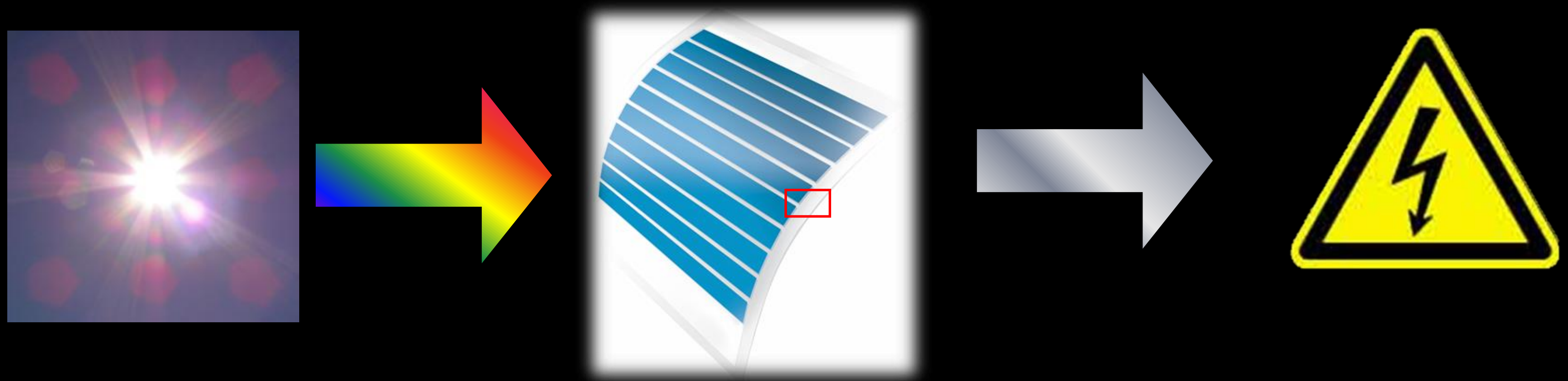
Solar Photovoltaics & Energy Systems

Lecture 3. Crystalline Semiconductor Based Solar Cells

ChE-600

Wolfgang Tress, March 2018

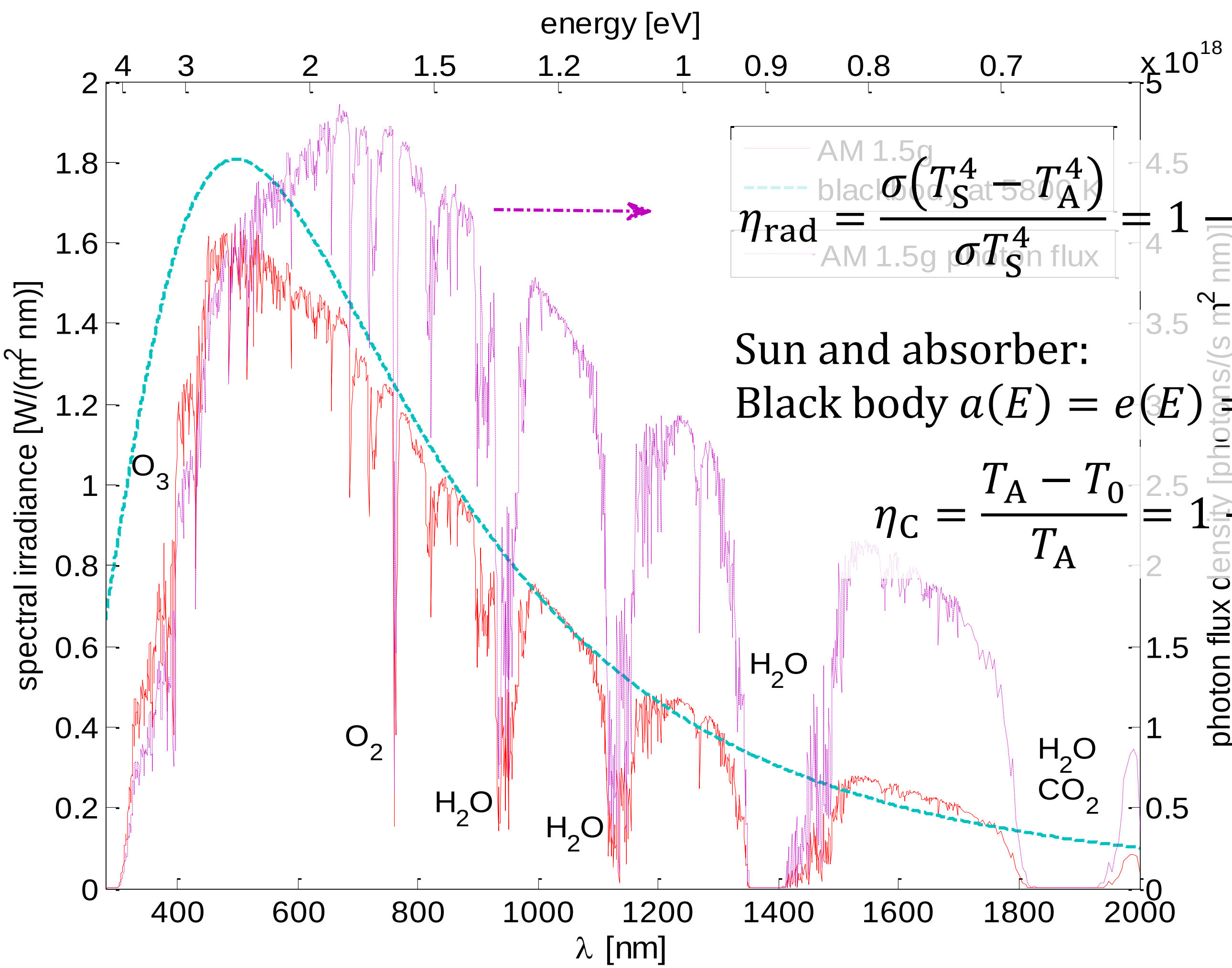
Photovoltaic Solar Energy Conversion



Outline

- Recap: Thermodynamics of semiconductor-based energy conversion
- From chemical to electrical energy
- pn and metal-semiconductor junctions
- Silicon solar cell technology
- Photovoltaic installations

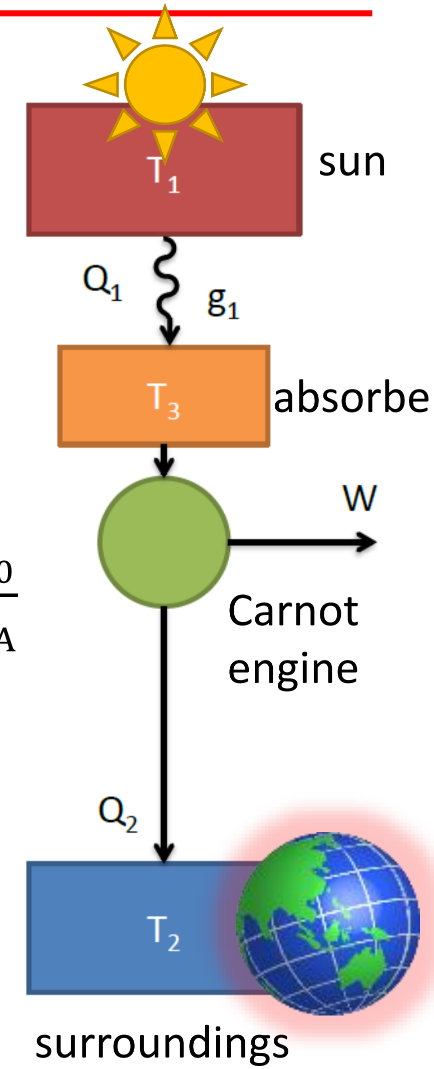
Semiconductor vs. **Heat Engine**



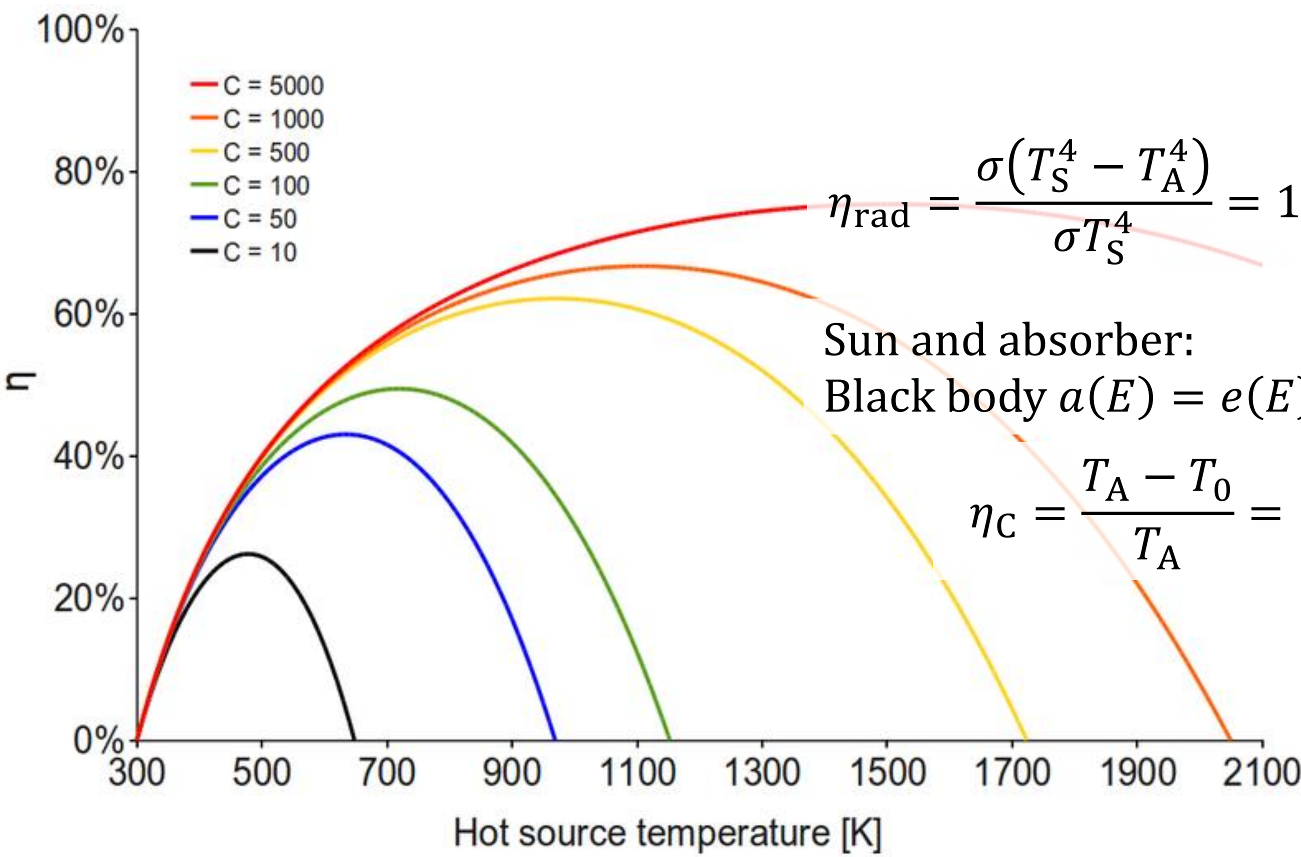
$$\eta_{\mathrm{rad}} = \frac{\sigma\left(T_S^4 - T_A^4\right)}{\sigma T_S^4} = 1 - \frac{T_A^4}{T_S^4}$$

Sun and absorber:
Black body $a(E) = e(E) = 1$

$$\eta_C = \frac{T_A - T_0}{T_A} = 1 - \frac{T_0}{T_A}$$



Semiconductor vs. **Heat Engine**



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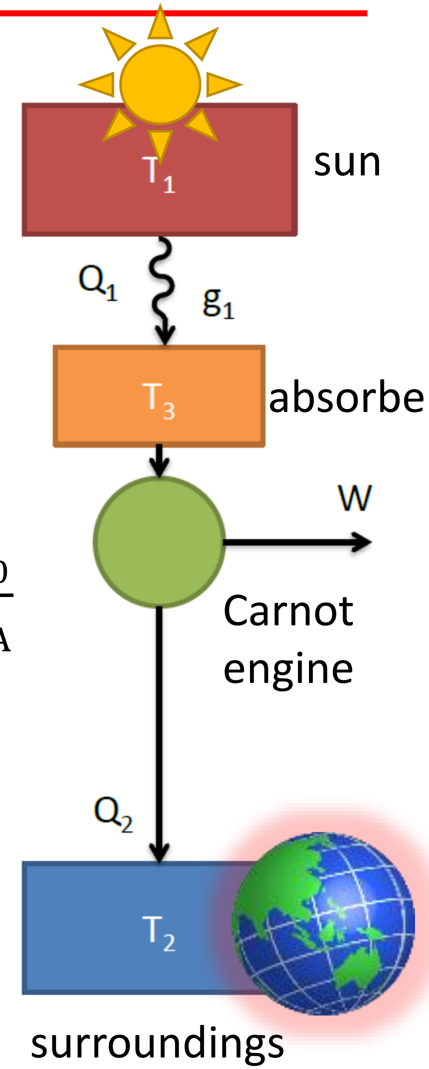

→ Absorber is at elevated temperature

Semiconductor vs. Heat Engine

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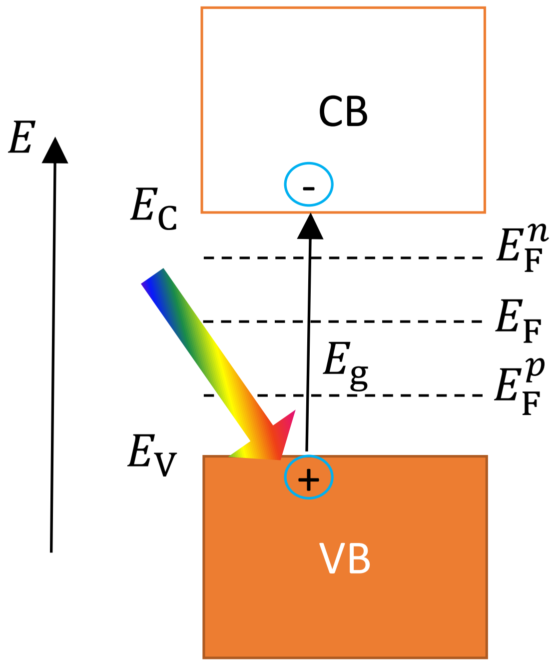
Band gap: $a(E) = e(E) = \begin{cases} 0\,; E < E_g \\ 1\,; E \geq E_g \end{cases}$

