Technology Options for Photo-voltaic Solar Cells

Claudio Fiegna

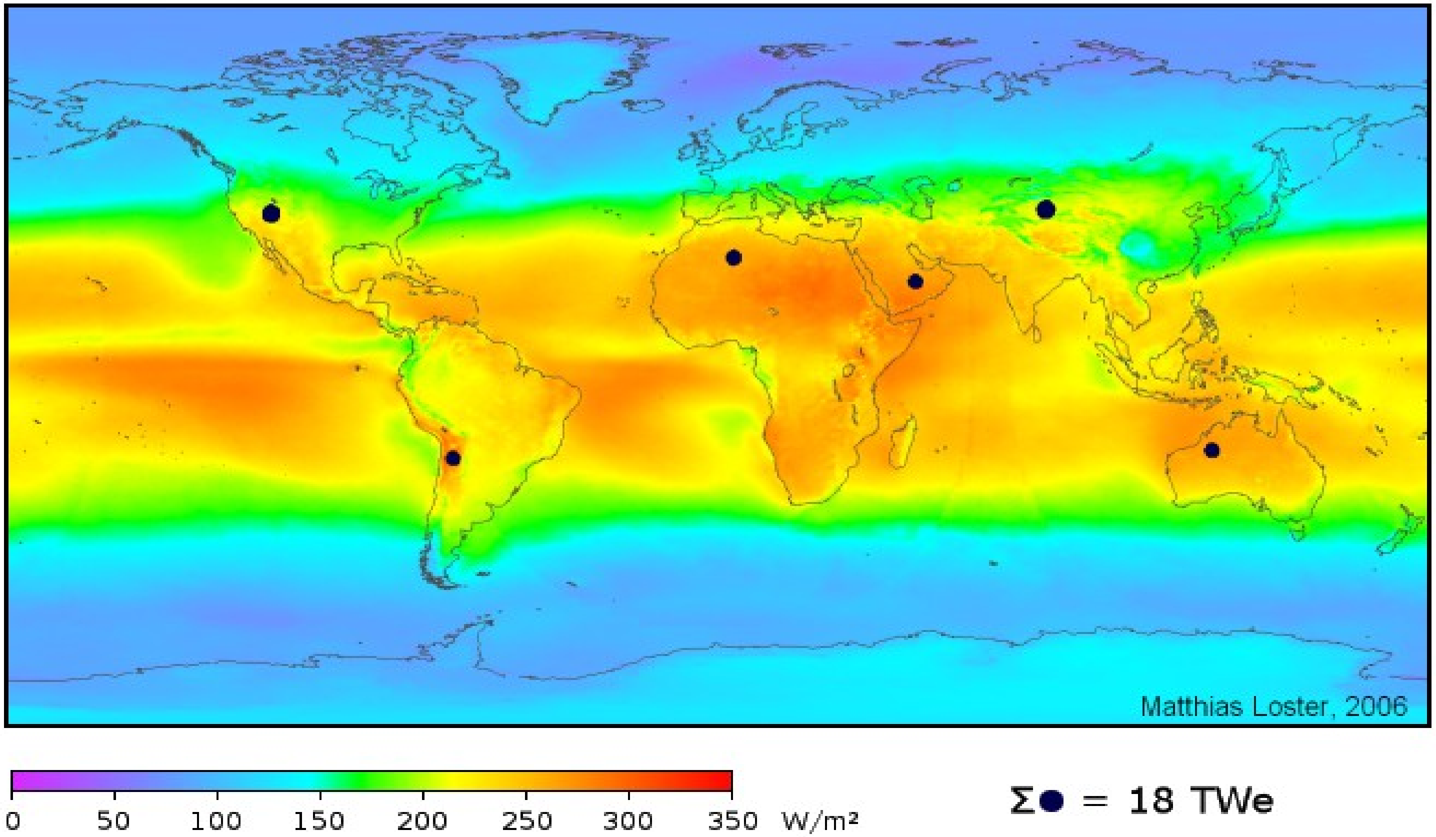
Outline

- Introduction
- Working principle for solar cells
- Silicon based solar cells
  - Crystalline
  - Thin film a-Si or μc-Si
- Other thin-film technologies
- Organic solar cells

Solar Energy and Photo-voltaic conversion

- La potenza che colpisce l’atmosfera terrestre è di circa 170 10^{15} Watt (170 PW).
- In meno di un’ora il sole invia sulla Terra una quantità di energia pari all’intero consumo complessivo mondiale annuale.
- Il flusso di energia solare è molto diluito ed intermittente
- La conversione fotovoltaica sfrutta il meccanismo di generazione di carica elettrica prodotto dalla radiazione luminosa in un materiale semiconduttore

Solar Energy and Photo-voltaic conversion



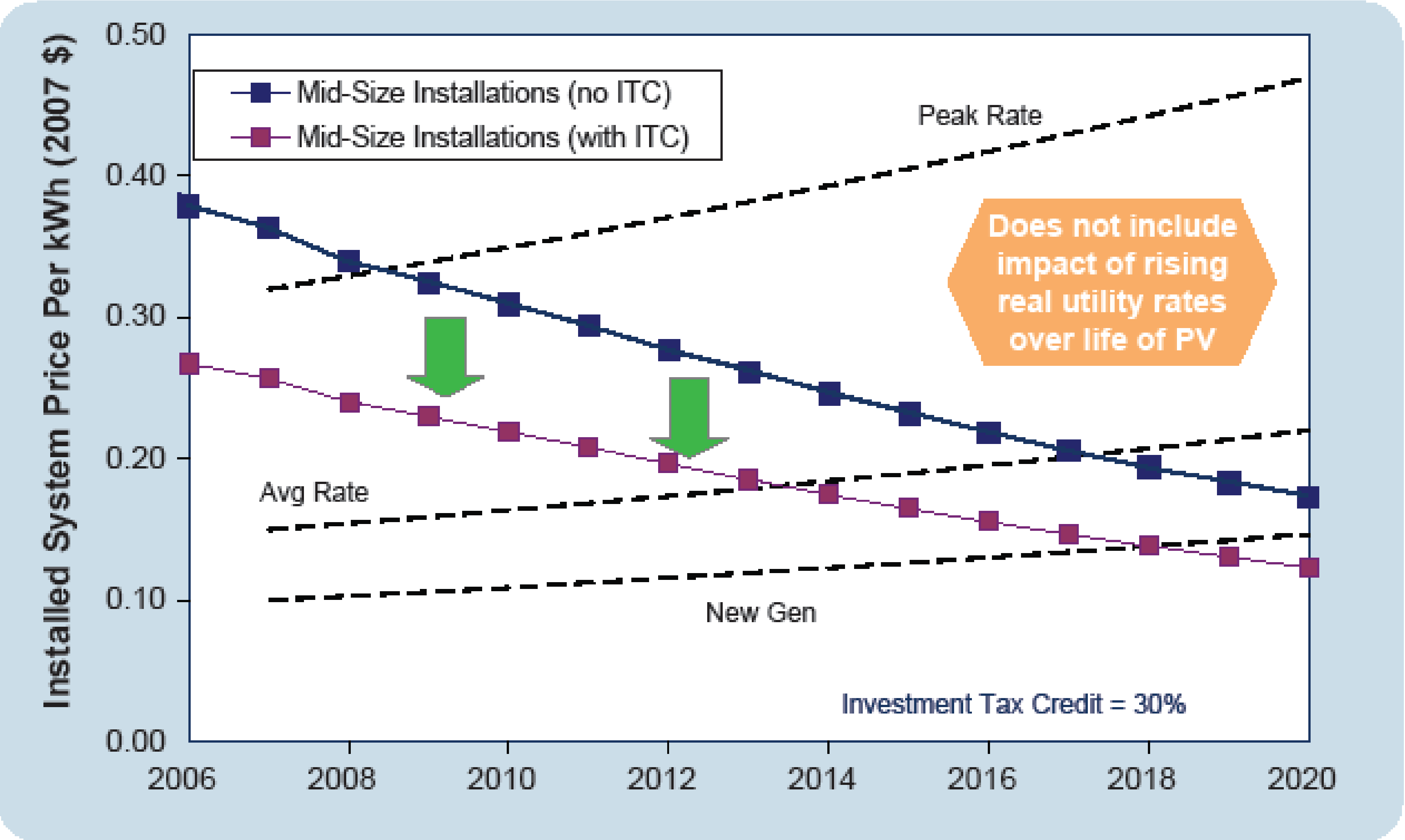
Development of PV technology

- The photovoltaic (PV) effect was discovered in 1839 by Edmond Becquerel
- After the introduction of silicon as the prime semiconductor material in the late 1950s, silicon PV diodes became available; main applications: TLC equipments in remote locations and satellites
- The oil crisis of 1973 led to public investments for technology development
- Since the beginning of the 1990s, ecological considerations acted as a main driving force in promoting PV solar energy

Global Status of Solar Photovoltaics

- By the end of 2007, the cumulative installed capacity of solar photovoltaic (PV) systems around the world had reached more than 9,200 MW. (1,200 MW at the end of 2000).
- Installations of PV cells and modules around the world have been growing fast
- solar electricity industry that it is now worth more than an annual € 13 billion
- The cost of PV electricity is decreasing steadily

Equivalent PV Electricity Cost (CA)



Assumptions:
PV Cost reduction past 2010 = 6% per year
CA 2007 base utility rates, increase = 3% per year

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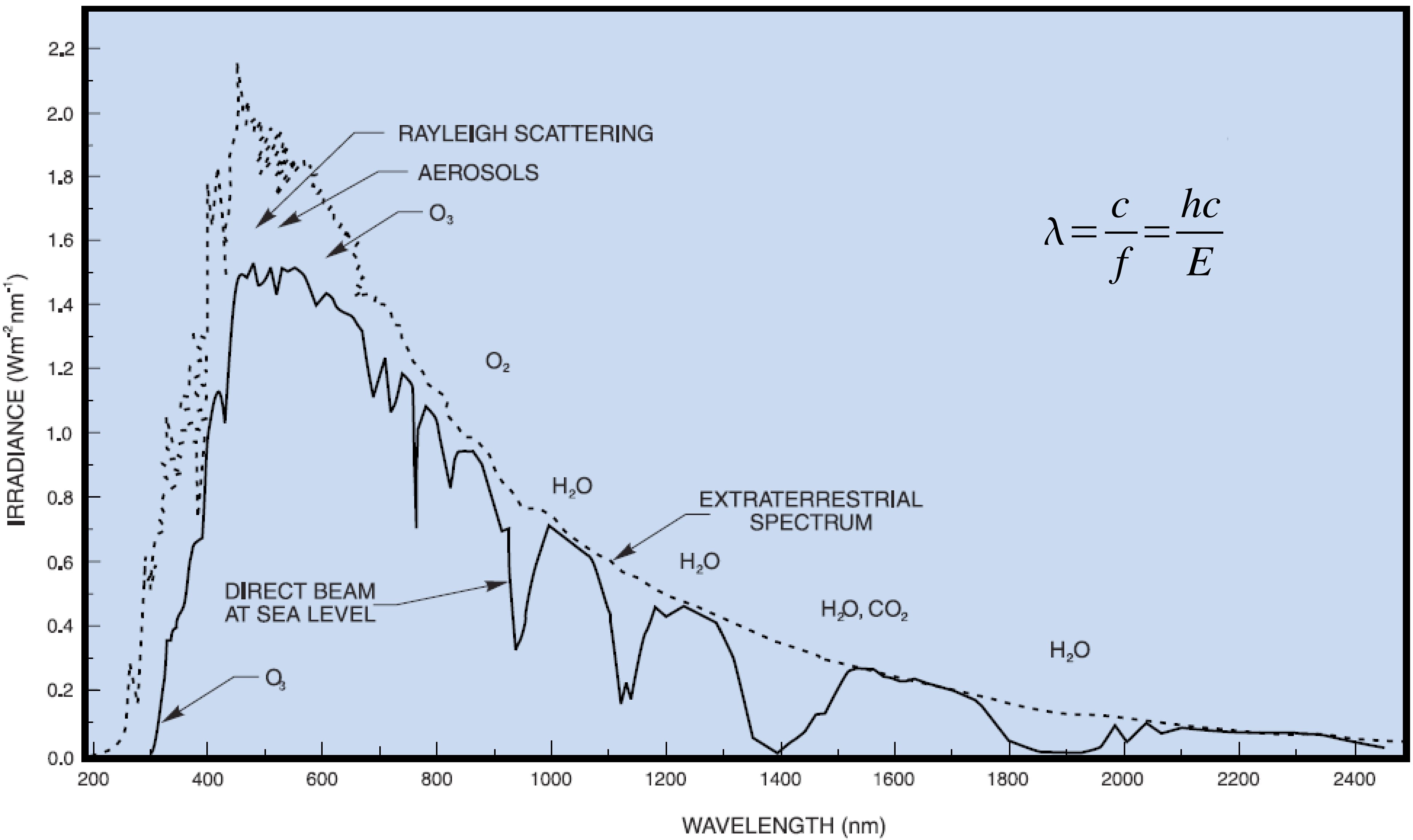
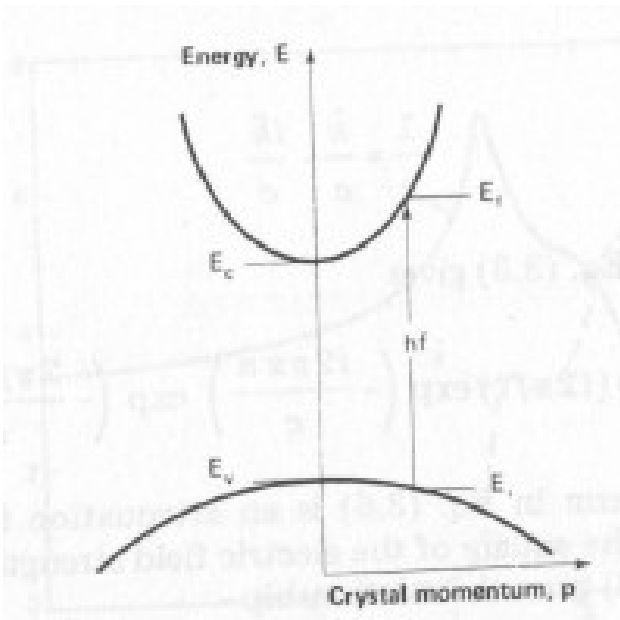
Interaction of light with semiconductors

