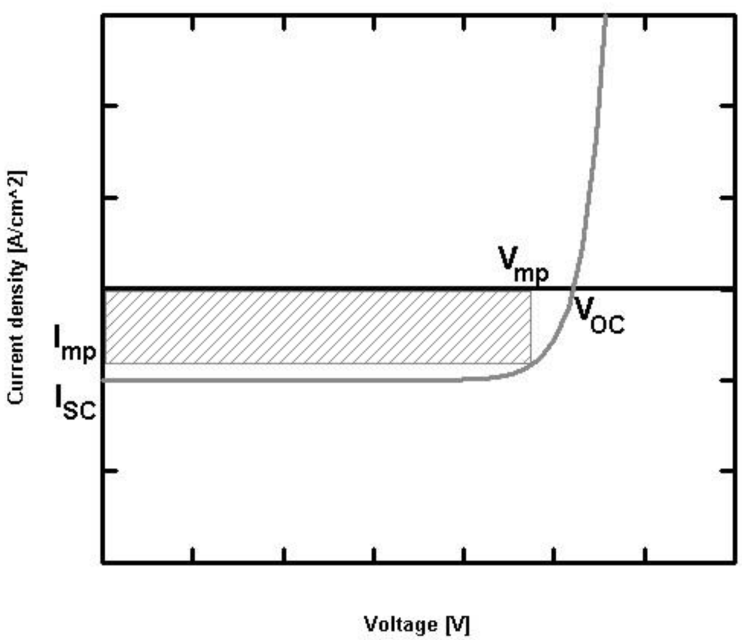


Solar cell efficiency revisited

- η is defined at the maximum power point of the solar cell.

$$\eta = P_{mp}/P_{sun}$$
$$= I_{mp} \cdot V_{mp}/P_{sun}$$

- η is sometimes called the **conversion efficiency** of a solar cell.



Irradiance

- P_{sun} is given by

$$P_{sun} = \int_0^{\infty} E \cdot b_s(E) \cdot dE$$

The central parameters in this equation are

- E photon energy given by $E = hf = hc/\lambda$
- $b_s(E)$ incident spectral photon flux density

Quantum efficiency

- The quantum efficiency ($QE(E)$) is a measure of the probability of an incident photon generating one electron that is successfully collected at the terminals
- The **external** quantum efficiency ($EQE(E)$) is given by

$$EQE(E) = [1 - R(E)] \cdot \eta_{coll}(E) \cdot a(E)$$

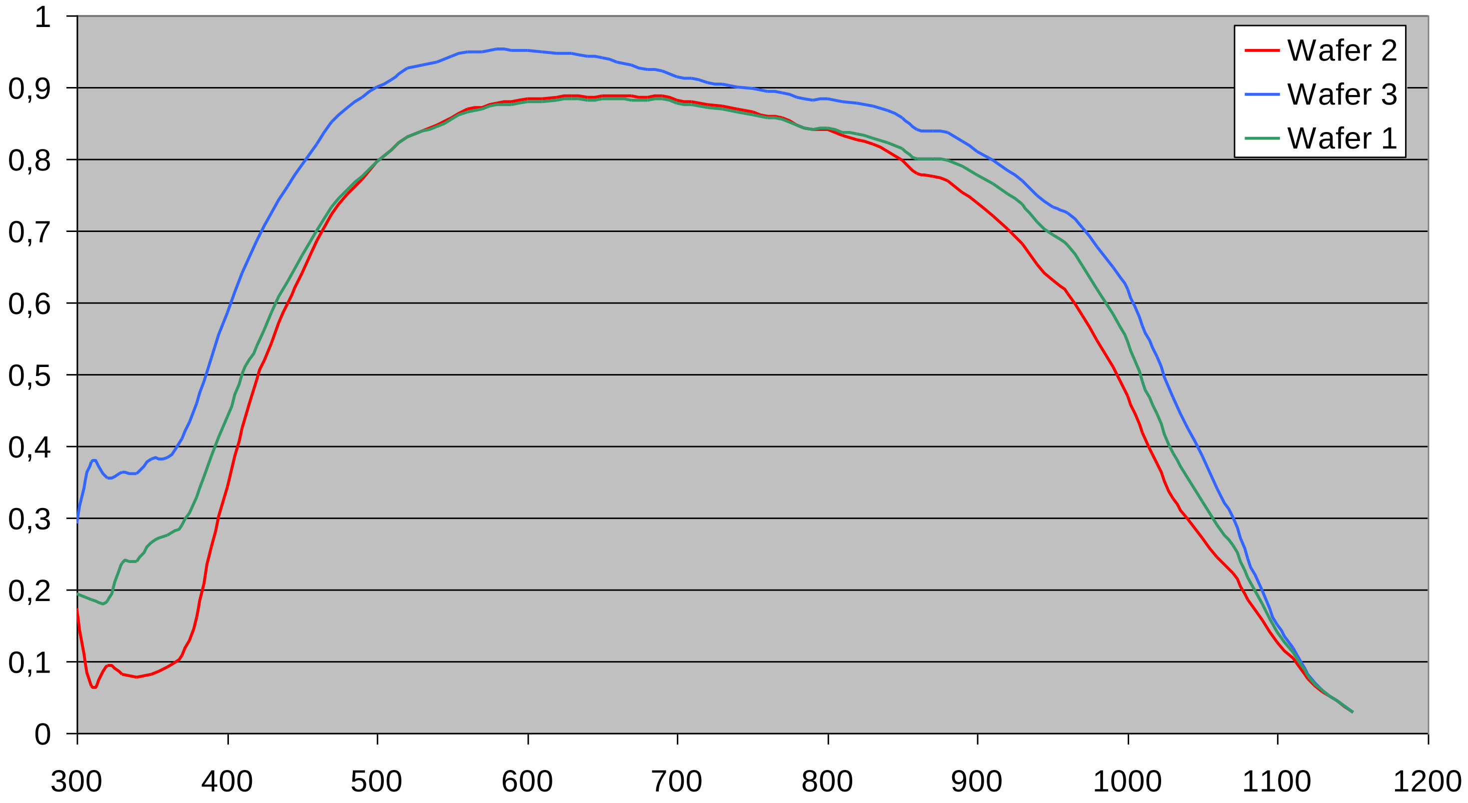
$$I_{SC}(E) = q \cdot A \cdot EQE(E) \cdot b_s(E)$$

- The **internal** quantum efficiency ($IQE(E)$) neglects reflective losses, and is given by

$$IQE(E) = \eta_{coll}(E) \cdot a(E)$$

$$I_{SC}(E) = q \cdot A \cdot [1 - R(E)]\, IQE(E) \cdot b_s(E)$$

EQE


Wafer 2
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700
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900
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1200

Data: IFE

The importance of efficiency

We know that:

$$P_{cell} = \eta \cdot P_{sun}$$

A cell irradiated by $1\ \mathrm{kW/m^2}$ of sunlight for $1\ \mathrm{h}$ will produce power equal to:

$$\eta \cdot 1\ \mathrm{kWh}$$

The importance of efficiency

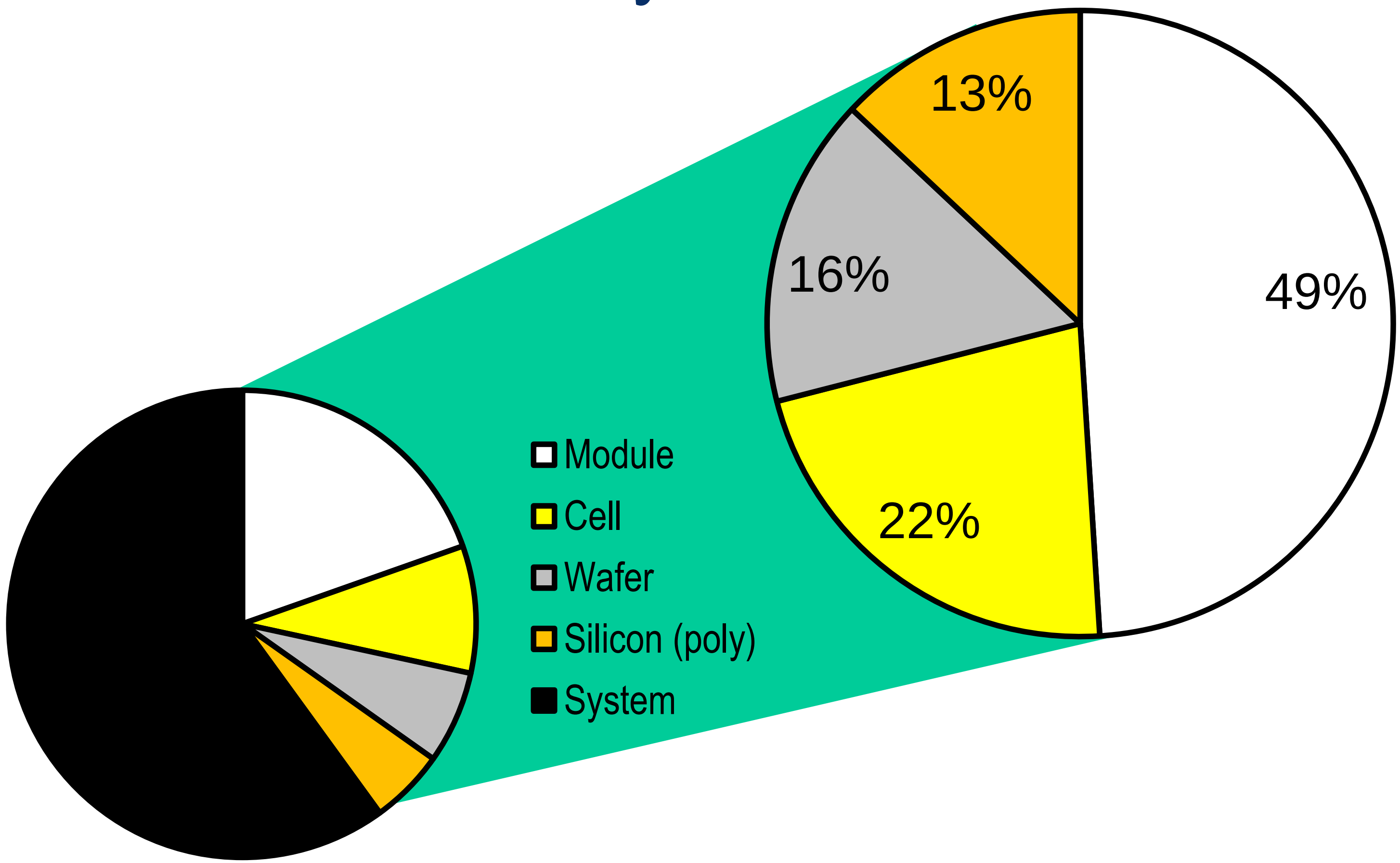
- The cost of solar electricity, often measured in $\$/\mathrm{kWh}$, is clearly dependent on two factors:

  1. The production costs of the solar energy system.
  2. The solar energy system efficiency.

- The two approaches to reducing the cost of solar electricity are therefore

  1. To reduce the costs of producing and installing a solar energy system
  2. To increase the amount of power delivered by a solar energy system through increased η

Efficiency ***matters***!