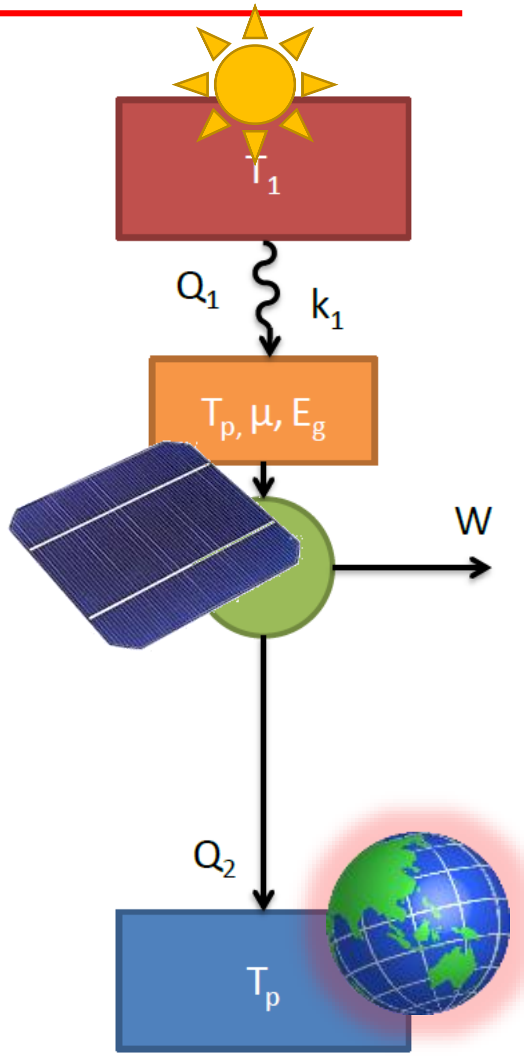


$$n = N_C \exp\left(-\frac{E_C - E_F^n}{k_B T}\right)$$

Quasi-Fermi level splitting → chemical energy → potential

$$p = N_V \exp\left(-\frac{E_F^p - E_V}{k_B T}\right)$$

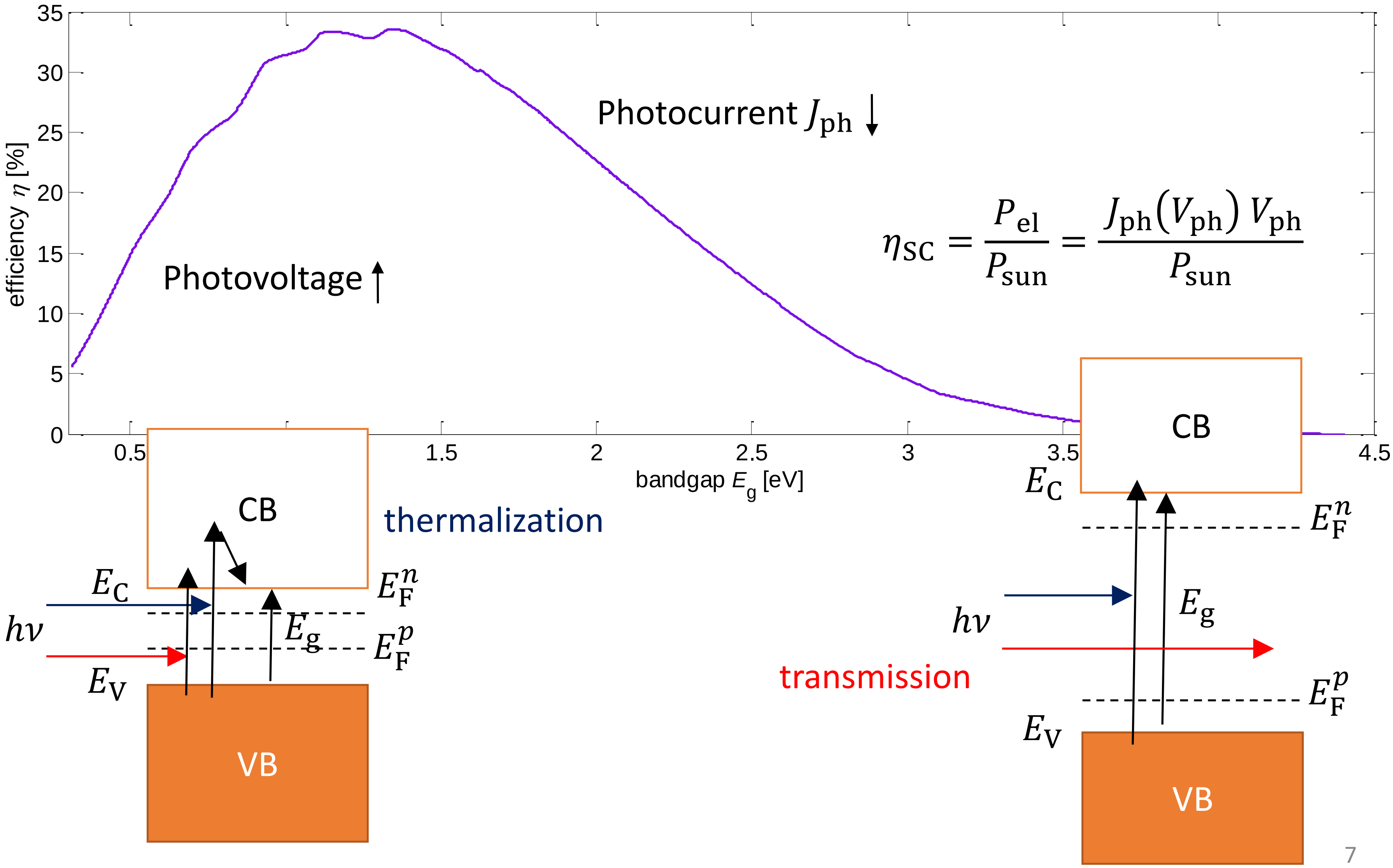
Charge flow → electrical current



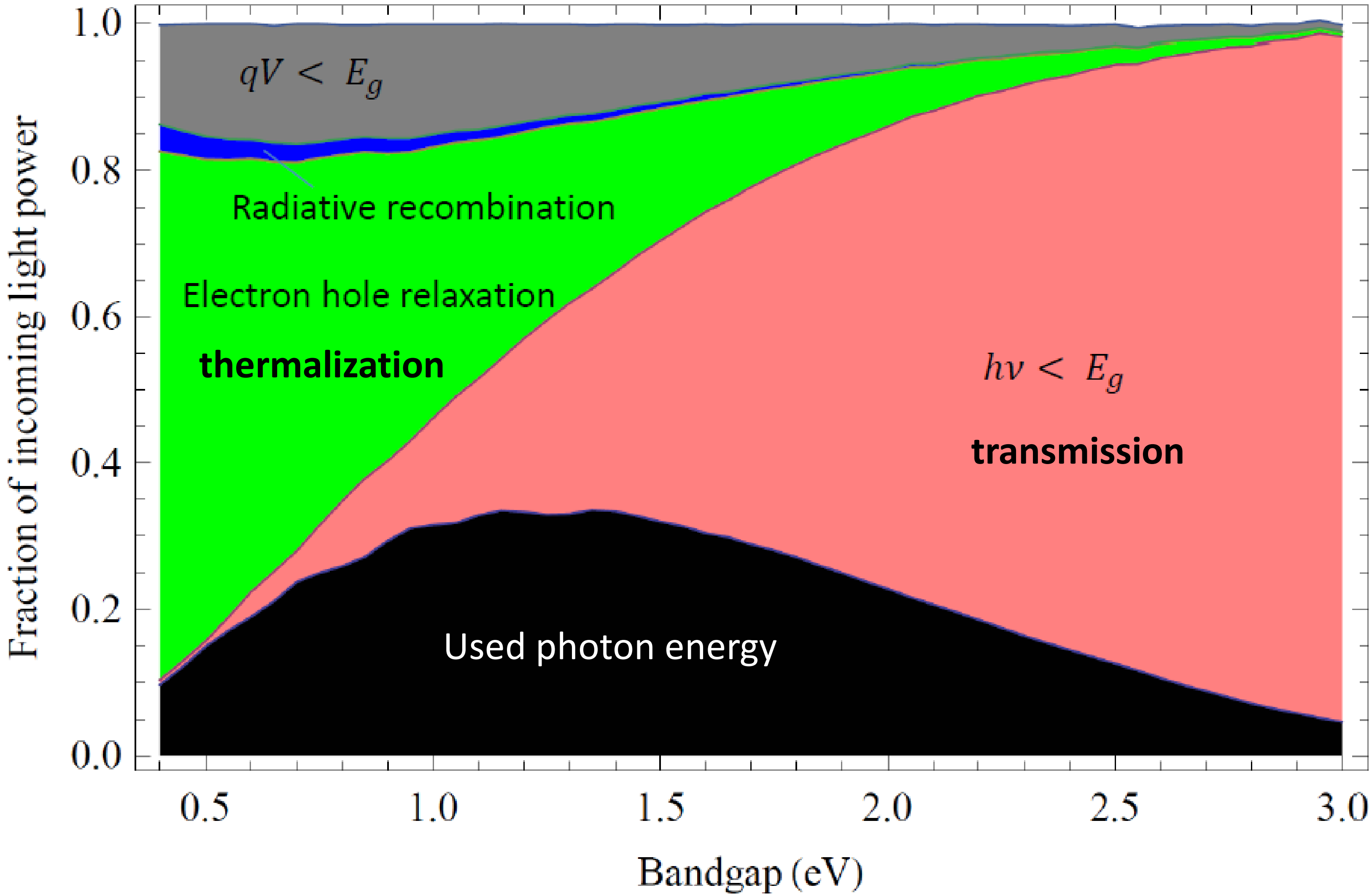
→Absorber is at surrounding temperature

→Radiation is converted into chemical energy

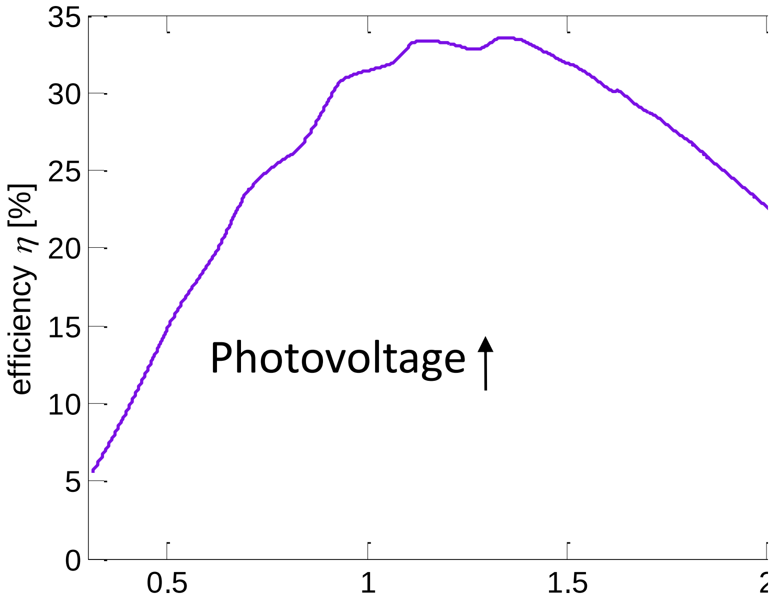
Shockley-Queisser Limit

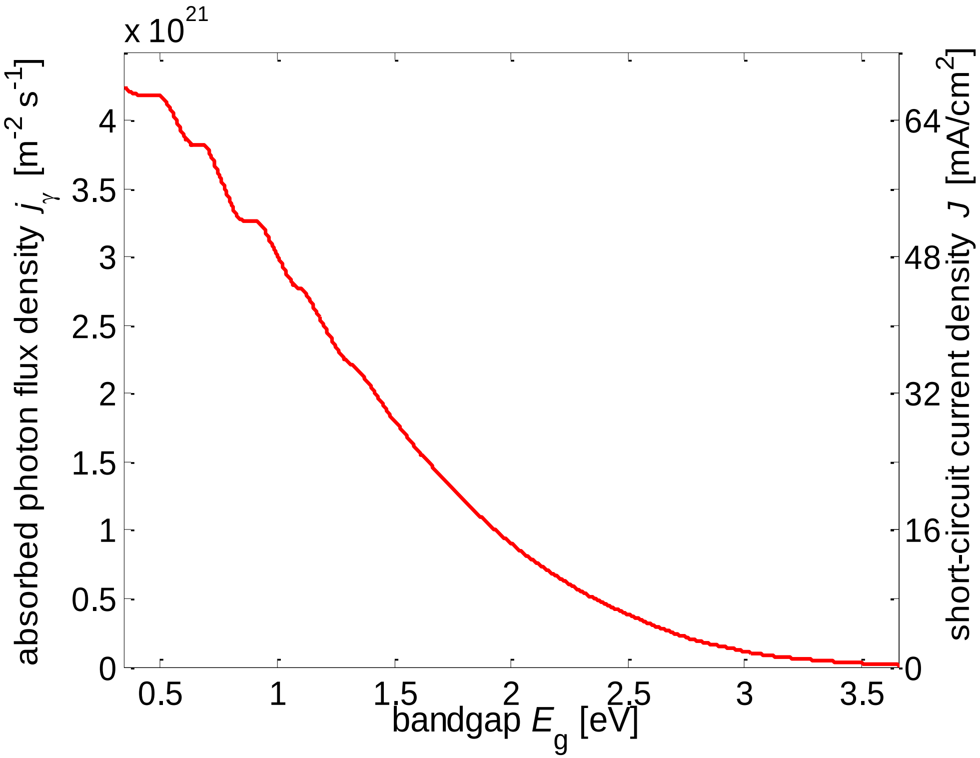


Losses in Single-Bandgap Material



Shockley-Queisser Limit





$$J_{\text{ph,max}} = e \int a(E)\Phi_{\text{AM1,5g}}(E)dE = e\int_{E_g} \Phi_{\text{AM1,5g}}(E)dE$$

$$V_{\text{ph,max}} = ?$$

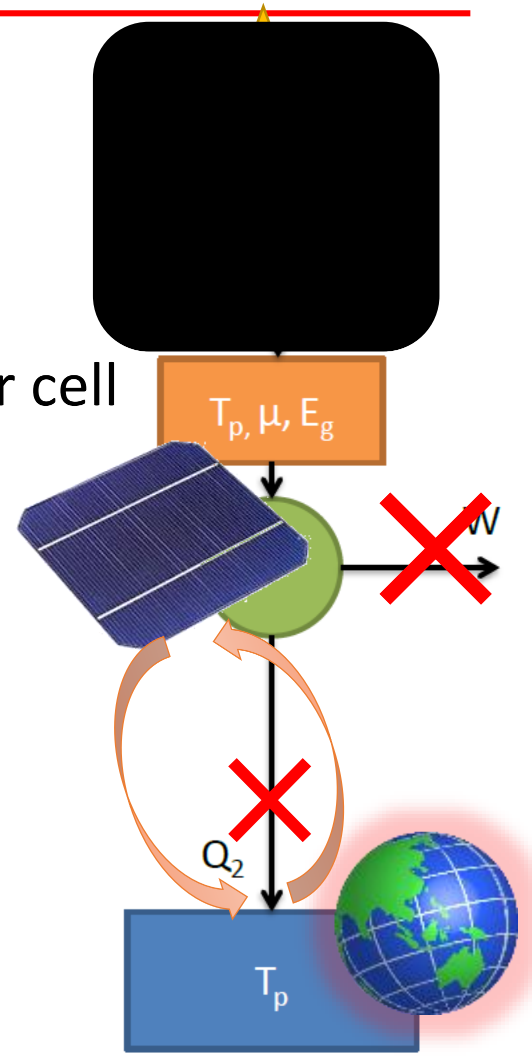
Detailed Balance Limit

$$B(E) = \begin{cases} 0 & for\ E \le E_g \\ \frac{2\pi}{c^2 h^3} \frac{E^2}{exp\left(\frac{E-\mu}{k_B T}\right) - 1} & for\ E > E_g \end{cases}$$

Boltzmann approx.

$$\phi_{\mathrm{BB}}(E,T)\exp\left(\frac{eV}{k_{\mathrm{B}}T}\right)$$

- In the dark: thermal equilibrium between solar cell surroundings: $B_0(E) = a(E)\ \phi_{\mathrm{BB}}(T_0)$



Detailed Balance Limit

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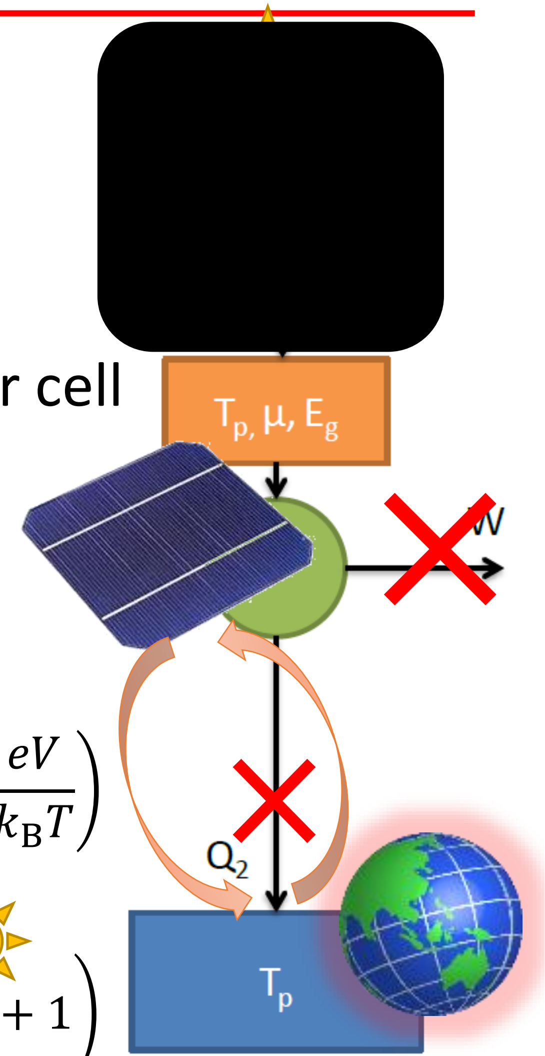


- In the dark: thermal equilibrium between solar cell surroundings: $B_0(E) = a(E)\ \phi_{\mathrm{BB}}(T_0)$
- Balance under light:

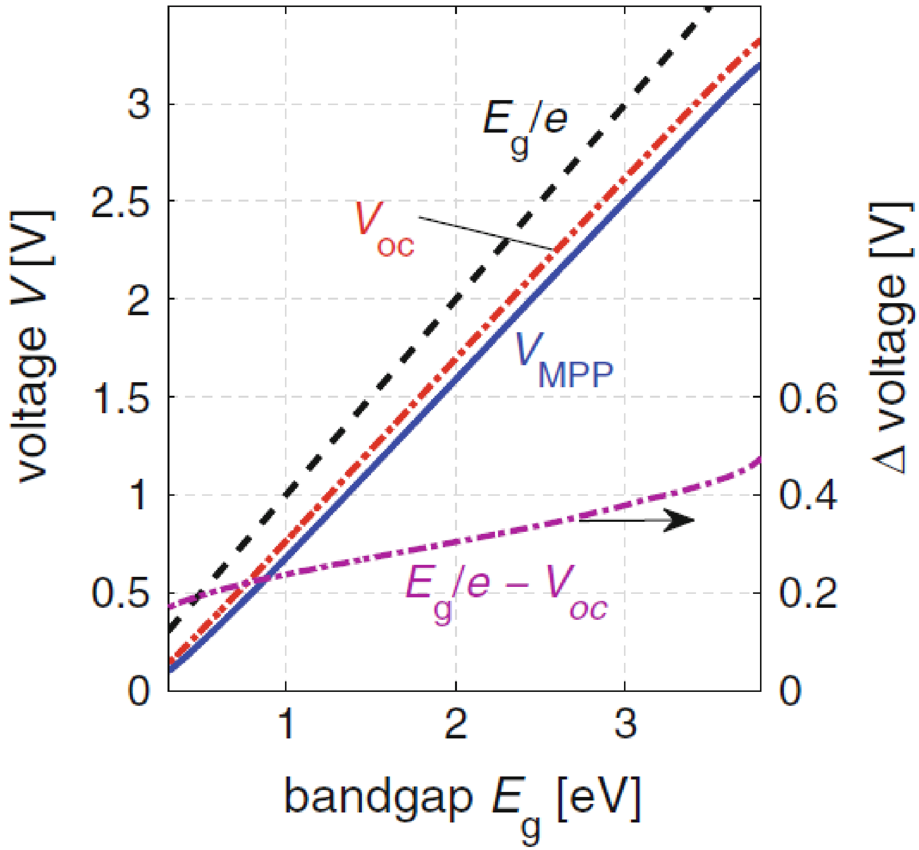
$$J_{\mathrm{ph}}(V) =$$

$$e\int a(E)\Phi_{\mathrm{AM1,5g}}(E)dE + e\int B_0(E)dE - e\int B_0(E)dE\,\exp\left(\frac{eV}{k_{\mathrm{B}}T}\right)$$

$$J_{\mathrm{ph,max}} \qquad J_{\mathrm{em,0}}$$

- Open circuit ($J_{\mathrm{ph}}(V) = 0$): $V_{\mathrm{oc,rad}} = \dfrac{k_{\mathrm{B}}T}{e}\ln\left(\dfrac{J_{\mathrm{ph}}}{J_{\mathrm{em,0}}} + 1\right)$

Detailed Balance Limit



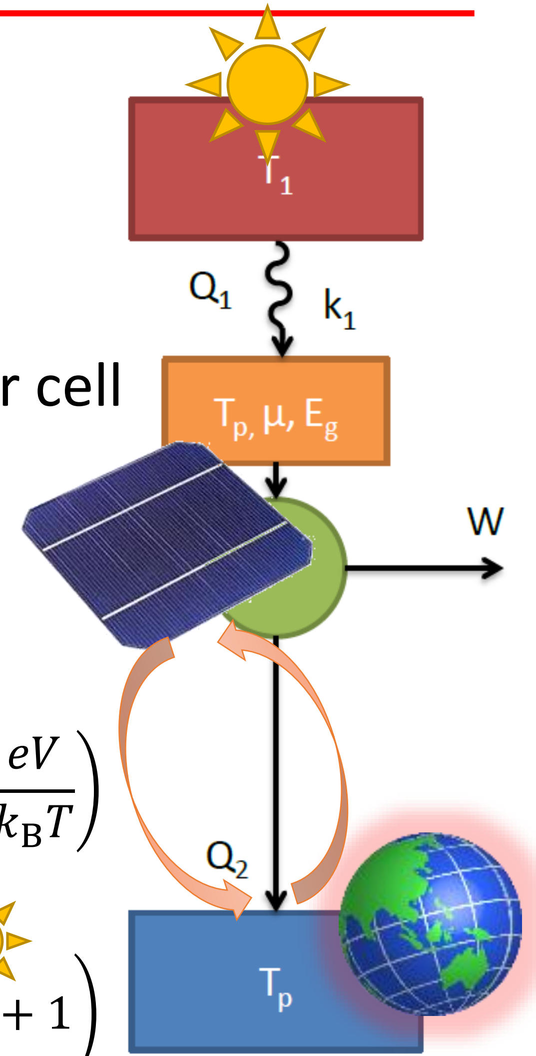
ıann approx.

')exp $\left(\frac{eV}{k_B T}\right)$

tween solar cell

$T_0)$

$_0(E)dE \exp\left(\frac{eV}{k_B T}\right)$



- Open circuit ($J_{ph}(V) = 0$): $V_{oc,rad} = \frac{k_B T}{e} \ln\left(\frac{J_{ph}}{J_{em,0}} + 1\right)$

JV-Curve of Ideal Solar Cell with E_g =1.6 eV

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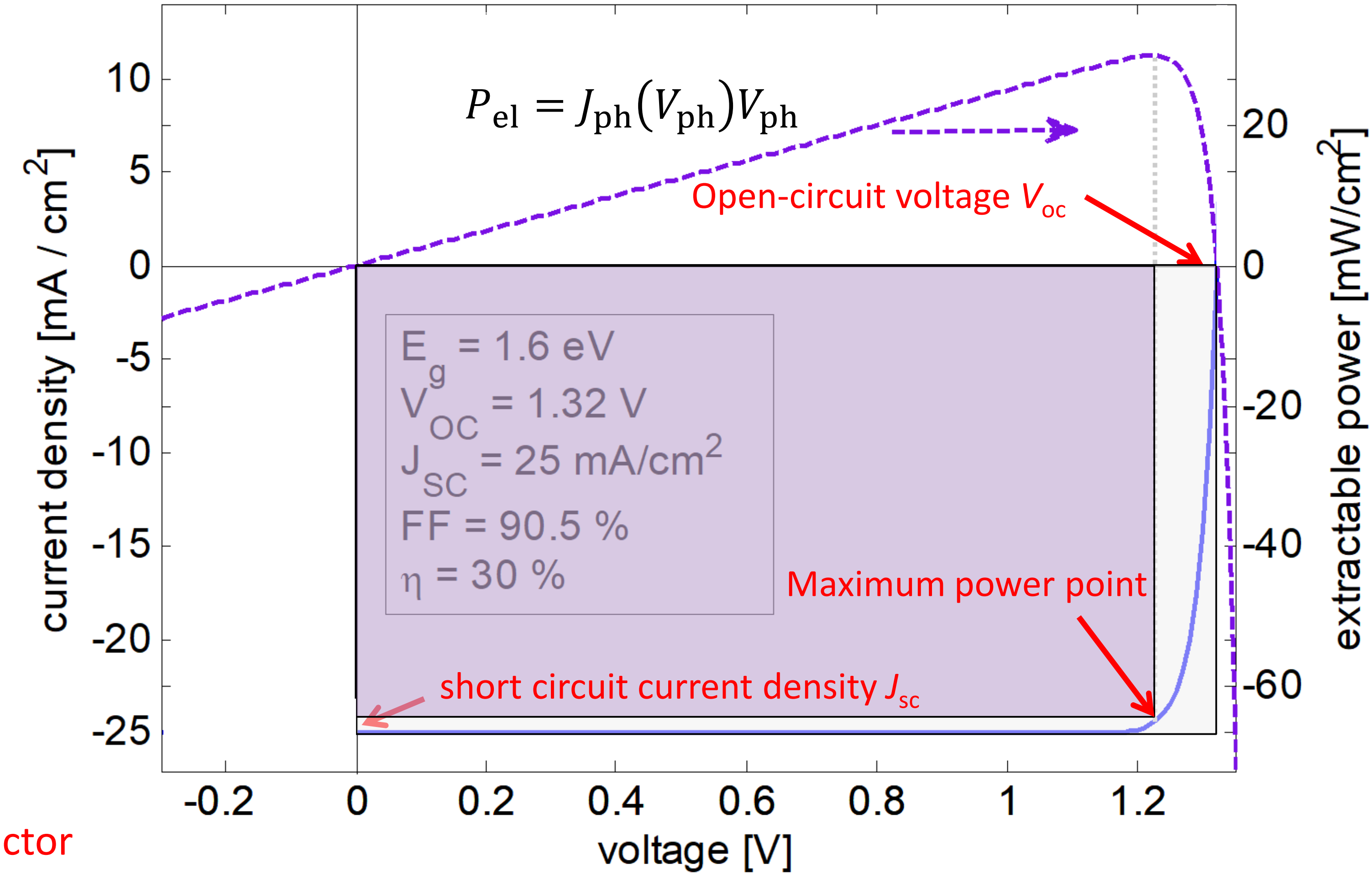
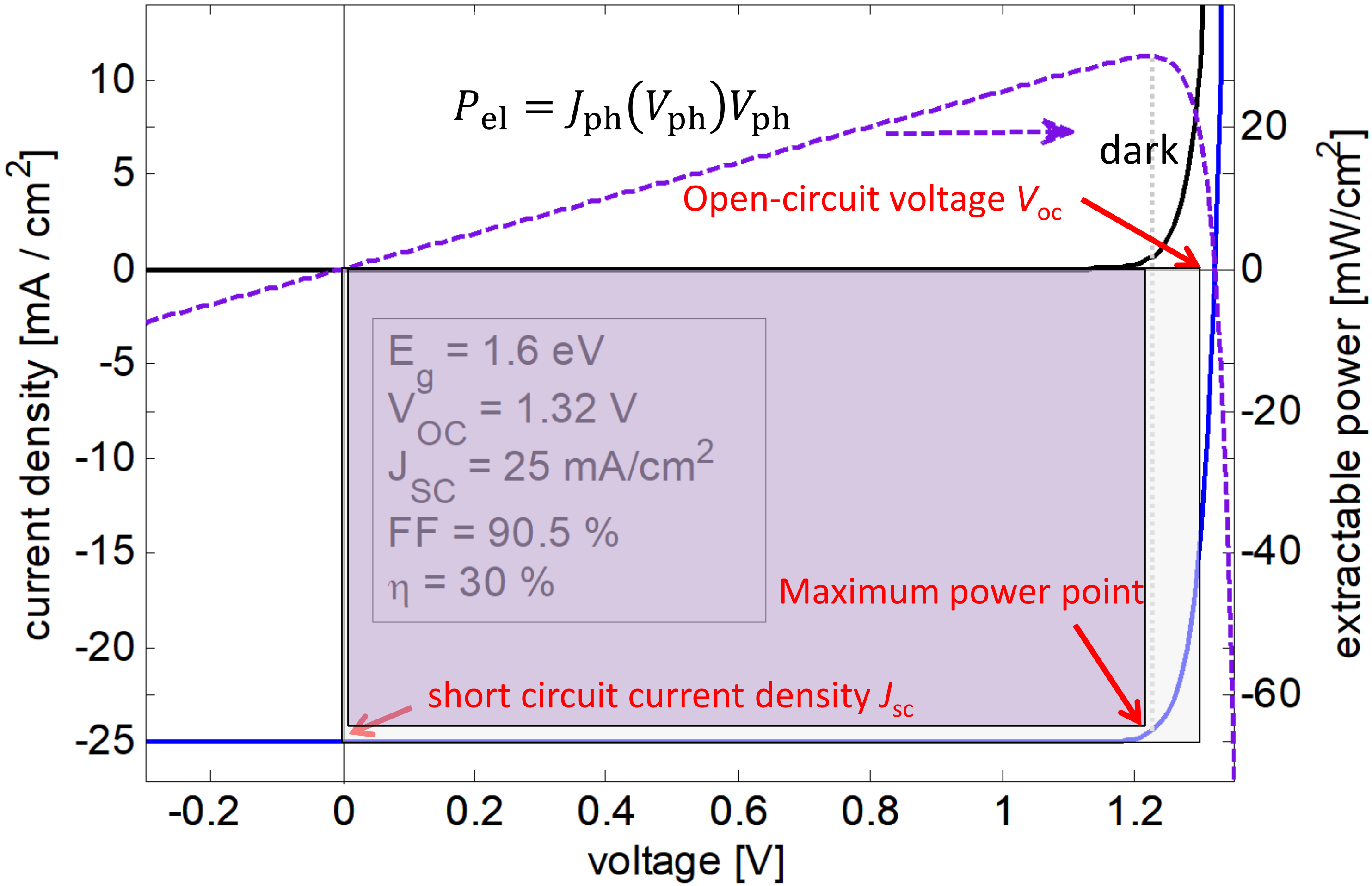


Fill factor

FF = (area of the maximum-power rectangle) / (area of the $J_{sc} \times V_{oc}$ rectangle)

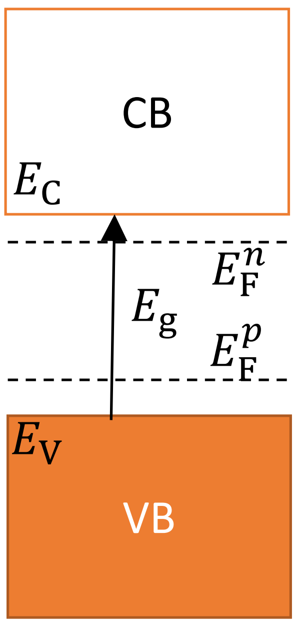
$$\eta_{SC,max} = \frac{P_{el,max}}{P_{sun}} = \frac{\max J_{ph}(V_{ph})\, V_{ph}}{P_{sun}} = \frac{J_{sc} V_{oc} FF}{P_{sun}}$$

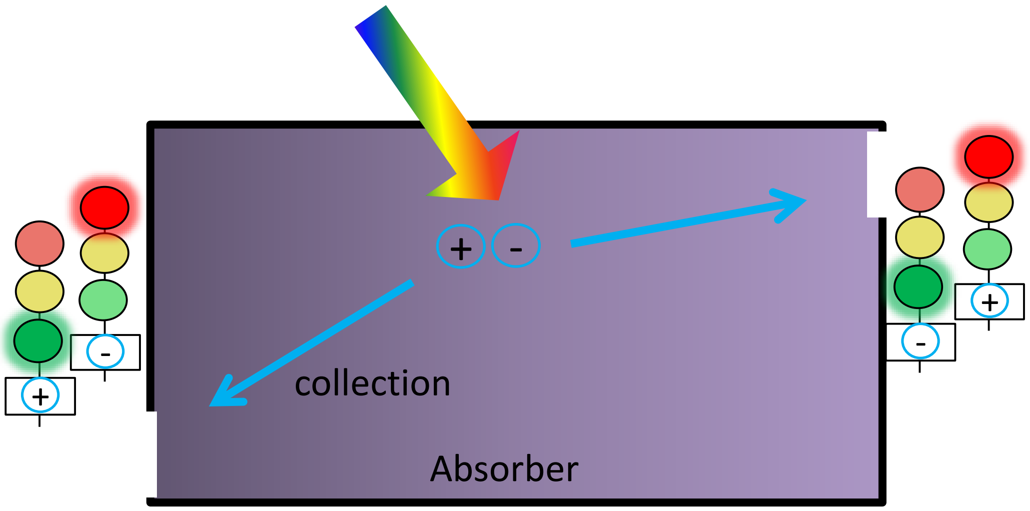
JV-Curve of Ideal Solar Cell with E_g =1.6 eV



