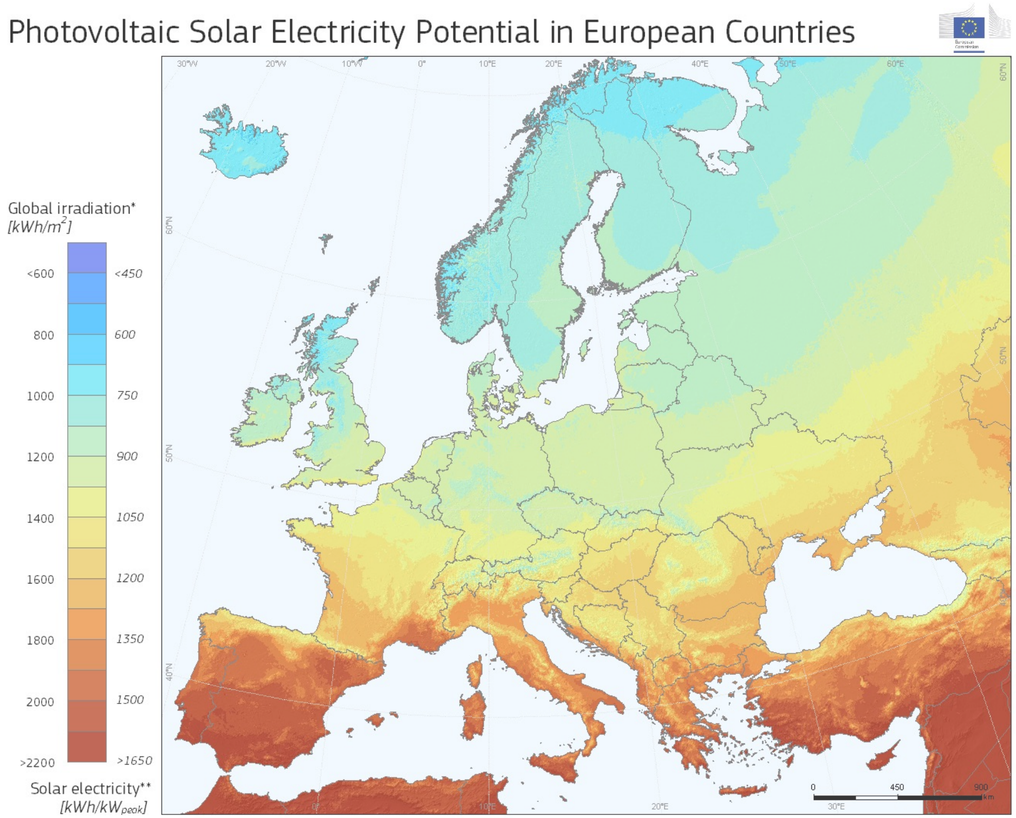
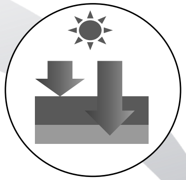


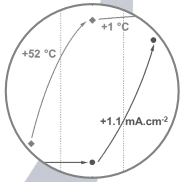
| M. Amara

Modeling and Simulation of Photovoltaic Devices and Systems

OUTLINE



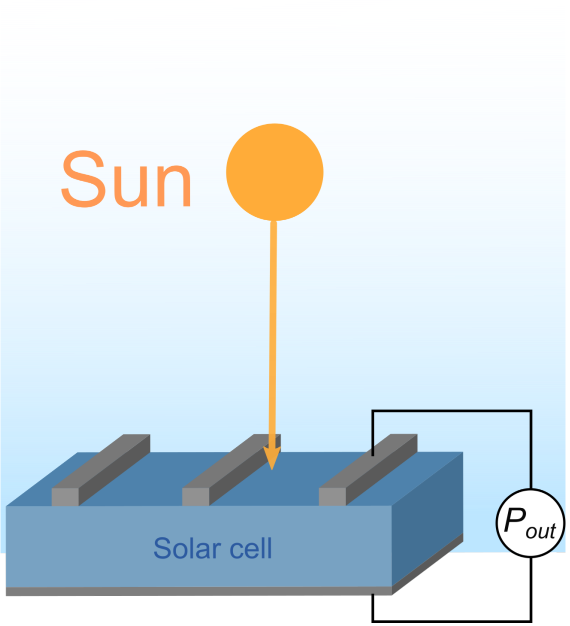
Basic concept of solar cells



PV modeling & simulation

Conclusions

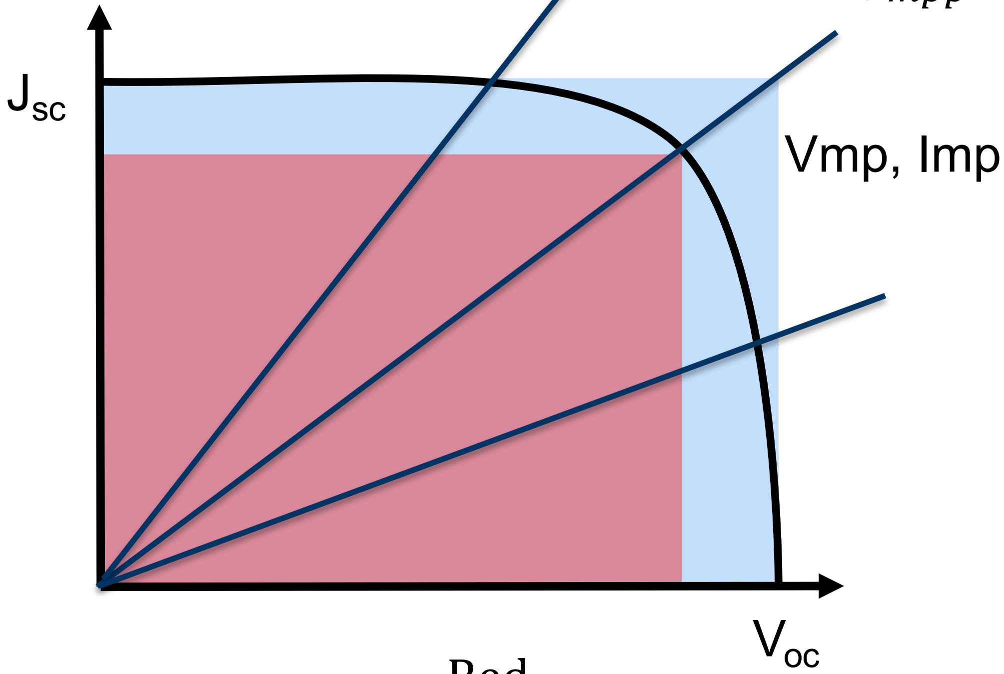
What is a Solar Cell ?



- Short circuit current
- Open circuit voltage
- Fill factor

$$\eta = \frac{J_{sc} \times V_{oc} \times FF}{P_{iin}}$$

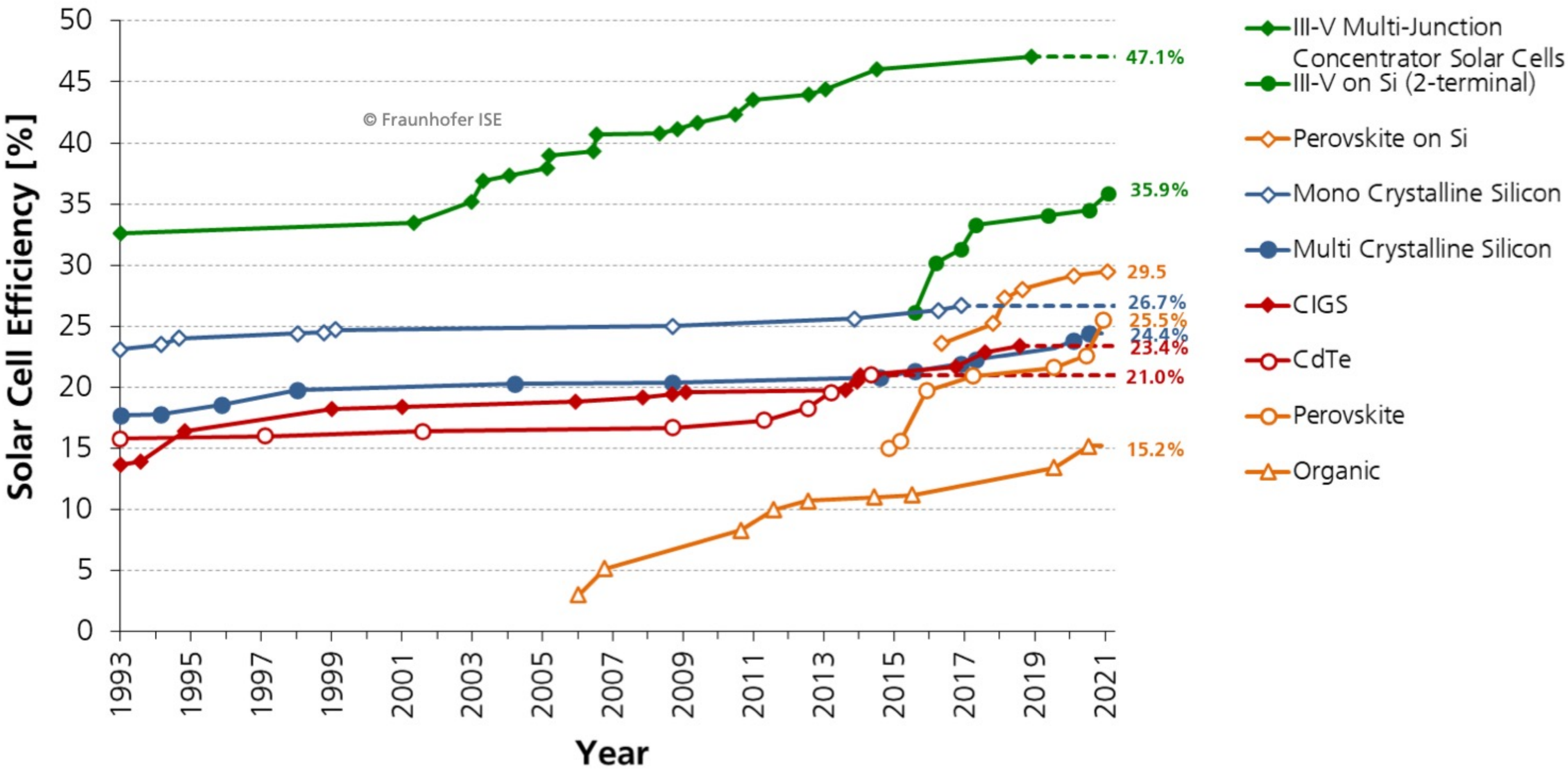
$$R_{ch} = \frac{V_{mpp}}{J_{mpp}}$$



$$\text{FF} = \frac{\text{Red}}{\text{Blue}}$$

➢ What is the best solar cells performances?

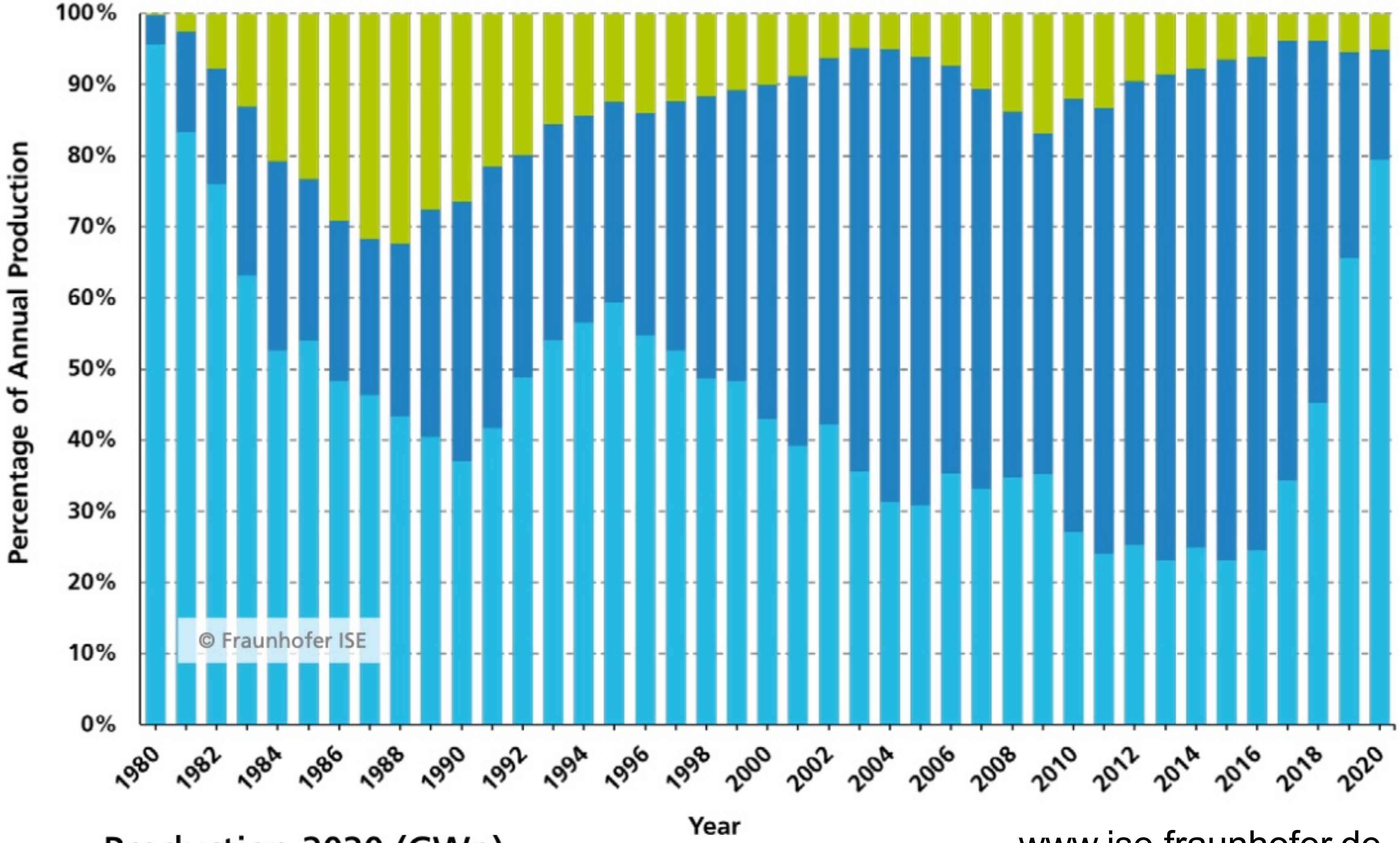
To day solar cell efficiency @ 25°C and 1000 W/m²



www.ise.fraunhofer.de

However !!

Annual PV production by technology



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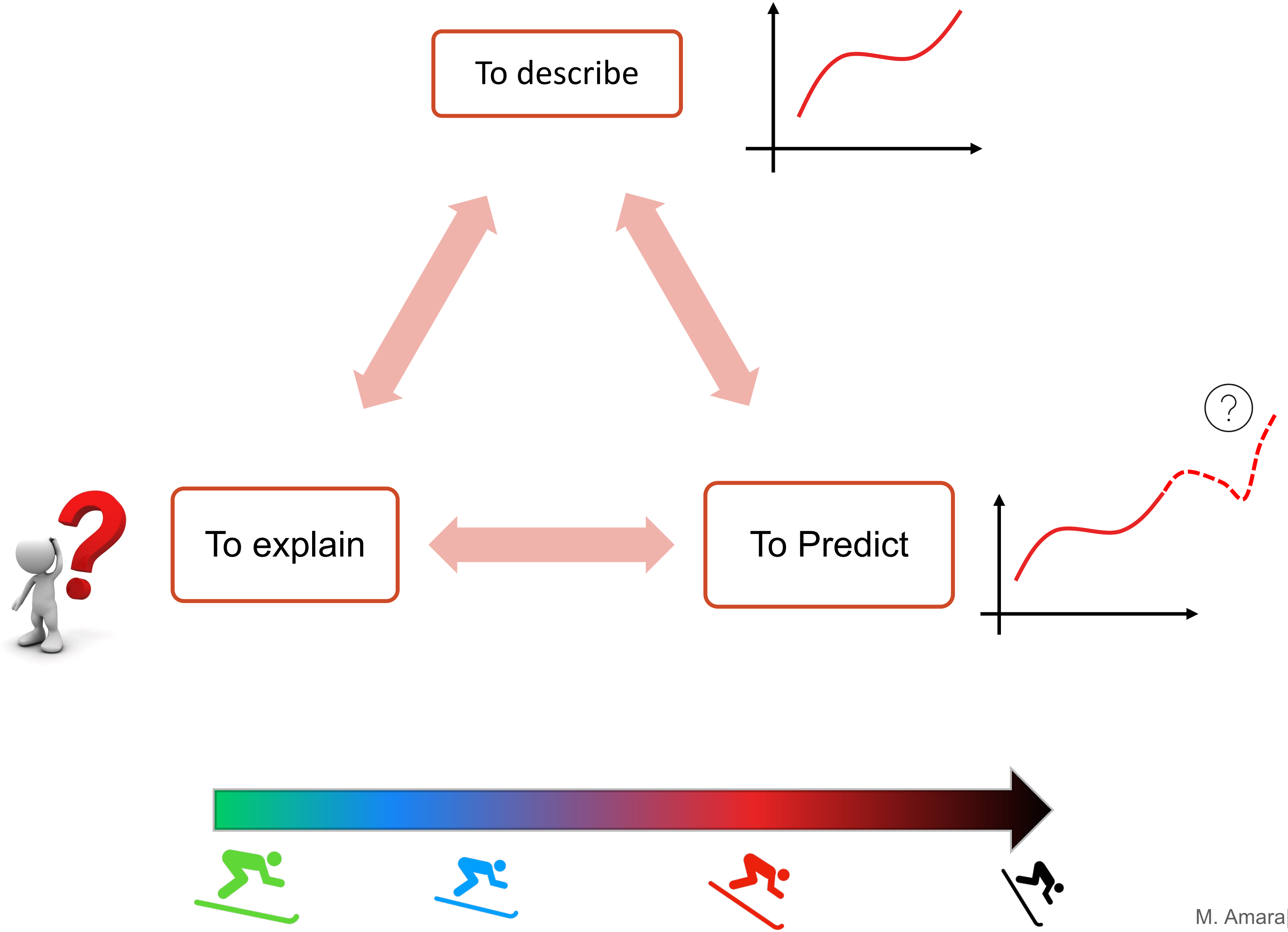
Production 2020 (GWp)