Data: ITRPV (2013)

Clever student question:

”How efficient can a solar cell become?”

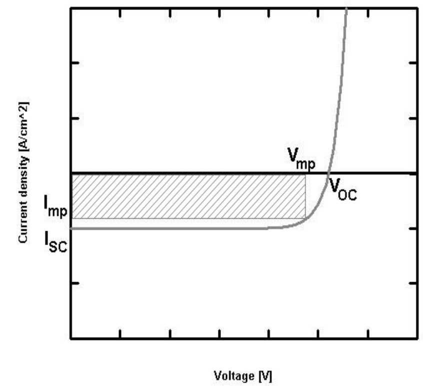
Calculation of efficiency limits

Calculation of efficiency limits

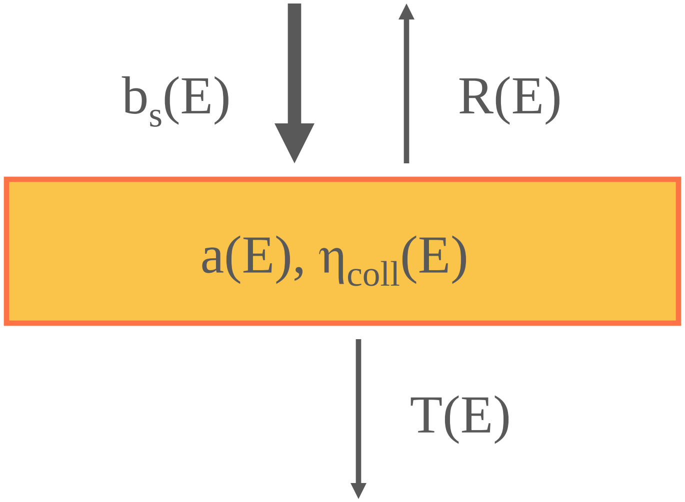
- The maximum delivered power (P_m) from a solar cell is given by:

$$P_m = I_m \cdot V_m$$

, where I_m and V_m are the current and voltage delivered by the cell at the maximum power point



Photogenerated current



$$I_{SC}(E) = q \cdot A \cdot ([1 - R(E)] \cdot \eta_{coll}(E) \cdot a(E) \cdot b_s(E))$$

Efficiency limit calculations

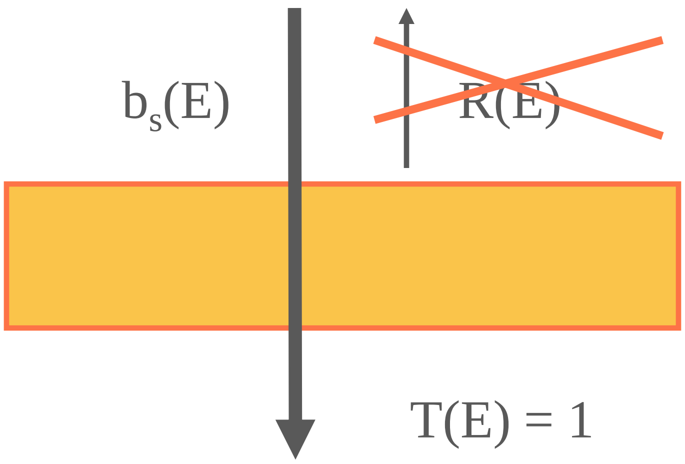
- We shall now attempt to put a number on the obtainable solar cell efficiencies, which at least in principle are obtainable for a conventional (two-band) homojunction solar cell
- We make use of the following important simplifications:

1. The solar cell is modelled by an **ideal solar cell model**
2. The solar cell is made from an electronic two-band system exhibiting instantaneous **thermalization** of charge carriers
3. All objects radiate as **black bodies**

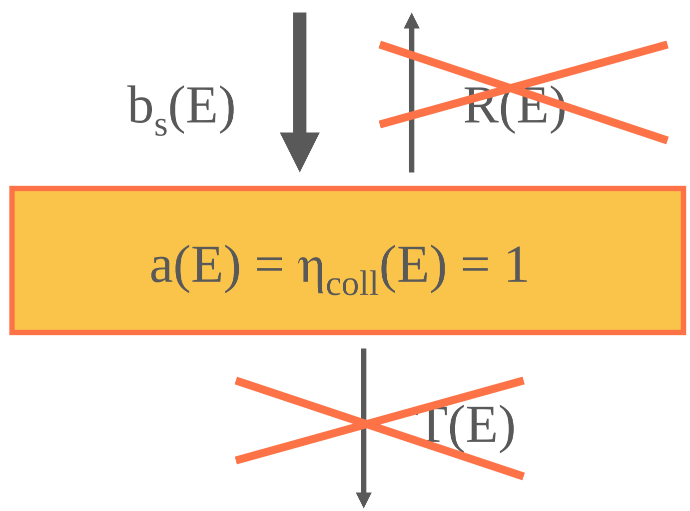
Assumption 1: ideal solar cell model

- For simplicity, we will use the following idealistic solar cell model
  - Perfectly non-reflecting solar cell
    - $R(E) = 0$ for all E
  - Perfect carrier collection
    - $\eta_{coll}(E) = 1$ for all E
  - Perfect absorption
    - $a(E) = \begin{cases} 1 \text{ for } E \geq E_g \\ 0 \text{ for } E < E_g \end{cases}$
  - Hence, $EQE(E) = 1$ and $IQE(E) = 1$ for all $E \geq E_g$

Ideal solar cell model ($E < E_g$)

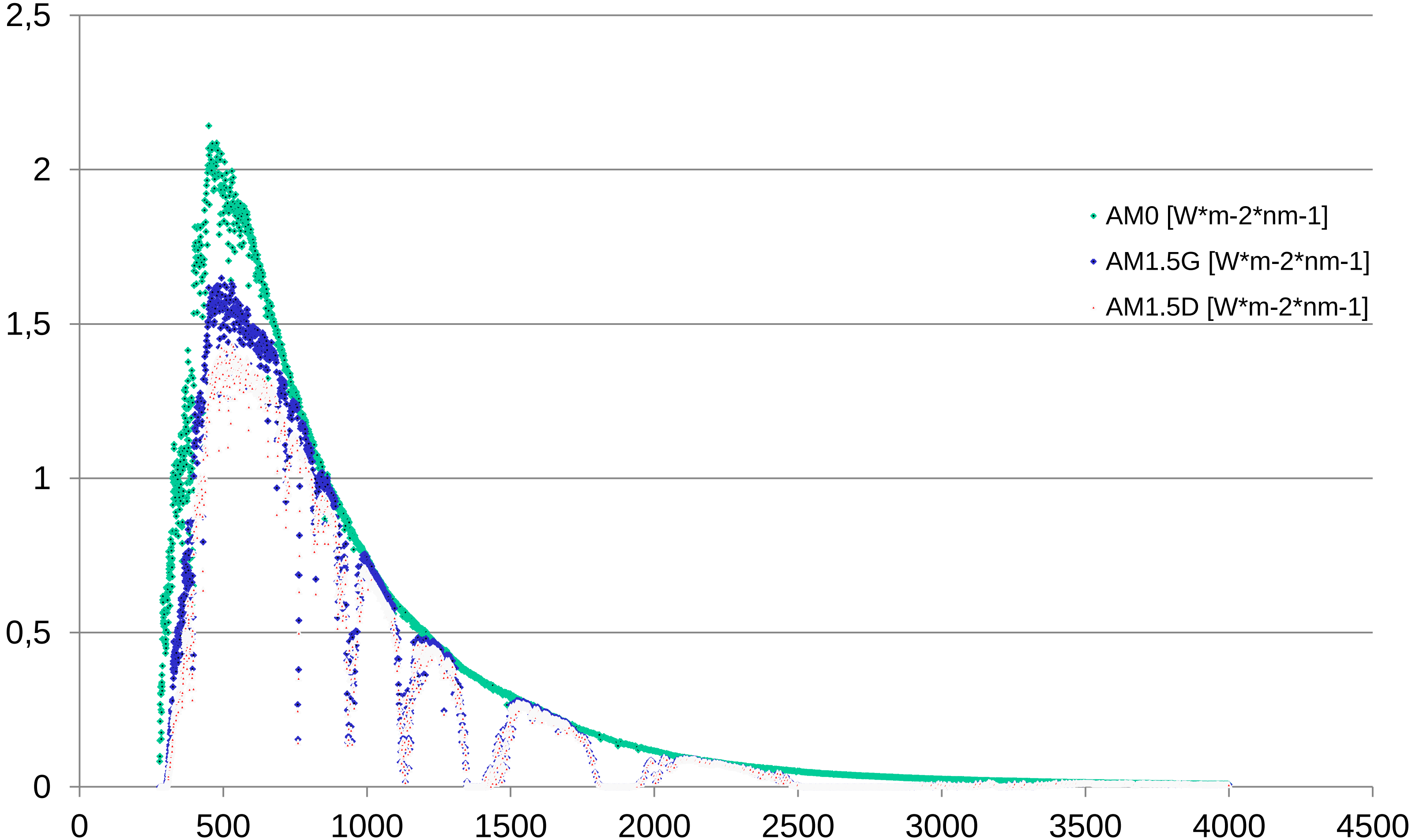


Ideal solar cell model ($E > E_g$)



