

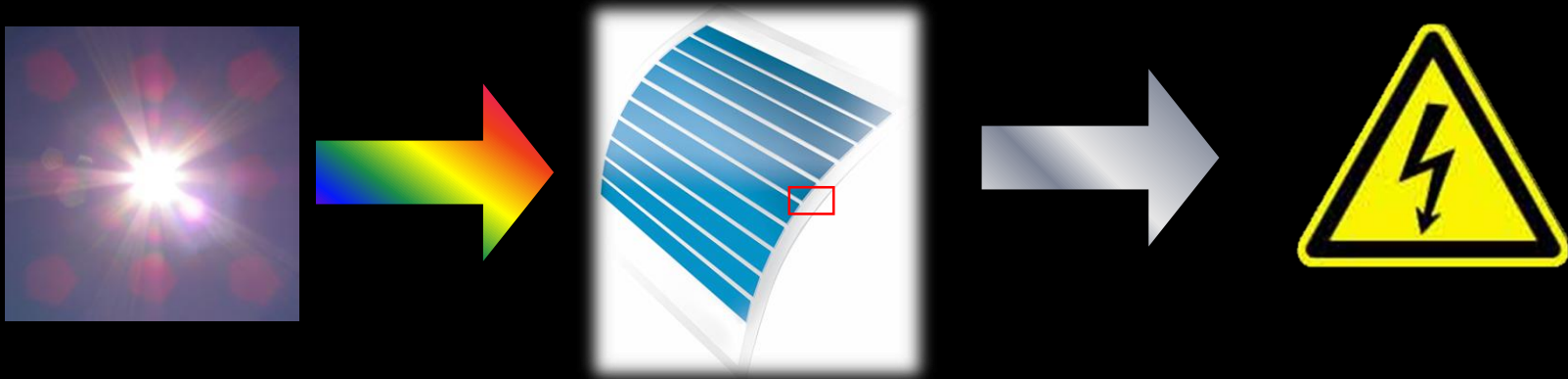
Solar Photovoltaics & Energy Systems

Lecture 3. Crystalline Semiconductor Based Solar Cells

ChE-600

Wolfgang Tress, March 2018

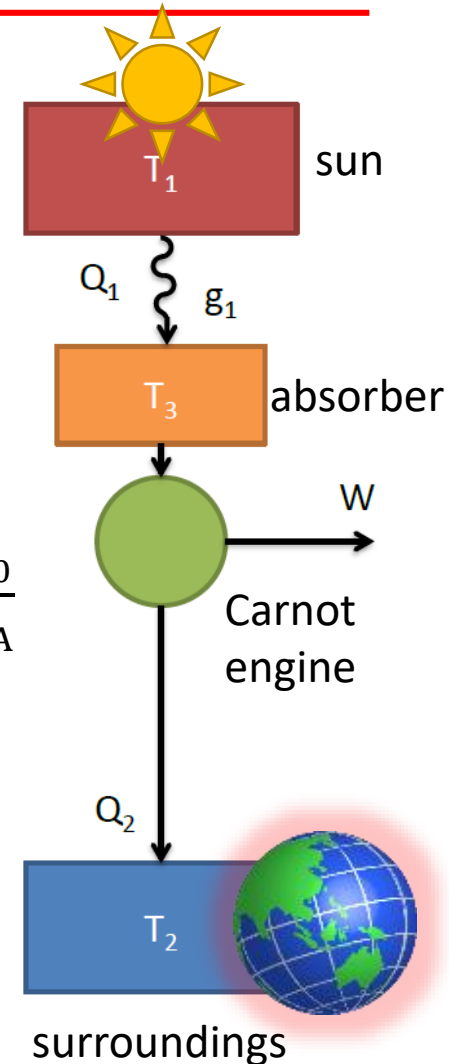
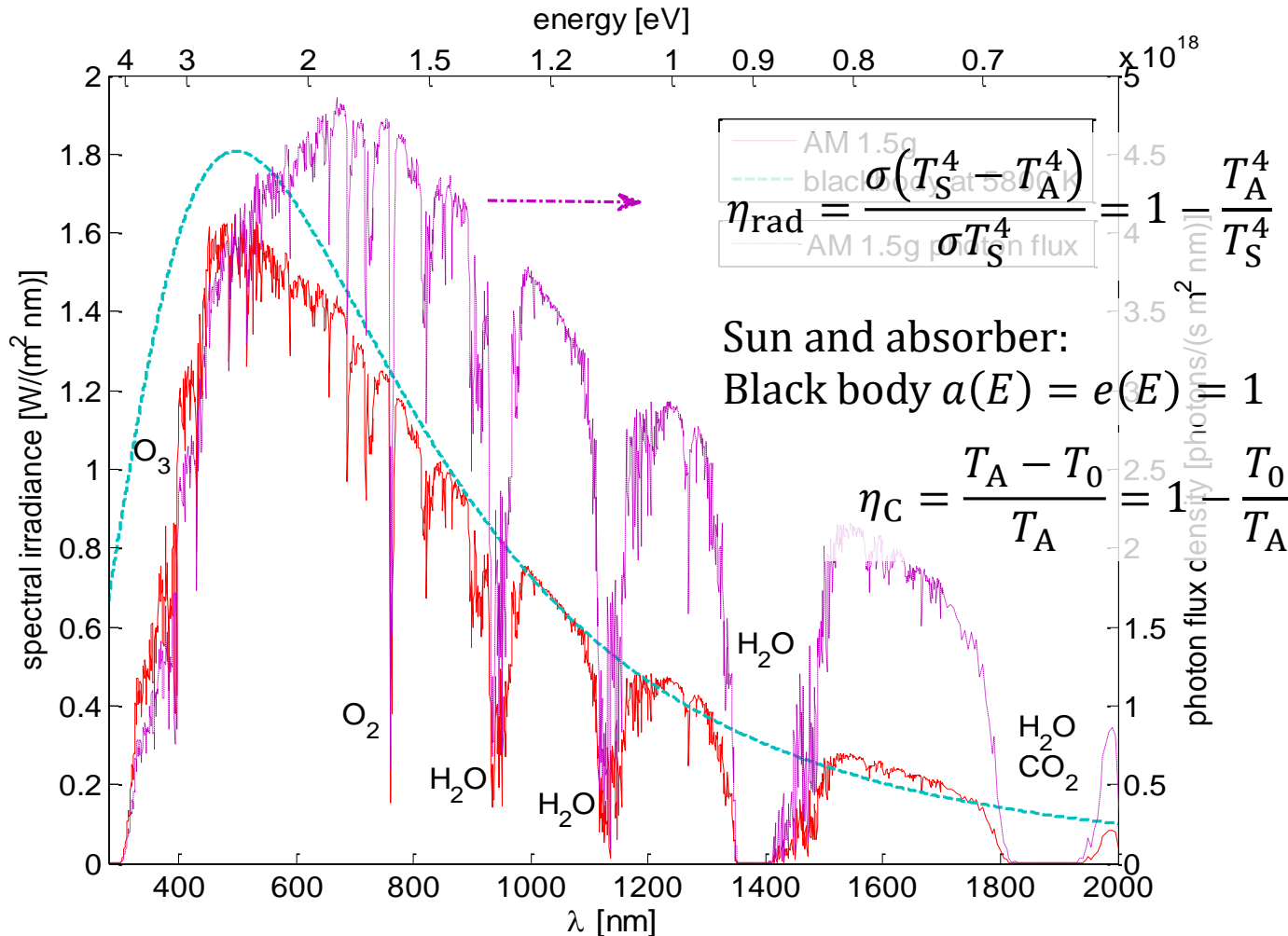
Photovoltaic Solar Energy Conversion



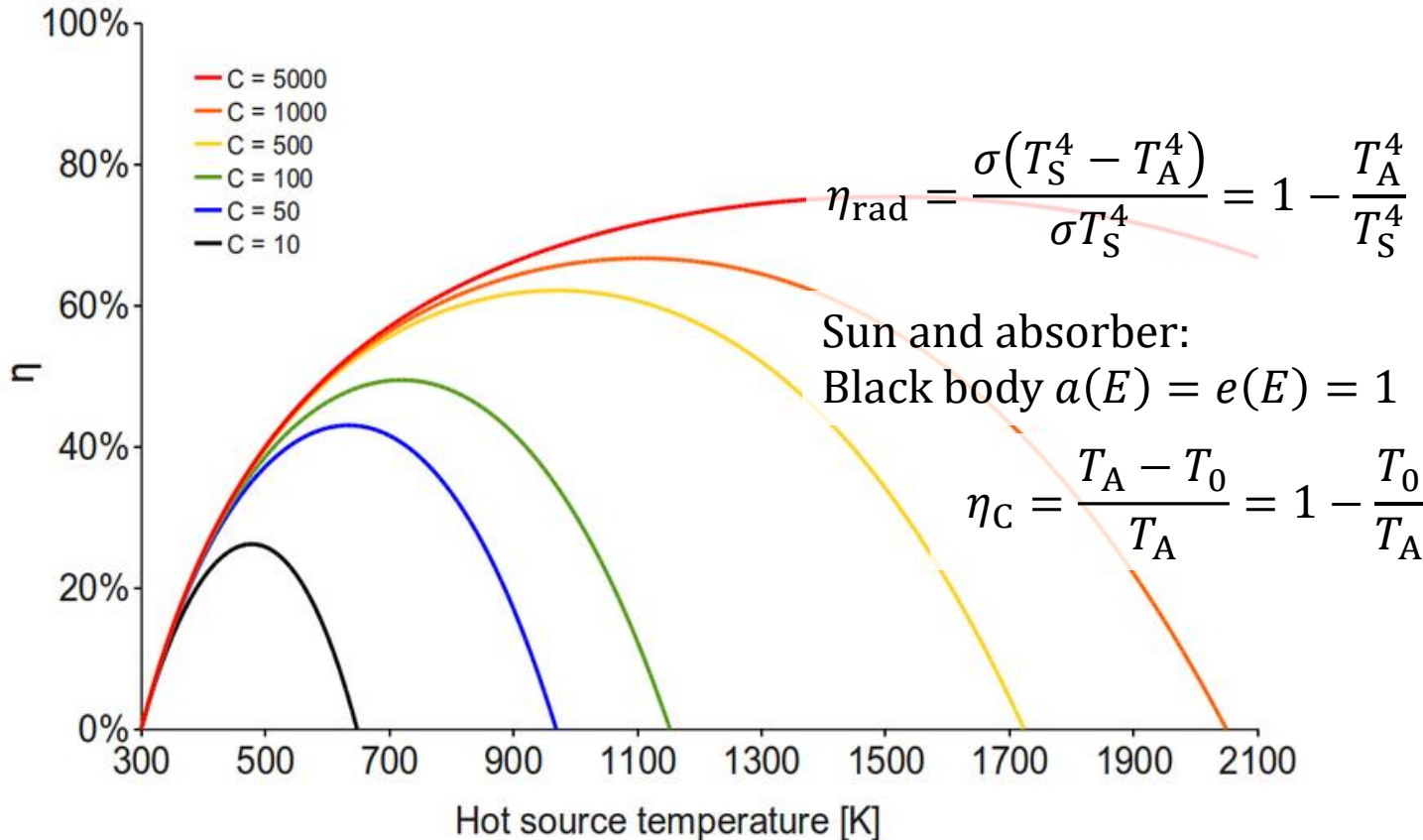
Outline

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

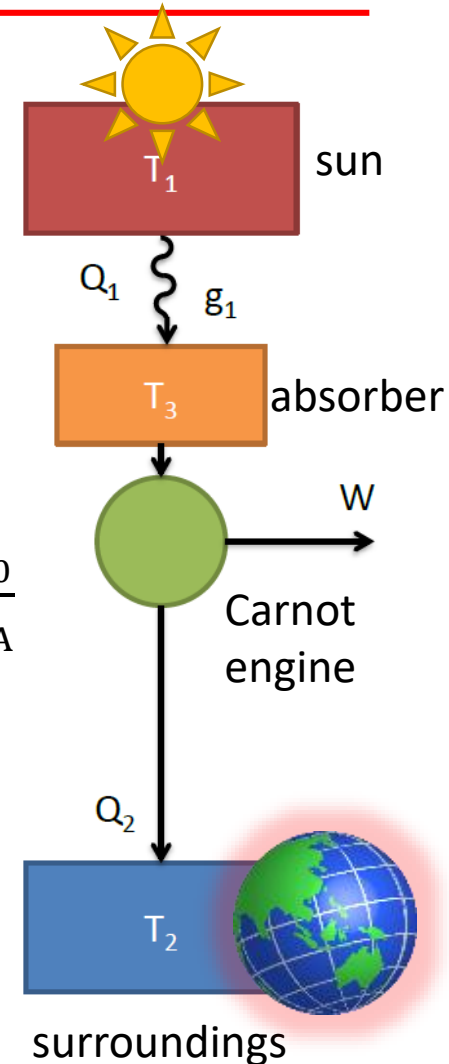
Semiconductor vs. Heat Engine



Semiconductor vs. Heat Engine

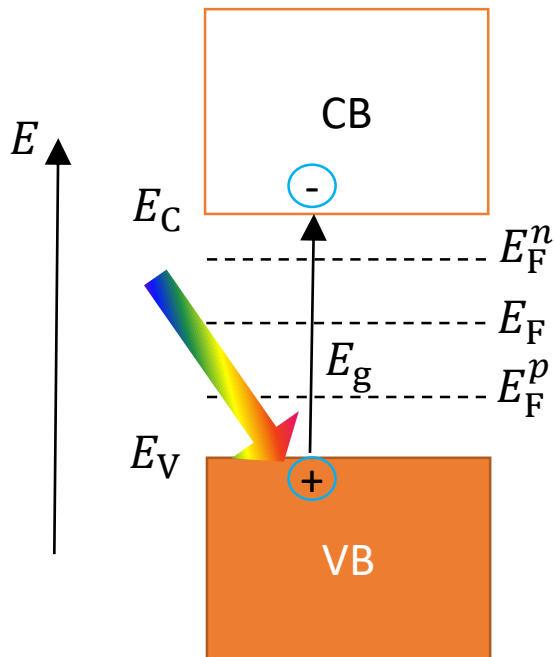


→ Absorber is at elevated temperature



Semiconductor vs. Heat Engine

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



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

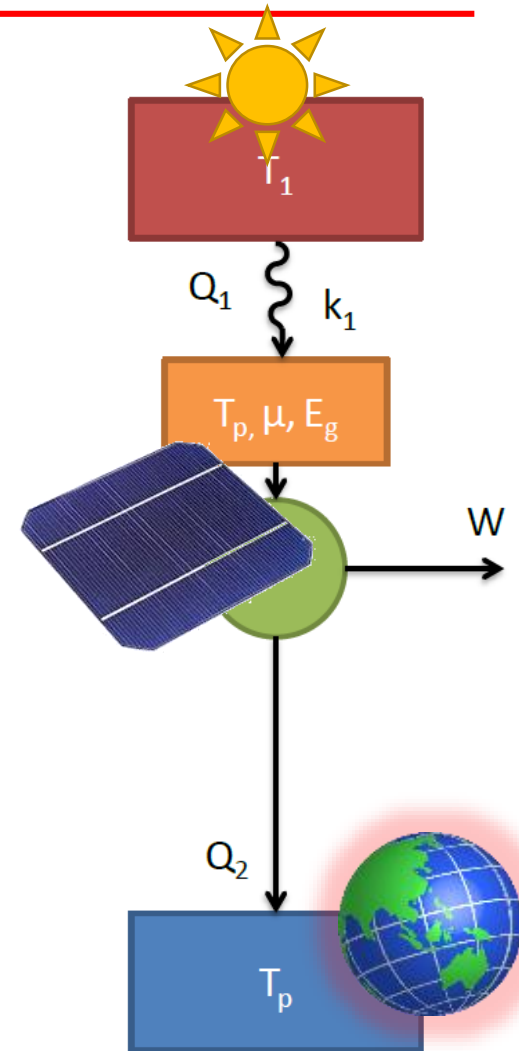
Quasi-Fermi level splitting \rightarrow
chemical energy \rightarrow potential

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

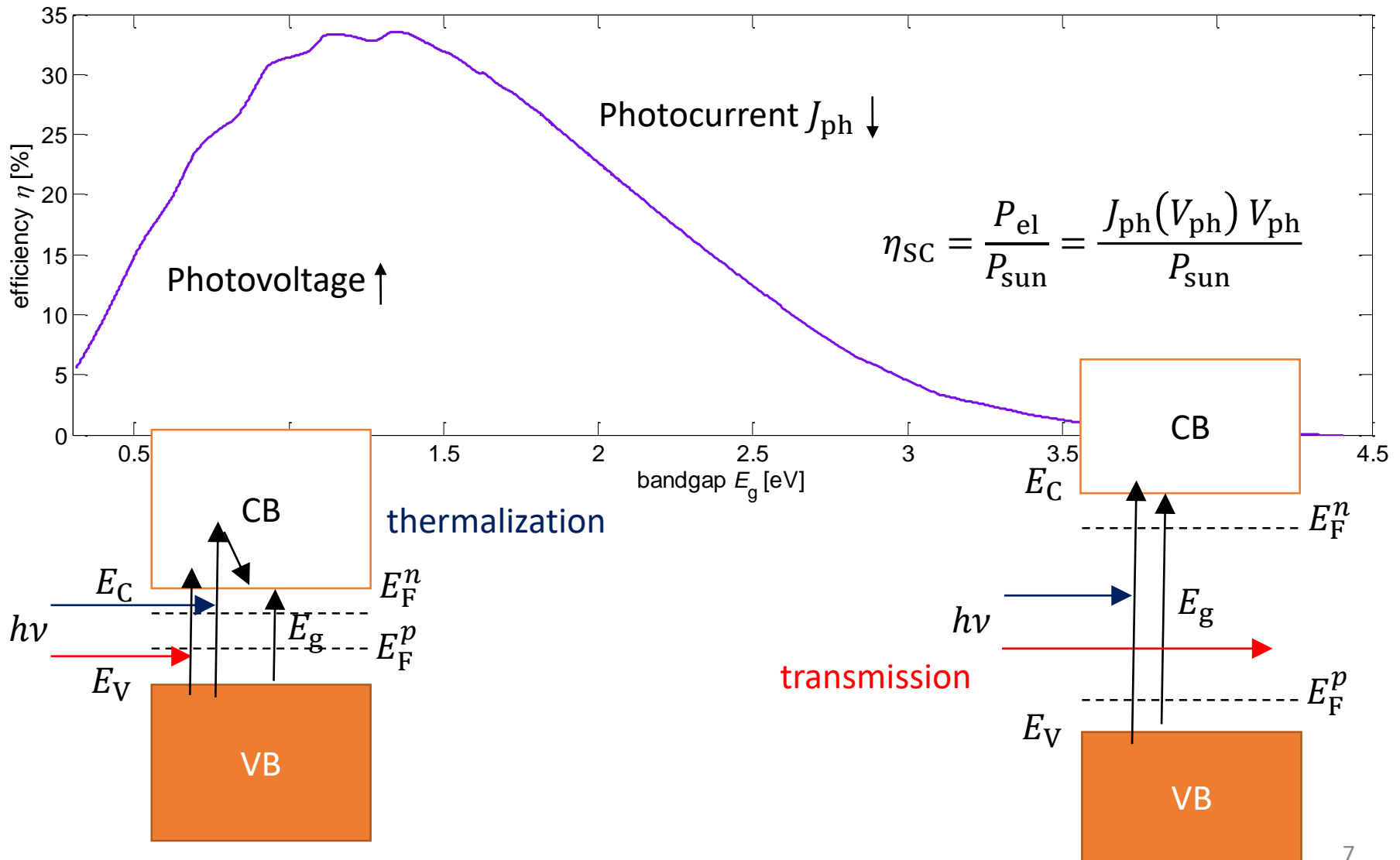
Charge flow \rightarrow electrical current

\rightarrow Absorber is at surrounding temperature

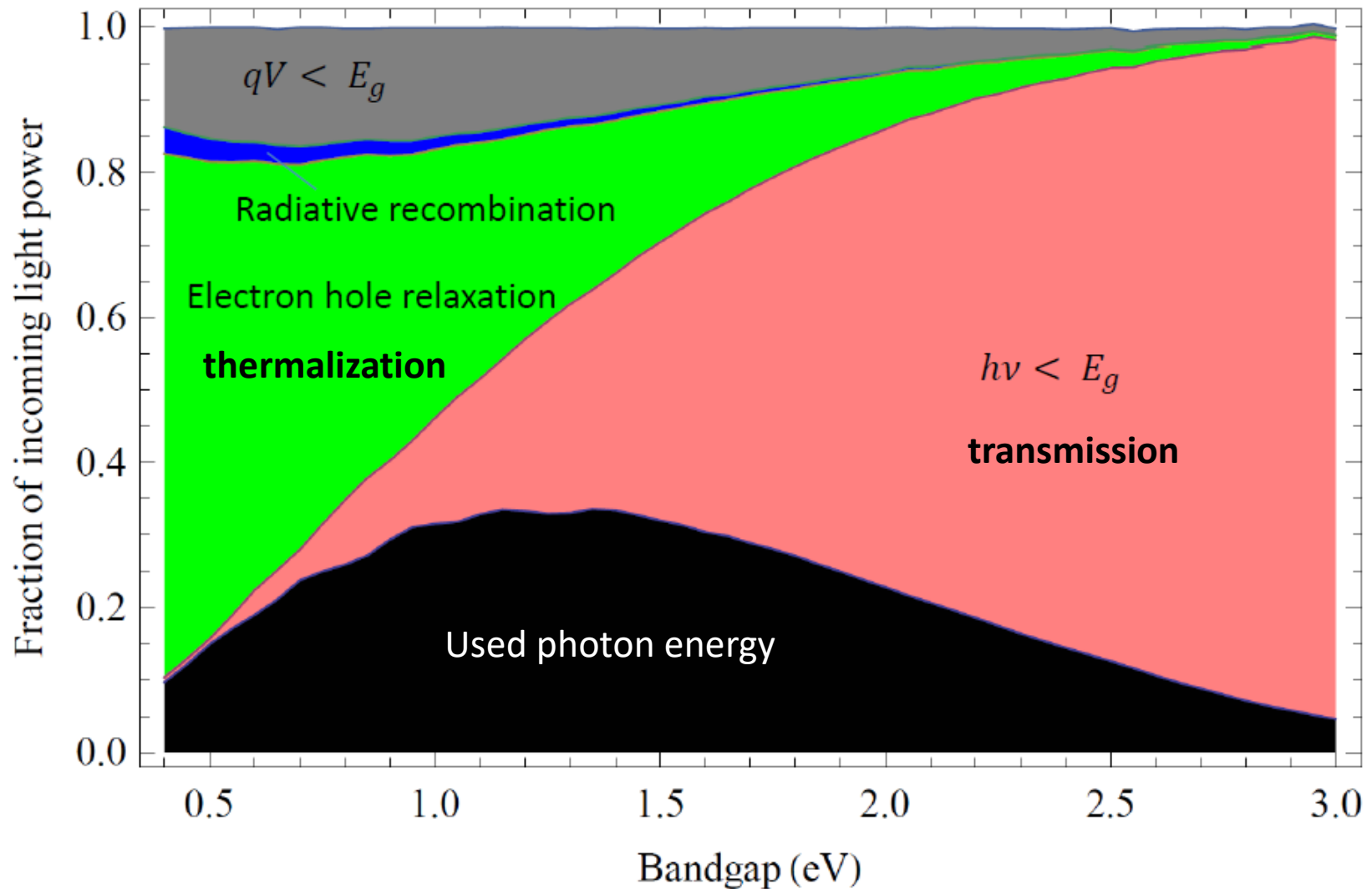
\rightarrow Radiation is converted into chemical energy