Thin film	7.7
Multi-Si	23.3
Mono-Si	120.6

CdTe: 6.1
CIGS :1.5
a-Si : 0.2

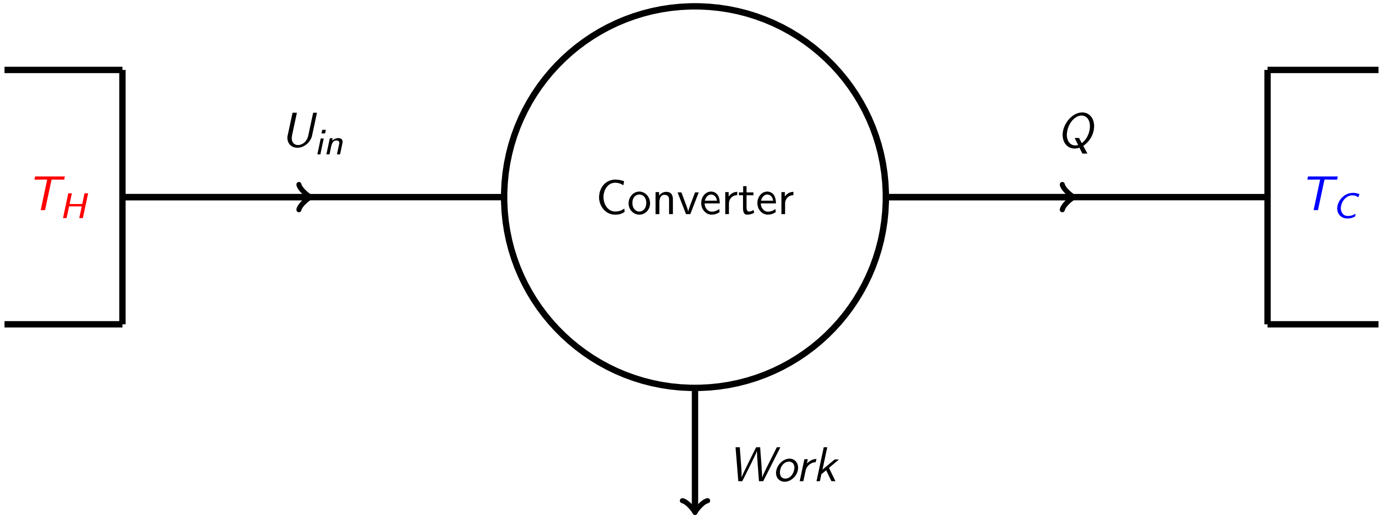
PV modeling & simulation

Why modeling & simulation



Basic concepts

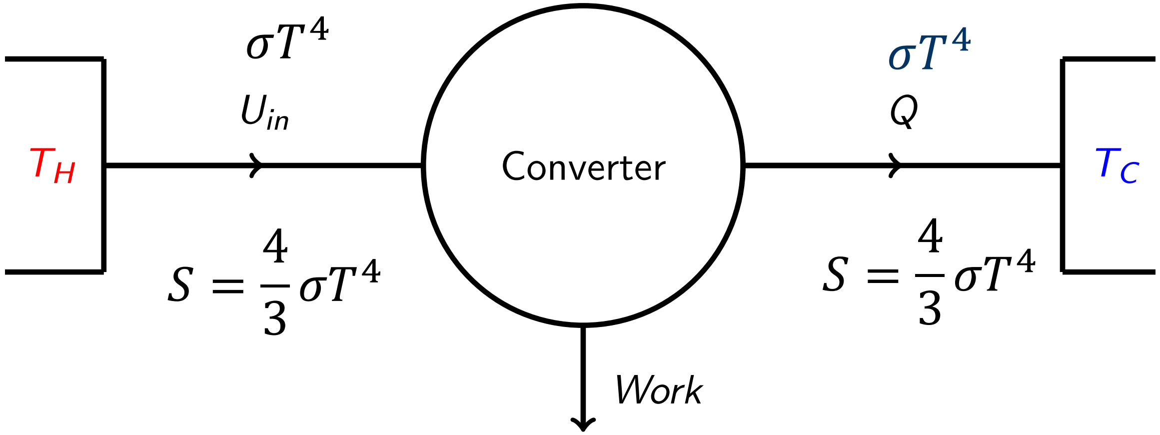
➢ What does thermodynamics tell-us: the sky is the limit



No entropy generation

➡ $$\eta = 1 - \frac{T_C}{T_H} \approx 95\%$$

Basic concepts



Helmholtz free energy

- The useful work: $F = U_{in} - T \times S$

$$\Rightarrow \quad \eta = 1 + \frac{1}{3}\frac{T_C^4}{T_H^4} - \frac{4}{3}\frac{T_C^4}{T_H^4} \approx 86\%$$

keep in mind

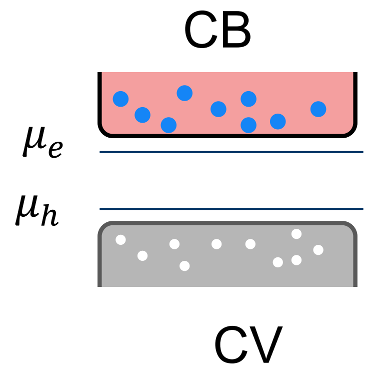
$$S = k_B \log \Omega$$

P. T. Landsberg and G. Tonge, J. Appl. Phys., (1980)

Basic concepts

μ =variation of the free energy when adding/removing 1 particle

$$\mu_e = \left.\frac{\partial F}{\partial N_e}\right|_{V,T,N_h}$$



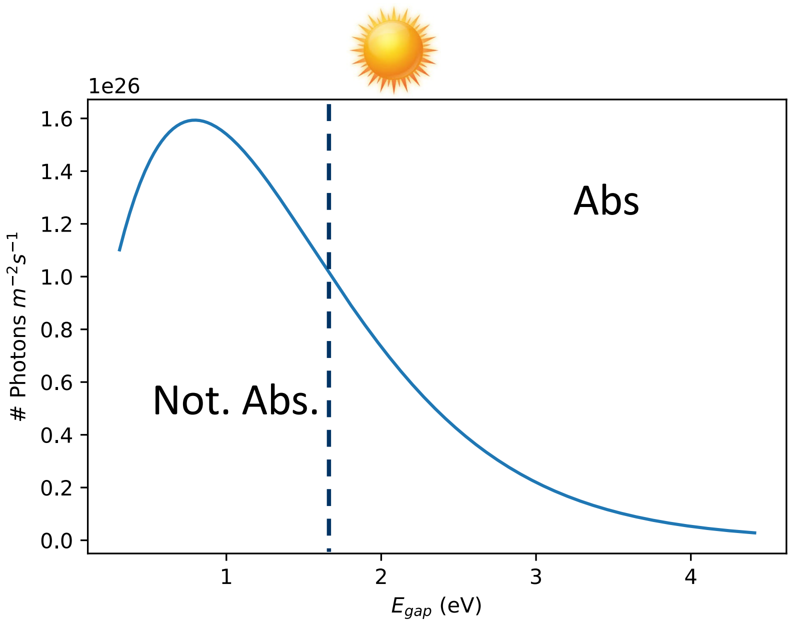
Change in free energy = maximal amount of work recoverable over the transformation

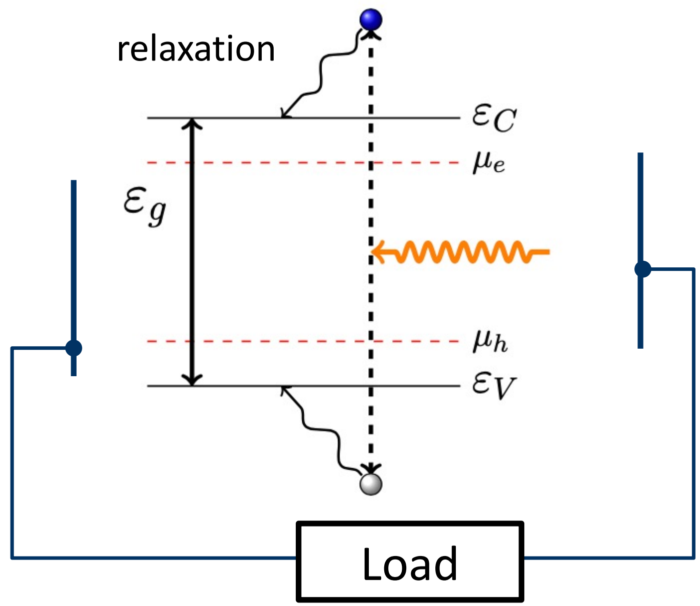
Remove 1 electron from CB, add 1 electron to VB ⟹ $W_{\text{out}} = \Delta F = \mu_e - \mu_h$

→ If two systems exhange energy, they will same temperature

→ If they exhange particle, they will reach same chemical potential

Basic concepts





$$J = qN^{\cdot} \propto q \int_{\hbar\omega > \varepsilon_g}^{\infty} \phi_s(\hbar\,\omega)\,d\omega$$

→ Energy par electron $\sim \varepsilon_g$

→ Useful power: $\mathrm{P} = \dot{N} \times W = J \times \underbrace{q \times \Delta\mu}_{V}$

What is the best solar cells ?

Carriers (absorption) and collection

→ how carriers are collected ?

$$\vec{J}_{e,h} = \sigma_{e,h} \vec{\nabla} \left(\frac{\mu_{e,h}}{q} \right)$$

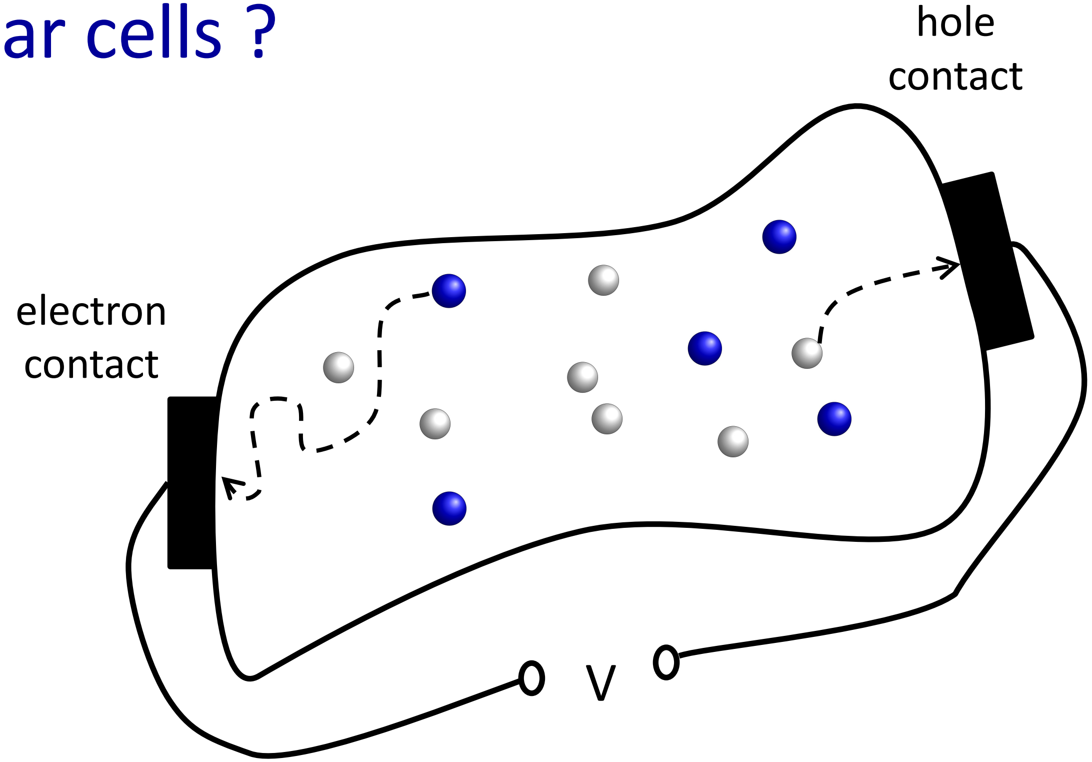
Selectivity:
e/h have to move toward different contacts (assymetry)