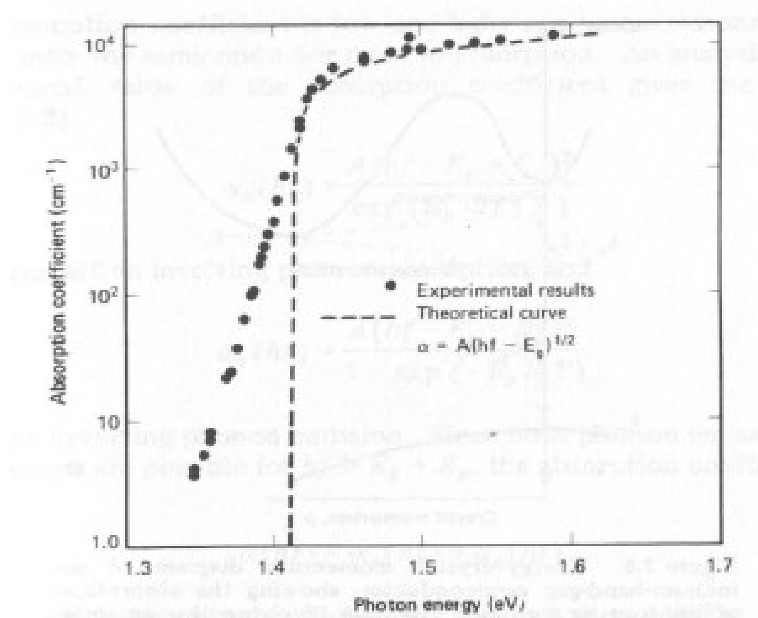
- When light strikes the surface of a semiconductor it is partially transmitted and partially reflected;
- The transmitted light is absorbed by the semiconductor;
- The energy associated to absorbed light promotes the transition of electrons from occupied states (e.g. valence band) to the higher-energy unoccupied states (conductions band.

Solar spectrum



Absorption of light in semiconductors

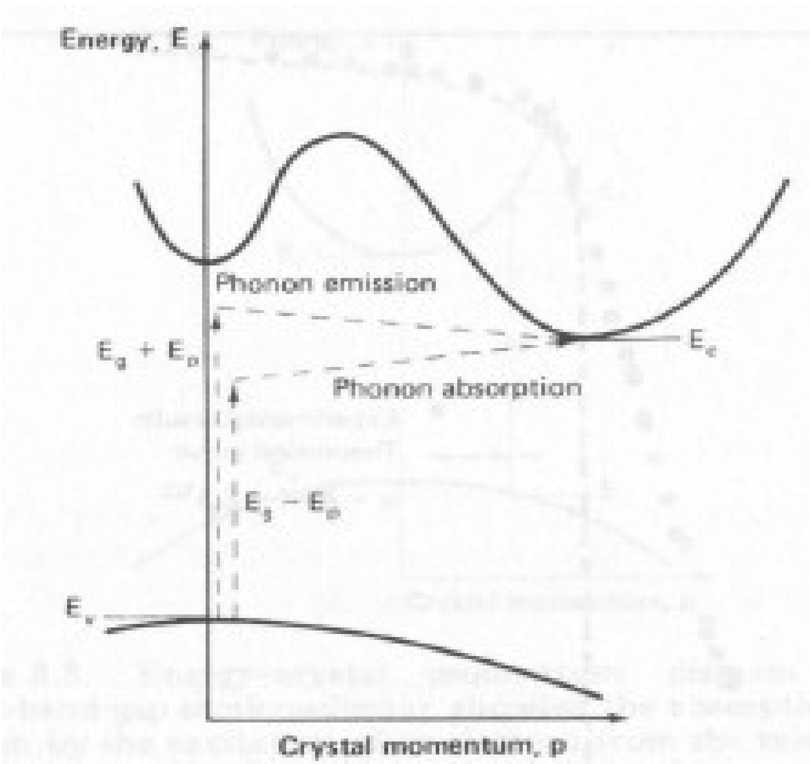


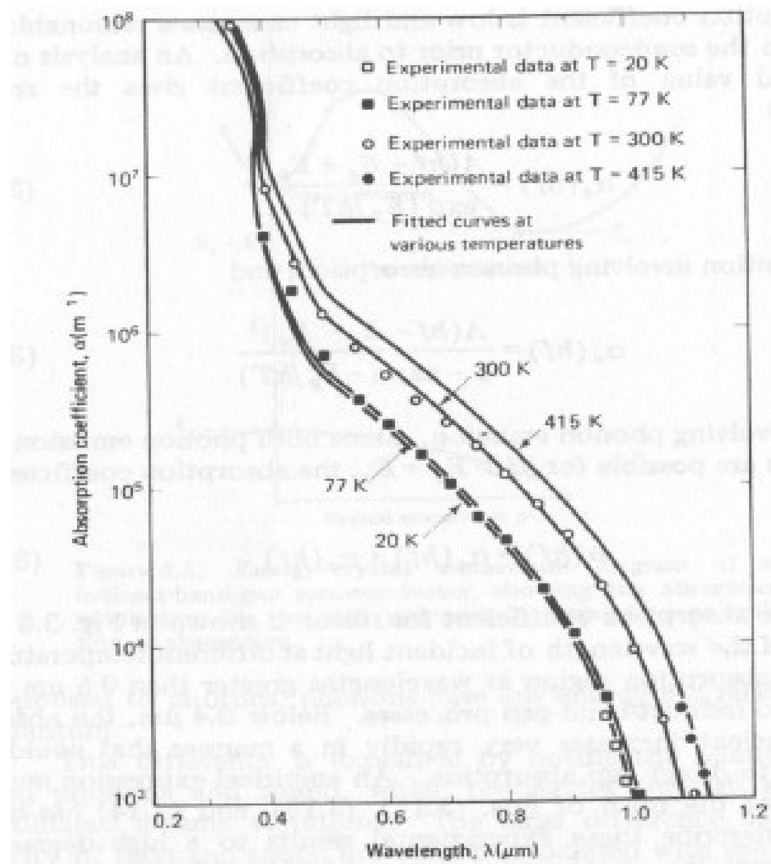


M.A. Green, “Solar Cells”, Univ. South Wales.

Absorption of light in a direct-bandgap semiconductor (right) and absorption coefficient as a function of photon energy in GaAs.

Absorption of light in semiconductors





$$\lambda = \frac{c}{f} = \frac{hc}{E}$$

M.A. Green, “Solar Cells”, Univ. South Wales.

Absorption of light in an indirect-bandgap semiconductor (right) and absorption coefficient as a function of photon wave-length in Silicon.

Other absorption mechanisms

- Phonon-assisted absorption in indirect-gap semiconductors;
- free-carrier absorption (no electro-hole generation)
- two-steps absorption through an energy level within the bandgap
- electric-field assisted sub-bandgap absorption
- effects of bandgap narrowing at large doping levels

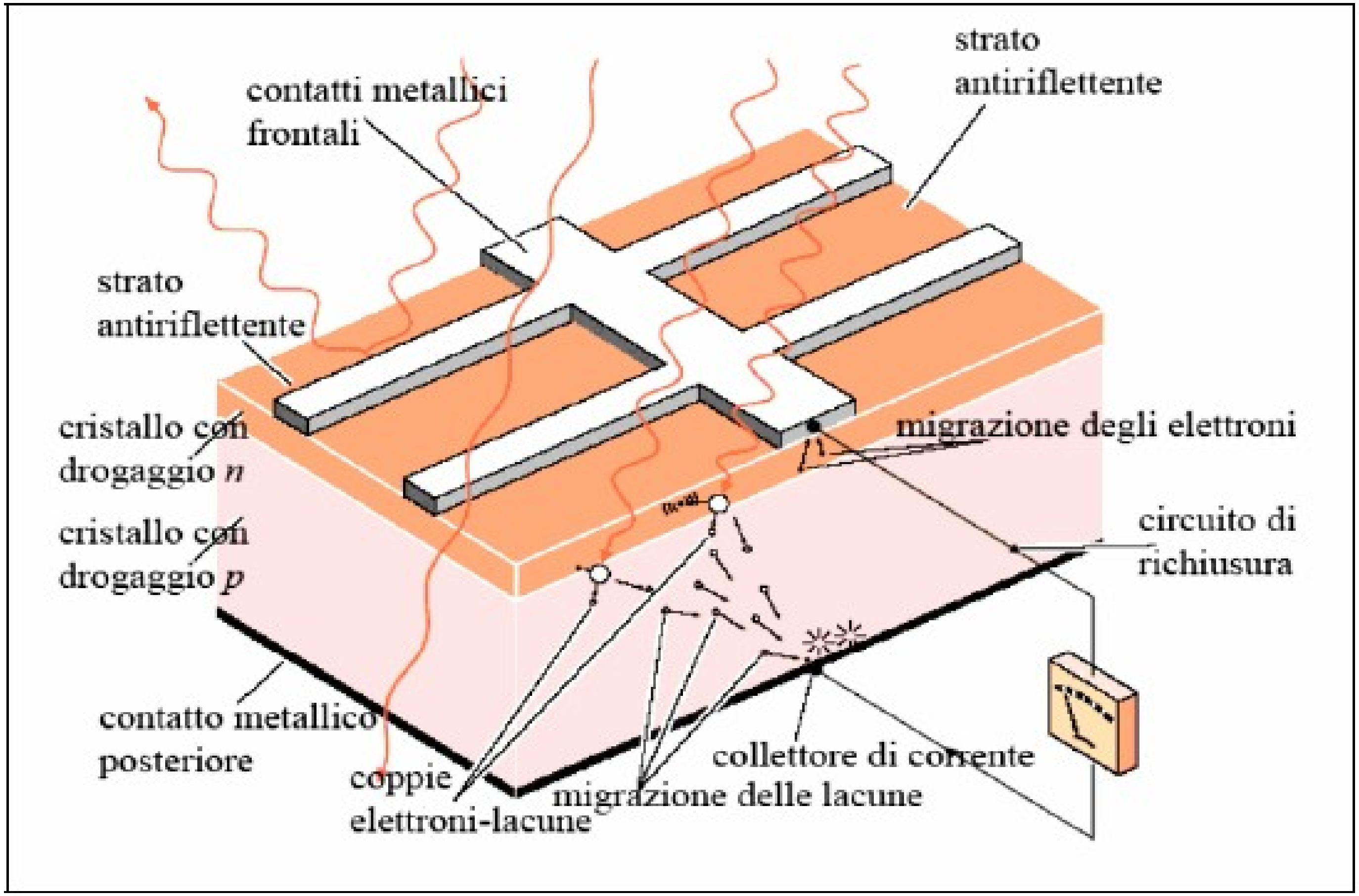
Light absorption (normal flux)

- $F(x)$: photon flux - number of photons crossing the unit-area per unit-time [cm^{-2} s^{-1}]
- $\alpha(x)$: absorption coefficient [cm^{-1}]
- Optical generation rate: $G_{OPT}=\alpha(x)F(x)$
- $\alpha(x)F(x)dx$: number of absorptions per unit time within dx
- $dF(x) = - \alpha(x)F(x)dx$
- Let $\alpha(x)$ = const; let x_0 be a reference abscissa (eg. Surface) ---> $F(x) = F(x_0)\ \exp[-(x-x_0)\alpha]$

Solar cells

- Basic requirements for solar-cell operation:
  - optical generation of electron-hole pairs under sun illumination: the band-gap must correspond to wavelength included in the spectrum of solar light.
  - Built-in electric field for separation of carriers.
  - low recombination rate – low defect density.