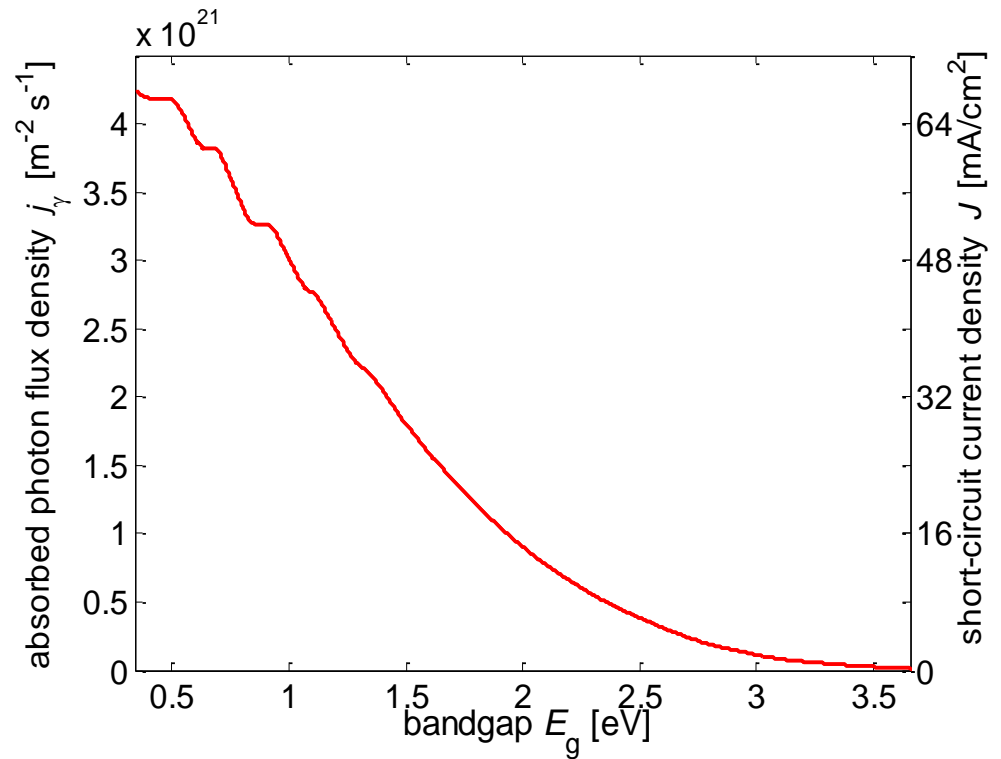
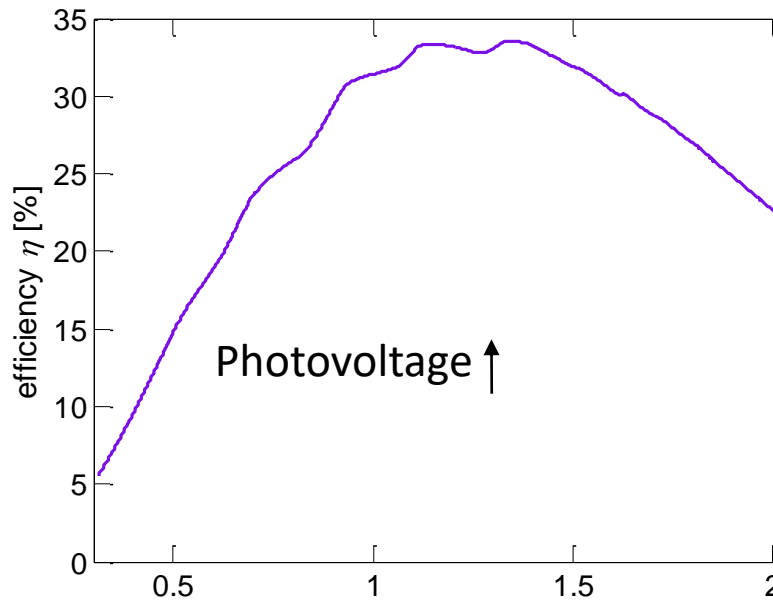
Shockley-Queisser Limit



Losses in Single-Bandgap Material



Shockley-Queisser Limit



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

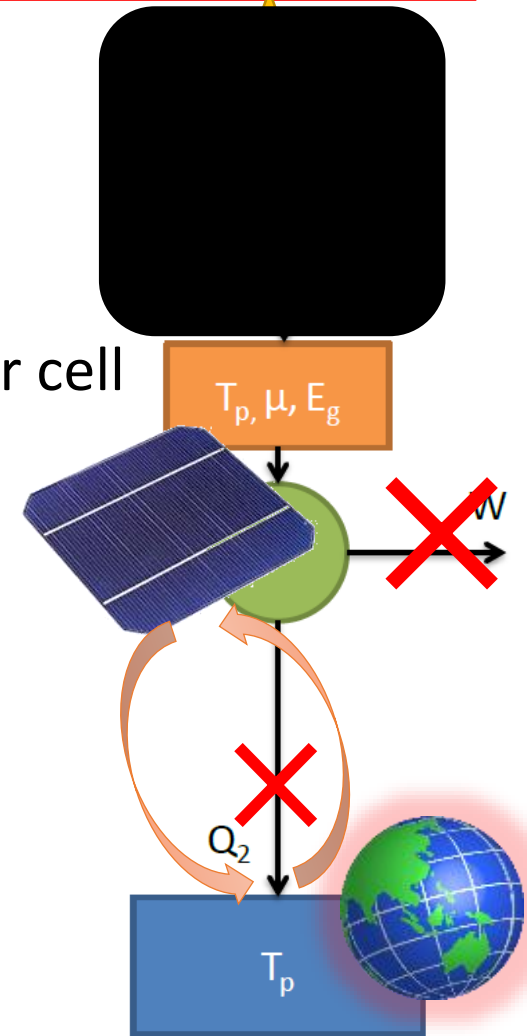
$$V_{\text{ph,max}} = ?$$

Detailed Balance Limit

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

Boltzmann approx.
 $\phi_{\text{BB}}(E, T) \exp\left(\frac{eV}{k_B T}\right)$

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



Detailed Balance Limit

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

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

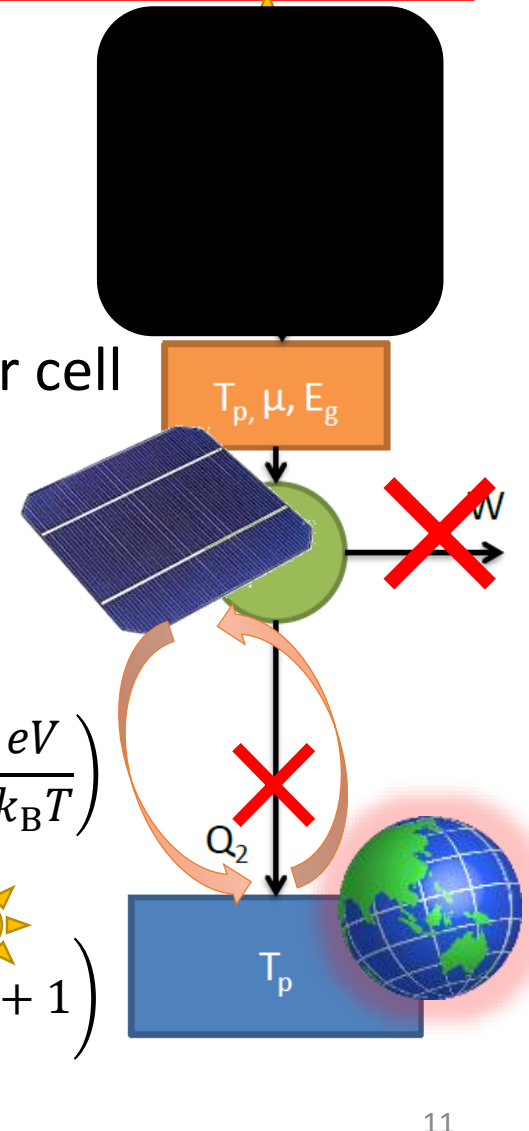
- In the dark: thermal equilibrium between solar cell surroundings: $B_0(E) = a(E) \phi_{BB}(T_0)$

- Balance under light:

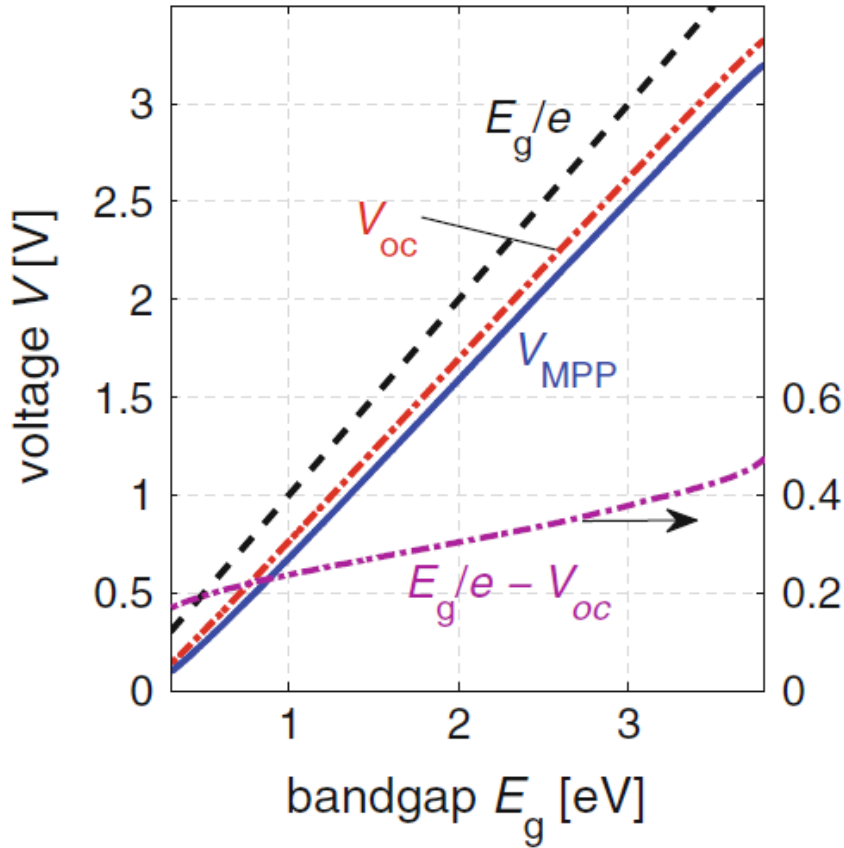
$$J_{ph}(V) = e \int a(E) \Phi_{AM1,5g}(E) dE + e \int B_0(E) dE - e \int B_0(E) dE \exp\left(\frac{eV}{k_B T}\right)$$

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

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



Detailed Balance Limit



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

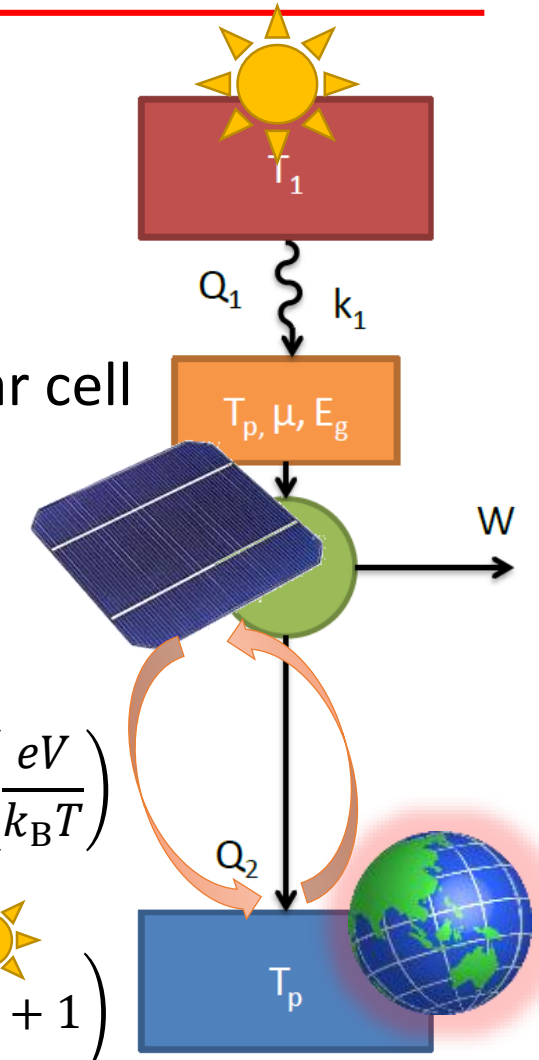
Planck approx.

$$J_{em,0} \exp\left(\frac{eV}{k_B T}\right)$$

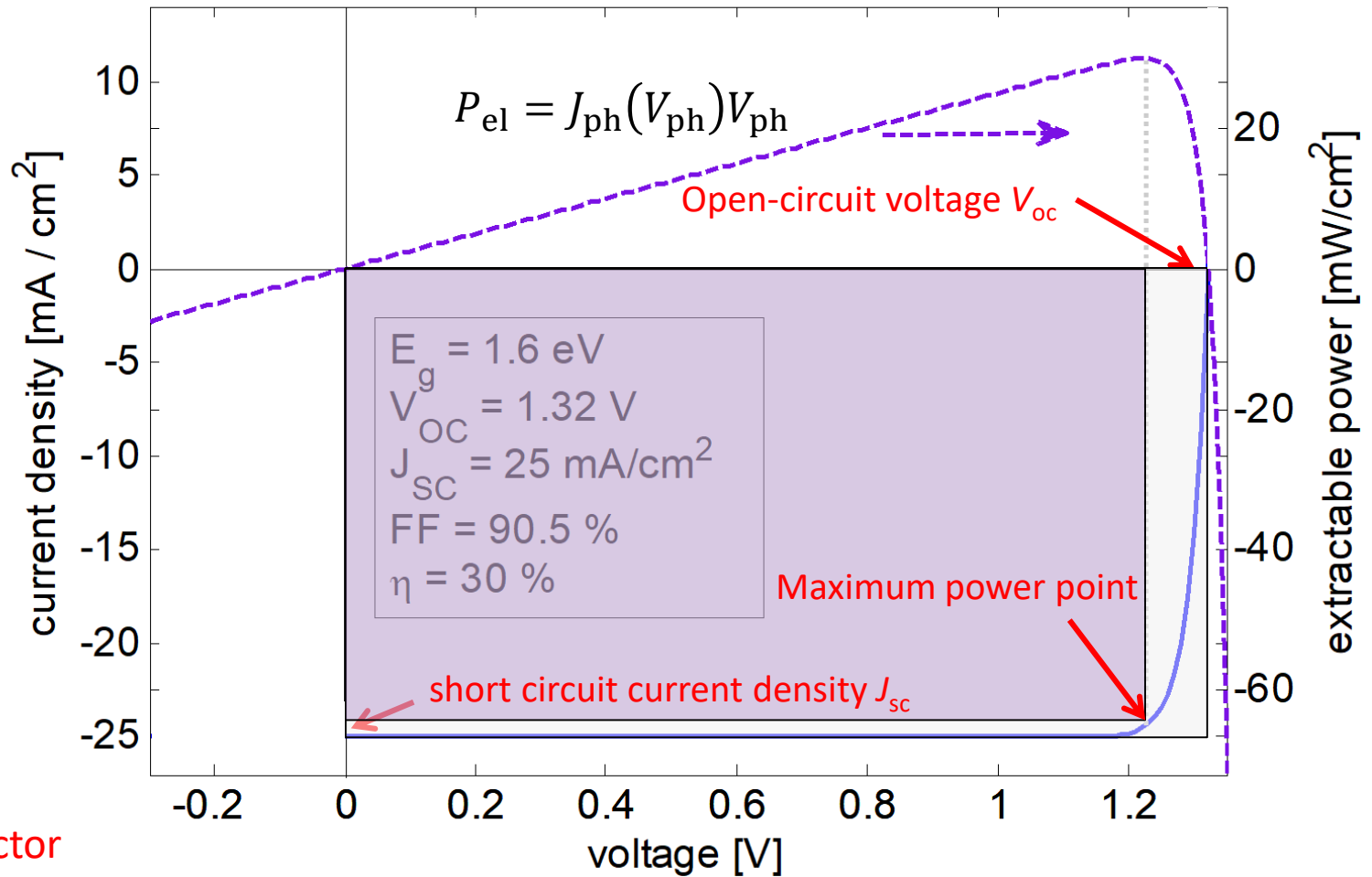
Temperature between solar cell

T_p

$$J_{em,0}(E) dE \exp\left(\frac{eV}{k_B T}\right)$$



JV-Curve of Ideal Solar Cell with $E_g = 1.6 \text{ eV}$

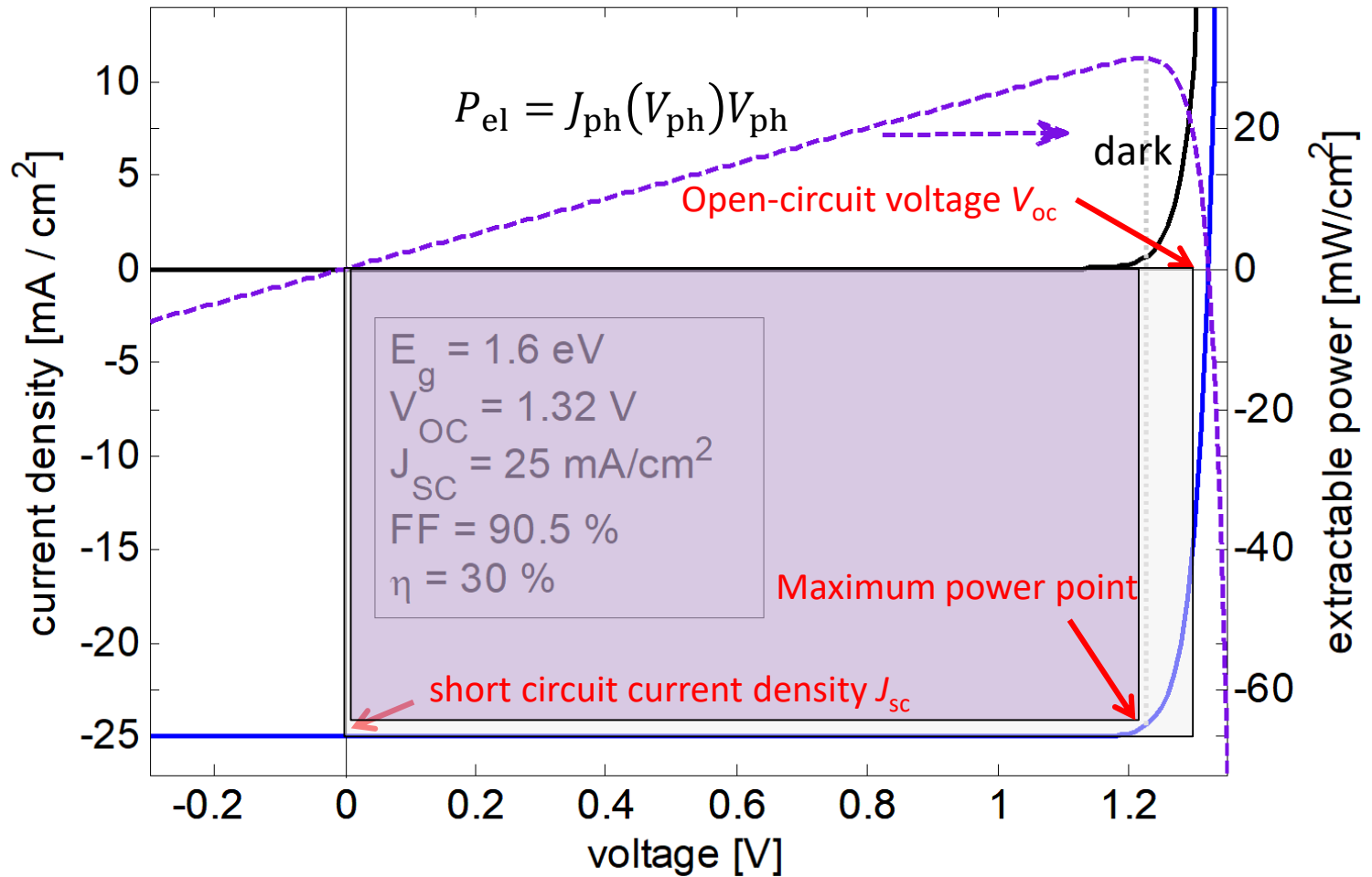


Fill factor

$$FF = \frac{\text{shaded area}}{\text{total area}}$$

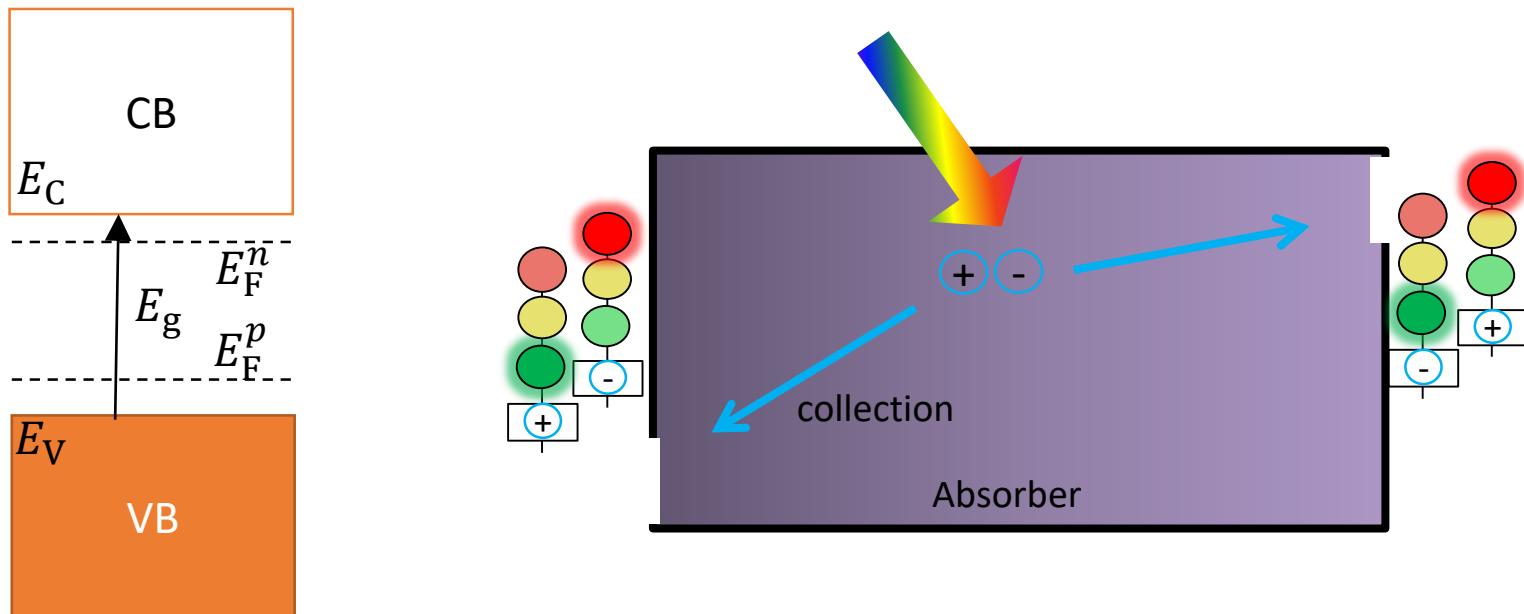
$$\eta_{SC,max} = \frac{P_{el,max}}{P_{sun}} = \frac{\max J_{ph}(V_{ph})V_{ph}}{P_{sun}} = \frac{J_{sc}V_{oc}FF}{P_{sun}}$$