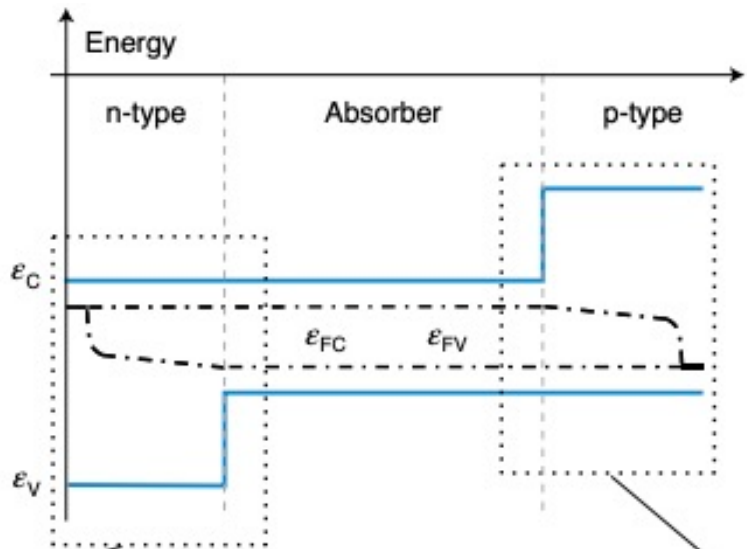
→ incomplete light absorption → α

→ Charge-carrier transport → μ

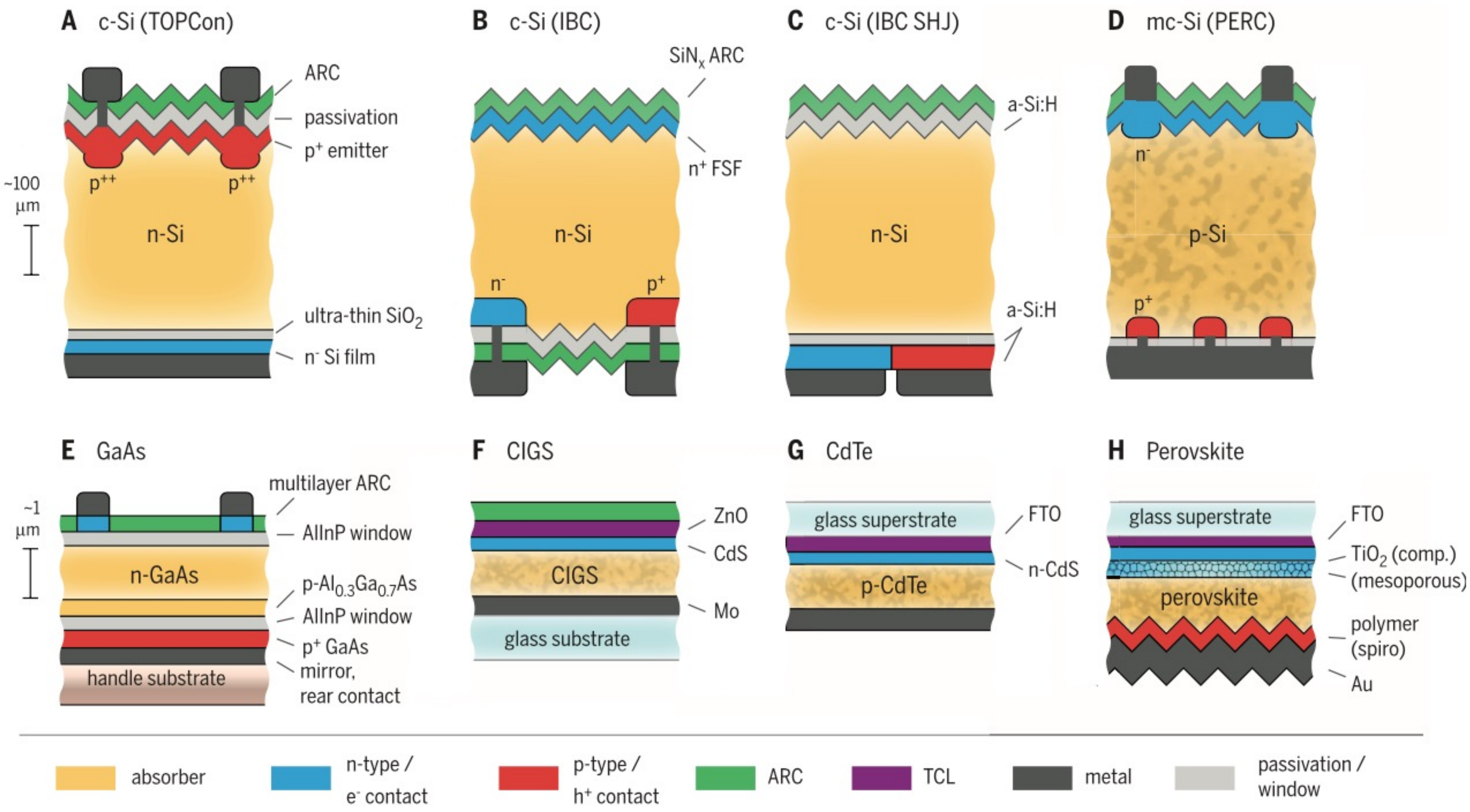
→ Charge-carrier recombination → τ

$\alpha \; \mu \; \tau$ the higher is the better



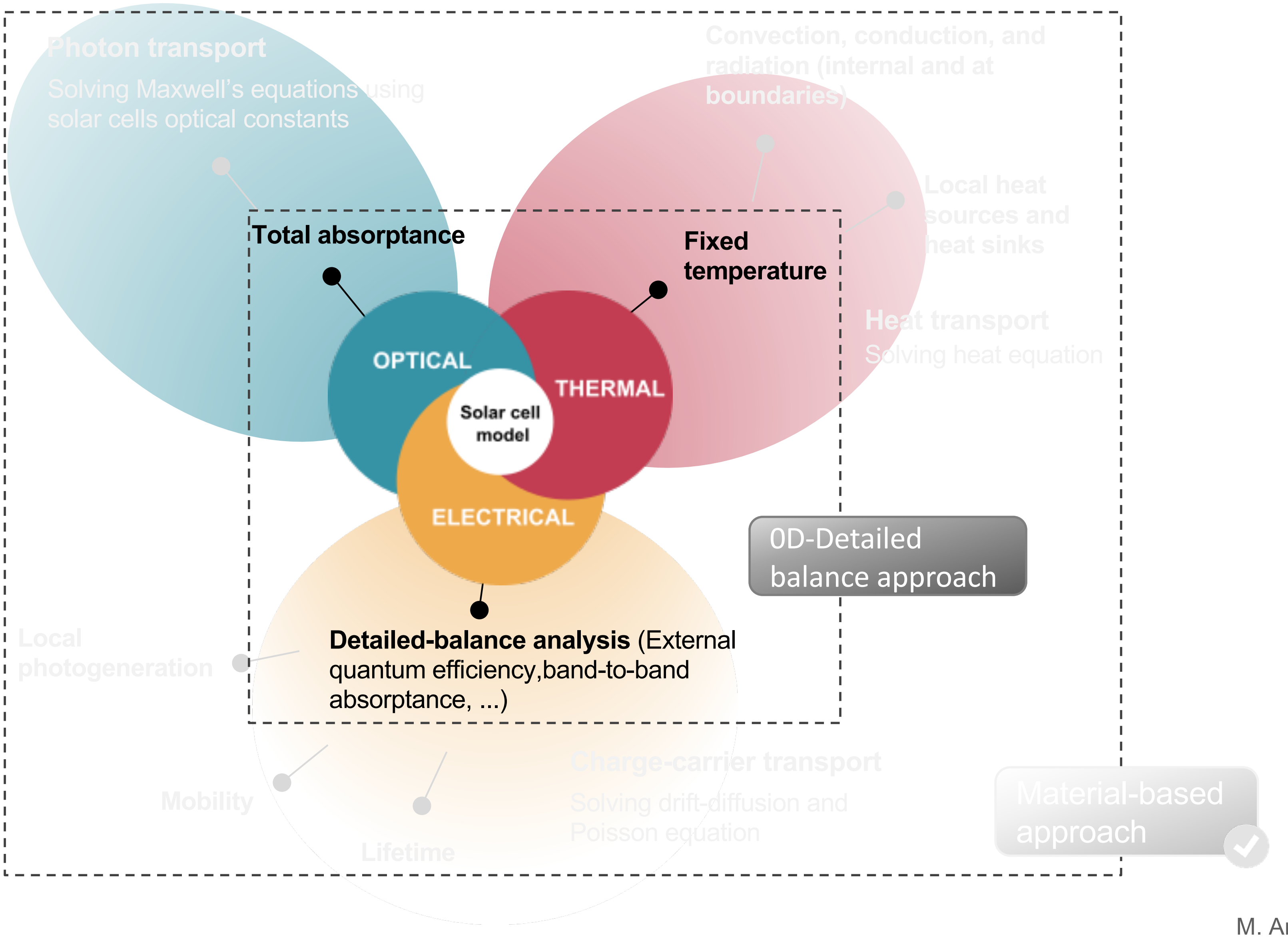


Solar cells architecture



PV modeling & simulation

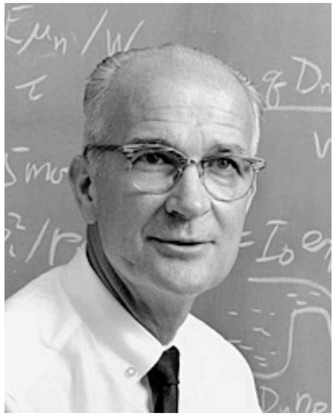
- A detailed opto-electro-thermal (OET) modelling approach



JOURNAL OF APPLIED PHYSICS VOLUME 32, NUMBER 3 MARCH, 1961

Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells*

WILLIAM SHOCKLEY AND HANS J. QUEISSER
Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California
(Received May 3, 1960; in final form October 31, 1960)



→"harshly" rejected after its first submission to JAP in 1960

→cited ~13,1700 times until its publication in 1961.

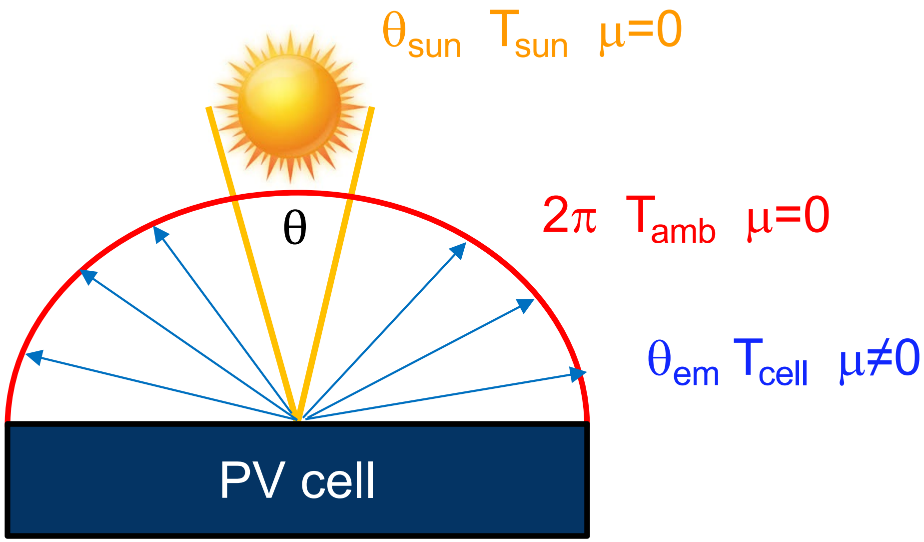
W. Shockley (1910-1989)
Nobel Prize in Physics in1956

H. Queisser

→ Only 3 parameters are required

- Temperature of the Sun
- Ambient temperature
- Electronic gap of the SC material

Shockley Queisser limit



$$\dot{N}\ (\hbar\omega) = \theta\, \frac{2\pi}{h^3 c^2} \int_{E_i}^{E_j} \frac{(\hbar\omega)^2}{e^{\frac{\hbar\omega-\mu}{k_B T}}}\, d(\hbar\omega)$$

The Würfel generalised black-body law

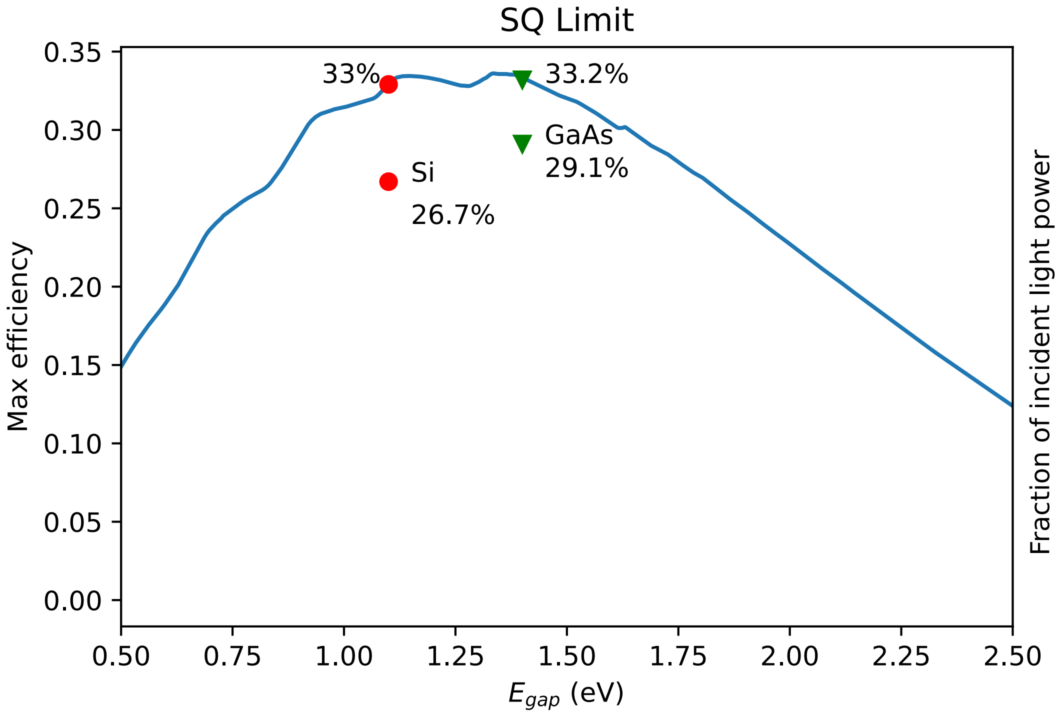
If the cell absorbe photon, it must emit ligth

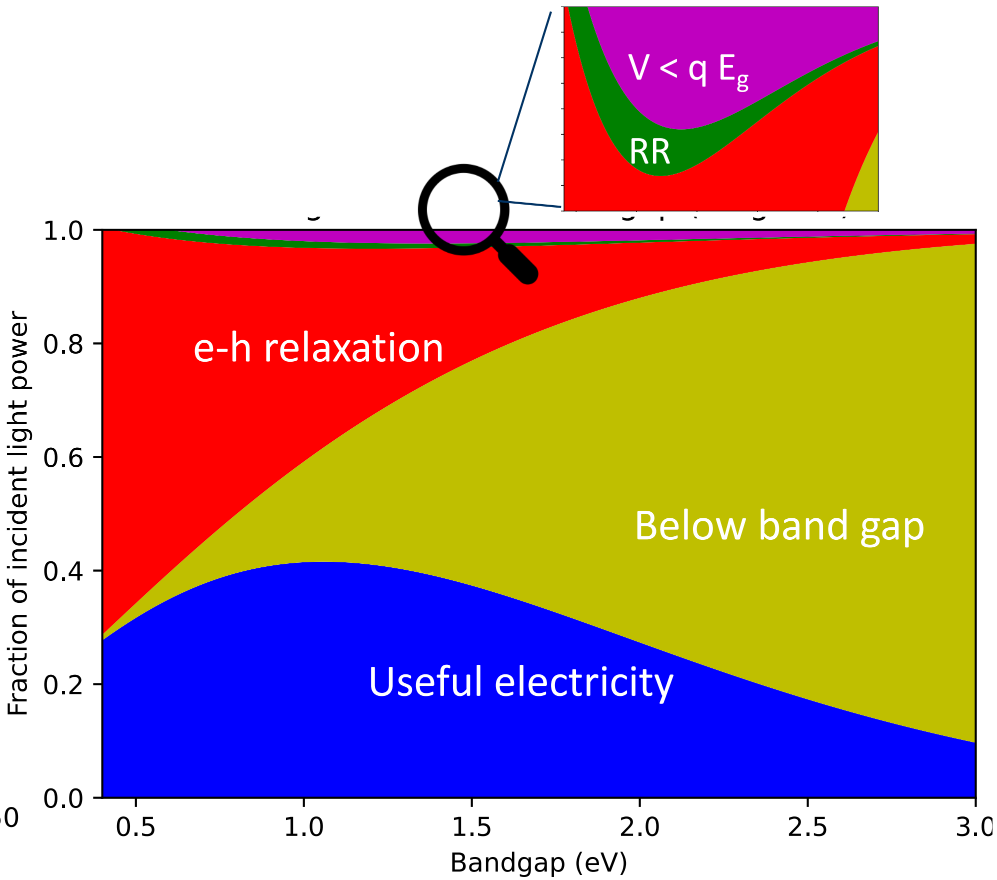
$$W_{elec} = \dot{N}_{sun}\left(\theta_{sun}, T_{sun}, E_i, E_j, \mu = 0\right) + \dot{N}_{amb}\left(2\pi, T_{amb}, E_i, E_j, \mu = 0\right) - \dot{N}_{em}\left(\theta_{em}, T_{amb}, E_i, E_j, \mu \neq 0\right)$$

→ The maximum electric work which can be extracted from a solar cell can be written as the difference between absorbed and emitted radiation.

→ A loss due to radiative recombination is fundamental i.e. unavoidable

Shockley Queisser limit



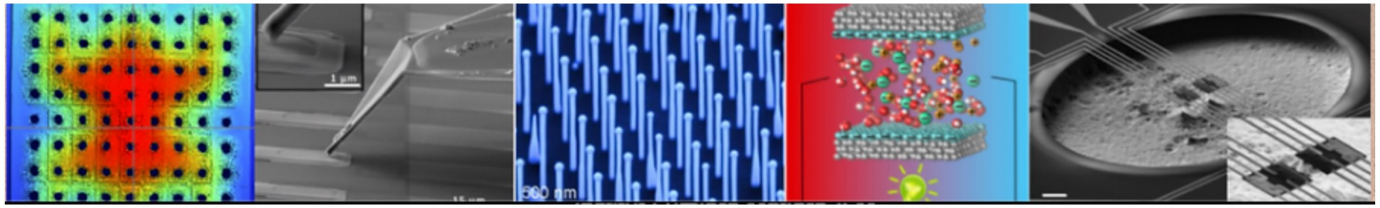


→ For silicon: the more realistic limit is about 29.1 %

jupyter **sq** Dernière Sauvegarde : vendredi dernier à 13:36 (auto-sauvegardé)

File Edit View Insert Cell Kernel Widgets Help | Non fiable | Python 3

Exécuter | Markdown



This tutorial was prepared by M. Amara (mohamed.amara@insa-lyon.fr) for the MONACOST School 2022

The code is adapted from the work of Steve Byrnes

Shockley-Queisser Limit Calculator

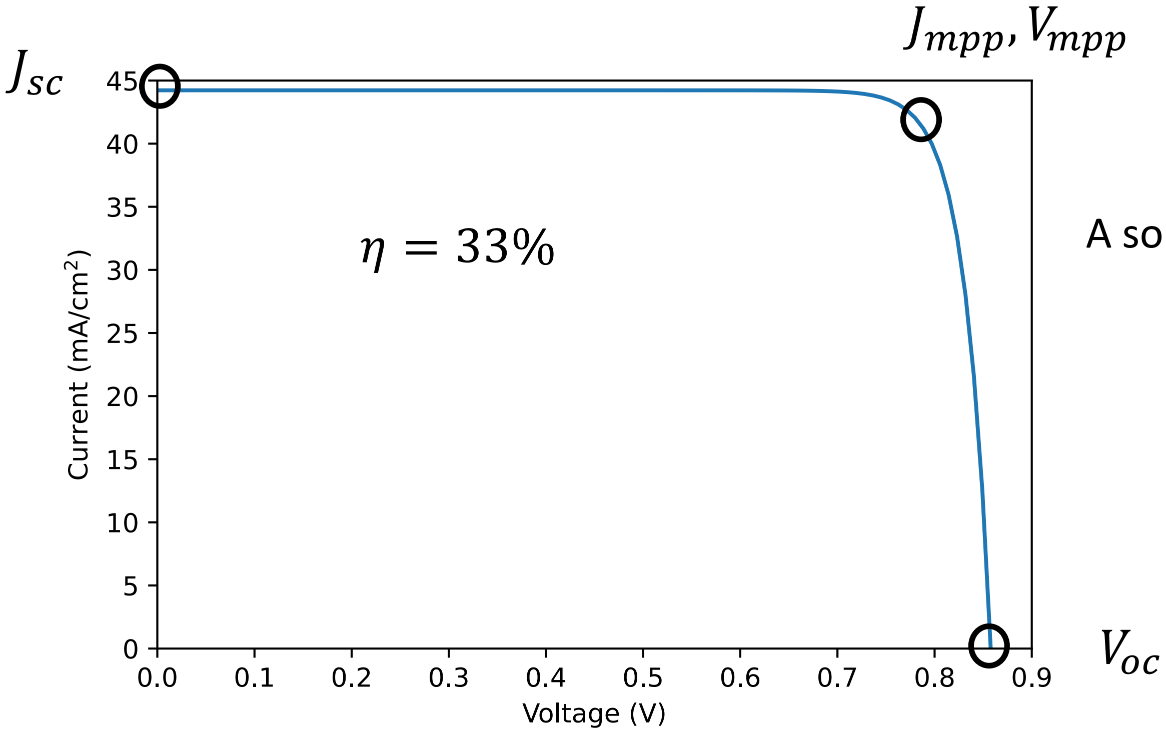
Entrée [59]:

```python
import math
import numpy as np
import matplotlib.pyplot as plt
import scipy.interpolate, scipy.integrate, pandas, sys
import scipy.constants as constants

# SciPy only comes with minimization, not maximization. Let's fix that...
from scipy.optimize import fmin
def fmax(func_to_maximize, initial_guess=0):
    """return the x that maximizes func_to_maximize(x)"""
    func_to_minimize = lambda x : -func_to_maximize(x)
    return fmin(func_to_minimize, initial_guess, disp=False)[0]

#Problem constants
```

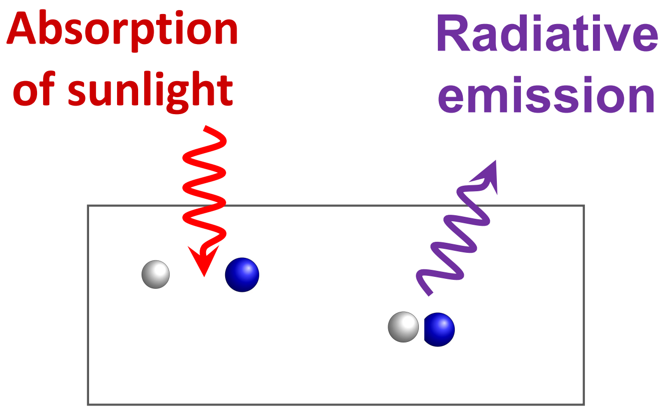
The current voltage curve



A solar cell is a power device

Diode equation → $J = J_{sc} - J_0\left(e^{\frac{qV}{k_B T}} - 1\right)$

How can we improve voltage ?