Cella fotovoltaica convenzionale al silicio



Efficienza di conversione: 16% - 20%
Massimo teorico: 31%
Tecnologie alternative:
- Film sottile silicio amorfo (7% - 9%)
- Celle multi-giunzione (fino a 40%)
- Celle in materiale organico (basso costo, bassa efficienza 5%)

The PN junction as a solar cell

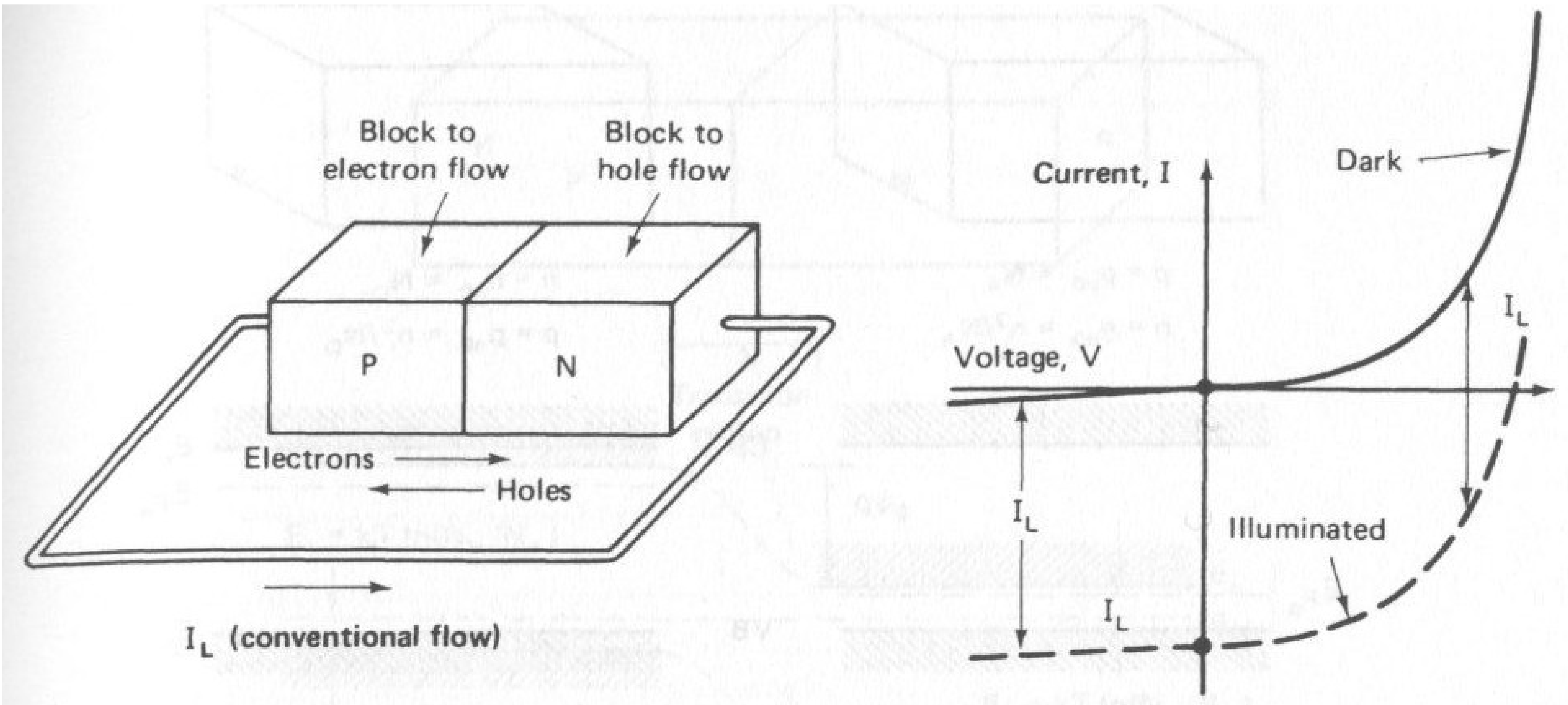


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Photo-generated carriers surviving recombination and separated by the junction field contribute a negative current $-I_L$ that (approximately) superimposes to the conventional I-V characteristic.

The PN junction as a solar cell

- Under the simplifying assumption of uniform optical generation rate G_{OPT}
- Neutral region in region N: $$\frac{d^2 \Delta p}{dx^2} = \frac{\Delta p}{L_h^2} - \frac{G}{D_h}$$
- performing the same derivation as in the “dark” case

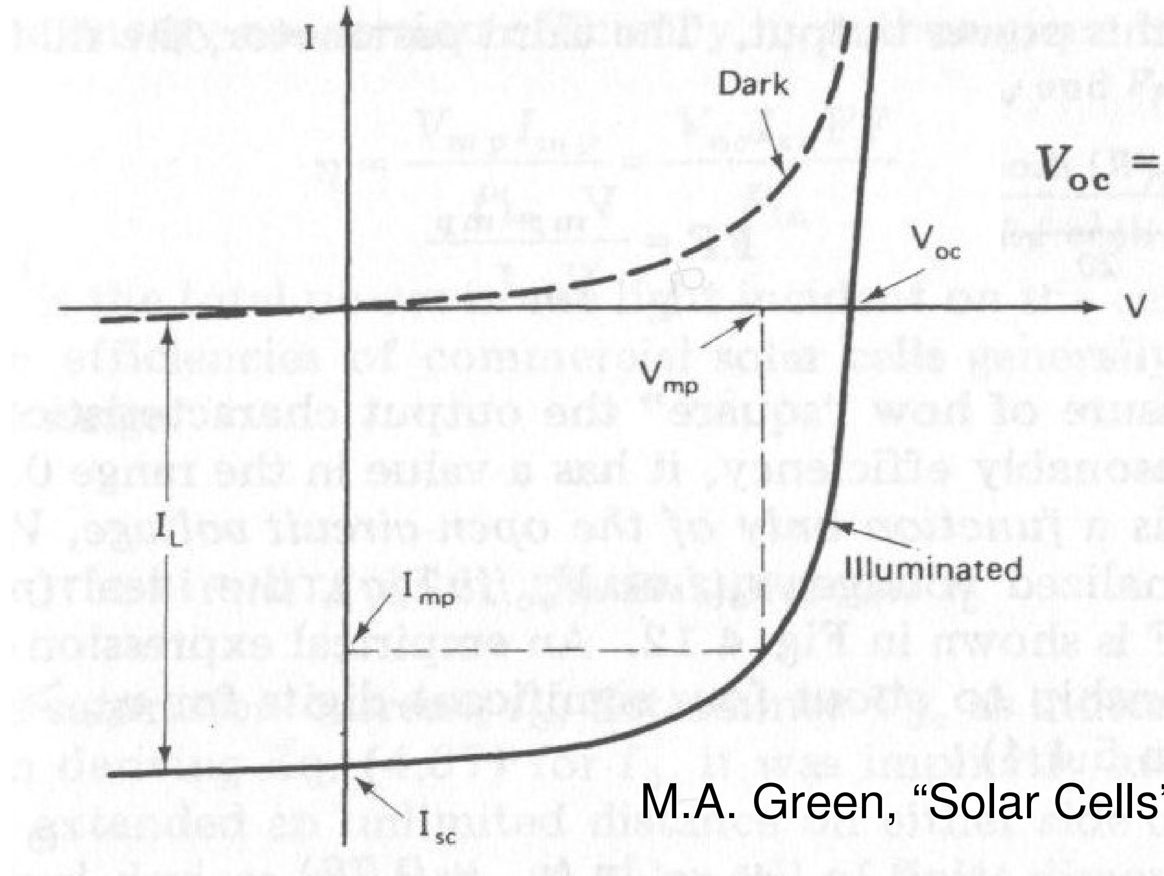
$$J_h(x) = \frac{qD_h p_{n0}}{L_h}(e^{qV/kT} - 1)e^{-x/L_h} - qGL_h e^{-x/L_h}$$

- Optical generation in the depletion region:

$$|\delta J_e| = |\delta J_h| = qGW$$

- repeating for electrons at the P side and combining results: $$I = I_0(e^{qV/kT} - 1) - I_L \qquad I_L = qAG(L_e + W + L_h)$$
- the photo-generated current is contributed by the depletion region plus two adjacent regions within a diffusion length on each side

PN junction solar cell



$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

M.A. Green, “Solar Cells”, Univ. South Wales.

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$

$$\eta = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

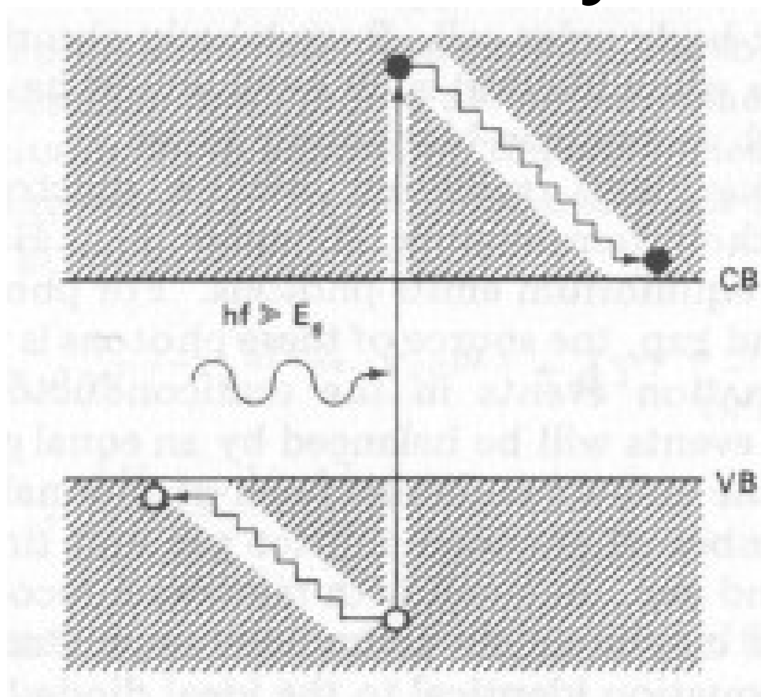
Conversion Efficiency

- Efficiency requires:
  - large open-circuit voltage V_{OC}
  - Low saturation current I_O (dark I-V charact.)
  - Large short-circuit current I_{SC}
- Low I_O --> low recombination rates
- Large I_{SC} --> small band-gap (downside: energy wasted into heat generation).

Loss mechanisms

- Non absorption ($E_{ph} < E_g$)
- Thermalization ($E_{ph} > E_g$)
- Optical Losses (Reflection, Transmission, Area Loss)
- Collection Losses (Recombination)
  - Bulk Recombination
  - Surface Recombination
  - Mid Gap States (Dangling Bonds) in Amorphous materials

Fundamental energy losses limiting efficiency



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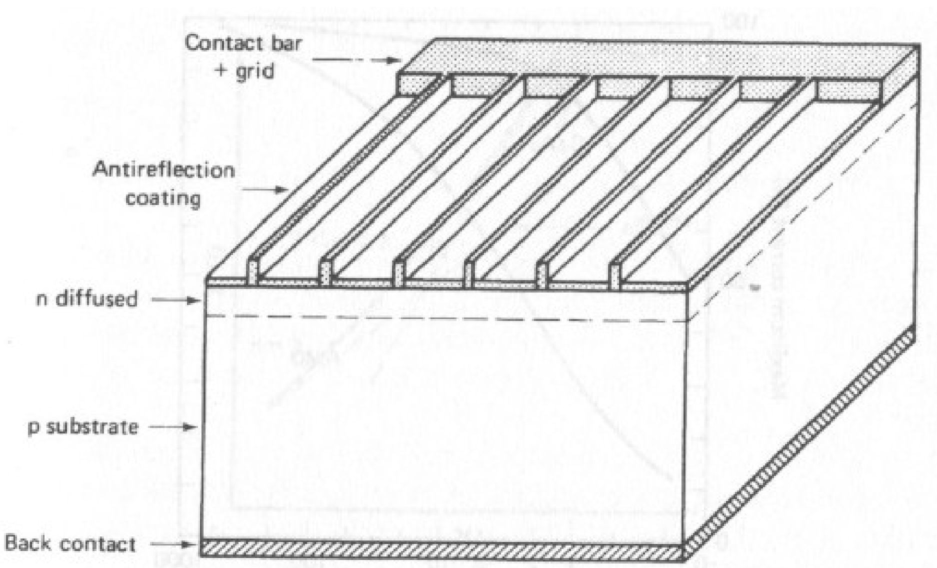
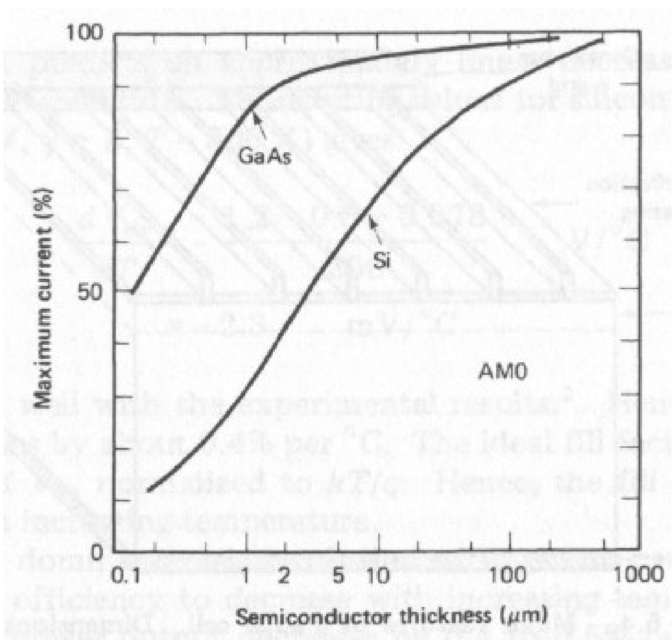
- For high-energy photons, the energy in excess of the bandgap is lost through phonon emission (heating).
- Although the carriers are separated in energy by a bandgap, V_{OC} is limited to a fraction of E_G/q.