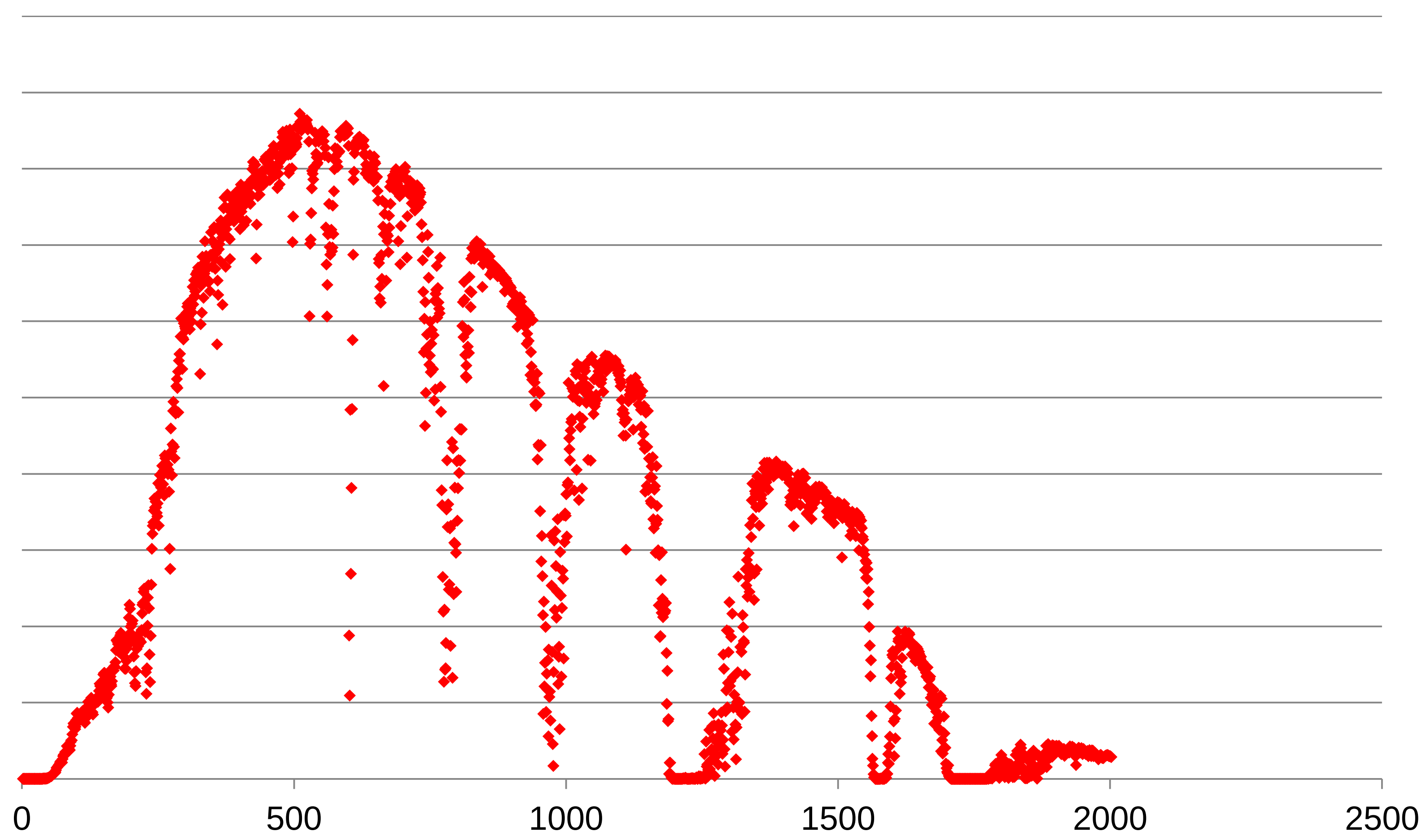
$$J_{SC}(E) = q \cdot b_s(E)$$

The solar spectrum – irradiance



Data: ASTMG173

Photon flux density – $b_s(E)$



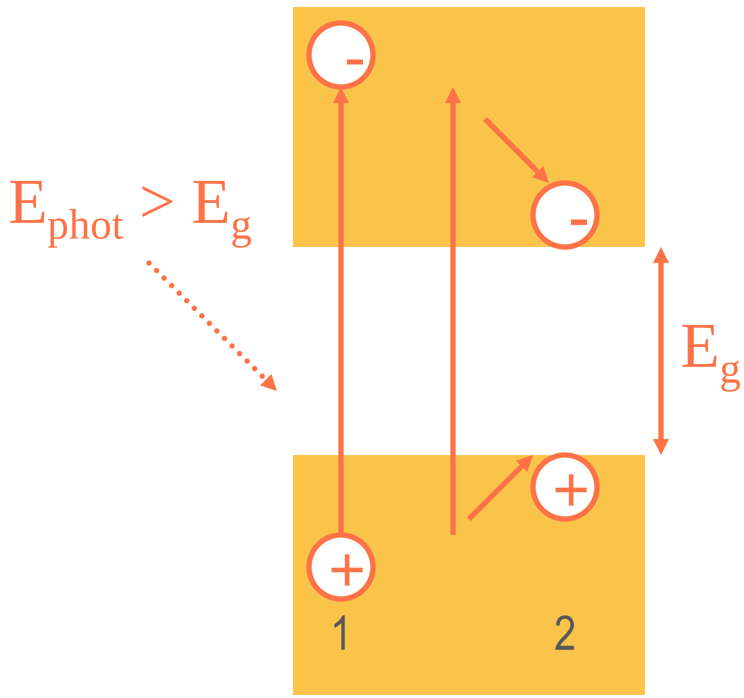
Data: ASTMG173

Thermalization

- Immediately upon generation, the energy distribution of excited charge carriers resembles that of the absorbed photons (1)

- The excited carriers loose energy through collision with charge carriers and lattice atoms (2)
  - Phonons are generated, resulting in a rapid change of the energy distribution
  - Any excess energy is given off as heat
  - Typical time scale: fs to ps range

- After reaching the band edge energies, further energy losses are governed by recombination across the band gap
  - Typical time scale: µs to ms range



Thermalization

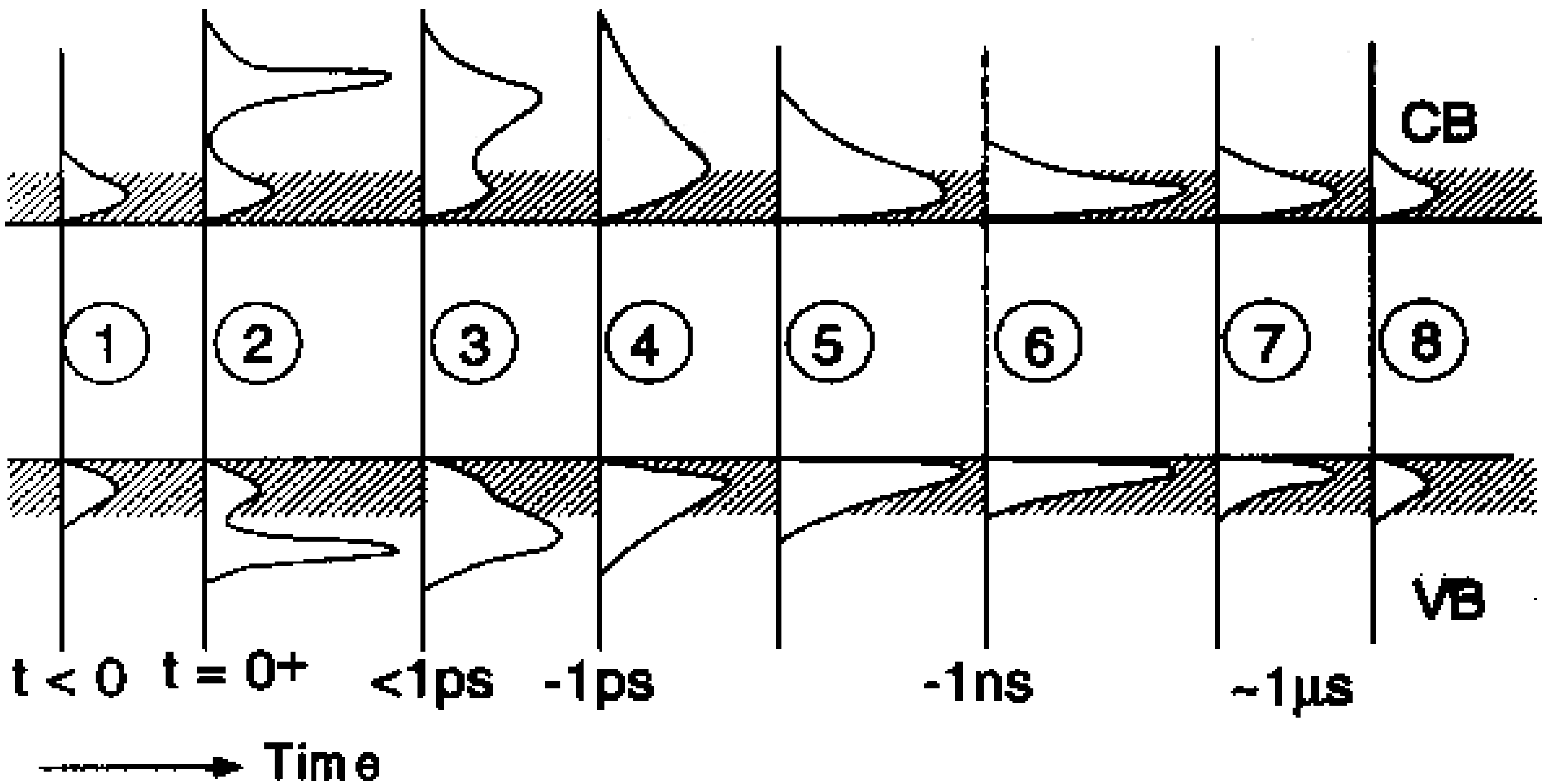
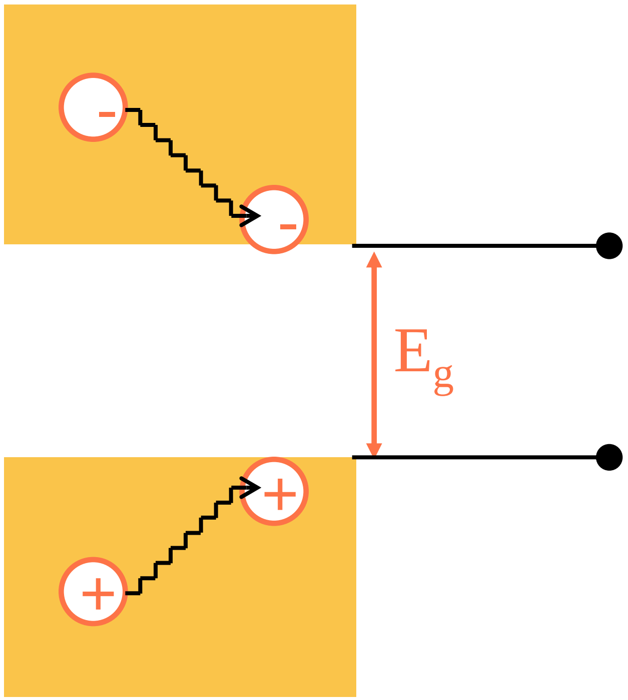