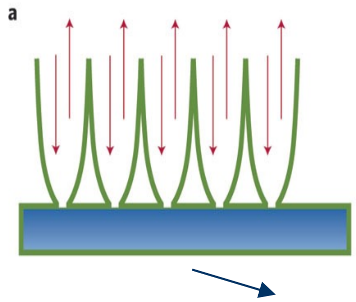


Poor light extraction

$$qV_{oc} = k_B T_c \log\left(\frac{\iint A(E,\theta)\phi_s(E)\cos\theta\, dE d\theta}{\iint A(E,\theta)\phi_{bb}(E,T_c)\cos\theta\, dE d\theta}\right) + k_B T_c \log Q_e^{LED}$$

R.T. Ross « Some Thermodynamics of photochemical systems ». J. Chem. Phys. (1967)

How can we improve voltage ?



Photon cooling : +77 meV

Directivity information -280 meV

Poor quantum efficiency - [0-300] meV

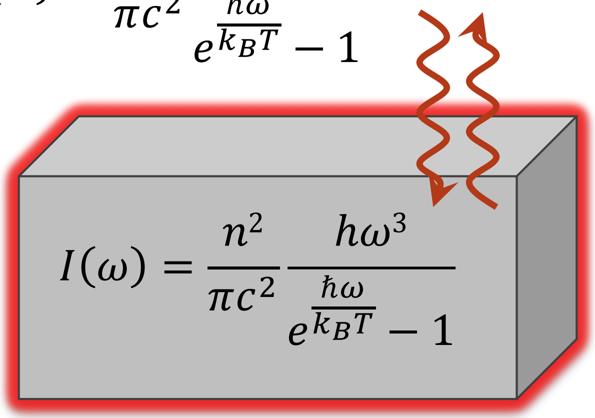
$$qV_{oc} \approx E_g\left(1 - \frac{T_c}{T_s}\right) + k_B T_c \log\frac{T_s}{T_c} + k_B T_c \log\left(\frac{\Omega_{in}}{\Omega_{out}}\right) + k_B T_c \log(Q_e^{LED})$$

$$F = U_{in}. \quad - \quad T \times S$$

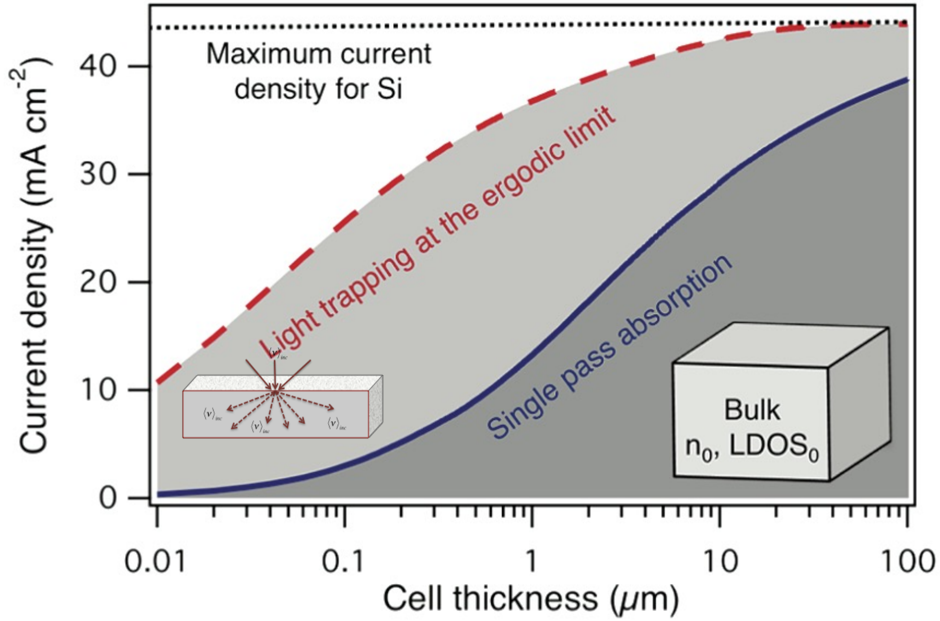
- A small band gaps are particularly vulnerable to entropy

How can we improve current ?

$$I(\omega) = \frac{1}{\pi c^2} \frac{h\omega^3}{e^{\frac{\hbar\omega}{k_B T}} - 1}$$



$$I(\omega) = \frac{n^2}{\pi c^2} \frac{h\omega^3}{e^{\frac{\hbar\omega}{k_B T}} - 1}$$

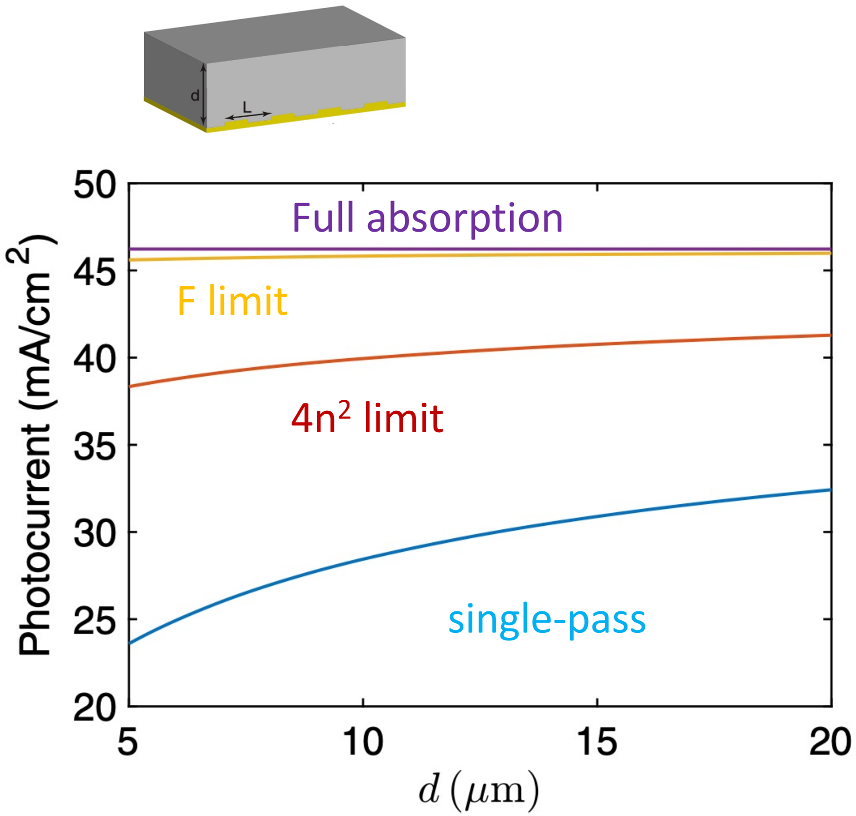


- In weakly absorbing medium, $4n^2$ absorption enhancement (for Si, ~50x)
- Reduce costs by reduced materials consumption and improved throughput (CIGS, CdTe)

D. Callahan, et.al., Nano Letters 12 pp 214-218 2012, Yablonovitch and Cody. IEEE Trans. Elect. Dev. 29 300 (1982)

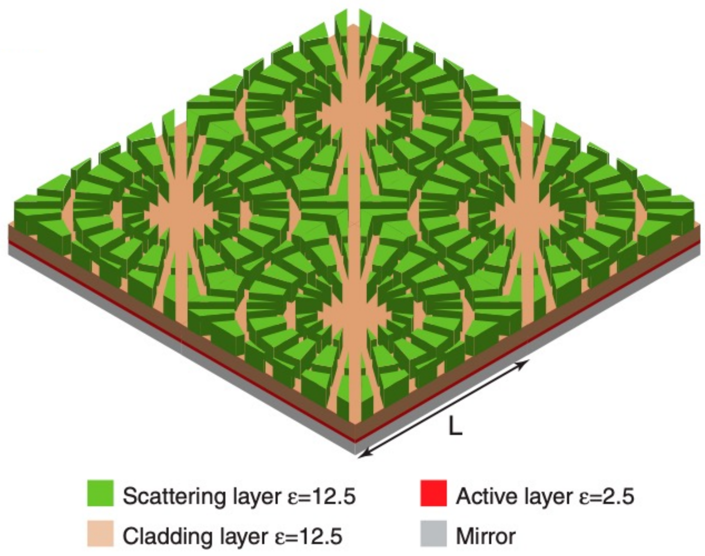
How can we improve current ?

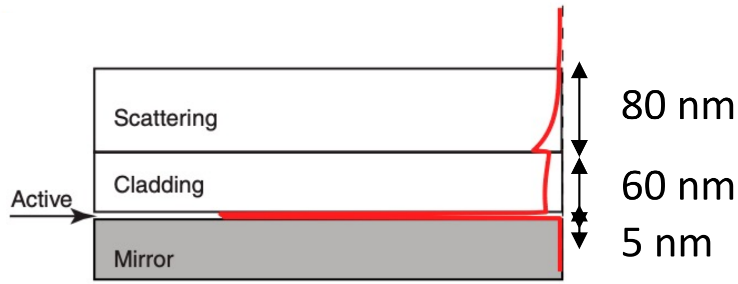
Ultimate limit of nanophotonic light trapping : Beating the $4n^2$ ray optic limit



$$F(\omega) = \left(\alpha d + \frac{\pi}{2}\left(\frac{c}{n\omega L}\right)^2\right)^{-1}$$

Numerical validation





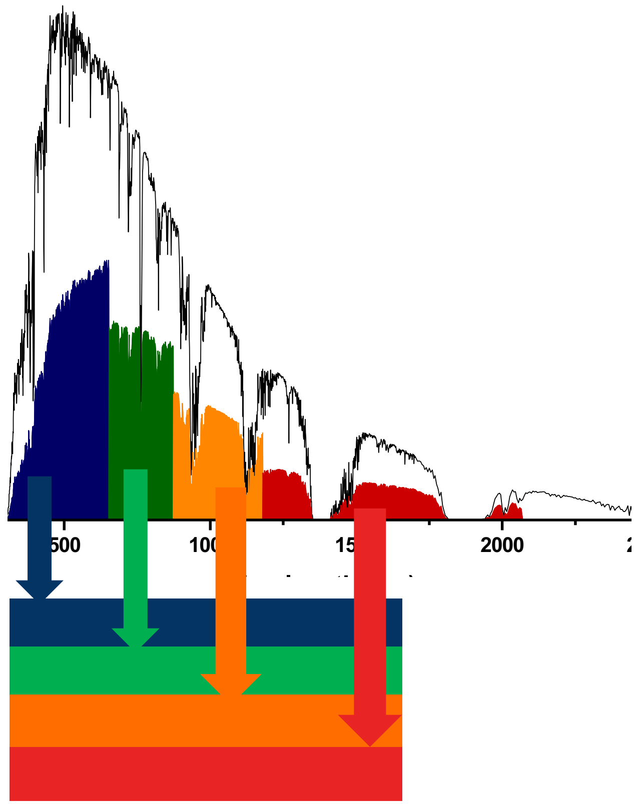
12╳$4n^2$ absorption enhancement

Yu, Raman and Fan **PNAS** 107 1749(2010).

Beyonf SQ: multi-junction solar cells

- MJ cells are designed assuming a given combination of: spectral content of the light (f(λ)), temperature (T_C), and illumination level (X).
- Achieving high solar→ electricity efficiency requires to find the (E_1,….,E_n) combination of band gaps for which the power of the whole stack is maximized

$$P_{ij}(X,f,T_c) = \max\left\{\mu\left(X\int_{E_i}^{E_j} f_{1\,sun}(E)\,\mathrm{dE} + \frac{2\pi}{h^3c^2}\int_{E_i}^{E_j}\frac{E^2}{\exp\left(\frac{E}{kT_a}\right)-1}\,\mathrm{dE} - \frac{2\pi}{h^3c^2}\int_{E_i}^{E_j}\frac{E^2}{\exp\left(\frac{E-\mu}{kT_c}\right)-1}\,\mathrm{dE}\right)\right\}$$



Current matching condition between subcells

A. Vossier, E. Al Alam, A. Dollet, M. Amara, IEEE Journal of Photovoltaics (2015).

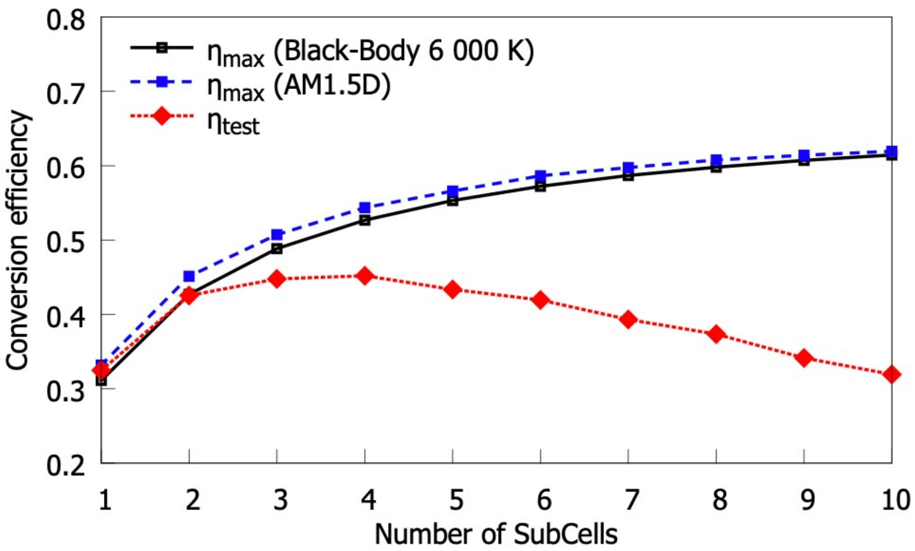
TABLE I. OPTIMUM EFFICIENCIES AND BANDGAPS FOR MJ SOLAR CELLS COMPRISING UP TO 10 SUBCELLS, UNDER AM1.5D AND 6 000 K BLACK-BODY SPECTRUM, AND FOR ONE-SUN ILLUMINATION