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



→ Diode behavior

From Chemical to Electrical Energy

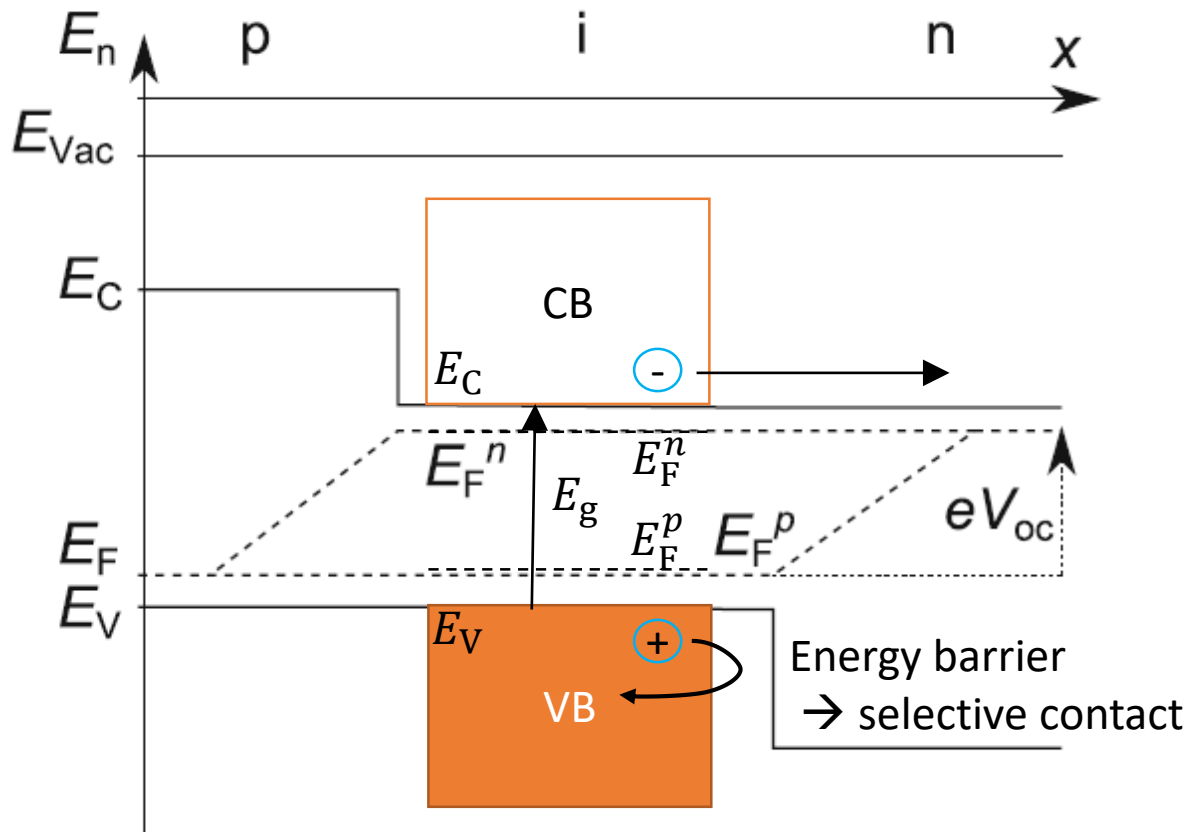


Requirement:

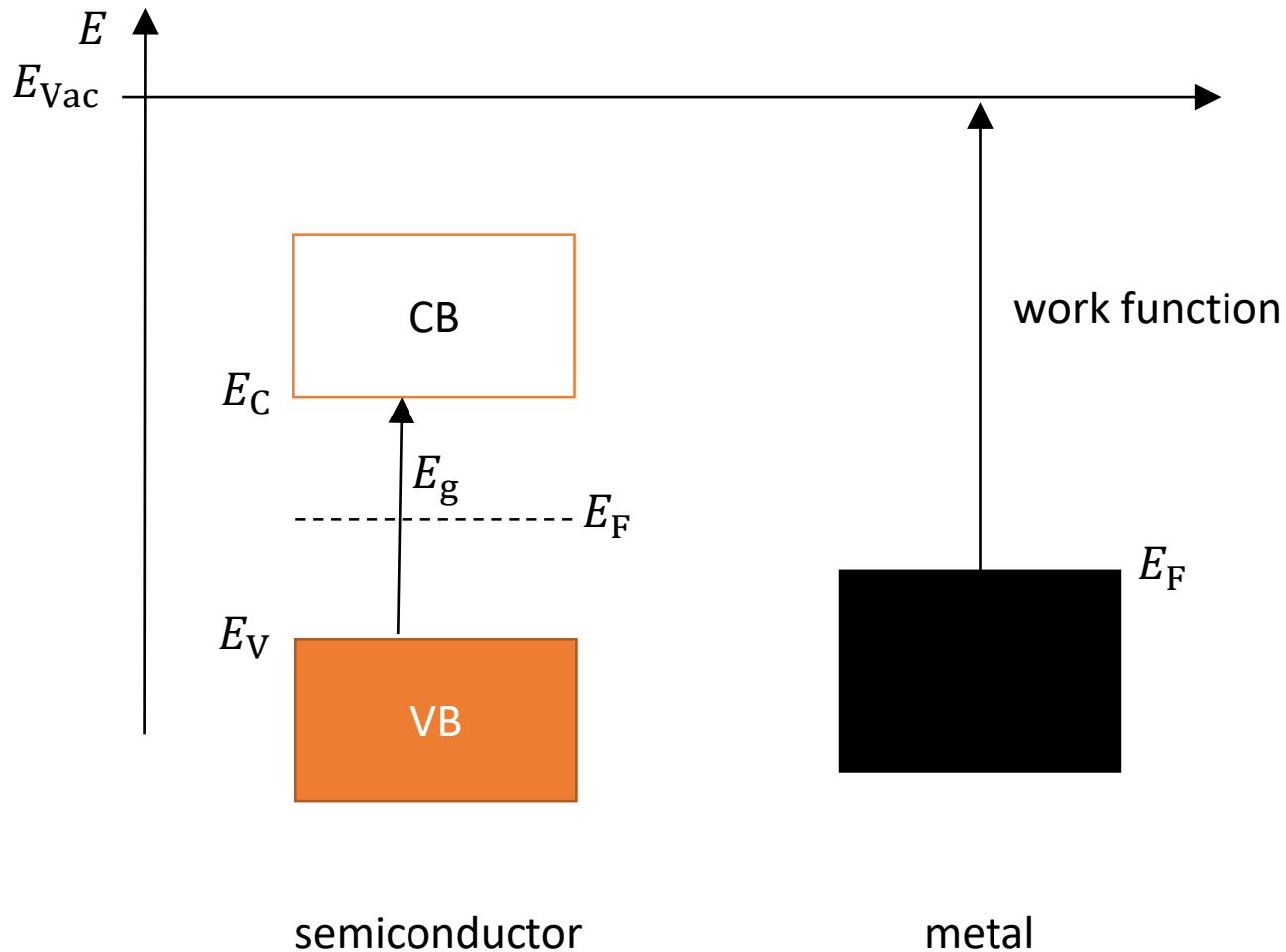
→ Charge selective contacts

From Chemical to Electrical Energy

Ideal solar cell structure (Würfel)



Metal Contacts



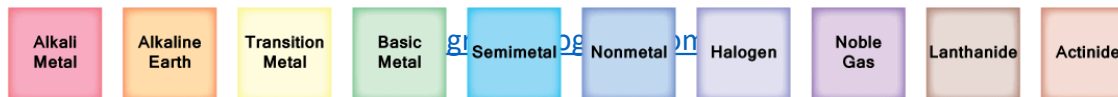
When put in contact in equilibrium \rightarrow Fermi levels will align

Doping

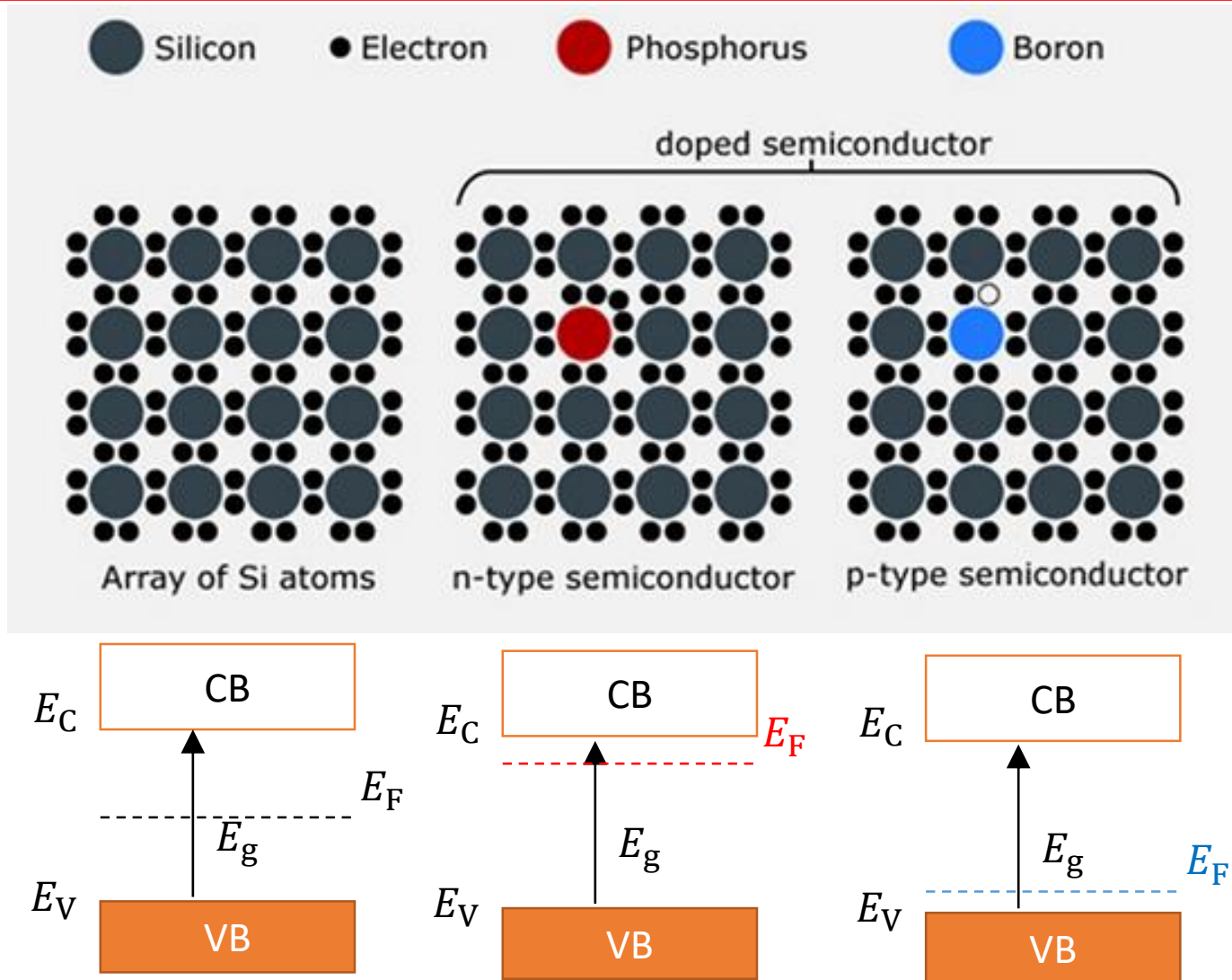
Periodic Table of the Elements

1 IA 1A																	18 VIIIA 8A
1 H Hydrogen 1.008	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Ff Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

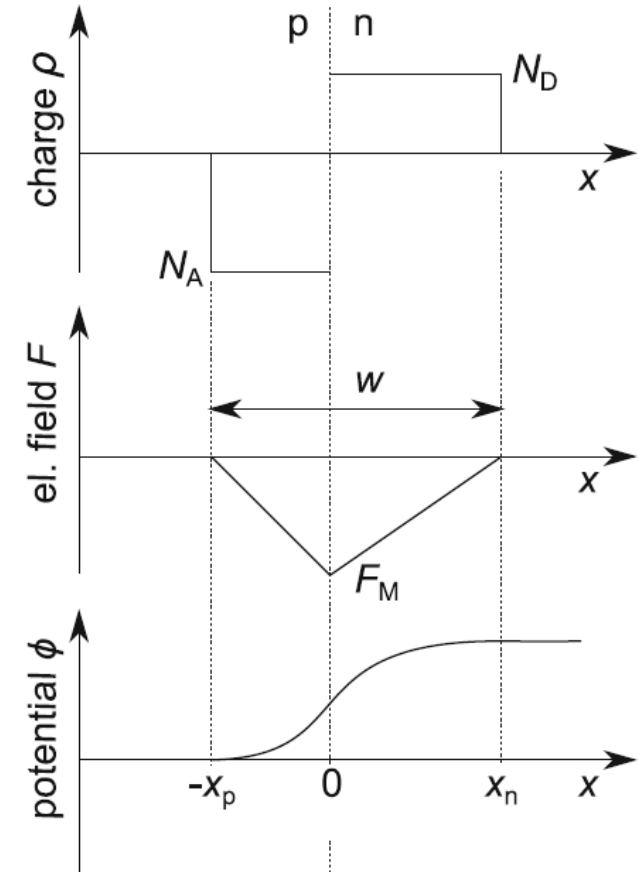
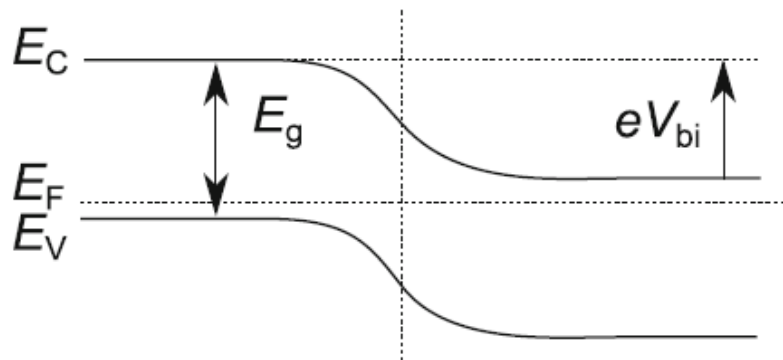
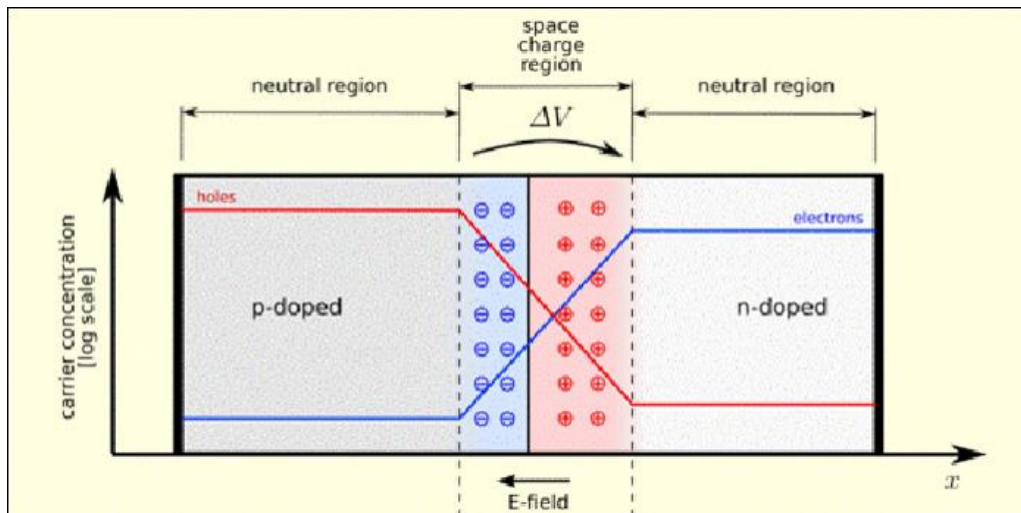
Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]



Doping → Fermi Level Shift

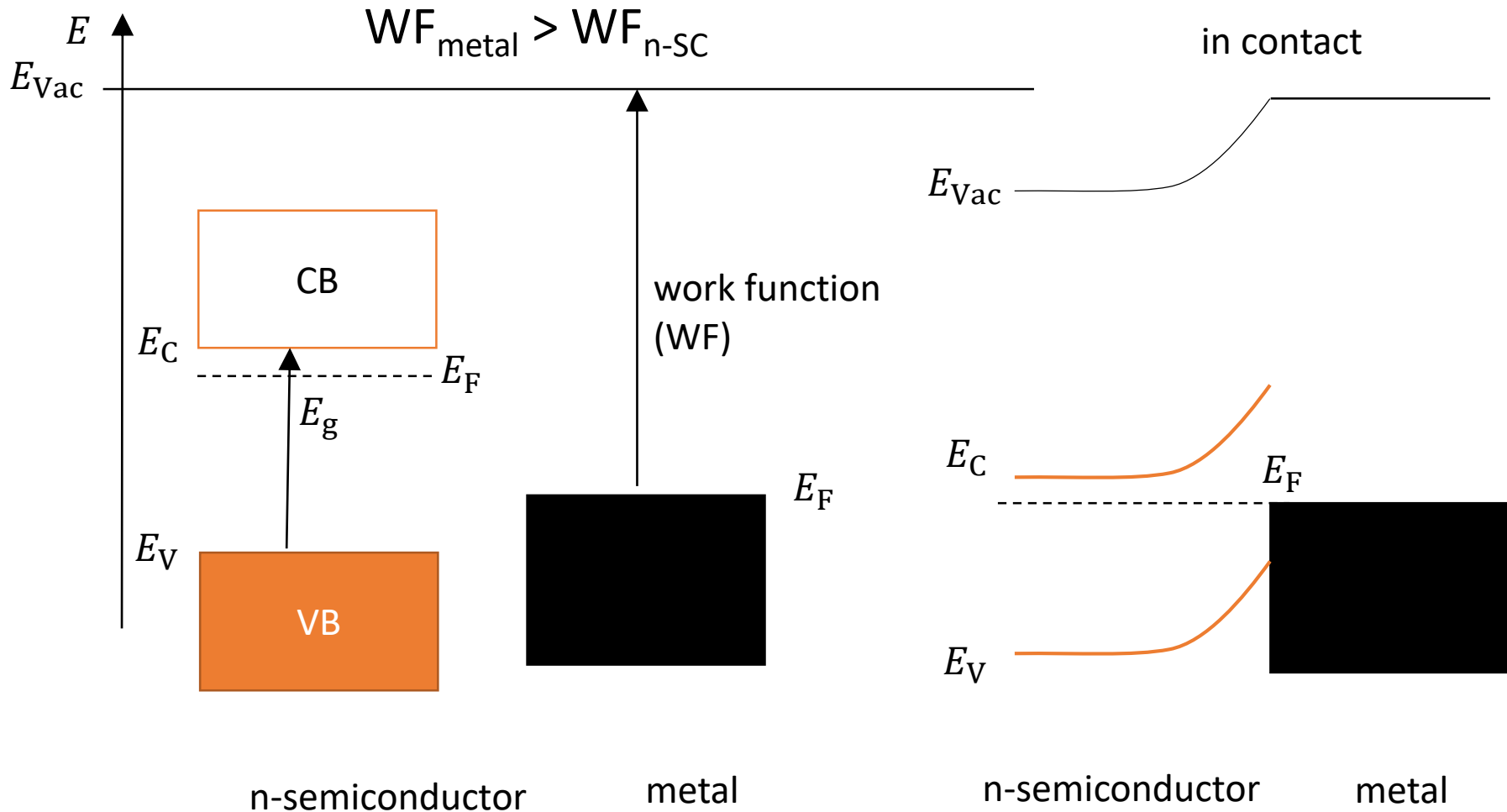


pn Junction



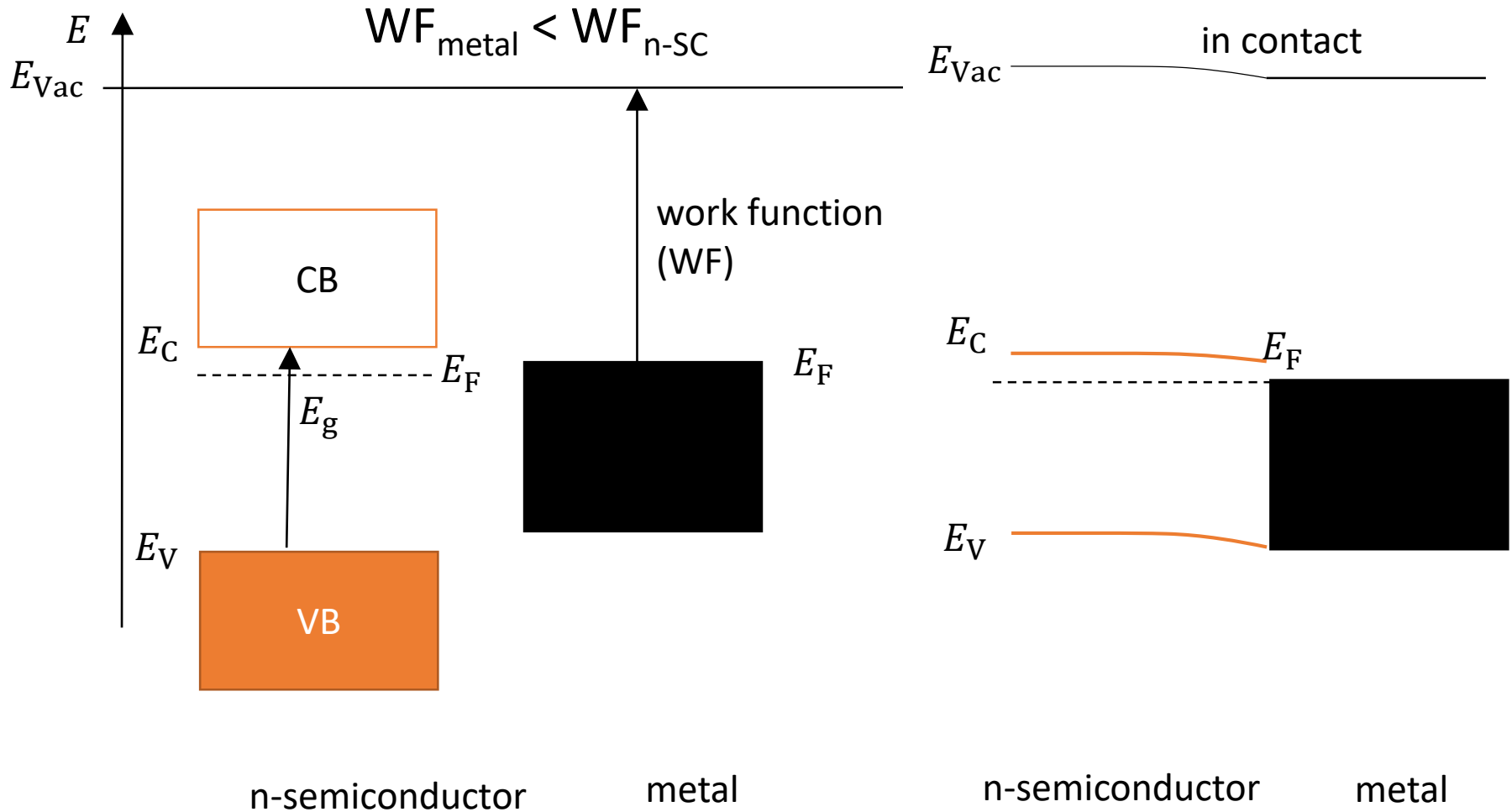
$$J(V) = J_0 \left(\exp\left(\frac{eV}{k_B T}\right) - 1 \right)$$