→ Diode behavior

From Chemical to Electrical Energy





Requirement:

→Charge selective contacts

From Chemical to Electrical Energy

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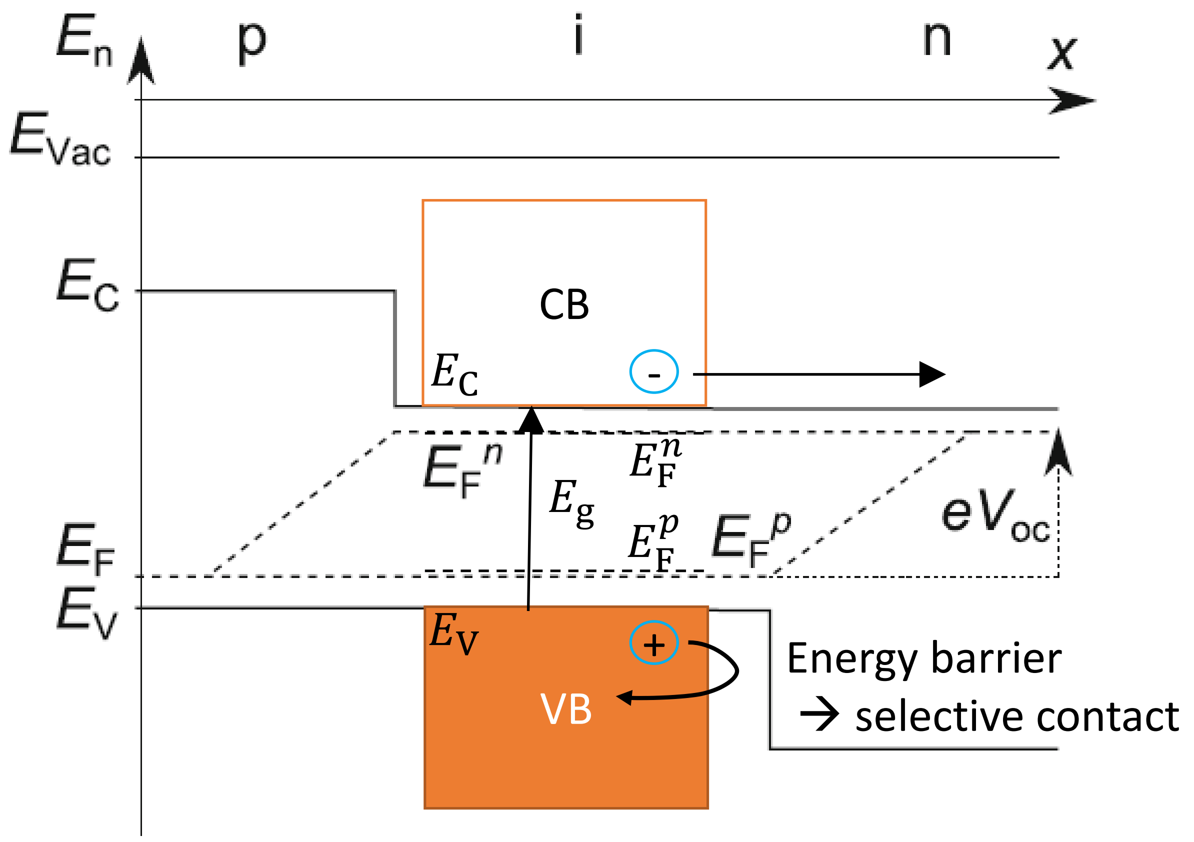
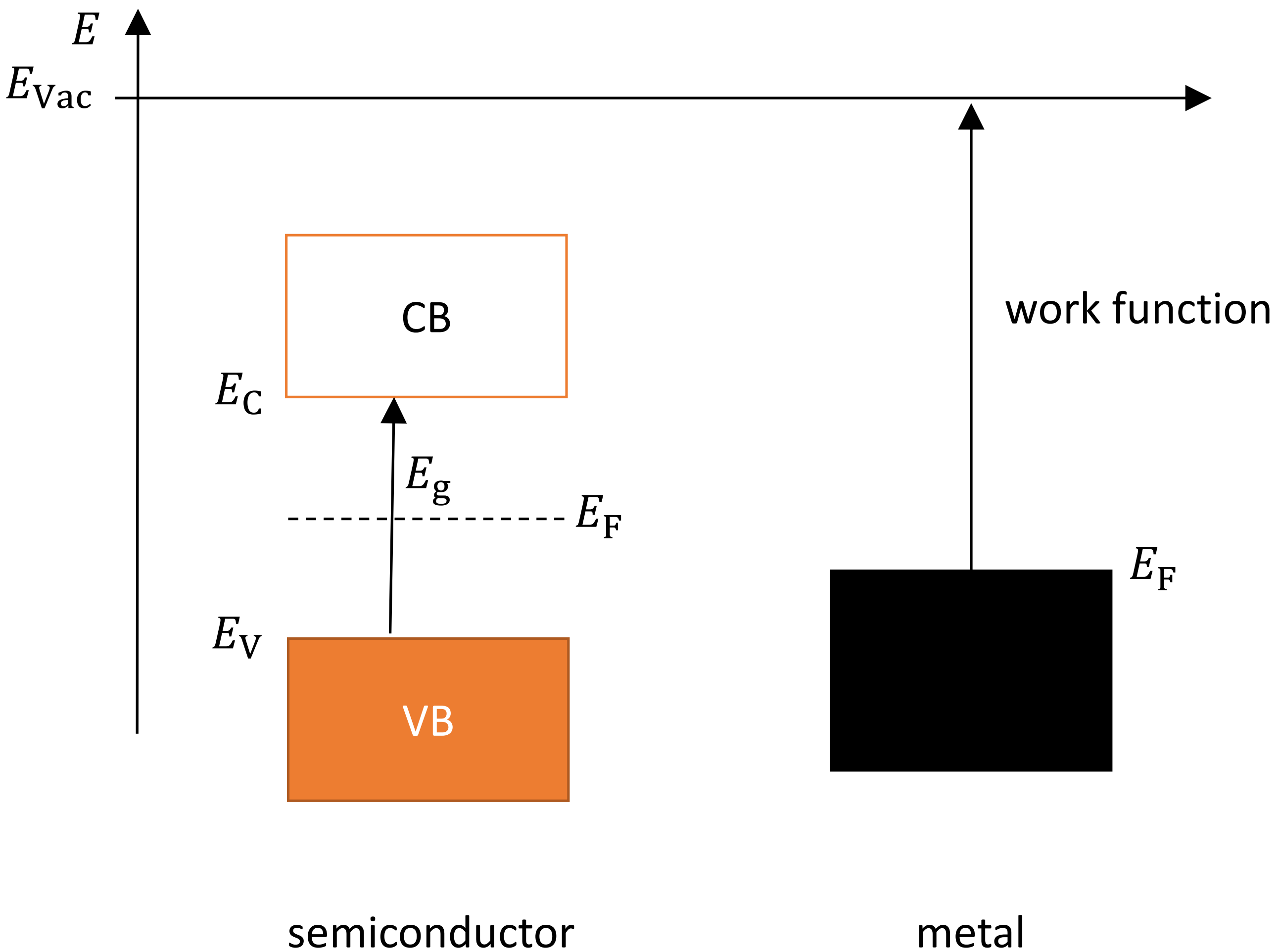
Ideal solar cell structure (Würfel)



Metal Contacts



When put in contact in equilibrium → Fermi levels will align

Doping

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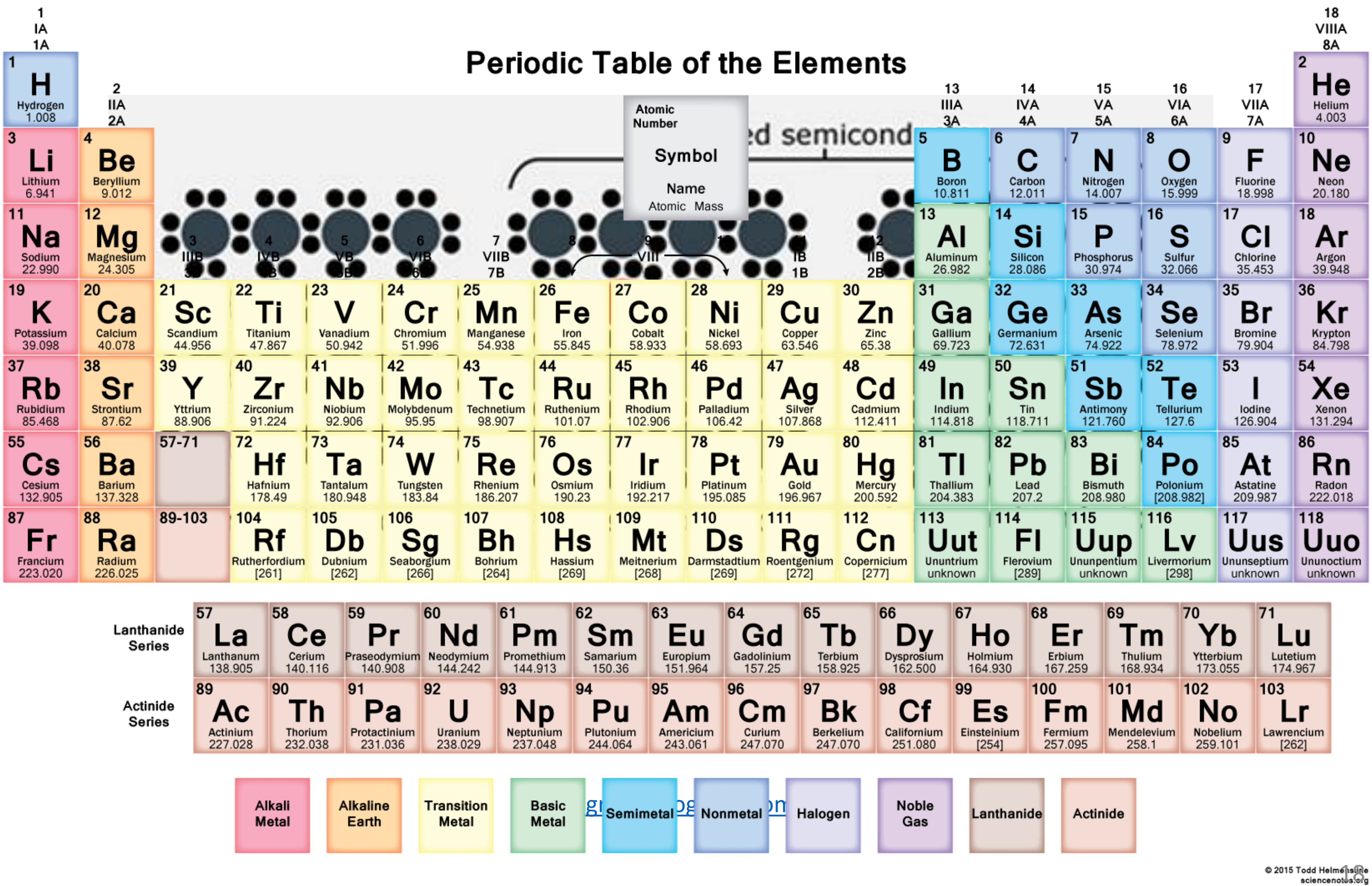
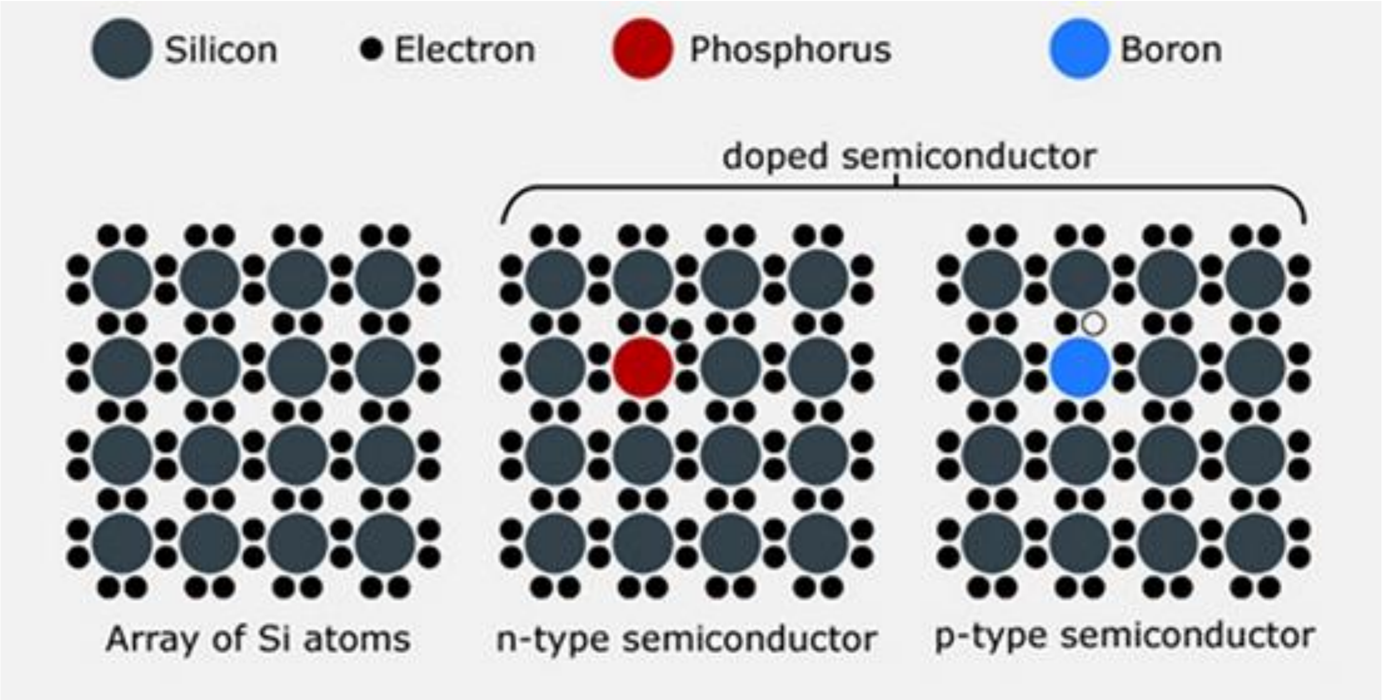
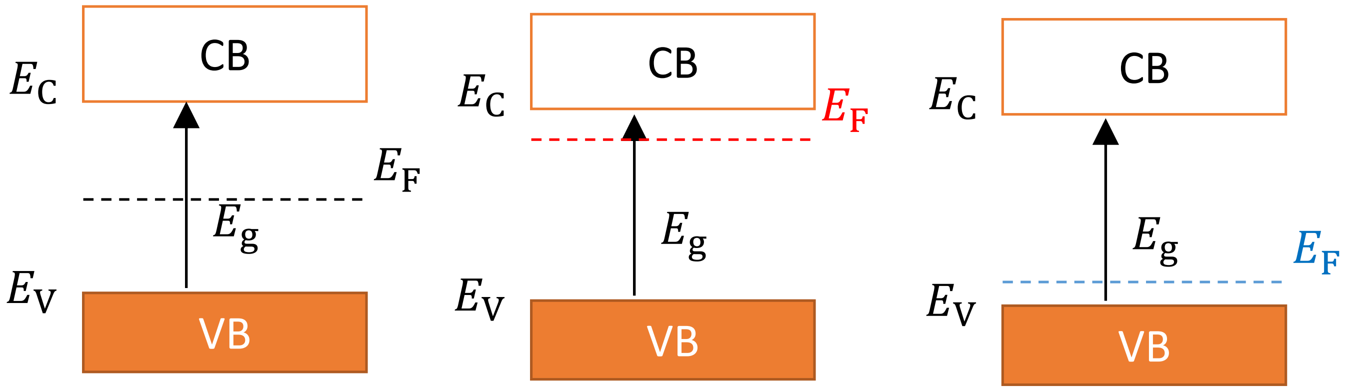
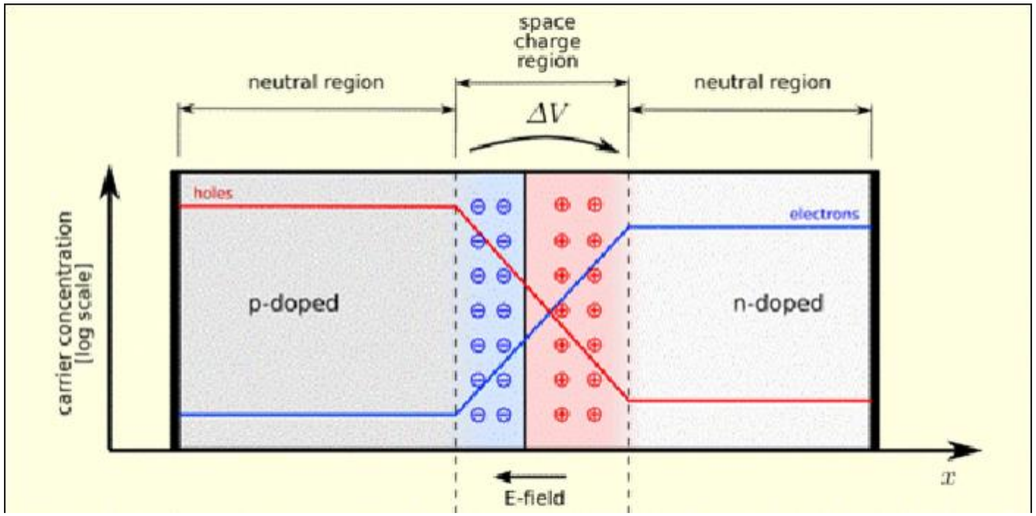


