

# Fotowoltaika - jak zamienić fotony na prąd?



# Przerwa energetyczna

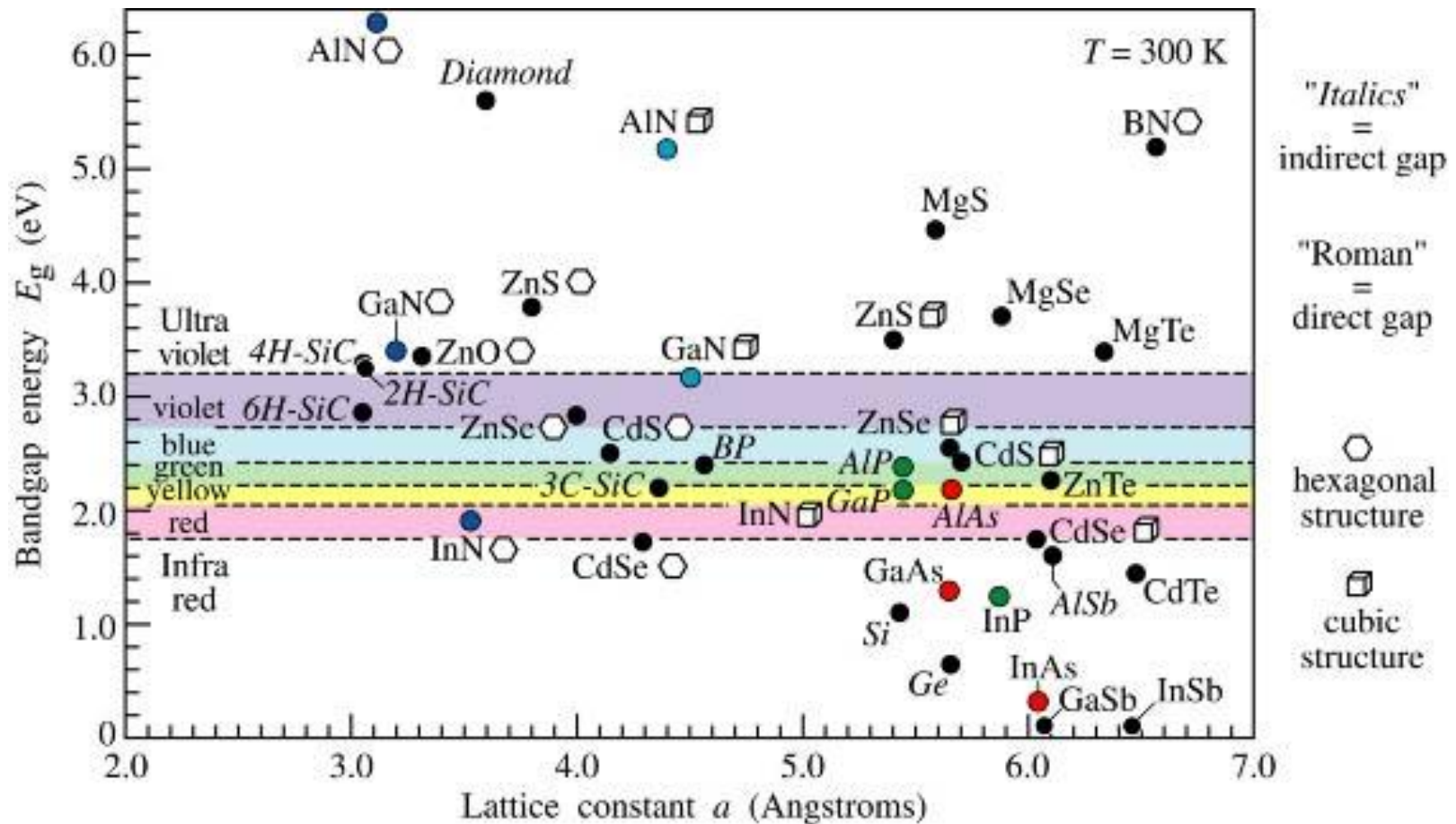
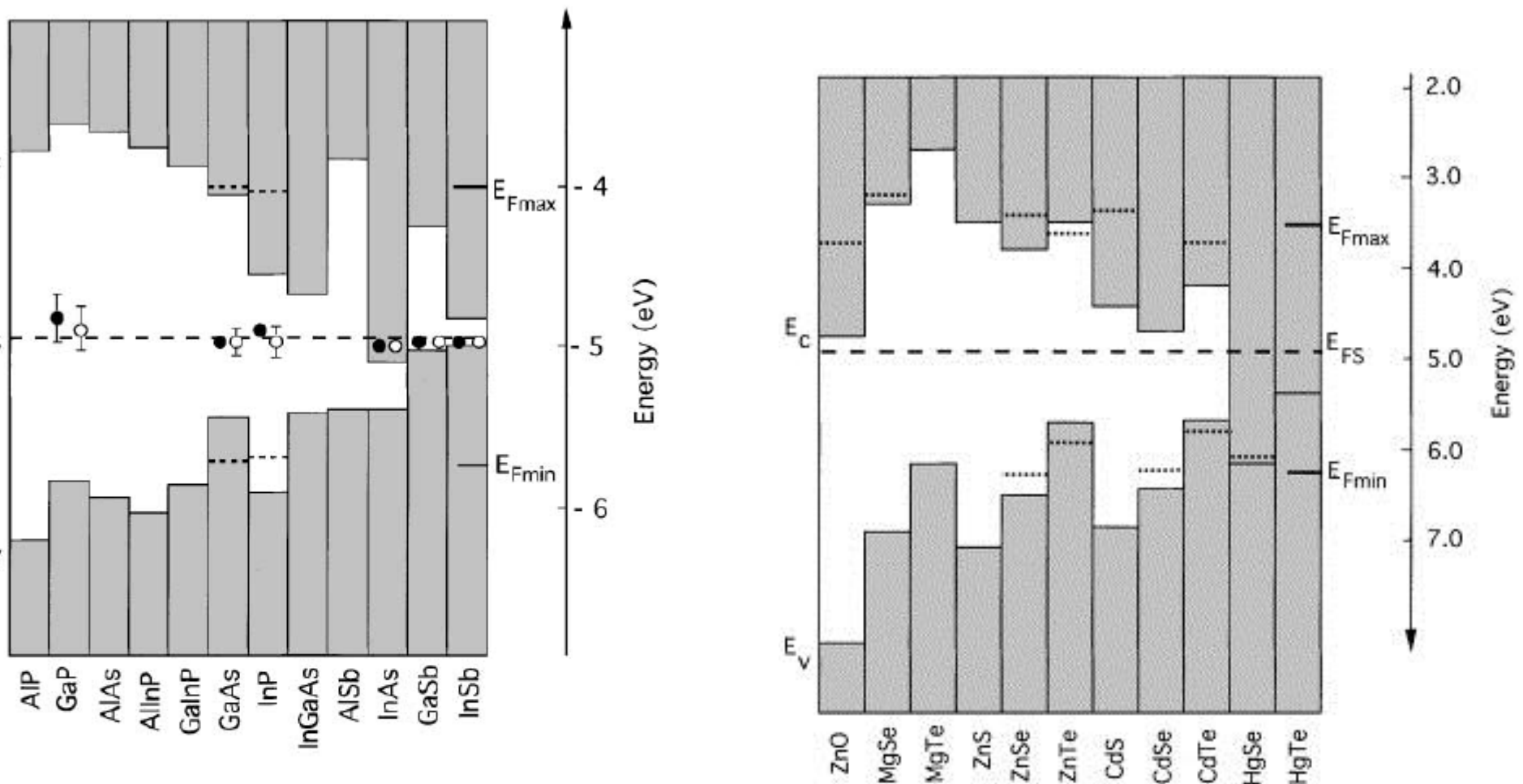


Fig. 11.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.

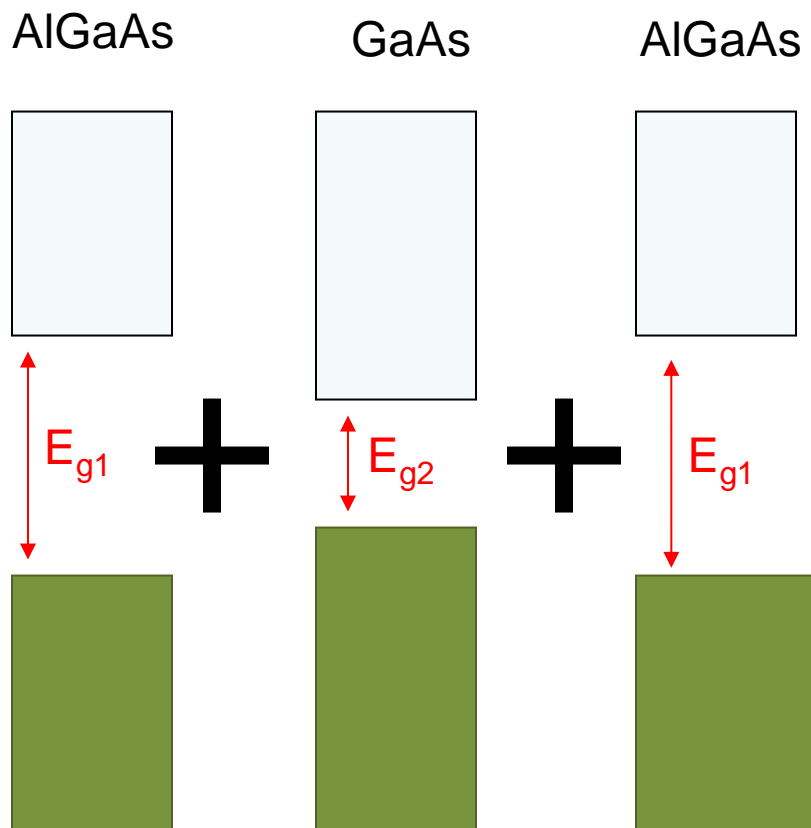
# Bandgap engineering

## Valence band offset

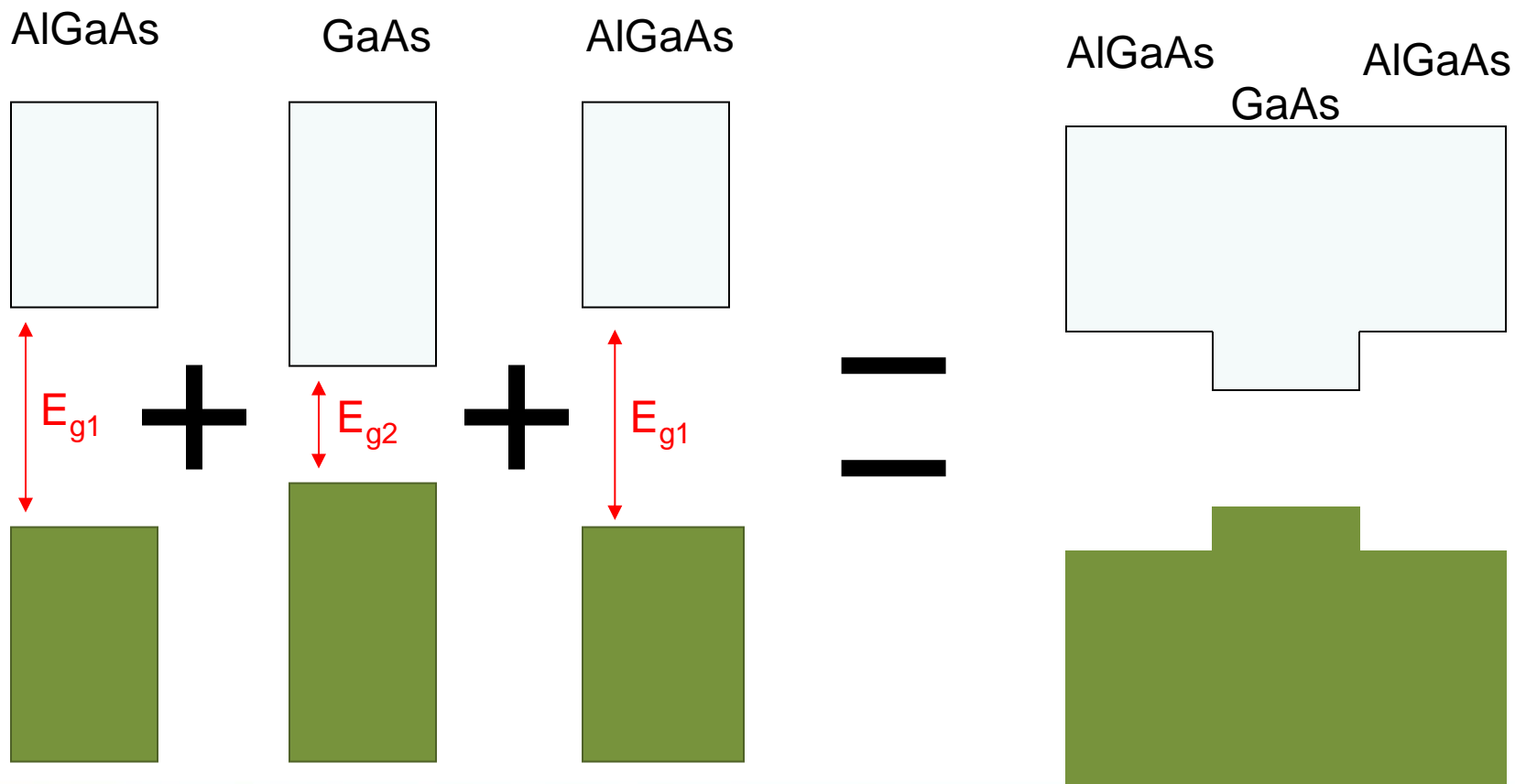


Band offsets and the Fermi level stabilization energy in III-V compounds. The energy is measured relative to vacuum level. The filled circles represent stabilized Fermi levels in heavily damaged materials, exposed to high energy