Image: M. Green

Assumption 2: instantaneous thermalization

- We shall assume that charge carriers, once generated, immediately loose any energy in excess of E_g
- This means that every excited charge carrier **”only”** will be able to deliver an energy of E_g to an external circuit

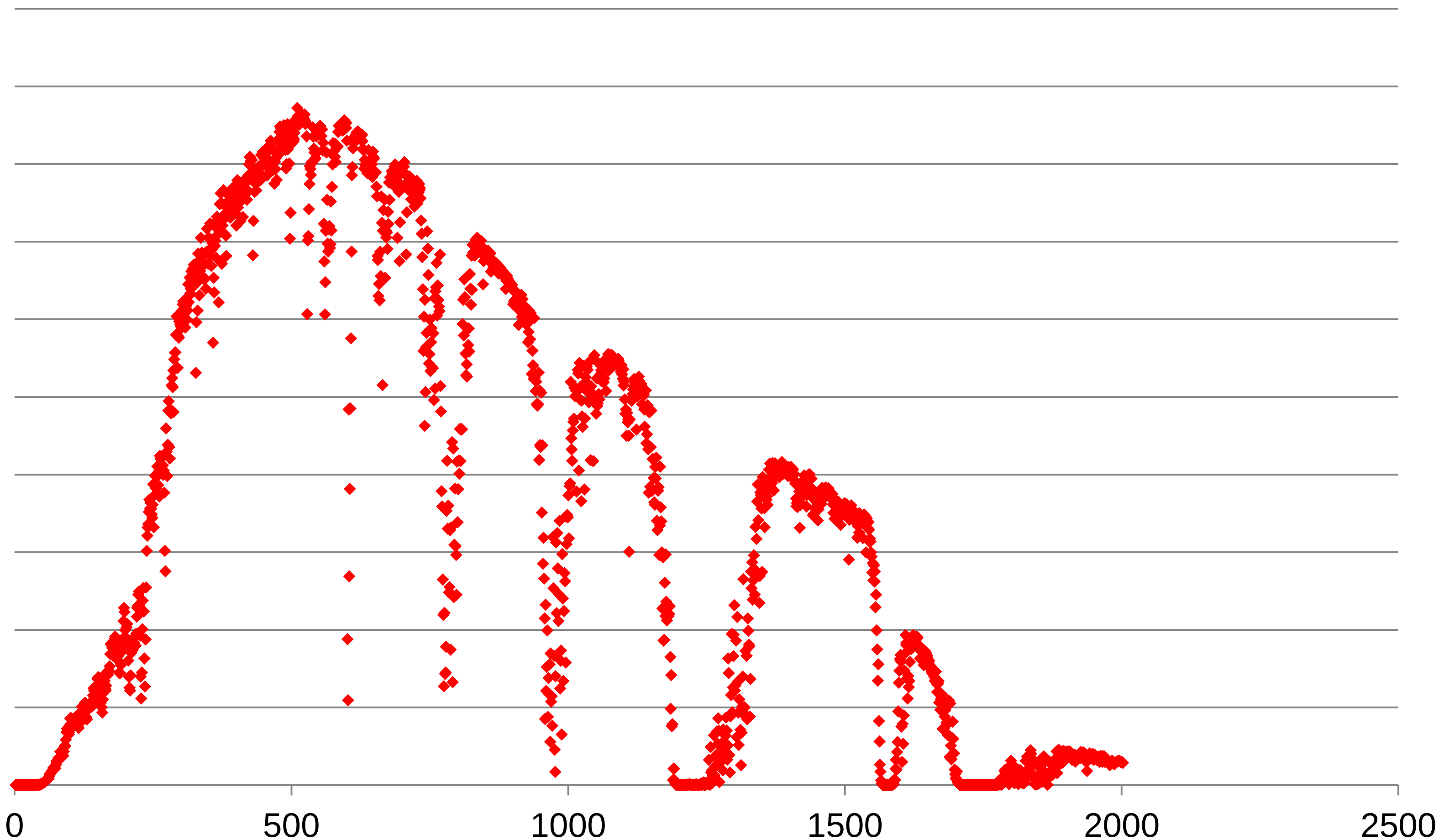
Assumption 2: instantaneous thermalization



Assumption 3: black body radiation

- For now, a simpler $b(E)$ is assumed.

Real $b_s(E)$ – AM1.5G



Data: ASTMG173

Simpler $b_s(E)$: Black body radiation

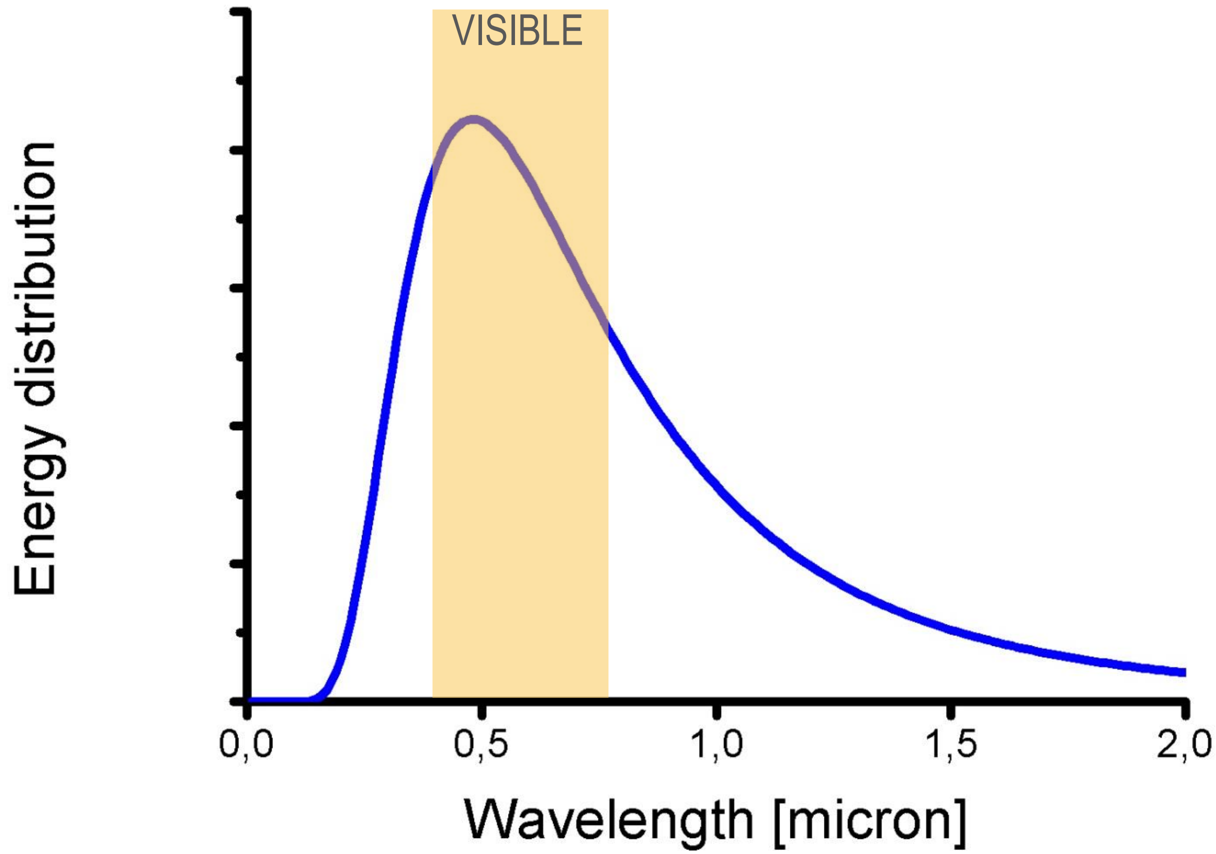
- Definition: *"The radiation from a black body is **uniquely** determined by its characteristic temperature,* T*"*

- The value of $b(E,T)$ perpendicular to the surface of the black body is described by the Planck law of radiation:

$$b(E,T) = (2F/h^3c^2) \cdot (E^2/(e^{(E/kT)} - 1))$$

- Here, we have assumed that T is isotropic, and we make use of a geometrical factor, F
  - The solar cell and the ambient radiate like black bodies
  - 1 sun irradiation (concentration will be discussed in a later lecture)

Black body radiation (5762 K)

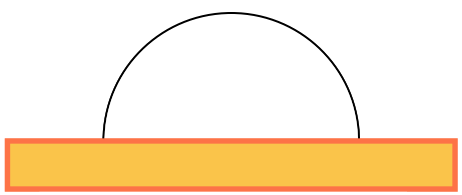


Assumption 3: Black body radiation

- In the following calculations, we shall assume that all objects radiate as black bodies
  - Sun: $b_S(E,T_S) = (2F_S/h^3c^2) \cdot (E^2/(e^{(E/kT_S)} - 1))$
  - Solar cell: $b_c(E,T_c) = (2F_c/h^3c^2) \cdot (E^2/(e^{(E/kT_c)} - 1))$
  - Atmosphere: $b_a(E,T_a) = (2F_a/h^3c^2) \cdot (E^2/(e^{(E/kT_a)} - 1))$

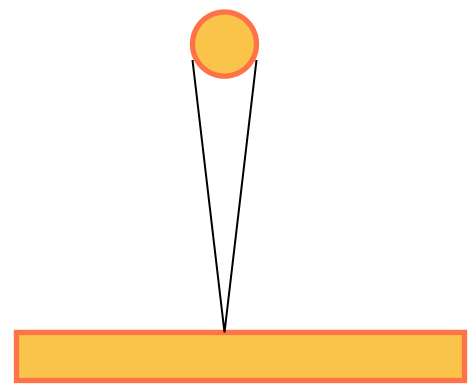
The geometrical factor (F)