Metal Semiconductor Junctions I



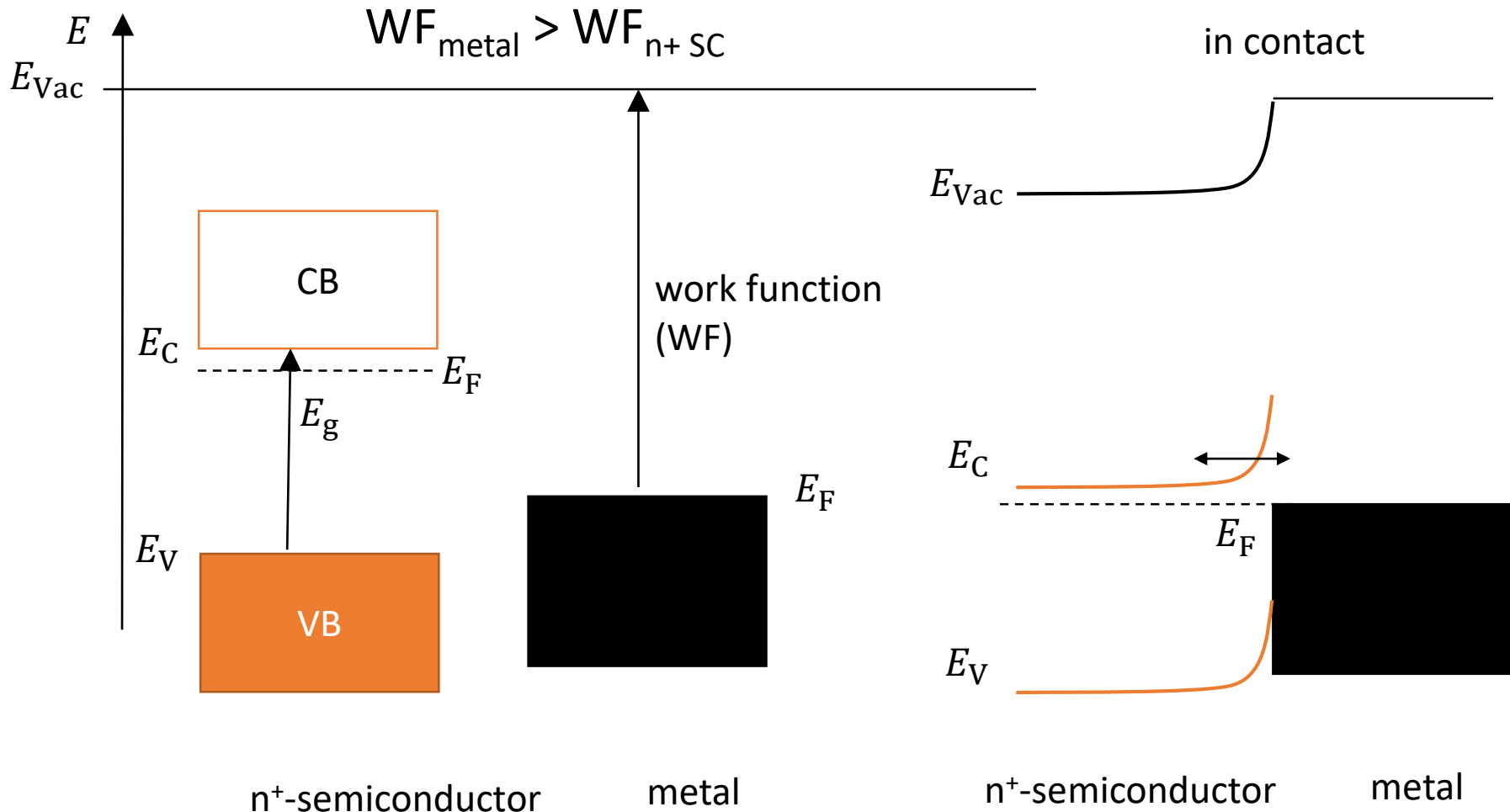
Schottky Contact \rightarrow Diode

Metal Semiconductor Junctions II



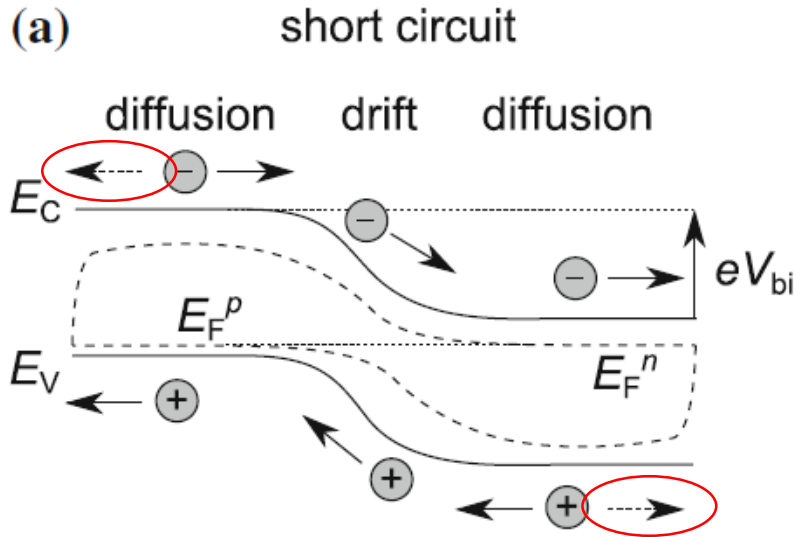
Ohmic Contact

Metal Semiconductor Junctions III



Tunneling junction → Ohmic contact, not selective

Diode under Illumination

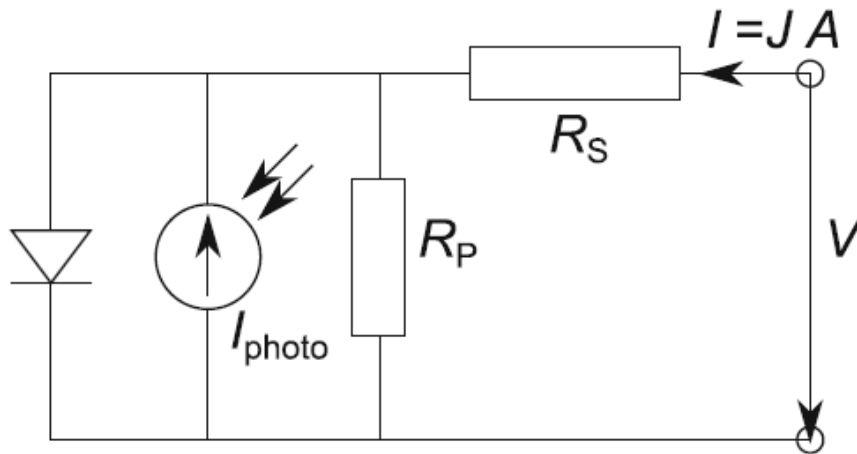


Superposition of dark and photocurrent ($J_{ph}(V) = J_{sc}$):

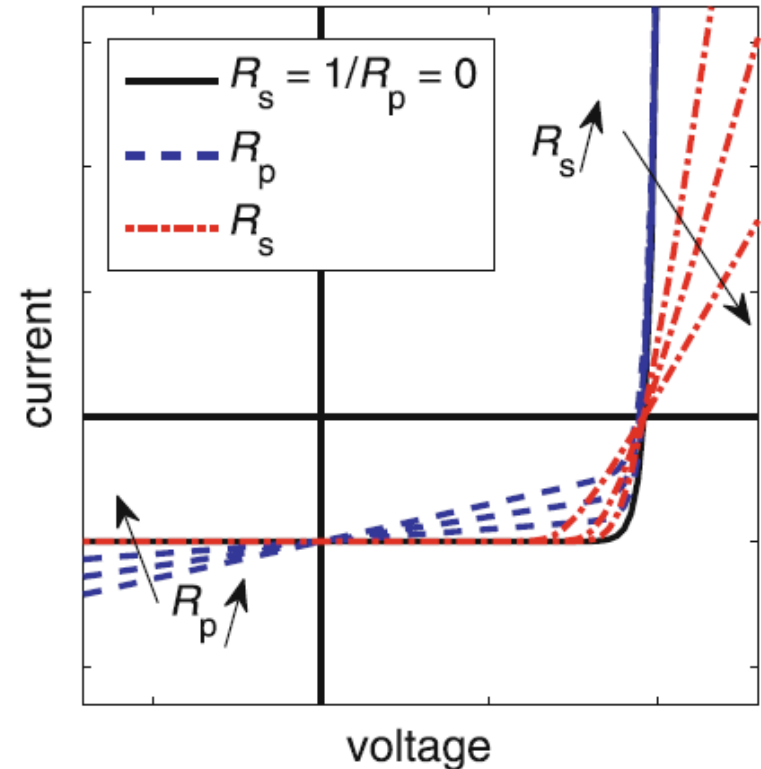
$$J(V) = J_0 \left(\exp\left(\frac{eV}{k_B T}\right) - 1 \right) - J_{sc} \quad V_{oc} = \frac{k_B T}{e} \ln\left(\frac{J_{sc}}{J_0} + 1\right)$$

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

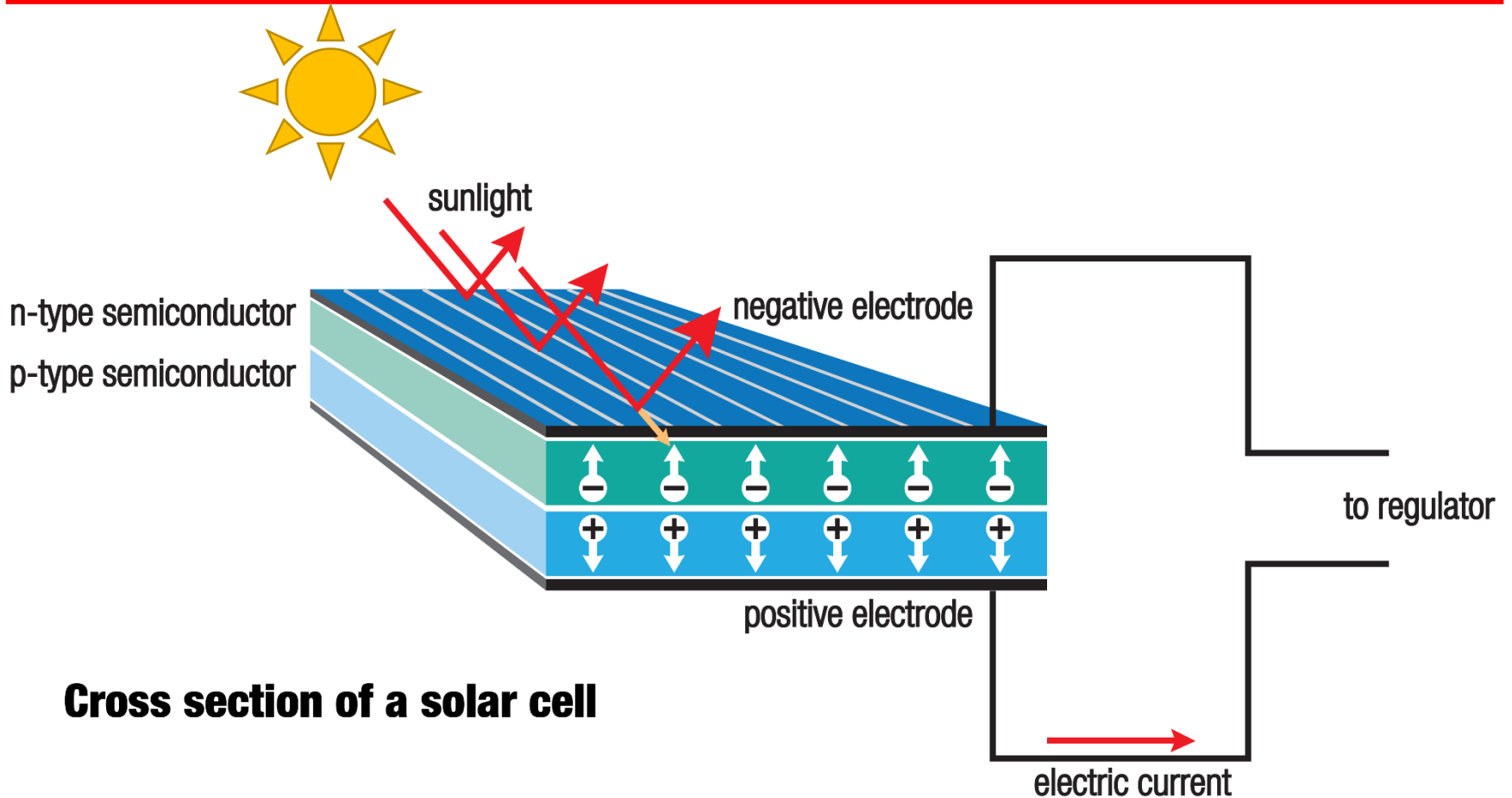
Equivalent Circuit



- 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

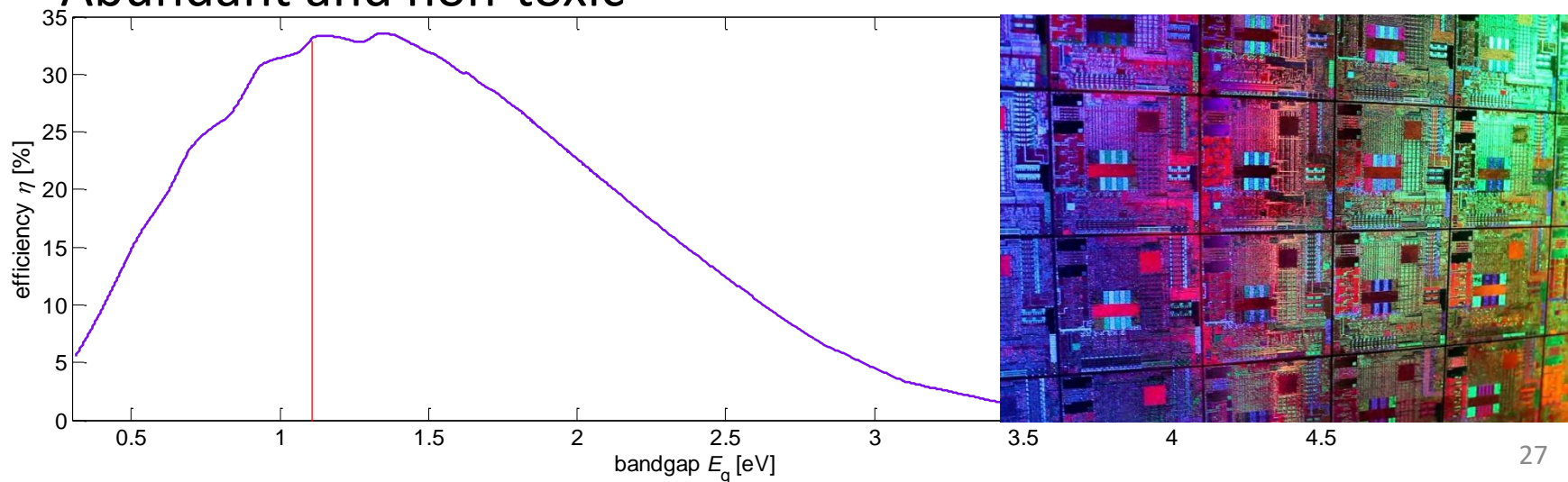
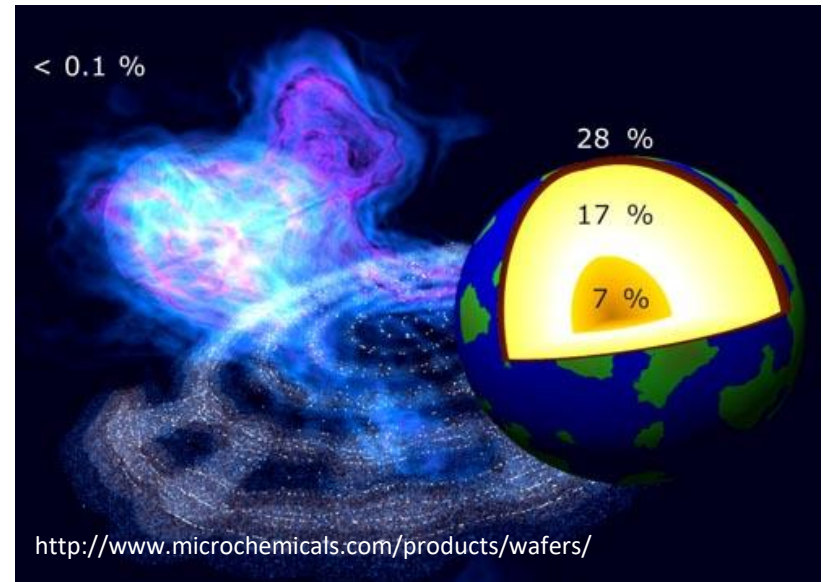


<http://www.redarc.com.au/solar/about/solarpanels/>

Realization: Which material?

Silicon: Why?

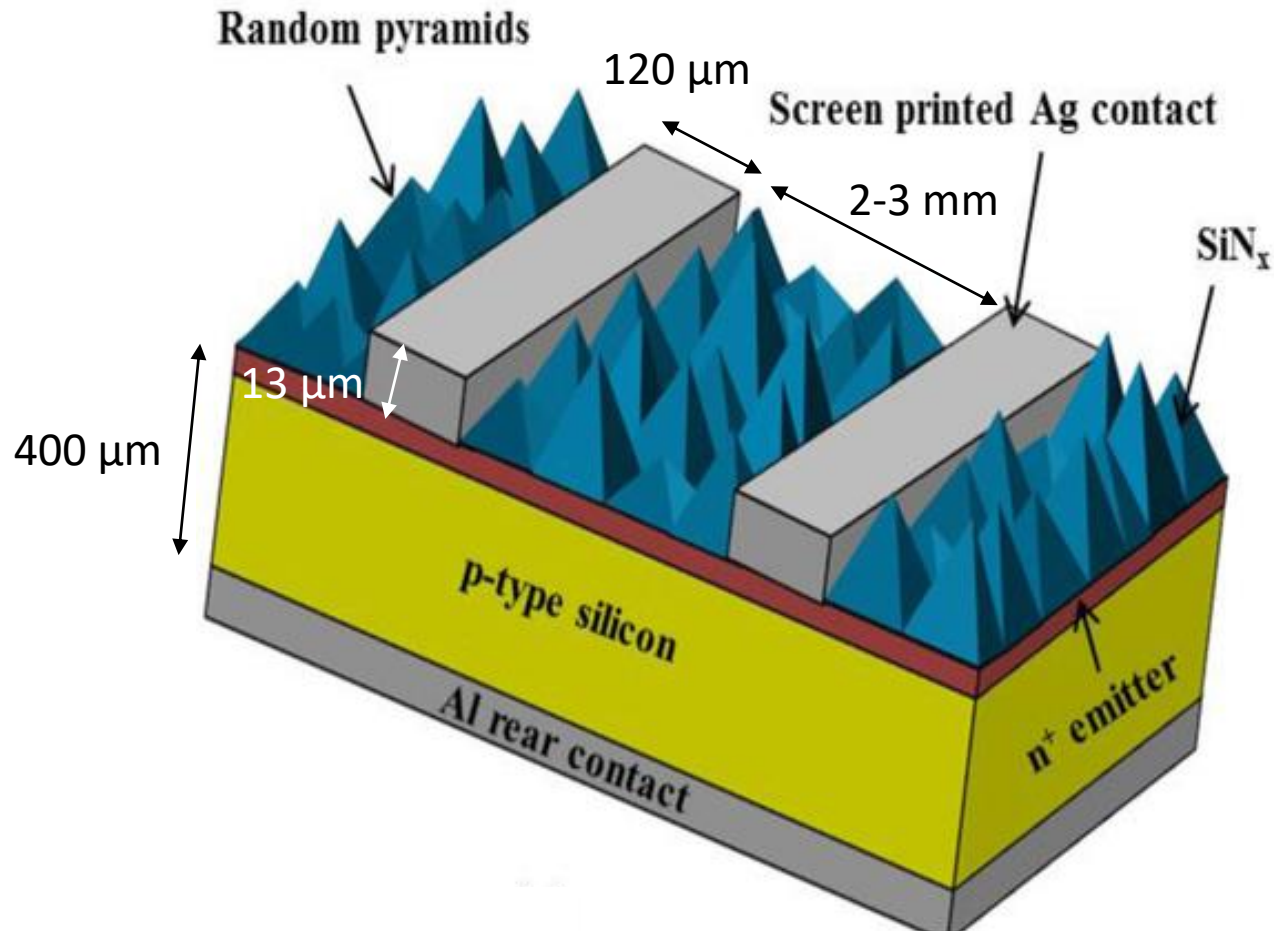
- E_g is suitable
- Doping is possible
- Mostly used in microelectronics
- Native oxide as passivation layer
- **Abundant and non-toxic**