Extrinsic energy losses

- The surface of the cell is partially reflective; anti-reflective coating reduces reflection to 10%
- Electrical contacts on the exposed surface blocks 5%-10% of the incoming light
- If the cell is too thin, part of the light may not be absorbed





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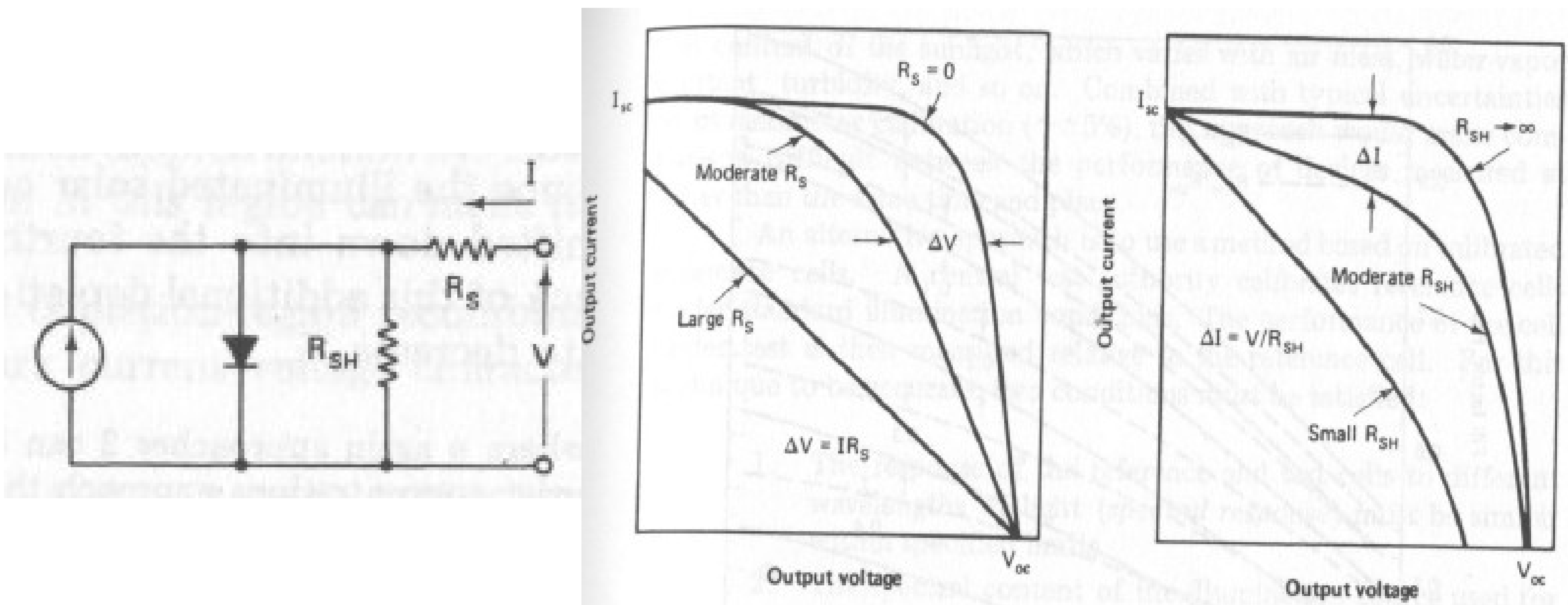
Extrinsic energy losses

- Recombination in bulk silicon and at the surfaces limits VOC
- The fill factor is degraded by parasitic series and shunt resistances



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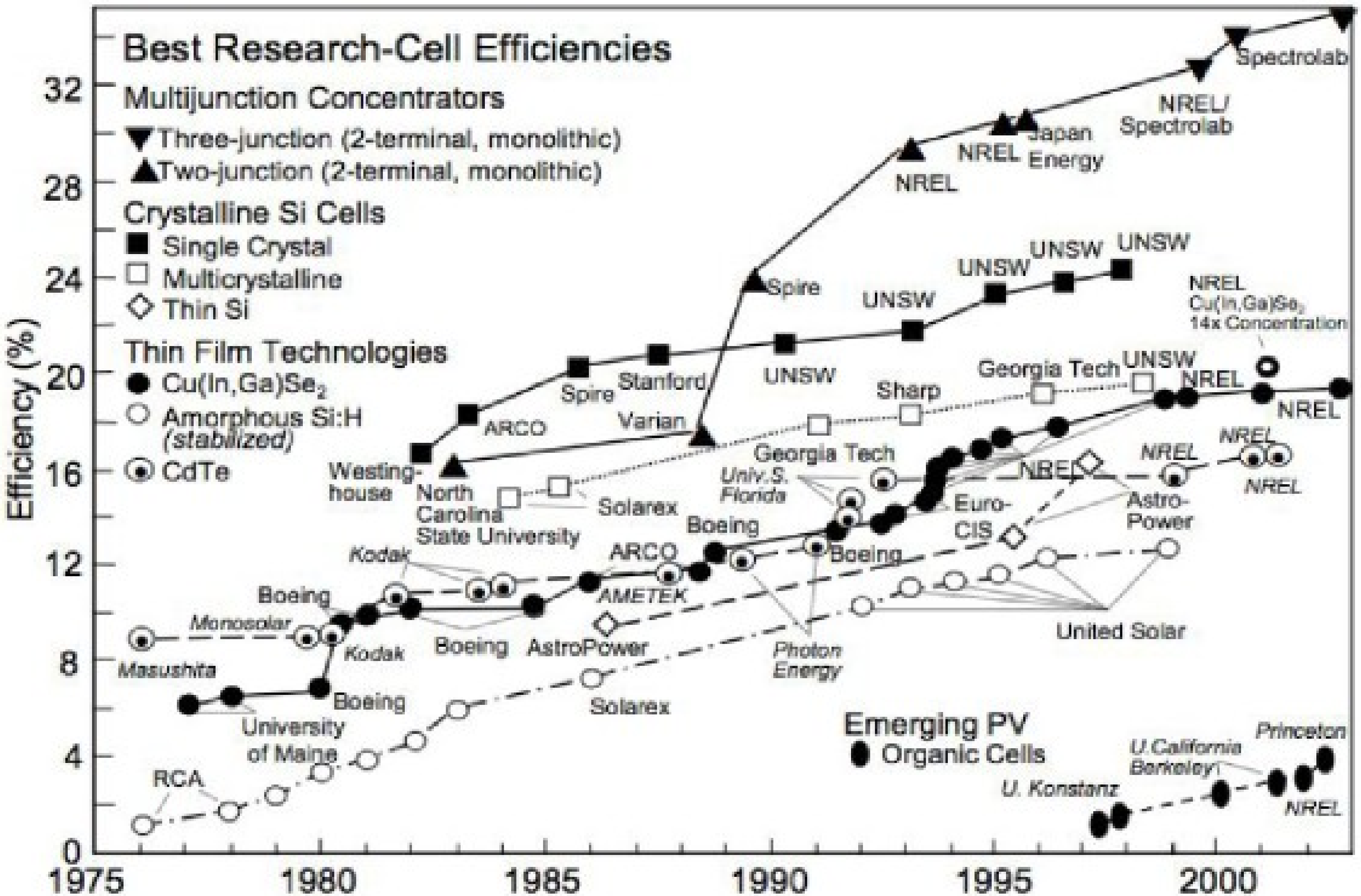
Main technology options

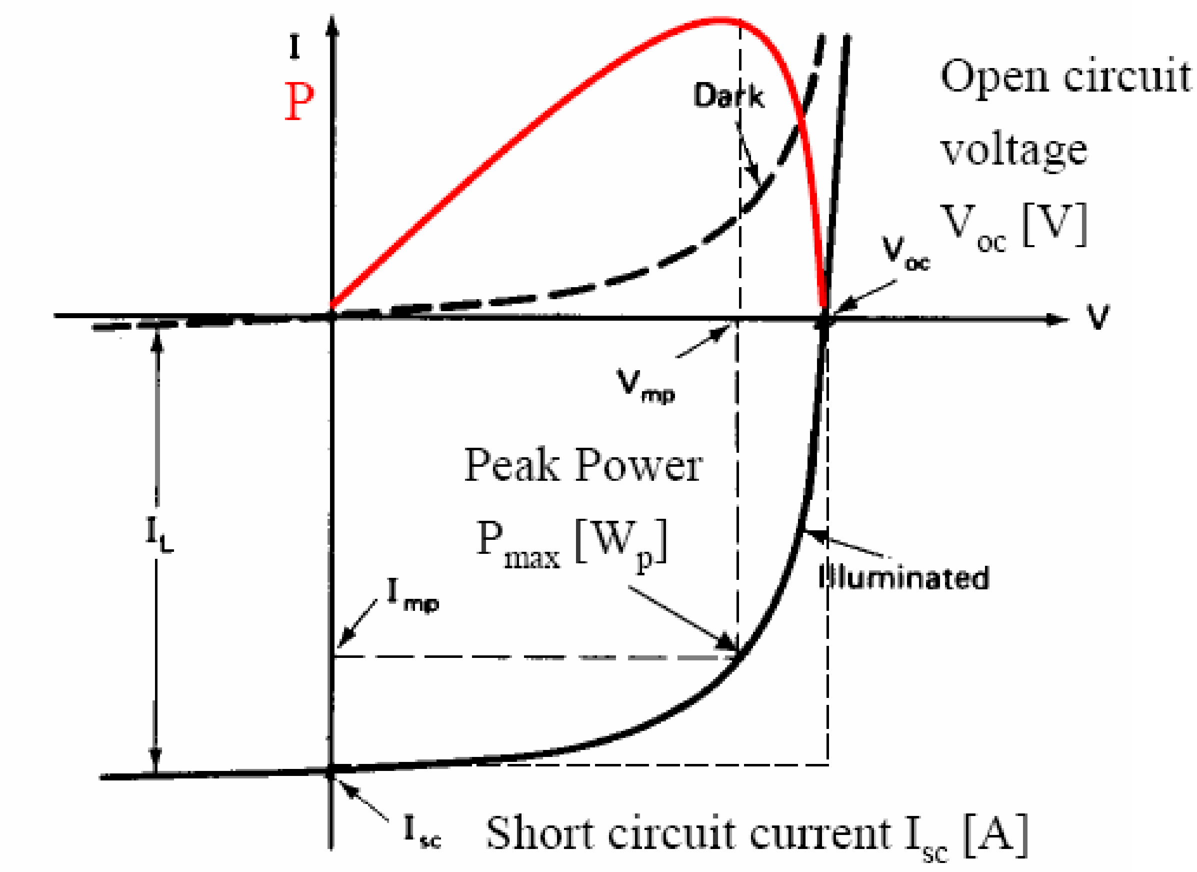
- Crystalline Silicon PV cells; effic.: 16% - 20%
- Thin film cells (7% - 10%)
  - Silicon based
  - CdS/CIS
  - Cds/CdTe
- Organic Cells (5%)
- Concentrator PV cells

Best Solar Cells Efficiencies



Theoretical Limits of photovoltaic conversion

Performance parameters



$$\eta = \frac{P_{max}}{P_I} = FF \cdot V_{OC} \cdot \frac{I_{sc}}{P_I}$$

$$P_{max} = V_{mp} \cdot I_{mp} = FF \cdot V_{OC} \cdot I_{sc}$$

Solar cell performance

- **Optimal design keys:**
  - **High J_{sc}**
    - Minimize front surface reflection (ARC)
    - Minimize transmission losses (thick absorber)
    - Minimize surface recombination (passivation layers)
    - Minimize bulk recombination
      - large diffusion lengths
      - high electronic quality material
  - **Low I_0**
    - High doping densities
    - Low surface recombination velocities
    - Large diffusion lengths