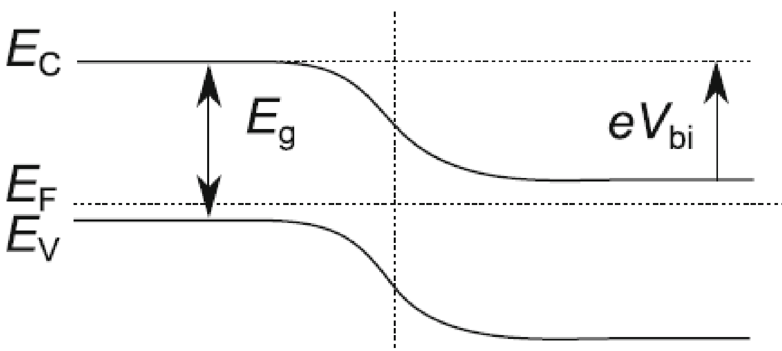
Doping → Fermi Level Shift

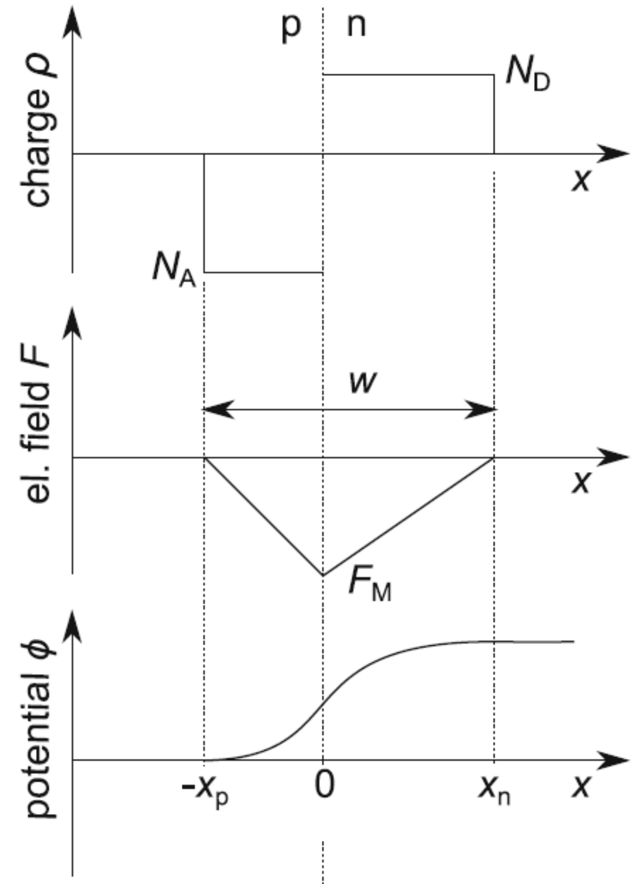




pn Junction







$$J(V) = J_0\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

Metal Semiconductor Junctions I

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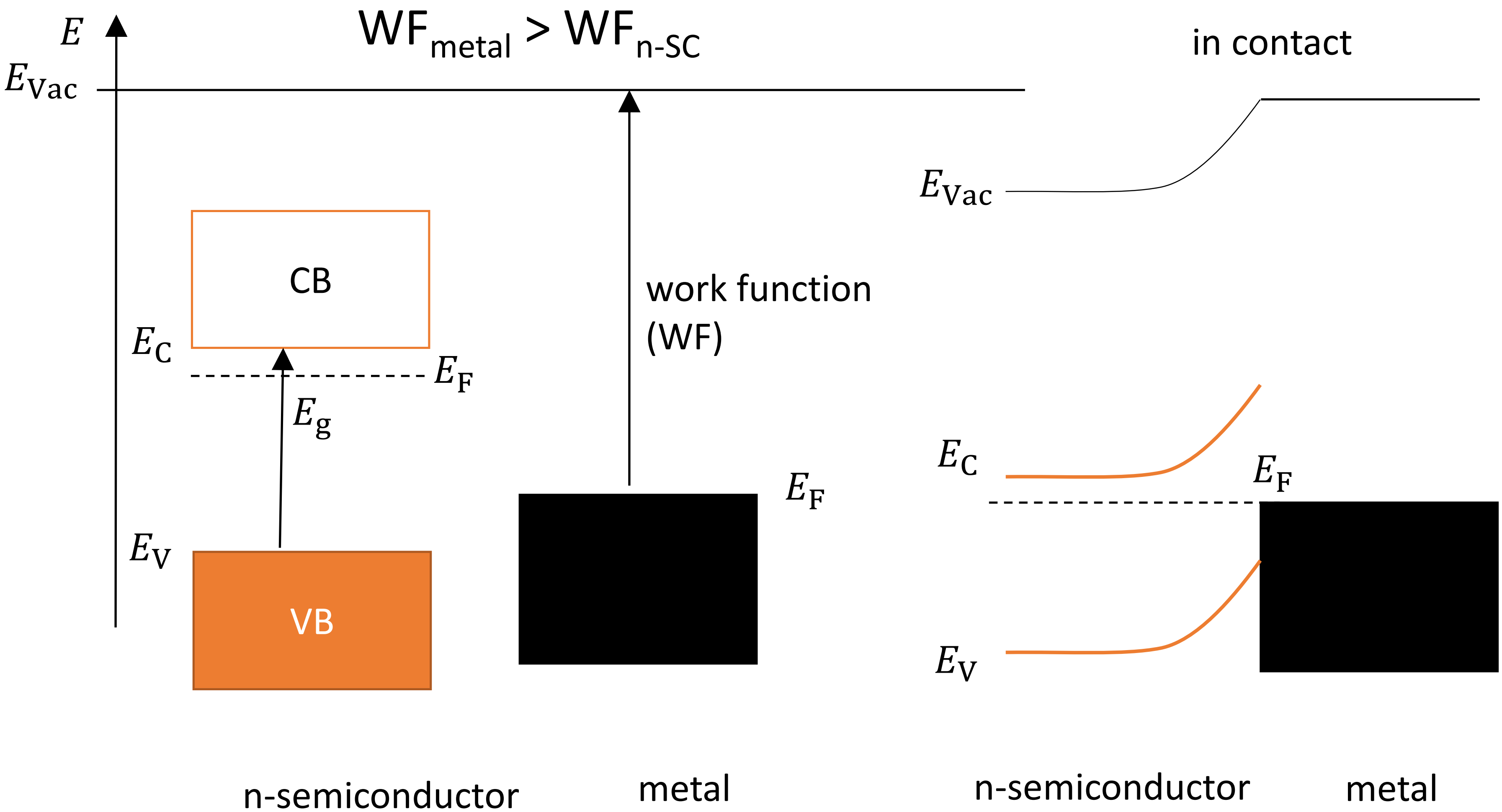
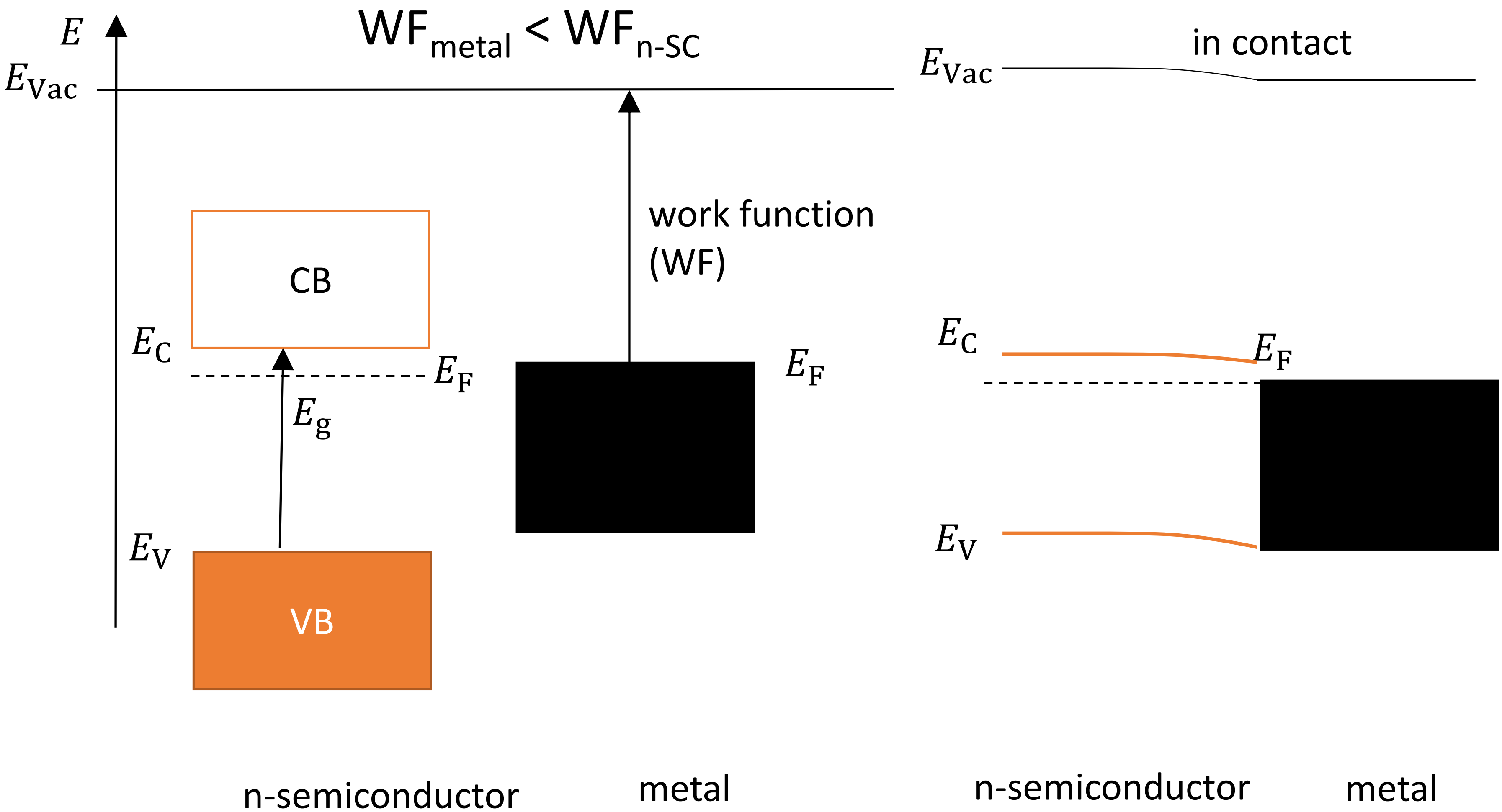


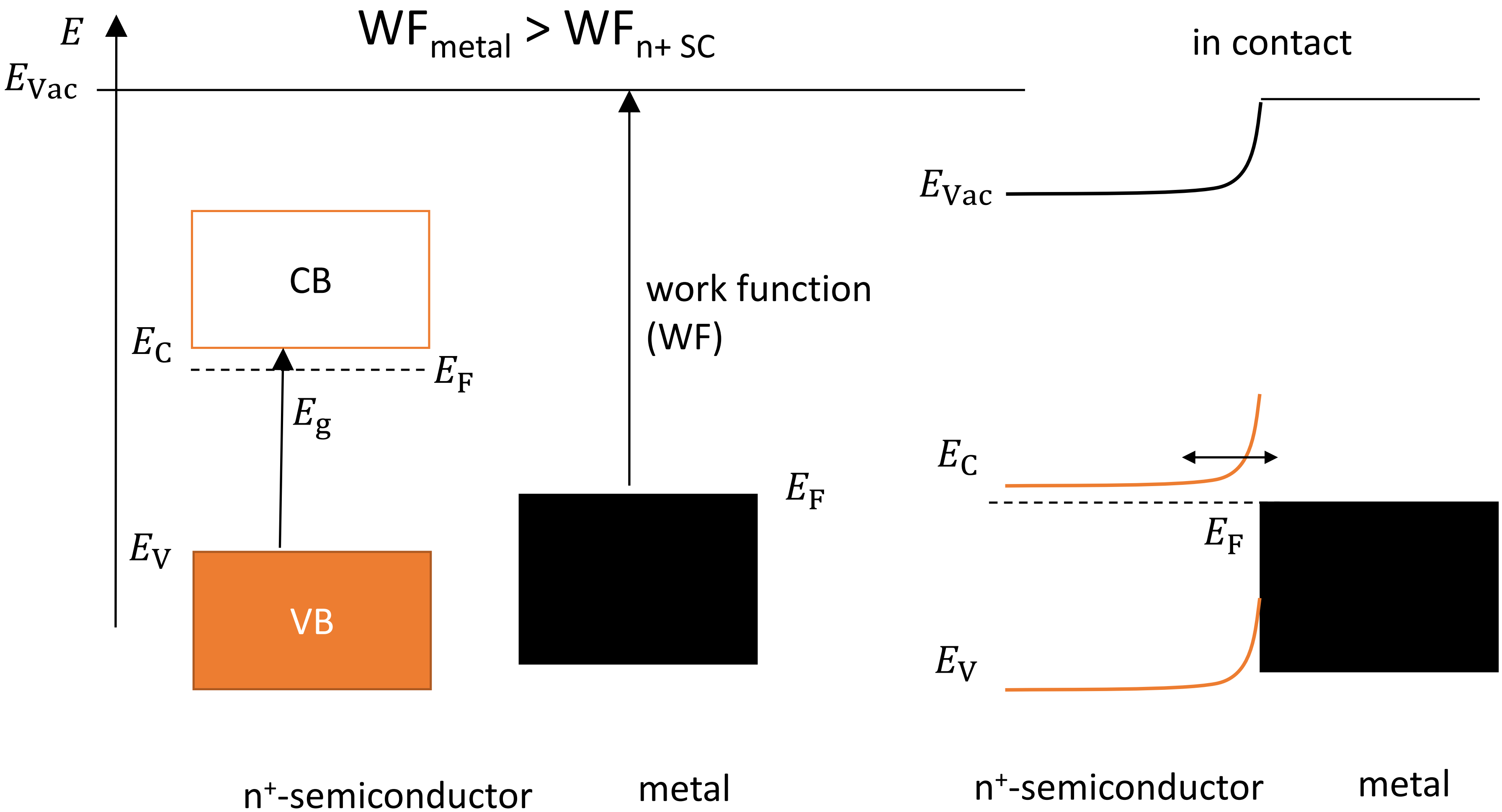
Schottky Contact → Diode

Metal Semiconductor Junctions II



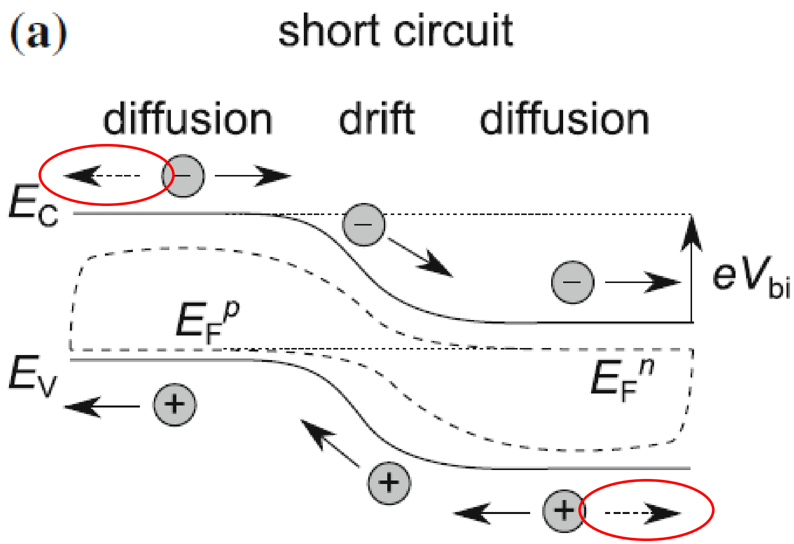
Ohmic Contact

Metal Semiconductor Junctions III



Tunneling junction → Ohmic contact, not selective

Diode under Illumination

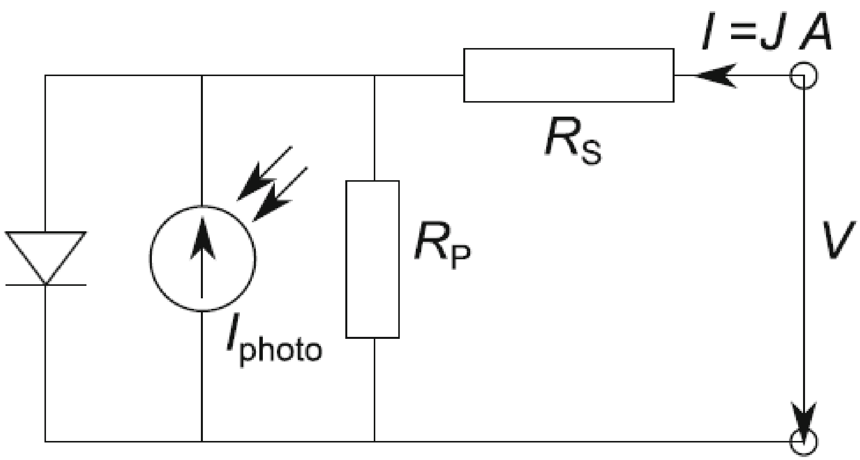


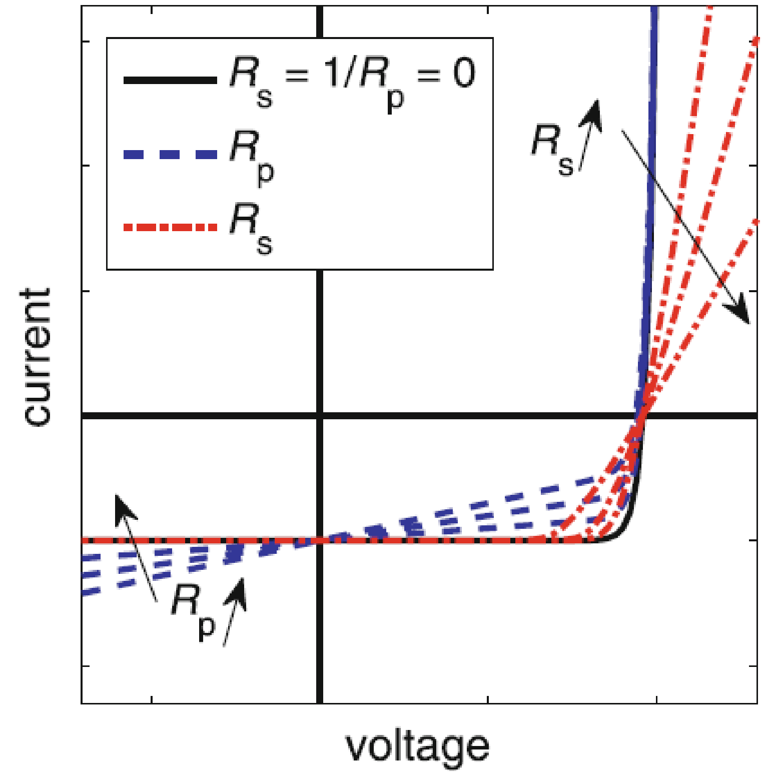
Superposition of dark and photocurrent ($J_{ph}(V) = J_{sc}$):

$$J(V) = J_0\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right) - J_{sc} \qquad V_{oc} = \frac{k_B T}{e}\ln\left(\frac{J_{sc}}{J_0} + 1\right)$$

$$J_{ph}(V) = J_{ph,max} + J_{em,0}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right) \qquad V_{oc,rad} = \frac{k_B T}{e}\ln\left(\frac{J_{ph}}{J_{em,0}} + 1\right)$$

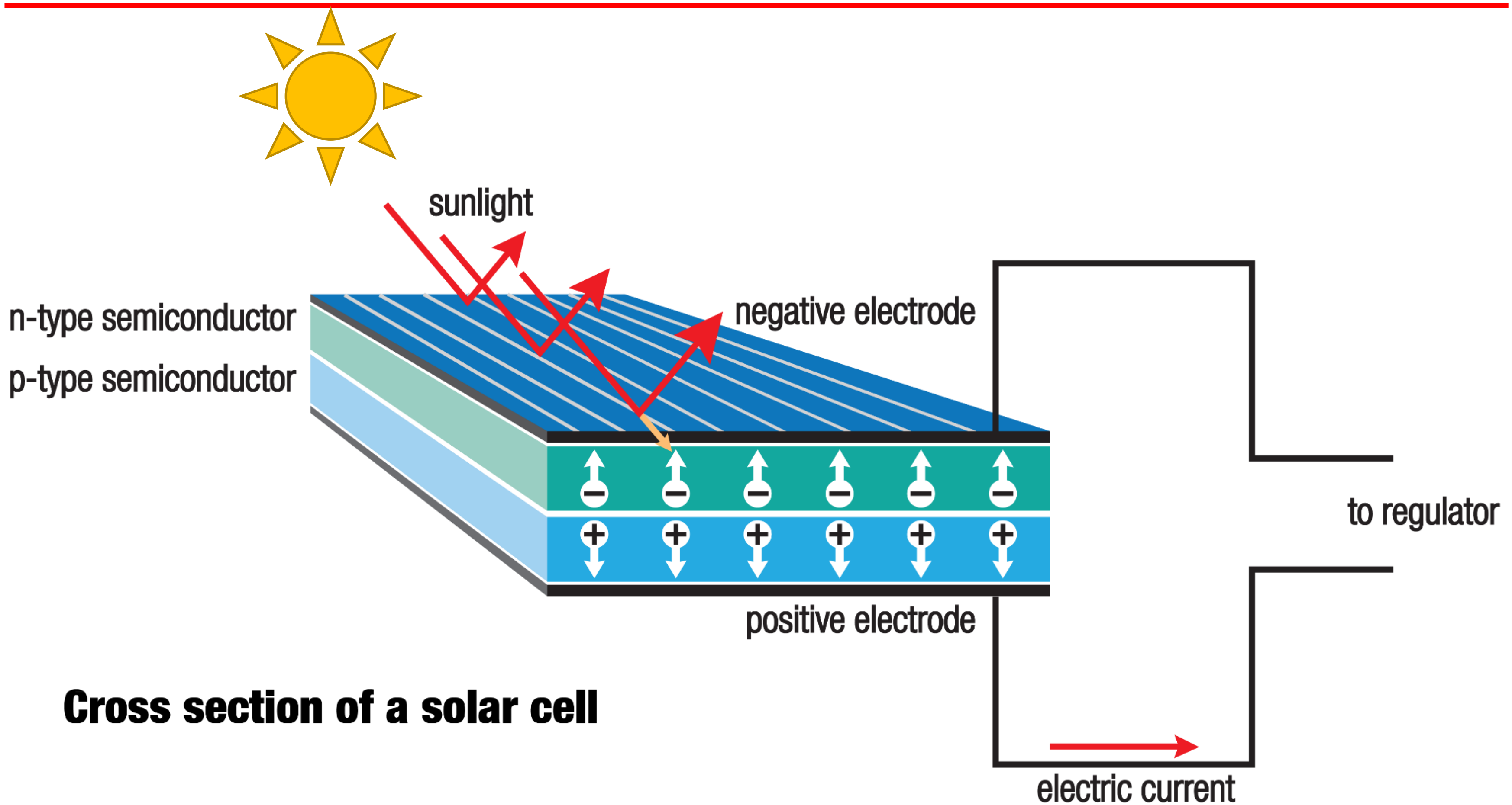
Equivalent Circuit





- Diode
- Current source controlled by light
- Resistances account for:
  - R_s: Voltage loss due to charge transport resistance
  - R_p: Current loss due to shunt paths

Sketch of a Solar Cell



http://www.redarc.com.au/solar/about/solarpanels/

Realization: Which material?

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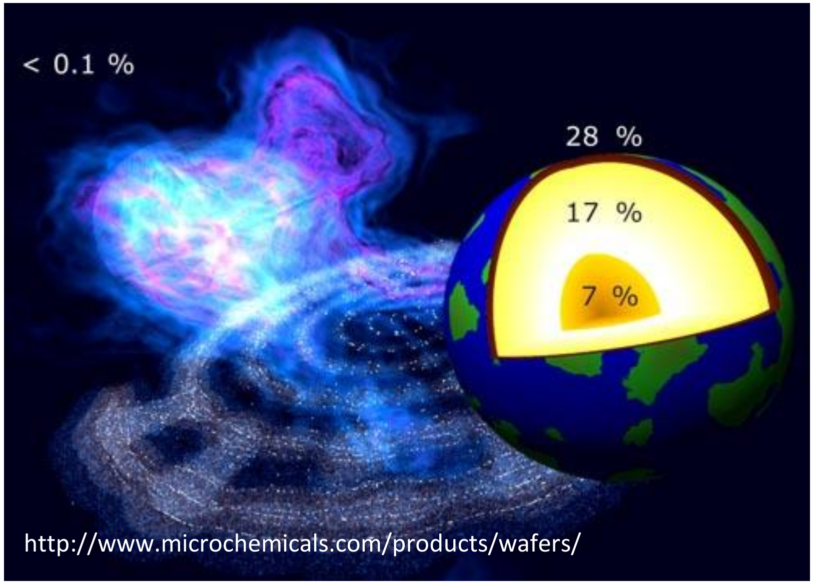
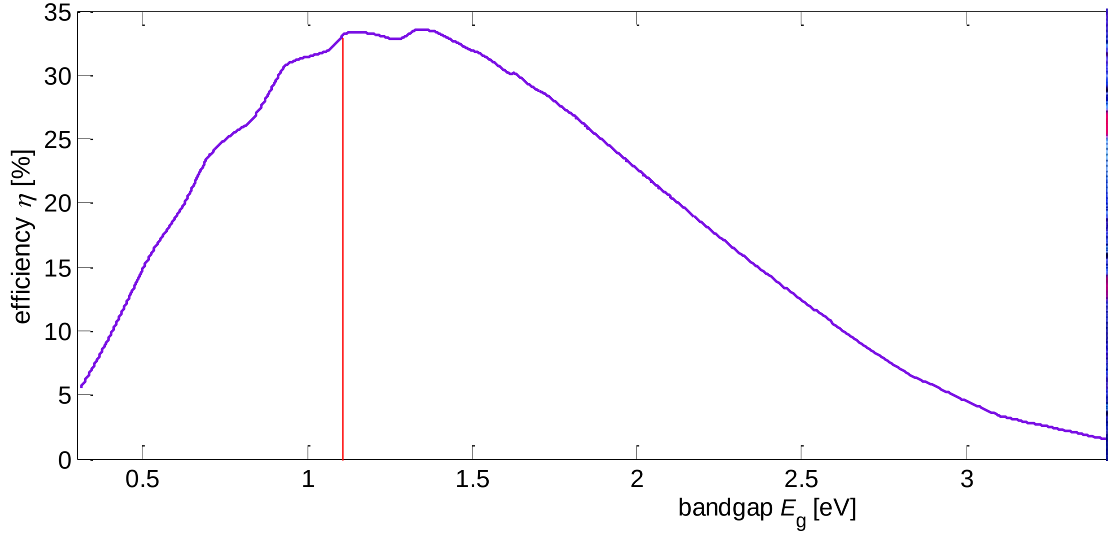
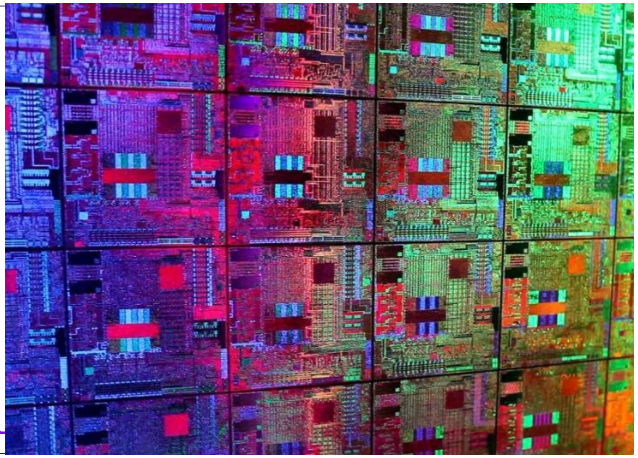
Silicon: Why?