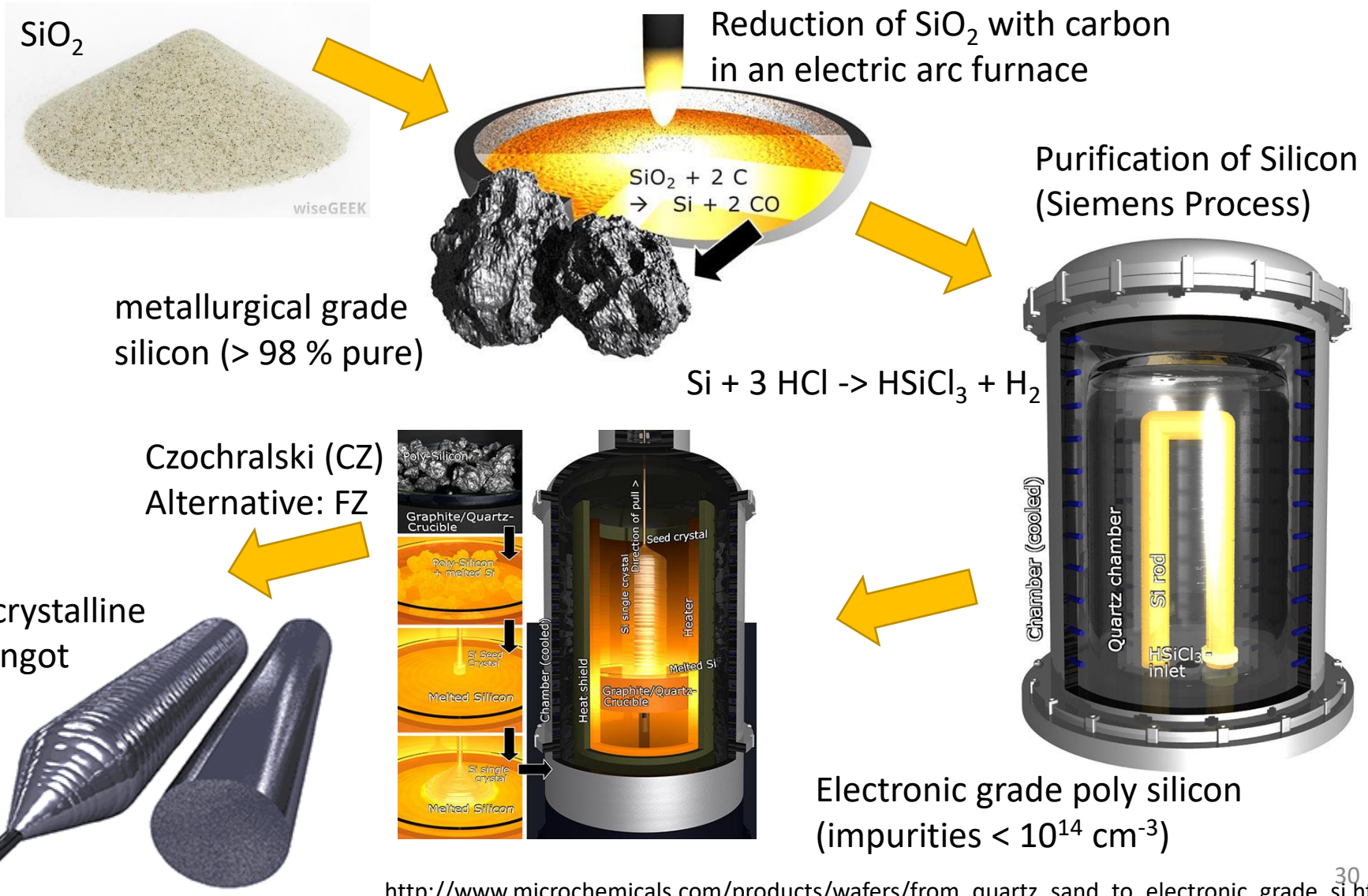
Crystalline Silicon Solar Cells



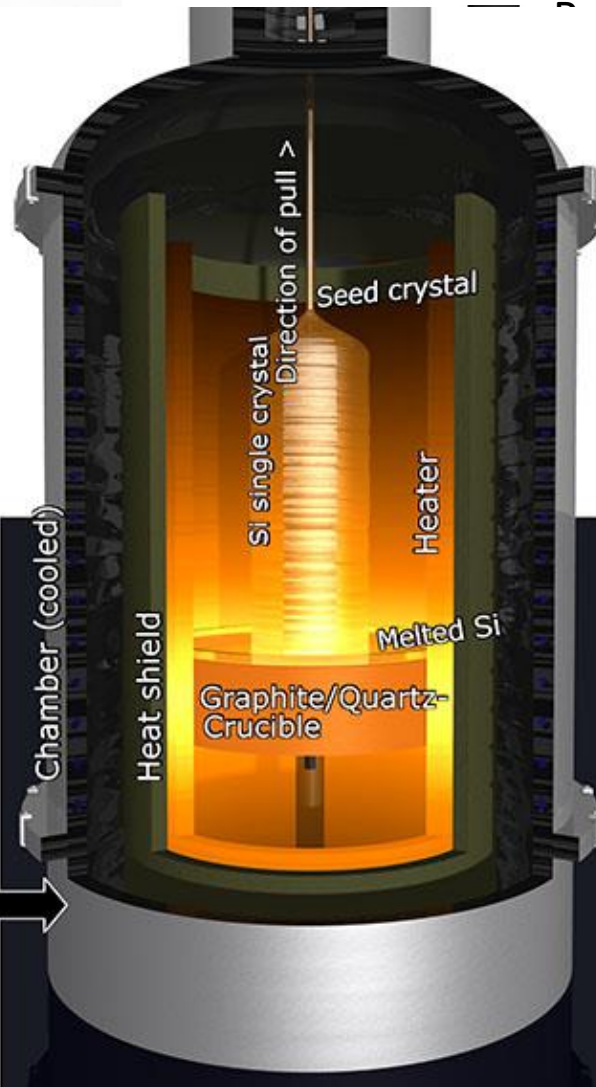
Basic Structure of Silicon Solar Cell



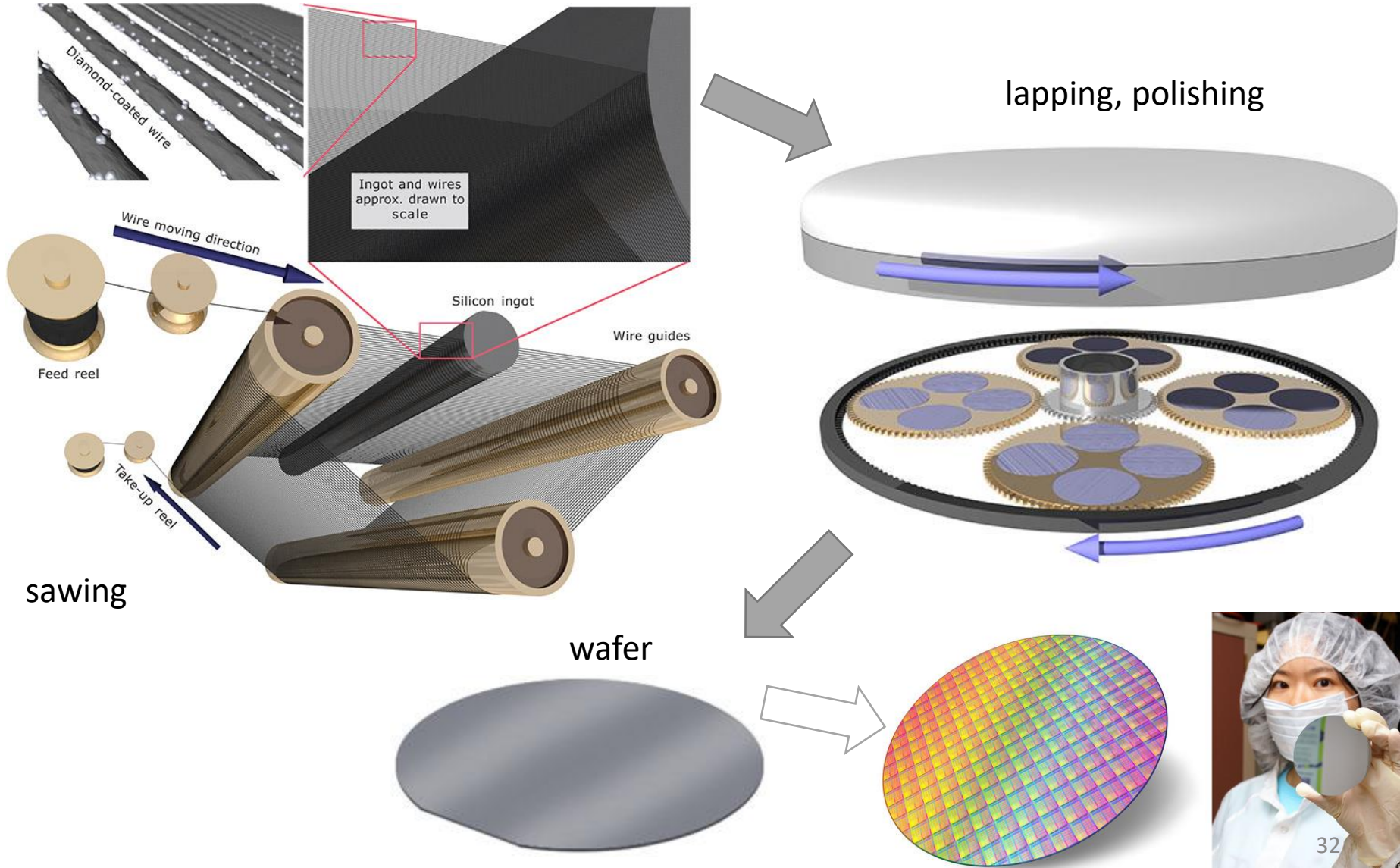
From Sand to Solar: The Ingot



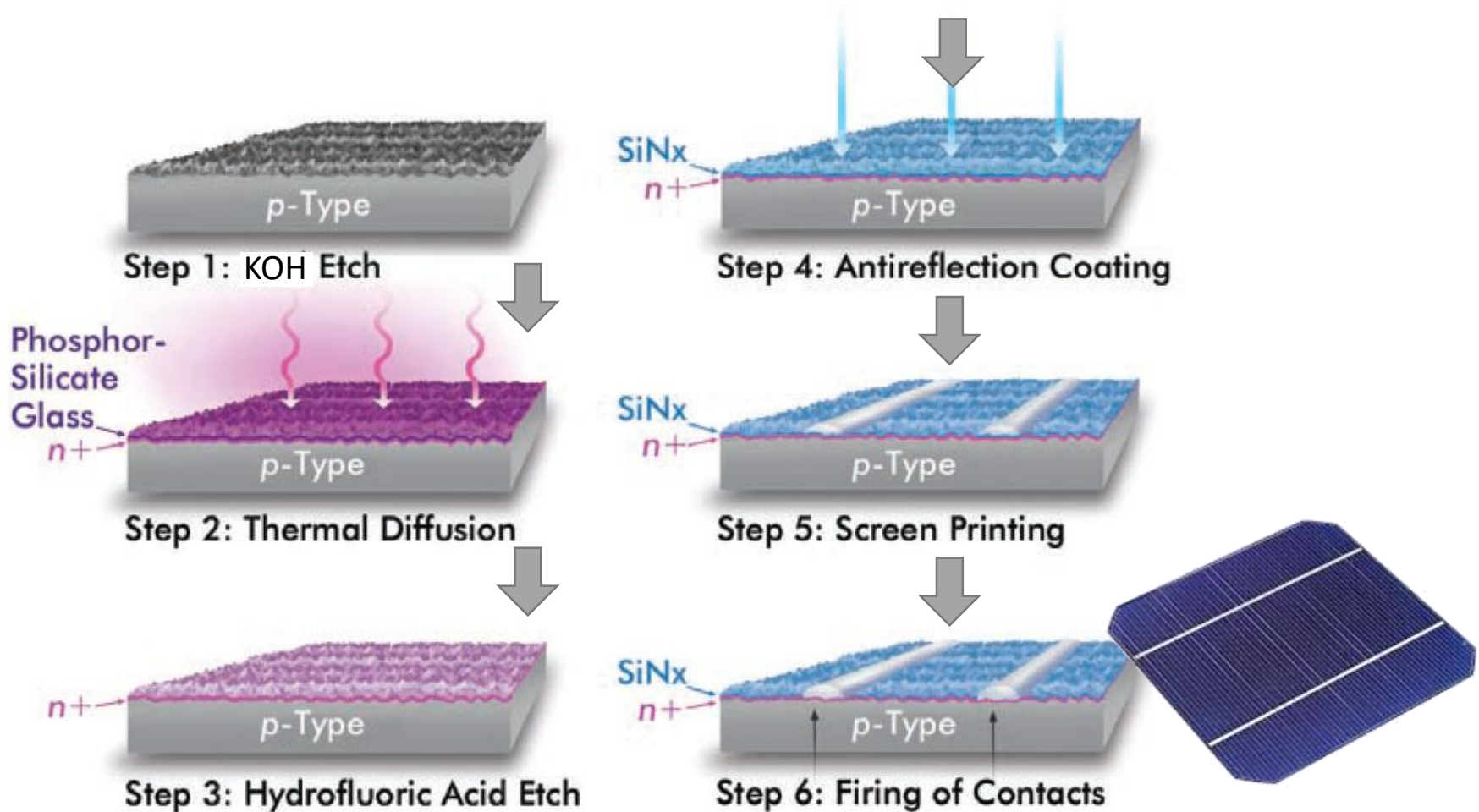
From Sand to Solar: The Ingot



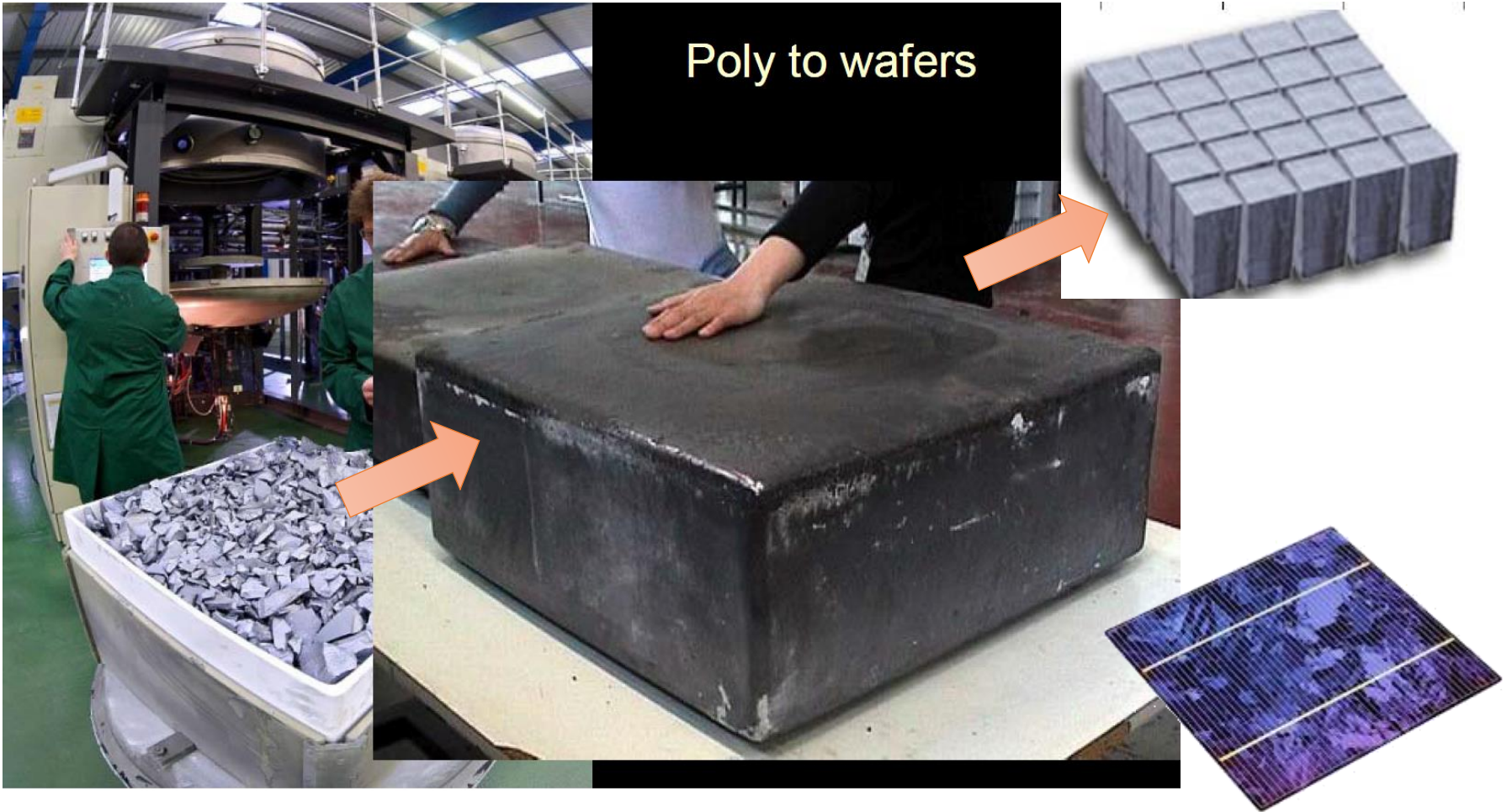
From Sand to Solar: The Wafer



From Sand to Solar: The Solar Cell



Multicrystalline Solar Cell



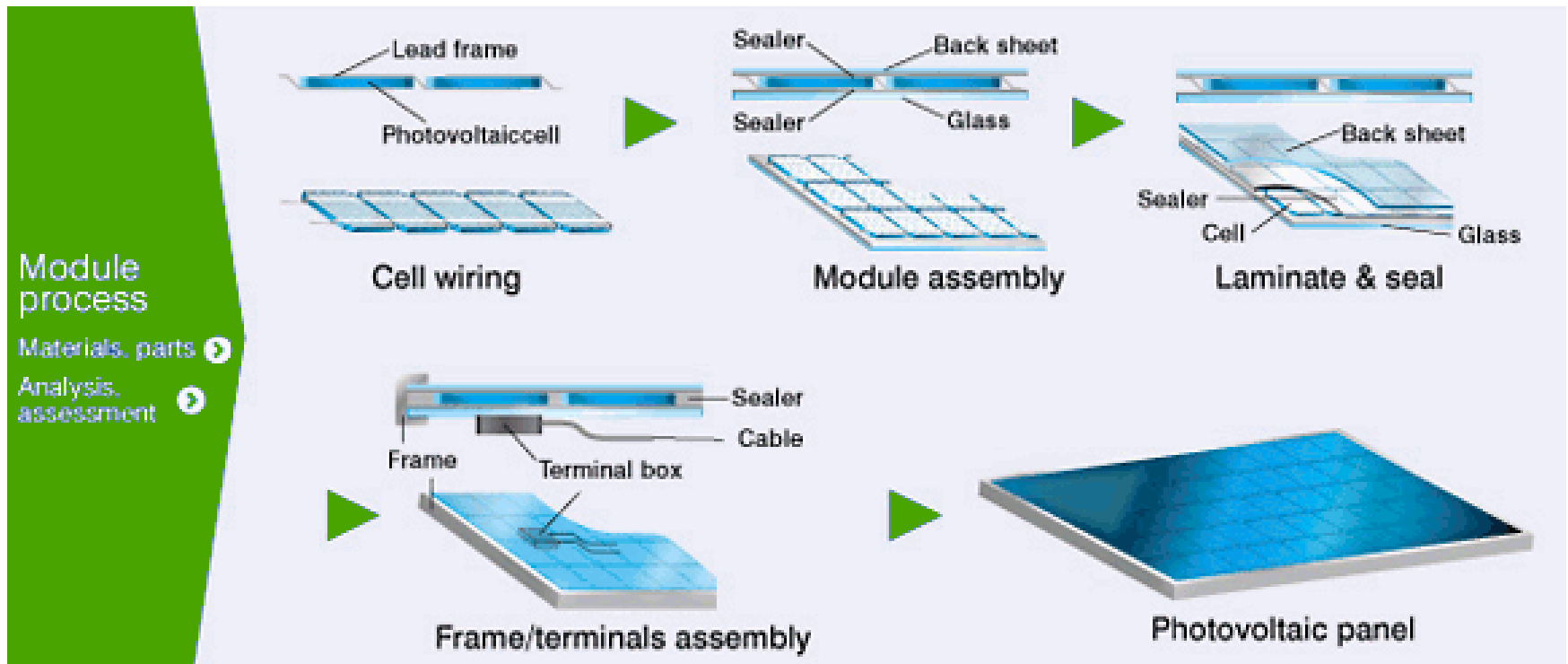
Martin Green

**Poly-Crystalline
Solar Cell**

From Sand to Solar: The Module



www.think-solar-power.com



Modules



DIMENSIONS / WEIGHT

<i>Length</i>	1675 mm
<i>Width</i>	1001 mm
<i>Height</i>	33 mm
<i>Weight</i>	18.0 kg

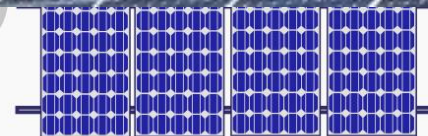
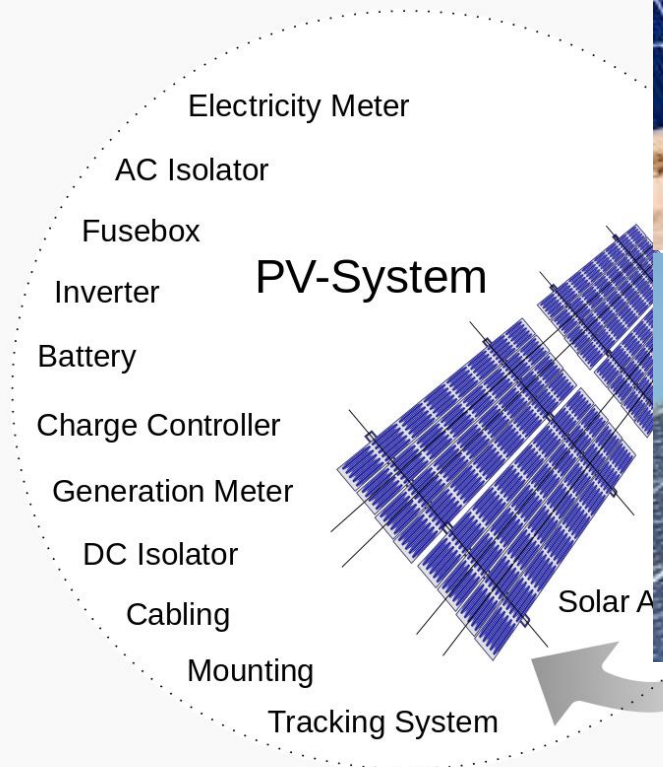
SolarWorld