Solar cell performance (P-n junction)

- **Short circuit current** (V=0)

$$Isc = -I_L$$

- **Open circuit voltage** (I=0)

$$V_{OC} = \frac{KT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

- **Saturation current**

$$I_0 = A\left(\frac{q D_n n_i^2}{L_n N_A} + \frac{q D_p n_i^2}{L_p N_D}\right)$$

Theoretical limits of energy conversion in solar cells

- Theoretical upper bounds of **efficiency** (η), **short circuit current** (Jsc) and **open circuit voltage** (Voc) as a function of band gap energy and thickness of a material slab are investigated.
- We evaluate the relevance of losses due to:
- recombination mechanisms
- the absence of a light trapping strategy

Theoretical limits of energy conversion in solar cells

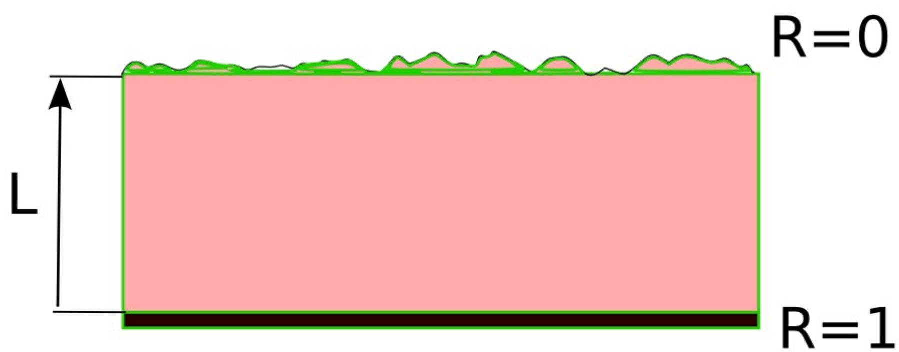
- ***AM1.5 Standard Global Spectrum*** with 100 mW/cm^2
- Optical absorption coefficients α(E) and refractive indexes n(E) for a-Si:H and c-Si from literature
- Accounted recombination mechanisms:
- Auger and Radiative (c-Si)
- Recombination on Dangling Bond (DB) states and Band Tails in a-Si:H

Absorbance

- **One-pass** (specular with no back reflector)

$$a(E) = 1 - \exp\left[-2\alpha(E)L\right]$$

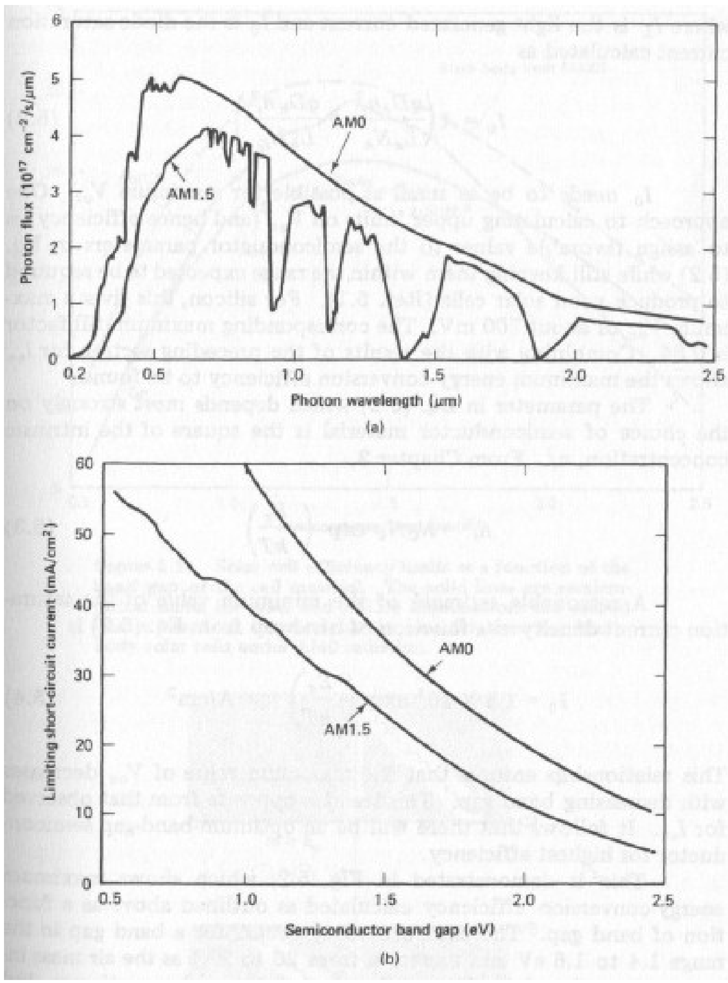
- **Lambertian** (randomized multiple scattering surfaces with back reflector)



$$a(E) = \frac{\alpha(E)}{\alpha(E) + \frac{1}{4n^2 L}}$$

- **Step function**: all photons with E > Eg are absorbed and converted into electron-hole pairs; a(E)=1 if E > Eg.

Optical solar spectrum and maximum short-circuit current



$$\lambda = \frac{c}{f} = \frac{hc}{E}$$

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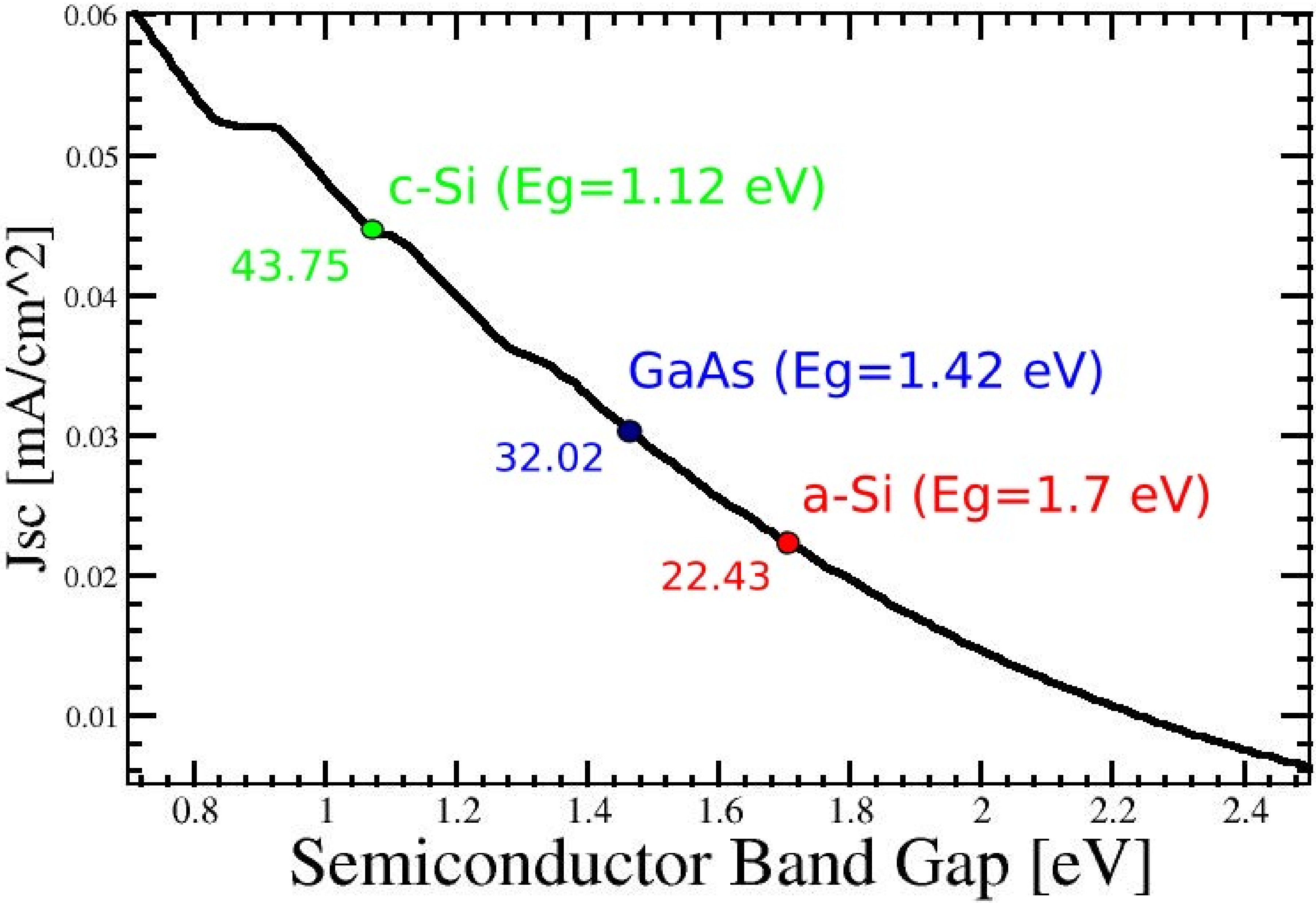
Short-circuit current increases for decreasing bandgap (larger number of photons contribute to generation

Limiting short-circuit current (AM1.5G)