# Studnia Kwantowa



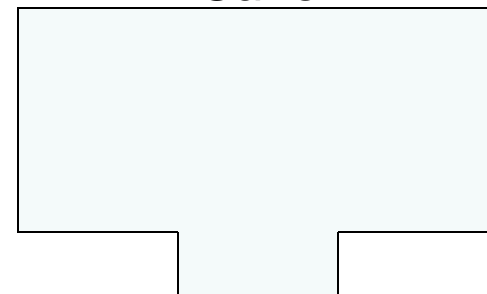
# Studnia Kwantowa



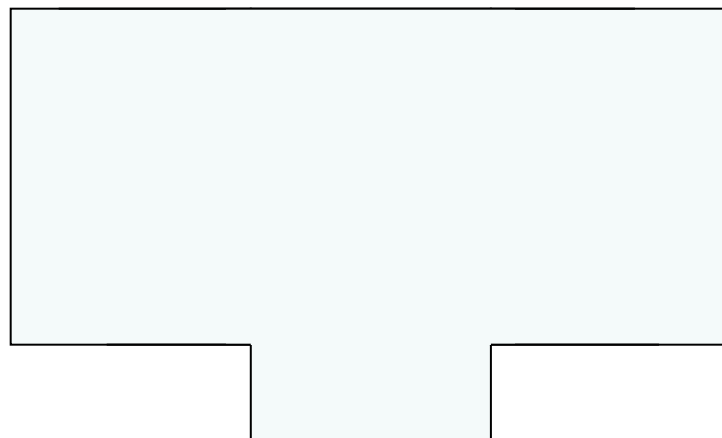
# Studnia Kwantowa



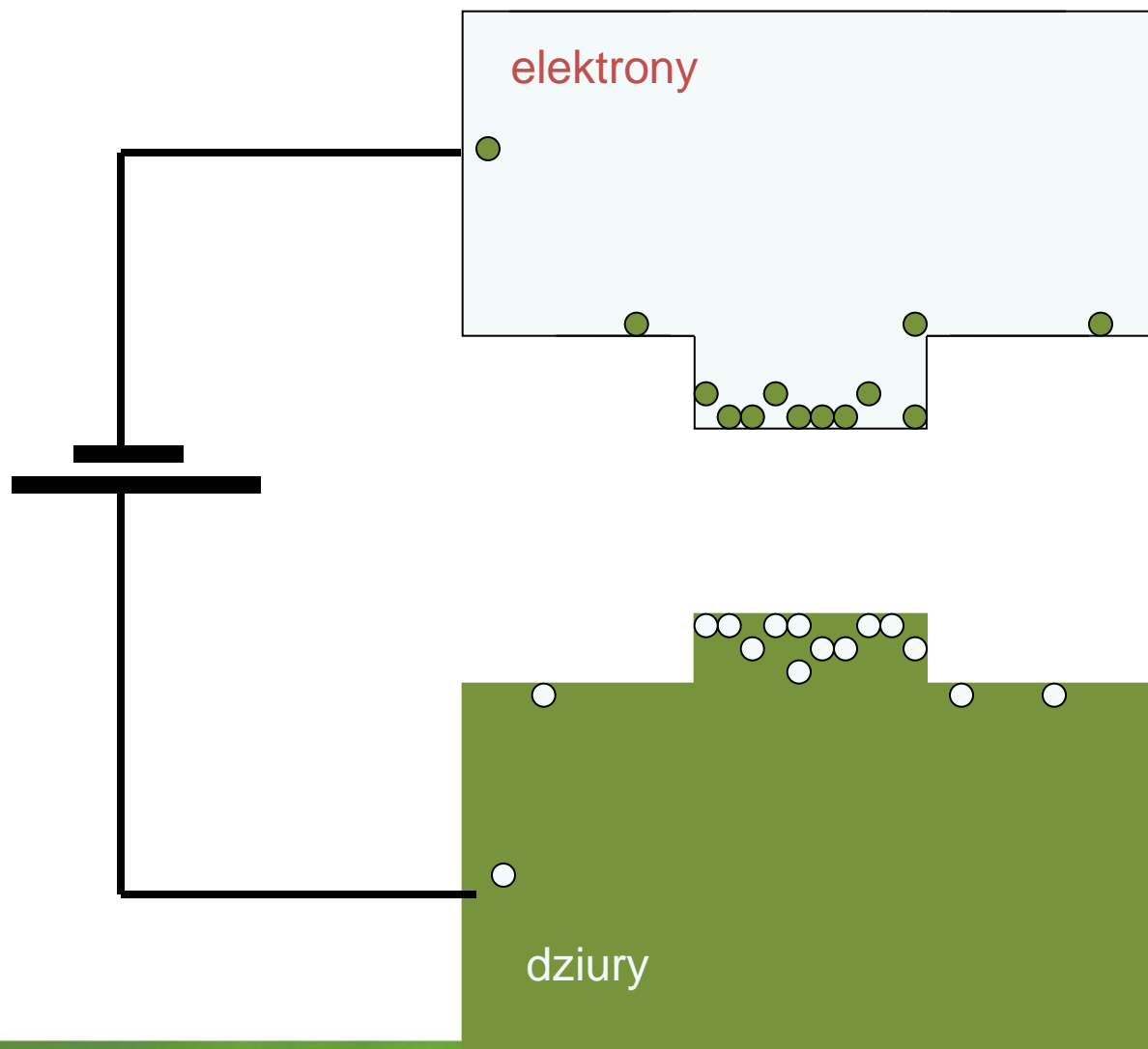
AlGaAs      GaAs      AlGaAs



# Studnia Kwantowa

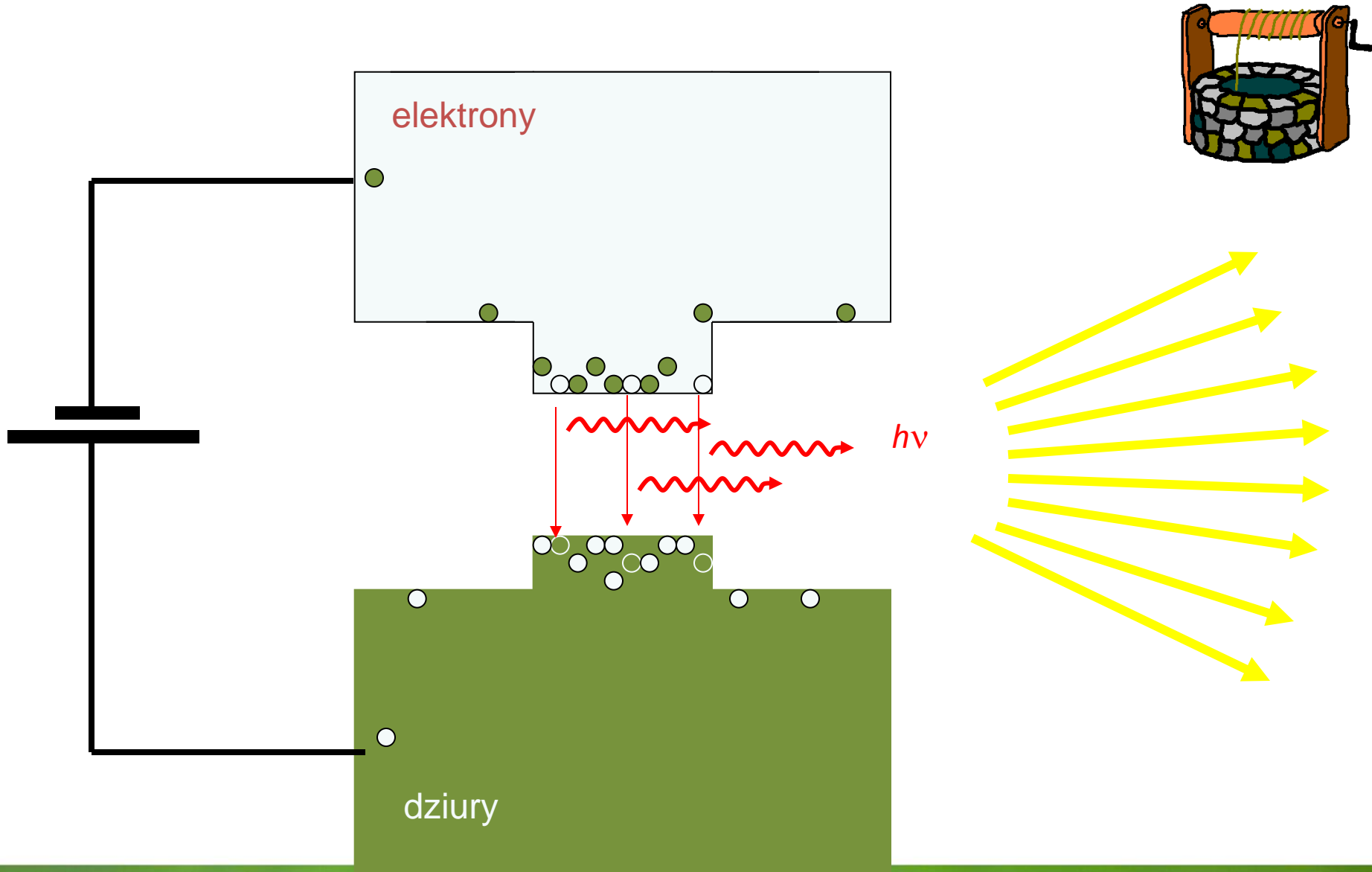


# Studnia Kwantowa





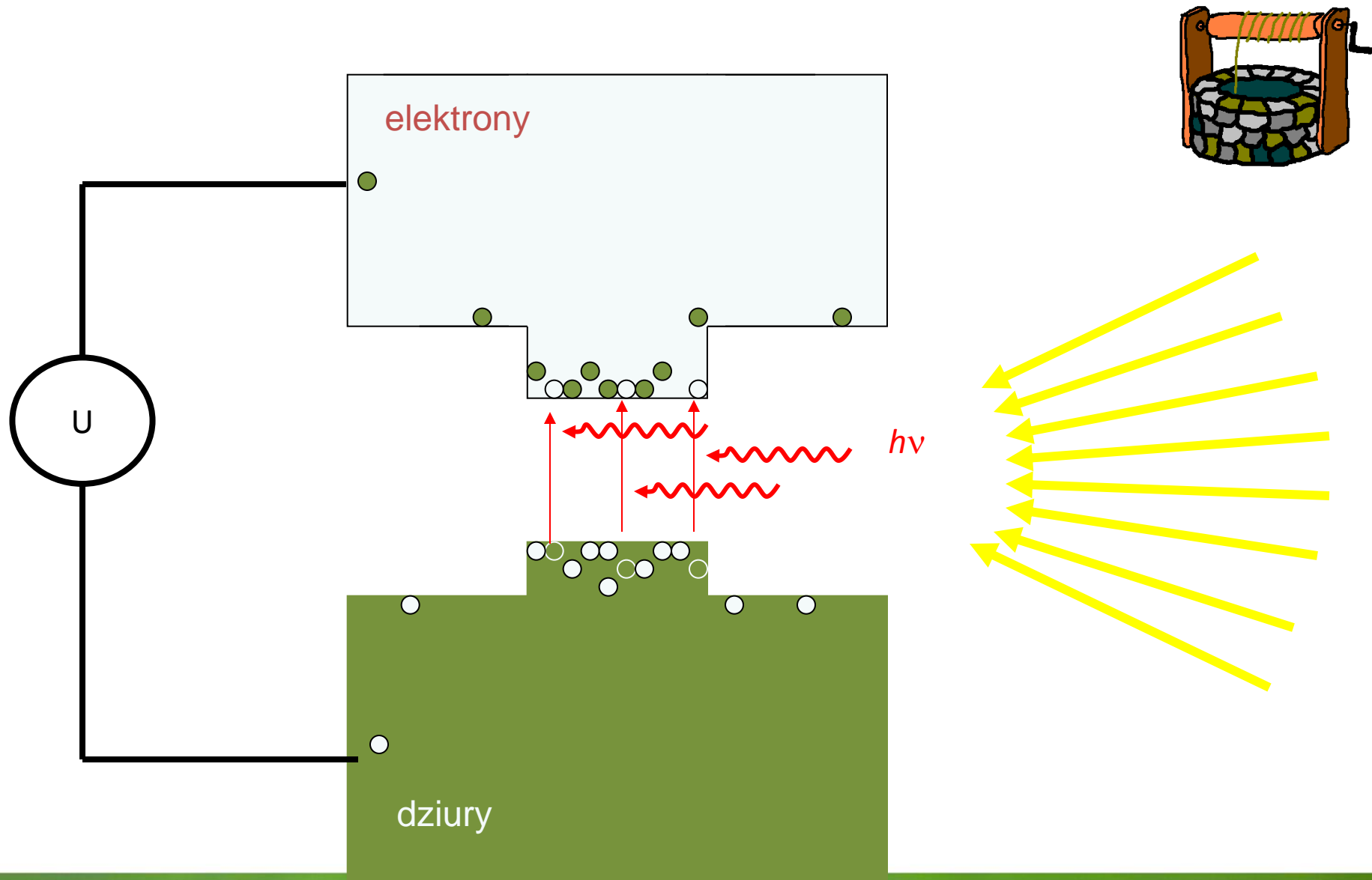
# Studnia Kwantowa



# Studnia Kwantowa

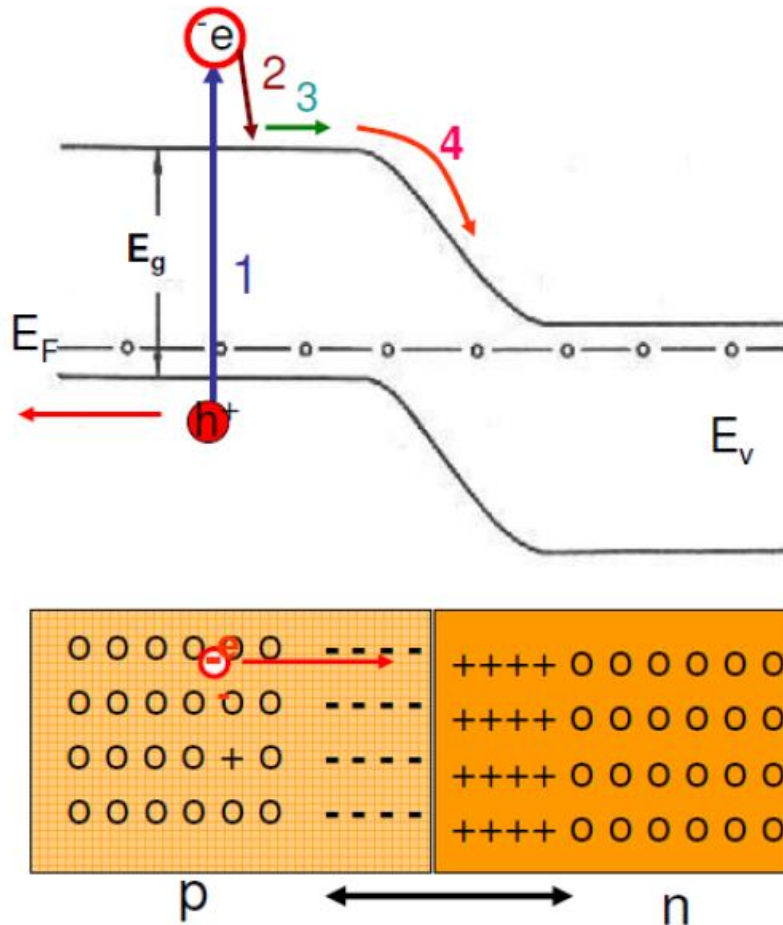


# Studnia Kwantowa



# Fotovoltaika

## Photovoltaic effect in pn junction

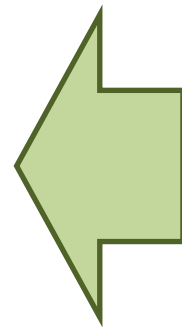
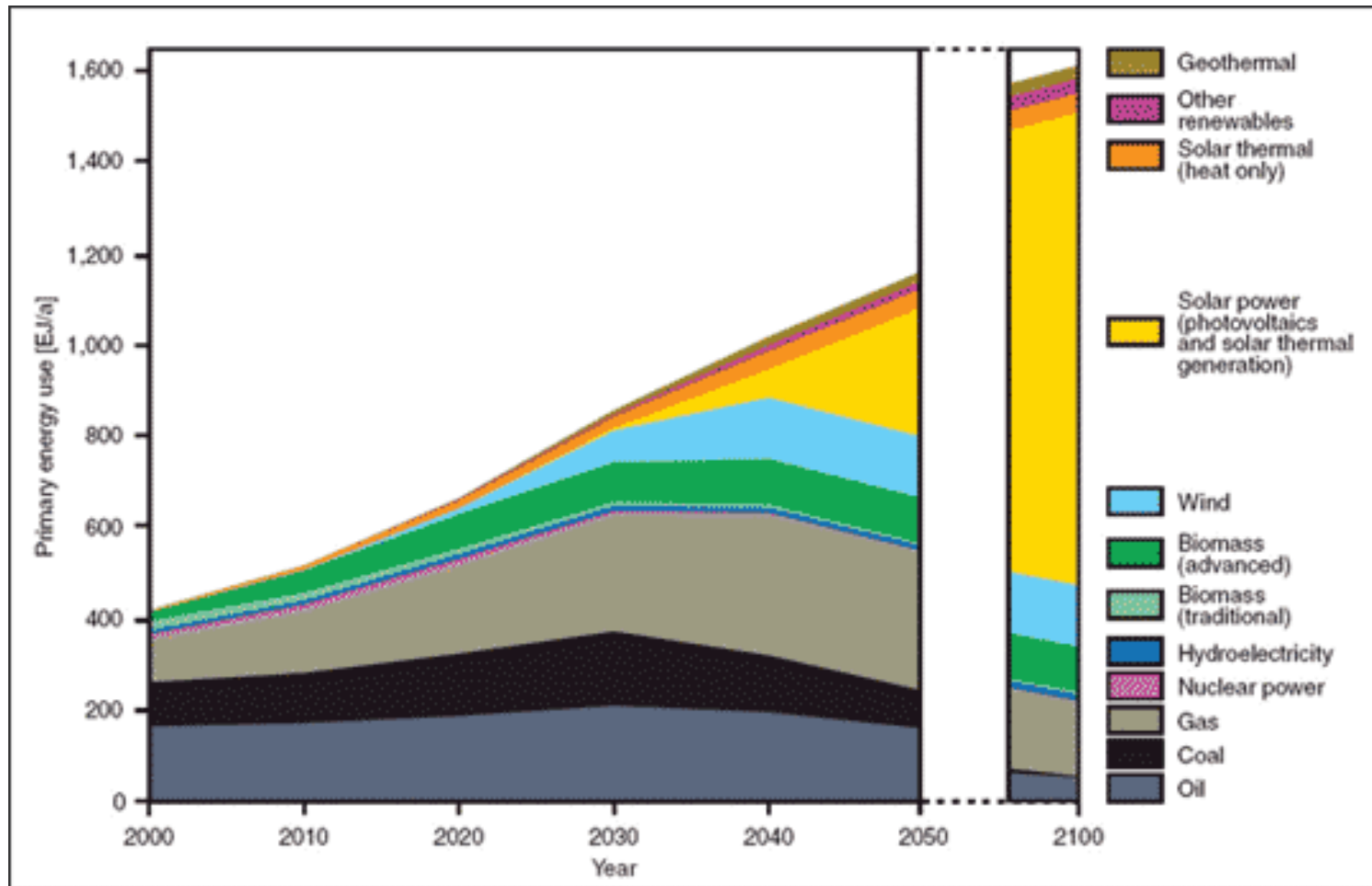


1. absorption
2. thermalisation
3. diffusion
4. drift

### important parameters:

- o band gap  $E_g$
- o doping level
- o absorption coefficient  $\alpha$
- o lifetime of carriers  $\tau$
- o diffusion length  $L_d$
- o mobility  $\mu$

# Źródła energii



*German Advisory Council on Global Change*

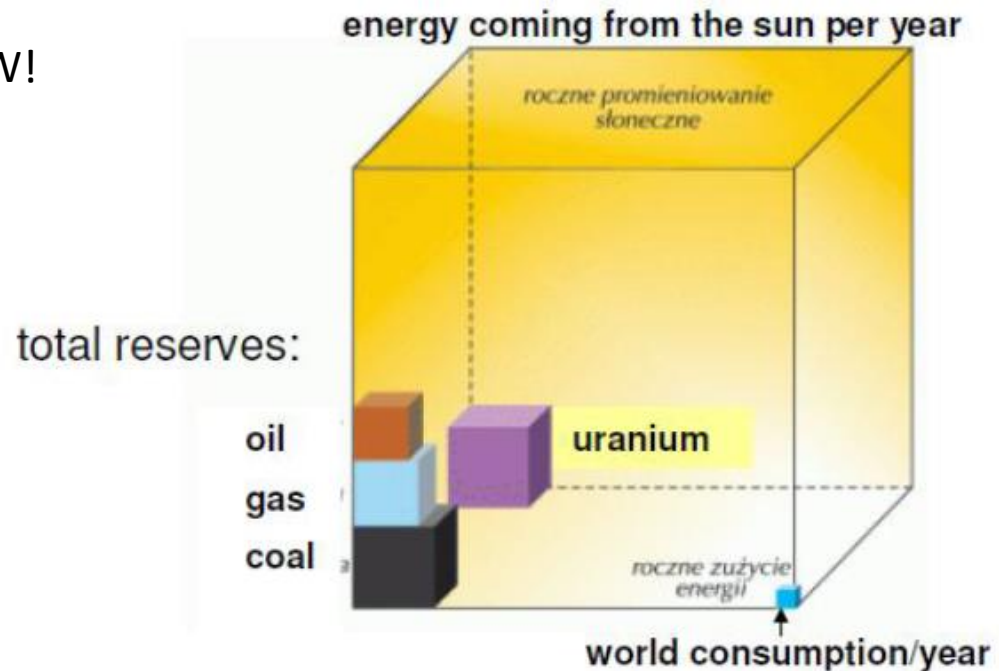
# Źródła energii

Ziemskie źródła ropy naftowej są szacowane na 3 tryliony baryłek i zawierają  $1.7 \times 10^{22}$  J energii, którą Słońce dostarcza do Ziemi w 1,5 dnia.

**Ilość energii, którą ludzkość zużywa rocznie wynosi około  $4.6 \times 10^{20}$  J, Słońce dostarcza ją w ciągu godziny.**

Moc, którą Słońce dostarcza ciągle do Ziemi,  $1.2 \times 10^5$  TW, jest znacznie większa od wszystkich innych form energii.

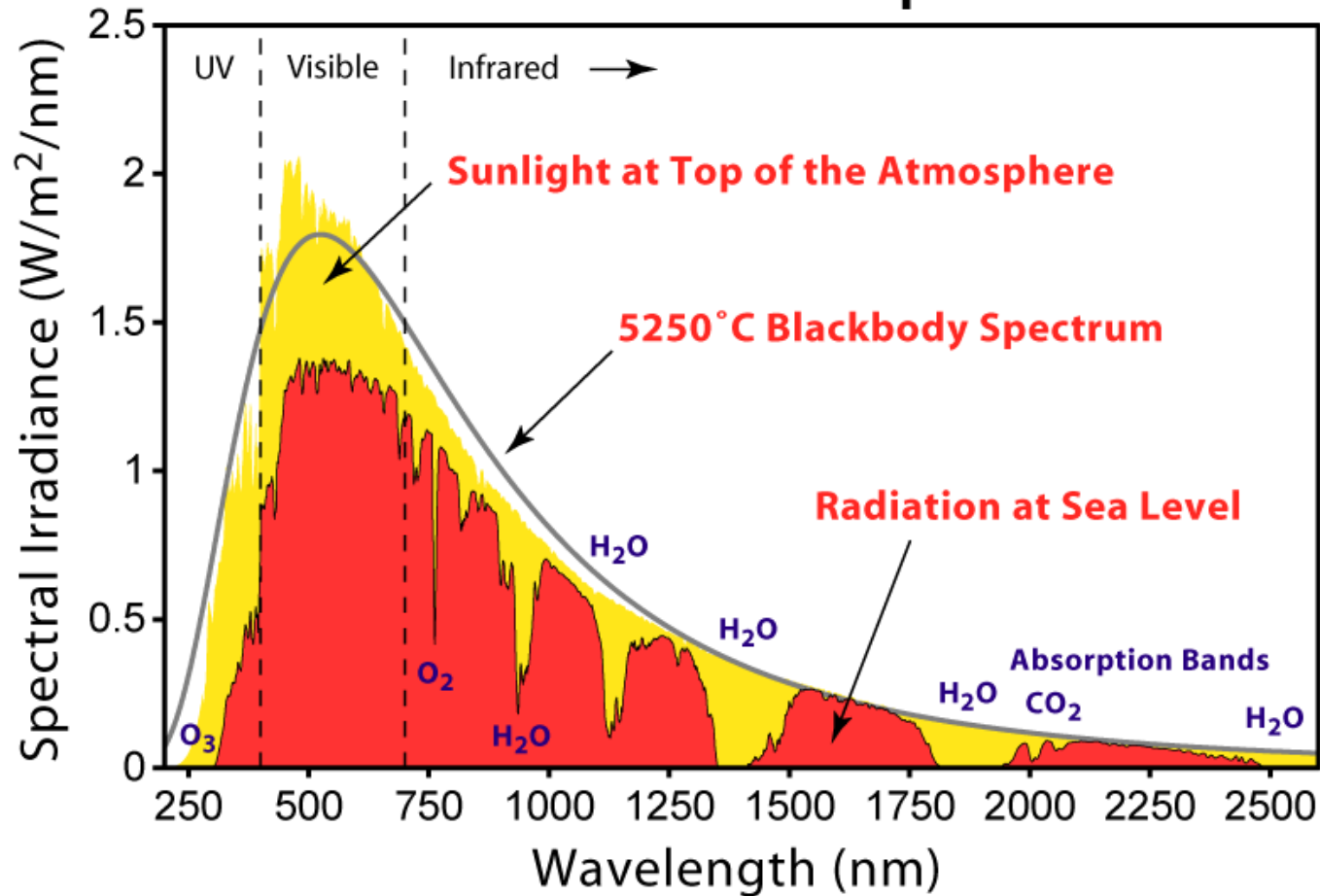
2020: Szacowane potrzeby ludzkości to 20 TW!



# Źródła energii

Słońce:

## Solar Radiation Spectrum



[http://commons.wikimedia.org/wiki/File:Solar\\_Spectrum.png](http://commons.wikimedia.org/wiki/File:Solar_Spectrum.png)

# Źródła energii

Obszar potrzebny do produkcji 20 TW w samej PV: 6 miejsc, każde 250 x 250 km<sup>2</sup> produkujące 3.3 TW

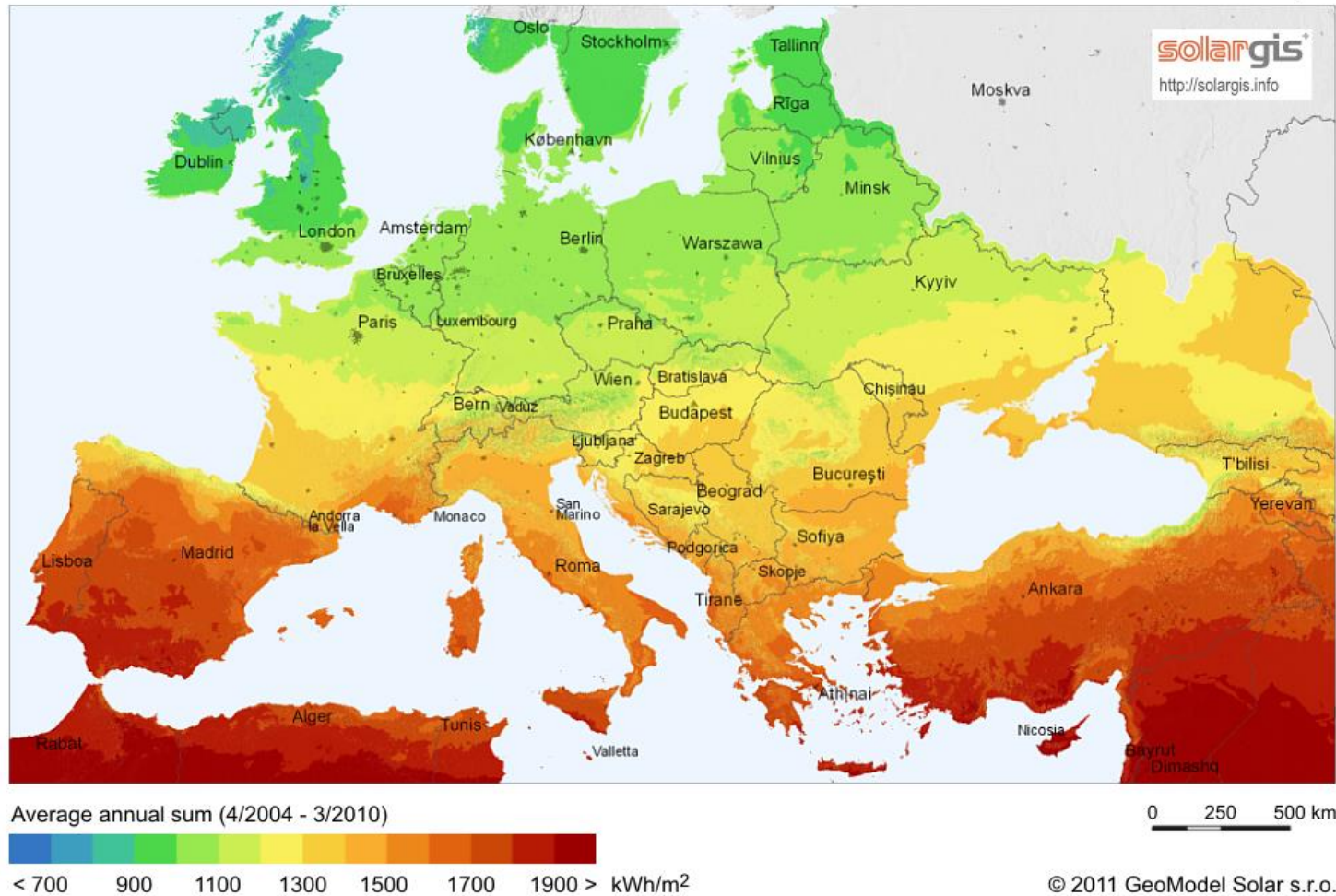


*Prof. M. Kamińska*



# Źródła energii

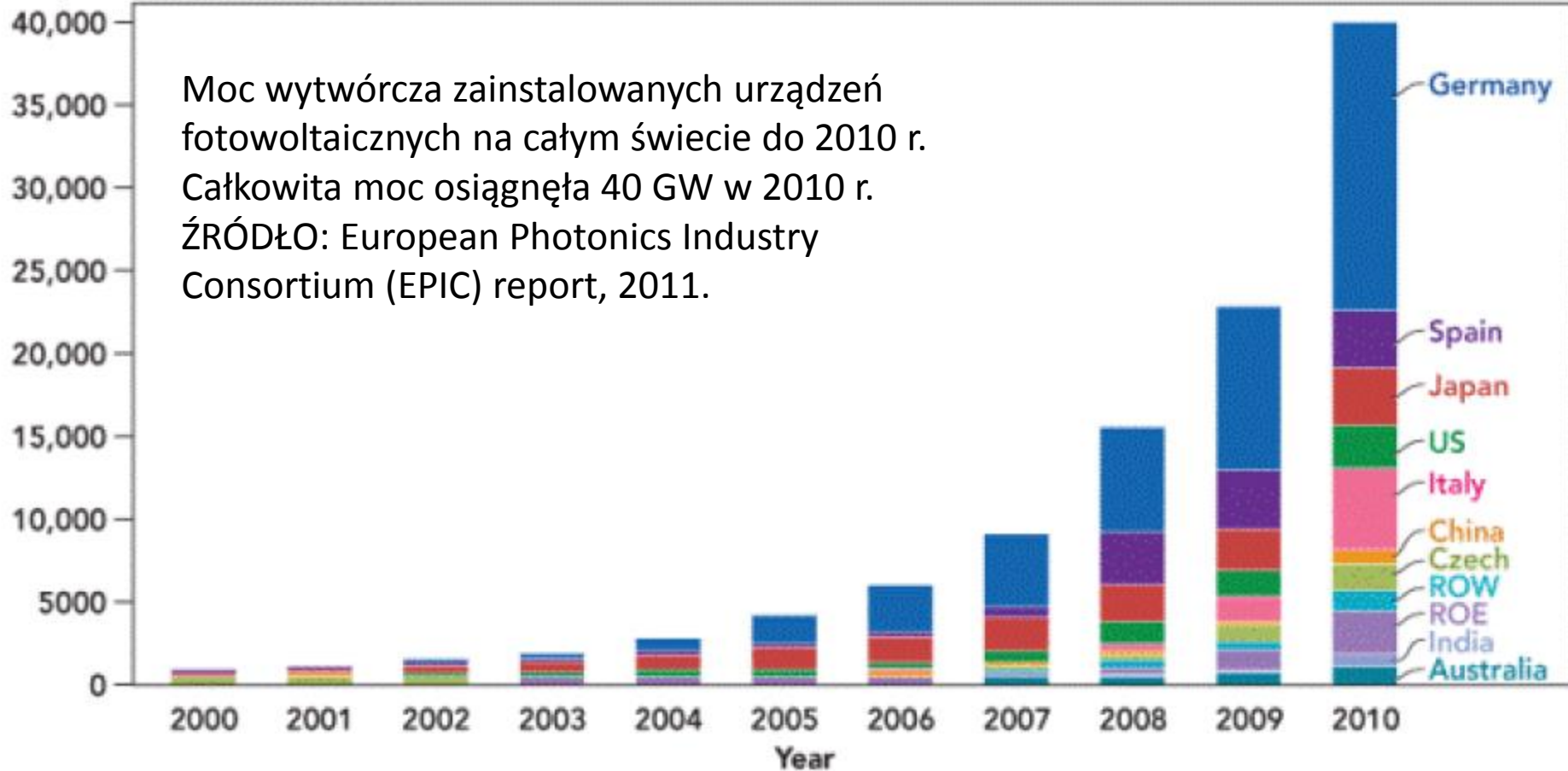
Obszar potrzebny do produkcji 20 TW w samej PV: 6 miejsc, każde 250 x 250 km<sup>2</sup> produkujące 3.3 TW Global horizontal irradiation Europe