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



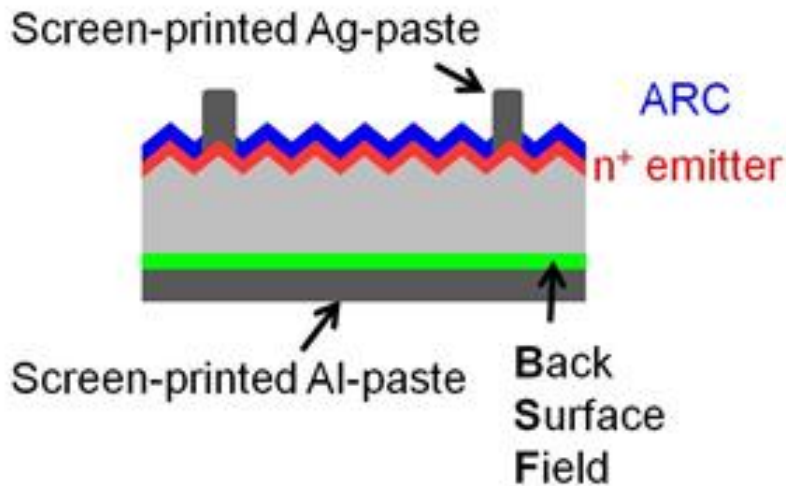
From Sand to Solar: The PV Installation

From a solar cell to a PV System

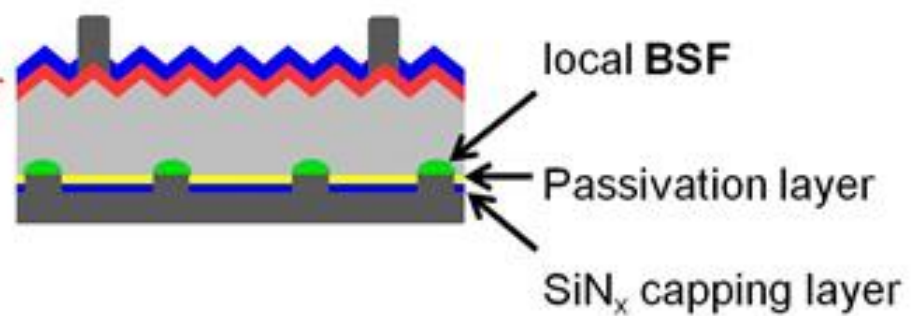


Different Architectures

Standard solar cell

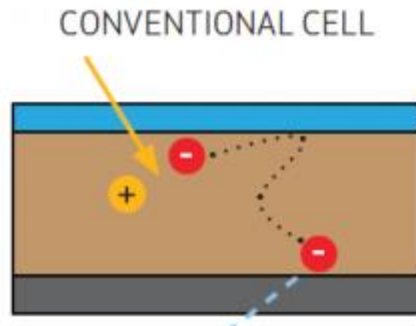


PERC solar cell

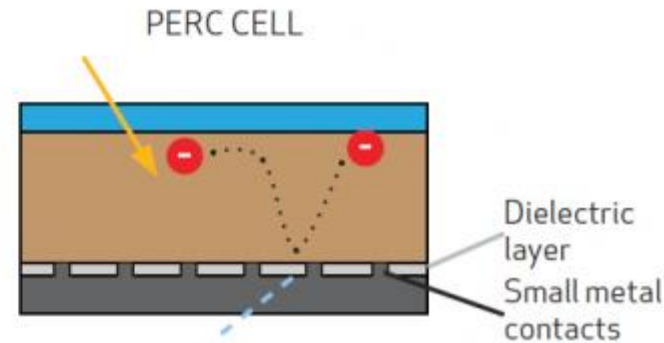


www.greentechmedia.com

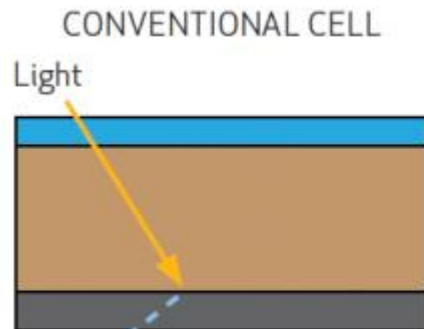
Different Architectures: PERC



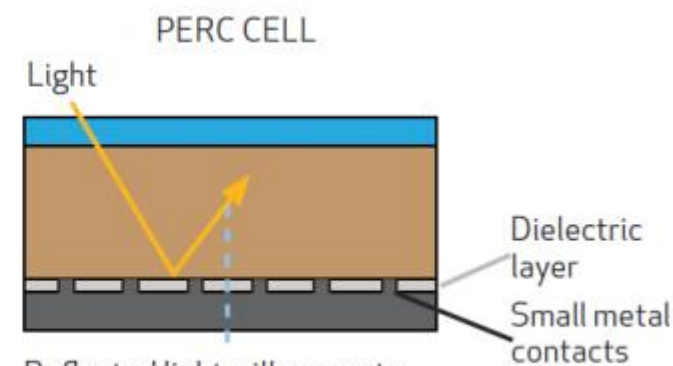
If an electron reaches the back surface, it is frequently captured and can no longer contribute to the current.



PERC technology stops the electron from being captured, and gives it a 'second chance' to reach the emitter and contribute to the current.



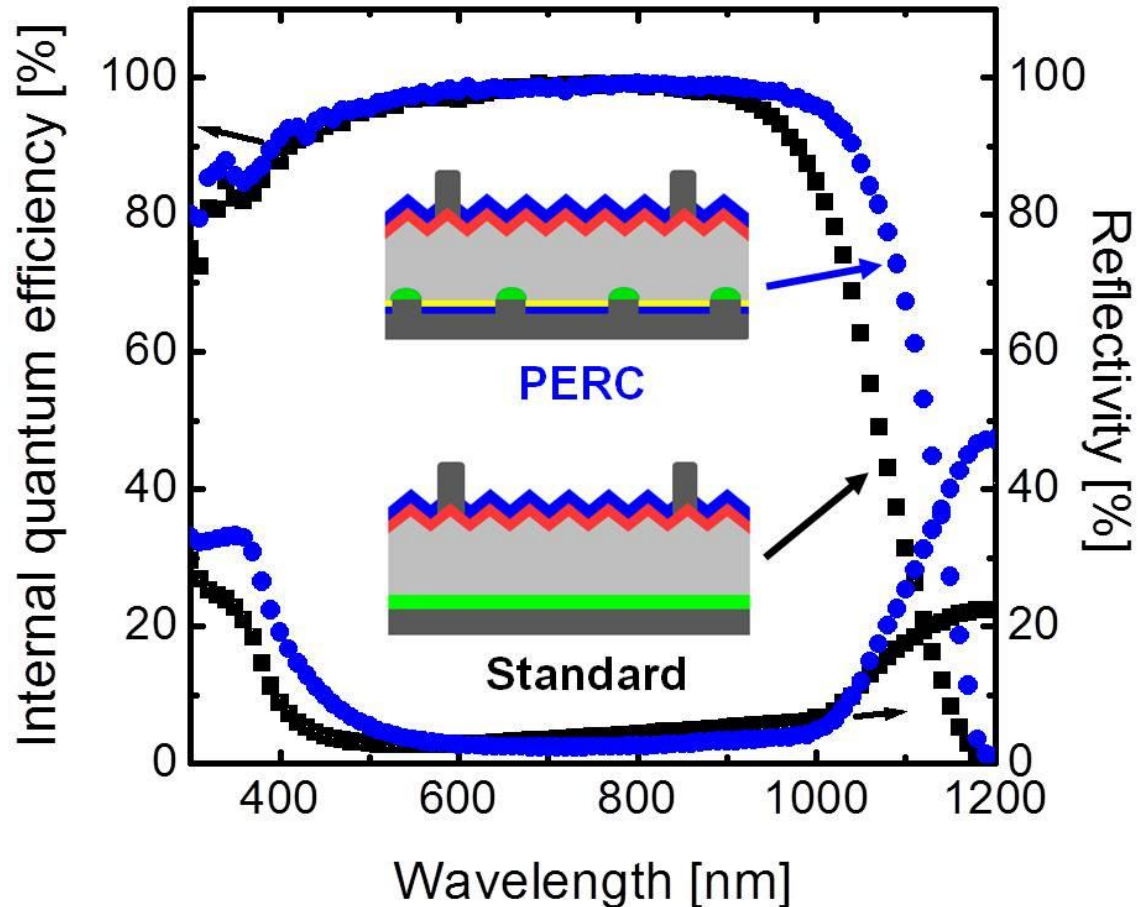
Light is absorbed by the aluminum metallization.



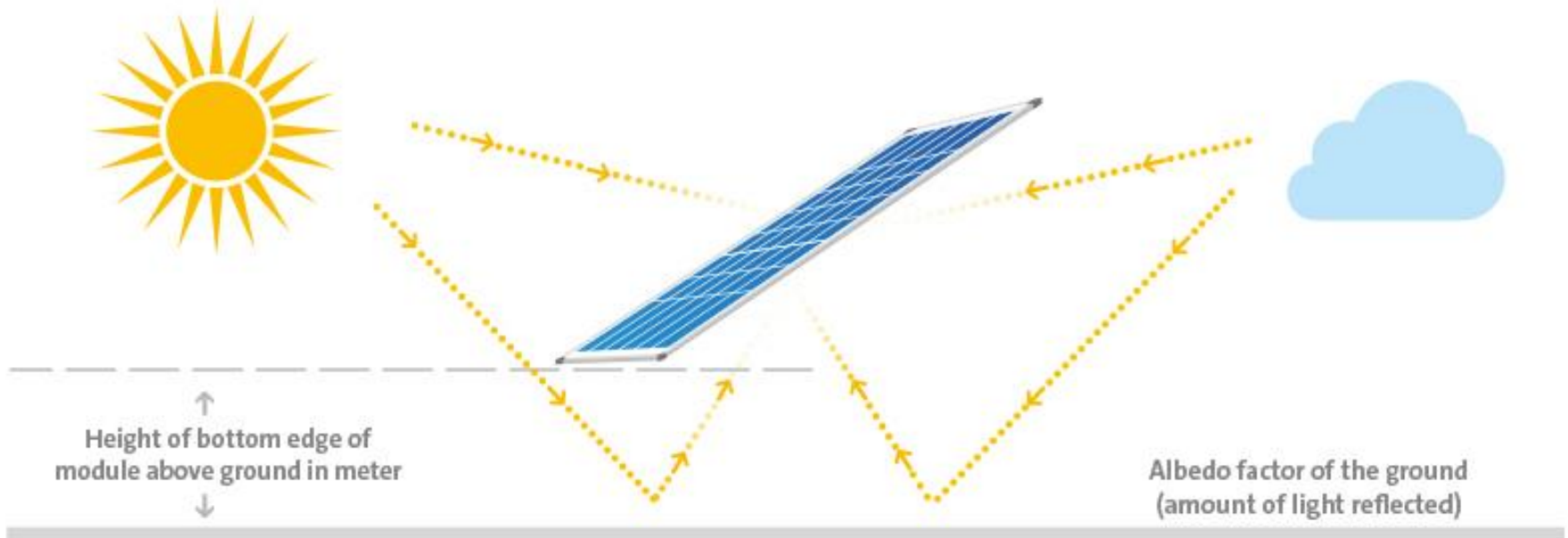
Reflected light will generate additional current.

Different Architectures: PERC

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

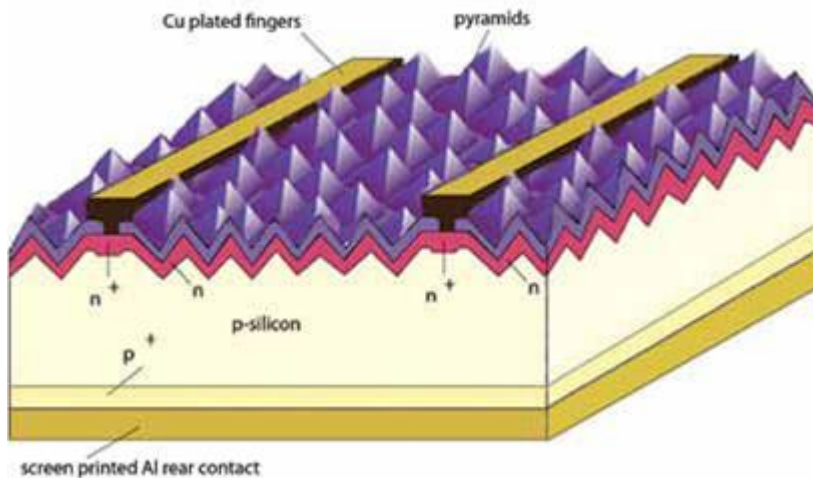


Different Architectures: Bifacial Module



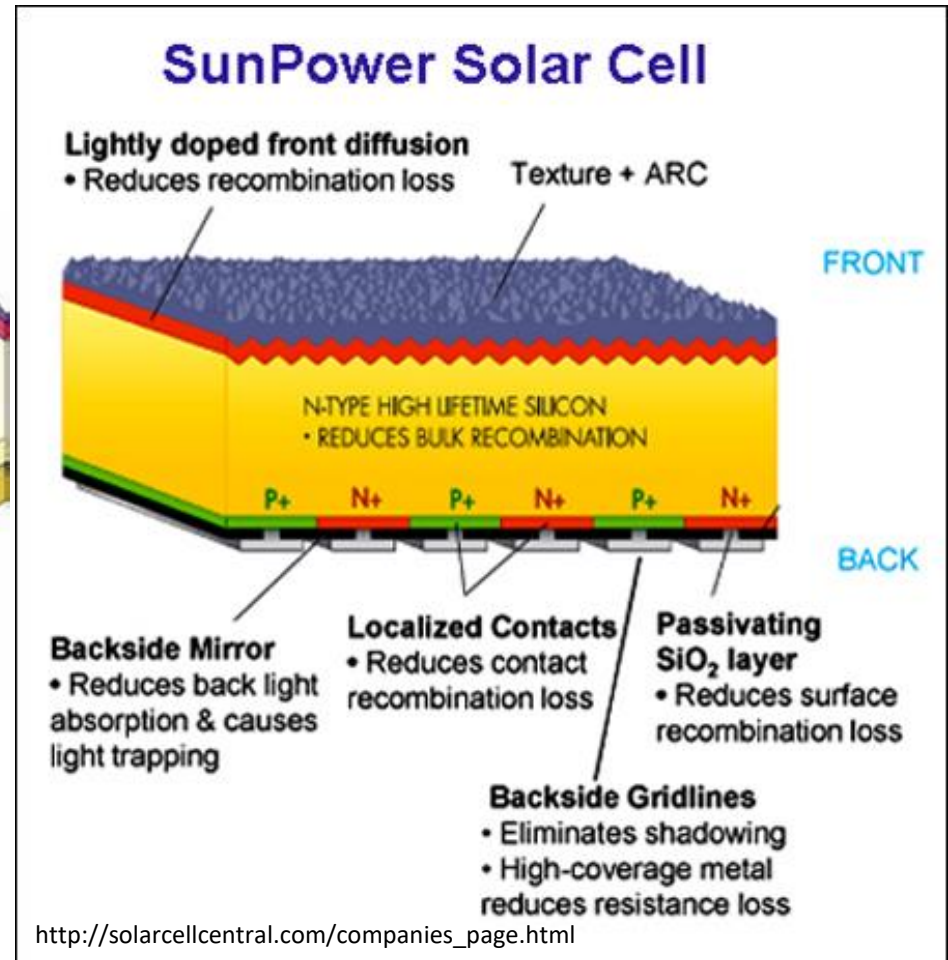
Different Architectures

Laser-doped selective contact



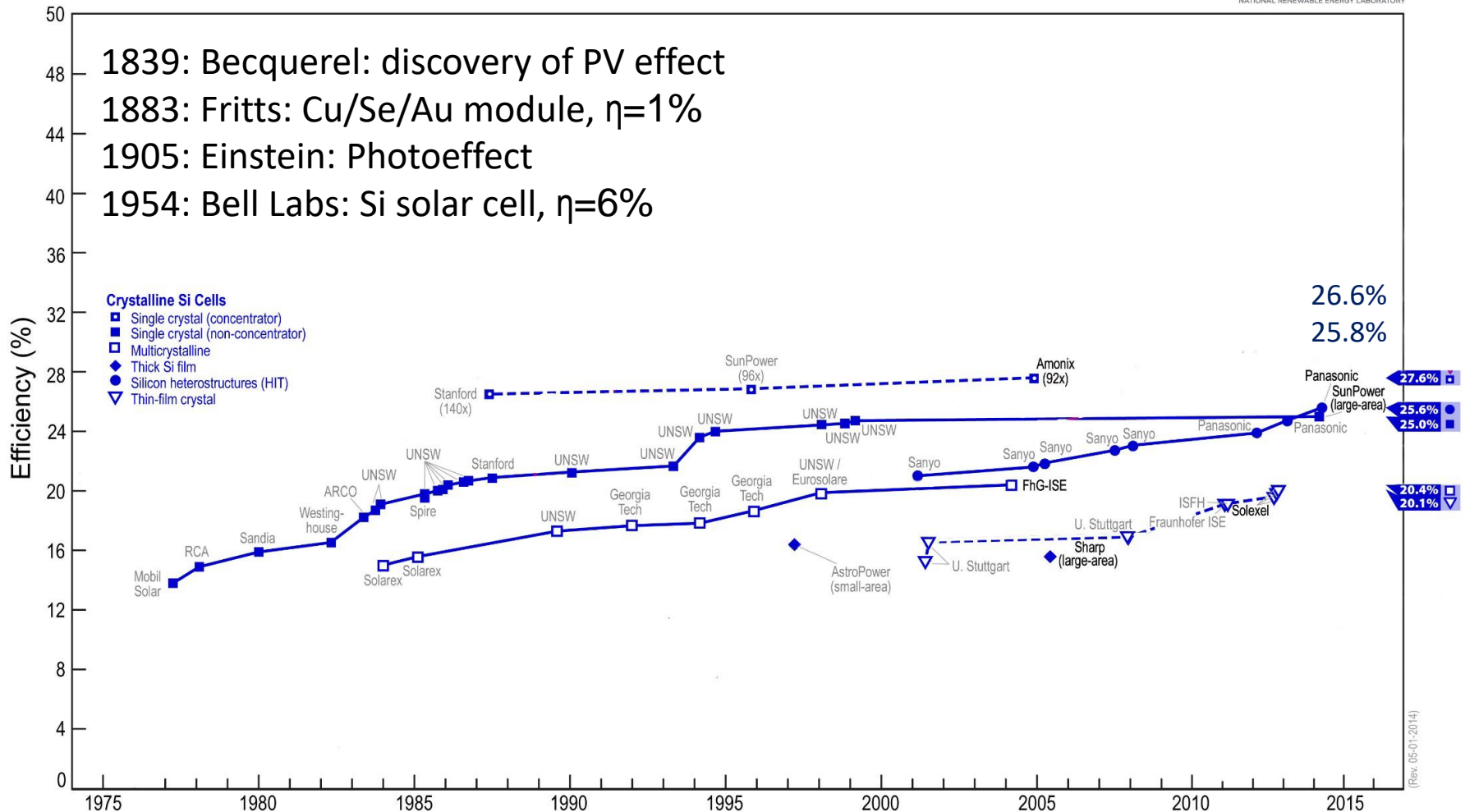
http://www.pv-magazine.com/news/details/beitrag/unsw-hits-194-percent-on-mass-produced-solar-cell--what-next_100003631/#axzz47sdUyPzSa

Interdigitated back contact design (IBC)