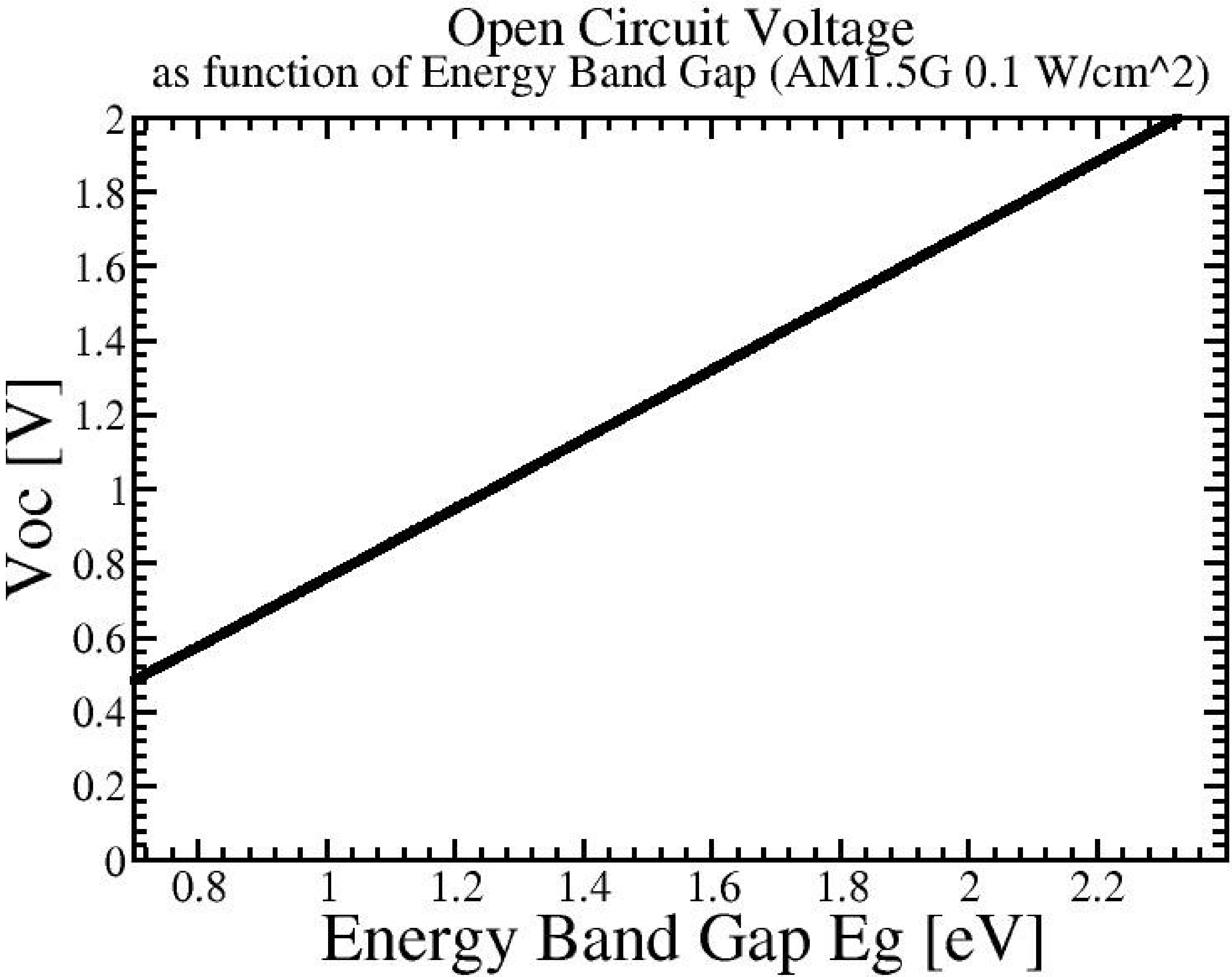
Limit to the open-circuit voltage

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

$$I_0 = A\left(\frac{qD_e n_i^2}{L_e N_A} + \frac{qD_h n_i^2}{L_h N_D}\right)$$

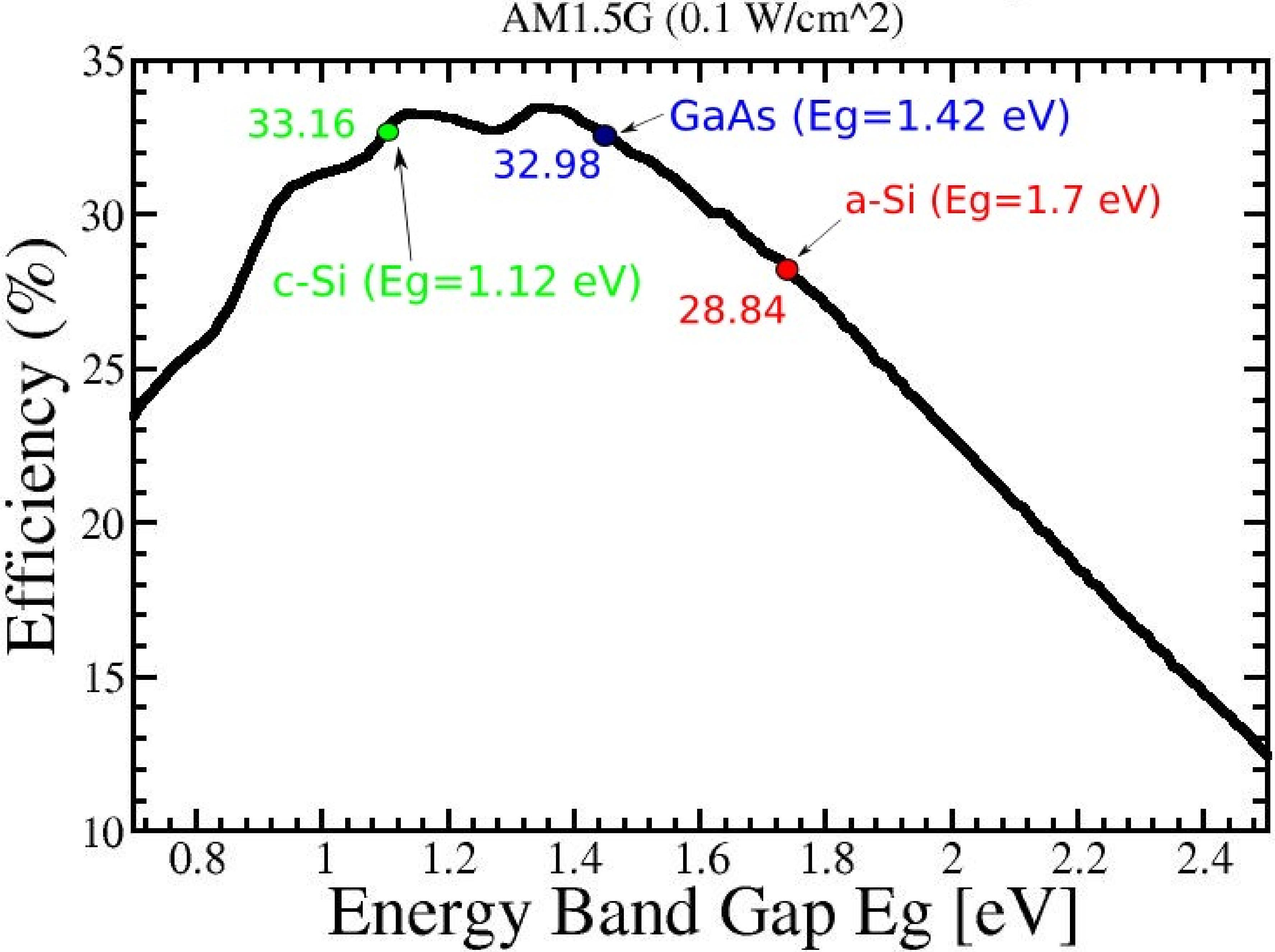
$$n_i^2 = N_C N_V \exp\left(-\frac{E_g}{kT}\right)$$

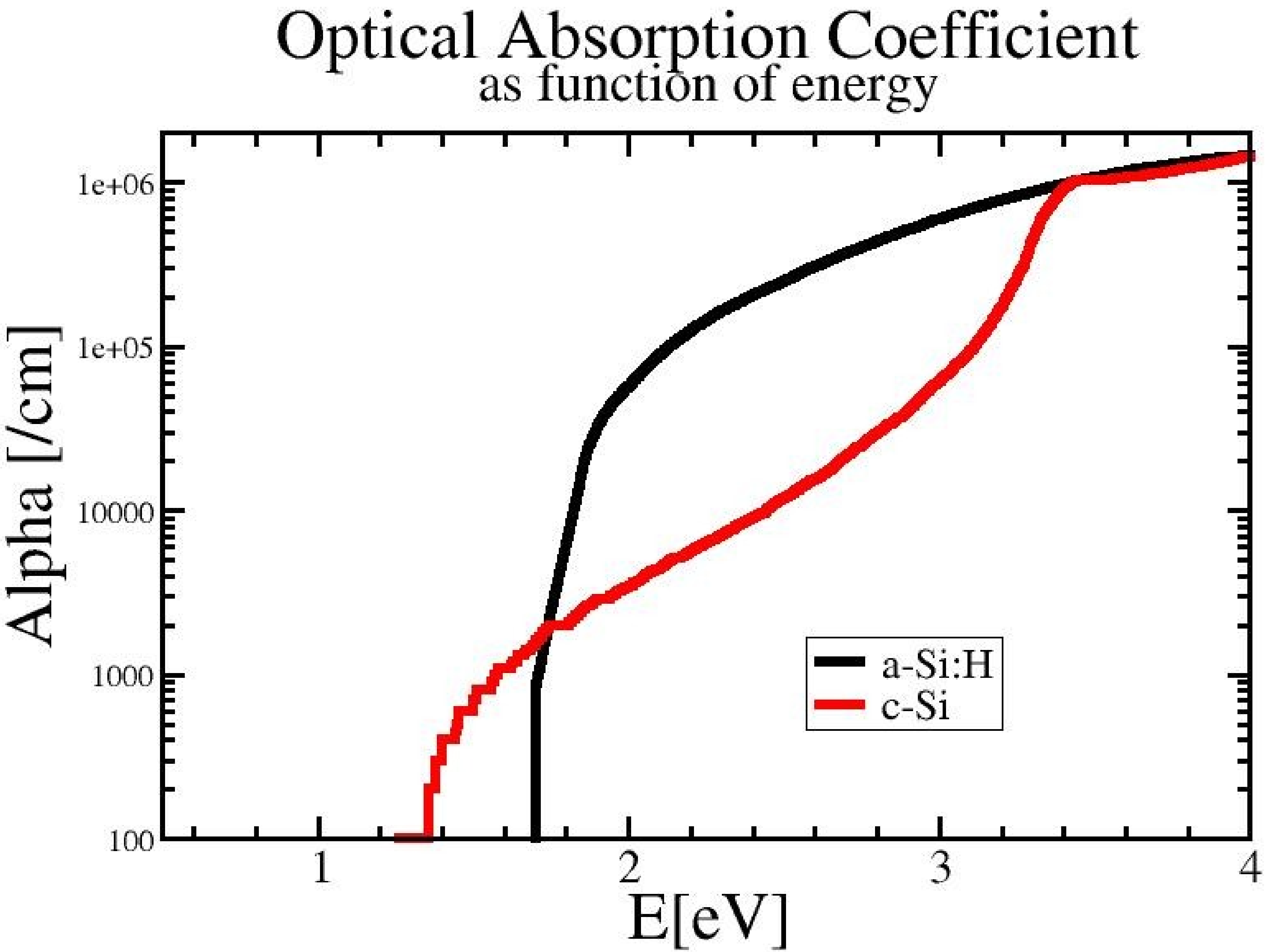
V_{OC} increases for low recombination rates (large diffusion lengths) and small intrinsic concentration (large bandgap)



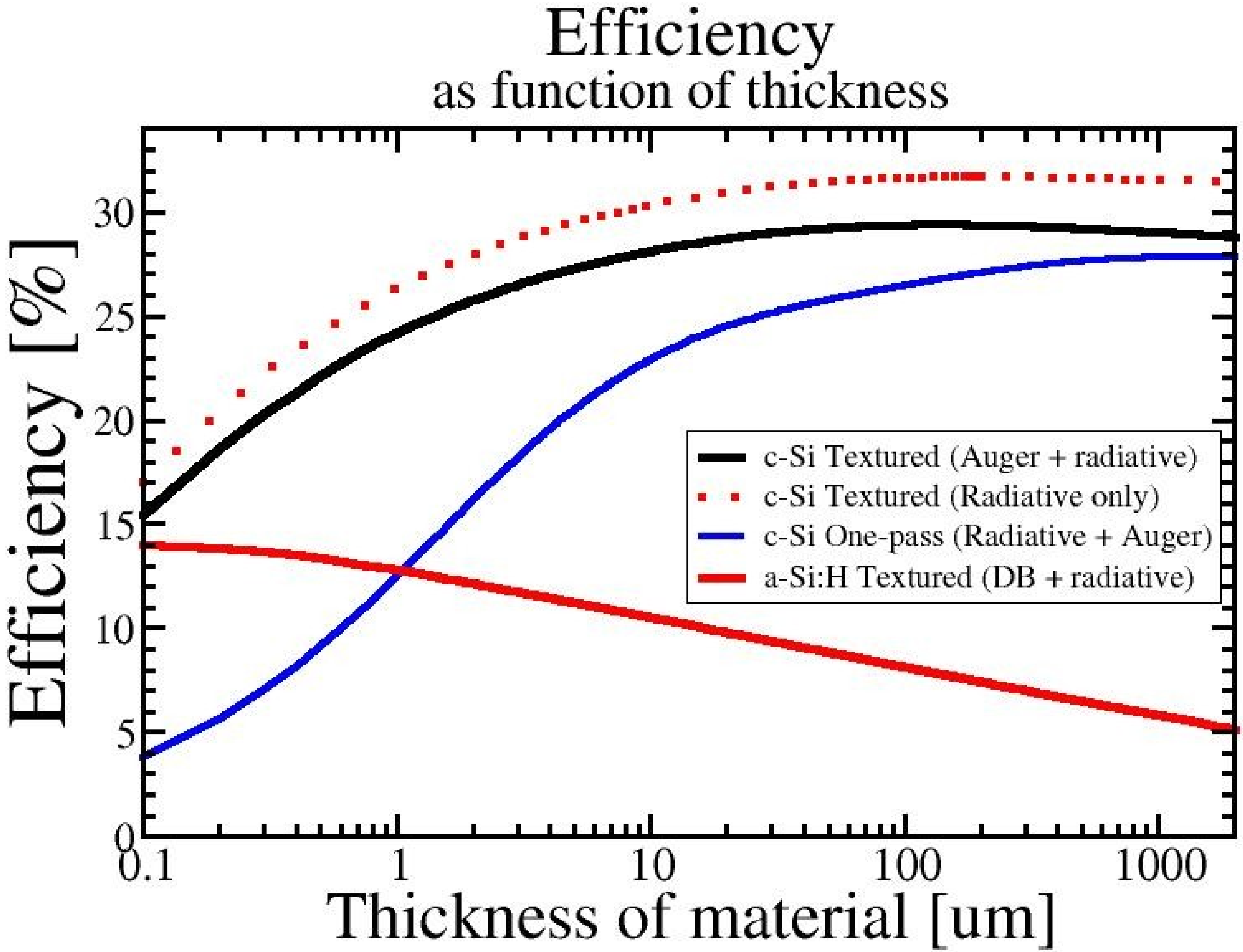
Open Circuit Voltage
as function of Energy Band Gap (AM1.5G 0.1 W/cm^2)
Voc [V]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.8
1
1.2
1.4
1.6
1.8
2
2.2
Energy Band Gap Eg [eV]

Radiative recombination-limited efficiency of solar cells





Optical Absorption Coefficient
as function of energy
Alpha [/cm]
E[eV]
1e+06
1e+05
10000
1000
100
1
2
3
4
a-Si:H
c-Si



- $C=C_n+C_p=3.88*10^{-31}$ cm^{-6} s^{-1} (Auger, c-Si)
- $R_{DB} = 4*10^4$ cm^{-3} s^{-1}(recombination in mid gap states, a-Si:H)

Theoretical limitis: partial conclusions

- In case of c-Si there is a full knowledge of all loss mechanisms, but only radiative and Auger recombinations are enable since all other losses can be reduced by improving the design of the device .
- In case of a-Si:H not all recombination models were included in this analysis and what is not currently defined is the contributions of each loss mechanism
- By considering the I_{sc} limit (22.43 mA/cm^2) and the solar cell fabricated in laboratory (up to I_{sc}=17 mA/cm^2), a substantial gain in short circuit current can therefore still be obtained by improving the light trapping.