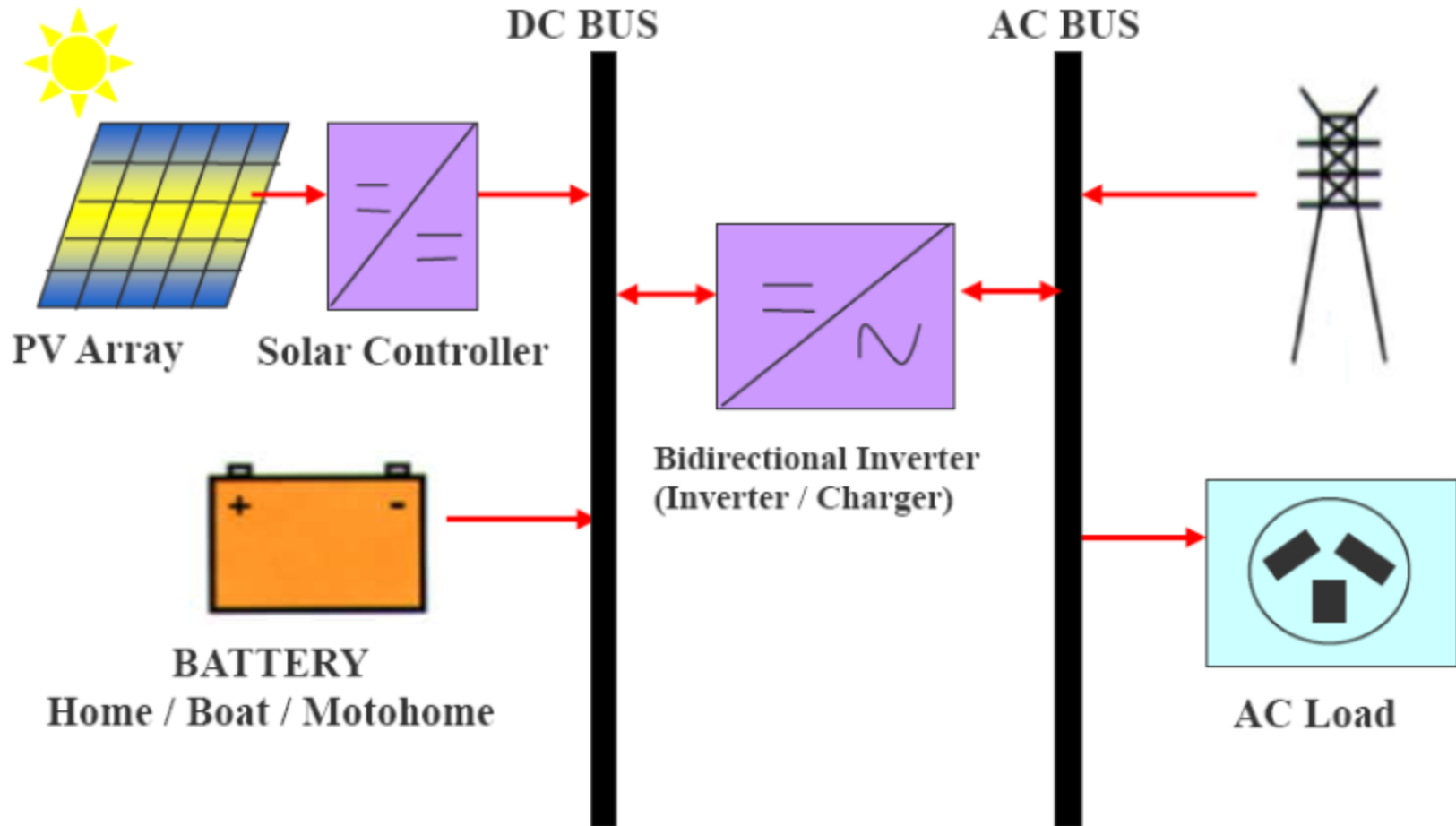
Prof. M. Kamińska

# Źródła energii

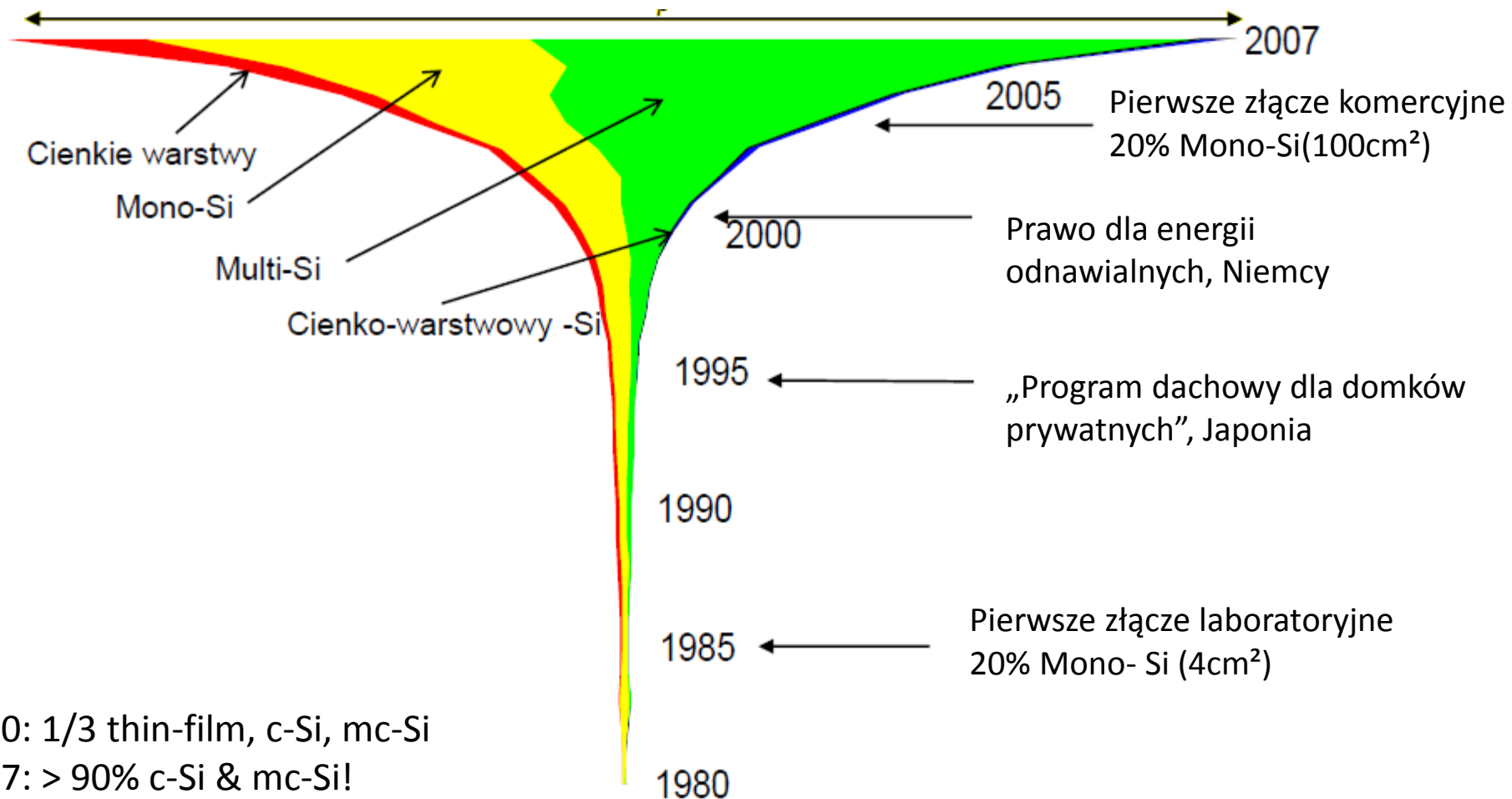
Installed power (megawatts)



# Fotowoltaika



# Fotowoltaika

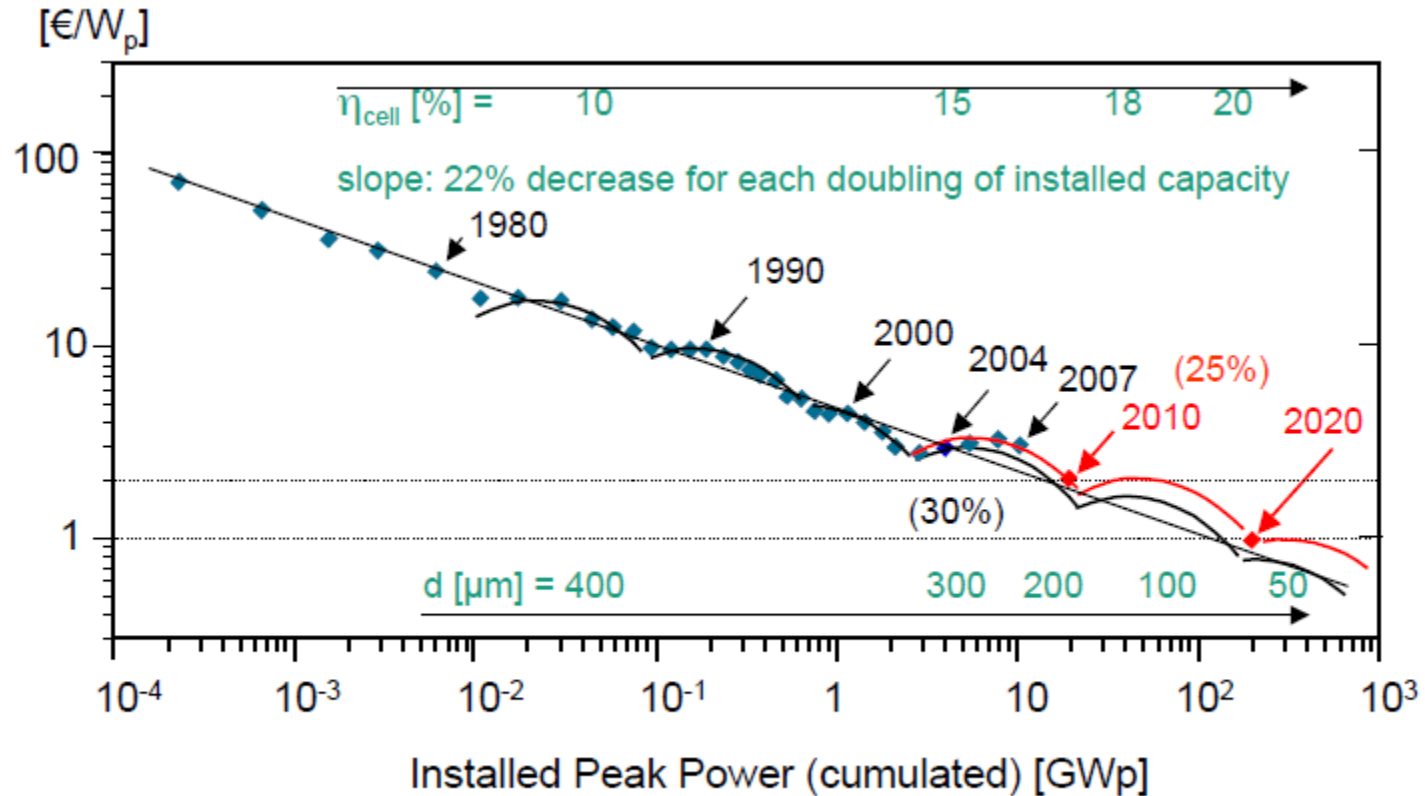


1990: 1/3 thin-film, c-Si, mc-Si

2007: > 90% c-Si & mc-Si!

# Fotowoltaika

## Krzywa cen modułów PV z krystalicznego krzemu

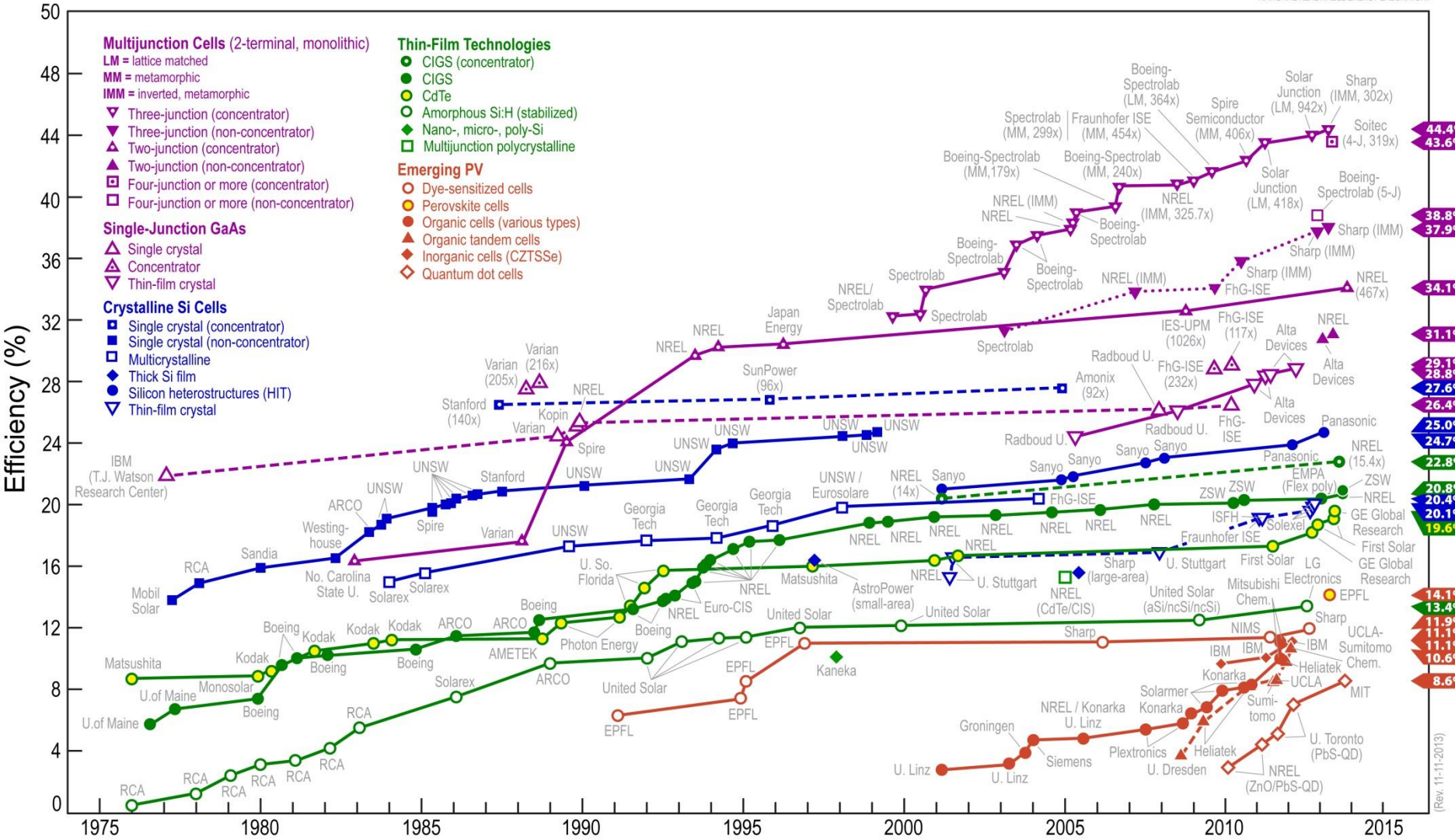


5Slide courtesy of G. Willeke

100% RE for SKA et al., Berlin, April 7, 2011

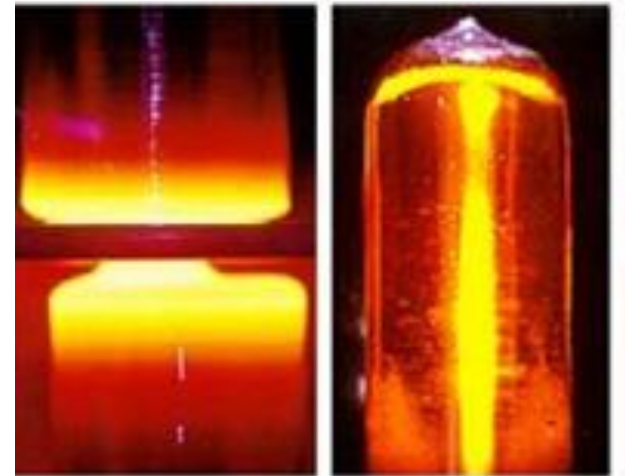
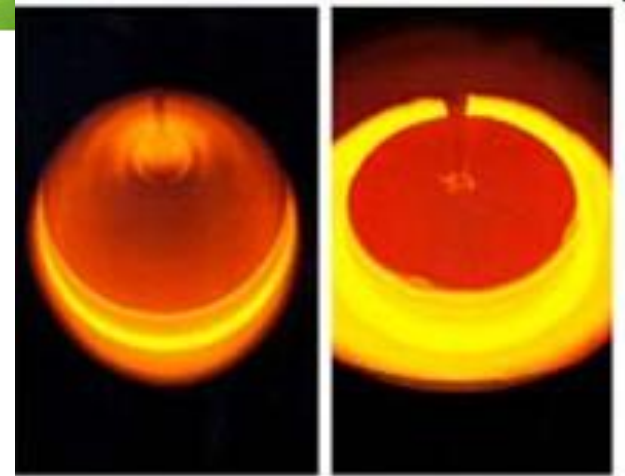
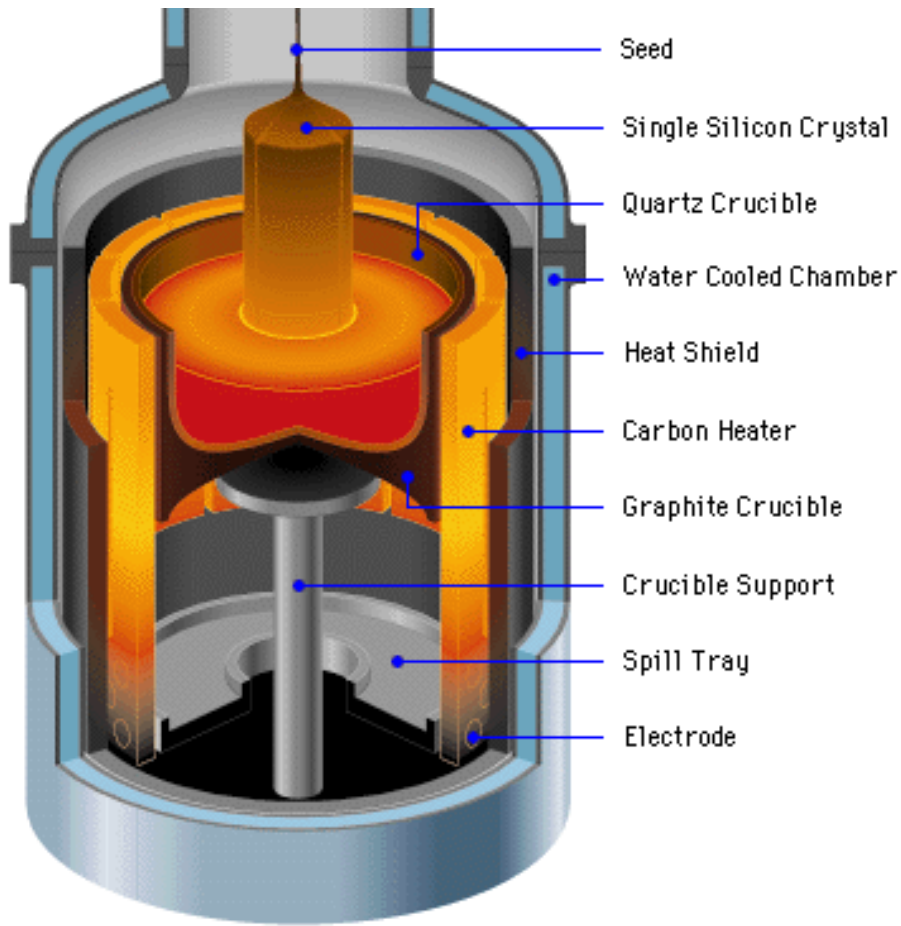
Prof. M. Kamińska

# Best Research-Cell Efficiencies



(Rev. 11-11-2013)