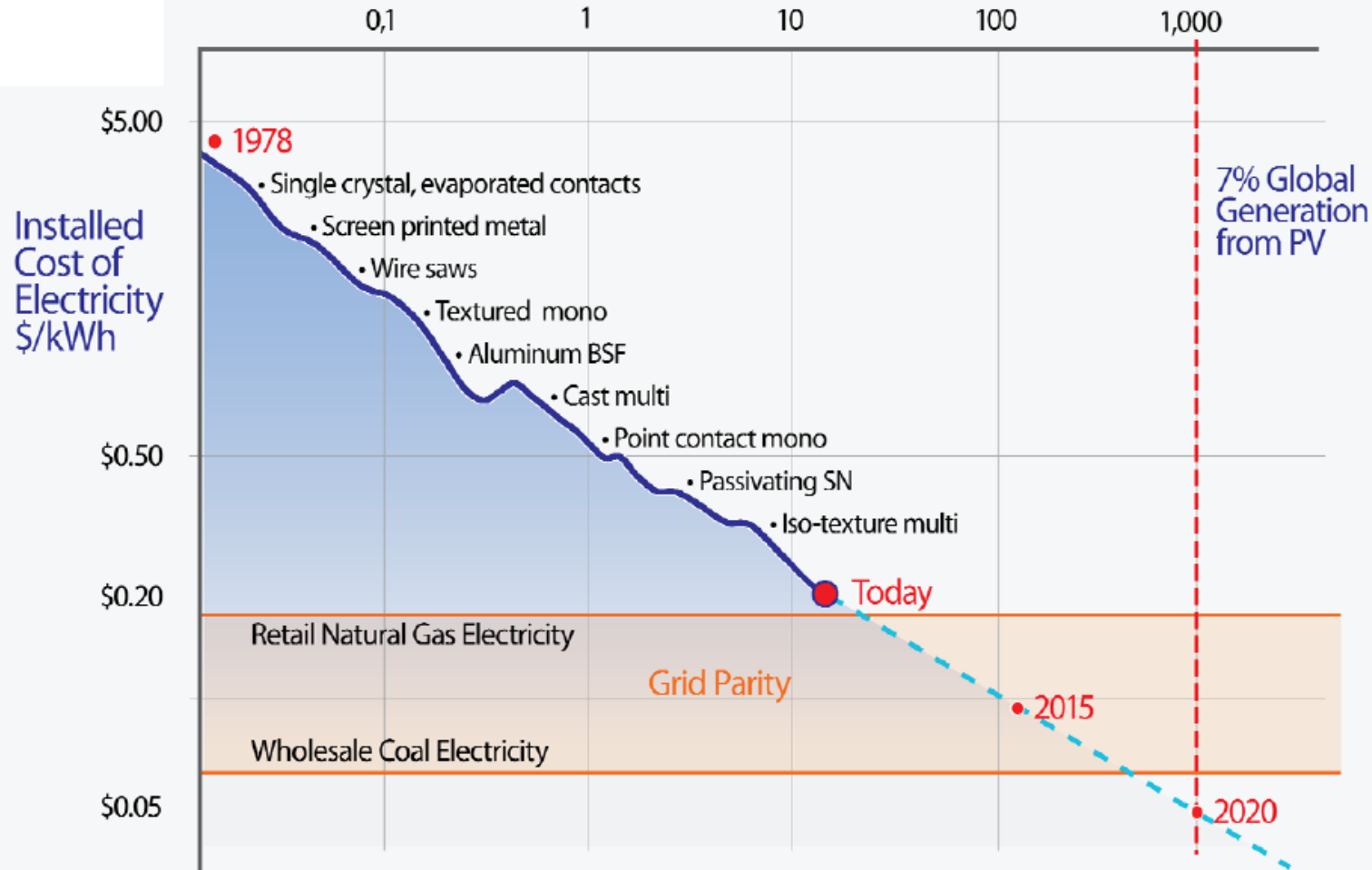
History and Record Lab Efficiencies

Best Research-Cell Efficiencies



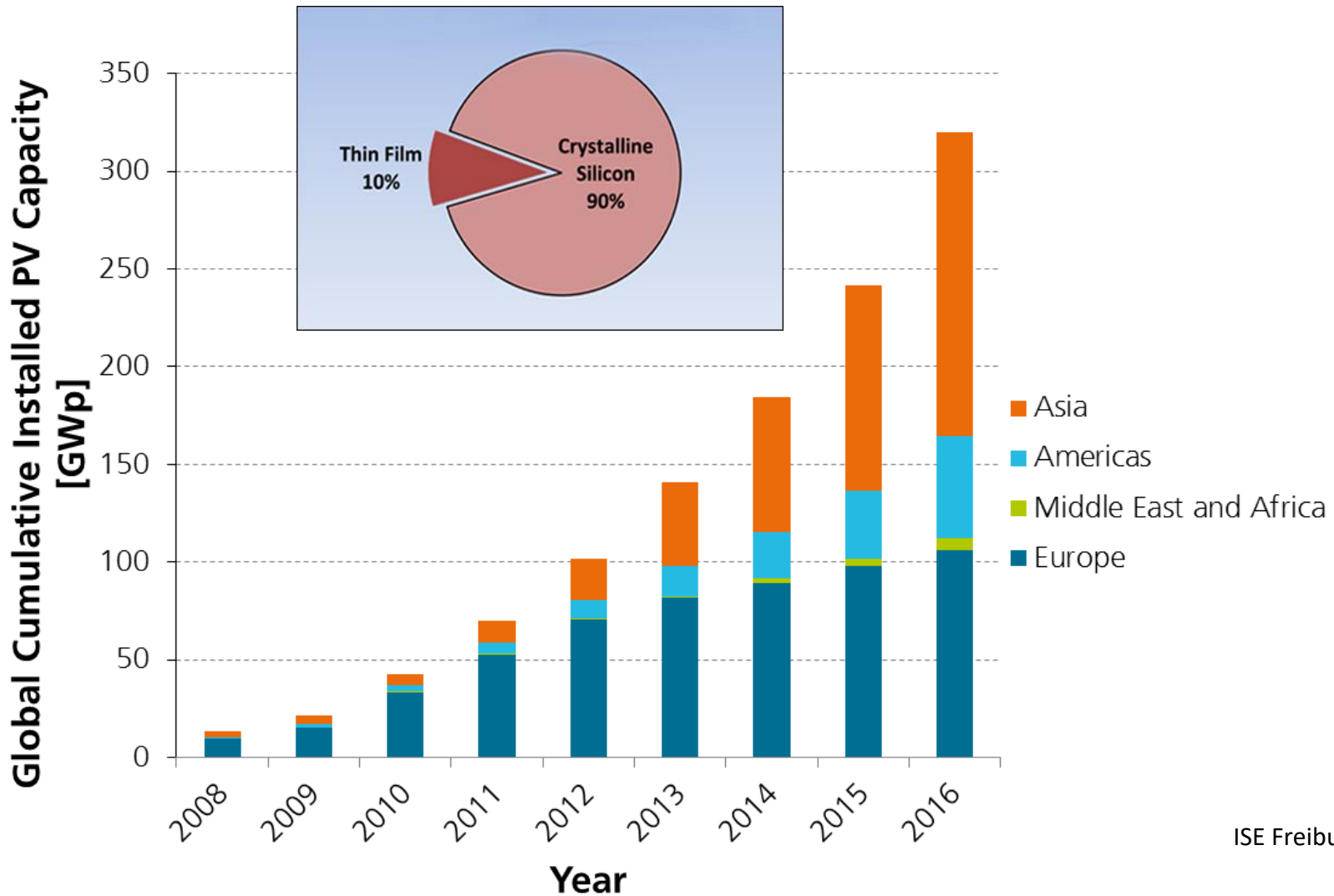
Technical Breakthroughs Reduce Costs

Cumulative production GigaWp



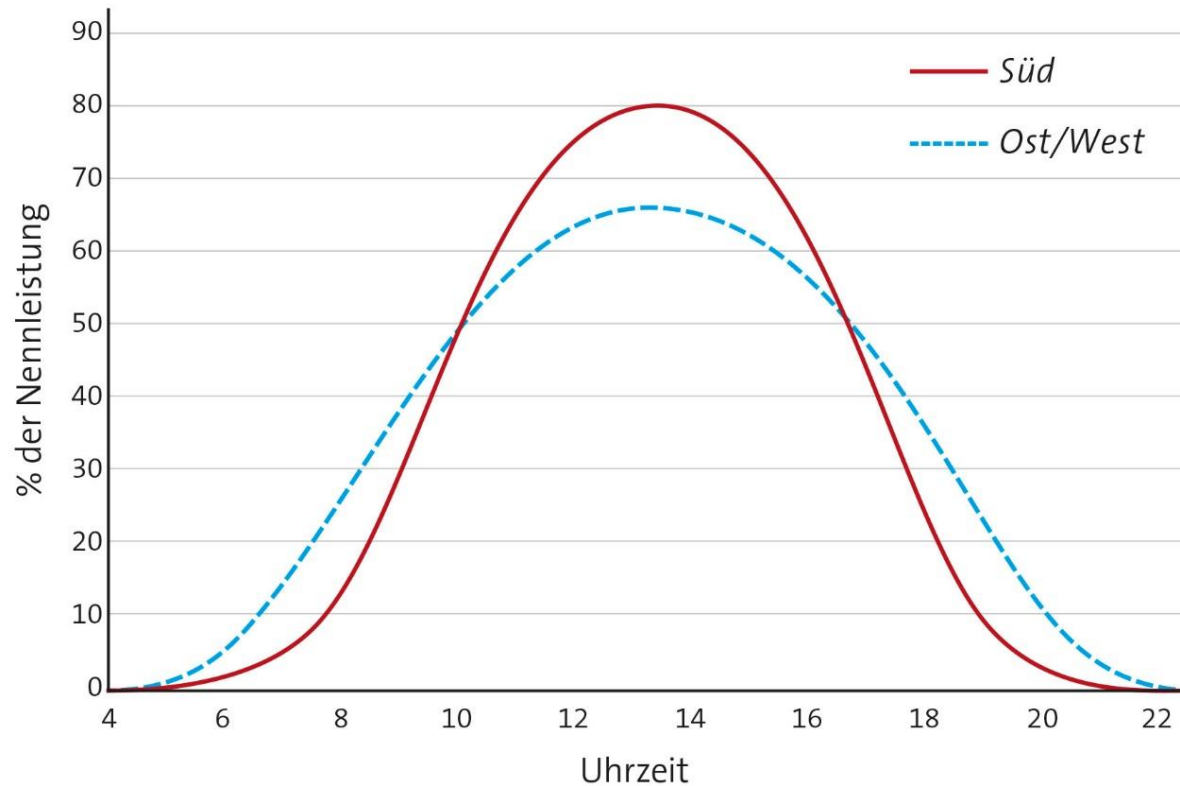
Source: Professor Emanuel Sachs, Massachusetts Institute of Technology
 *Assumes annual production growth of 35% and an 18% learning curve. PV costs based on 18% capacity factor and 7% discount rate.

PV Installations Worldwide



ISE Freiburg, 2018

PV Installations Worldwide

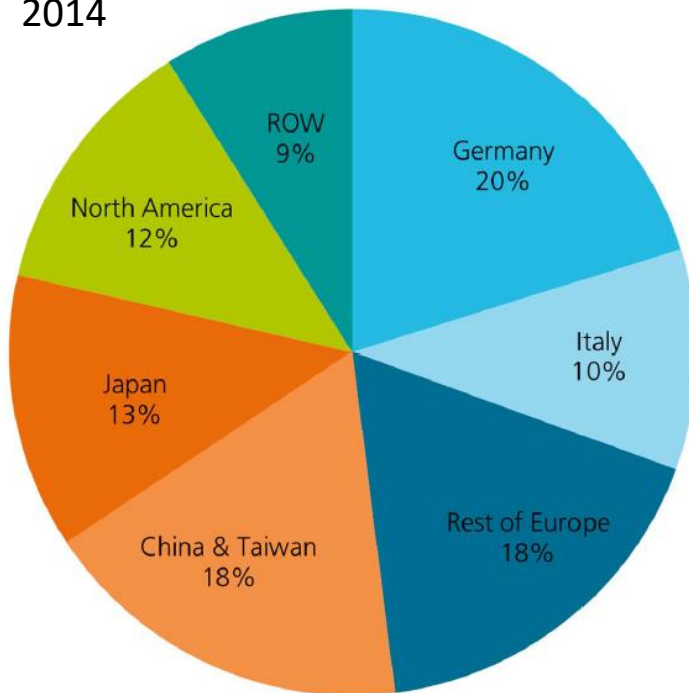


Vergleich von Photovoltaikanlagen unterschiedlicher Ausrichtung an einem Sonnentag (8. July 2013)

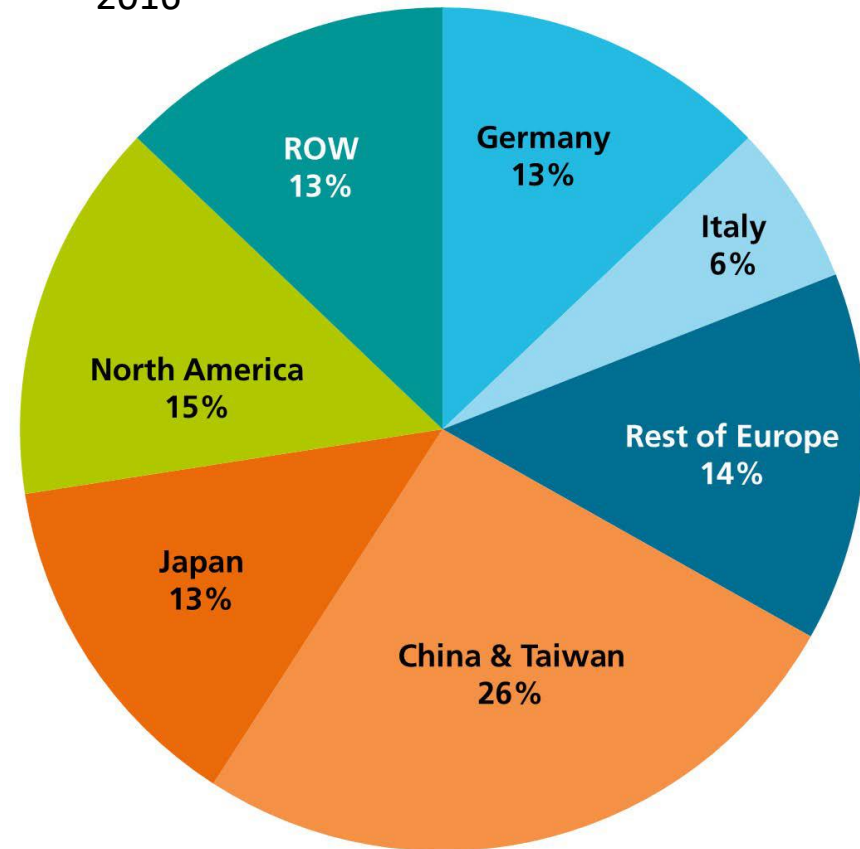
ISE Freiburg, 2018

PV Installations Worldwide

2014

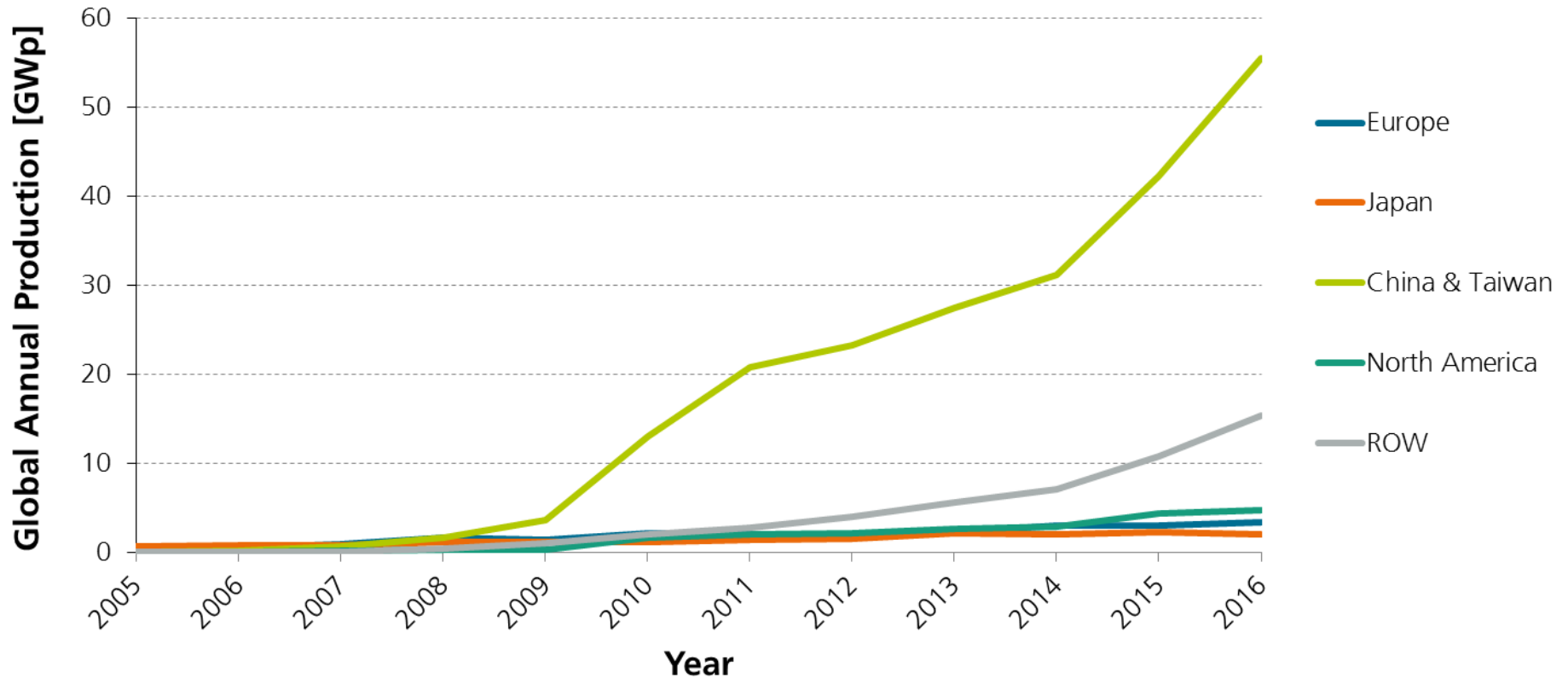


2016



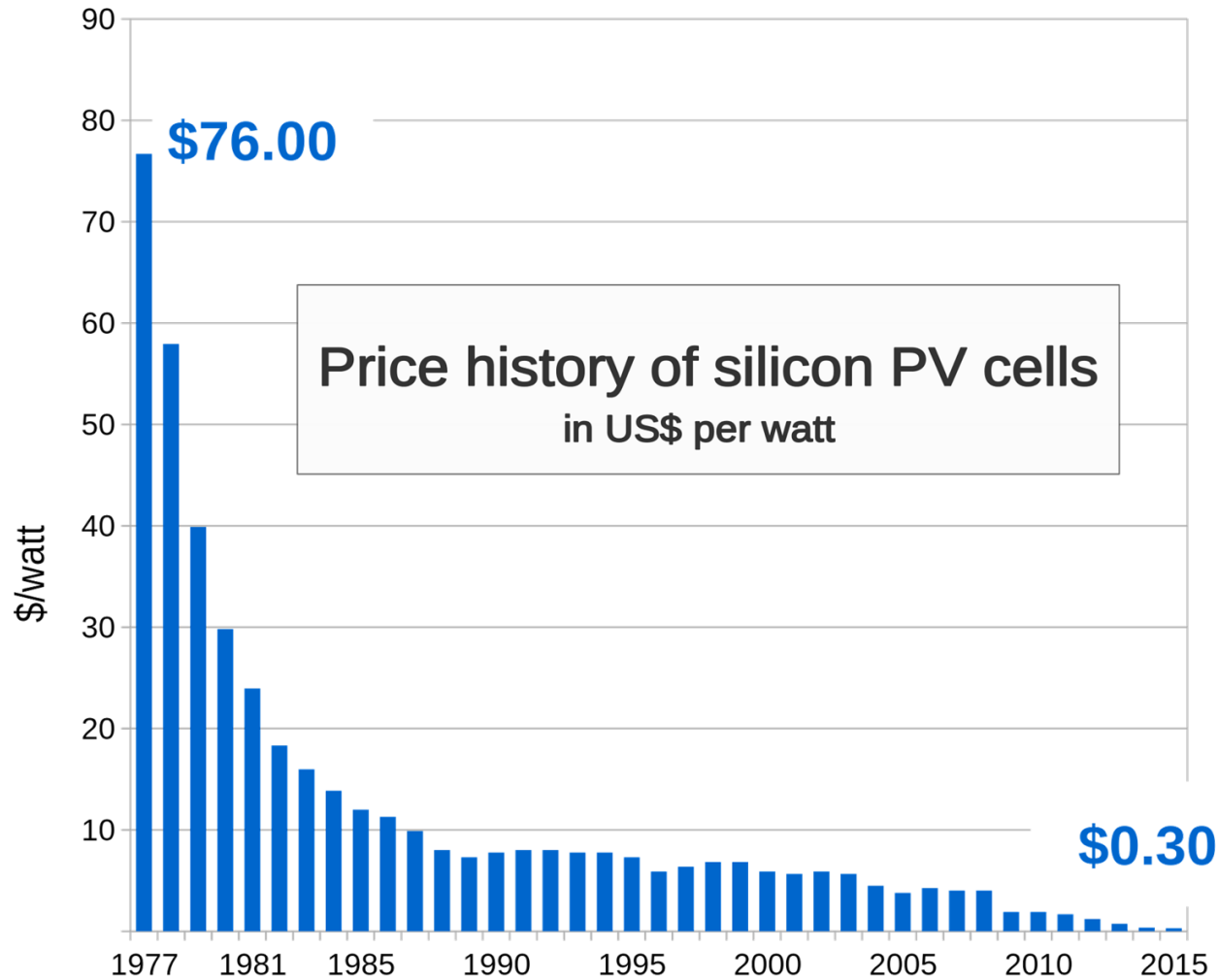
ISE Freiburg, 2018

PV Production



ISE Freiburg, 2018

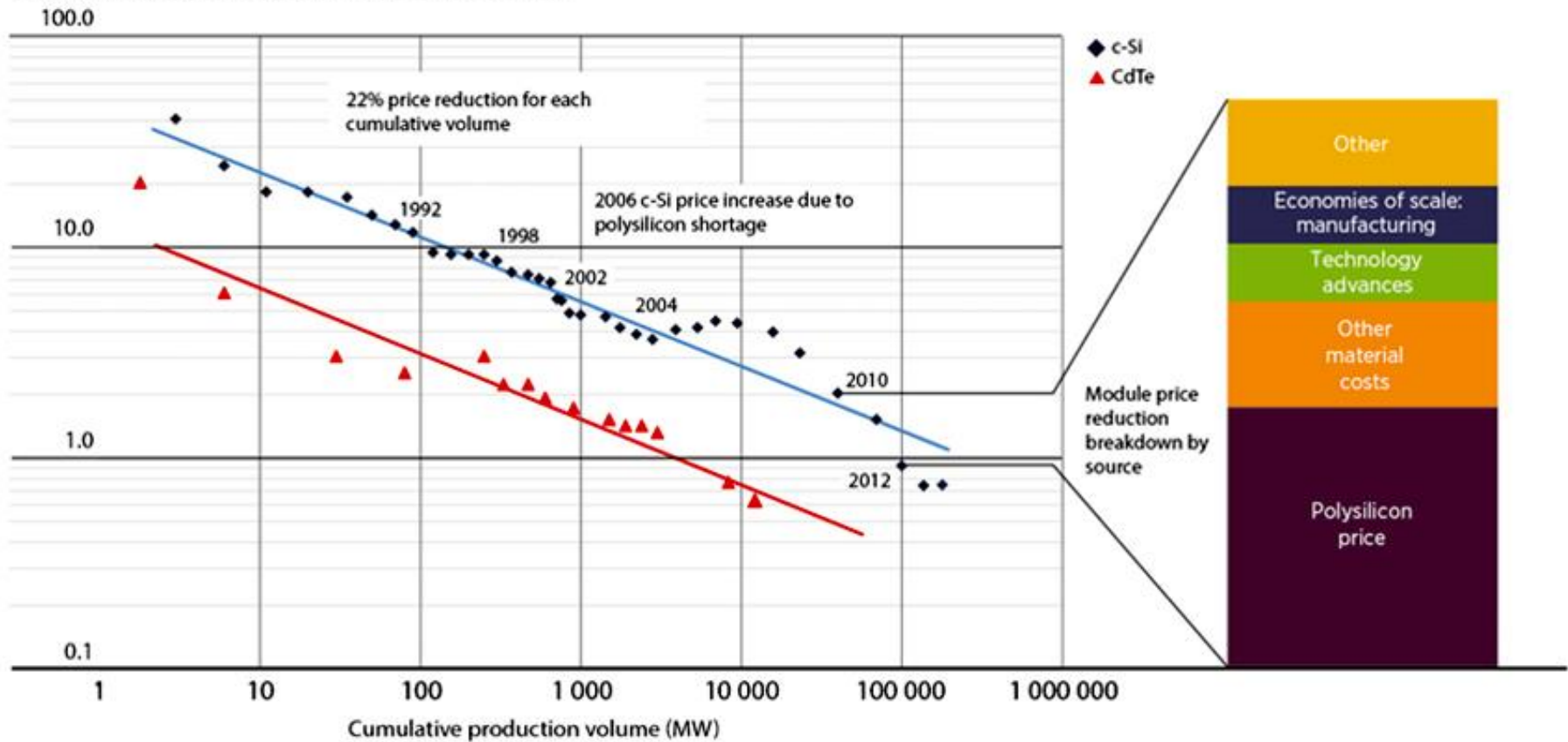
Price



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

Costs and Prices: The Learning Curve

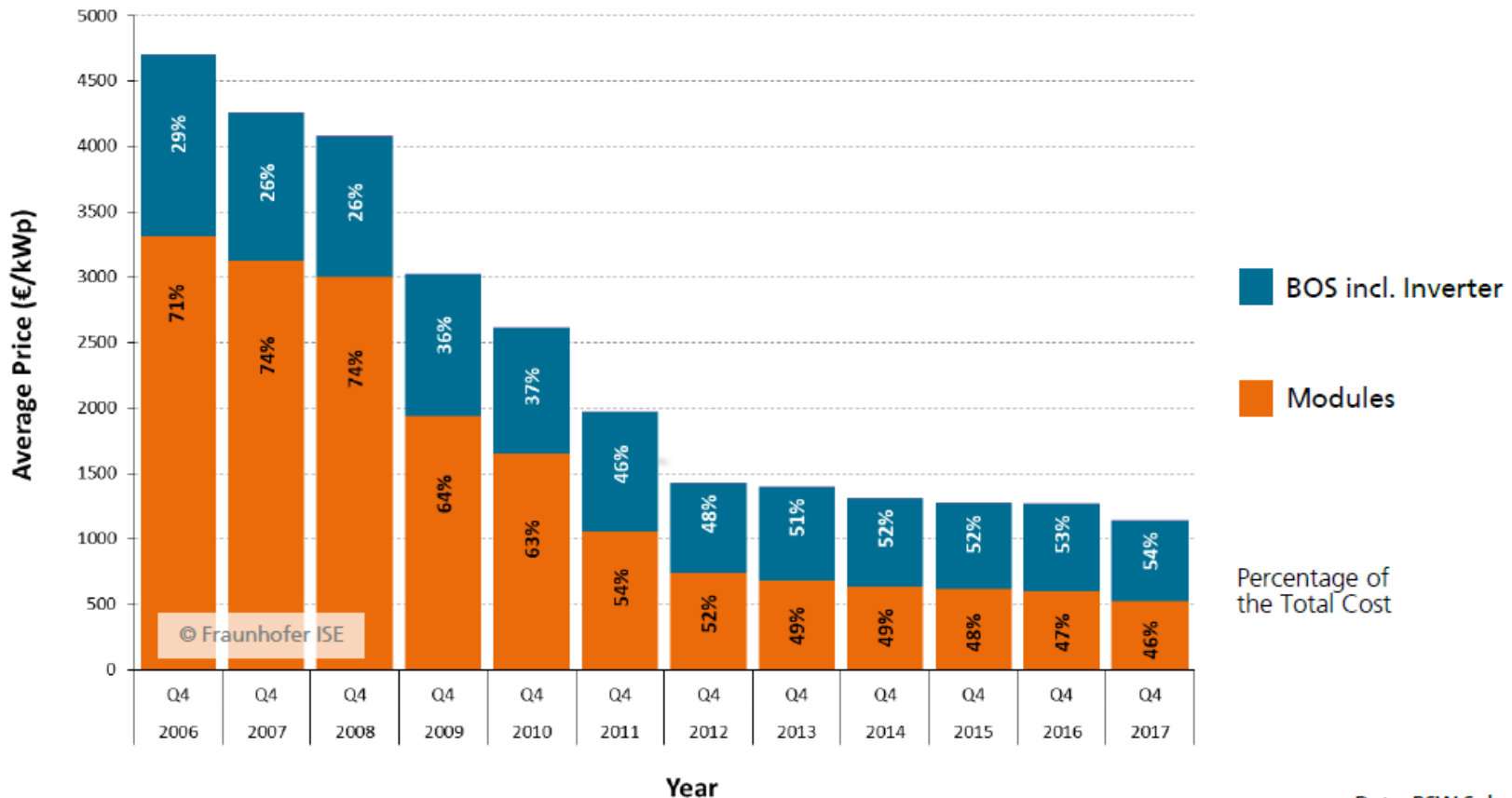
Global average module price (2014 USD/W)