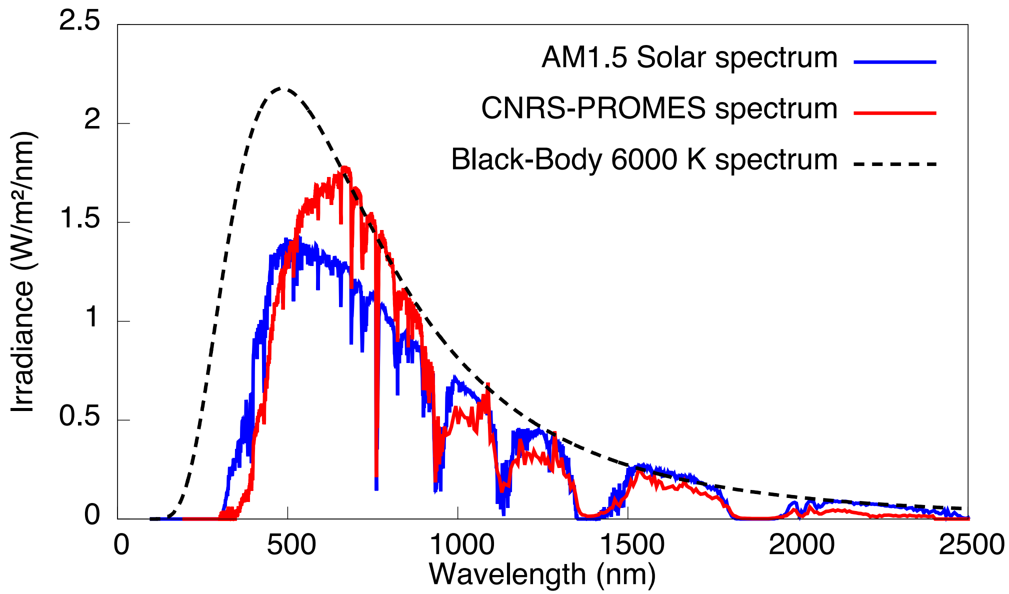
Spectrum	N. cell	Band gap [eV]										Efficiency [%]
		Eg 1	Eg 2	Eg 3	Eg 4	Eg 5	Eg 6	Eg 7	Eg 8	Eg 9	Eg 10	
AM1.5D	1	1.14	–	–	–	–	–	–	–	–	–	33.2
	2	1.57	0.94	–	–	–	–	–	–	–	–	45.1
	3	1.75	1.18	0.7	–	–	–	–	–	–	–	50.7
	4	1.94	1.44	1.05	0.7	–	–	–	–	–	–	54.4
	5	2.07	1.61	1.26	0.99	0.7	–	–	–	–	–	56.6
	6	2.18	1.74	1.44	1.17	0.95	0.68	–	–	–	–	58.7
	7	2.27	1.85	1.56	1.33	1.12	0.92	0.70	–	–	–	59.8
	8	2.29	1.88	1.59	1.37	1.16	0.96	0.74	0.5	–	–	60.8
	9	2.35	1.96	1.69	1.47	1.26	1.09	0.94	0.74	0.53	–	61.4
	10	2.41	2.03	1.77	1.56	1.39	1.21	1.05	0.92	0.74	0.55	62
Black-Body 6 000 K	1	1.30	–	–	–	–	–	–	–	–	–	31.1
	2	1.68	0.96	–	–	–	–	–	–	–	–	42.7
	3	1.95	1.30	0.82	–	–	–	–	–	–	–	48.9
	4	2.12	1.51	1.08	0.70	–	–	–	–	–	–	52.7
	5	2.28	1.69	1.30	0.97	0.66	–	–	–	–	–	55.3
	6	2.40	1.82	1.45	1.15	0.88	0.60	–	–	–	–	57.2
	7	2.51	1.95	1.59	1.30	1.05	0.82	0.58	–	–	–	58.7
	8	2.59	2.04	1.68	1.41	1.17	0.96	0.75	0.52	–	–	59.8
	9	2.68	2.13	1.79	1.52	1.30	1.10	0.91	0.72	0.52	–	60.7
	10	2.73	2.20	1.86	1.60	1.38	1.19	1.01	0.84	0.67	0.48	61.4

A. Vossier, E. Al Alam, A. Dollet, M. Amara, IEEE Journal of Photovoltaics (2015).

Multi-junction solar cells: Influence of the spectrum

Applying AM1.5D spectrum to a 6000K BB optimized MJ solar cell



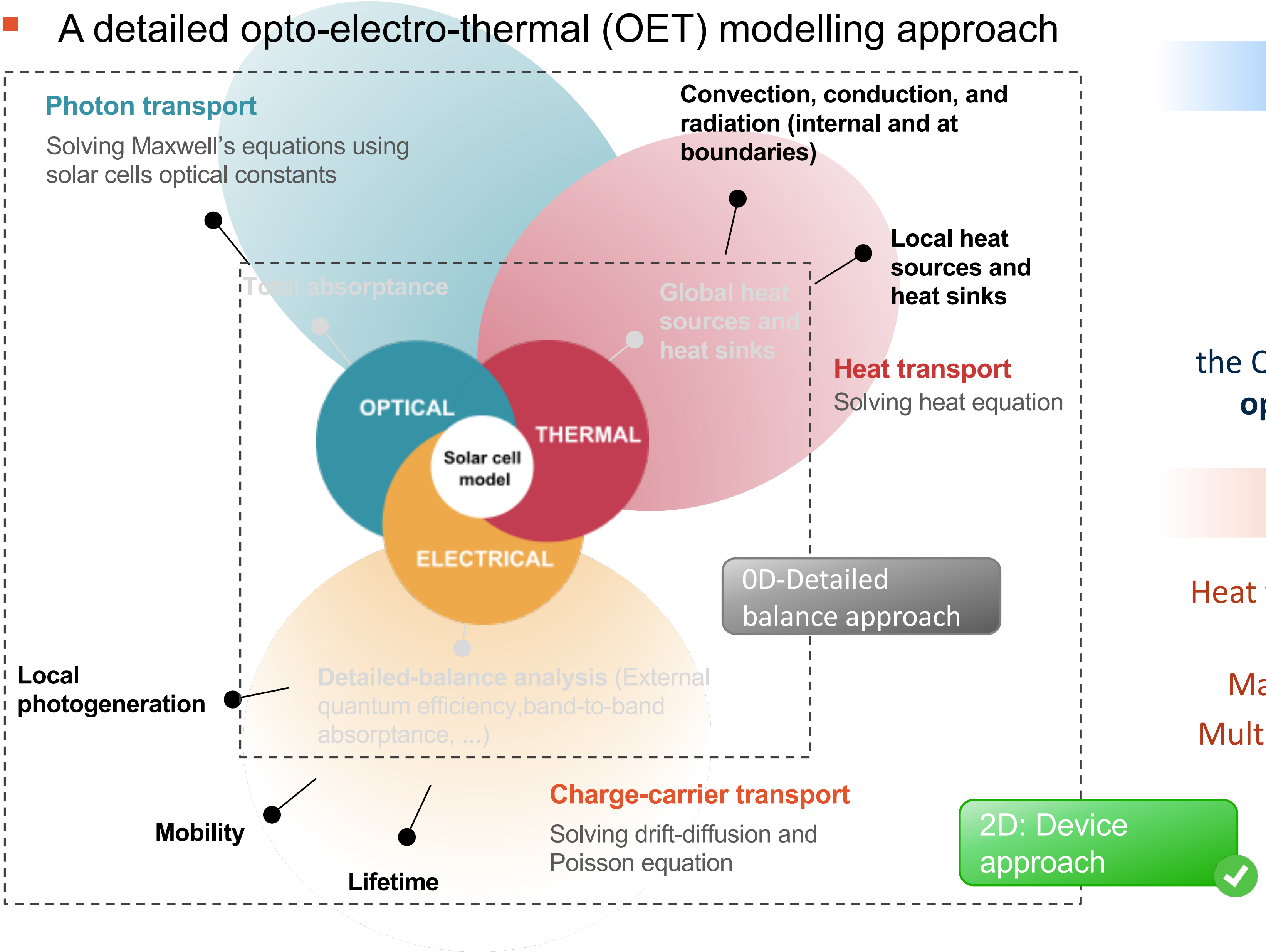


- Above 4 subcells, the penalty associated with the extra sensitivity of the device is not counterbalanced by the gain in efficiency brought by the extra subcells.

A. Vossier, E. Al Alam, A. Dollet, M. Amara, IEEE Journal of Photovoltaics (2015).

About opto-electro-thermal modelling

- A detailed opto-electro-thermal (OET) modelling approach



Objectives

Describe ←
Explain ←
Predict ←
and optimize..←
the OET behavior **in real operating conditions**

Challenges

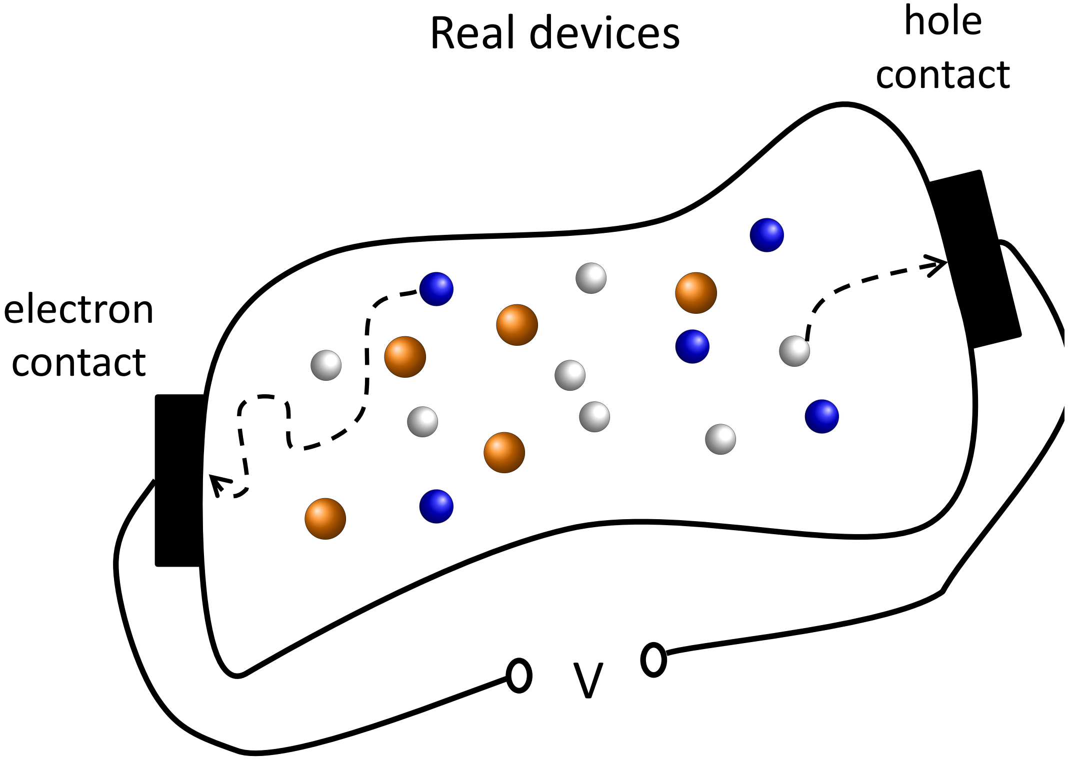
Heat transfer in active layers (silicon) ←
Material properties ←
Multiphysics coupling ←

About opto-electro-thermal modelling

- Thermodynamics of irreversible processes: Onsager-Callen theory

$$-\vec{J}_N = L_{11}\frac{1}{T}\vec{\nabla}\mu + L_{12}\vec{\nabla}\frac{1}{T}$$

$$\vec{J}_Q = L_{12}\frac{1}{T}\vec{\nabla}\mu + L_{22}\vec{\nabla}\frac{1}{T}$$



$L_{i,j}$ Calculated with Boltzmann equation under the relaxation time approximation

L. Onsager, Phys Rev, 15, 1931
H. B. Callen, Phys. Rev, *73,* 1948

About opto-electro-thermal modelling

- Thermodynamics of irreversible processes: Onsager-Callen theory

Current density

$$\vec{J_n} = qD_n\vec{\nabla}n + q\mu_n\Pi_n\frac{\vec{\nabla}(T)}{T} + q\mu_n n\left(\vec{E} - \frac{\vec{\nabla}\chi}{q} - \frac{k_BT}{q}\vec{\nabla}(\ln(N_c))\right)$$

$$\vec{J_p} = -qD_p\vec{\nabla}p - q\mu_p\Pi_h\frac{\vec{\nabla}(T)}{T} + q\mu_p p\left(\vec{E} - \frac{\vec{\nabla}\chi}{q} - \frac{\vec{\nabla}(\varepsilon_G)}{q} + \frac{k_BT}{T}\vec{\nabla}(\ln(N_v))\right)$$

Diffusion — Drift

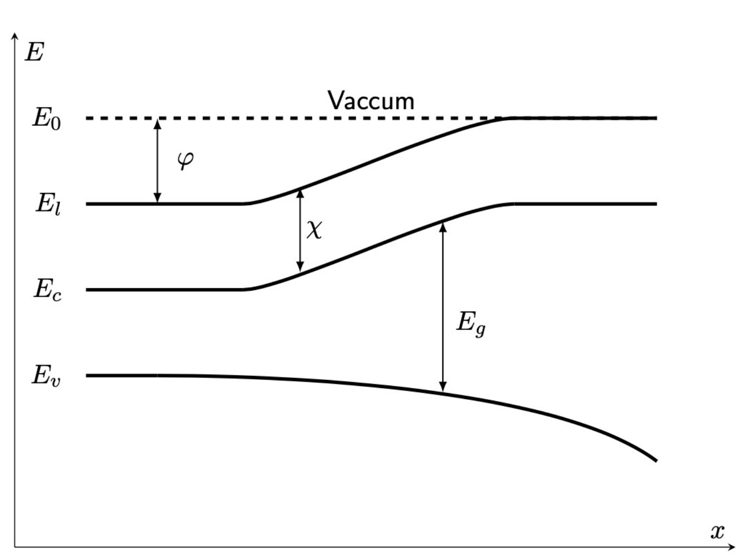
$$\vec{\nabla}.\vec{j} = q(R - G)$$

$$\epsilon\Delta V = q(p - n + N)$$

Continuity

Energy current density

$$\vec{J}_u = -(\Pi_n - \varepsilon_{FC})\vec{J_n} + (\Pi_p - \varepsilon_{FV})\vec{J_p} - \lambda\vec{\nabla}(T)$$



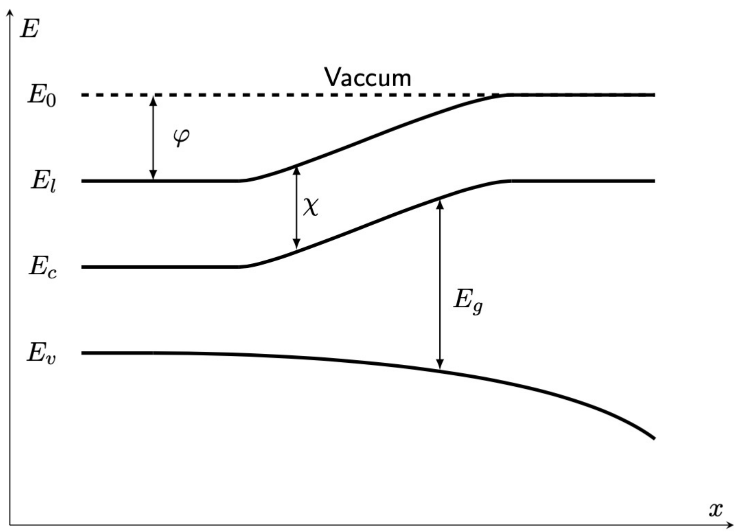
L. Onsager, Phys Rev, 15, 1931
H. B. Callen, Phys. Rev, *73*, 1948

About opto-electro-thermal modelling

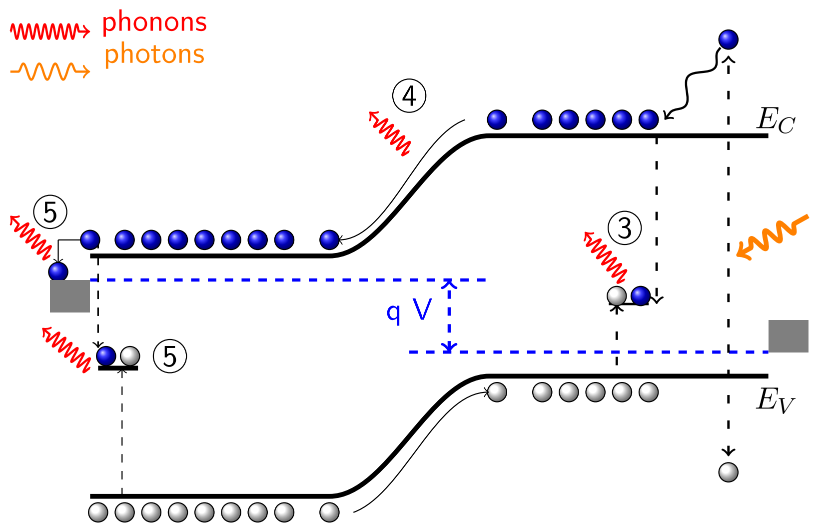
→ General formulation of heat source

ligth

$$H = \vec{E}.\vec{J} + \left(E_g + 3k_BT\right).R - \overrightarrow{J_n}.\vec{\nabla}\left(\chi - \frac{3}{2}\frac{k_BT}{q}\right) - \overrightarrow{J_p}.\vec{\nabla}\left(\chi + \frac{1}{q}E_g + \frac{3}{2}\frac{k_BT}{q}\right) + \vec{\nabla}.\left\{\pi_n^0\overrightarrow{J_n} - \pi_p^0\overrightarrow{J_p}\right\} + H_T - S_r$$



A More general device



PN junction

R. Couderc, M. Amara, and M. Lemiti, "IEEE JPV (2016)

Under the Hood of numerical methode

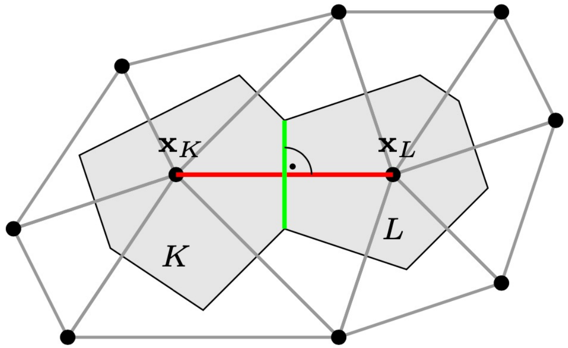
- Scaling of variables
  - ✓ Concentration (n, p, Nc, NV) → Max(N_A, N_D)≈ $10^{20}cm^{-3}$
  - ✓ Length (hi, hj) → cell maximum dimenssion ≈ 1-200 µm
  - ✓ Temperature → T_{amb}
  - ✓ Potential $(V, \frac{\varepsilon_F}{q}, E_g) \rightarrow \frac{k_B T_0}{q} \approx 0.0035\ V$
  - ✓ mobility $(\mu_{n,h}) \rightarrow \mu_{max}$