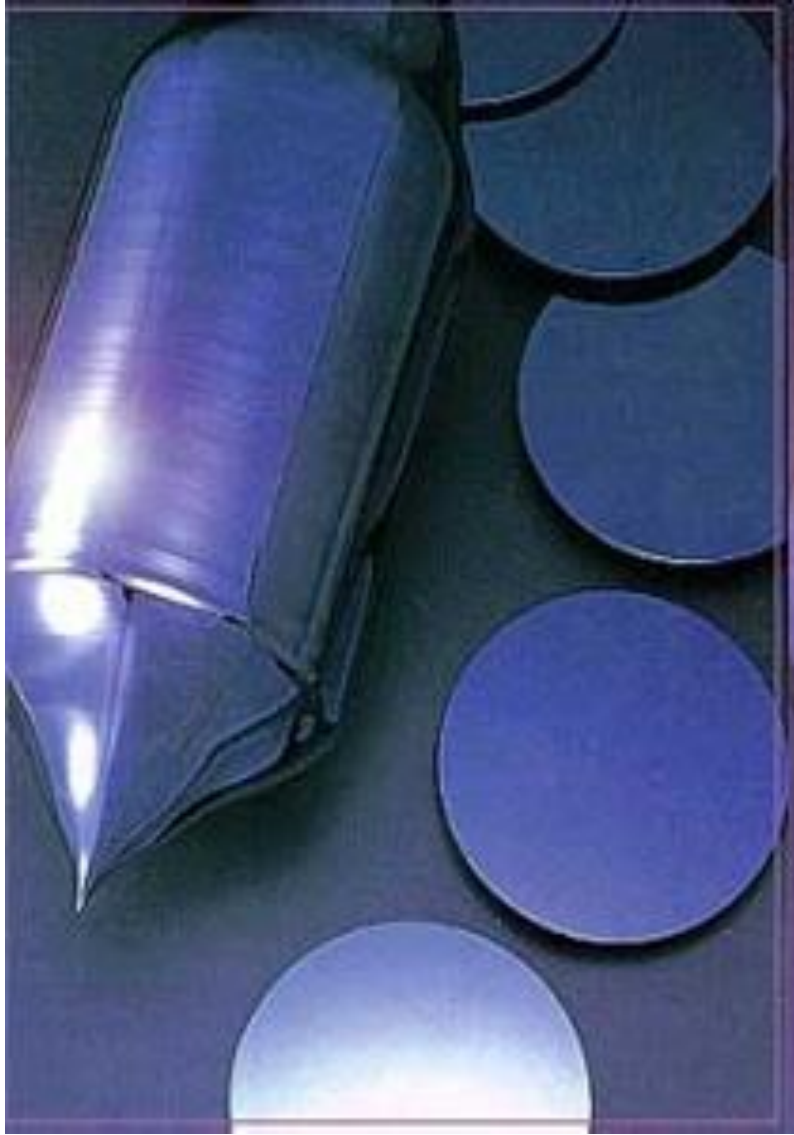
# Metoda Czochralskiego



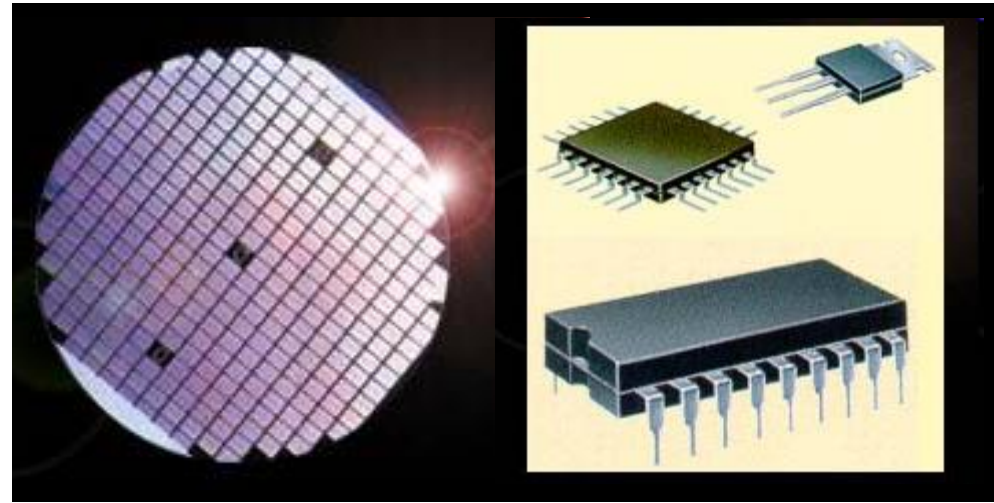
[http://people.seas.harvard.edu/~jones/es154/lectures/lecture\\_2/materials/materials.html](http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/materials/materials.html)

<http://www.sehmy.com/Product/abtWafers.htm>

# Metoda Czochralskiego



<http://www.sehmy.com/Product/abtWafers.htm>





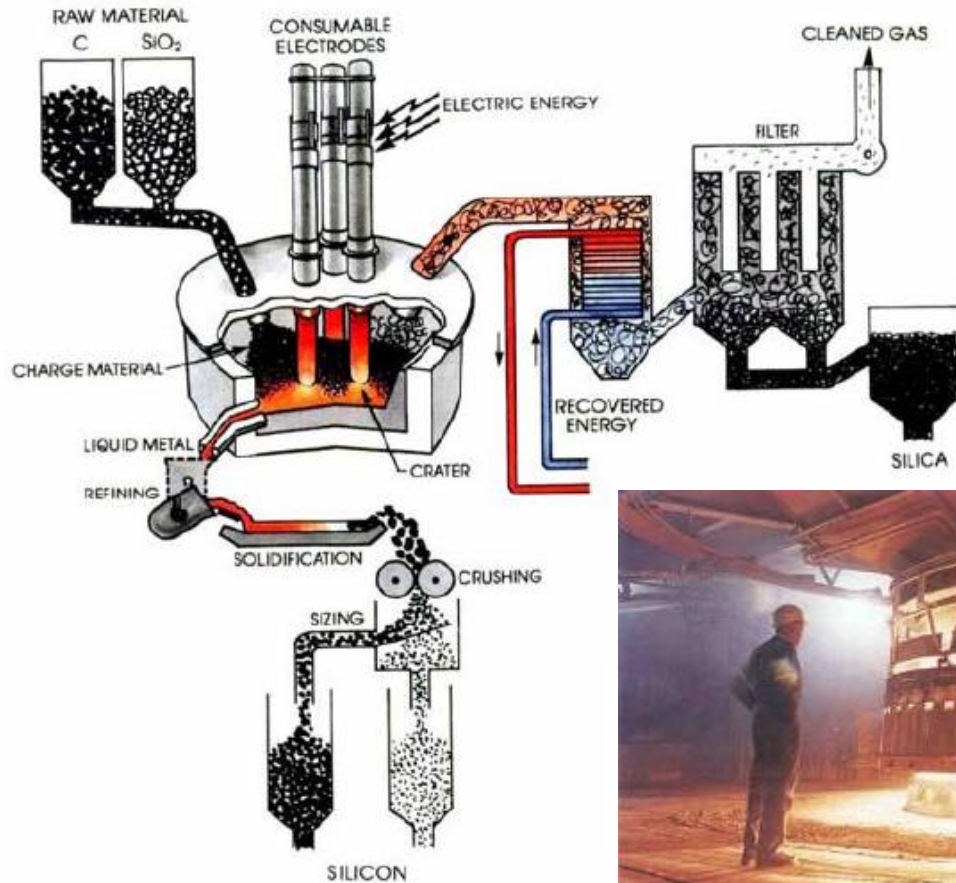
# Fotovoltaika



# Fotowoltaika



# Fotovoltaika

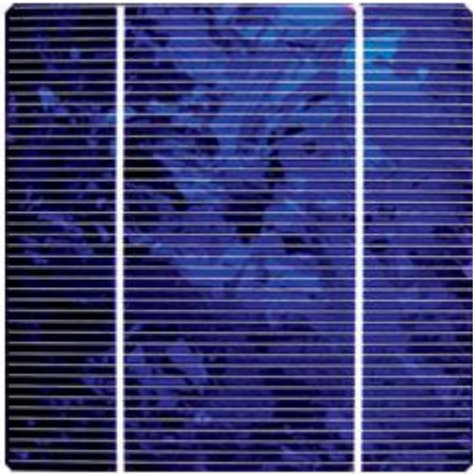


**Metallurgical grade silicon** is commercially prepared by the reaction of high-purity silica with wood, charcoal, and coal in an electric arc furnace using carbon electrodes. At temperatures over 1,900°C, the carbon in the aforementioned materials and the silicon undergo the chemical reaction:

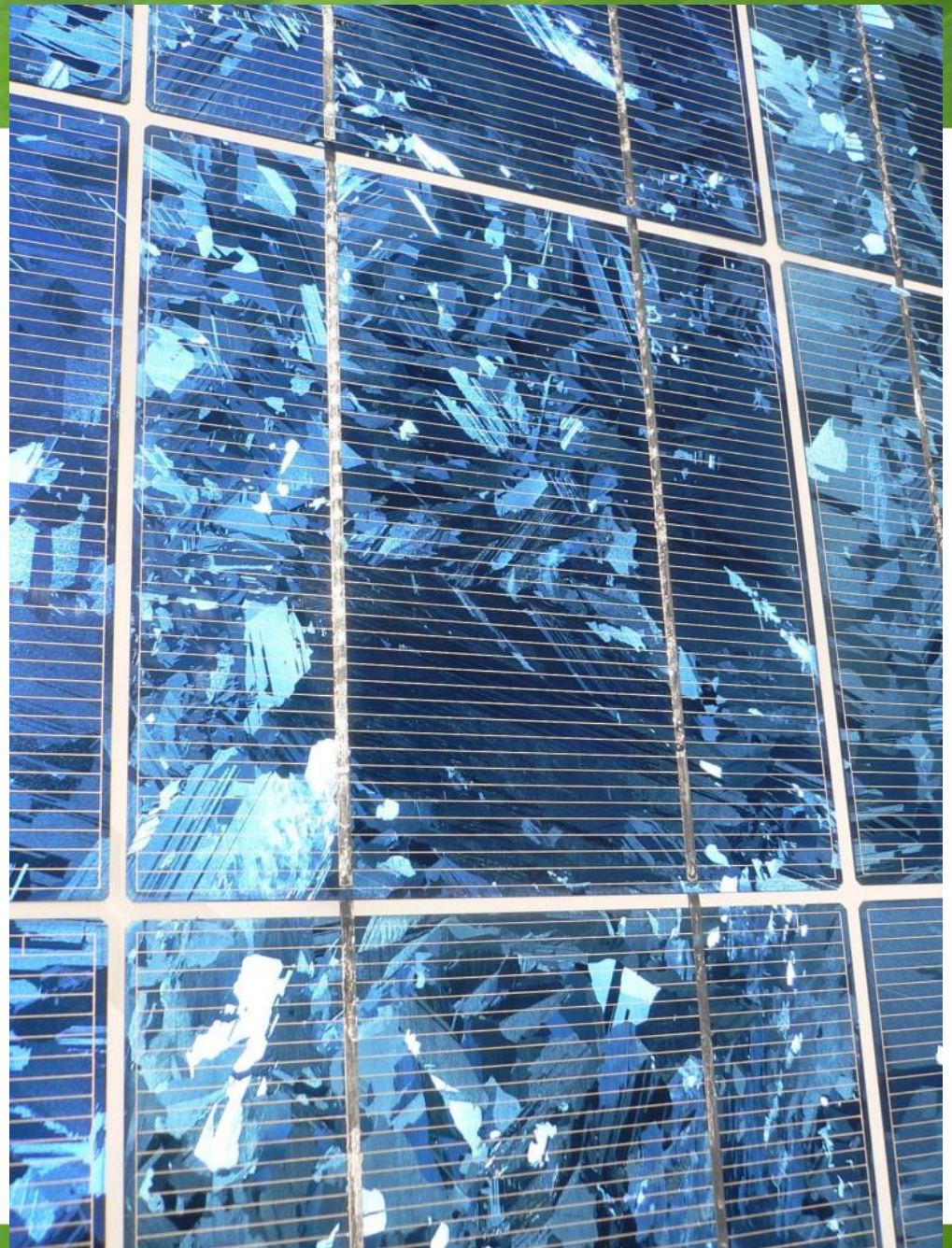
$$\text{SiO}_2 + 2 \text{C} \rightarrow \text{Si} + 2 \text{CO}.$$


**Figure 1:** Schematic representation of a furnace for production of metallurgical grade silicon. Reproduced from Schei A, Tuset J, Tveit H, *Production of High Silicon Alloys*, Tapir forlag, Trondheim (1998).

# Fotowoltaika



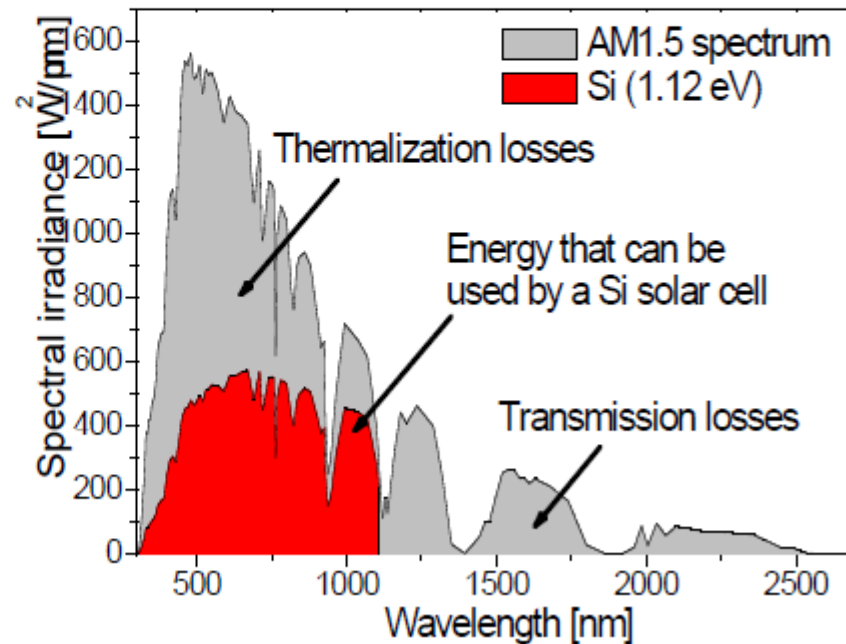
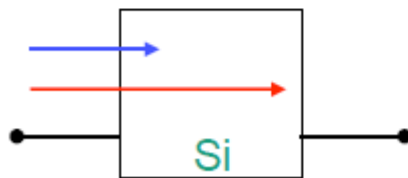
Komórka fotowoltaiczna z monokrystalicznego Si



# Fotovoltaika

## The efficiency limit for a single-material PV Cell

For Silicon:  
(AM1.5g, 1000 W/m<sup>2</sup>, 25°C)  
 $\eta_{\max, \text{theo}} = 28 \%$   
Lab cell = 24 %



<http://microtec-career.com/wp-content/uploads/2012/10/Prof.-Dr.-Eicke-Weber-The-Fraunhofer-Institute-for-Solar-Energy-Systems-ISE.pdf>

# Fotovoltaika

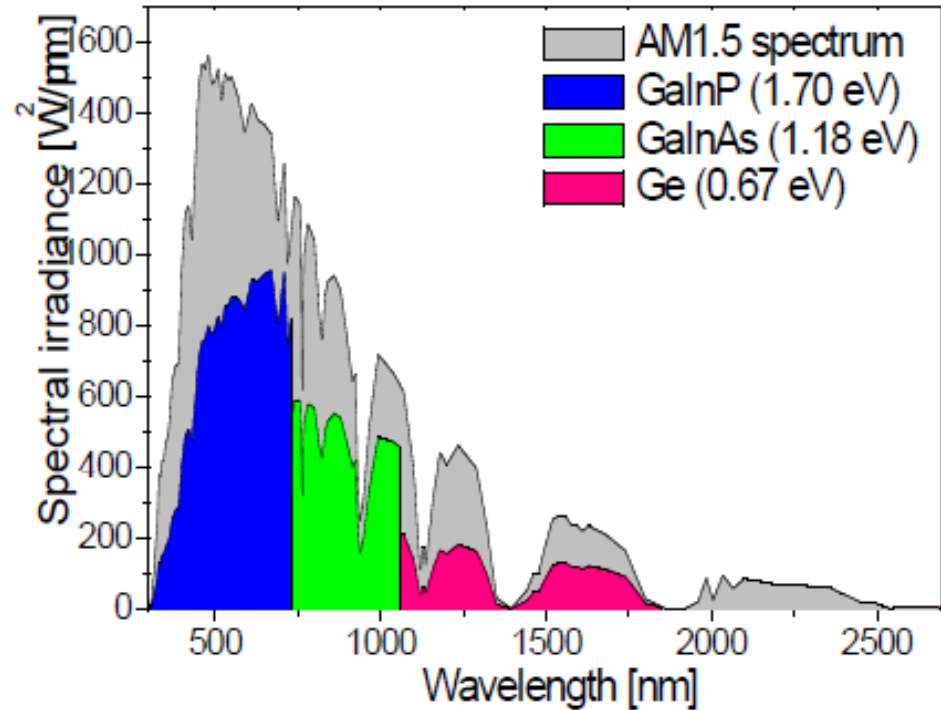
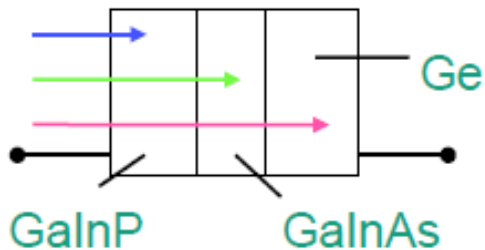
For triple-junction  
concentrator cells:

$$\eta_{\max, \text{theo}} = 61 \%$$

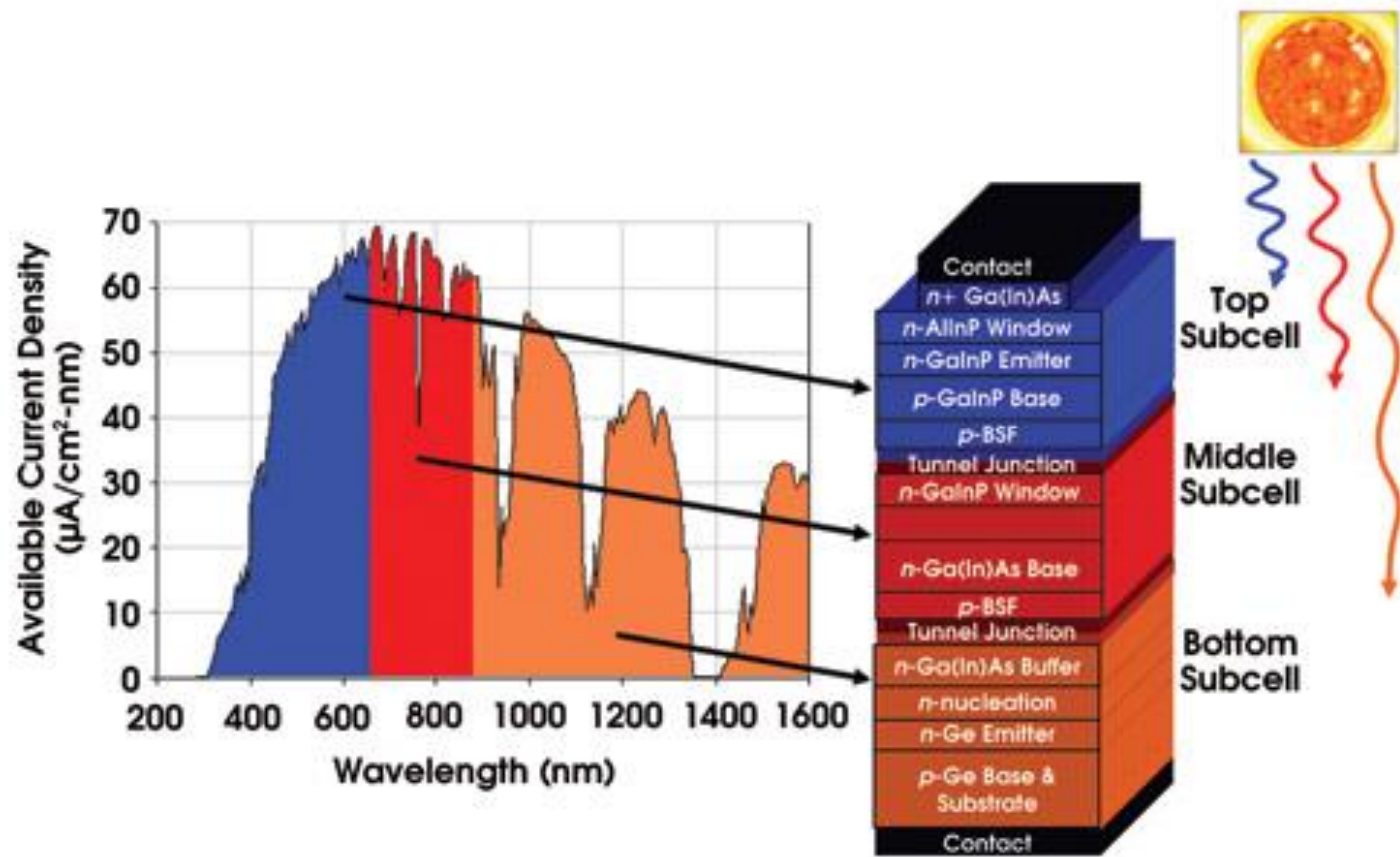
(1000xAM1.5d, 1000 W/m<sup>2</sup>)

Lab. cell = 40.8 %

230xAM1.5d, 1000 W/m<sup>2</sup>)