http://solarcellcentral.com/cost_page.html

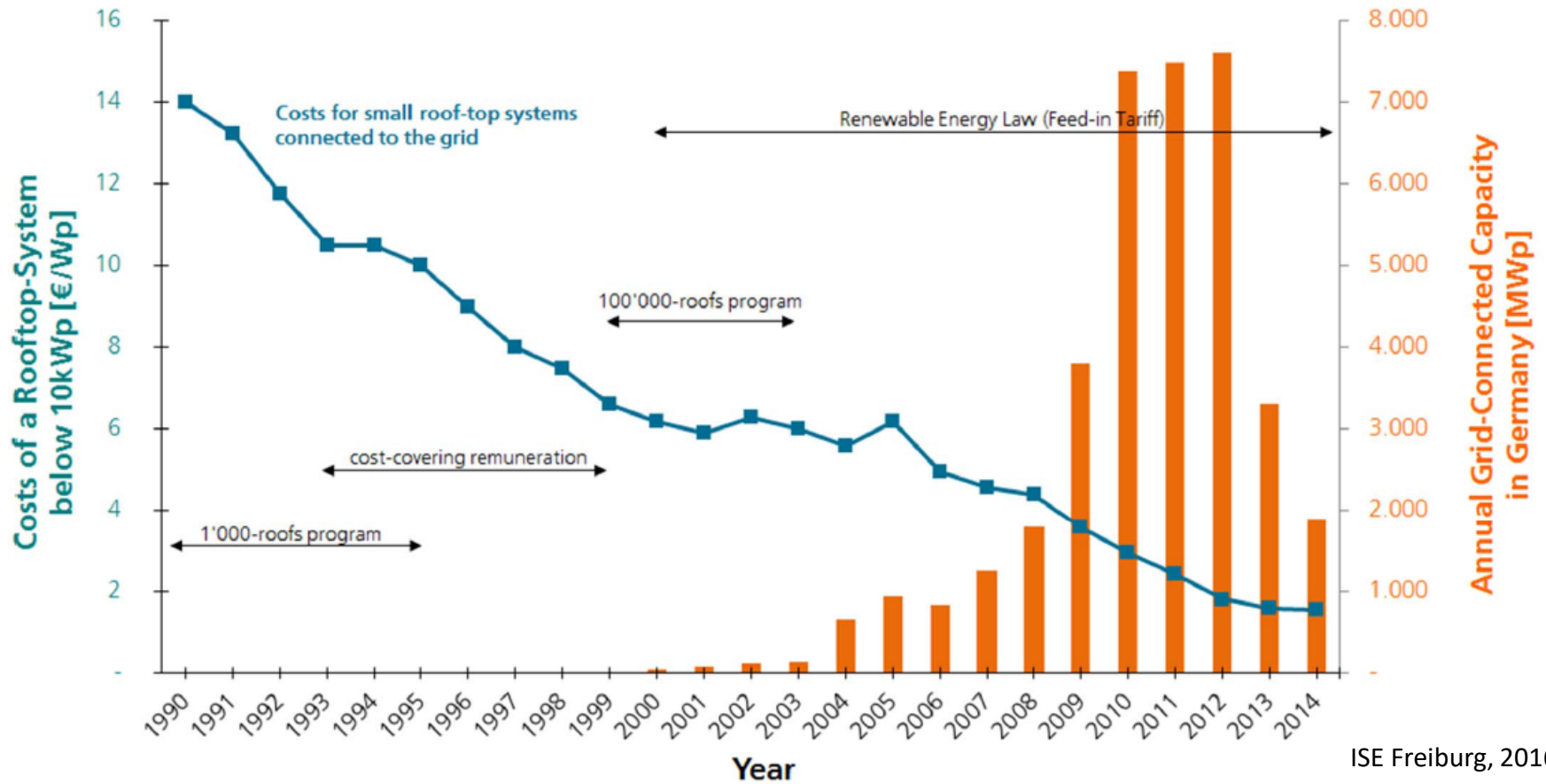
Average Price PV Rooftop System In D

Historical Price Development Germany for 10 to 100 kWp roof-top PV-Systems



Data: BSW-Solar. Graph: PSE 2018

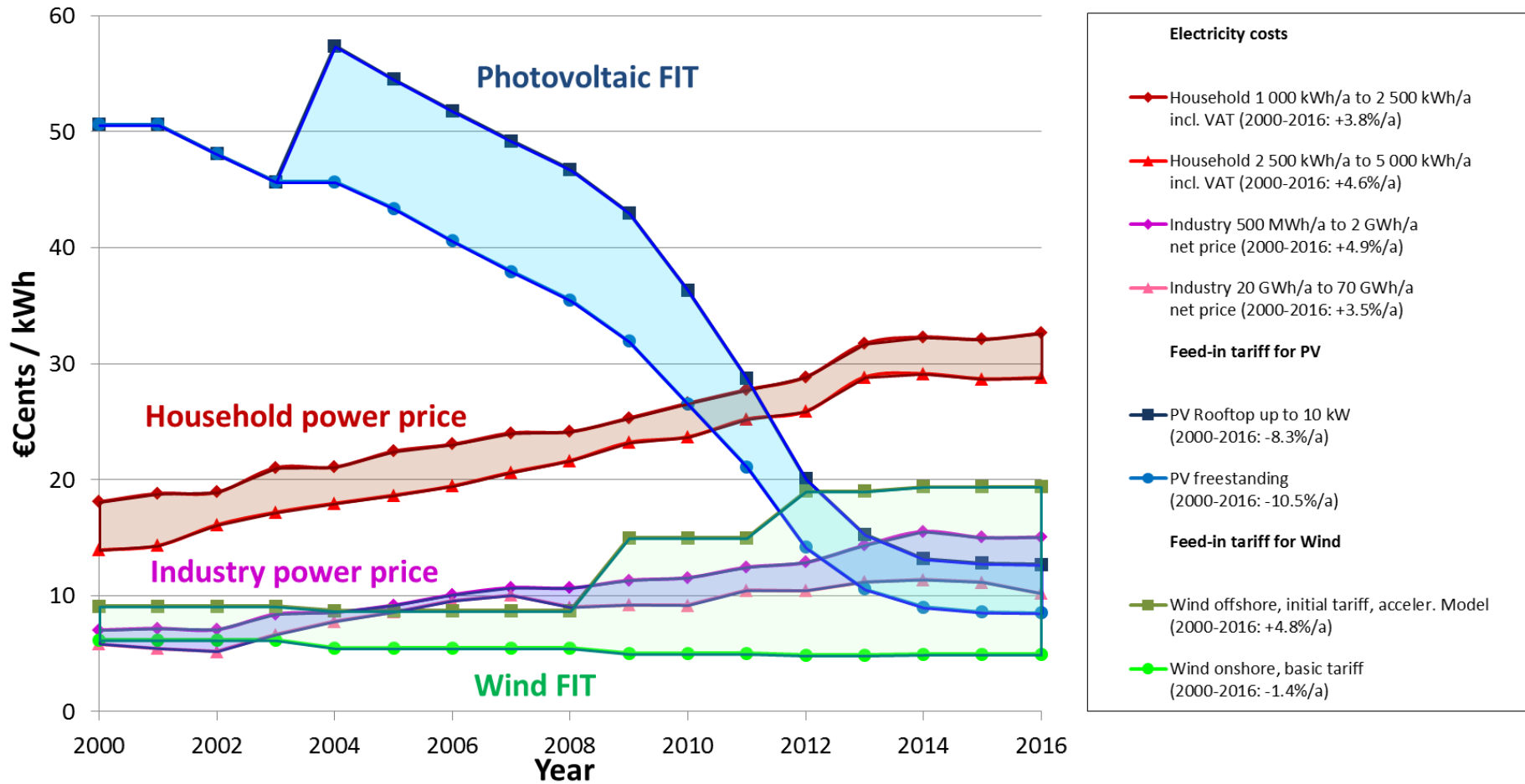
Incentives in Germany



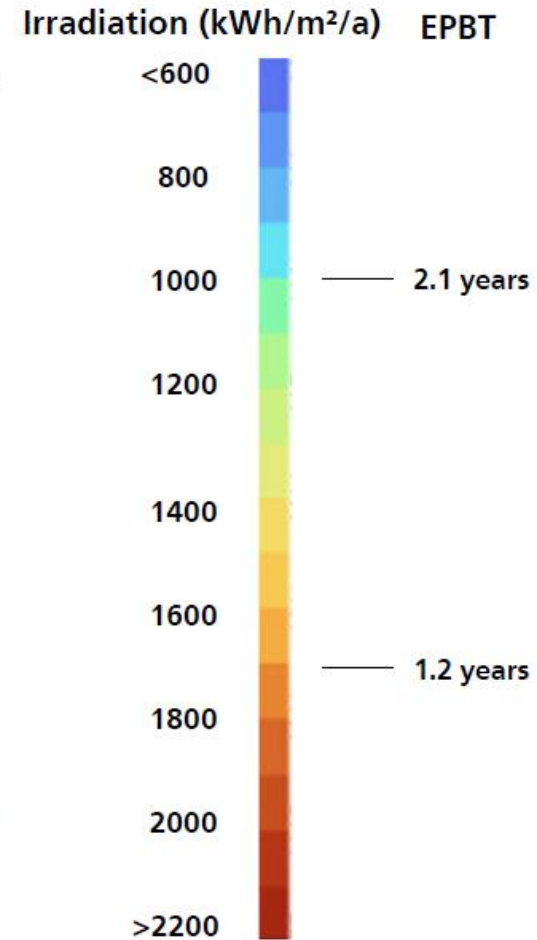
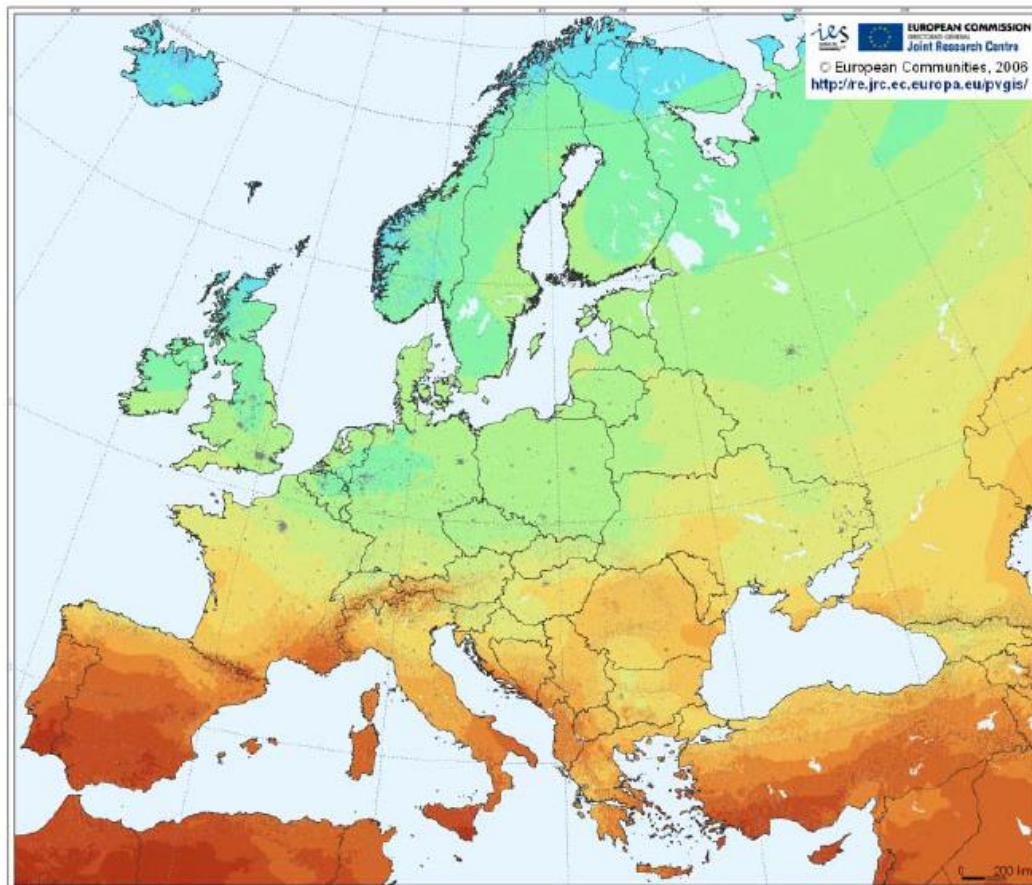
ISE Freiburg, 2016

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

Electricity Costs: Feed in Tariffs in D



Energy Payback Time (EPBT)

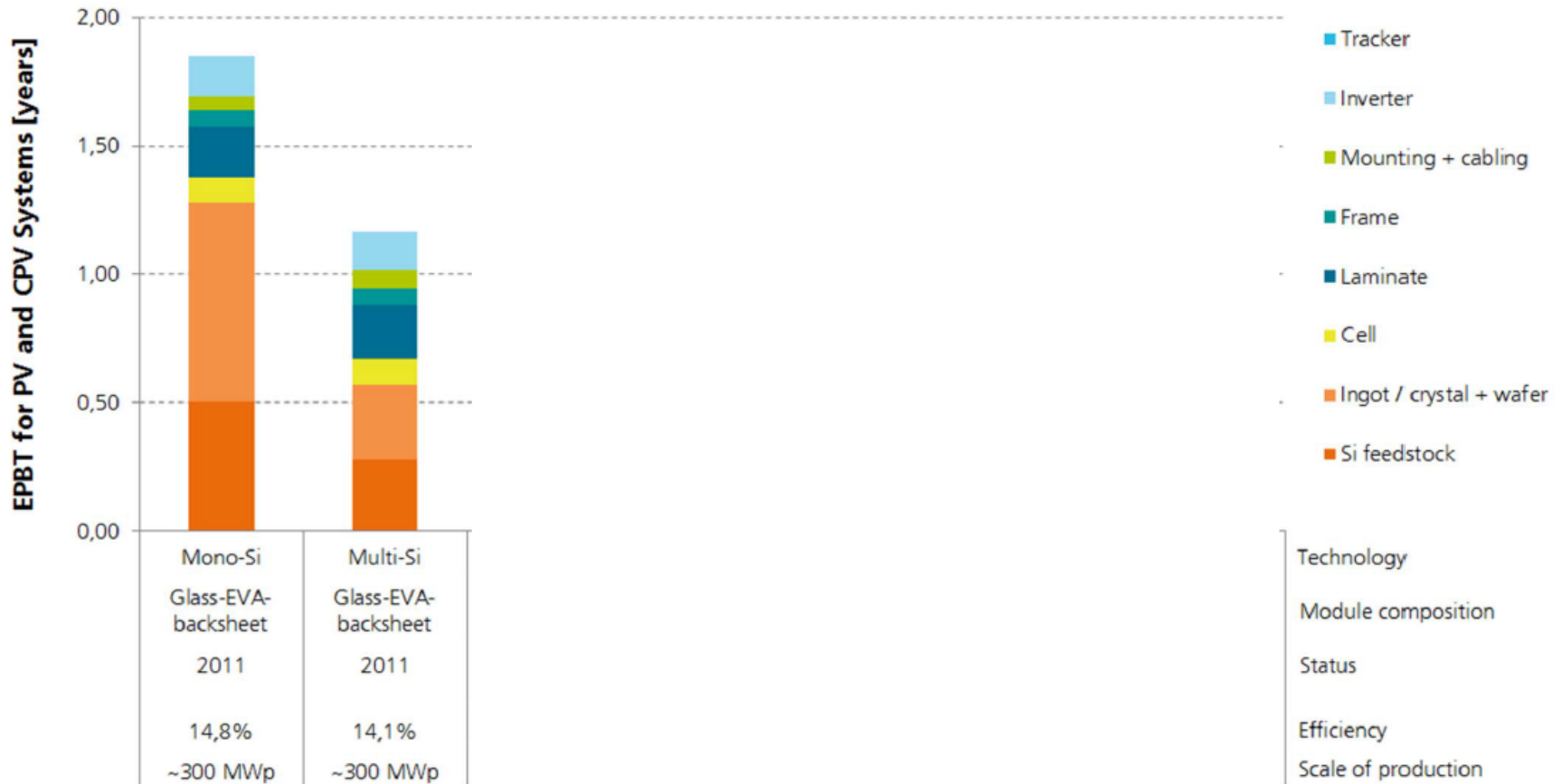


ISE Freiburg, 2016

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

Energy Payback Time (EPBT)

Global Irrad.: 1925 kWh/m²/yr, Direct Normal Irrad.: 1794 kWh/m²/yr



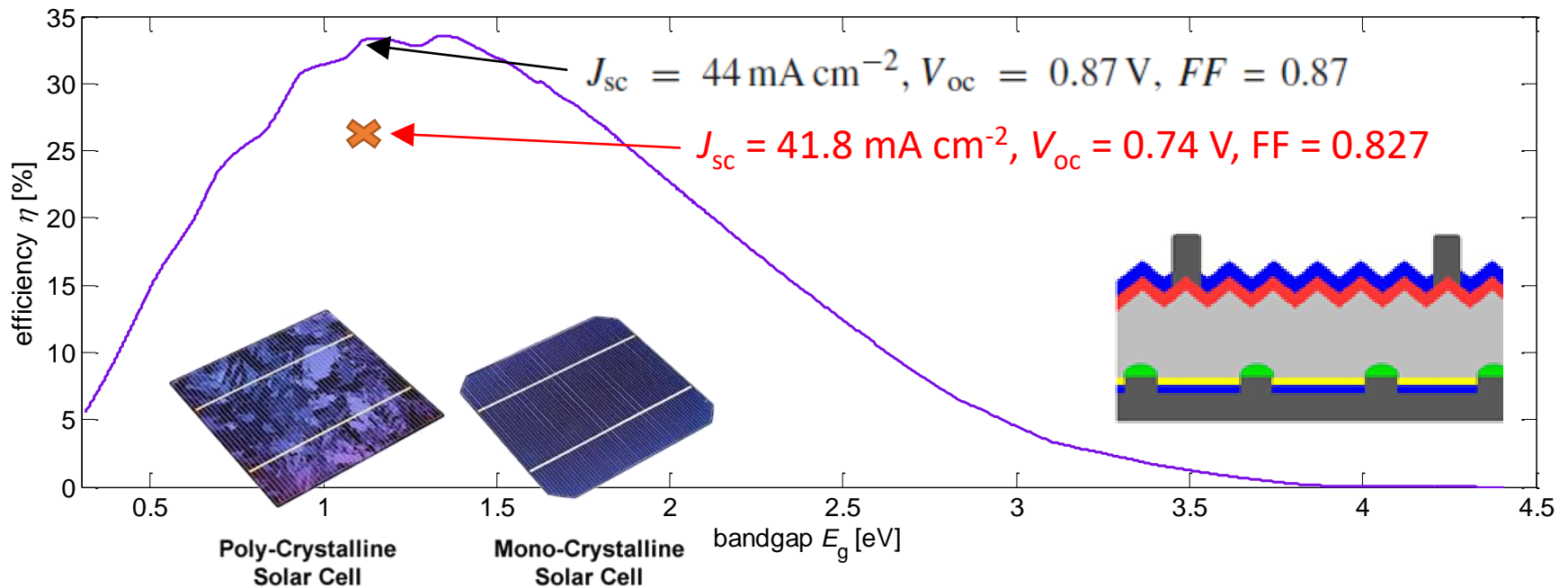
Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014

Example: Rooftop Installation

- Irradiation: 1200 kWh/m²a
 - 20% module → 240 kWh/m²a → 0.2 kW_p/m²
 - 20 m² → 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



- mono-Si, n-type, rear (79 cm² cell)
- mono-Si, n-type, rear (module)
- multi-Si, n-type (4 cm² cell)
- multi-Si, p-type, PERC (module)