- E_g is suitable
- Doping is possible
- Mostly used in microelectronics
- Native oxide as passivation layer
- Abundant and non-toxic



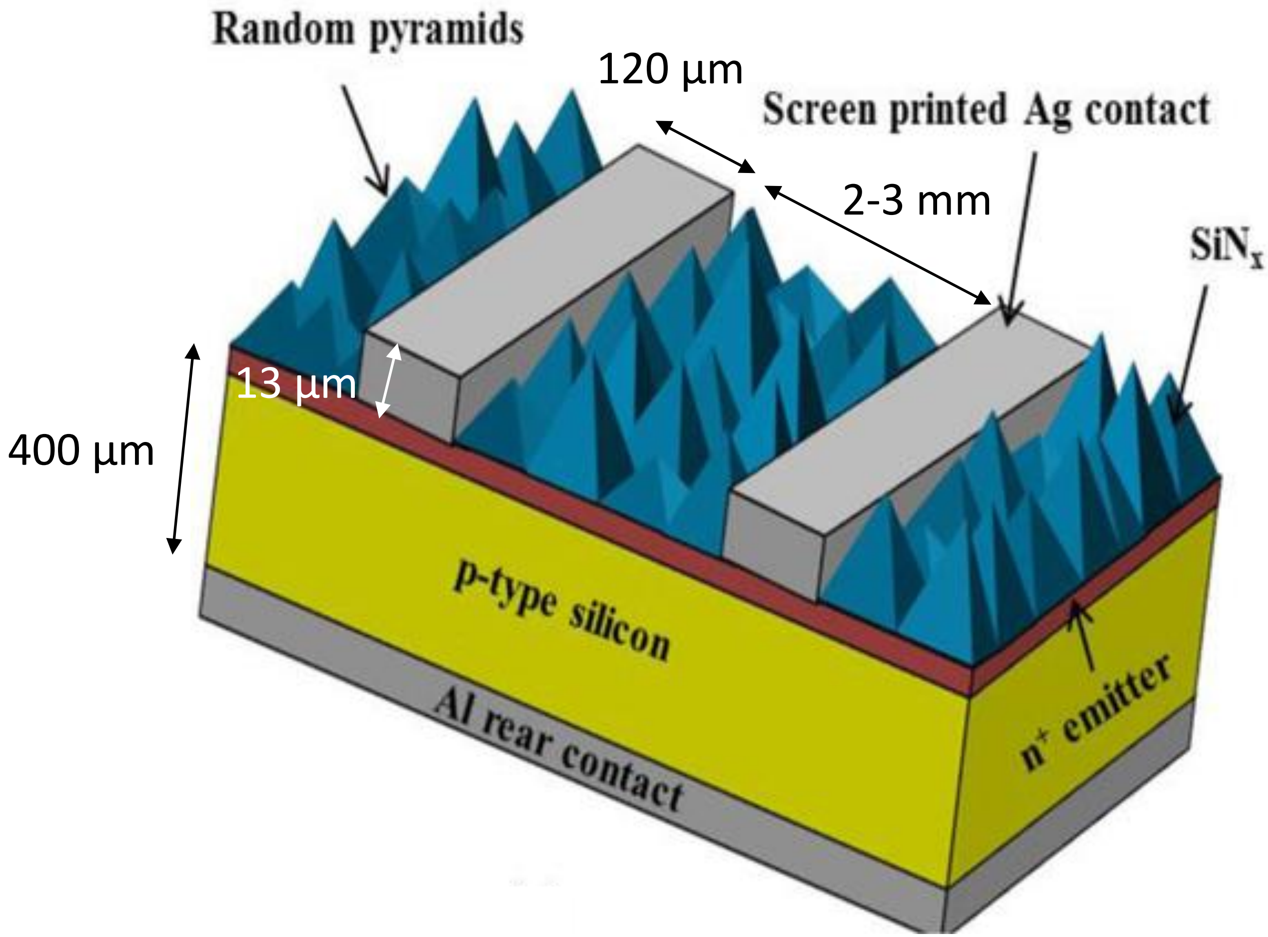




Crystalline Silicon Solar Cells

inhabitat.com

Basic Structure of Silicon Solar Cell

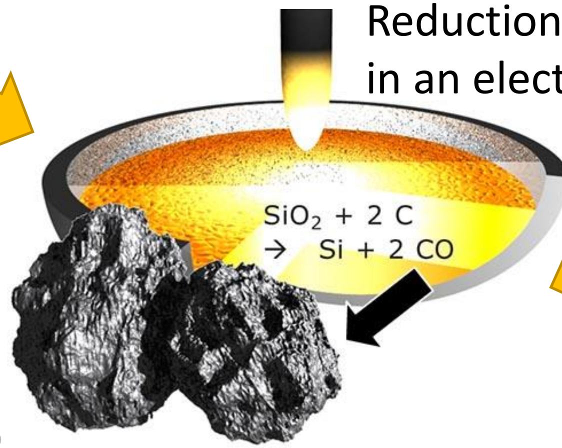


http://www.mdpi.com/1996-1944/7/2/1318/htm

From Sand to Solar: The Ingot

SiO_2

Reduction of SiO_2 with carbon in an electric arc furnace



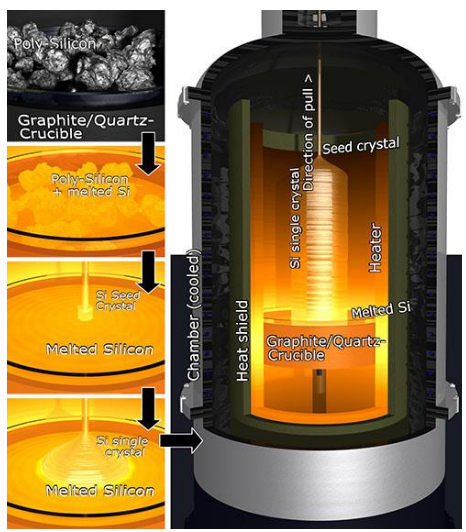
metallurgical grade silicon (> 98 % pure)

Purification of Silicon (Siemens Process)

$Si + 3\,HCl \rightarrow HSiCl_3 + H_2$

Electronic grade poly silicon (impurities < 10^{14} cm^{-3})

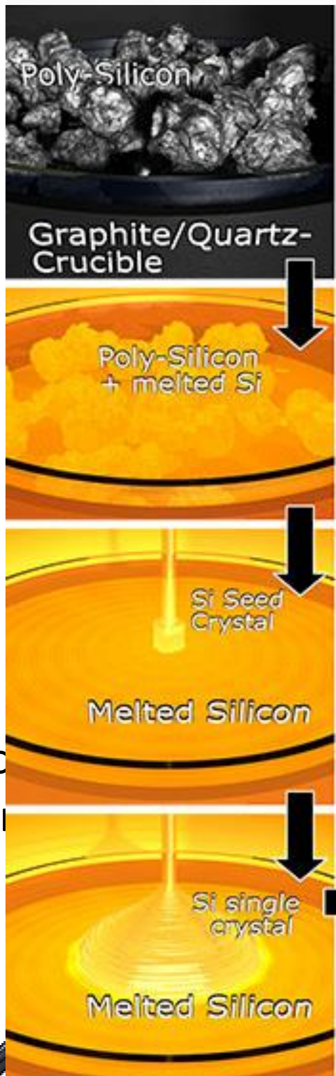
Czochralski (CZ)
Alternative: FZ

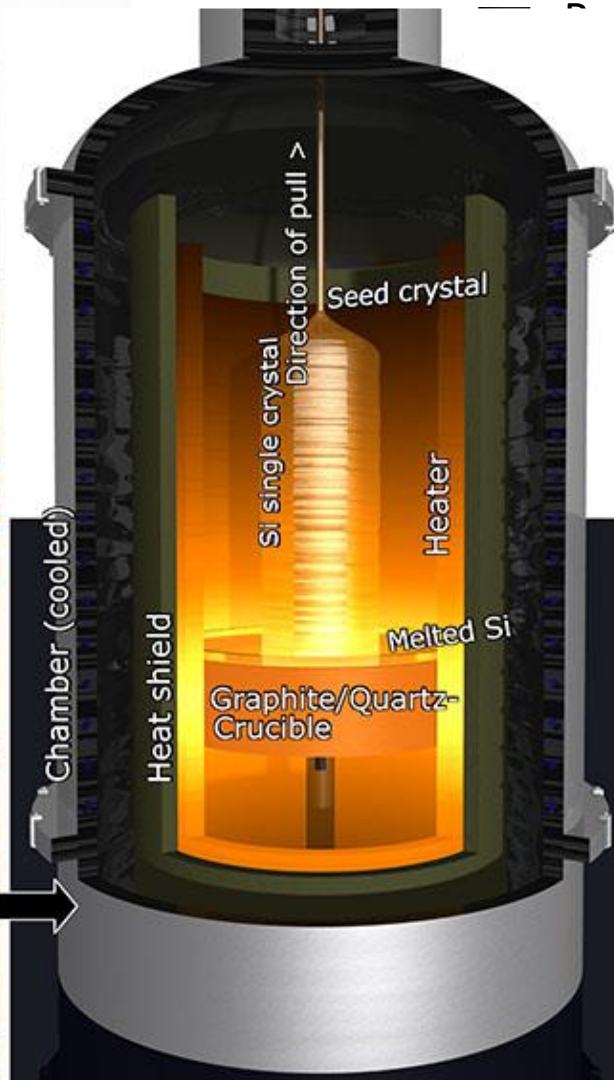


crystalline ingot

http://www.microchemicals.com/products/wafers/from_quartz_sand_to_electronic_grade_si.html

From Sand to Solar: The Ingot





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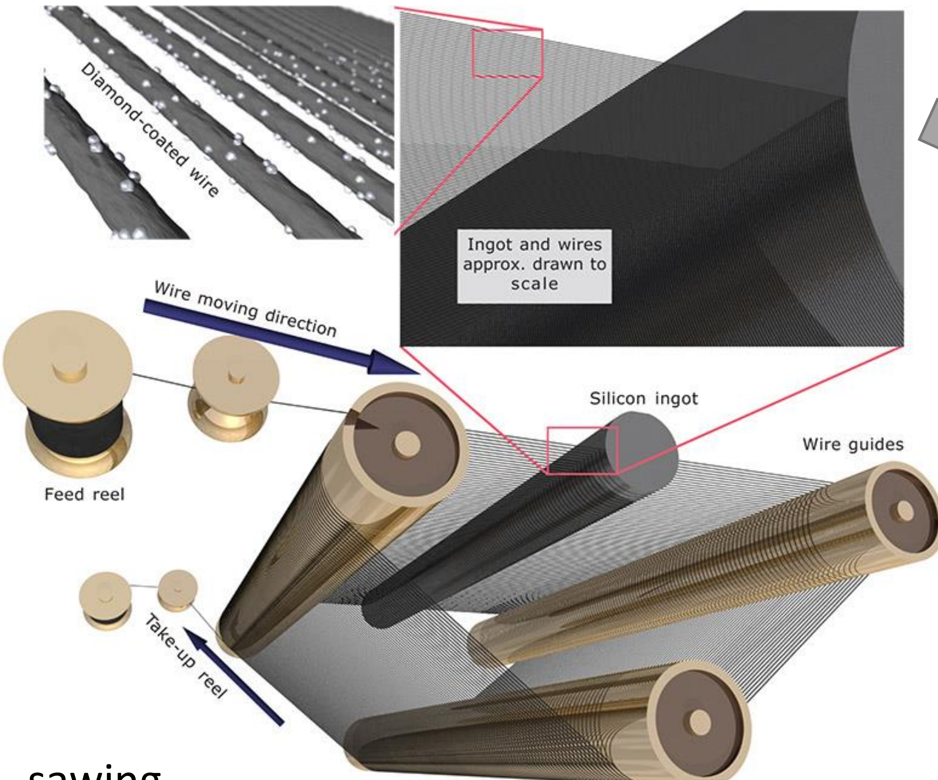
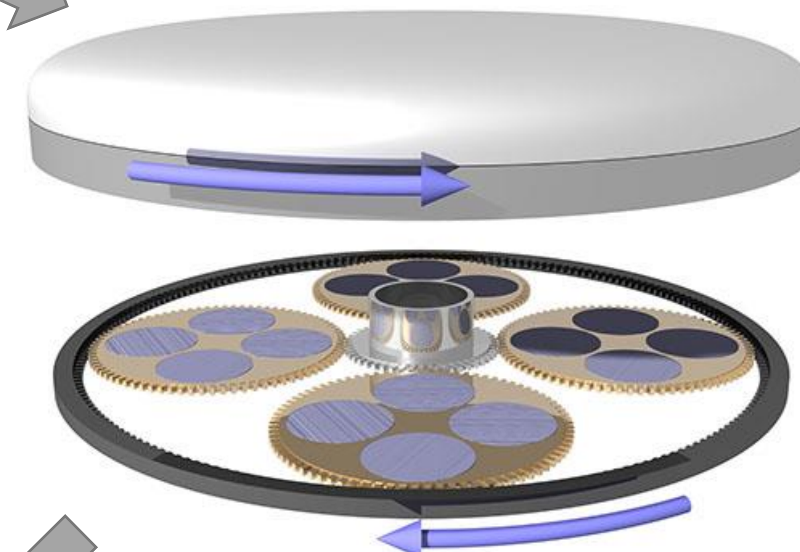
http://www.microchemicals.com/products/\

From Sand to Solar: The Wafer

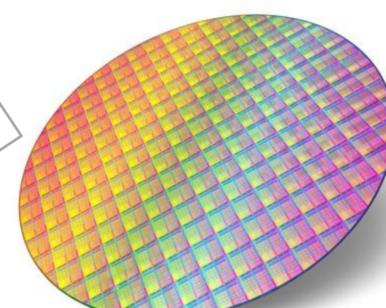


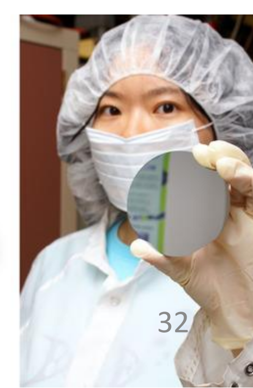
sawing

lapping, polishing

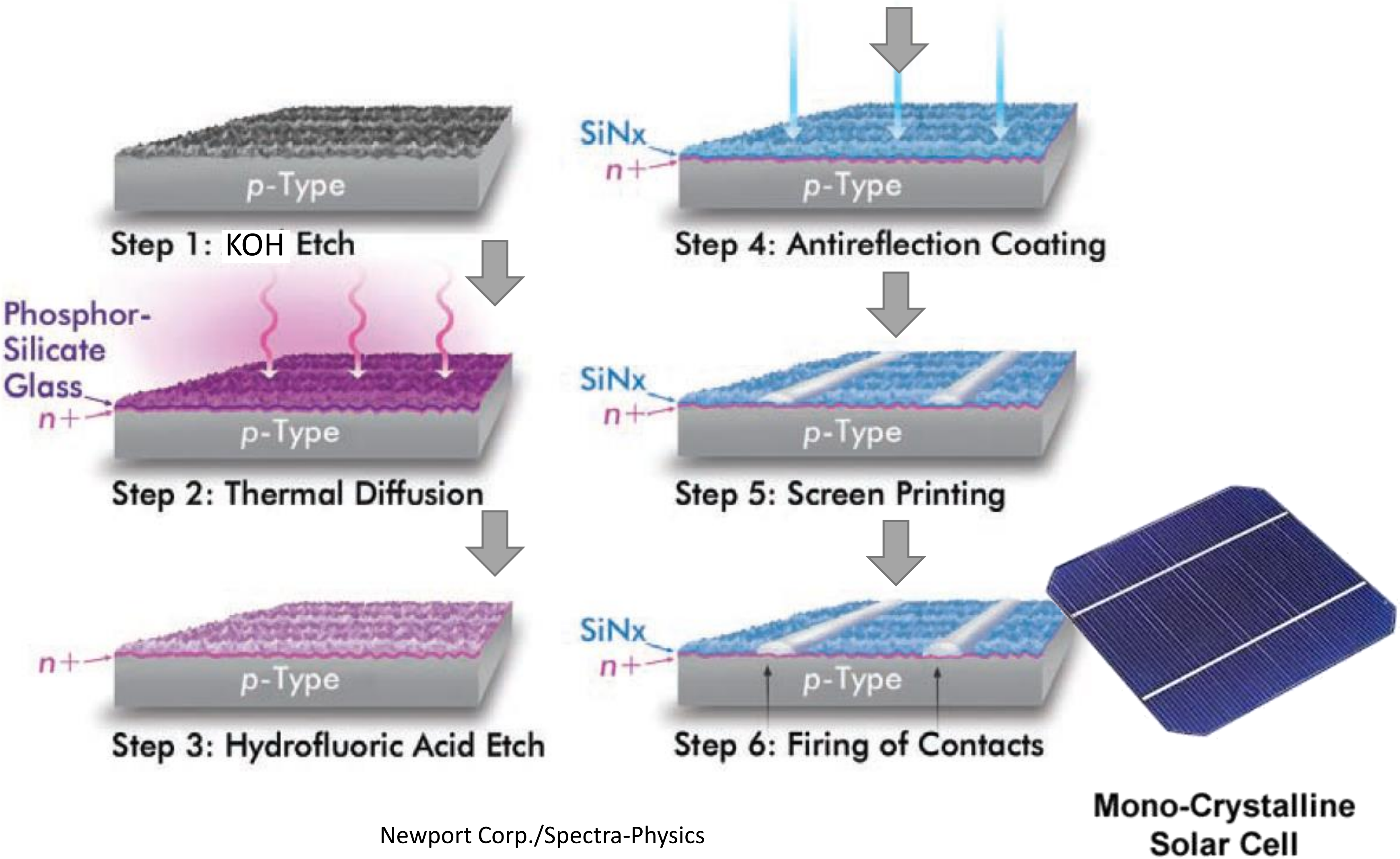


wafer



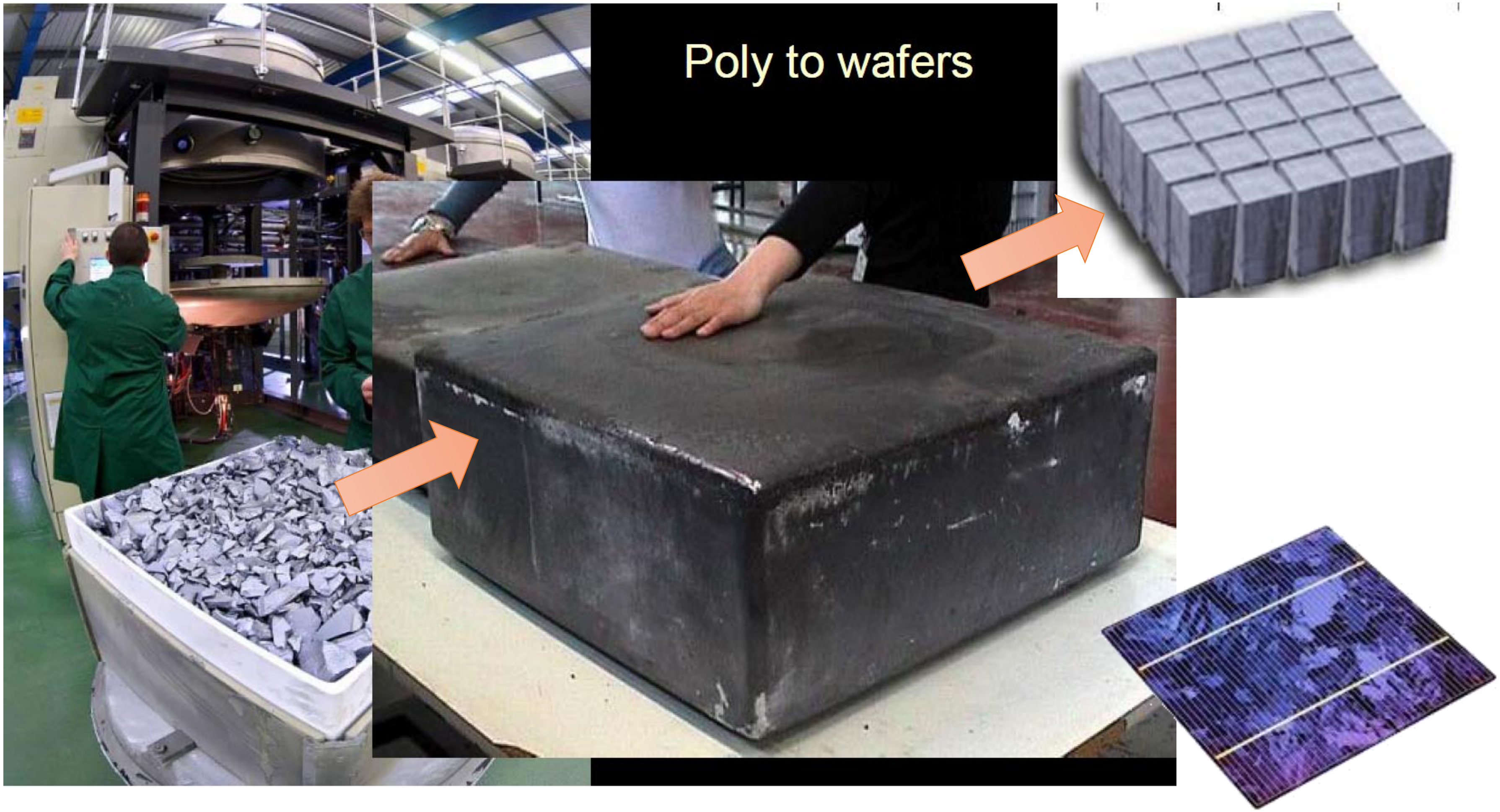


From Sand to Solar: The Solar Cell



Newport Corp./Spectra-Physics

Multicrystalline Solar Cell

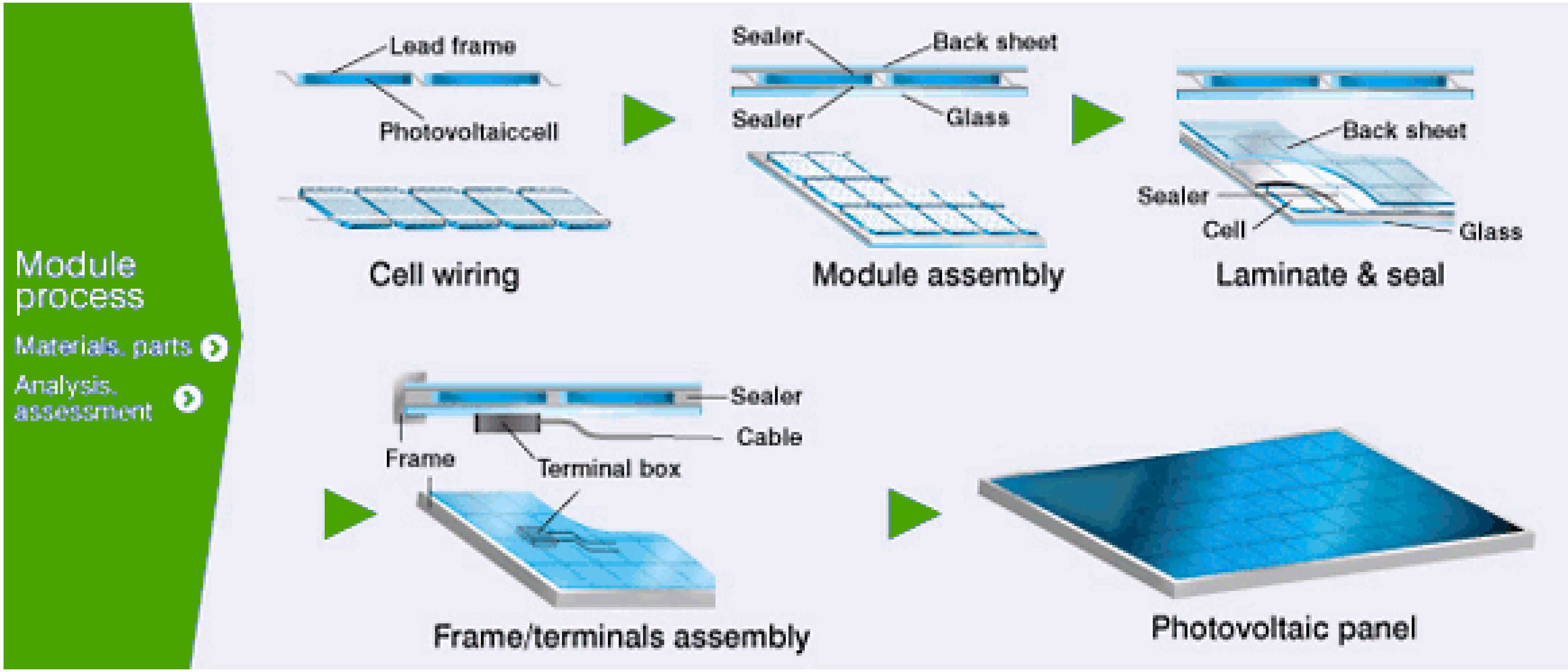


Martin Green

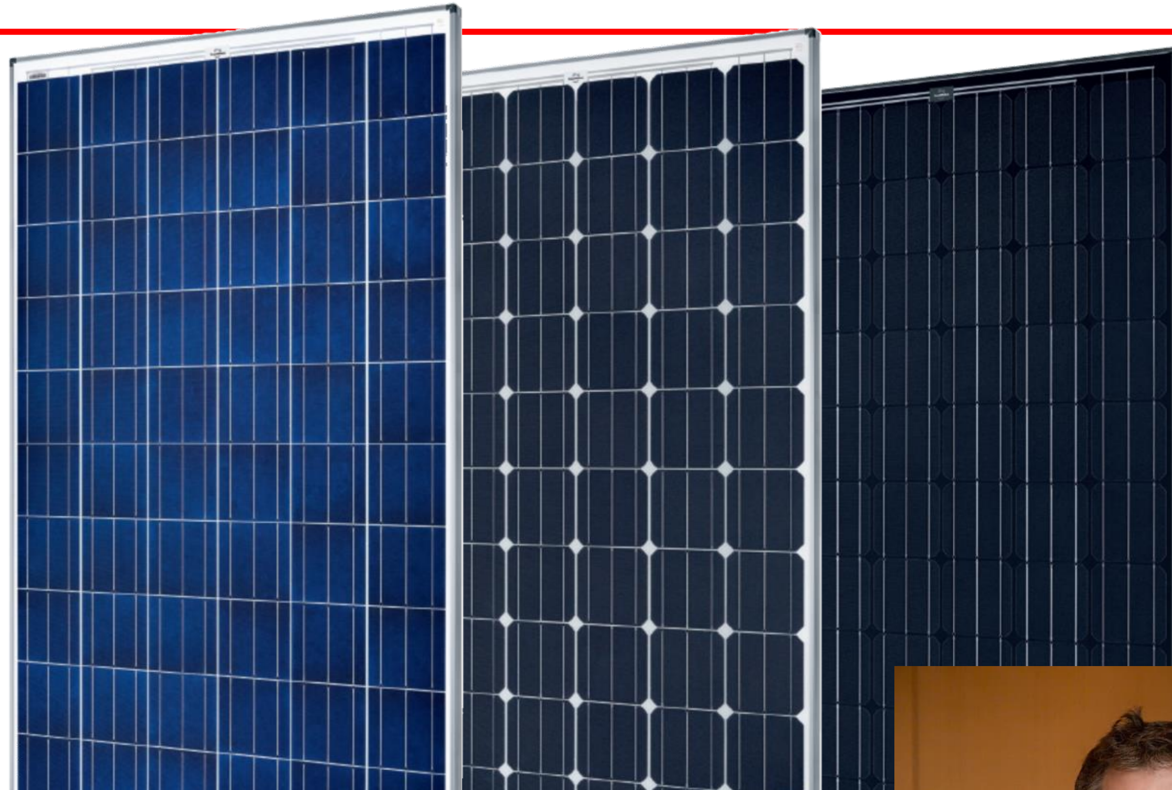
Poly-Crystalline Solar Cell

From Sand to Solar: The Module

www.think-solar-power.com



Modules



DIMENSIONS / WEIGHT

Length	1675 mm
Width	1001 mm
Height	33 mm
Weight	18.0 kg

SolarWorld

	SW 260	SW 285
Maximum power	260 Wp	285 Wp
Open circuit voltage	38.4 V	39.7 V
Maximum power point voltage	31.4 V	31.3 V
Short circuit current	8.94 A	9.84 A
Maximum power point current	8.37 A	9.2 A
Module efficiency	15.51 %	17.0 %