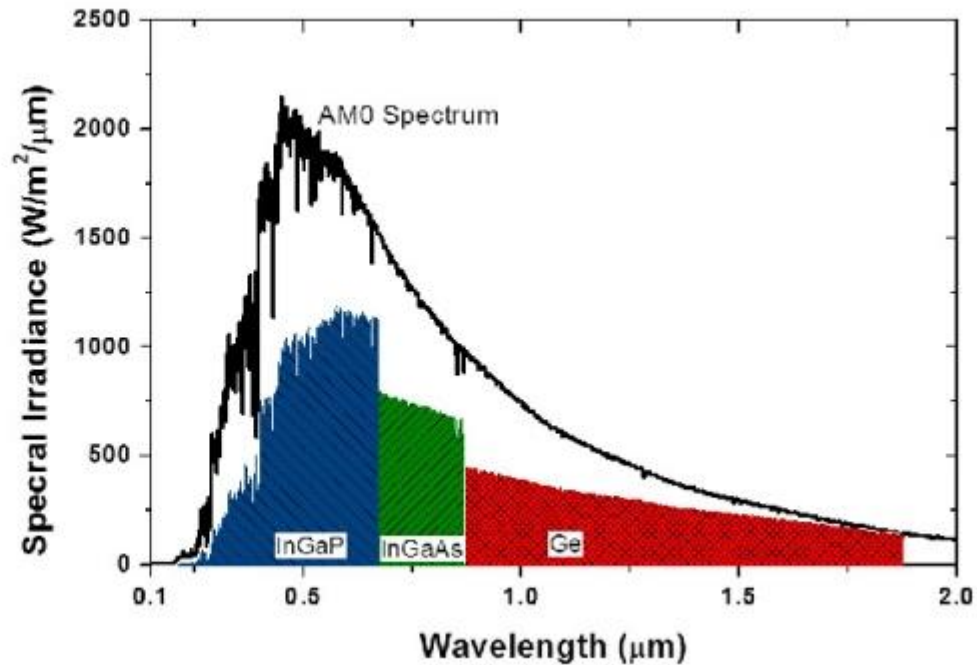
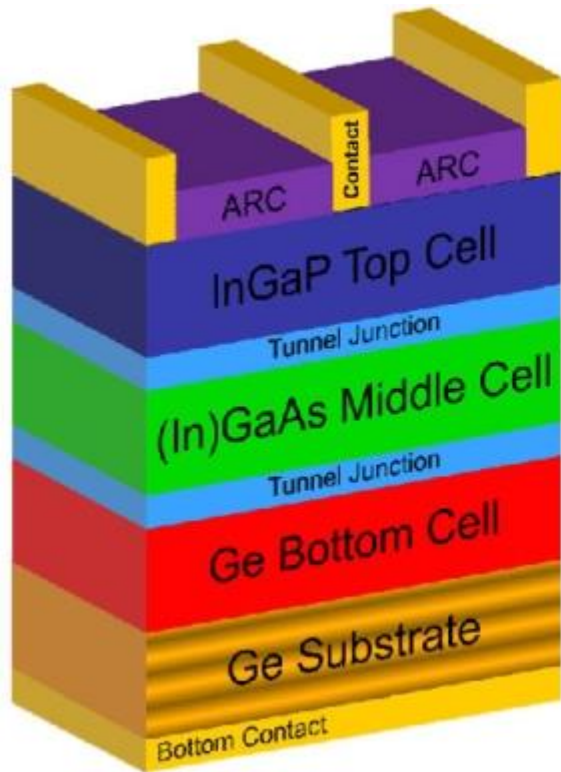
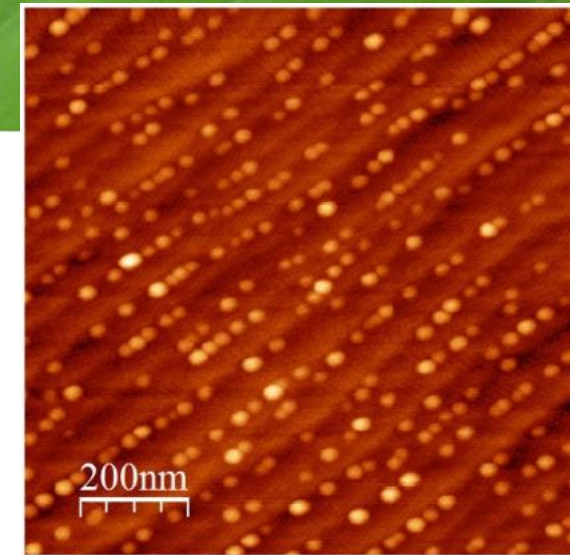
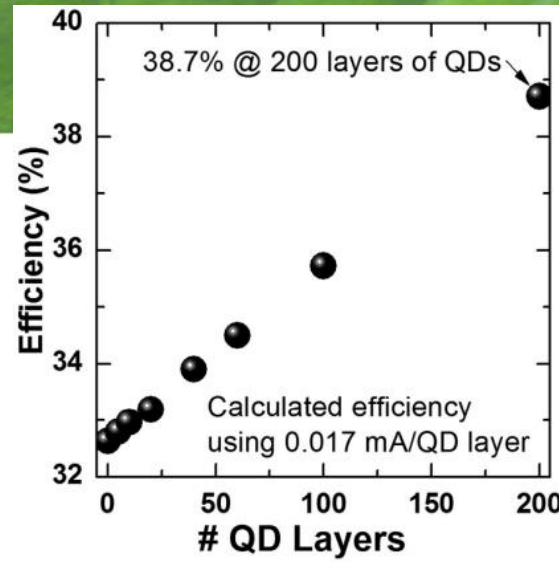
# Fotovoltaika



<http://photonics.com/Article.aspx?AID=35235>

# Fotovoltaika

Solar-cell-efficiency enhancement using nanostructures



//spie.org/x41195.xml



# Plazmonika



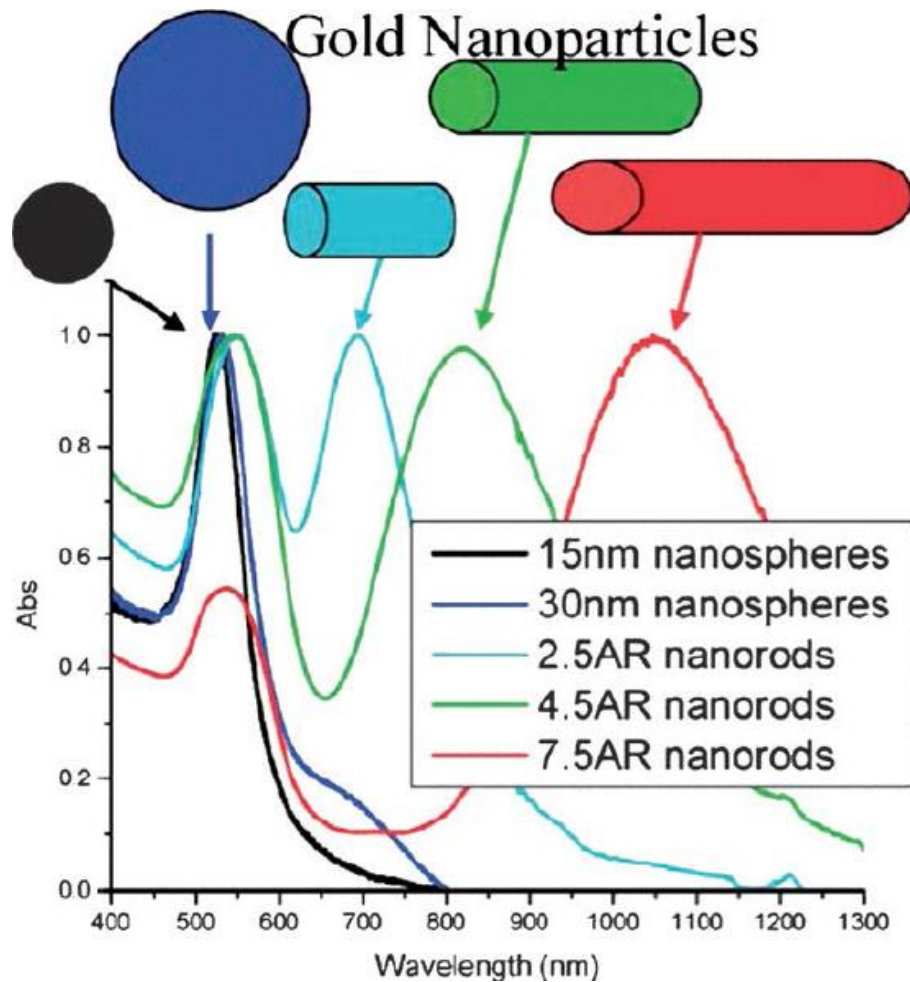
Au hydrosols prepared by M. Faraday, 1857, Royal Institution.

The Lycurgus Cup (glass; British Museum; 4th century A. D.)

Working monk, 1480, Norwich, Anglie.

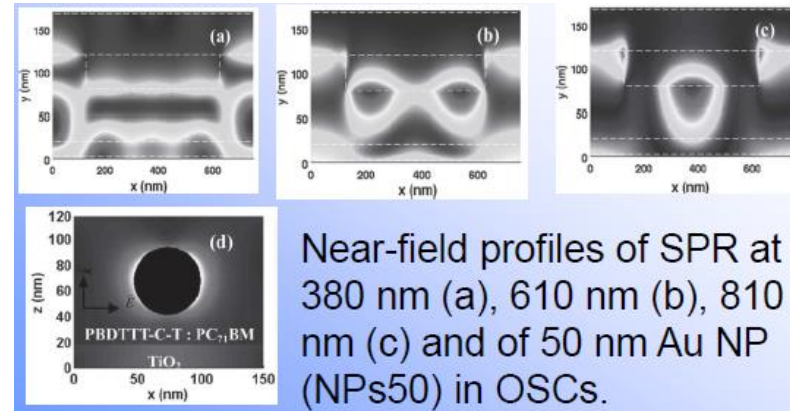
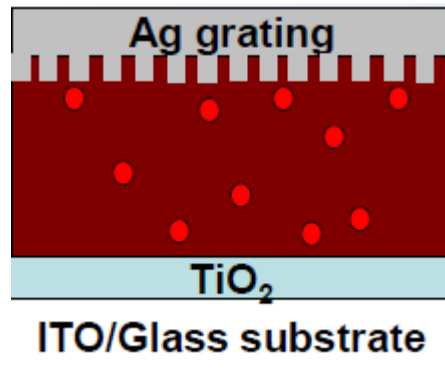
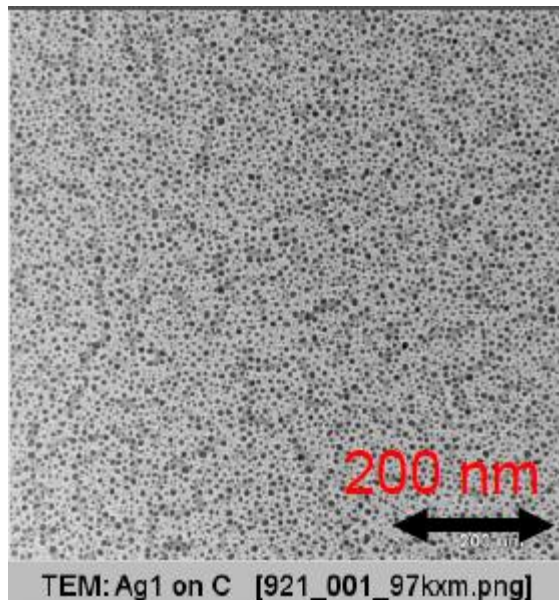
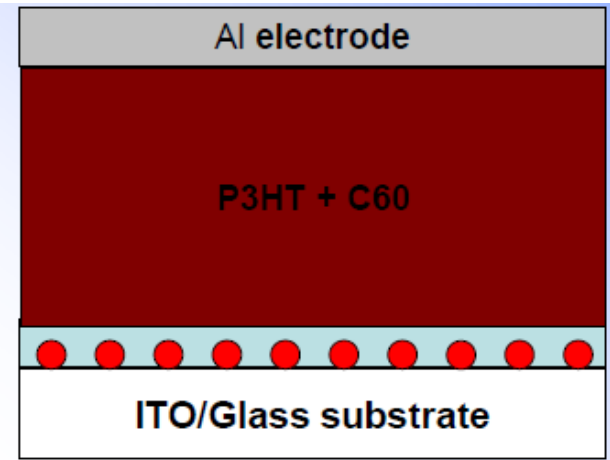
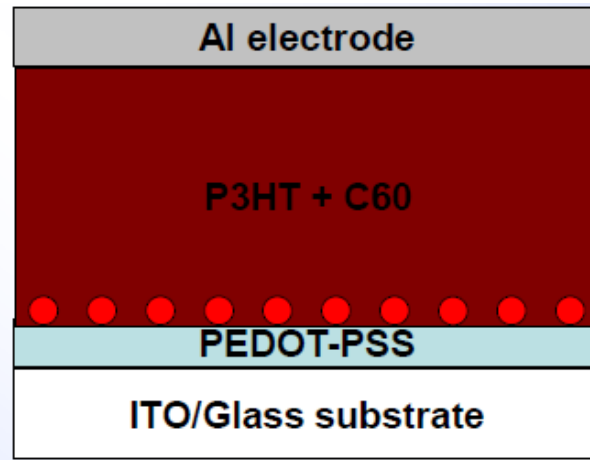
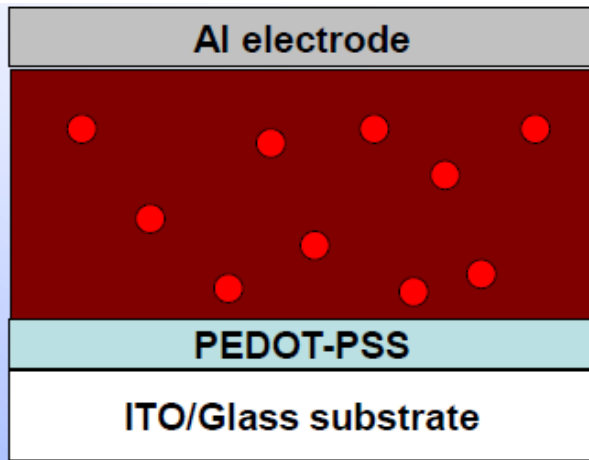


# Plazmonika



*G. Walters et al., J. Mater. Chem. 2009*

# Plazmonika



Jiří Pflieger Institute of Macromolecular Chemistry AS CR Prague, Czech Republic

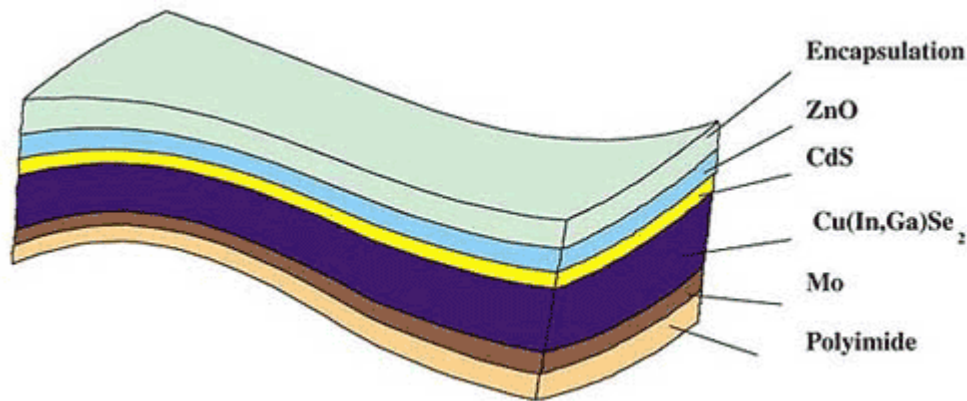
# Energia



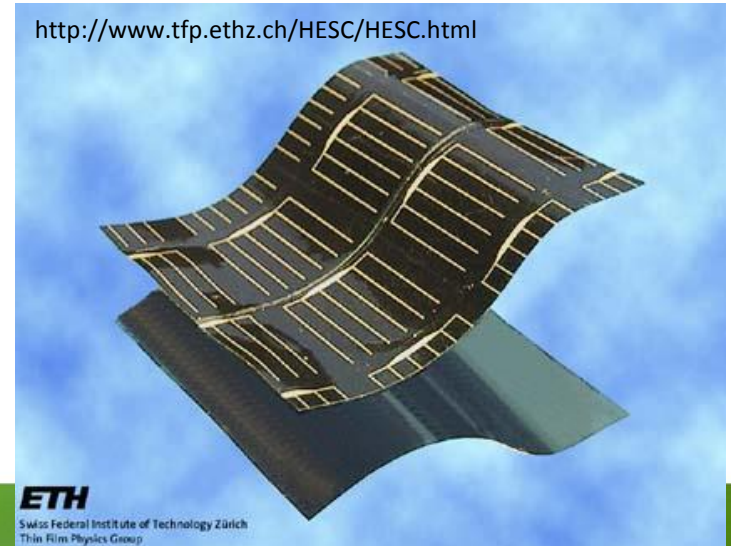
<http://www.daystartech.com/lightfoil.cfm>



$\text{Cu(In,Ga)Se}_2$  (also called CIGS) compound semiconductor  
solar electricity conversion efficiency of 12.8%

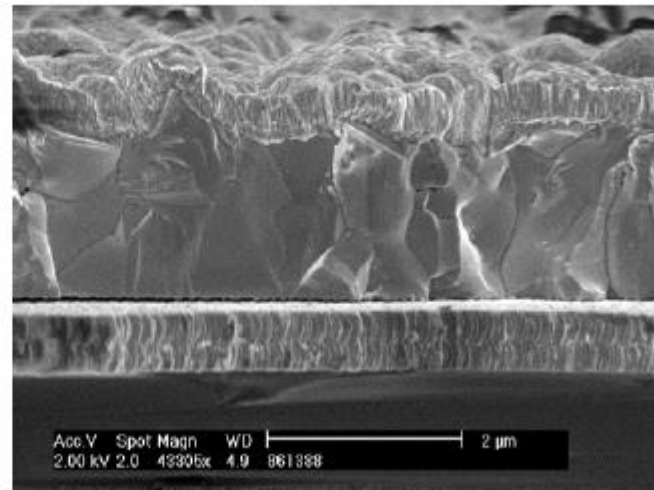
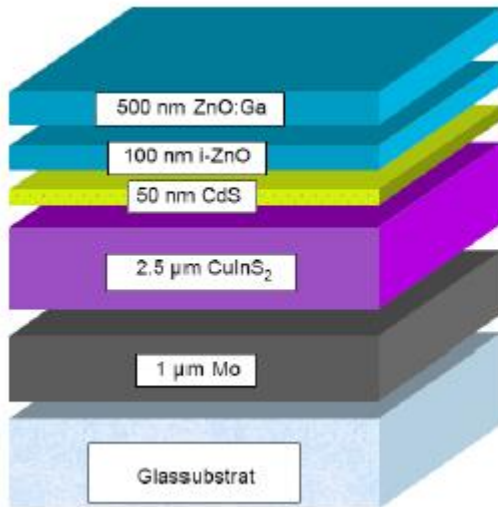


<http://www.tfp.ethz.ch/HESC/HESC.html>

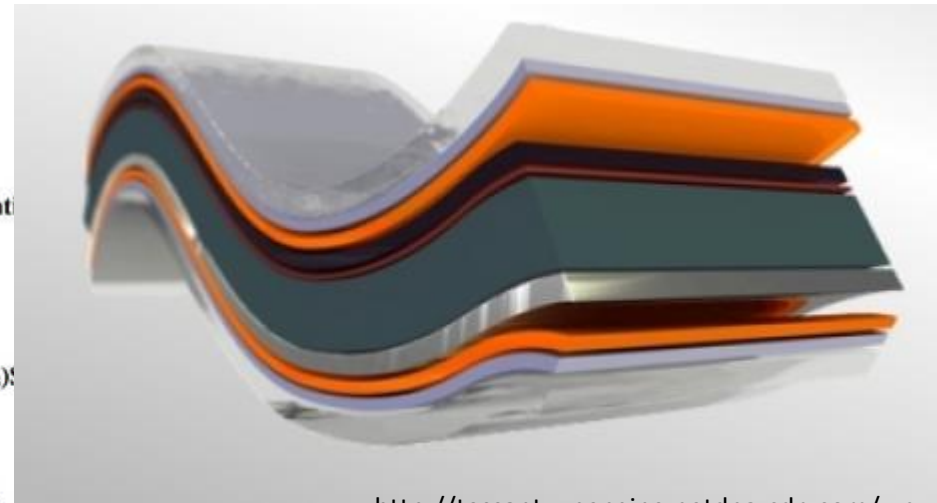
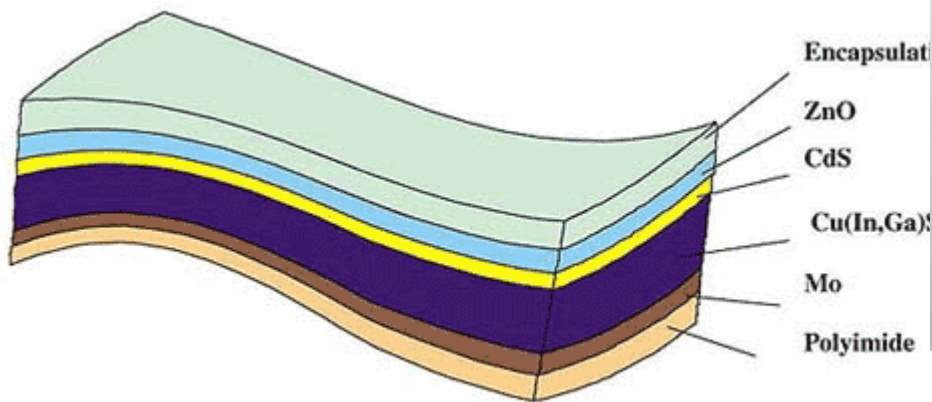


**ETH**  
Swiss Federal Institute of Technology Zürich  
Thin Film Physics Group

# Energia



TCO (ZnO:Al)  
buffer film  
absorber (CIS)  
back contact  
Substrate  
SLS glass



<http://tessant.wpengine.netdna-cdn.com/wp-content/uploads/2013/01/cigs-flexible.jpg>

# Koncentratory słoneczne



*Concentrator receivers from Solar Systems Pty. Ltd. of Hawthorn, Australia, are designed for utility application at 400× to 500×. Courtesy of Solar Systems Pty. Ltd., Australia.*

# OSC – Organic Solar Cells

## Inorganic vs. Organic Solar Cell

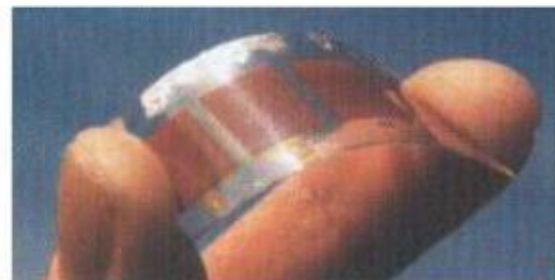
### Inorganic Solar Cell

- Power conversion efficiency up to 24% in lab
- High energy consumption at fabrication
- Cost-intensive fabrication