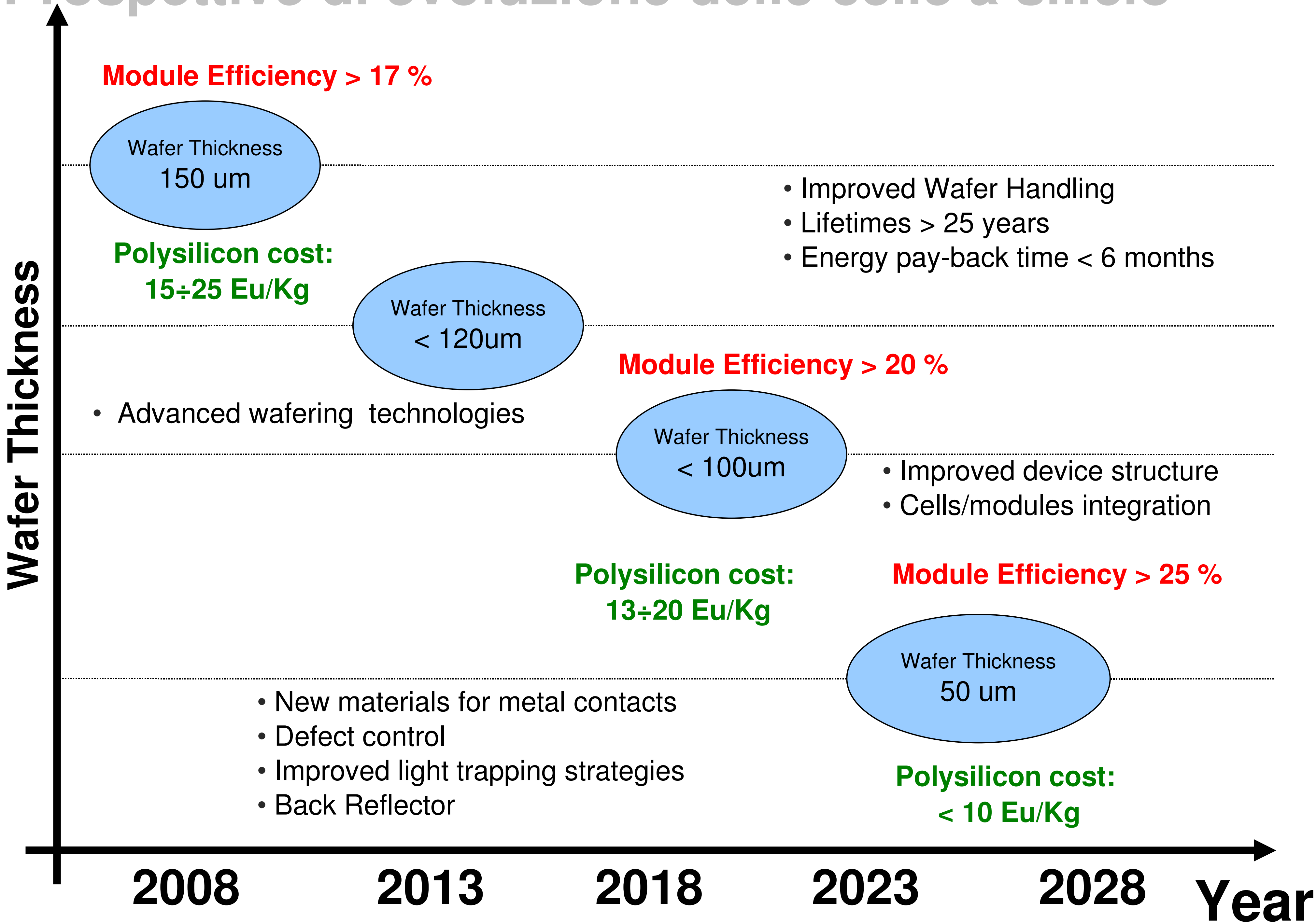
Theoretical limitis: partial conclusions

- In terms of efficiency, for a-Si:H the performance record (9% single junction, 12% tandem, 13% triple junction) is still too far from the upper limit (28%) and most of ths gap is due to poor material quality (defects, enhanced recombinations in intrinsic layers).
- The different optical absorption profile of a-Si:H compared to c-Si allows to design very thin slabs of absorbing material.
- The efficiency degradation ("Staebler-Wronski effect") is not included in this analysis.
- The analysis was performed with the p-n junction electrical model, but a-Si:H devices use p-i-n configuration.

Silicon solar cells

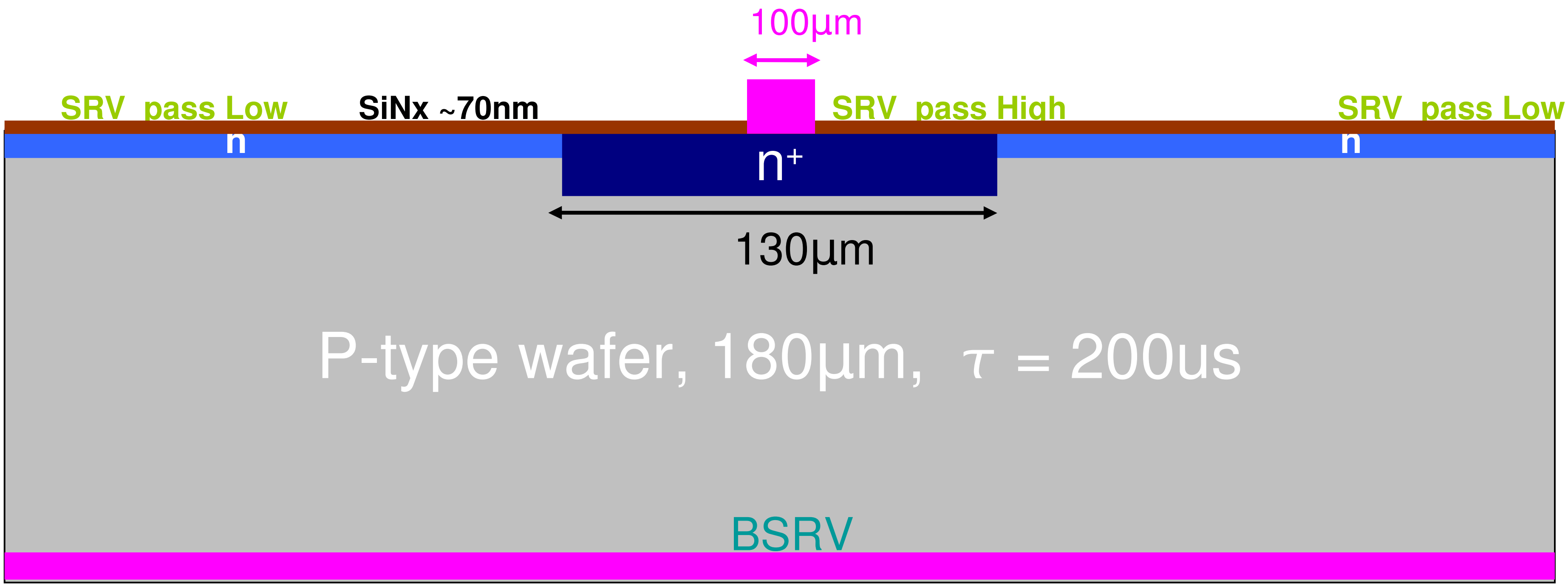
- Crystalline solar cells
  - low defect density.
  - low recombination rates
  - η: 15% - 20%
- Amorphous-Si (thin film) solar cells
  - cheaper
  - thinner and lighter
  - η: 7% - 10% (large recombination rate)

Prospettive di evoluzione delle celle a silicio



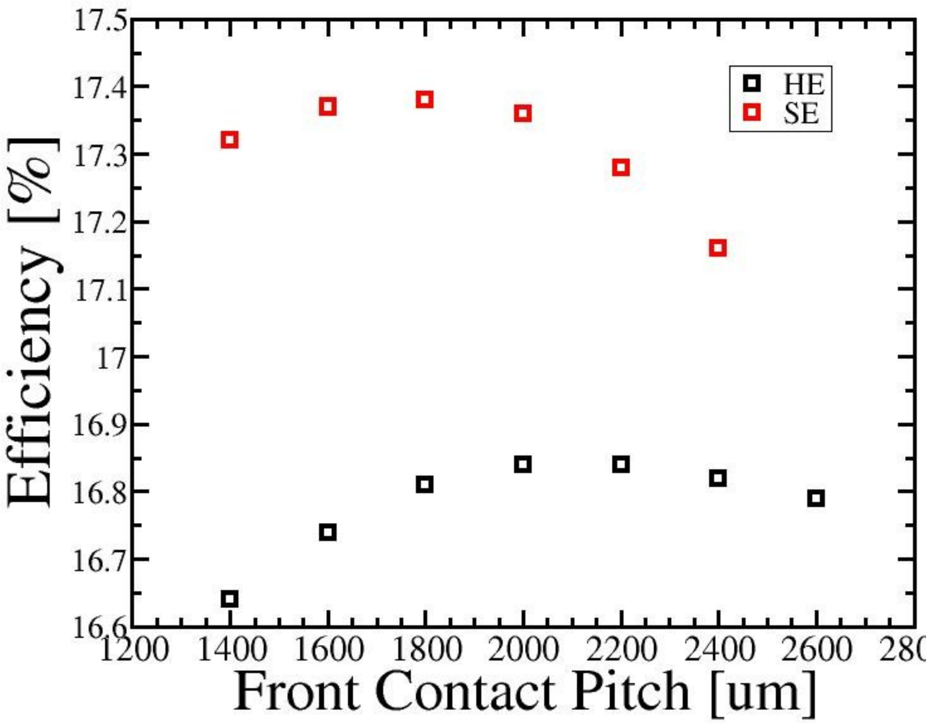
Advanced c-Si Solar Cells: Selective Emitter

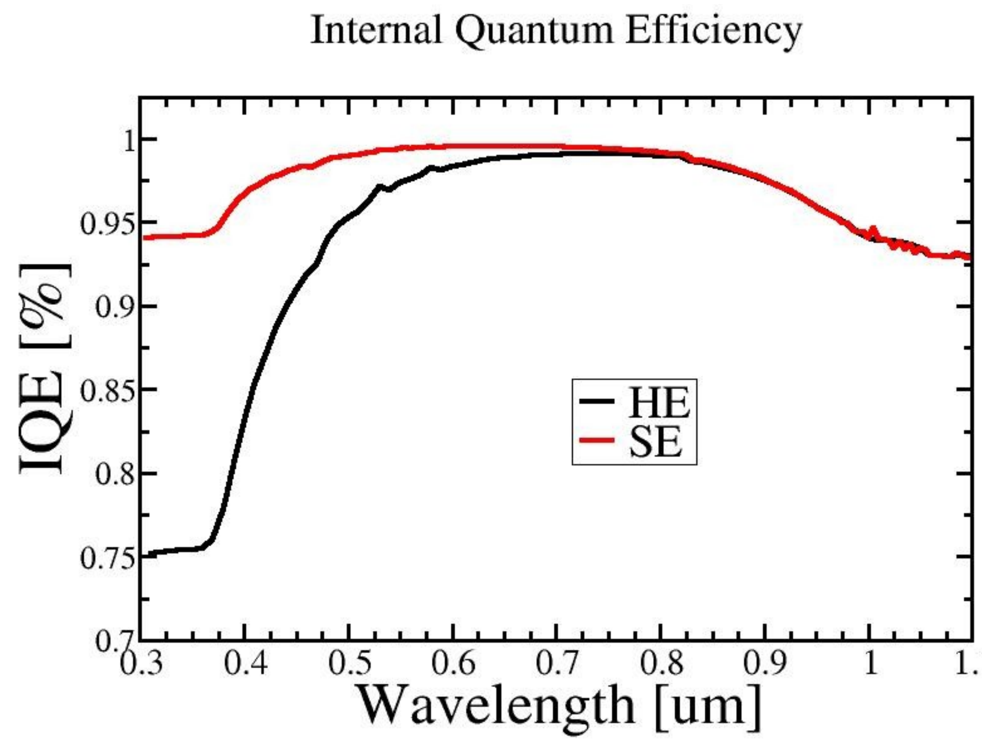
Selective Emitter



- Deep n^+ diffusion under front metalization (10 Ω□❑ .
- N-type diffusion between finger (117 Ω□❑ ▪ .
- P-Type bulk (ρ=1.33 Ω□ cm 1e16 cm^{-3})
- Contact resistance 1mΩ˙cm^2