- F is a geometrical factor taking into account the angular dependence of the emitted or absorbed radiation
- Example values:



$F_a = \pi$

Entire hemisphere / at surface



$F_S \approx 2 \cdot 10^{-5} \cdot \pi$

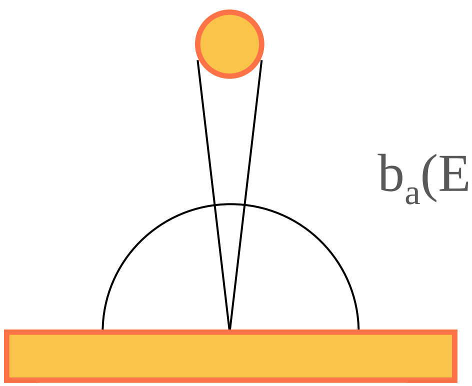
The Sun

Incident photon flux density upon a solar cell

- Contribution from the Sun:

$$b_S(E,T_S) = (2 \cdot \overbrace{2 \cdot 10^{-5} \cdot \pi}^{F_S}/h^3c^2) \cdot (E^2/(e^{(E/kT_S)} - 1))$$

- Contribution from the atmosphere:



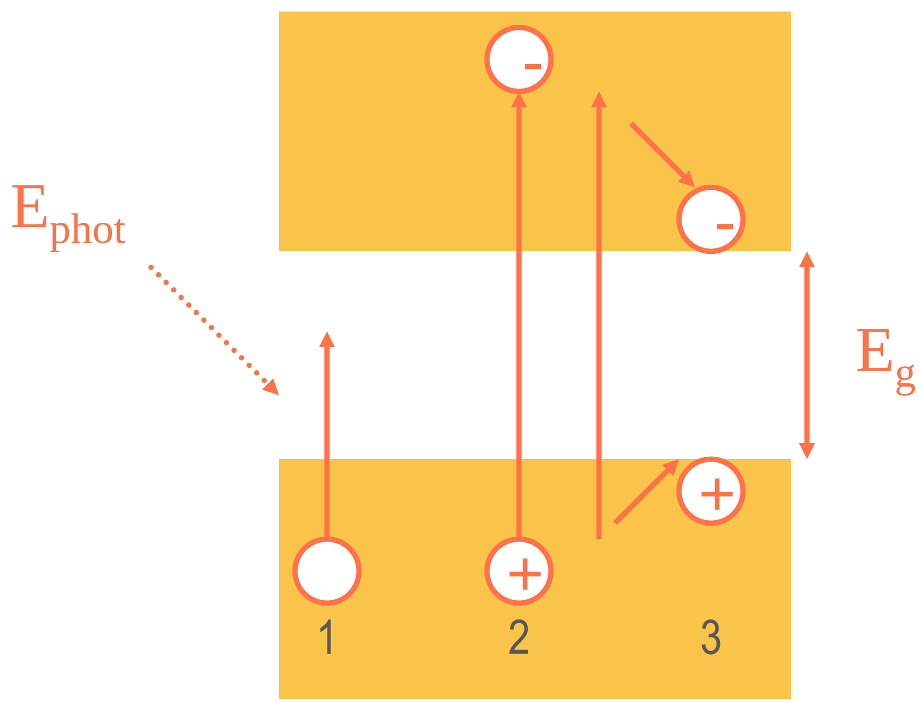
$$b_a(E,T_a) = (2 \cdot \overbrace{\pi \cdot (1 - 2 \cdot 10^{-5})}^{F_a = 1 - F_S}/h^3c^2) \cdot (E^2/(e^{(E/kT_a)} - 1))$$

$$\approx (2 \cdot \pi/h^3c^2) \cdot (E^2/(e^{(E/kT_a)} - 1))$$

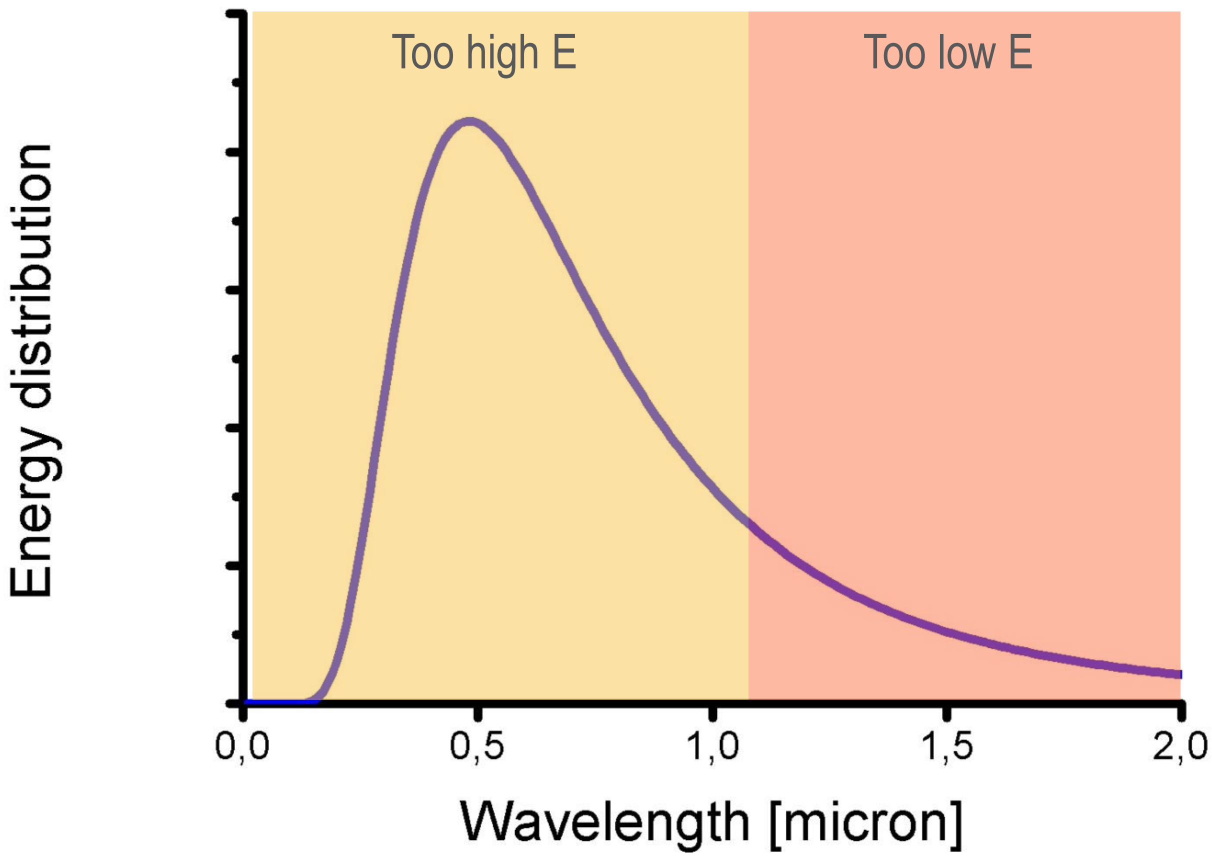
1st approach: Two-band systems

1^{st} approach: Two-band systems

- Only photons with sufficient energy can excite e^- across the band gap E_g
- Insufficiently energetic photons with $E_{phot} < E_g$ will **not** contribute to the photocurrent generation (1)
- Photons with $E_{phot} > E_g$ will initially generate energetic excited charge carriers (2)
- However, any energy in excess of E_g will be wasted heating up the solar cell through thermalization (3)



The case of silicon



- $E_{g,Si} = 1.12$ eV
- From $E_{phot} = hc/\lambda$ we can calculate a critical wavelength for absorption
  - $\lambda_c \approx 1\,108$ nm
- Every photon with $\lambda_c > \lambda$ will contribute with one pair of charge carriers
- This can be used for a simple estimation of the obtainable efficiency of an ideal solar cell

The case of silicon

- An E_g ~ 1.12 eV corresponds to a cutoff wavelength $\lambda \sim 1150$ nm
  - The number of photons in the solar spectrum with energies in excess of E_g will all create one electron, hence

$$J_{SC} \sim 45 \text{ mA/cm}^2$$

  - The band gap defines an absolute upper limit for the obtainable voltage, hence

$$V_{OC} < E_g/q \sim 1.1 \text{ V}$$

  - This leads to an upper limit of $\eta \sim 50$ %
  - Note that a perfectly square I-V curve and no voltage losses have been assumed!

1st approach: Two-band systems

- Conceptually simple, but…
- Too simple (unphysical) approach:
  - A solar cell with a temperature T_{cell} will radiate as a black body, thus giving off energy to the environment
  - The energy emitted by the solar cell this way will depend upon the number of excited e^-
  - Overestimates the obtainable efficiency by a relatively large amount
- 2nd approach: the Shockley-Queisser approximation
  - Main principle: **detailed balance**

2^{nd} approach: Shockley-Queisser

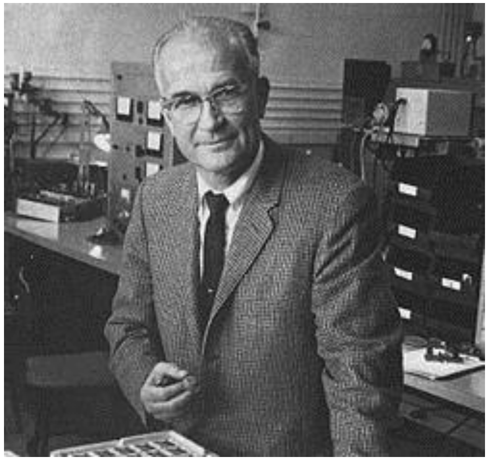
Classical literature:

"DETAILED BALANCE LIMIT OF EFFICIENCY OF P-N JUNCTION SOLAR CELLS"

SHOCKLEY, W & QUEISSER, HJ

JOURNAL OF APPLIED PHYSICS Volume: 32 Issue: 3 Pages: 510-
DOI: 10.1063/1.1736034 Published: 1961
Times Cited: 1,544

The Shockley-Queisser limit



William Bradford Shockley (1910 – 1989)