From Sand to Solar: The PV Installation

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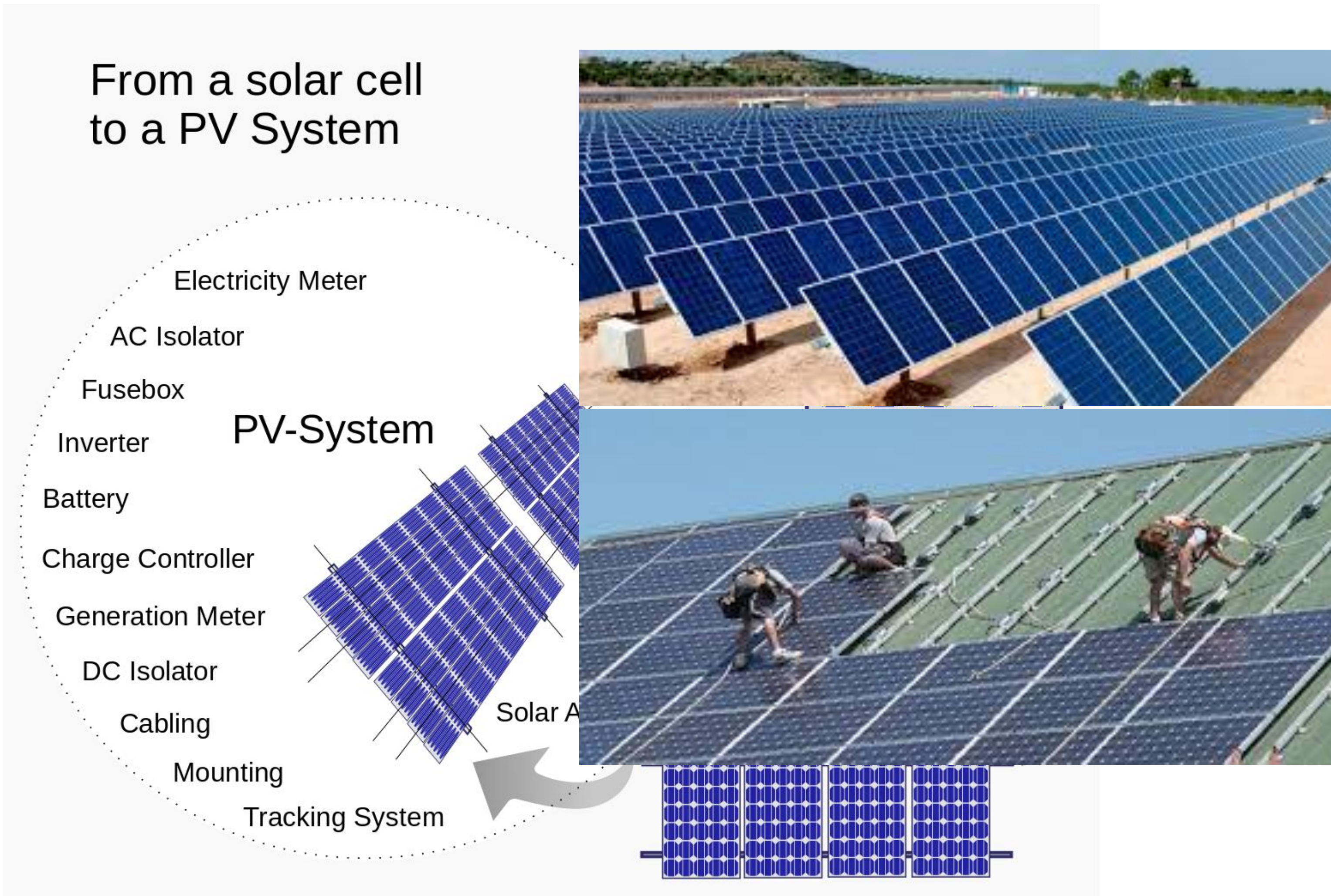

wikipeda

Different Architectures

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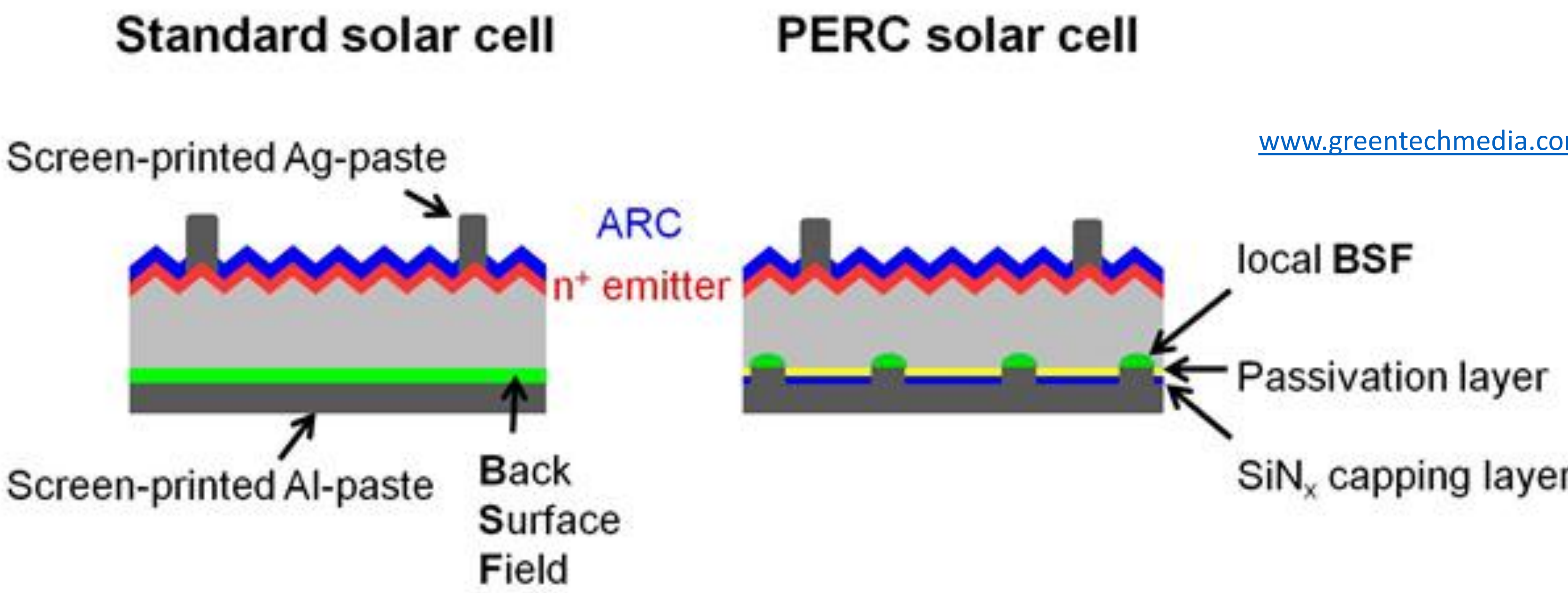
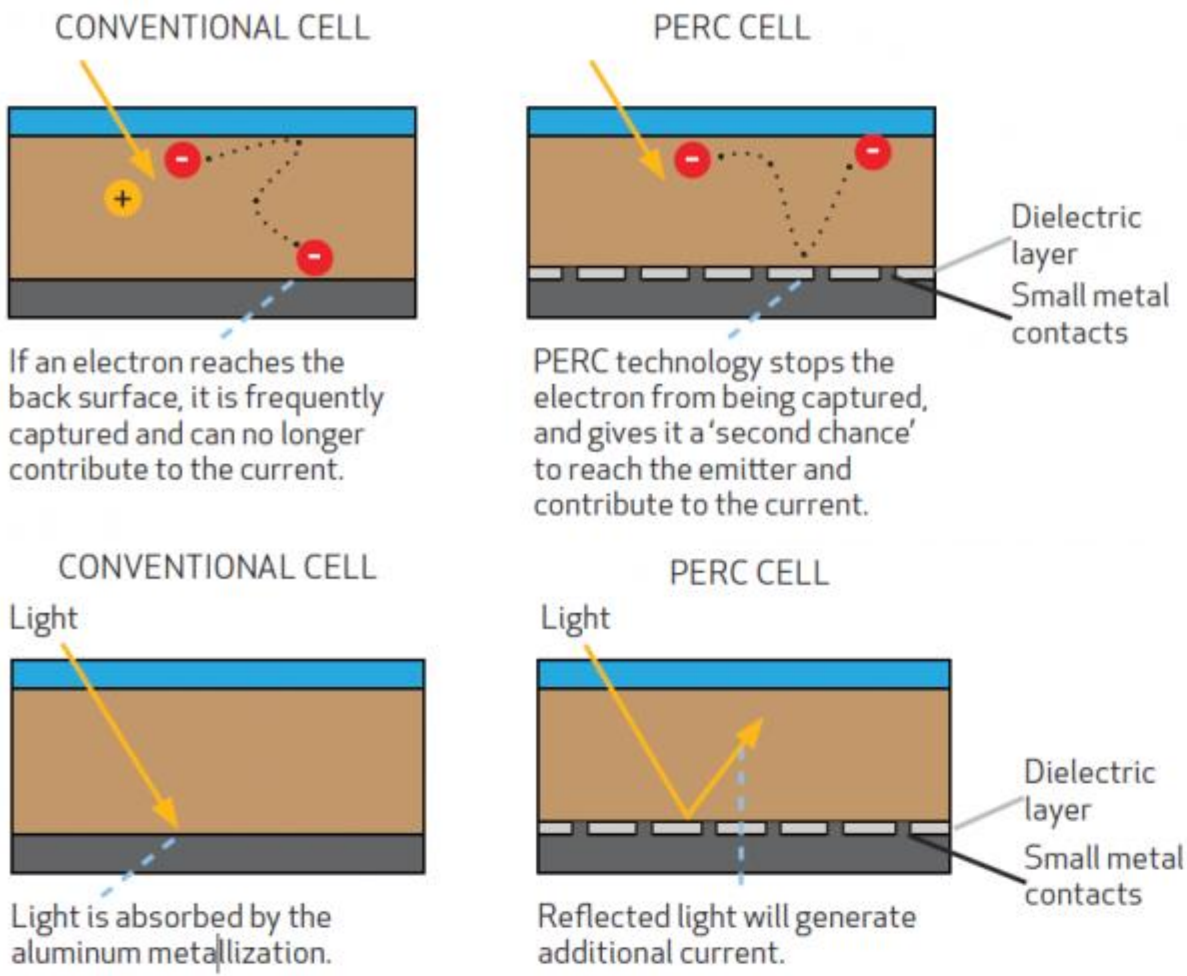


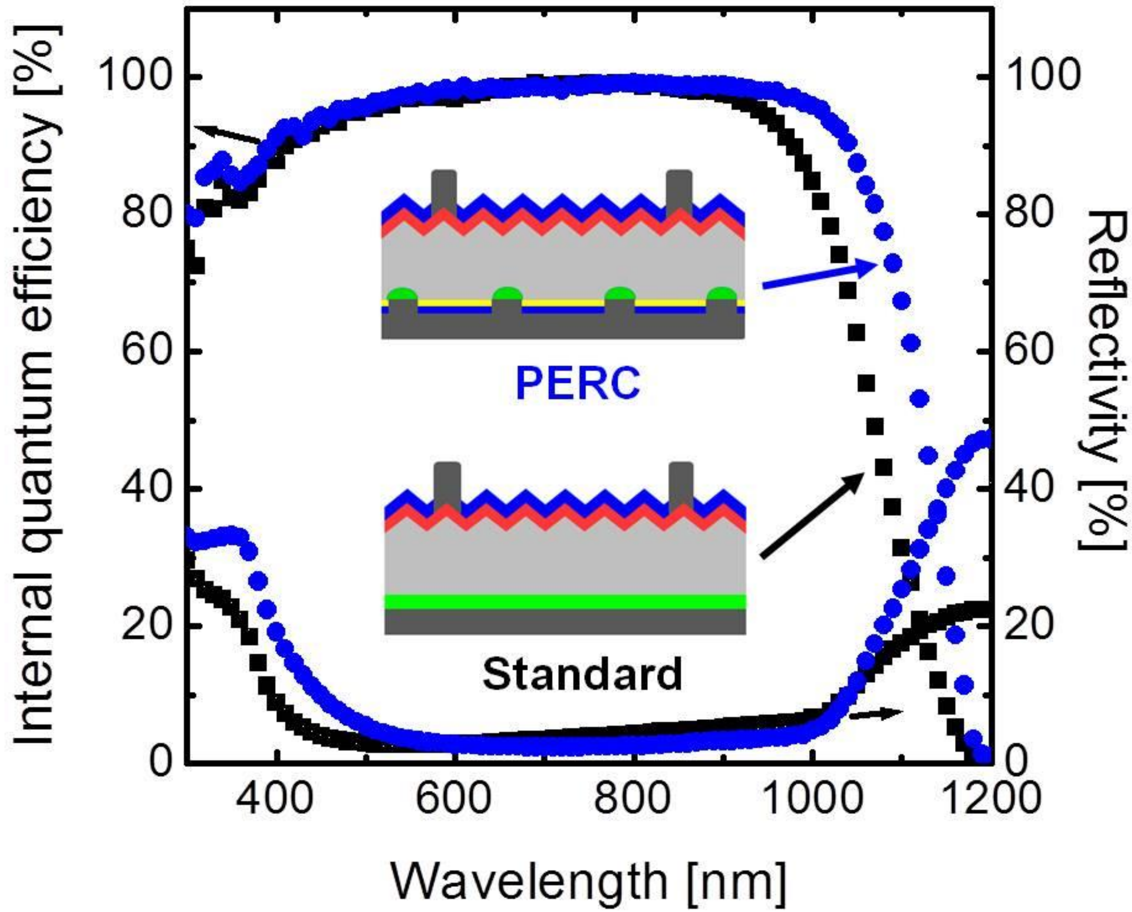
www.greentechmedia.com

Different Architectures: PERC



Different Architectures: PERC

www.pv-magazine.com/news/details/beitrag/unsw-hits-194-percent-on-mass-produced-solar-cell---what-next_100003631/#axzz47sdUyPzSa



Different Architectures: Bifacial Module

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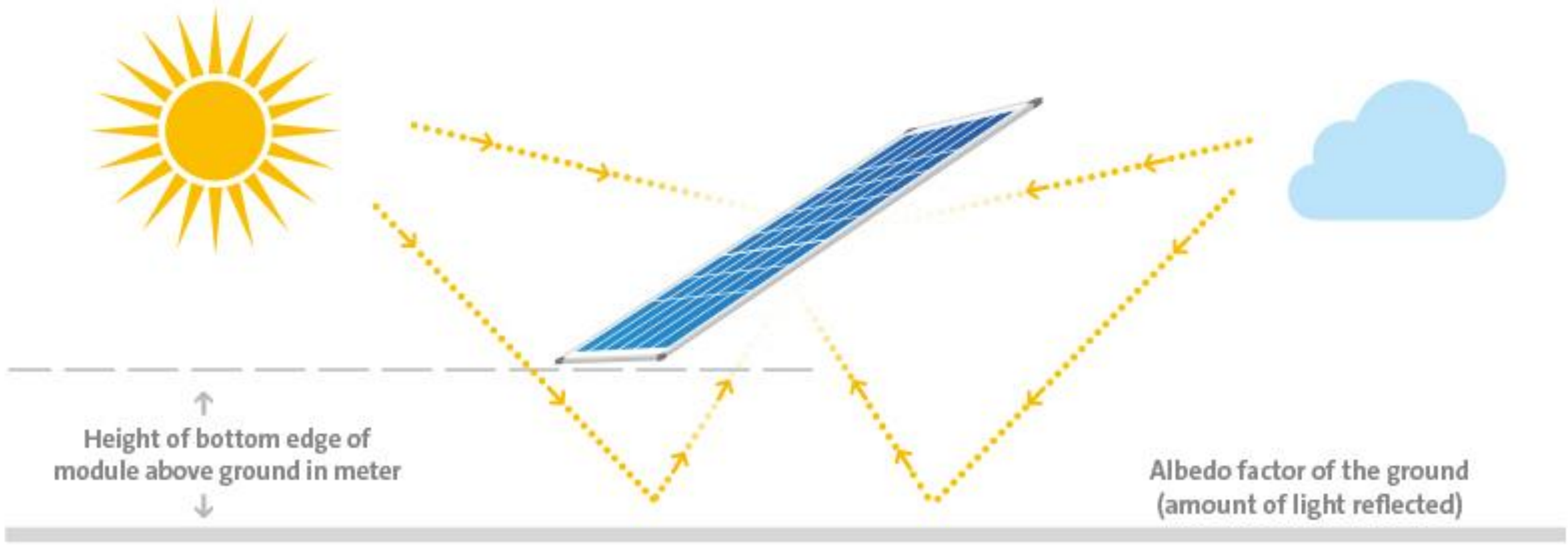

Different Architectures

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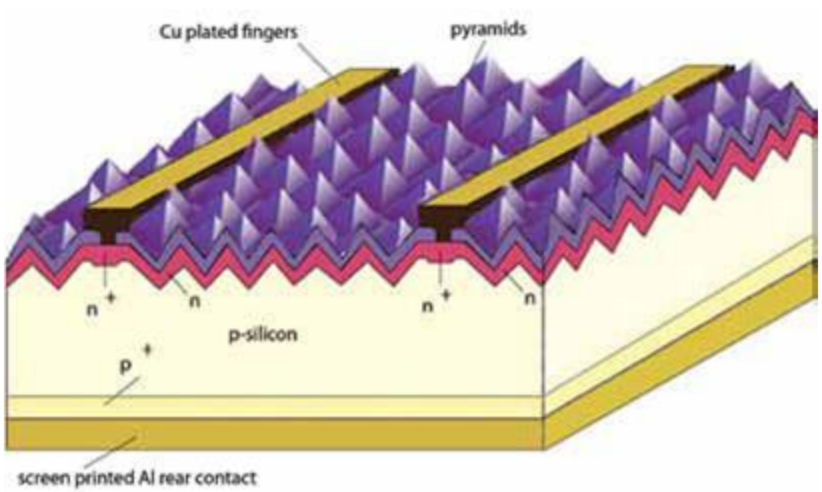
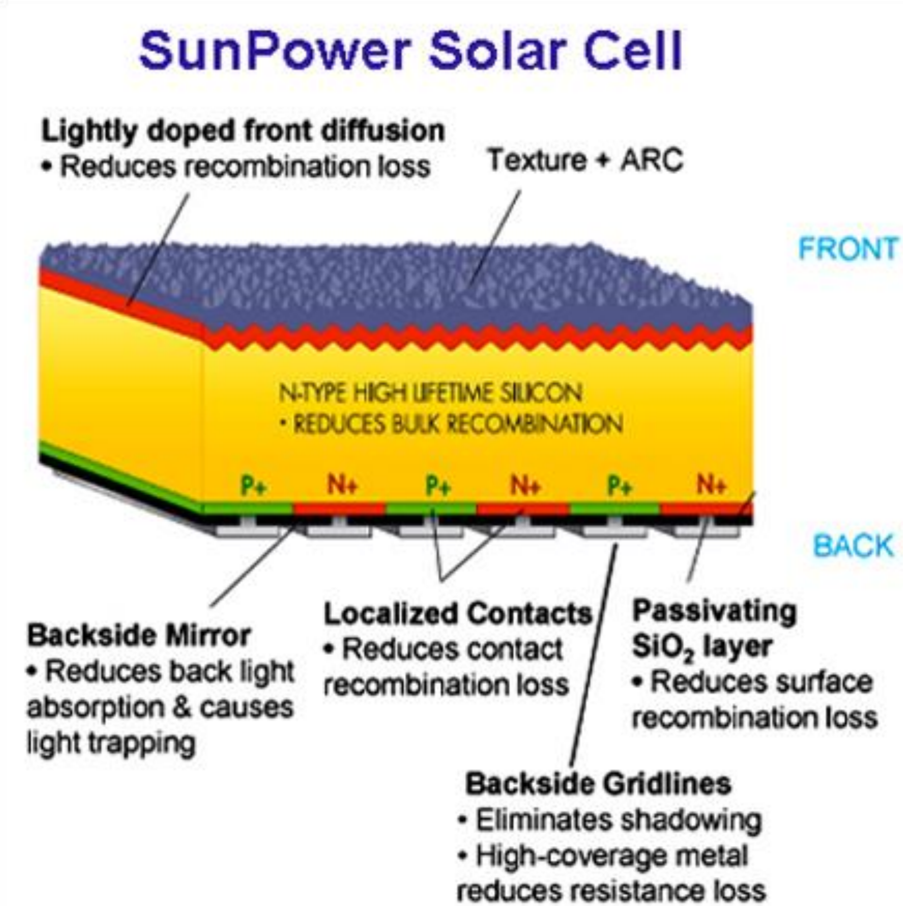
Laser-doped selective contact



http://www.pv-magazine.com/news/details/beitrag/unsw-hits-194-percent-on-mass-produced-solar-cell---what-next_100003631/#axzz47sdUyPzSa