Governing equation
↓
Discretization (FE, FD, FE, etc)
↓
System of Algebraic Equations
↓
Equation solver
↓
n,p,J

- Scharfetter-Gummel discretization of the continuity equation

$$J_{K\rightarrow L} = \frac{< U_T \mu_n >}{X_{K,L}} \left(n_K B\left(\frac{-\Delta V}{U_T}\right) - n_L B\left(\frac{-\Delta V}{U_T}\right)\right)$$

Bernoulli function : $B(x) = \frac{1}{e^x - 1}$



T. Kopruki at al. Opt Quant Electron (2014)

Minority carrier diffusion equation

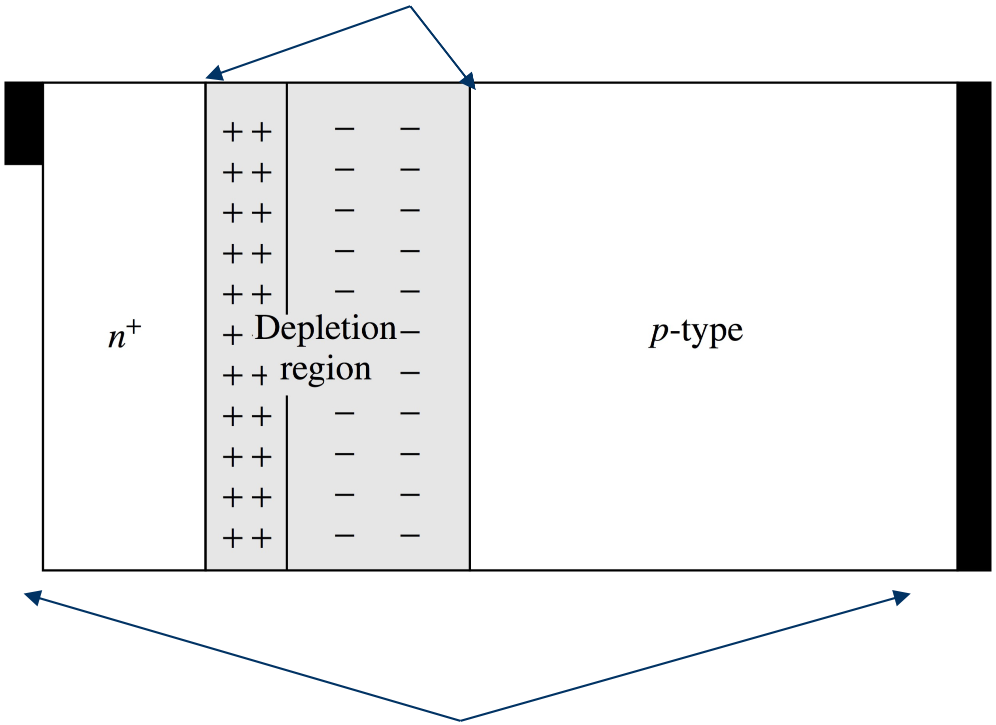
1. Depletion approximation
2. All carriers are decoupled

$$D_m \frac{\partial^2 m}{\partial x^2} - \frac{m - m_0}{\tau_m} = -g(x)$$

$$g_{op,\Delta\nu}(x) = \int_{\Delta\nu} \frac{\kappa_{\nu,interbande}(x)\, G_\nu(x)}{h\nu}\, d\nu$$

$$J = J_N + J_P + J_{DR}$$

$$P_{n,h} = \frac{n_i^2}{N_{D,A}} e^{qV/k_B T}$$



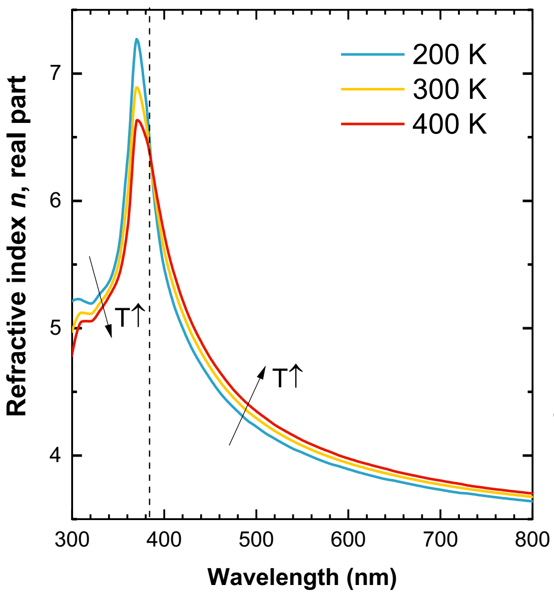
$$\frac{d\Delta n}{dx} = \frac{S}{D_n} \Delta n$$

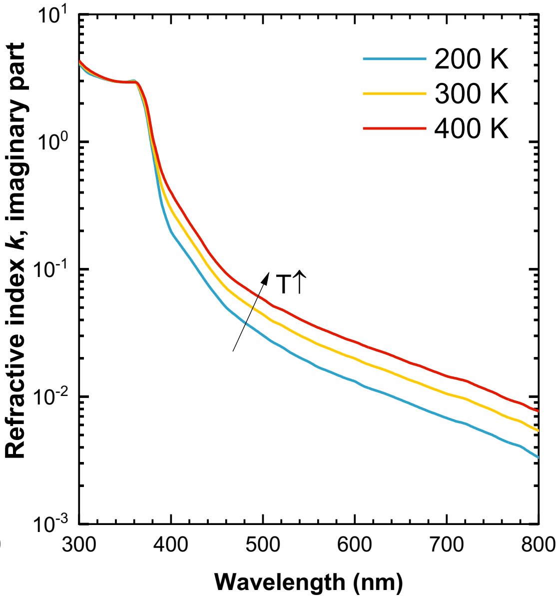
But, be aware

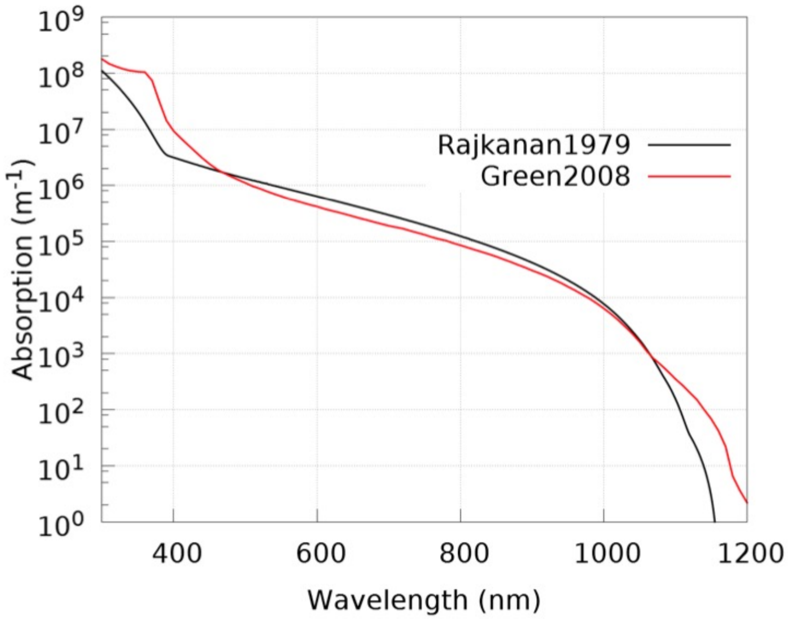
1. Low injection
2. Low series resistance
3. Recombination lifetime ≄ illumination

Physical properties issue

- → Mobility (T), lifetime (T), refractive index (T)
- → Green 2008 : Parameterization to determine n and k as a function of temperature
- → Rajkanan 1979: Physical model (only for k)
- → How about $\lambda > \lambda_g$: very few experimental data (intrinsic silicon)
- → How about other semiconductor materials: perovskite ?







$$\alpha(T) = \sum_{i,j} C_i A_j \left[\frac{(E_\lambda - E_{gi} + E_{pi})^2}{e^{E_{pi}/k_B T} - 1} + \frac{(E_\lambda - E_{gi} - E_{pi})^2}{1 - e^{-E_{pi}/k_B T}} \right] + A_d \sqrt{(E_\lambda - E_{gd})}$$

K. Rajkanan et al. Solid-State Electron. 22 (1979) 793–795
M.A. Green et al. Prog. Photovoltaics: Res. Appl. 3 (1995).

Modelling silicon VIS-NIR-MIR optical properties

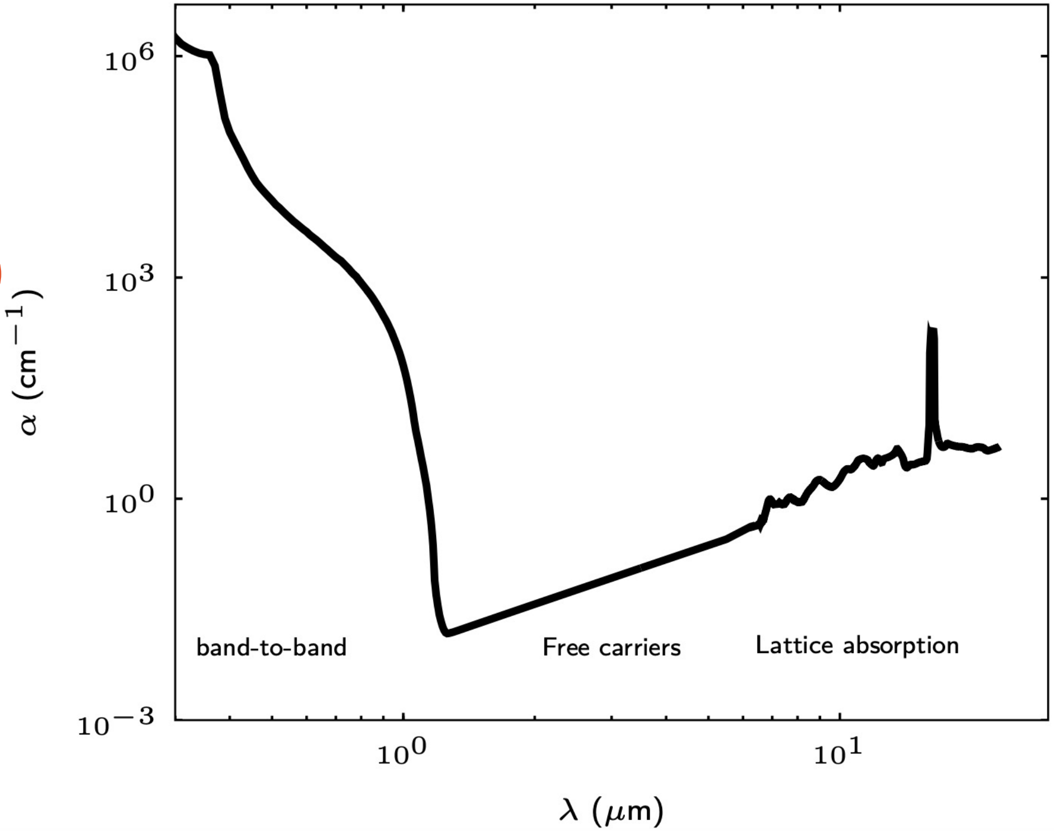
→ Objective: Si complex index as a function of temperature and doping in the UV-VIS-NIR-MIR range(0.25-50 μm)

$$N(\omega, T, N_d, N_a) = n + ik = \sqrt{\epsilon}$$

$$\varepsilon(\omega) = \varepsilon_{bl} - \frac{N_e e^2/\varepsilon_0 m_e^*}{\omega^2 + i\omega/\tau_e} - \frac{N_h e^2/\varepsilon_0 m_h^*}{\omega^2 + i\omega/\tau_h}$$

Two contribution :
1. inter-bande = f(T)
2. Lattice

3. Free carriers: Drude model

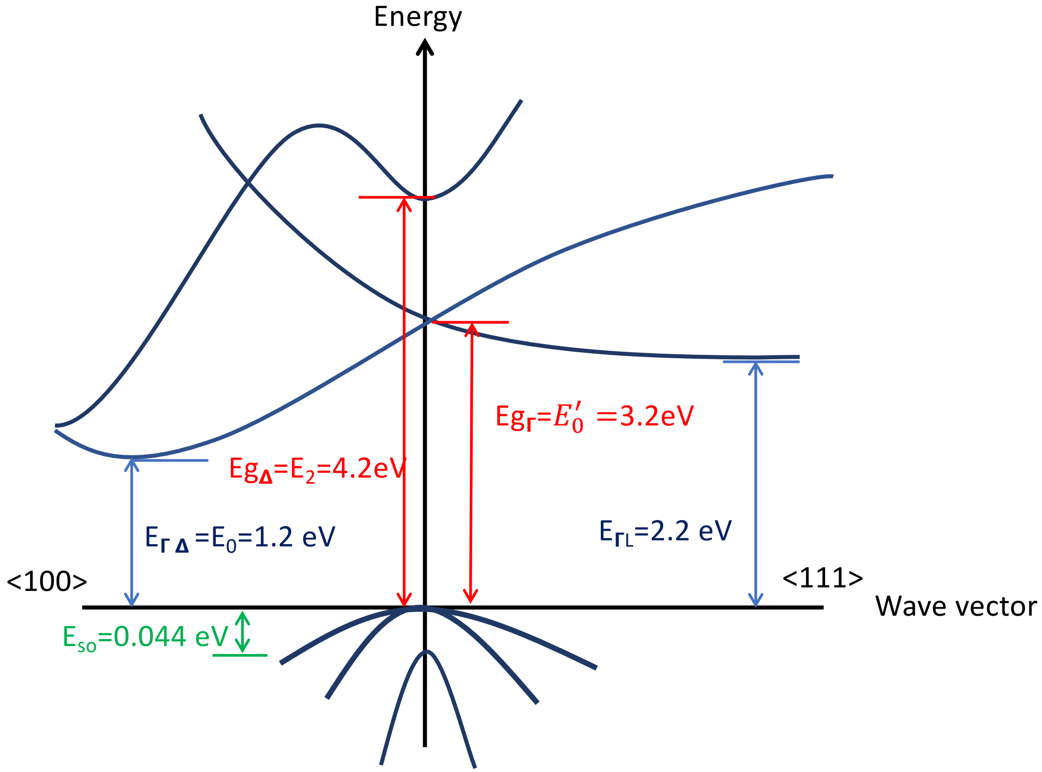


- Effective masses
- N_e et N_h with the calculation of the Fermi level (solving the neutrality equation) = f(T, doping)
- The collision time $\tau_{e,h} = m^* \times \mu / e$

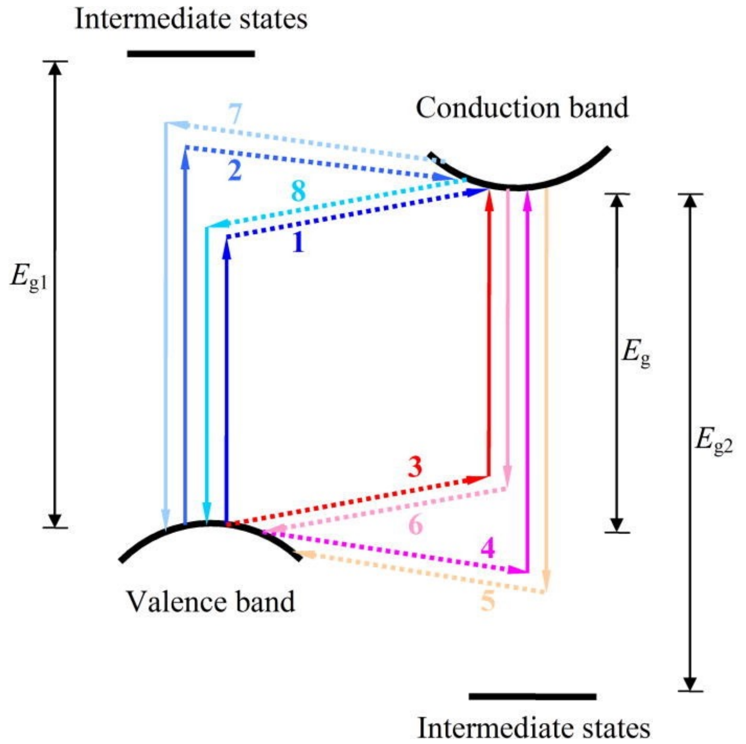
M. Amara et al. In preparation (2022).