Hans Joachim Queisser (1931 –)

Image: wikipedia

Definition: detailed balance

- ”The number of electrons extracted as current from a solar cell is equal to the difference between the number of photons absorbed and emitted by the solar cell”

- In steady state, this can simply be represented as follows:

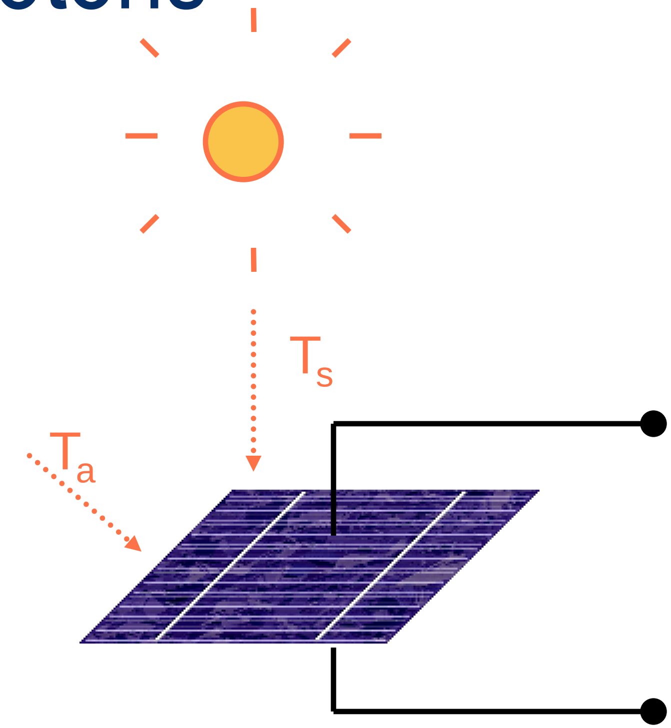
$$dN_{cc,net}(E)/dt = dN_{phot,abs}(E)/dt - dN_{phot,rad}(E)/dt$$

- $N_{cc,net}(E)$ = Number of electrons generated with energy E
- $N_{phot,abs}(E)$ = Number of absorbed photons with energy E
- $N_{phot,rad}(E)$ = Number of emitted photons with energy E

Absorbed photons

- The solar cell absorbs photons ($dN/dt_{phot,abs}(E)$) that originate both from the Sun and from the ambient surrounding the solar cell

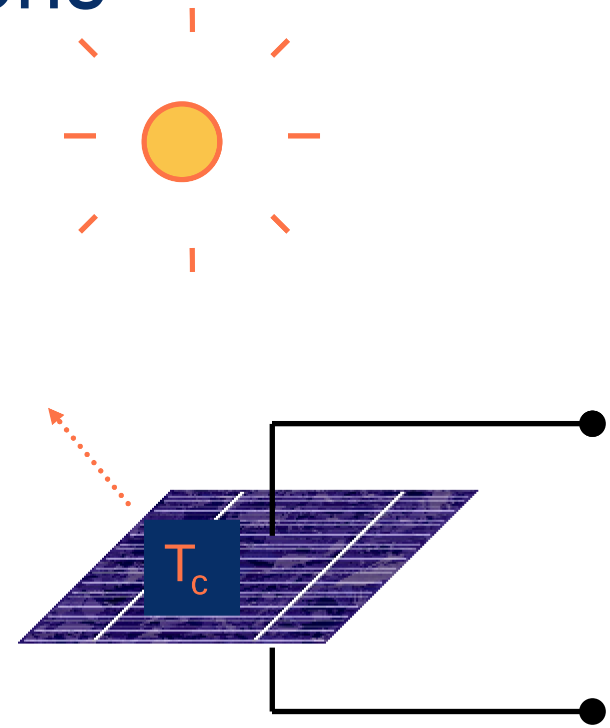
  - $b_S(E,T_S)$ = from the Sun
  - $b_a(E,T_s)$ = from the ambient



Emitted photons

- The solar cell emits photons ($dN/dt_{phot,rad}(E)$) back towards the Sun and the ambient surrounding the solar cell
  - $b_c(E,T_c)$ = from the solar cell

- In the following, we shall assume that the cell and ambient are in thermal equilibrium
  - $T_c = T_a$



Detailed balance – current densities

- The photons absorbed and emitted by the solar cell can be imagined to correspond to current densities in the following manner:

  - Photons absorbed by the solar cell from the ambient correspond to an absorption current density ($J_{abs,a}(E)$)

$$J_{abs,a}(E) = q \cdot ([1 - R(E)] \cdot a(E) \cdot b_a(E, T_a))$$

  - Photons emitted by the solar cell correspond to a radiated current density ($J_{rad}(E)$)

$$J_{rad}(E) = q \cdot ([1 - R(E)] \cdot e(E) \cdot b_c(E, T_c))$$

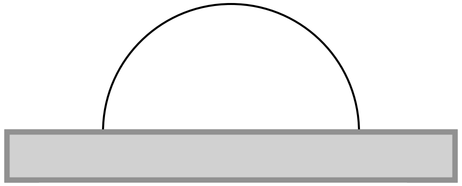
  - Here $e(E)$ is the spectral emissivity of the solar cell.
  - It can be shown that $e(E) = a(E)$ for all situations considered in the following

Detailed balance (dark): $J_{net}(E) = J_{abs,a}(E) – J_{rad}(E)$

Case 1: the solar cell in darkness

- In darkness, the only radiation absorbed by the solar cell comes from the ambient
- From now on, we assume an ideal solar cell model
  - $a(E) = 1$, $R(E) = 0$
- Detailed balance states that

$$J_{net}(E) = J_{abs,a}(E) - J_{rad}(E)$$



Detailed balance (dark): $J_{net}(E) = J_{abs,a}(E) - J_{rad}(E)$

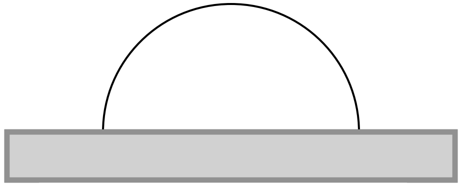
Case 1: the solar cell in darkness

- For simplicity, every point on the solar cell is assumed to absorb and emit radiation from the entire surrounding hemisphere

$$F_c = F_a = \pi$$

- Since thermal equilibrium is assumed ($T_c = T_a$), it immediately follows that

$$b_c(E,T_c) = (2F_S/h^3c^2) \cdot (E^2/(e^{(E/kT_c)} - 1))$$
$$=$$
$$(2F_a/h^3c^2) \cdot (E^2/(e^{(E/kT_a)} - 1)) = b_a(E,T_a)$$



Case 1: the solar cell in darkness

- Absorbed radiation only from the ambient:

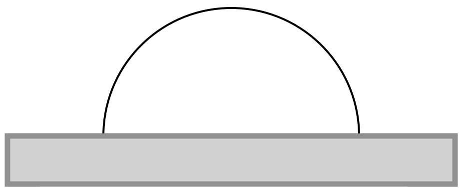
$$J_{abs,a}(E) = q \cdot b_a(E,T_a)$$

- Emitted radiation from the solar cell:

$$J_{rad}(E) = q \cdot b_a(E,T_a)$$

- Detailed balance:

$$J_{net}(E) = J_{abs,a}(E) - J_{rad}(E) = 0$$



- Hence ,in equilibrium, $J_{net}(E) = 0$, as expected

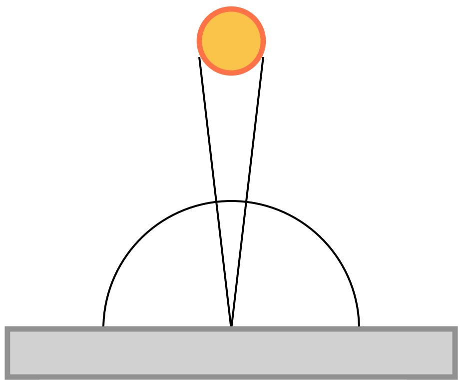
Detailed balance (light): $J_{net}(E) = J_{abs,a}(E) + J_{abs,S}(E) – J_{rad}(E)$

Case 2: the illuminated solar cell

- The radiation absorbed by the solar cell under illumination comes both from the Sun and the ambient:

$$J_{abs,S}(E) = q \cdot b_S(E,T_S)$$

$$J_{abs,a}(E) = q \cdot (1 – F_S/F_a) \cdot b_a(E,T_a)$$



Detailed balance (light): $J_{net}(E) = J_{abs,a}(E) + J_{abs,S}(E) - J_{rad}(E)$

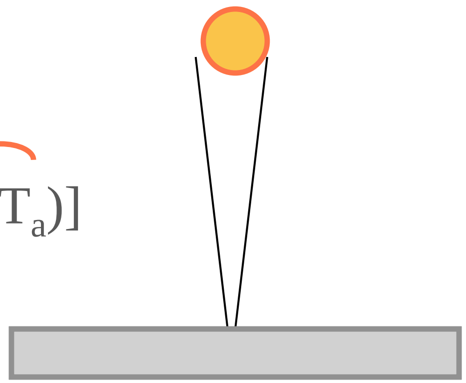
Case 2: the illuminated solar cell

- Recall that the form factors of these two terms are as follows

$$F_a(E) = \pi$$
$$F_S(E) \approx 2 \cdot 10^{-5} \cdot \pi$$

- The total absorbed current density becomes

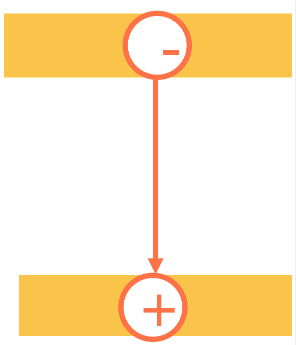
$$J_{abs,TOT}(E) = q \cdot [\overbrace{b_S(E\,,T_S)}^{\text{From Sun}} + \overbrace{(1 - F_S/F_a) \cdot b_a(E,T_a)}^{\text{From ambient}}]$$



Detailed balance (light): $J_{net}(E) = J_{abs,a}(E) + J_{abs,S}(E) - J_{rad}(E)$