Interdigitated back contact design (IBC)



http://solarcellcentral.com/companies_page.html

History and Record Lab Efficiencies

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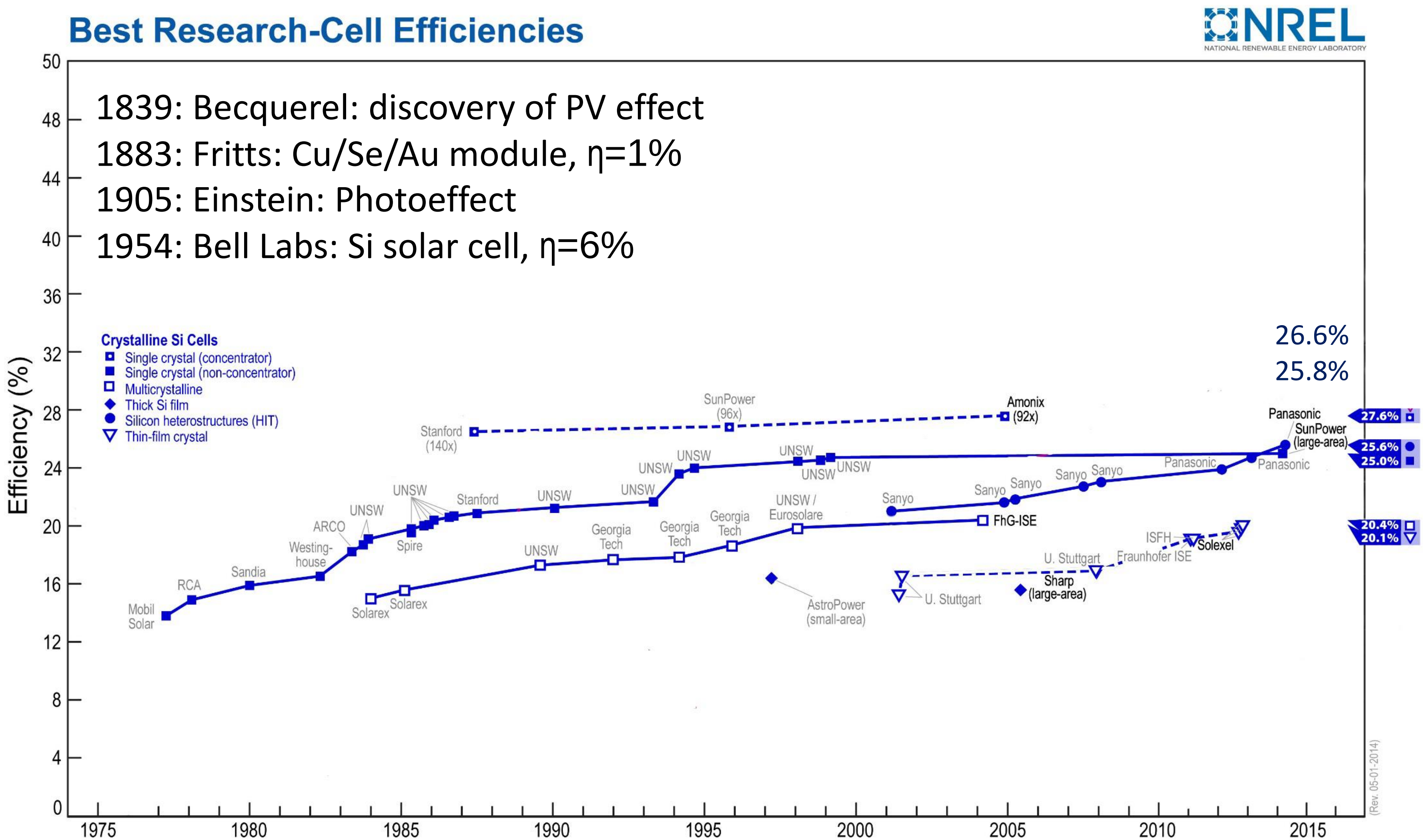
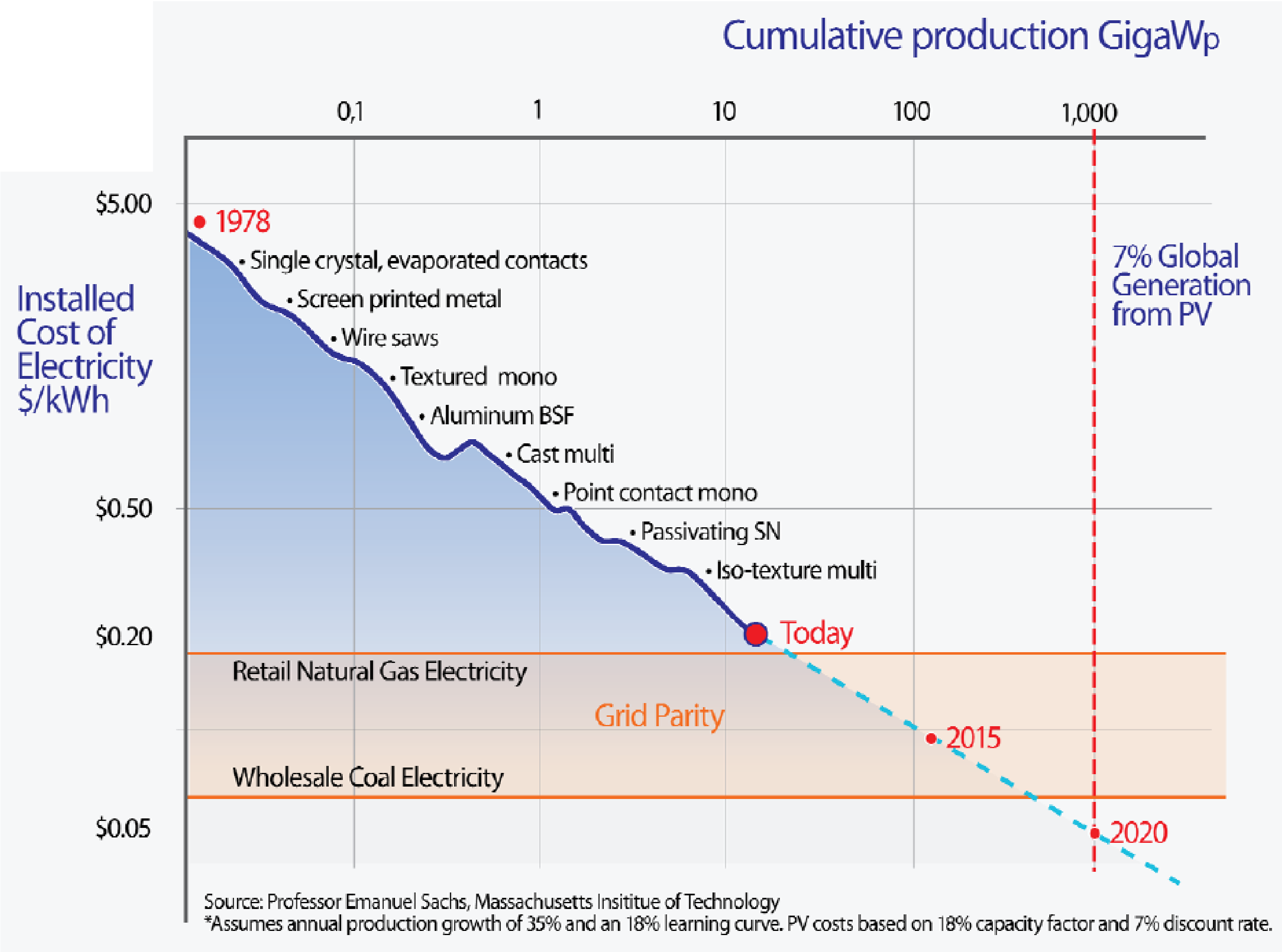
1839: Becquerel: discovery of PV effect
1883: Fritts: Cu/Se/Au module, η=1%
1905: Einstein: Photoeffect
1954: Bell Labs: Si solar cell, η=6%

26.6%
25.8%



Technical Breakthroughs Reduce Costs



PV Installations Worldwide

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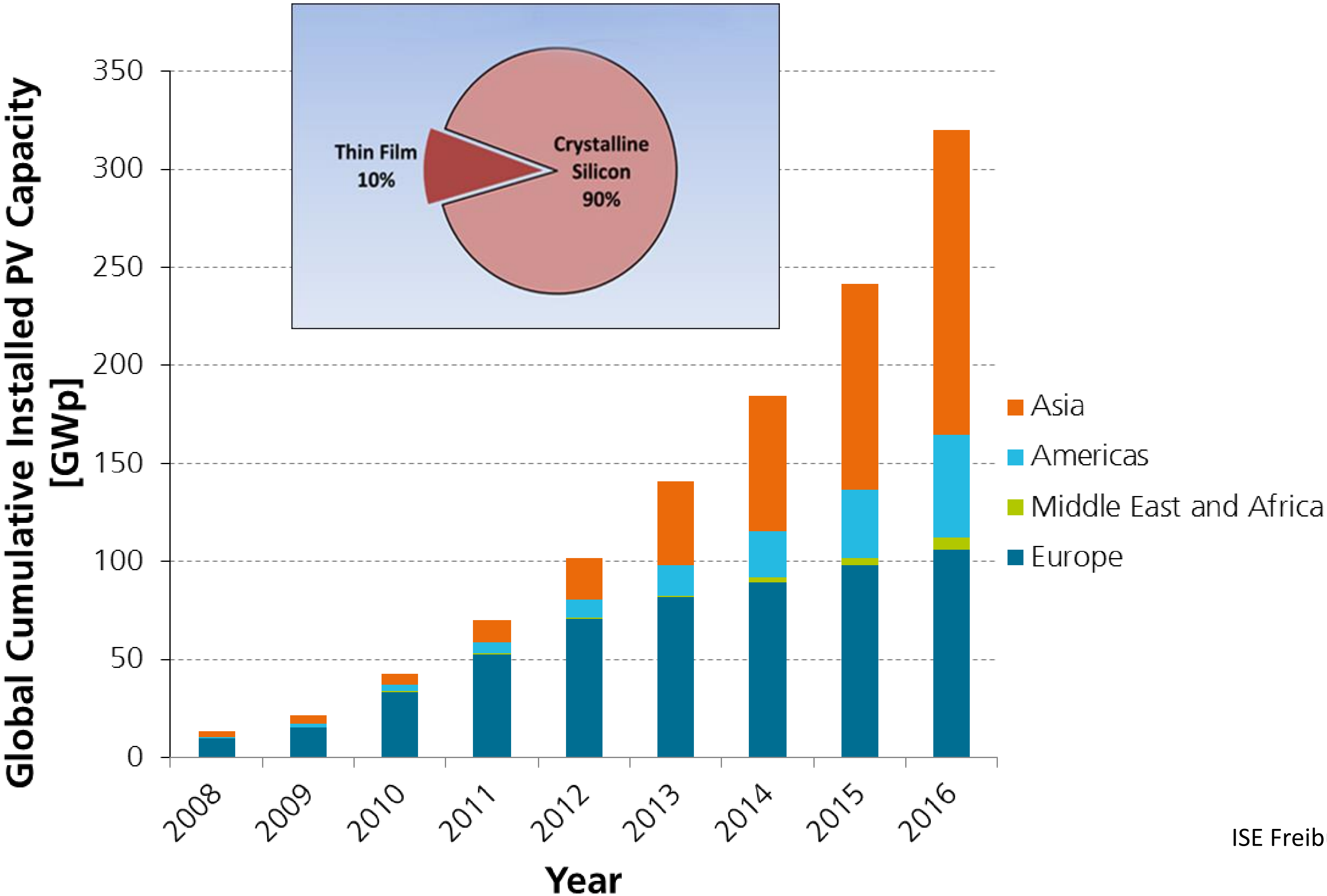
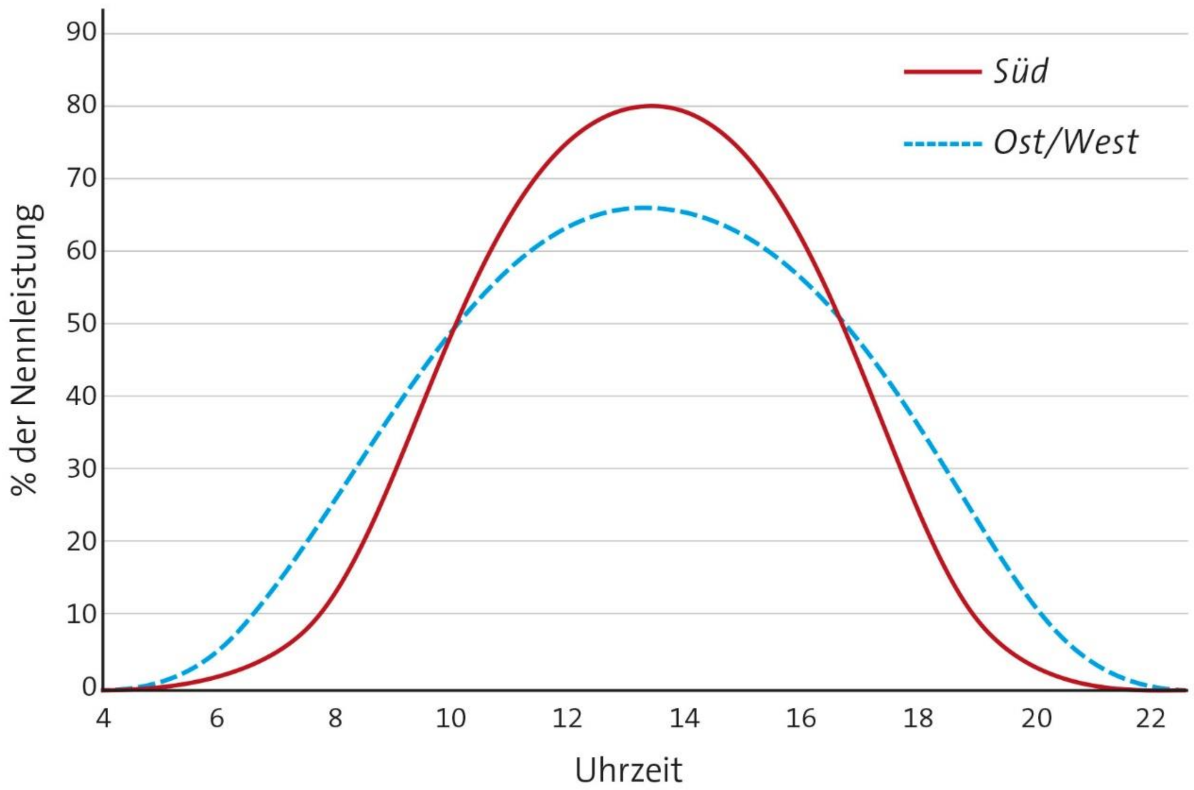


ISE Freiburg, 2018

PV Installations Worldwide

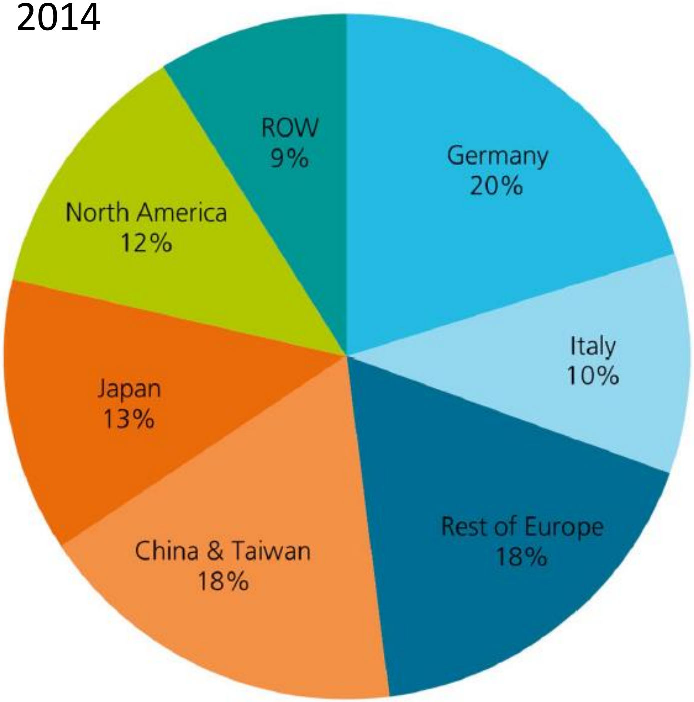


Vergleich von Photovoltaikanlagen unterschiedlicher Ausrichtung an einem Sonnentag (8. July 2013)