Modelling silicon VIS-NIR-MIR optical properties

Band gap with temperature



- $E_{g\Delta} = 4.34 - \frac{3.91 \times 10^{-4}\ T^2}{T+125}$ [3]
- $E_{g\Gamma} = 3.354 - \frac{3.5 \times 10^{-4}\ T^2}{T+580}$ [4]
- $E_g^0(T) = E_g^0(0) - \alpha\Theta \left[\gamma + \frac{3\Delta^2}{2} \left(1 + \frac{\pi^2}{3(1+\Delta^2)}\chi^2 + \frac{3\Delta^2-1}{4}\chi^3 + \frac{8}{3}\chi^4 + \chi^6 \right)^{\frac{1}{6}} - 1 \right]$



- 16 processes : absorption/emission of photons and phonons

- $h\omega_{TA}$= 18.27 meV and
- $h\omega_{TO}$=57.73 meV

Modelling silicon VIS-NIR-MIR optical properties

Band gap with temperature

$$\alpha_{\text{ind}} = \alpha_{\text{ind0}} \frac{E_{\text{g}}}{E_{\lambda}} \left[\frac{(E_{\lambda} - E_{\text{g}} + \hbar\omega_{ij})^2 N_q}{|E_{\text{g1}} - E_{\lambda} - i\Gamma|^2} \text{H}(E_{\lambda} - E_{\text{g}} + \hbar\omega_{ij}) \right.$$

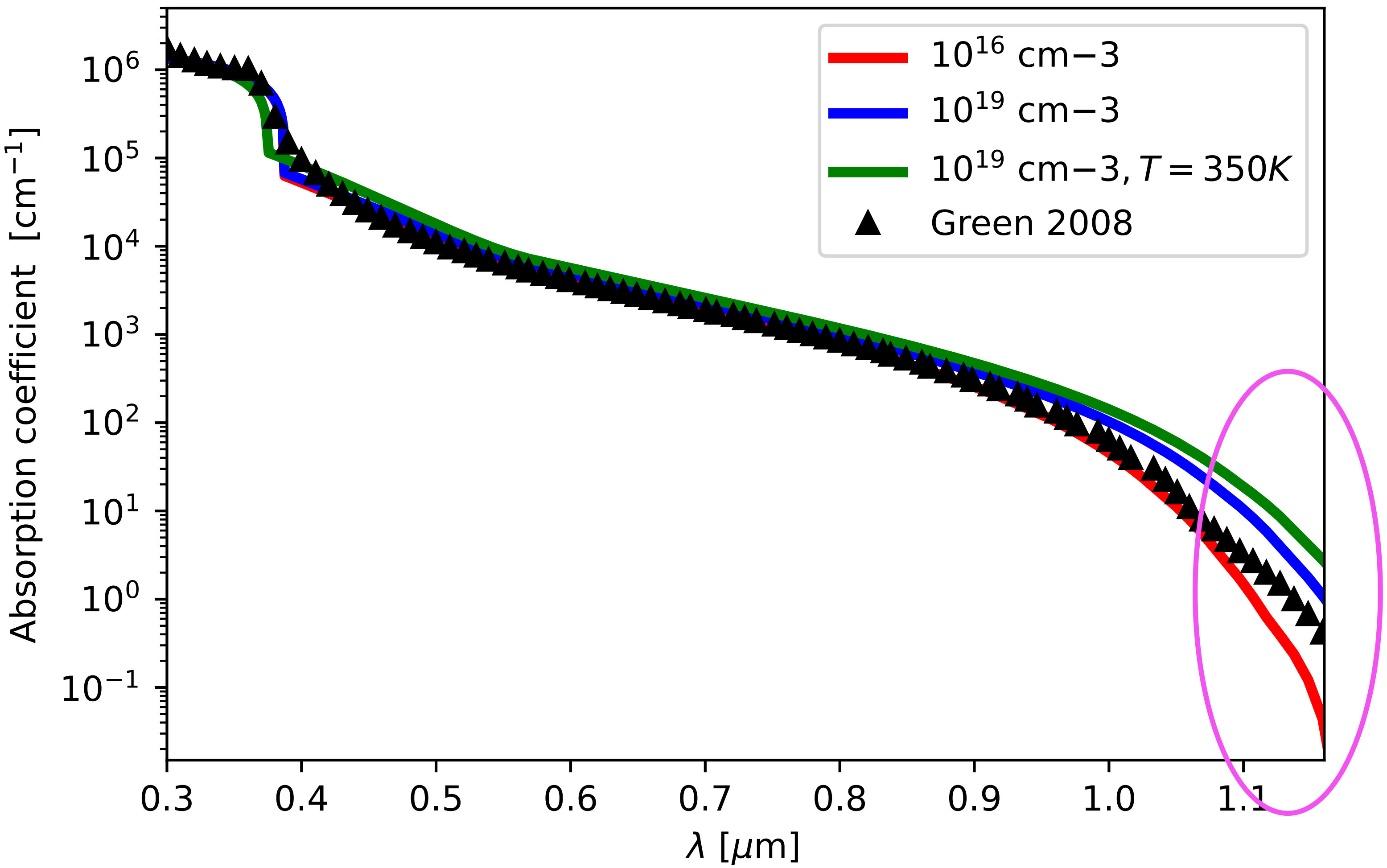
$$+ \frac{(E_{\lambda} - E_{\text{g}} - \hbar\omega_{ij})^2 (N_q + 1)}{|E_{\text{g1}} - E_{\lambda} - i\Gamma|^2} \text{H}(E_{\lambda} - E_{\text{g}} - \hbar\omega_{ij})$$

$$+ \frac{(E_{\lambda} - E_{\text{g}} + \hbar\omega_{ij})^2 N_q}{|E_{g2} - \hbar\omega_{\lambda} + i\Gamma|^2} \text{H}(E_{\lambda} - E_{\text{g}} + \hbar\omega_{ij})$$

$$\left. + \frac{(E_{\lambda} - E_{\text{g}} - \hbar\omega_{ij})^2 (N_q + 1)}{|E_{\text{g2}} - E_{\lambda} + i\Gamma|^2} \text{H}(E_{\lambda} - E_{\text{g}} - \hbar\omega_{ij}) \right]$$

Tsai, C. Y. *IEEE Journal of Selected Topics in Quantum Electronics* (2019).

Modelling silicon VIS-NIR-MIR optical properties

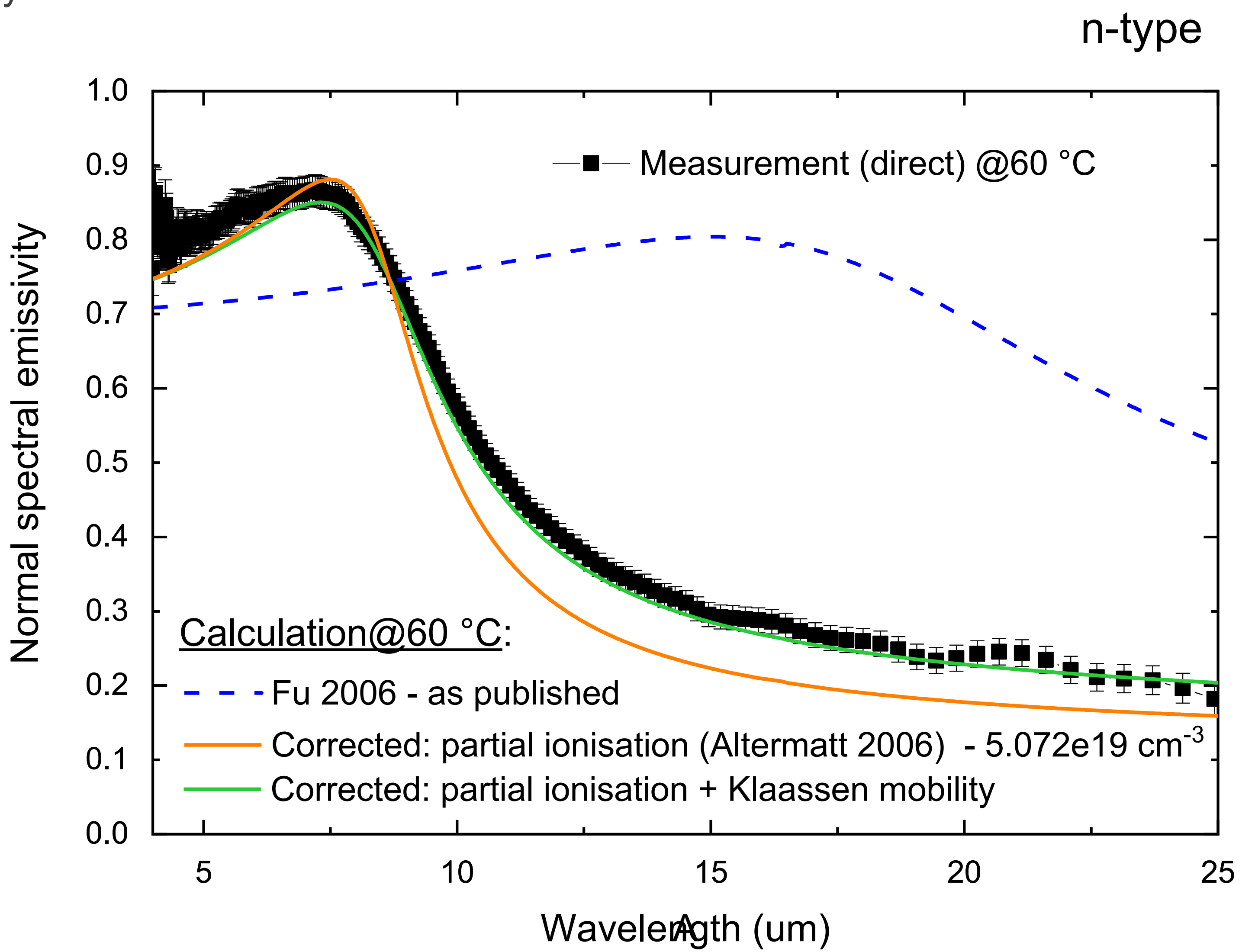


Free carriers

M. Amara et al. In preparation (2022).

Modelling silicon VIS-NIR-MIR optical properties

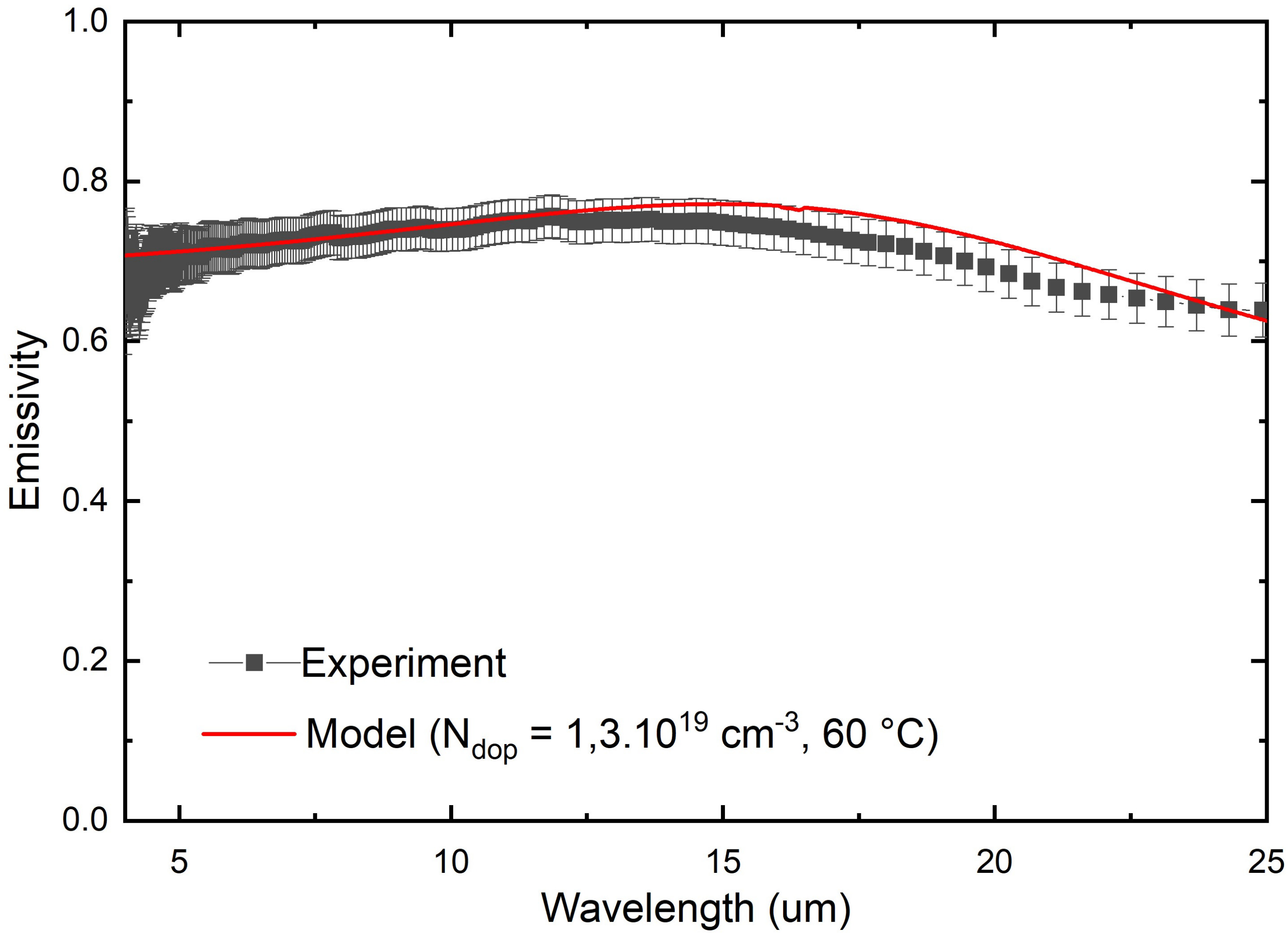
- **n-ype: OK, after correction of two ingedients**
  - → Partial ionization of dopants
  - → Mobility model



M. Amara et al. In preparation (2022).

Modelling silicon VIS-NIR-MIR optical properties

- **p-ype: OK, after correction of two ingedients**
  - → Partial ionization of dopants
  - → Mobility model



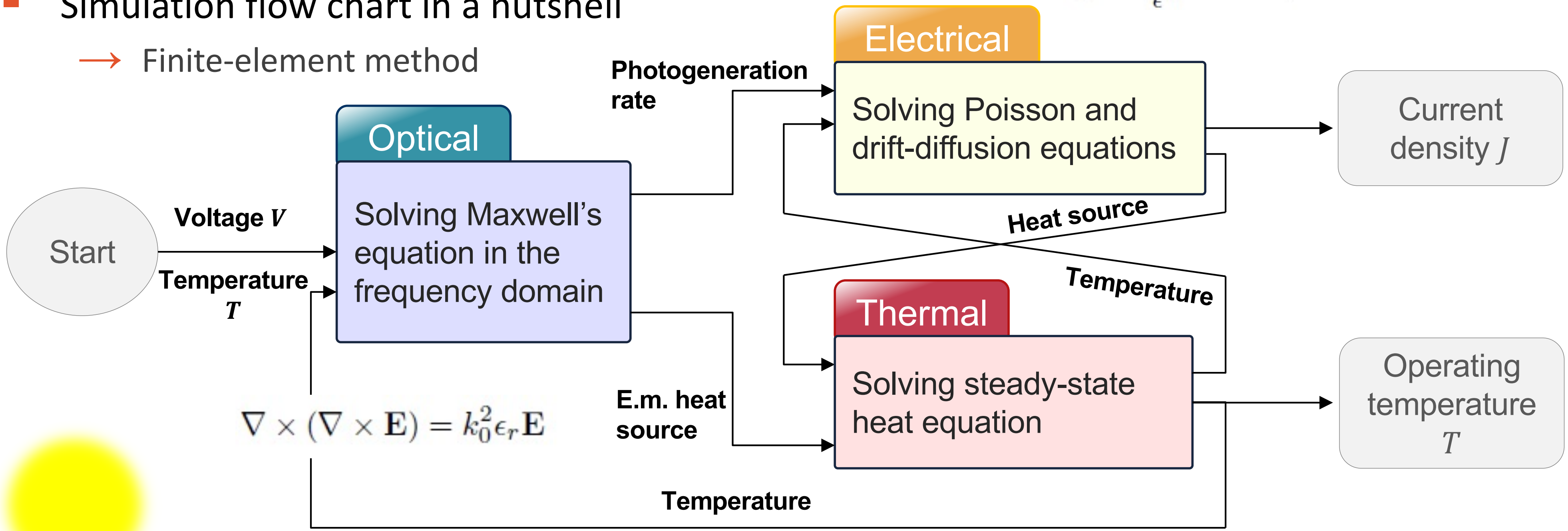
M. Amara et al. In preparation (2022).