Excited electron population

- The radiation emitted by the solar cell is affected by the illumination
  1. Illumination will excite a number of electrons
  2. The excited part of the electron population has increased its potential energy
  3. This extra electronic energy is described as an increased chemical potential ($\Delta\mu$)
  4. $\Delta\mu$ will affect the black body radiation by increasing the spontaneous emission rate and, hence ,the emitted spectral photon flux density
- Thus:



$$b_{rad,\ ill}(E,T_a) = (2\pi/h^3c^2) \cdot (E^2/(e^{((E)/kT_a)}) - 1)$$

$$\downarrow$$

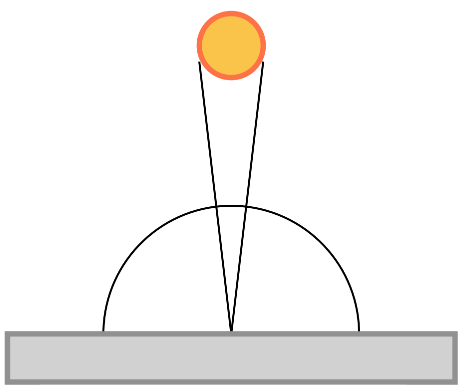
$$b_{rad,\ ill}(E-\Delta\mu,T_a) = (2\pi/h^3c^2) \cdot (E^2/(e^{((E-\Delta\mu)/kT_a)}) - 1) > b_{rad,\ ill}(E,T_a)$$

Detailed balance (light): $J_{net}(E) = J_{abs,a}(E) + J_{abs,S}(E) - J_{rad}(E)$

Case 2: the illuminated solar cell

- The resulting ratiation current density becomes

$$J_{rad}(E) = q \cdot b_{rad,\, ill}(E - \Delta\mu, T_a)$$



Detailed balance (light): $J_{net}(E) = J_{abs,a}(E) + J_{abs,S}(E) - J_{rad}(E)$

Detailed balance

$$J_{net}(E) = J_{abs,TOT}(E) - J_{rad}(E)$$

$$=$$

$$q \cdot [b_S(E,T_S) + (1 - F_s/F_a) \cdot b_a(E,T_a) - b_{rad,\,ill}(E - \Delta\mu, T_a)]$$

$$=$$

$$q \cdot \underbrace{[b_S(E,T_S) - (F_s/F_a) \cdot b_a(E)]}_{\text{Net absorption}} - \underbrace{[b_{rad,\,ill}(E - \Delta\mu, T_a) - b_a(E,T_a)]}_{\text{Net radiative recombination}}$$

Detailed balance

- Net absorption
  - The effect of substituting a small part of the ambient with the Sun
  - Gives absorption in excess of the equilibrium absorption

$$q \cdot [b_S(E,T_S) - (F_s/F_a) \cdot b_a(E)]$$

- Net radiative recombination
  - The emitted flux from the solar cell in excess of purely temperature-dependent black body radiation

$$q \cdot [b_{rad,\, ill}(E - \Delta\mu, T_a) - b_a(E,T_a)]$$

Detailed balance

- So far, we have derived a general expression for the net spectral current density in the case of detailed balance

$$J_{net}\,(E > E_g) = q \cdot ([b_S(E,T_S) – F_s/F_a) \cdot b_a(E)] – [b_c(E – \Delta\mu,T_a) – b_a(E,T_a)])$$

- If we also assume that F_s/F_a is negligible, we get

$$\boxed{J_{net}\,(E > E_g) = q \cdot (b_S(E,T_S) – [b_c(E – \Delta\mu,T_a) – b_a(E,T_a)])}$$

J_{sc} $\quad J_{rad}\,(E,\Delta\mu,T_a)$

Clever student question:

”What does this really mean?”

Theoretical limits to J_{sc}

- The light induced spectral current density simply becomes

$$J_{abs}(E) = J_{SC}(E) = q \cdot b_S(E,T_S)$$

- The resulting total short circuit current density (J_{SC}) is then given by

$$J_{SC} = q \int_{E_g}^{\infty} b_S(E,T_S)$$

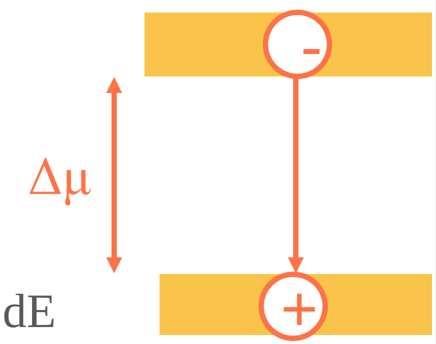
- Hence, J_{SC} is determined **uniquely** by E_g and b_s

The meaning of J_{rad}

- Quantifying the emitted spectral current density from the solar cell requires knowledge of the exact recombination mechanism and the excited carriers
  - We will **not** performed a detailed calculation here!
  - However, we might argue as follows:

1. In the very best case, only radiative recombination will reduce the efficiency
2. If transport through the solar cell proceeds without loss
   - No voltage losses associated with transport to external contacts
   - The voltage at the terminals must correspond to the extra potential energy of the electrons

$$\Delta\mu = qV$$



- Then

$$J_{net}(V) = q \int_{E_g}^{\infty} \left[b_S(E,T_S) - (b_a(E - qV,T) - b_a(E,T)) \right] \cdot dE$$

The meaning of J_{rad}

- We can rewrite the radiative part in the following manner

$$b_a(E - qV,T) - b_a(E,T) = (2F_aE^2/h^3c^2) \cdot [1/(e^{(E-qV)/kT} - 1) - 1/(e^{E/kT} - 1)]$$

- If qV becomes large (assuming $qV >> E$ and $E >> kT$), we **approximately** get

$$1/(e^{(E-qV)/kT} - 1) - 1/(e^{E/kT} - 1) \sim 1/e^{(E-qV)/kT} - 1/e^{E/kT} = e^{qV/kT} - 1/(e^{E/kT})$$

$$\sim e^{qV/kT}$$

$J_{net}(V)$

- Hence, for an ideal p-n homojunction solar cell, it can be shown that the expression:

$$J_{net}(V) = q \int_{E_g}^{\infty} [b_S(E,T_S) - (b_a(E,T_a - qV) - b_a(E,T_a))] \cdot dE$$

becomes:

$$J_{net}(V) = J_{SC} - J_0 \, e^{qV/kT}$$

which almost is the familiar:

$$J_{net}(V) = J_{SC} - J_0(e^{qV/kT} - 1)$$

Detailed balance – available work

- We recall that

$$\eta = P_{cell}/P_{sun}$$

- Hence,

$$\eta(V)$$
$$=$$
$$V \cdot A \cdot J(V) \,/\, P_{sun}$$
$$=$$
$$V \cdot A \cdot q \int_{E_g}^{\infty} [b_S(E,T_S) - (b_a(E,T_a - qV) - b_a(E,T_a))]dE \,/\, P_{sun}$$
$$=$$
$$V \cdot A \cdot (J_{SC} - J_0(e^{qV/kT} - 1)) \,/\, P_{sun}$$

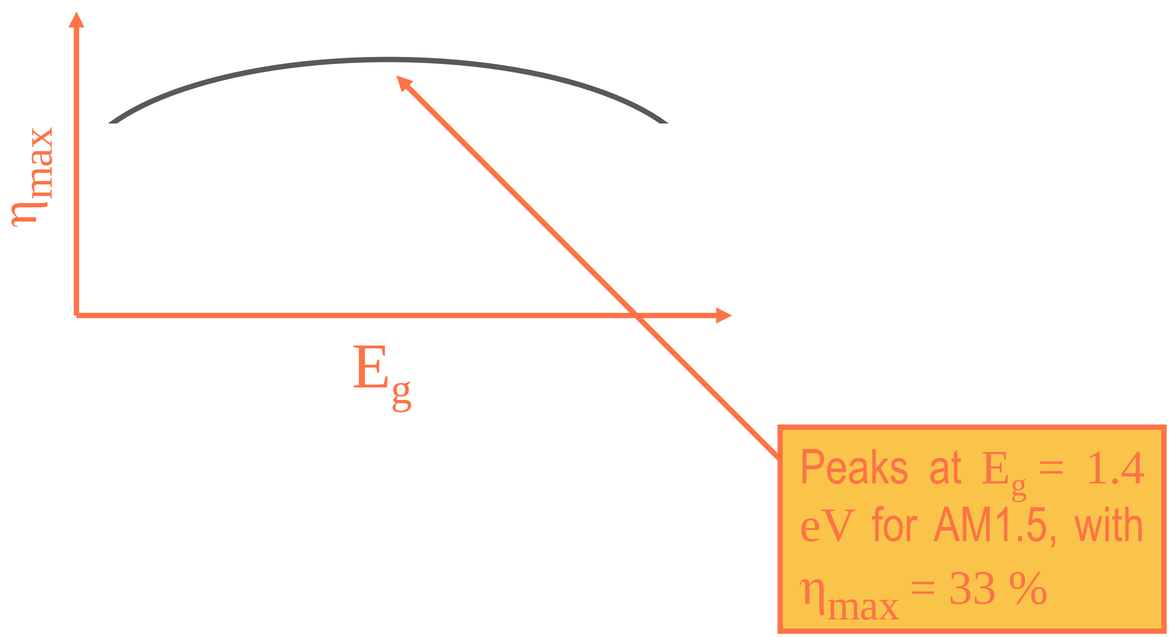
Detailed balance – available work

- Maximum η is achieved when

$$d\eta(V)/dV = d(V \cdot A \cdot J(V) / P_{sun})/dV = 0$$

Detailed balance – available work

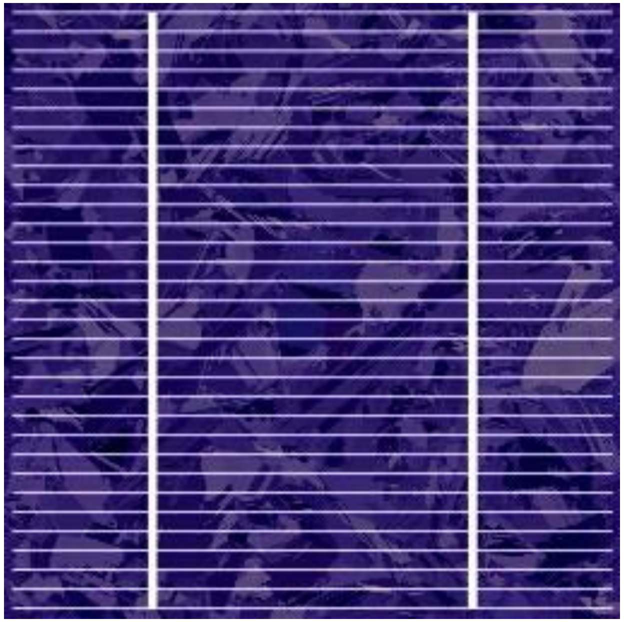
- If we plot η_{max} as a function of E_g, we get something like



Various calculated η_{max}

- AM1.5 spectrum
  - ~33% at 1.4 eV
  - ~29% at 1.1 eV (Si!)