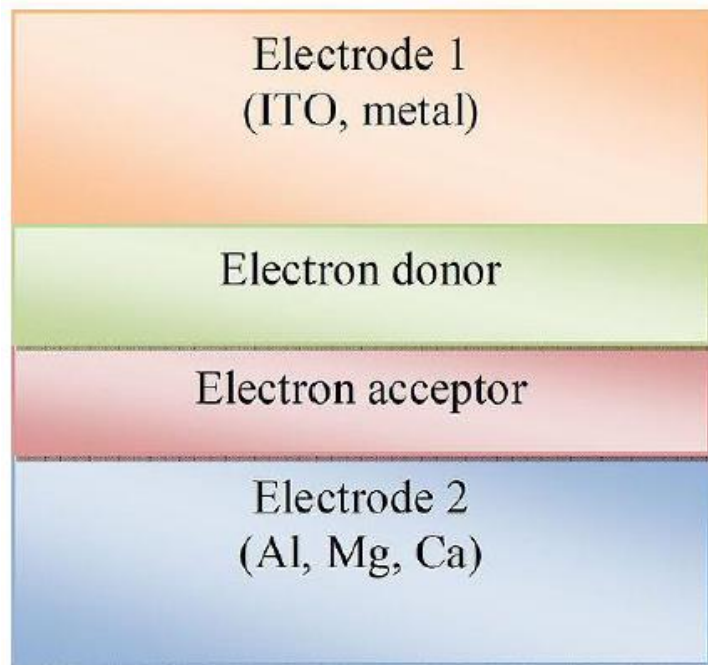
### Organic Solar Cell

- Only 6% achieved in lab
- Low energy consumption at fabrication
- Cheap fabrication
- Mechanical flexible on appropriate substrates



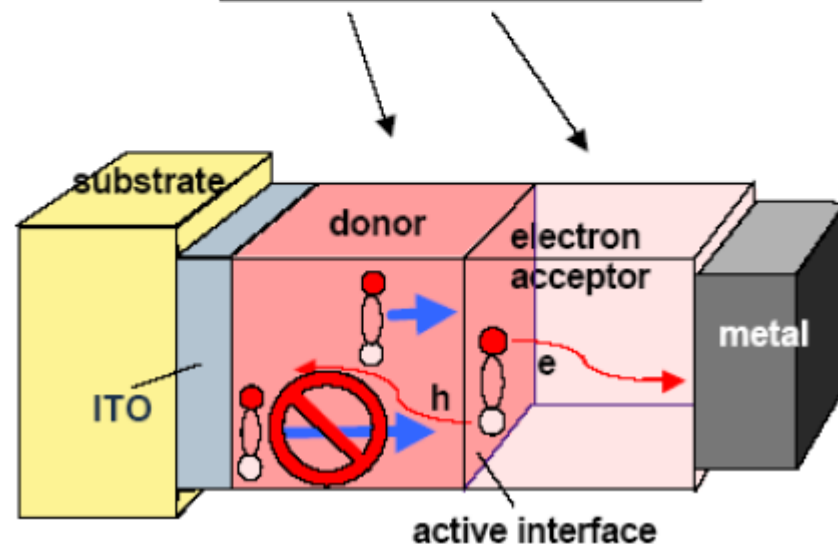
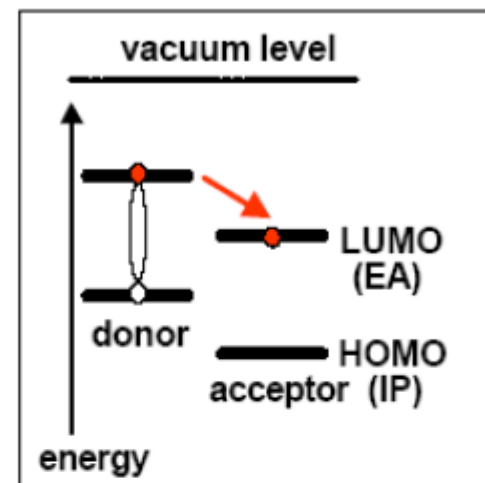
# OSC – Organic Solar Cells

## Bilayer organic photovoltaic cells



## Problems

The diffusion length of excitons in organic electronic materials is typically on the order of 10 nm. In order for most excitons to diffuse to the interface of layers and break up into carriers, the layer thickness should also be in the same range with the diffusion length.

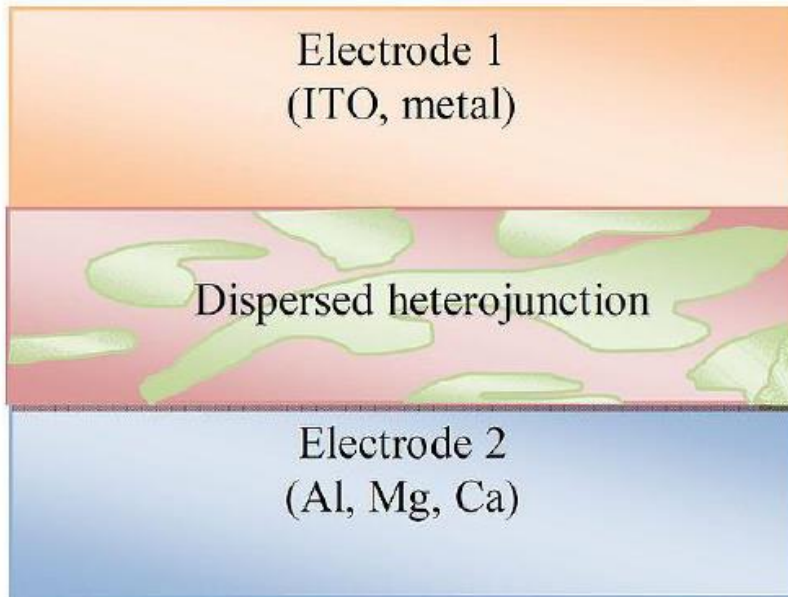


Dr. C. Gravalidis Aristotle University of Thessaloniki

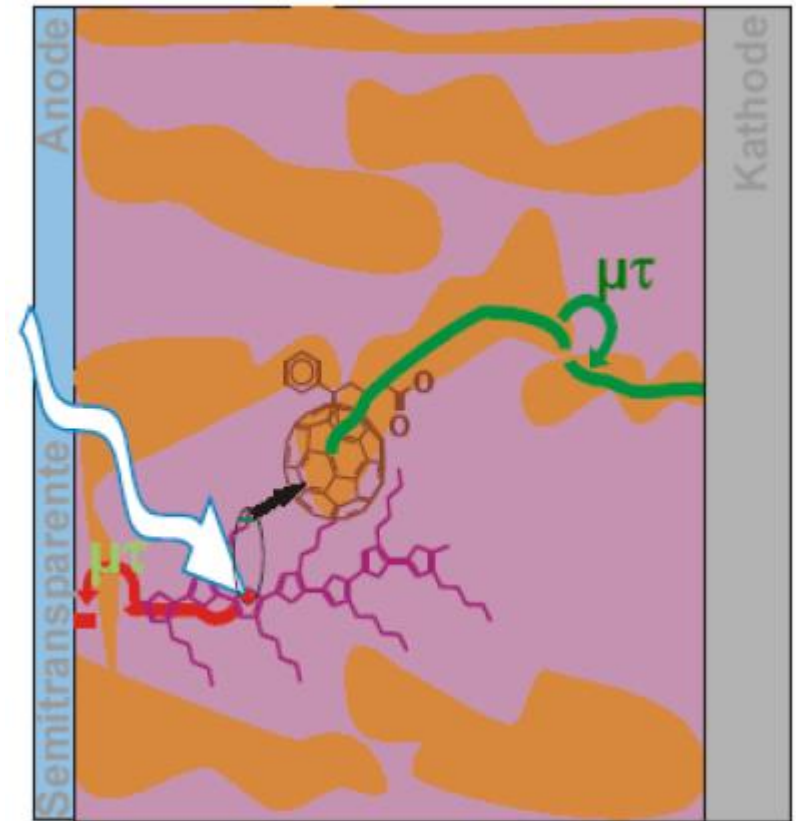


# OSC – Organic Solar Cells

Bulk heterojunction photovoltaic cells



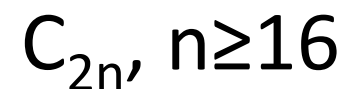
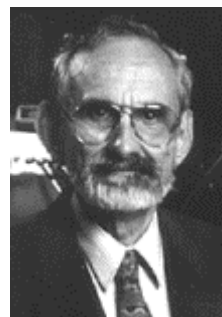
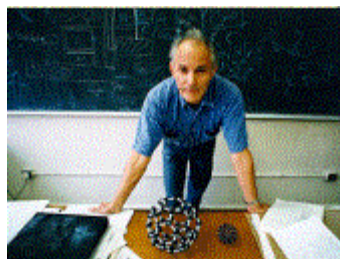
Electrons move to the acceptor domains then were carried through the device and collected by one electrode, and holes were pulled in the opposite direction and collected at the other side



# OSC – Organic Solar Cells

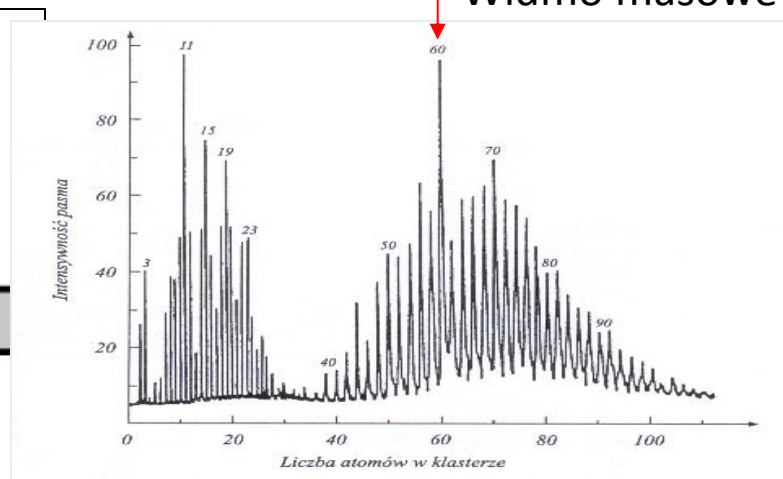
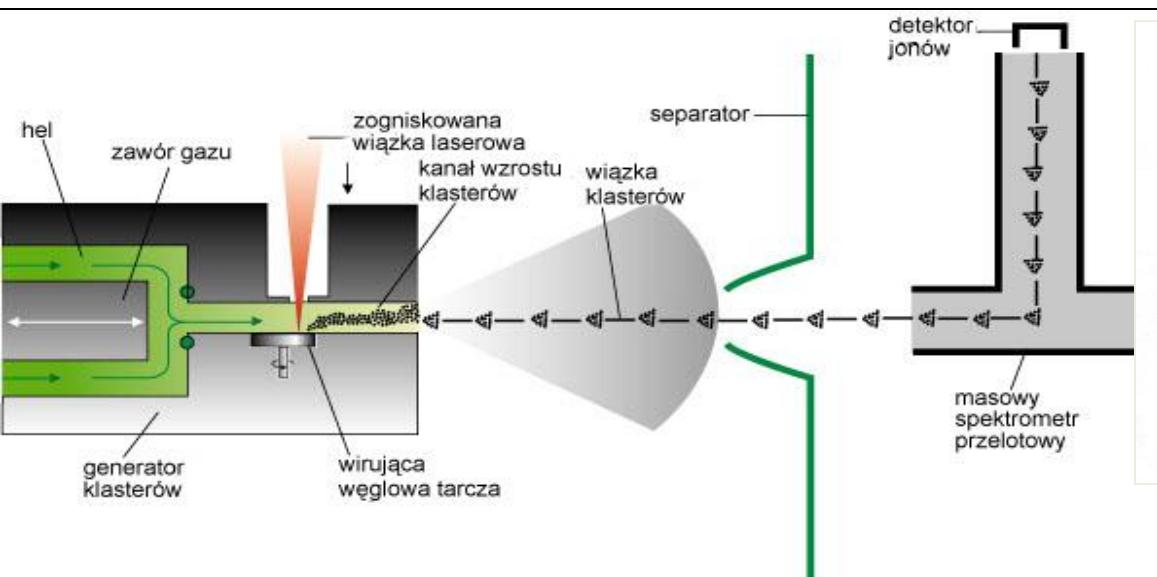
W latach 1975-1978, w zimnej przestrzeni międzygwiazdnej odkryto molekuly opisane formułą  $HC_{2n+1}N$  ( $n = 2, 3, 4$  i  $5$ )

W 1985 r. Richard Smalley, Harry Kroto i Bob Curl odkryli fulereny (Nobel 1996)