Opto-electro-thermal modelling

$$\frac{\mathbf{J_n}}{q} = n\mu_n \nabla E_c + D_n \nabla n - nD_n \nabla ln(N_c) + nD_{n,th} \nabla ln(T)$$

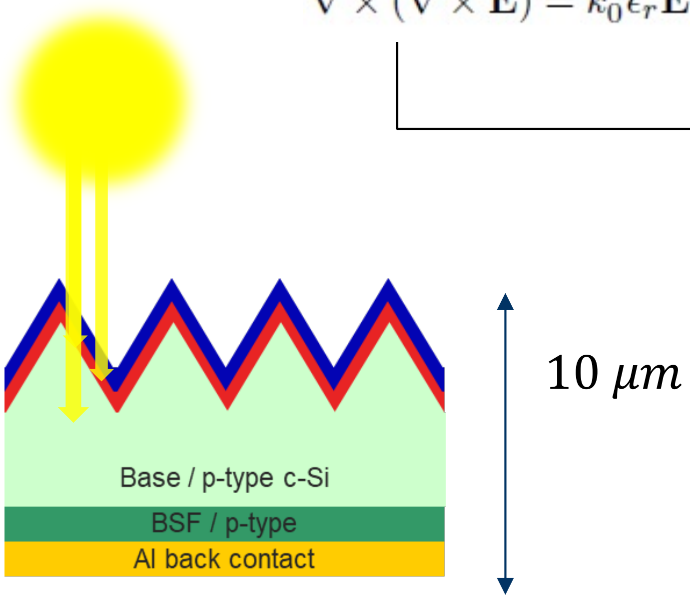
$$\Delta\phi = -\frac{q}{\epsilon}(p - n + C)$$

- Simulation flow chart in a nutshell
  - → Finite-element method



$$\nabla \times (\nabla \times \mathbf{E}) = k_0^2 \epsilon_r \mathbf{E}$$

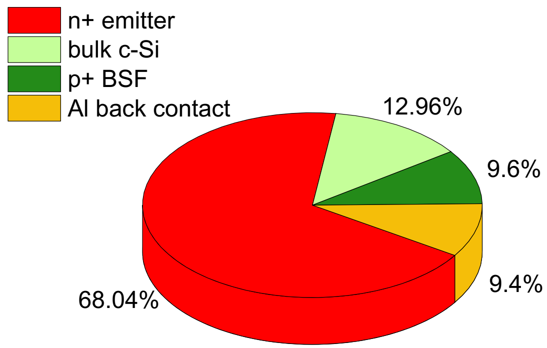
$$\nabla \cdot (-\kappa(T)\nabla T) = H$$

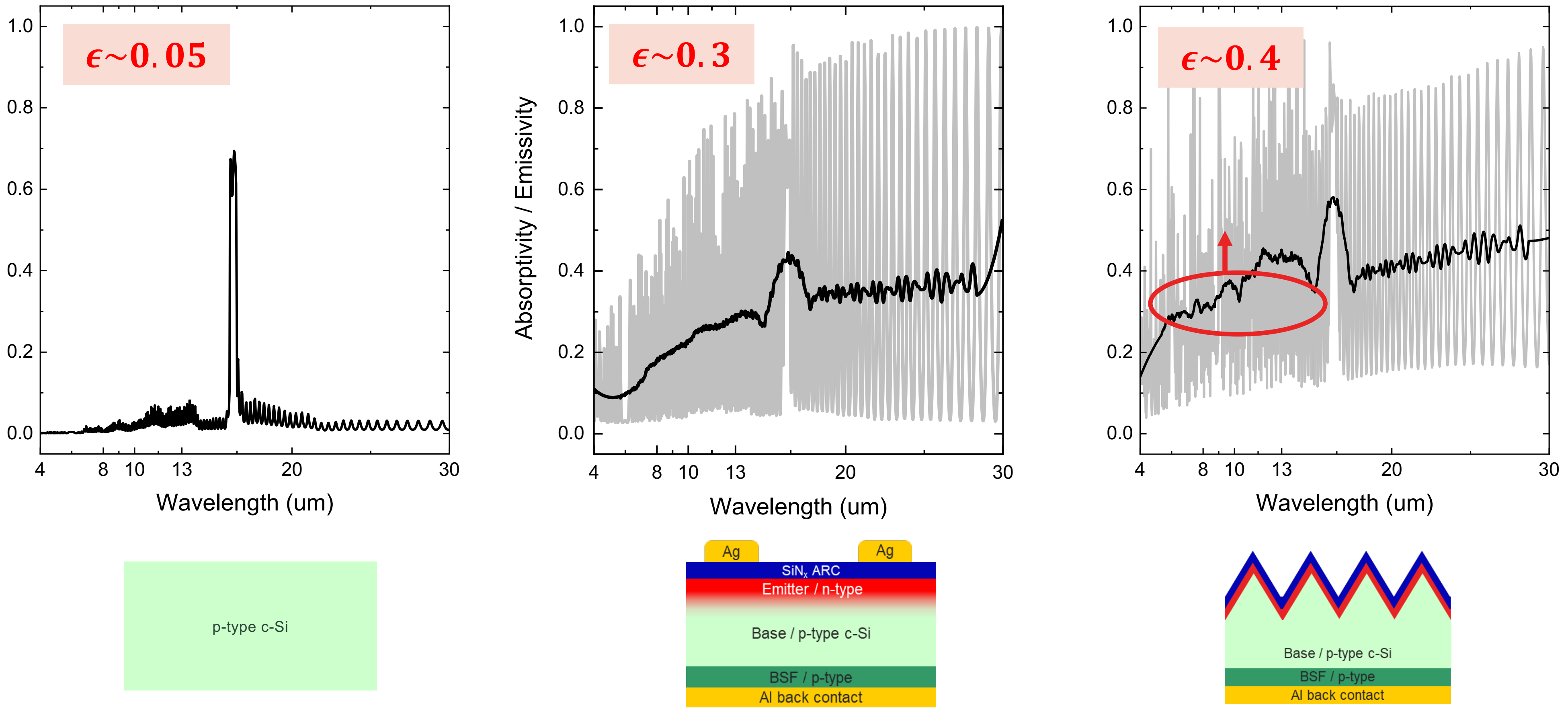


D. Dumoulin, E. Drouard, M. Amara et al. Under submission IEEE-JPV (2022).

Opto-electro-thermal modelling

- **What is the impact of the different layers and surface structuration on emissivity?**
  → $\epsilon(\lambda)$ should be large for $\lambda > 4\ \mu m$

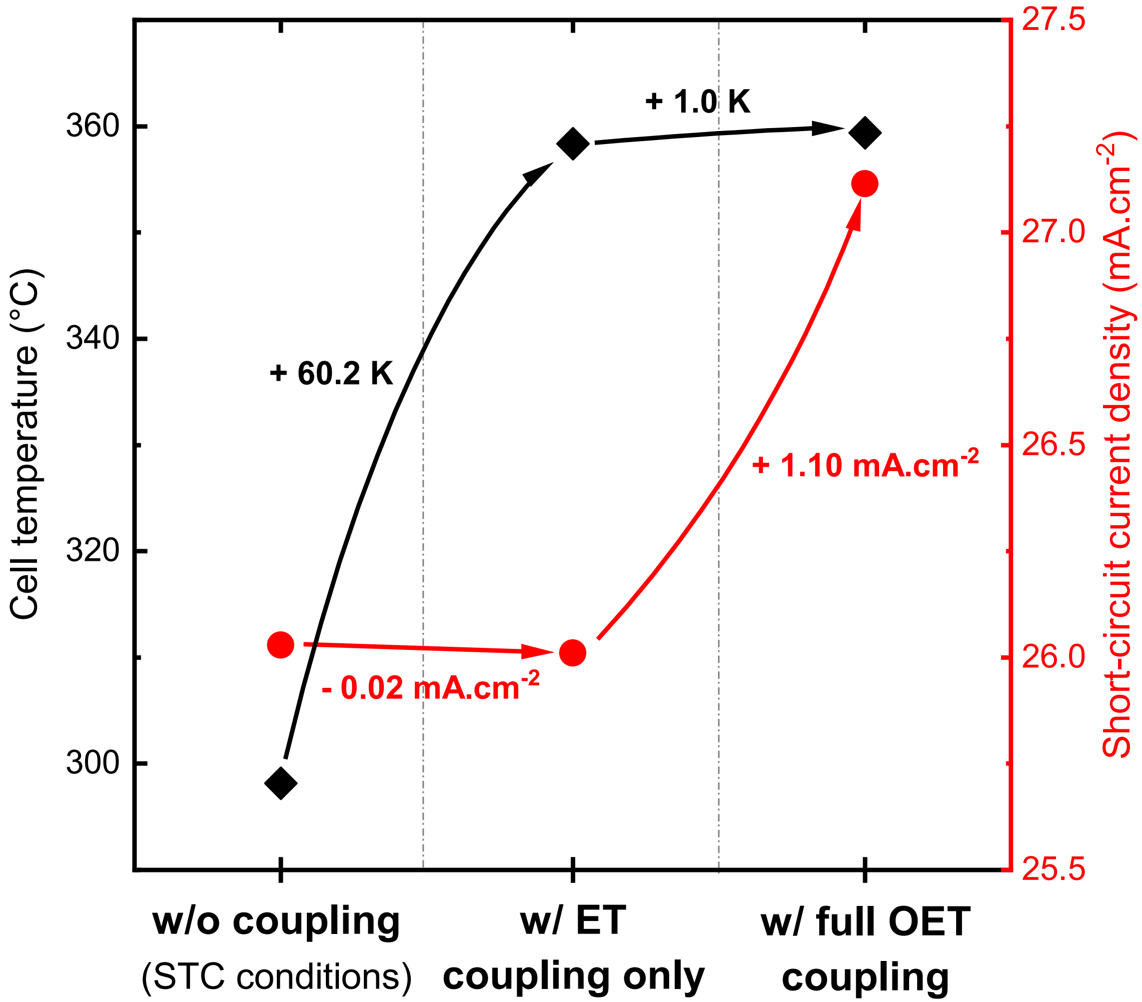




D. Dumoulin, E. Drouard, M. Amara et al. Under submission IEEE-JPV (2022).

Opto-electro-thermal modelling

- **What is the importance of having a fully coupled OET model?**
  → Comparing different coupling scenarios



ET coupling has the largest impact on the operating temperature...

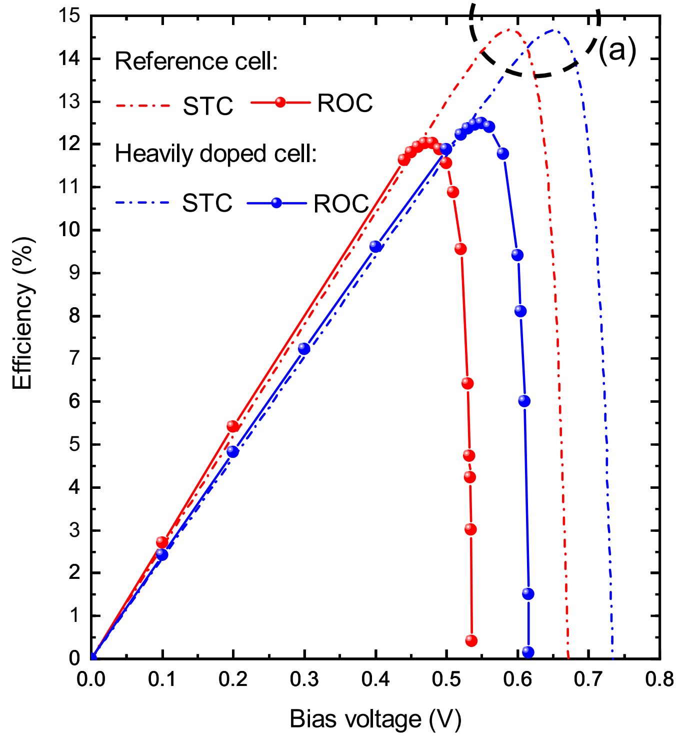
... but a full coupling is required to (1) describe the increase in short-circuit current with temperature (2) accurately predict the operating temperature

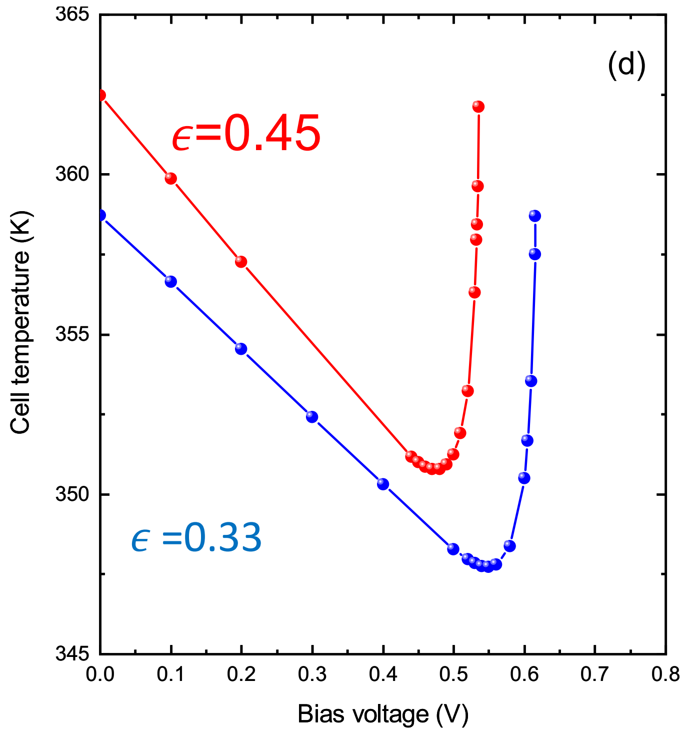
D. Dumoulin, E. Drouard, M. Amara et al. Under submission IEEE-JPV (2022).

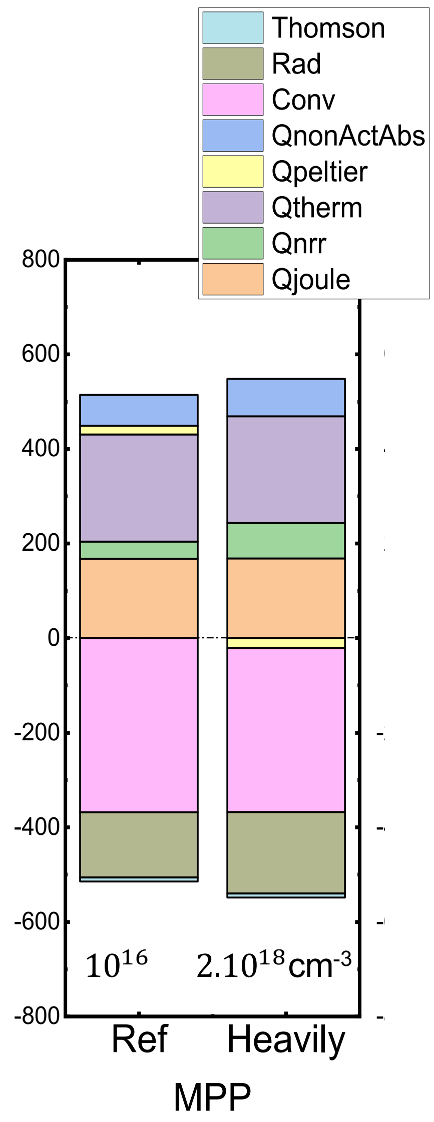
Results

→ Influence of the solar cell design

η = 14.6 %







12.5 %

η = 12 %

Heat sources/sinks

D. Dumoulin, E. Drouard, M. Amara et al. Under submission IEEE-JPV (2022).

CONCLUSION AND OUTLOOK

- **Conclusion**

  ✓ Developpement of an **OET model for silicon solar cells** in real operating conditions

  ✓ Highlighting the importance of a **fully coupled simulation** for accurate output

- **Outlook**

  - Fine-tuning of the underlying physics and experimental validation
  - Many numerical challenges: upscaling from 2D to 3D, and from a solar cell to a solar module

https://solairepv.fr

Le solaire photovoltaïque en France
réalité, potentiel et défis

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Des chercheuses et des chercheurs du CNRS et de la Fédération PV répondent à toutes vos questions sur le solaire PV en France.

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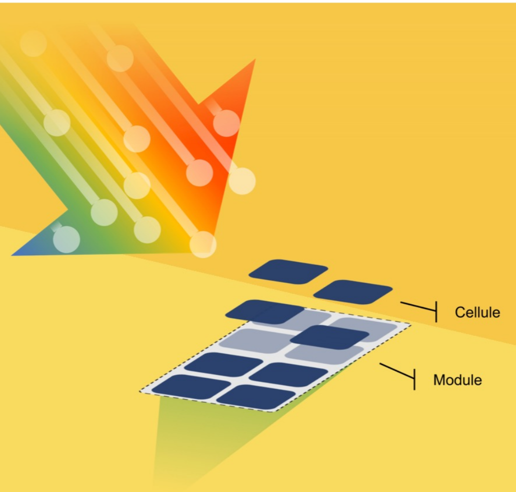
AVANT-PROPOS | QUI SOMMES NOUS ?



Crédits et contact

Ce document est issu d'un atelier mené par des équipes du Centre de Nanosciences et de Nanotechnologies (C2N, CNRS, Université Paris-Saclay) et de l'Unité Mixte de Recherche de l'Institut Photovoltaïque d'Ile-de-France (IPVF, CNRS, Ecole Polytechnique), et rejointes par d'autres membres de la Fédération de recherche du Photovoltaïque (FedPV),

sous l'impulsion et la supervision de Stéphane Collin et Jean-Francois Guillemoles,

et avec la participation d'Amaury Delamarre, Thomas Vezin, Guillaume Vidon, Capucine Tong, Bérengère Frouin, Marie Legrand, Mohamed Amara, Tiphaine Mathieu, Lucas Gavotto, Daniel Suchet...

Une première étape a été menée en octobre et novembre 2021 pour préparer une soirée-débat organisée aux Journées Nationales du PhotoVoltaïque (JNPV) le mercredi 1er décembre 2021, intitulée *Le photovoltaïque solaire en France : réalité, potentiel, et défis*. Les premiers résultats de ce travail ont alors été partagés et ont reçu un accueil enthousiaste de la part de la communauté scientifique du photovoltaïque. Cette étape a permis d'étoffer l'équipe de l'atelier et d'enrichir les questions abordées.

L'équipe de l'*Atelier SolairePV* remercie Daniel Lincot pour avoir inspiré ce travail, ainsi que ses très nombreux relecteurs.

Questions

Merci pour votre attention.

Institut des Nanotechnologies de Lyon – UMR 5270
Bâtiment Blaise Pascal
7, avenue Jean Capelle
69621 VILLEURBANNE Cedex – France
http://inl.cnrs.fr/