- Black body Sun (T_s = 5760K)
  - ~31% at 1.3 eV



Clever student question:

”How efficient are solar cells *really*?”

Record efficiencies – good reference

Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2013; **21**:827–837
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2404

ACCELERATED PUBLICATION

Solar cell efficiency tables (version 42)

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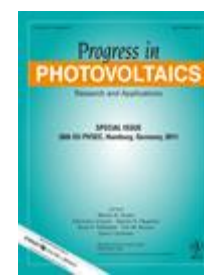
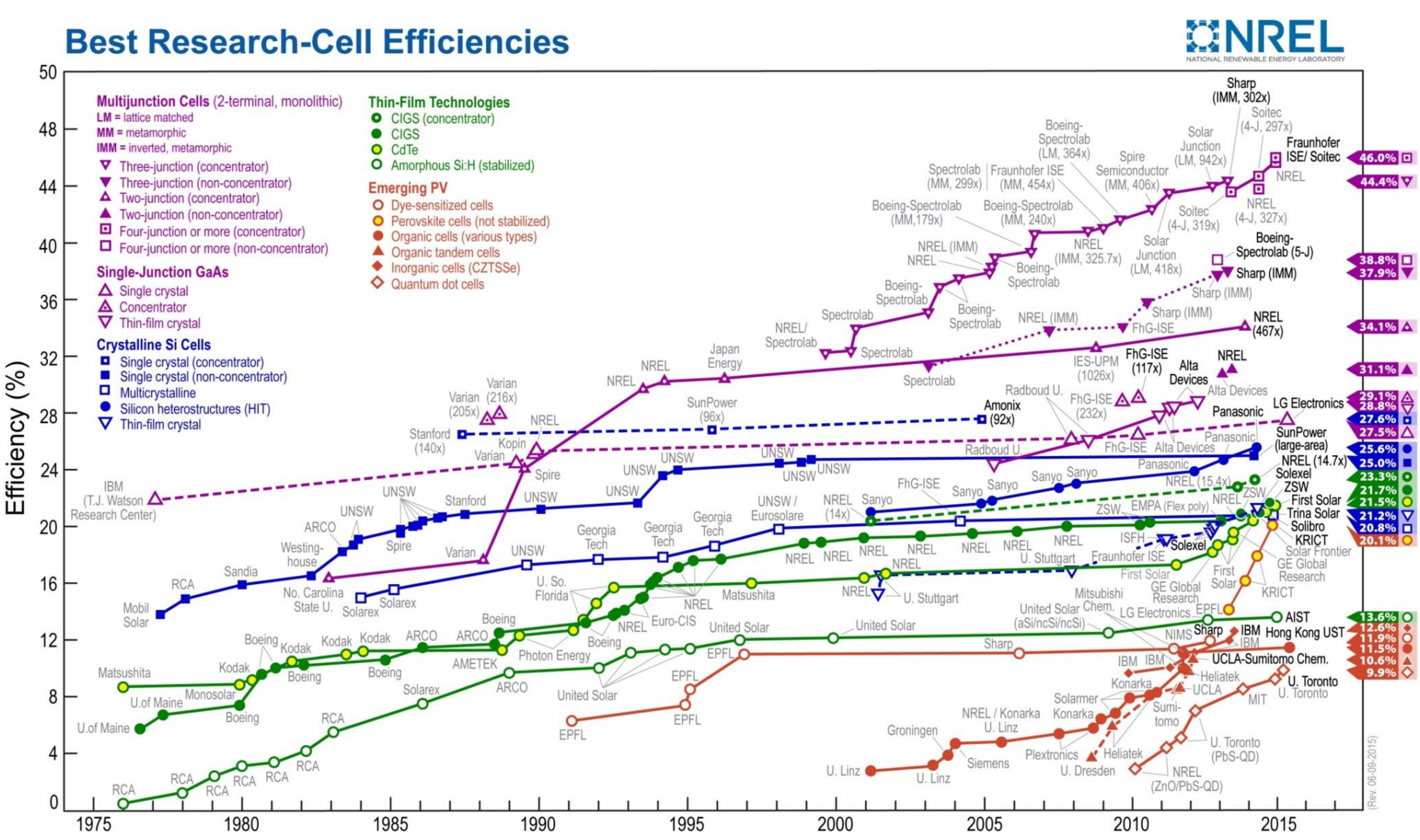


Image: PIP



Data: NREL (2015)

Solar cell operation

- The power generation in a solar cell can be divided into three steps

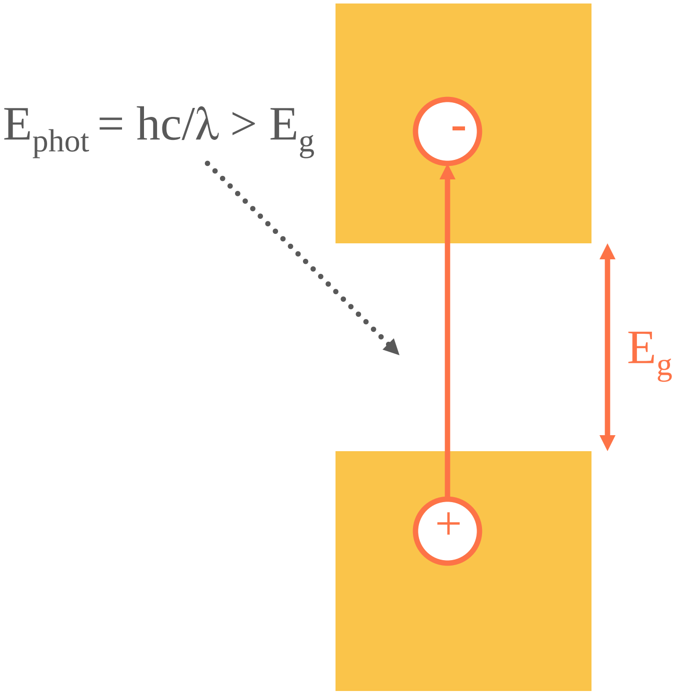
    1. Photogeneration of charge carriers
    2. Separation of charge carriers
    3. Transport of the charge carriers from the point of generation to the external electrical connections

- An efficient solar cell must perform all these tasks efficiently

Photogeneration

<u>Design rules</u>

1. Use materials with several electronic energy levels
   - Semiconductors, polymers…
2. Trap as much sunlight as possible
   - Use anti-reflective coatings and texturing
   - Minimize contact shading
3. Avoid excessive transmission
   - Weakly absorbing materials require optically thick solar cells
   - Strongly absorbing materials can be used for thin film solar cells

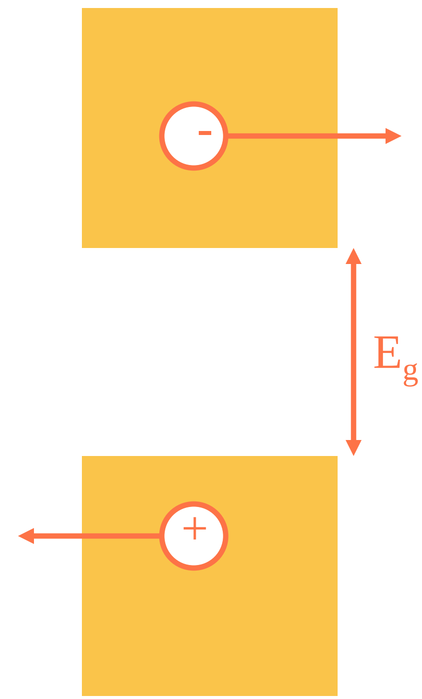


Separation

Design rules

1. Asymmetry must be built into the solar cell in order to obtain a net current
   - Built-in electrical fields
   - Combinations of hole and electron conductors
   - …

2. In order to obtain a high V_{oc}, the energy separation of the electrons and holes should be maintained as large as possible until the carriers are collected

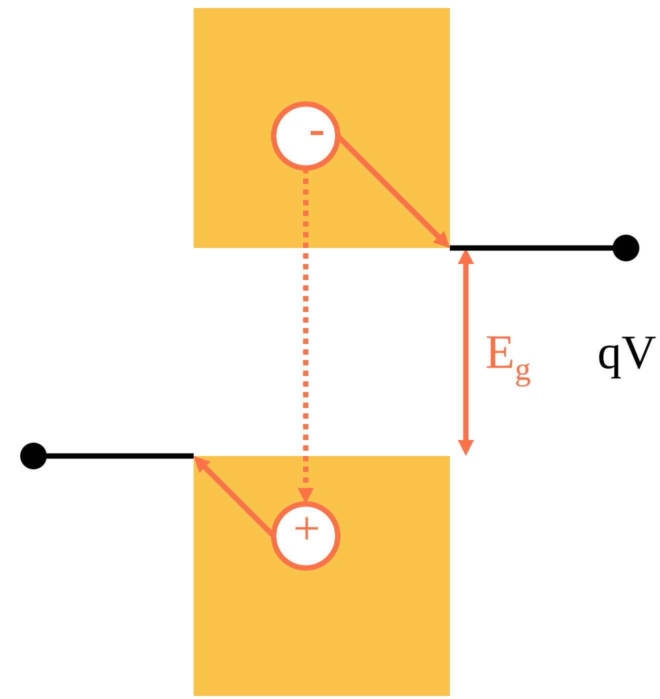


Transport

Design rules

1. Minimize resistive losses
   - Series resistance
   - Shunt resistance

2. Avoid recombination of charge carriers
   - Material (bulk) recombination
   - Surface (interface) recombination



Concluding remarks

- Much theoretical work on efficiency limit calculations has been done

- Si solar cells
  - Theoretical limit 29.4 %
  - Best «laboratory» cells 26.6 %
  - Good sc-Si industrial cell («high efficiency») > 20 %
  - Good mc-Si industrial cell > 16 %