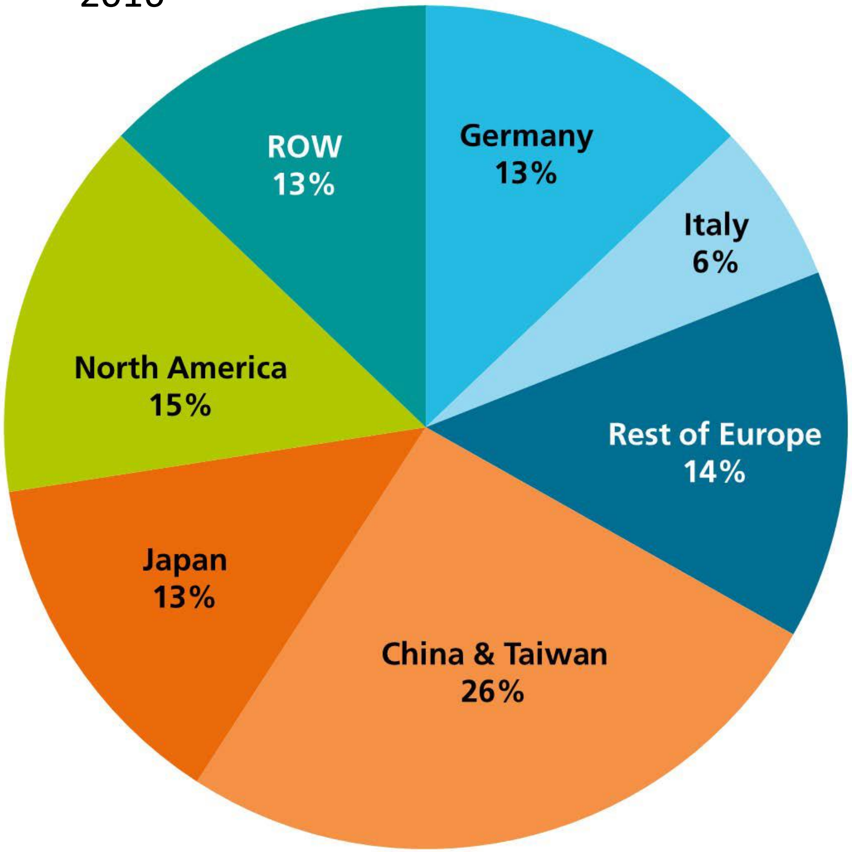
ISE Freiburg, 2018

PV Installations Worldwide

2014

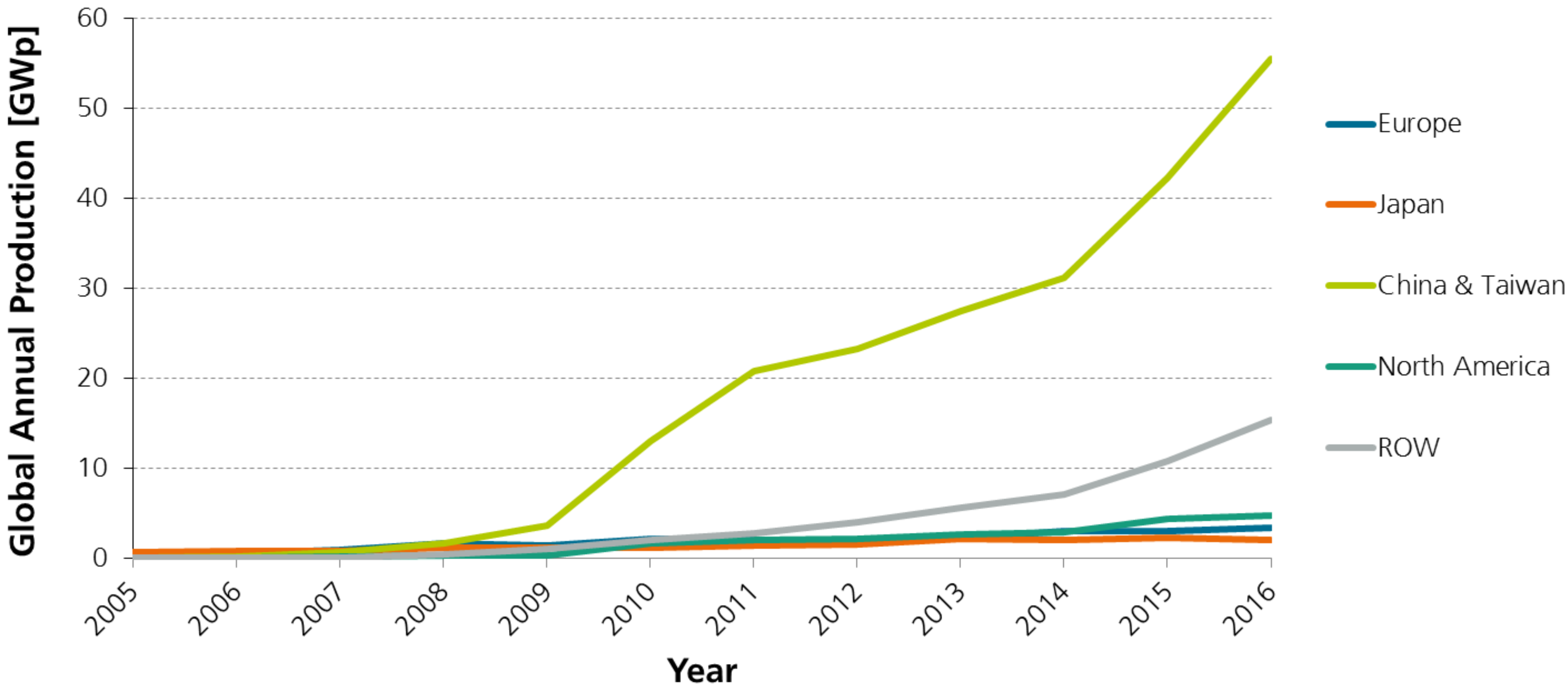


2016



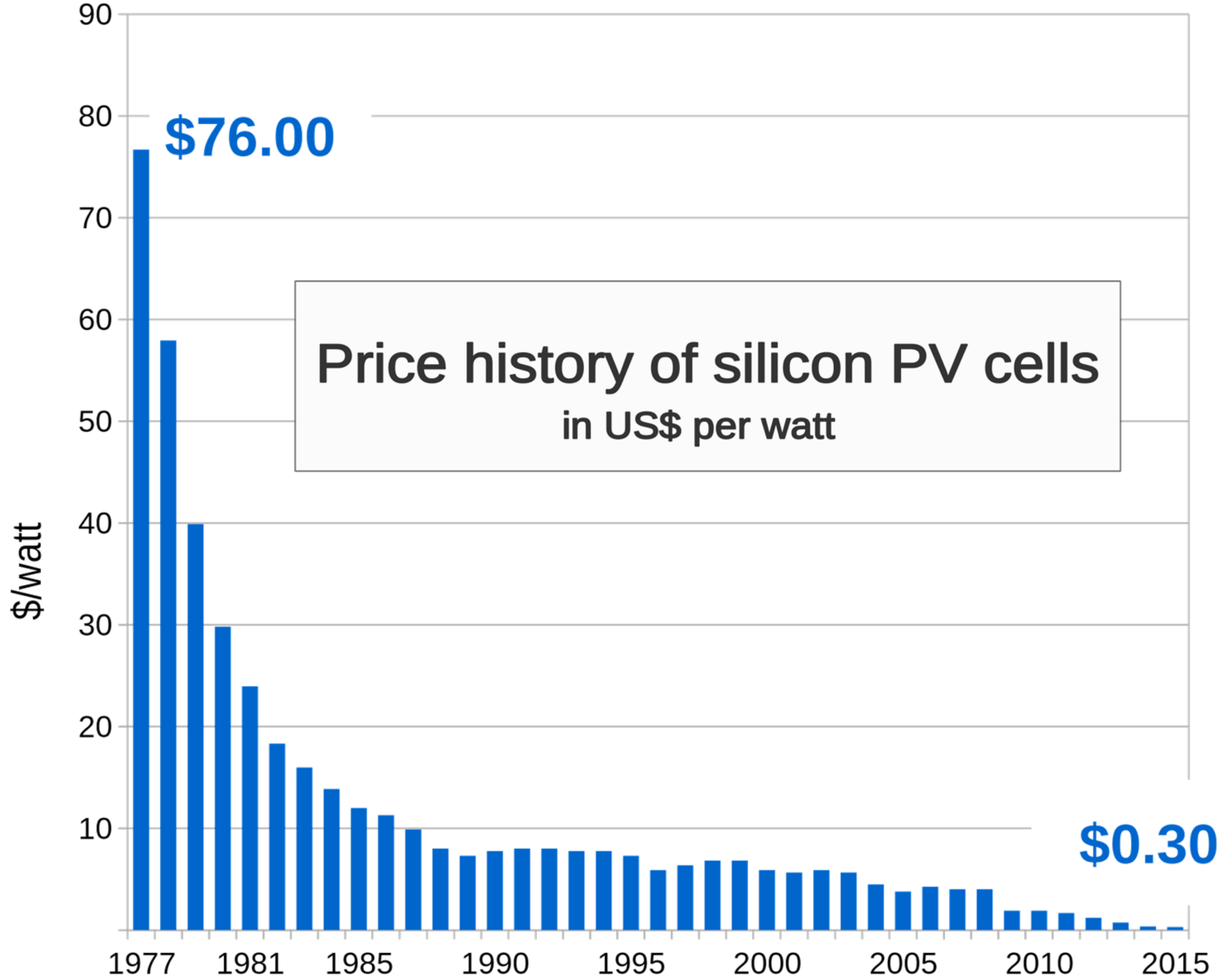
ISE Freiburg, 2018

PV Production



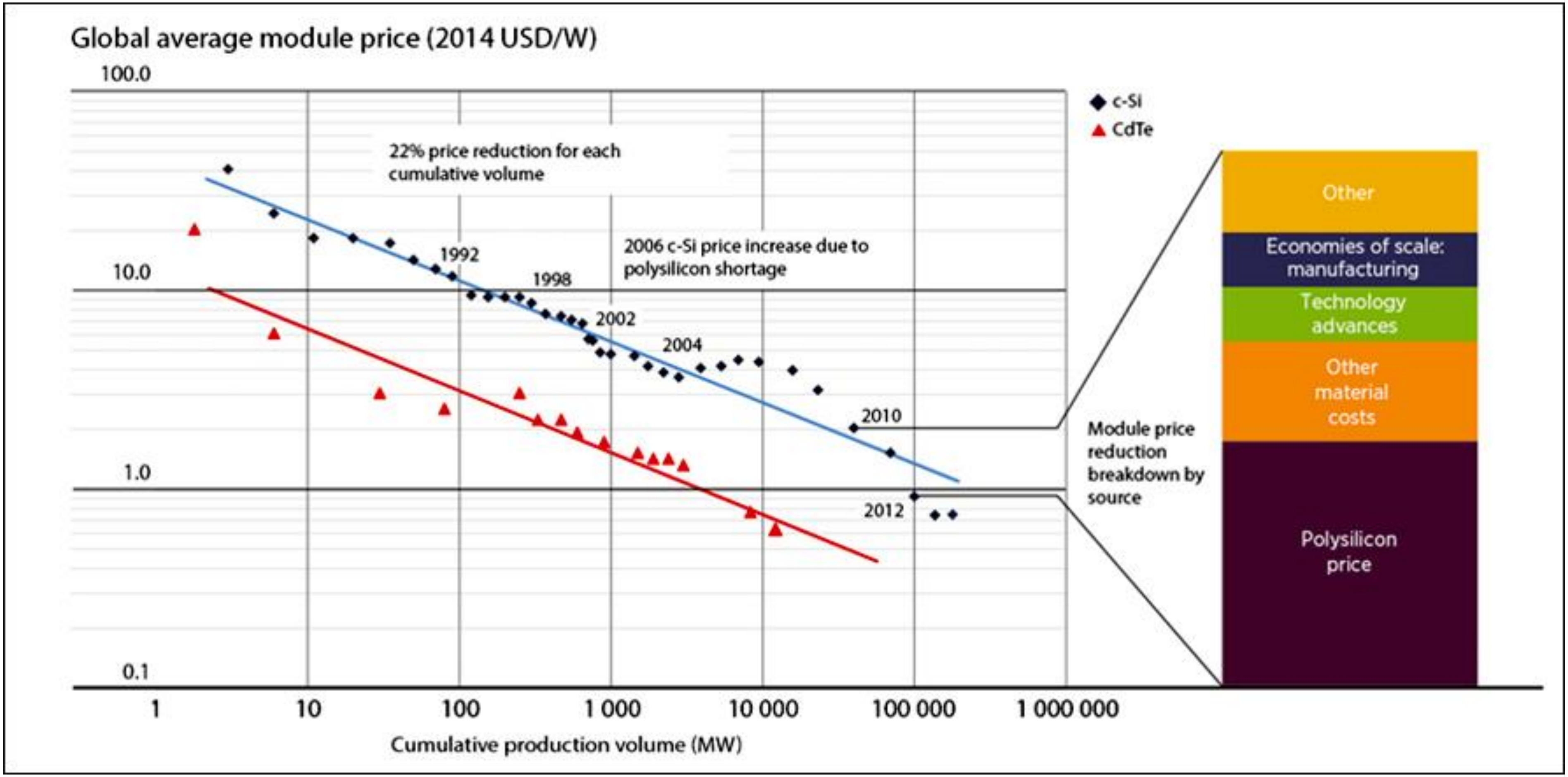
ISE Freiburg, 2018

Price



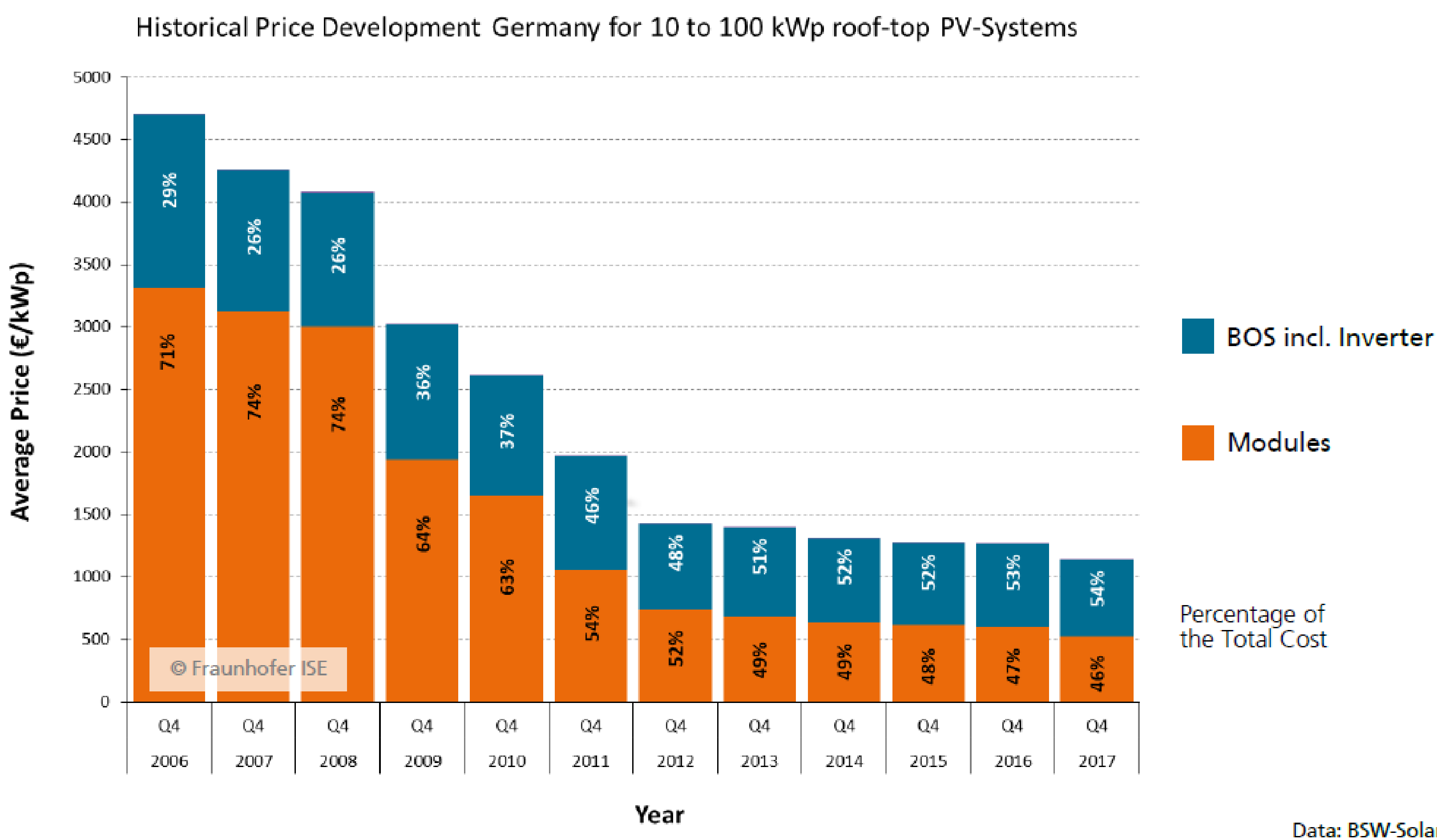
Source: Bloomberg New Energy Finance & pv.energytrend.com

Costs and Prices: The Learning Curve



http://solarcellcentral.com/cost_page.html

Average Price PV Rooftop System In D



Data: BSW-Solar. Graph: PSE 2018

Incentives in Germany

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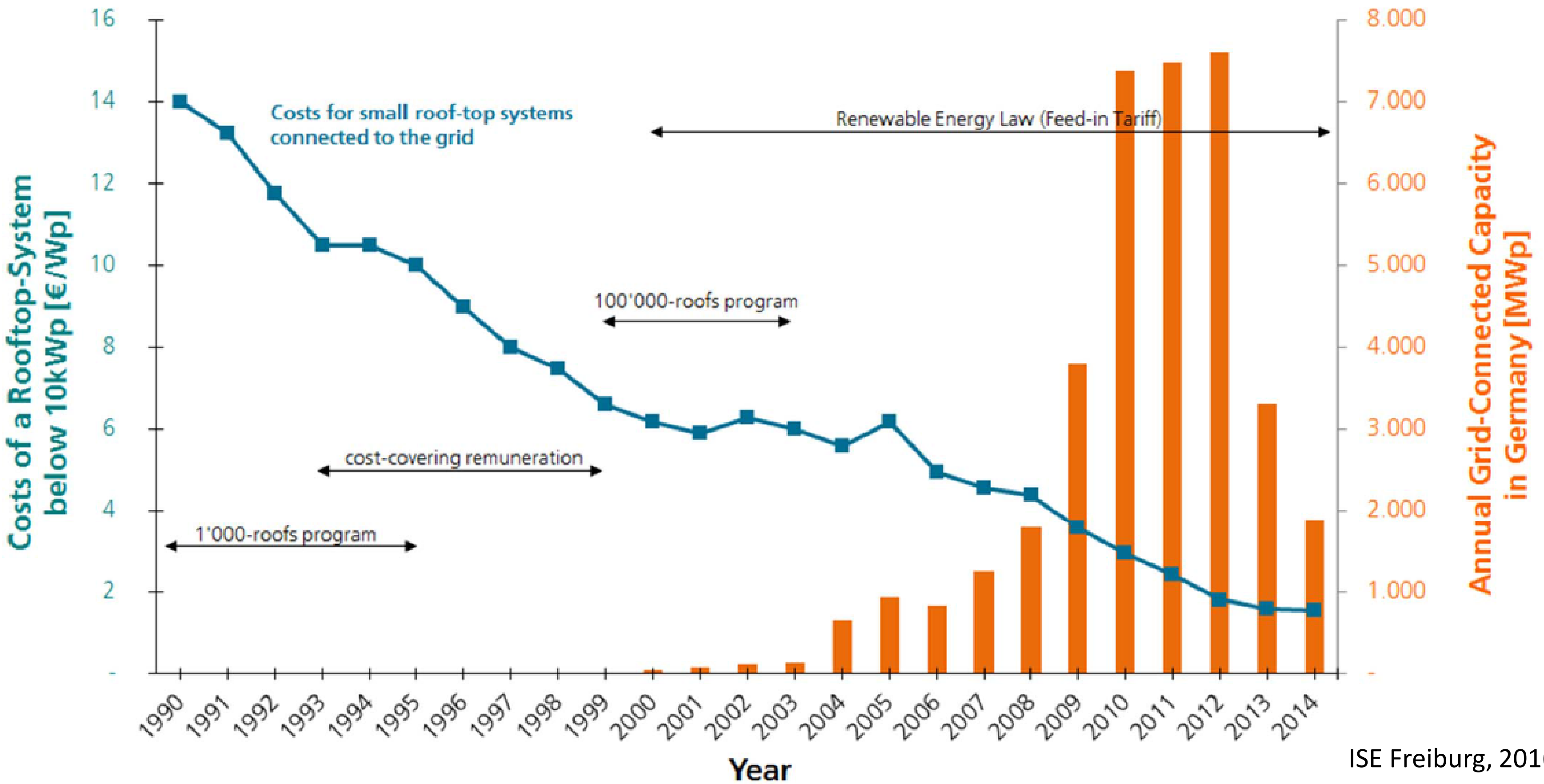
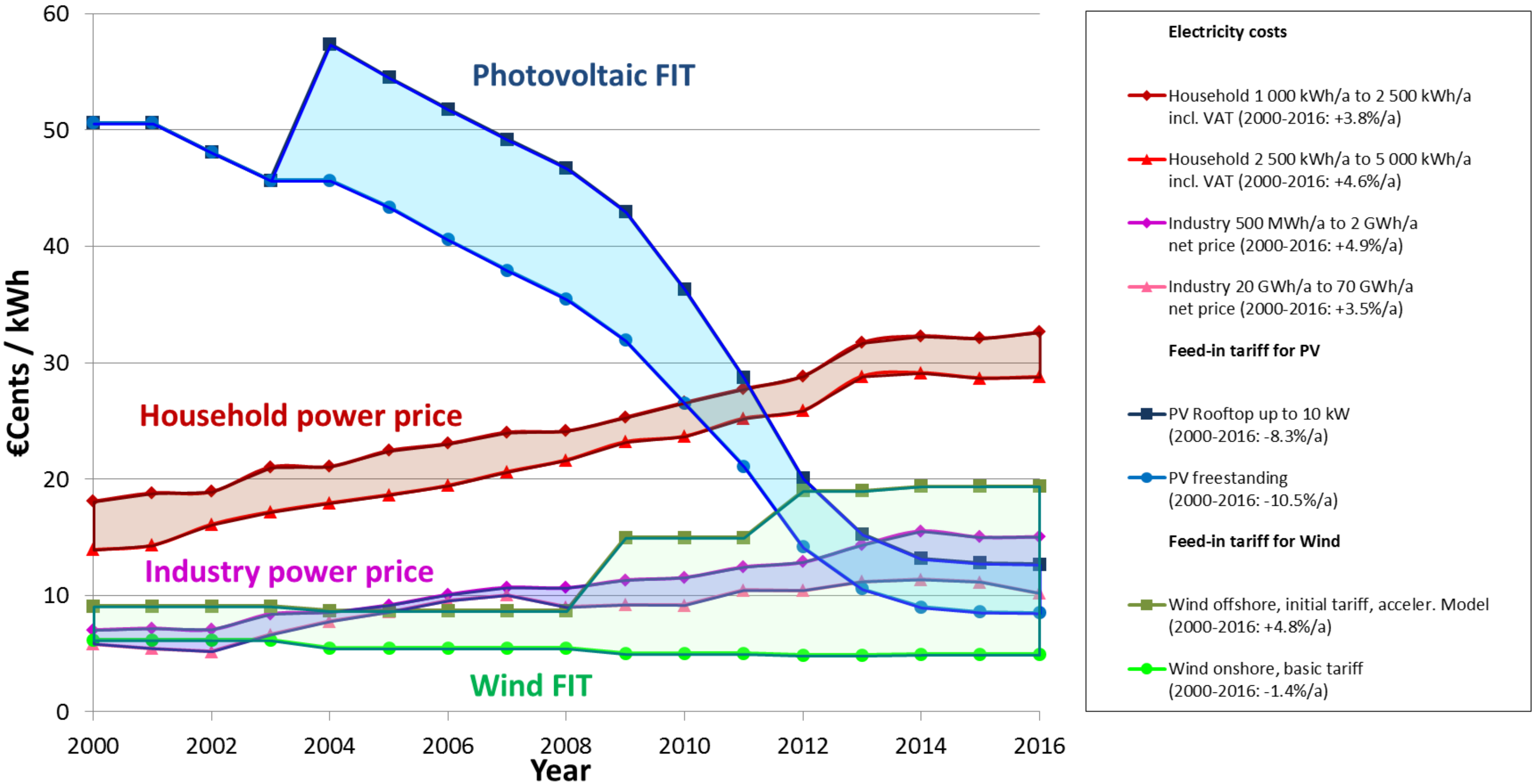


ISE Freiburg, 2016

Data: BSW-Solar, BNA. Graph: PSE AG 2015

Electricity Costs: Feed in Tariffs in D



Energy Payback Time (EPBT)

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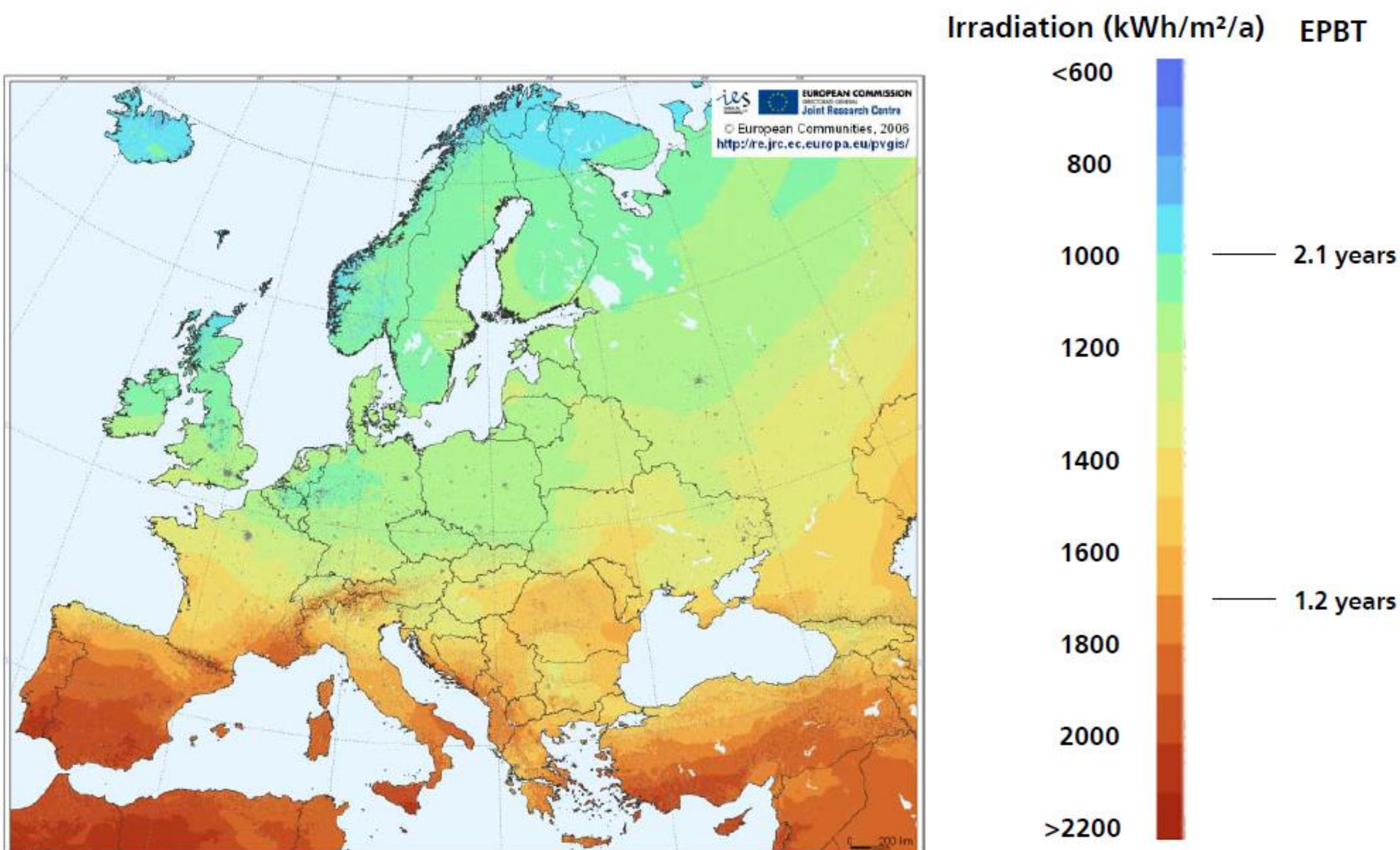
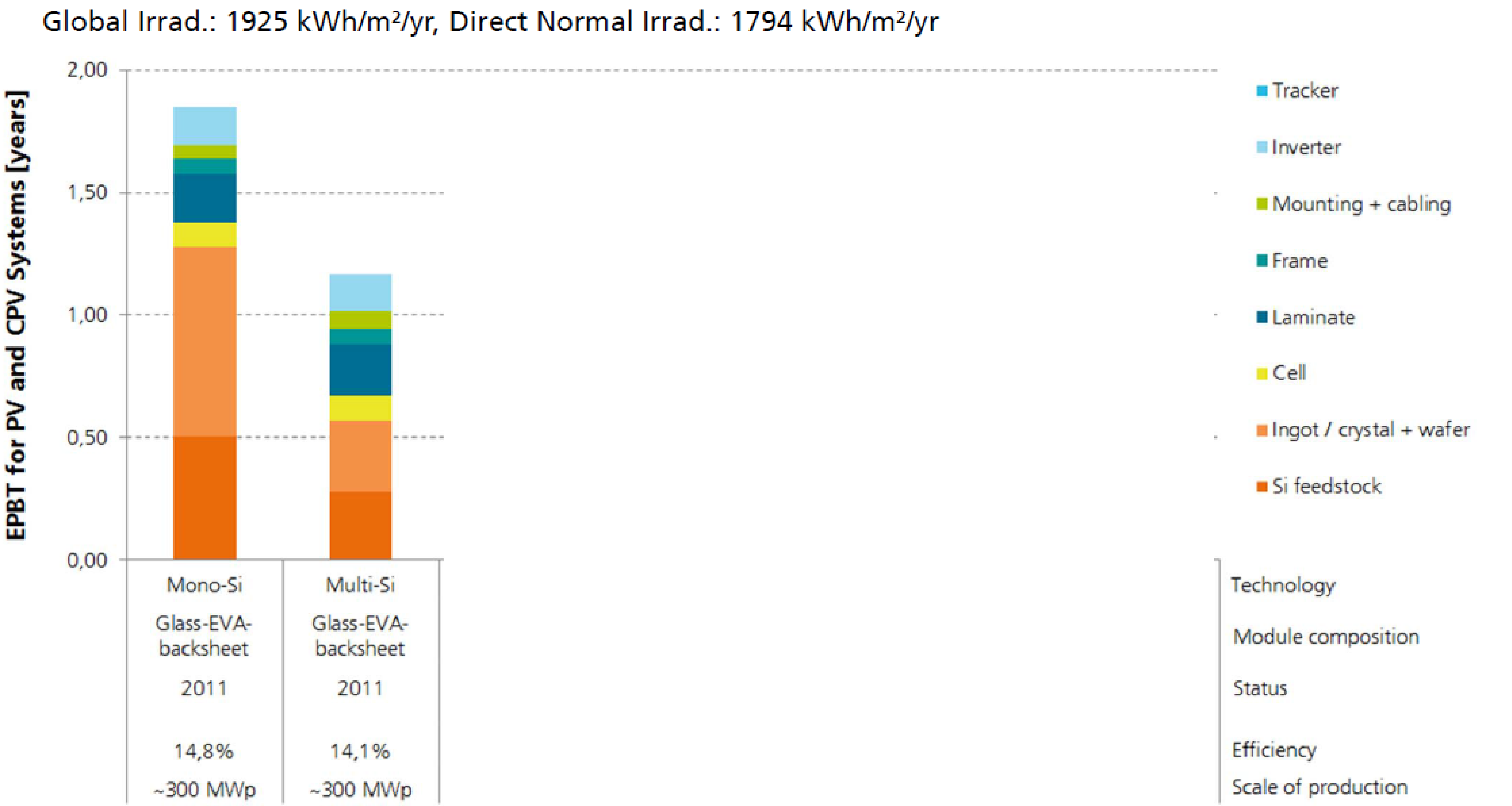


ISE Freiburg, 2016

Data: M.J. de Wild-Scholten 2013. Image: JRC European Commision. Graph: PSE AG 2014 (Modified scale with updated data from PSE AG and FraunhoferISE)

Energy Payback Time (EPBT)



Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014

ISE Freiburg, 2016

Example: Rooftop Installation

- Irradiation: 1200 kWh/m^2a
- 20% module → 240 kWh/m^2a → 0.2 kW_p/m^2
- 20 m^2 → 4800 kWh/a → 4 kW_p (20 modules)
- Investment costs 5200 Euro
- Household electricity cost 1600 Euro/a
- 4 kW continuous power → 34176 kWh/a

→ 14% capacity factor

→ volatile

(storage capacity and costs)

Summary Crystalline Silicon Solar Cells

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