Selective Emitter (SE) vs Homogeneous (HE)

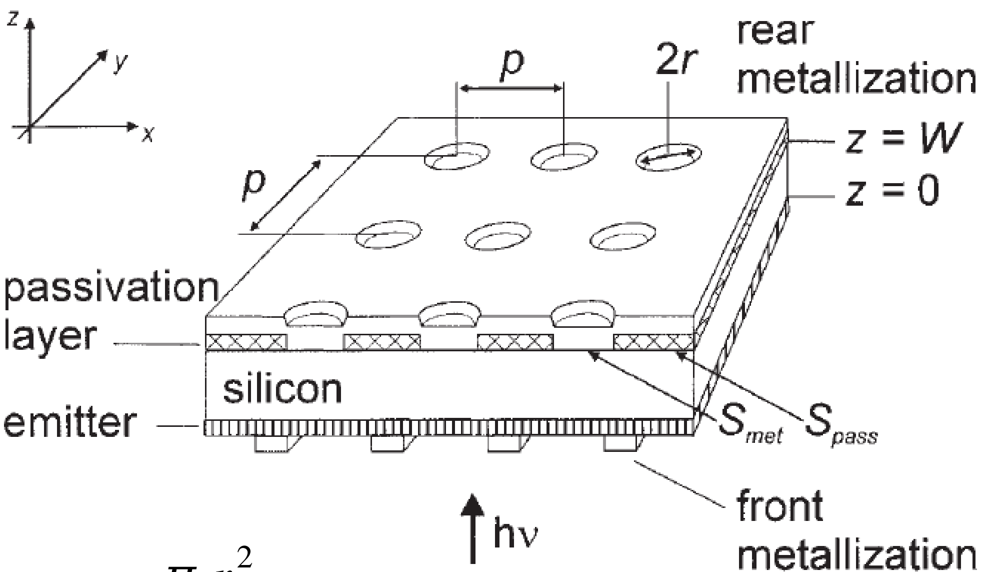




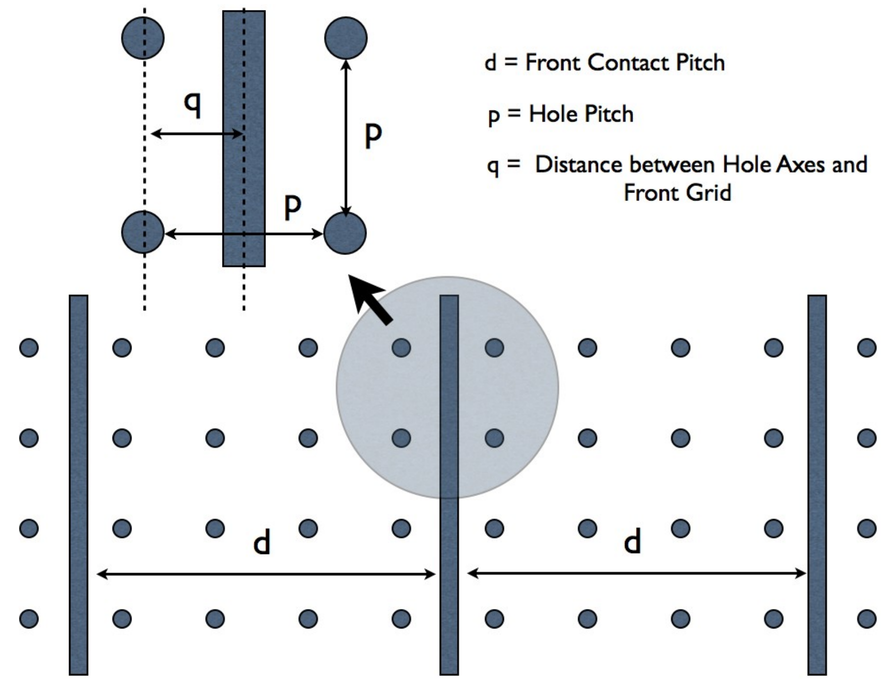
- **HE: max Eff at 2000 um** **(η=16.84%, Voc=0.611V, FF=0.803, Jsc=34.1 mA/cm^2)**
- **SE: max Eff at 1800 um** **(η=17.38%, Voc=0.621V, FF=0.795, Jsc=35.1 mA/cm^2)**
  - **SE+ Auger recombination**
  - **SE+ Surface recombination (between fingers)**
  - **SE+ Better Blue response**
  - **SE- Emitter Resistance**

Advanced c-Si Solar Cells: Local Point

Local Point Solar Cell



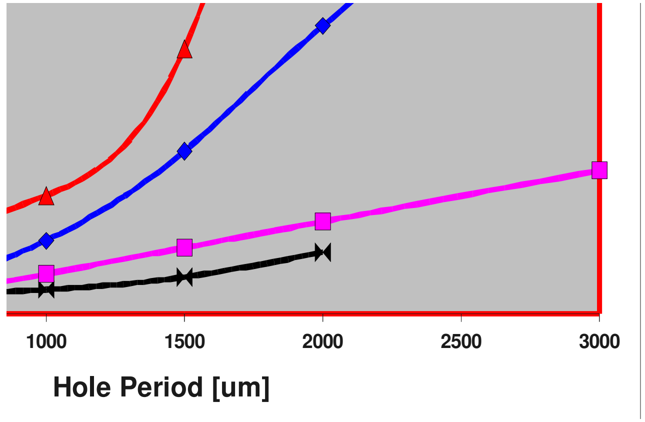
$$f \equiv \frac{\pi \cdot r^2}{p^2}$$



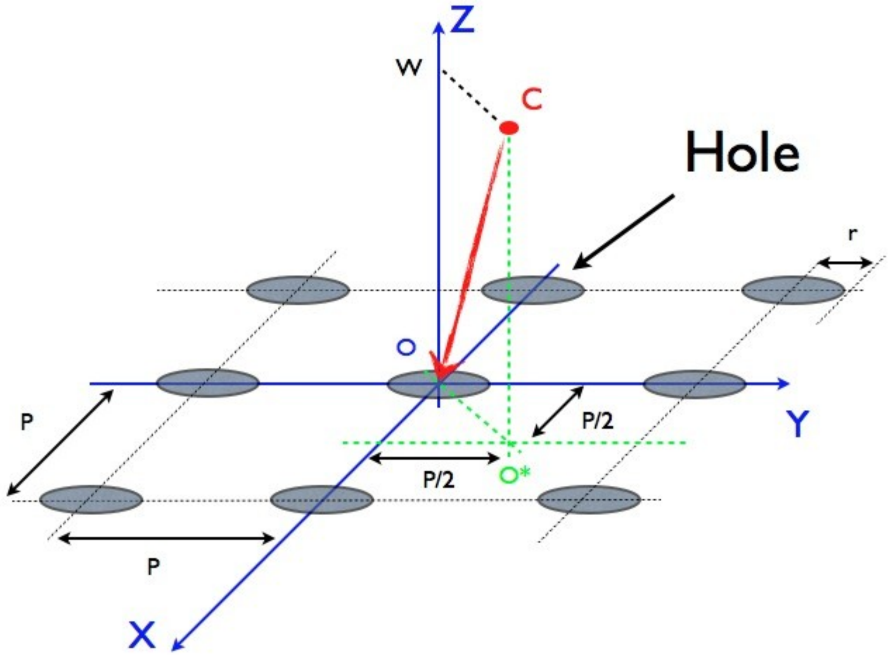
- Expected advantage (compared to a conventional full back contact cell):
  - Reduced back surface recombination velocities (BSRV)
- Trade-off between the metalization fraction ***f*** and efficiency (a reduced metalization factor would increase the effective base resistance $R_{s,eff}$)

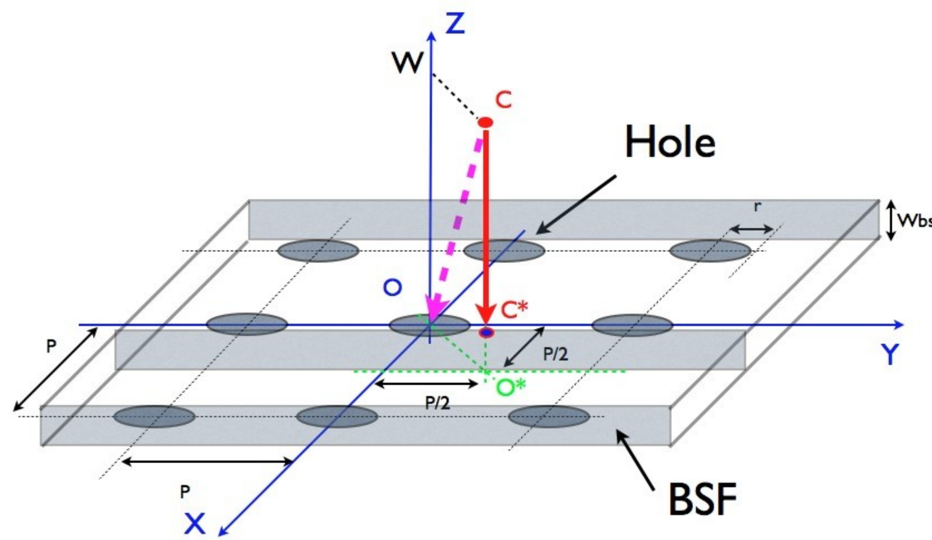
Local Point Solar Cell analysis strategy

- **Evaluation of the effective base series resistance $R_{s,eff}$ and of the effective back surface recombination velocity S_{eff} by using an analytical semi-empirical model.**
- **1D (fast) simulation to find the range of interest of the geometrical parameters (p,r,*f*) in order to maximize the efficiency of the device.**
- **Validation of the results by simulating the device with a 3D structure (Sentaurus).**



Local Point Solar Cell with BSF





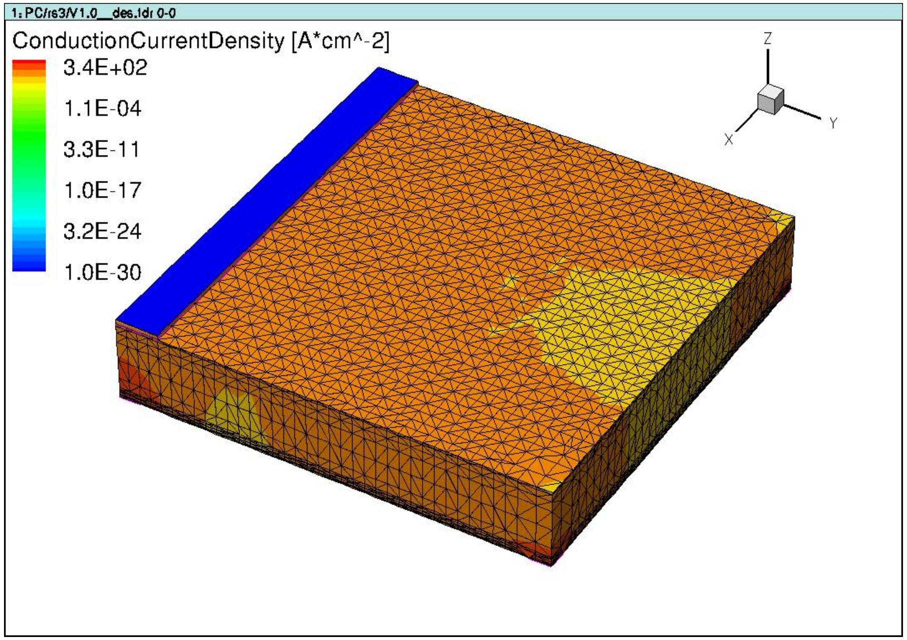
- W = wafer thickness
- W_{BSF} = BSF layer thickness
- Majority carrier path length $LC_{bsf} = |C^*-C|+|O^*-C^*|+|O-O^*|$
- Since BSF is heavily doped, $LC_{bsf} \approx |C^*-C| < LC_{no\_bsf}$

$$R_{s,eff}^{W/OBSF} = f\left(\rho, W, P, R\right) \rightarrow R_{s,eff}^{W/BSF} = f\left(\rho, \frac{W}{\alpha}, P, R\right)$$

$$\alpha = \sqrt{\left(1 + \frac{P^2}{2\cdot\left(W - W_{BSF}\right)}\right)} > 1$$

Local Point Solar Cell:

3D simulation and validation of the model to evaluate the effective base series resistance



- **Preliminary results**

Hole Pitch	Hole Size	Analytical Model	Sentaurus 3D
p	s=2r	Rs,eff	Rs,eff
[um]	[um]	$m\Omega*cm^2$	$m\Omega*cm^2$
200	100	40	160
1000	100	610	671
1000	200	280	385

No contact resistance assumed.

Front contact pitch = 2000 um

Wafer thickness = 185 um

Wafer resistivity = 1.33 Ω*cm, no BSF