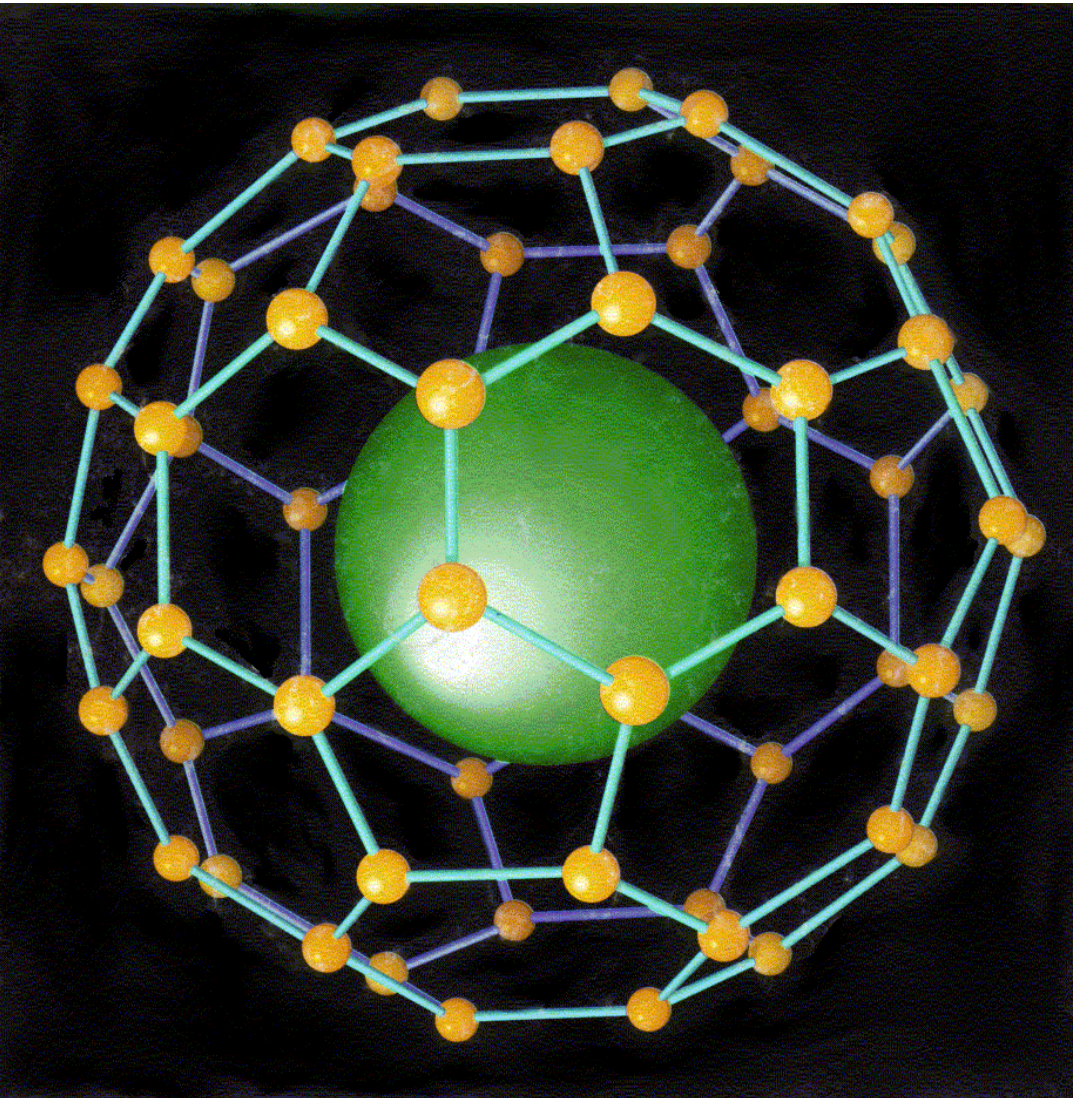
60

Widmo masowe



Paweł Tomasz Pęczkowski

# OSC – Organic Solar Cells



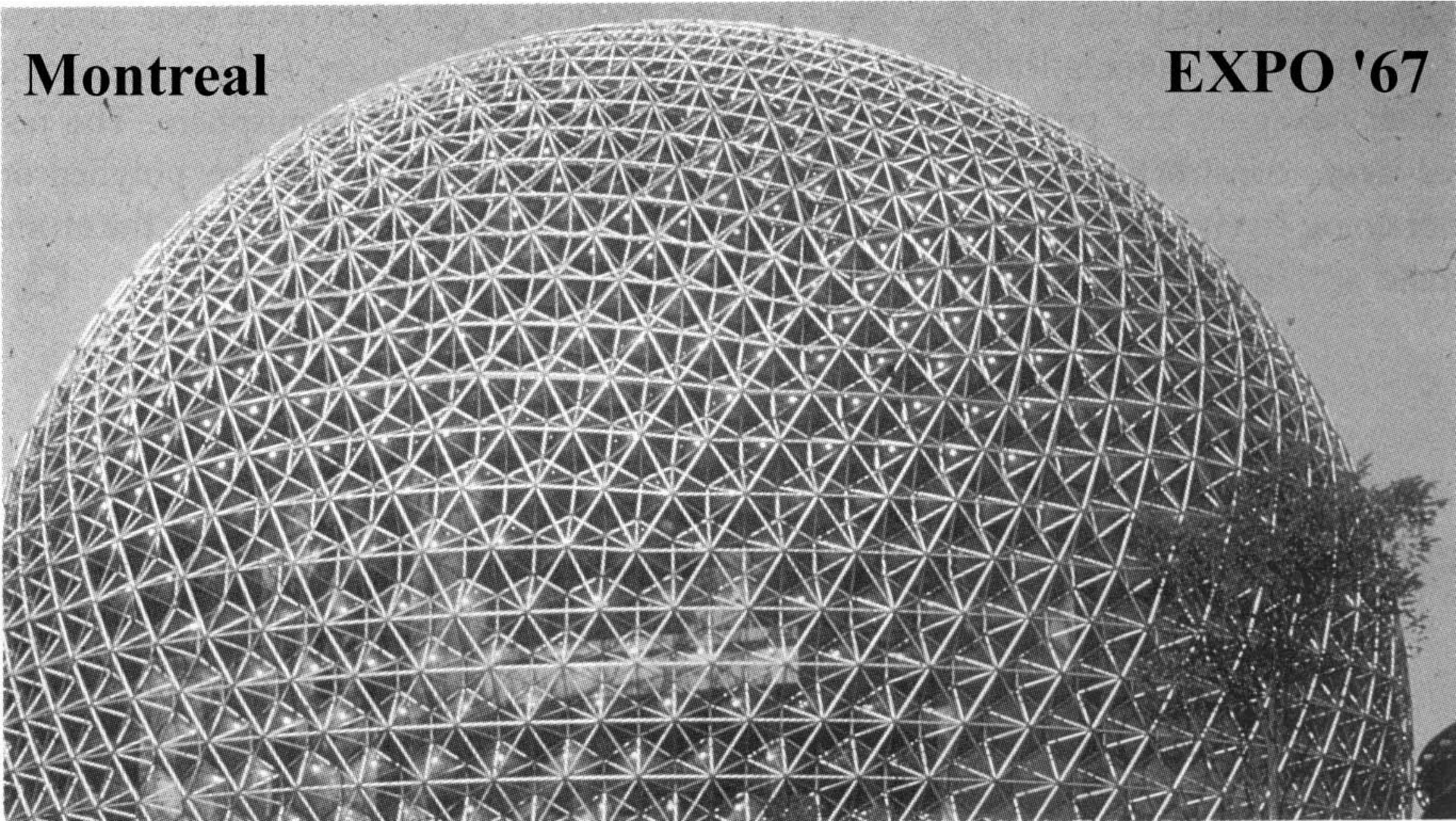
C<sub>60</sub>

0,71 ± 0,007 nm

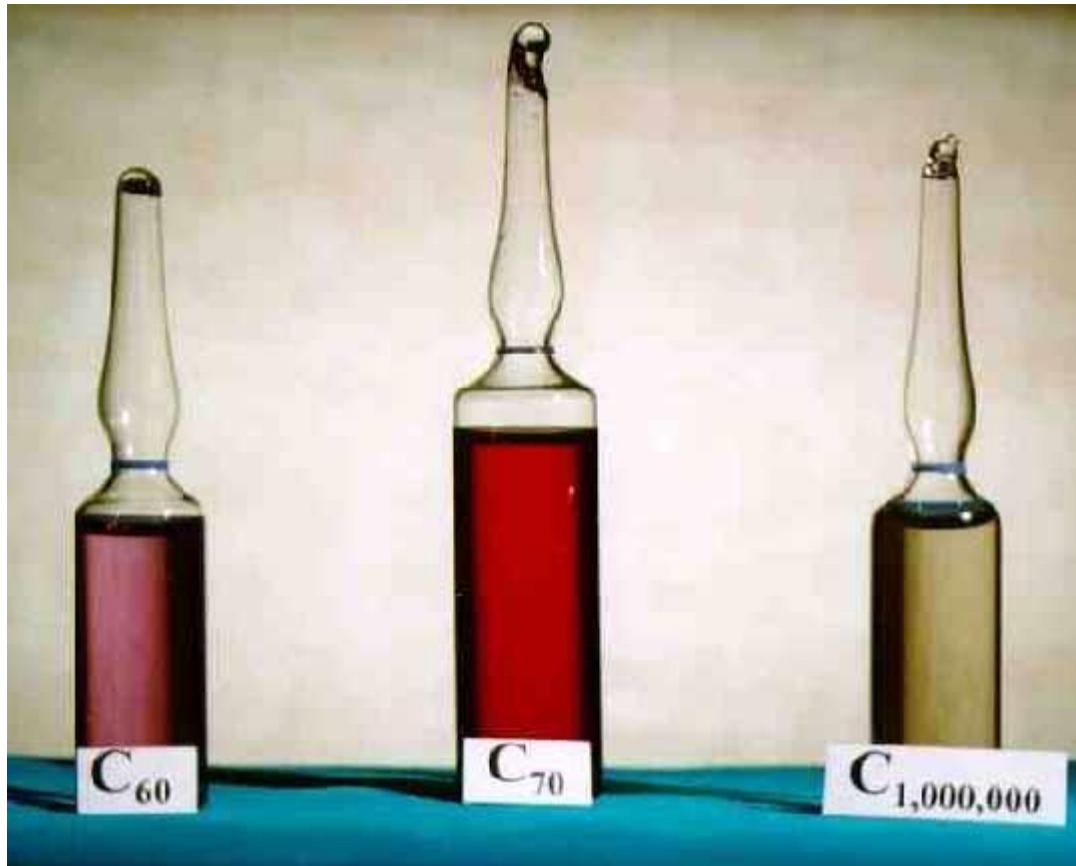


# OSC – Organic Solar Cells

Buckminster Fuller pour un exposition en 1967 à Montréal

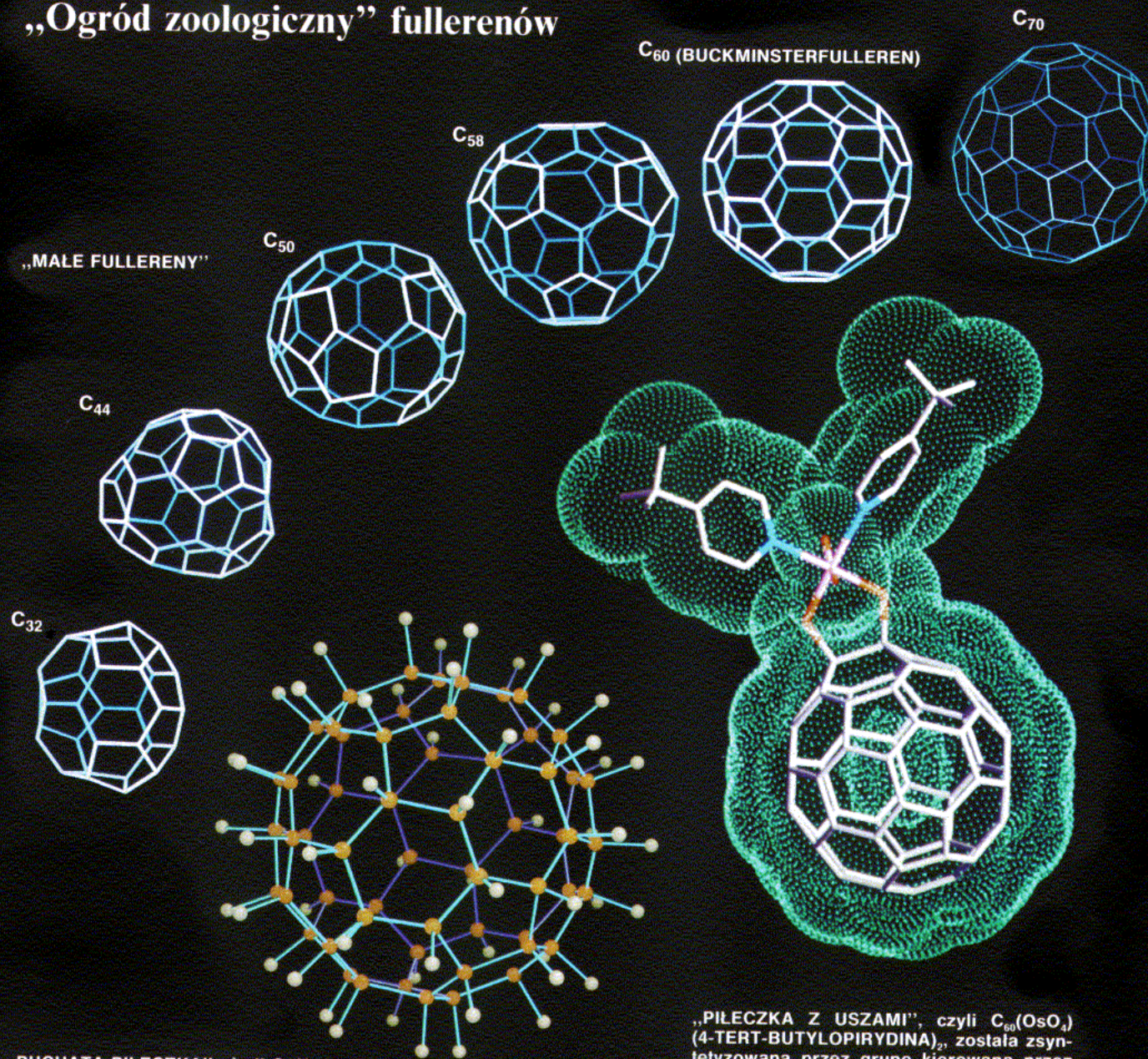


# OSC – Organic Solar Cells



Roztwory w toluenie

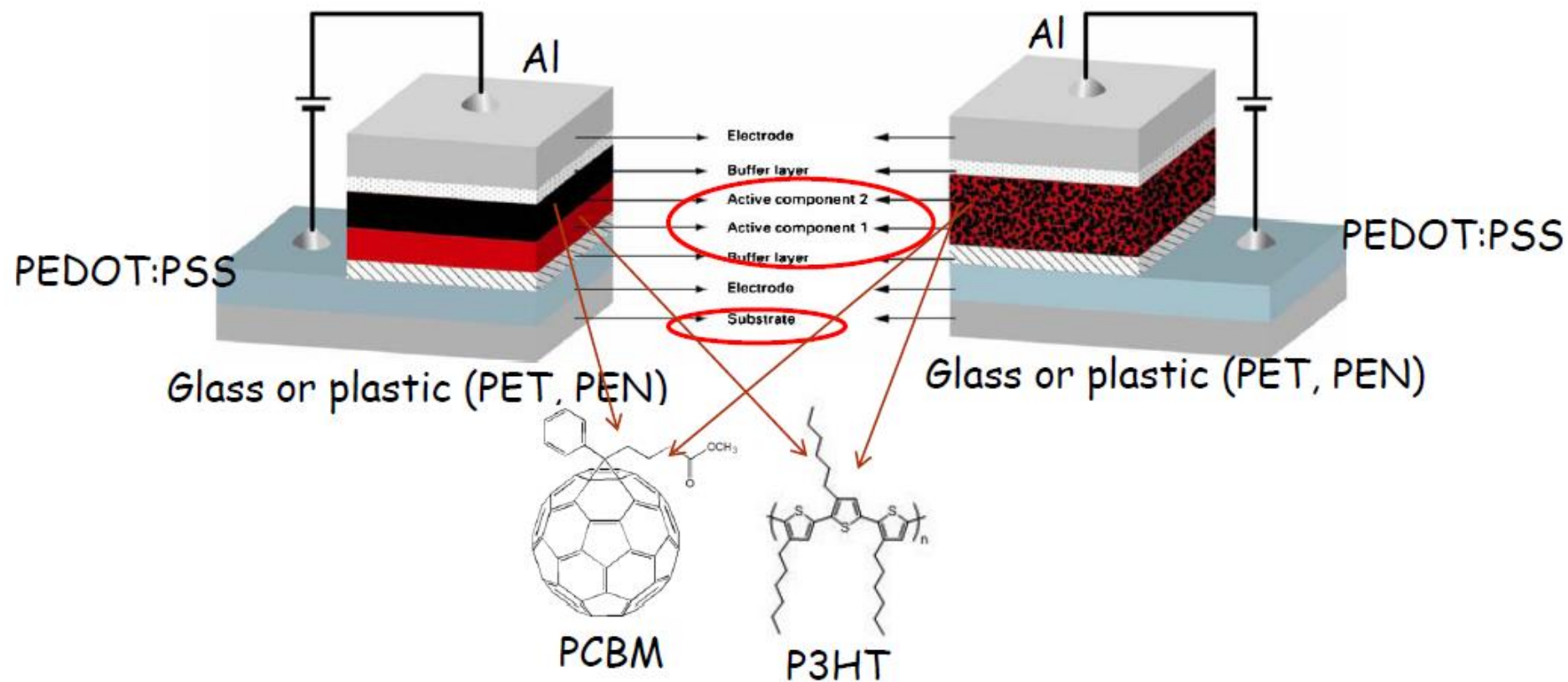
# „Ogród zoologiczny” fullerenów



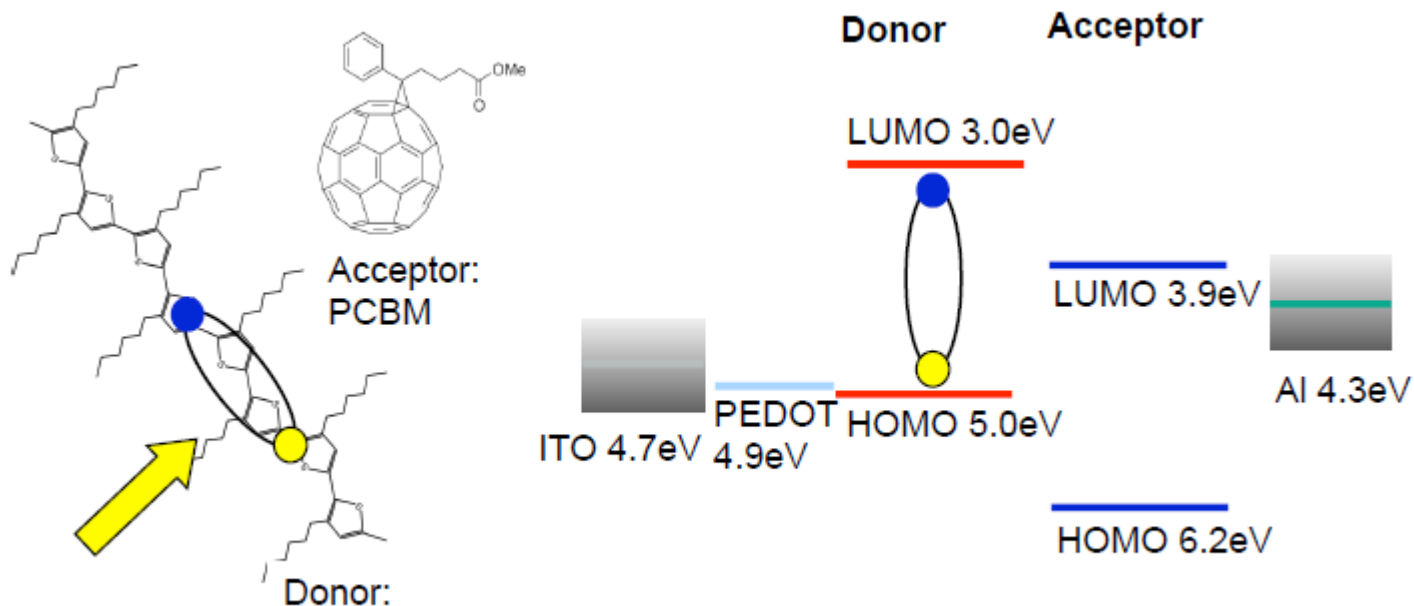
# OSC – Organic Solar Cells

## Bilayer Device Structure

## Bulk-Heterojunction Device Structure



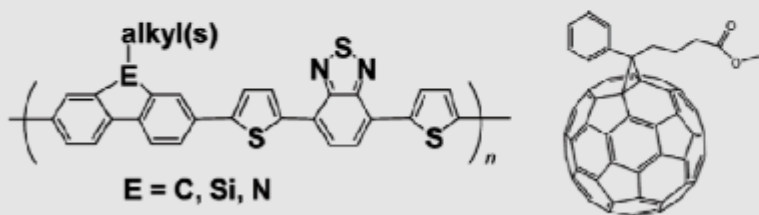
# OSC – Organic Solar Cells



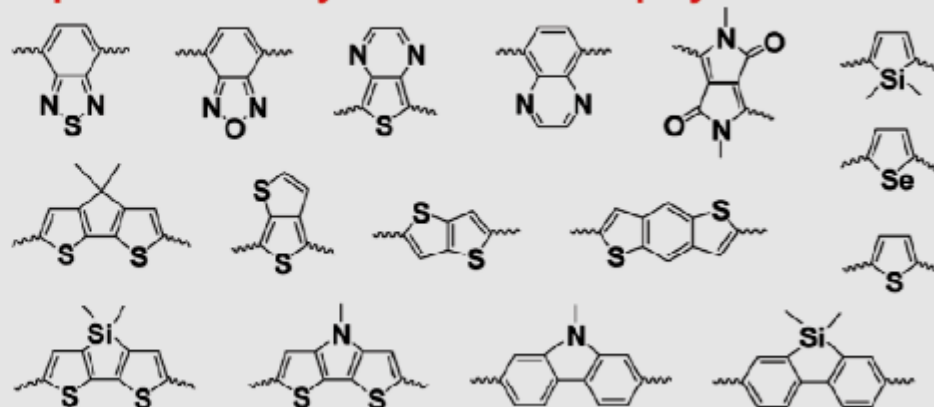
## Polymer Donor + Acceptor



## Polymeric Bulk-Heterojunction Solar Cell



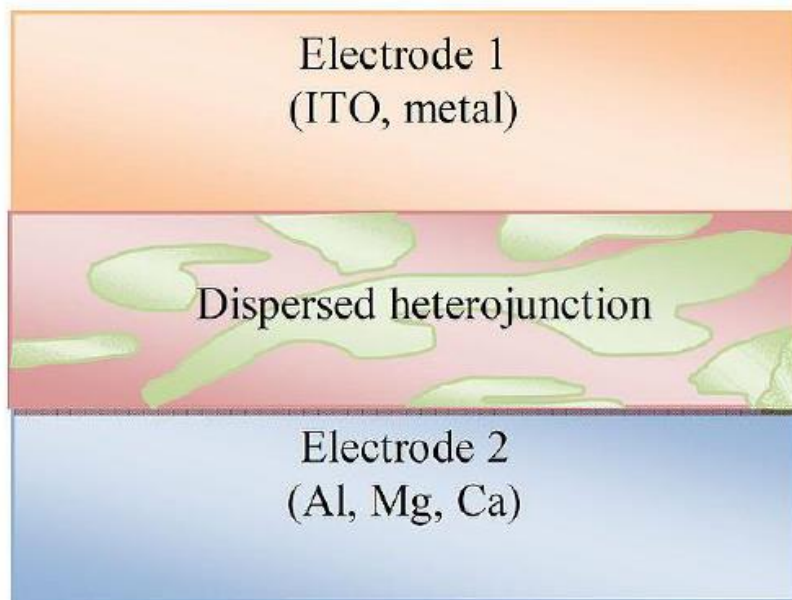
## Important heterocycles to construct polymer donors:



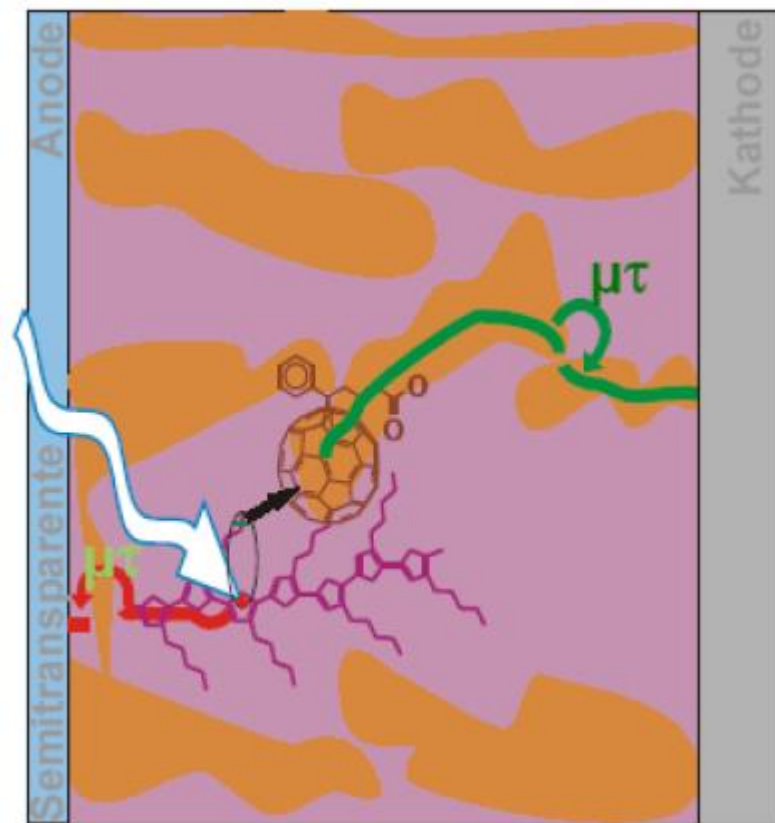


# OSC – Organic Solar Cells

Bulk heterojunction photovoltaic cells

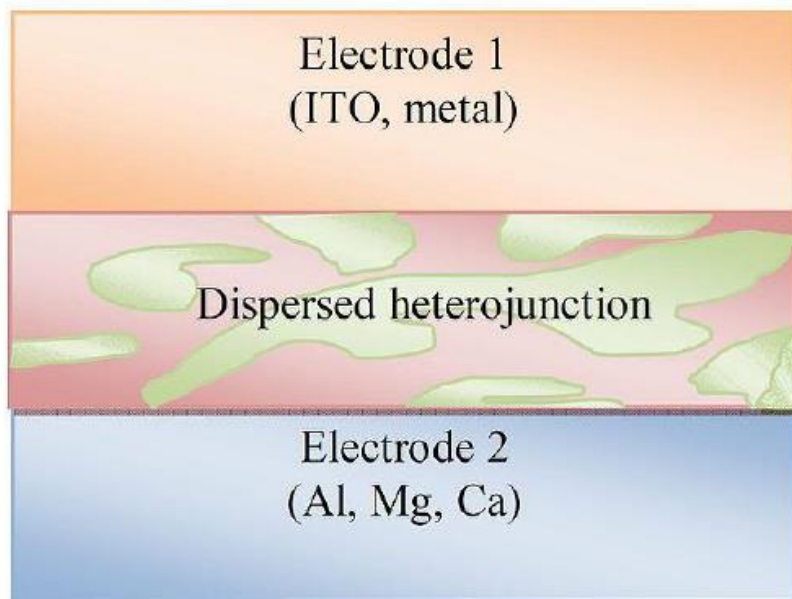


Electrons move to the acceptor domains then were carried through the device and collected by one electrode, and holes were pulled in the opposite direction and collected at the other side



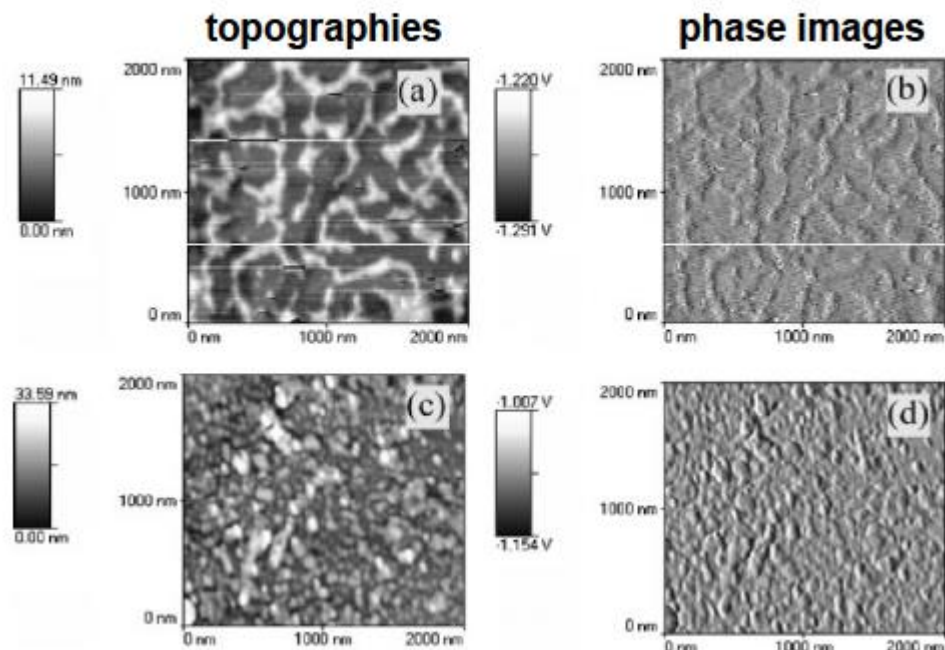
# OSC – Organic Solar Cells

Bulk heterojunction photovoltaic cells



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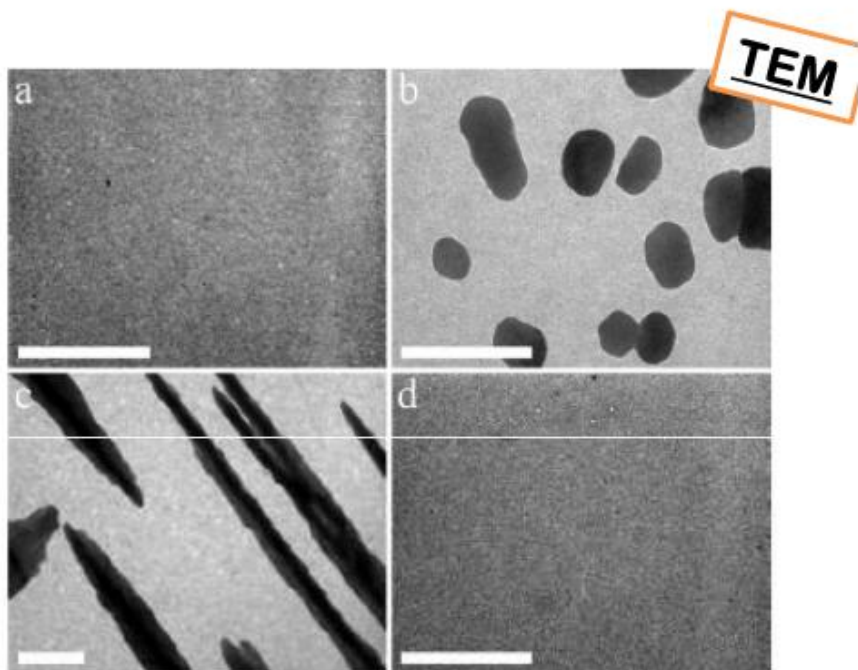
## Tapping mode AFM



X. Chen, B. Gholamkhash, X. Han, G. Vamvounis, S. Holdcroft  
Macromol. Rapid Commun. 2007, 28, 1792–1797

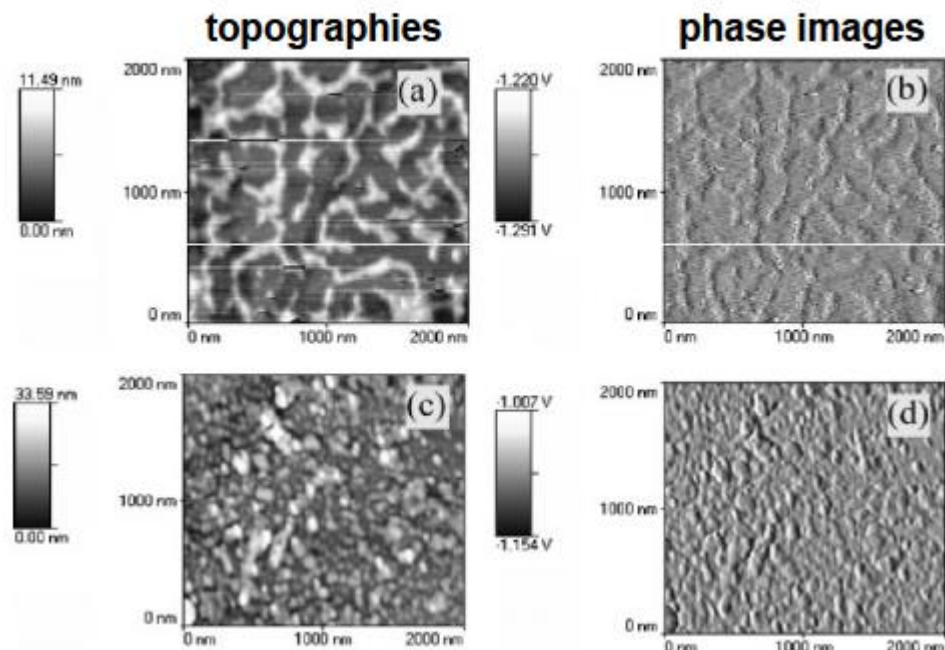
# OSC – Organic Solar Cells

## Tapping mode AFM



**Figure 1.** TEM image of a thin film of a) 1:1 P3HT/PCBM blend before annealing, and b) after annealing for 1 h at 140°C. c) 1:1 P3HT/PCBM + 5 wt.-% poly(1)-block-poly(2) after annealing (140°C). d) 1:1 P3HT/PCBM + 17 wt.-% poly(1)-block-poly(2) after annealing (1 h, 140°C). The white scale bars are 2  $\mu\text{m}$ . Solutions of the blends were spin-cast onto NaCl. After annealing, the films were floated onto water and placed on a 400-mesh copper grid. Images were obtained without stain; dark areas indicate fullerene-rich regions.

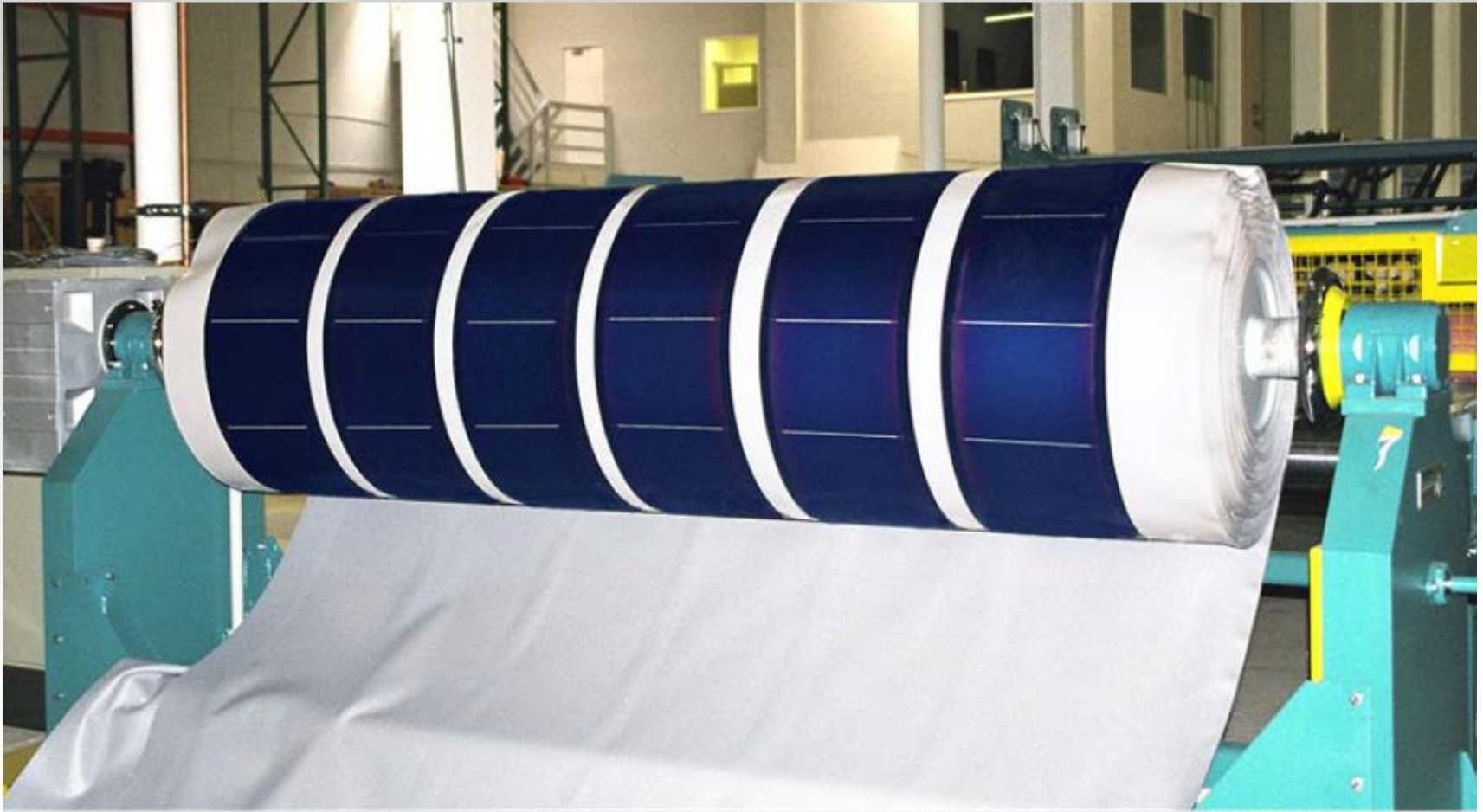
*K. Sivula, Z. T. Ball, N. Watanabe, J. M. J. Frechet, Adv. Mater. 2006, 18, 206.*



X. Chen, B. Gholamkhash, X. Han, G. Vamvounis, S. Holdcroft  
*Macromol. Rapid Commun.* 2007, 28, 1792–1797

# OPV – Organic Photovoltaic

**Solar cells on a roll, it's real!**



©2011 Coatema Coating Machinery GmbH

# OPV – Organic Photovoltaic

**Flexible solar cells on a roof!**







©2011 Coatema Coating Machinery GmbH



# Koncentratory słoneczne

## Concentrated Solar Thermal Technologies: CST

			
C ~ 70-90 commercial	C ~ 60-120 demo	C ~ 300-4000 demo	C ~ 500-1000 comm. demo
$\eta_a \sim 12\%-14\%$	$\eta_a \sim 10\%-12\%$	$\eta_a \sim 14\%-18\%$	$\eta_a \sim 10\%-15\%$
LEC <sub>2020</sub> ~ 5ct/kWh	LEC <sub>2020</sub> ~ 5ct/kWh	LEC <sub>2020</sub> ~ ?	LEC <sub>2020</sub> ~ 5ct/kWh

<http://www.mpifr-bonn.mpg.de/1192452/Weber.pdf>

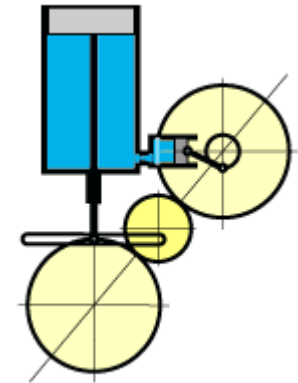
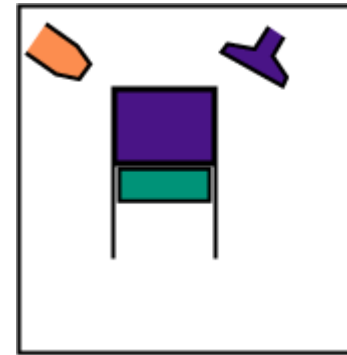
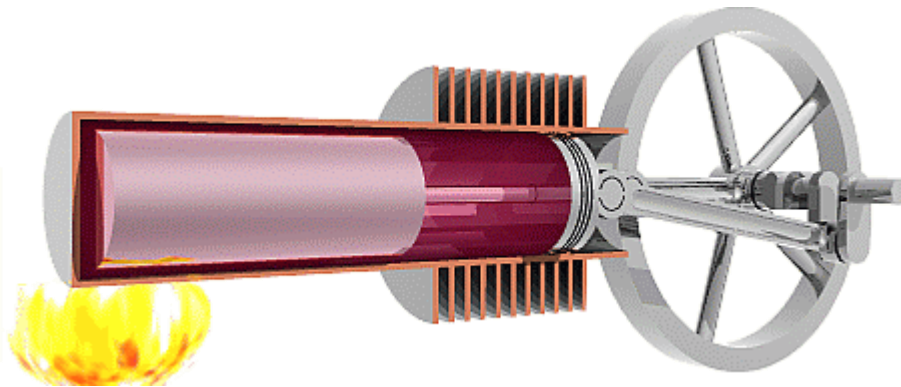
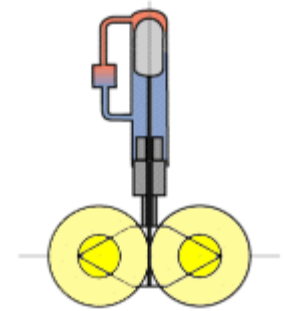
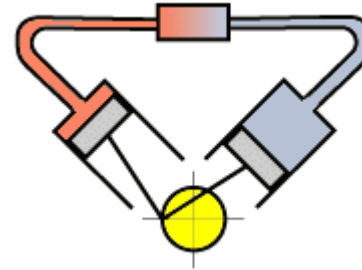
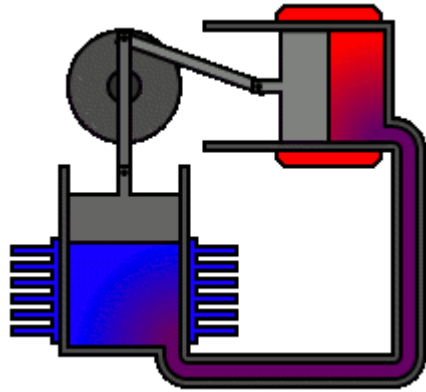
# Koncentratory słoneczne



<http://www.solarcurator.com/2013/05/23/power-of-concentration/>



# Koncentratory słoneczne



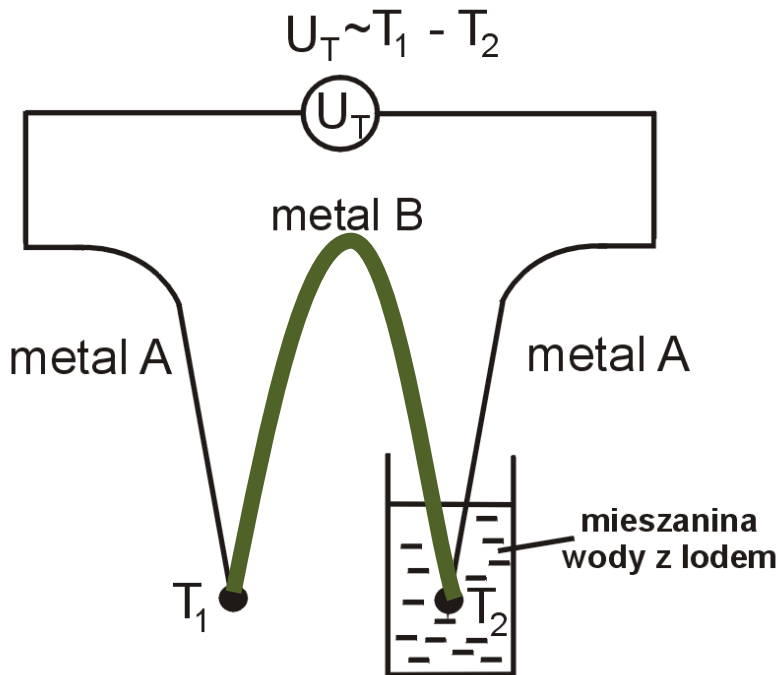
[http://pl.wikipedia.org/wiki/Silnik\\_Stirlinga](http://pl.wikipedia.org/wiki/Silnik_Stirlinga)

# Zjawiska termoelektryczne

## Siła termoelektryczna

$$\alpha(T) = -\frac{k_B}{q} \left[ \frac{\langle \varepsilon \tau \rangle}{\langle \tau \rangle} - \eta \right]$$

Siła termoelektryczna (współczynnik Seebecka):



$$\frac{dV_{12}}{dT} = \alpha_{ab} = \alpha_a - \alpha_b$$

$$V_{12} = \int_{T_1}^{T_2} \alpha_{ab}(T) dT$$

podczas pomiarów należy jeden materiał uznać za wzorcowy, i badać siłę termoelektryczną względem takiego wzorca (idealnie – względem nadprzewodnika)

znak siły termoelektrycznej zależy od rodzaju nośników: dla elektronów  $q < 0$  i  $\alpha > 0$  (znak zimnego końca – ujemny)  $\Rightarrow$  metoda gorącej sondy

$$\frac{k_B}{e} = 85 \frac{\mu V}{K}$$

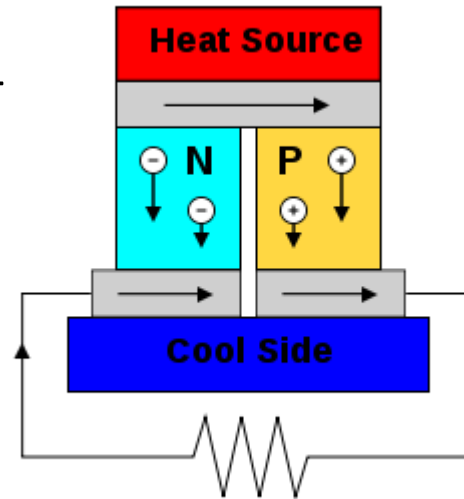
siły termoelektryczne niezdegenerowanych półprzewodników są rzędu kilkuset  $\mu V/K$

# Zjawiska termoelektryczne

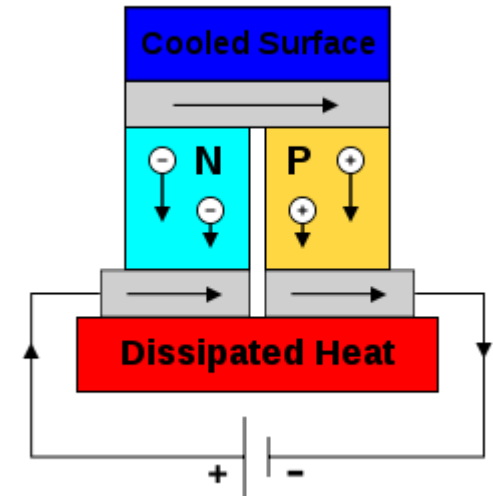
## Efekt Peltier

efekt odwrotny do efektu Seebecka – powstawanie różnicy temperatury pomiędzy złączami  $a-b$  i  $b-a$  dwóch różnych materiałów przez które przepuszczany jest prąd elektryczny:

efekt Seebecka

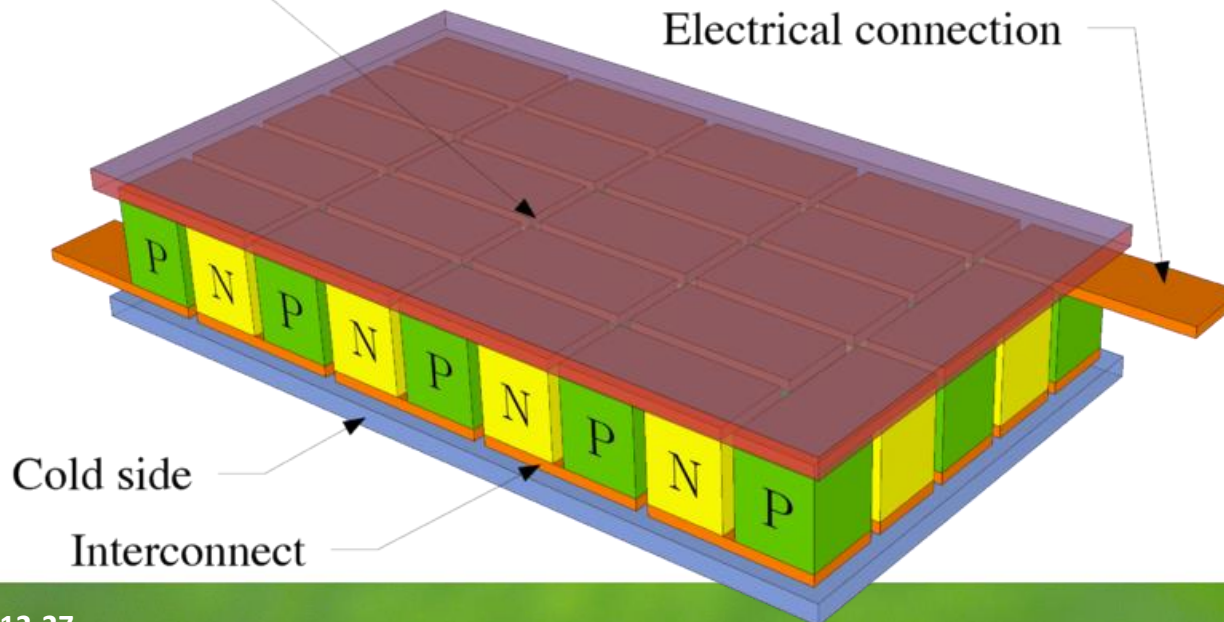


efekt Peltier



Hot side

Electrical connection



Cold side

Interconnect

# Zjawiska termomagnetyczne

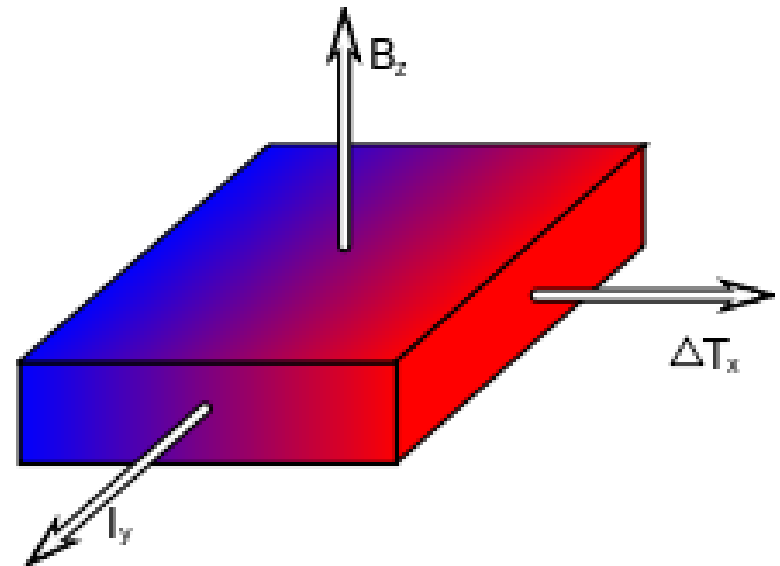
## Przykład: poprzeczne i podłużne zjawisko Nernsta-Ettingshausena (pole magnetyczne + gradient temperatury)

Istnieje szereg zjawisk termomagnetycznych (gradient temperatury, pole elektryczne, pole magnetyczne  $\Rightarrow$  możliwe przepływy prądu i ciepła); szczegóły – patrz np.: B.M. Askerov, „Electron transport phenomena in semiconductors”, World Scientific 1994

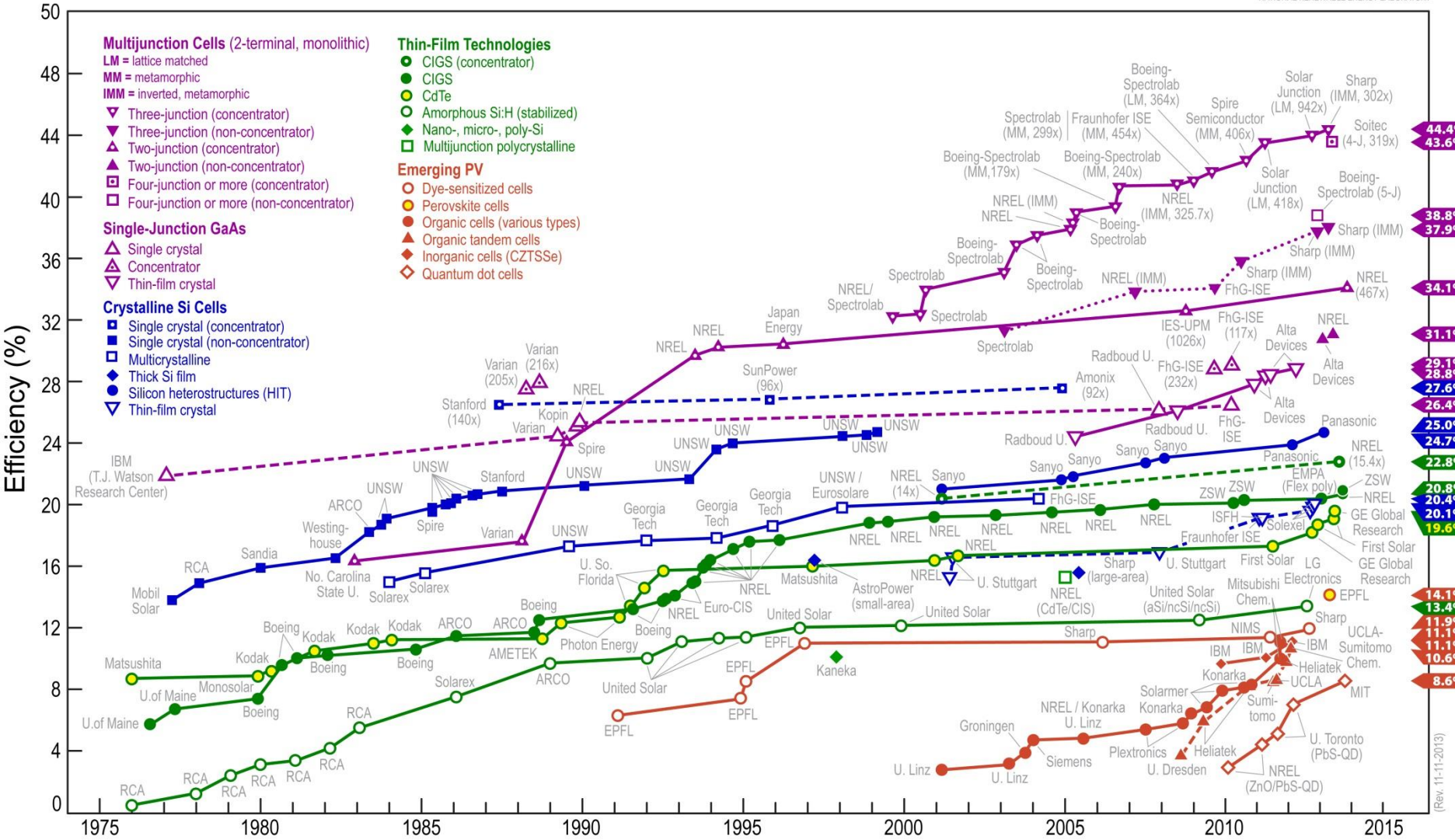
$$E_y = 1 \frac{1}{B} \frac{dT}{dx} \quad \text{poprzeczne}$$

$$\frac{dT}{dy} = PI_x B_z \quad \text{podłużne}$$

podłużny (zmiana siły termoelektrycznej w polu B) i poprzeczny efekt Nernsta-Ettingshausena



# Best Research-Cell Efficiencies



(Rev. 11-11-2013)