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ZUKUNFT SEIT 1386

Efficiency improvement in solar cells

MSc_TI | Winter Term 2015

Klaus Naumann

Agenda

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- Introduction
- Physical Basics
- Function of Solar Cells
- Cell Technologies
- Efficiency Improvement
- Outlook

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Introduction | Application Examples

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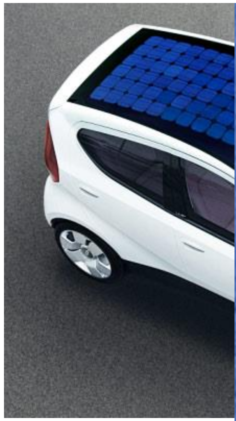
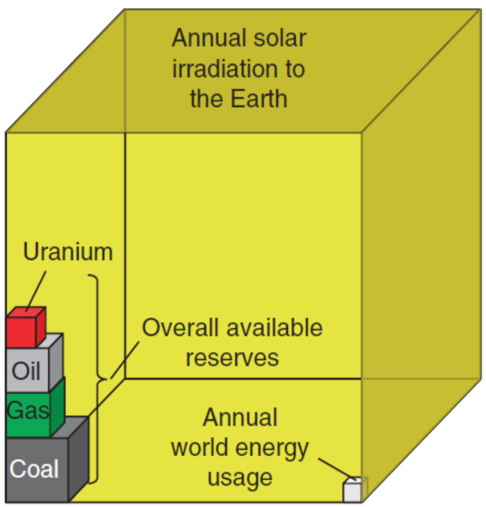
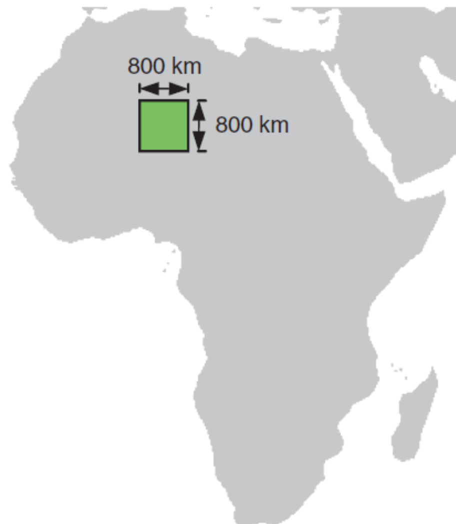


Introduction | Sun, Radiation and the Sahara Miracle





„Sun sends us more than 7000 time the energy than we use in a year"

$$W_{Earth} = 1.119 * 10^{18}\ kWh$$

$$W_{World} = 1.454 * 10^{14}\ kWh$$

Source:
Konrad Mertens, Photovoltaics – Fundamentals, Technology and Practice, Wiley 2014

- **Radiation power of sun:**

$$P_{Sun} = 3.845 \cdot 10^{26}\ W$$

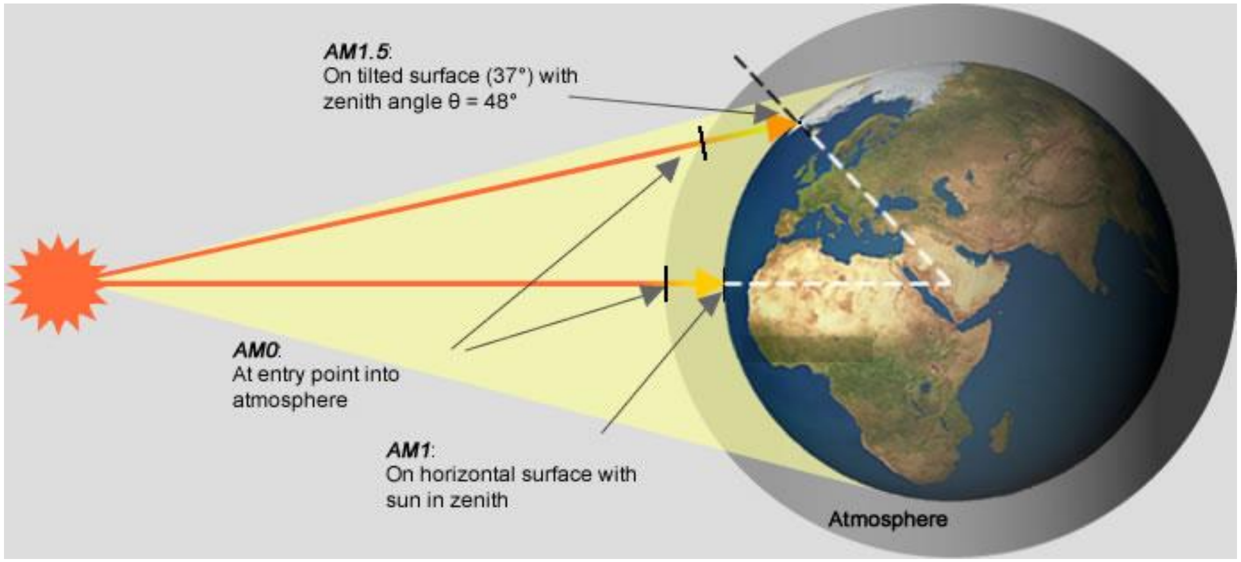
- **Solar constant:**
  outside Earth's atmosphere:

$$E_0 = 1367 \frac{W}{m^2}$$

- **Global radiation:**
  Inside the atmosphere:

$$E_G \approx 1000 \frac{W}{m^2}$$

Introduction | Air Mass



Source:
http://www.greenrhinoenergy.com/solar/radiation/spectra.php

- AM 0 (Air Mass 0): outside the atmosphere
- AM 1 (Air Mass 1): inside the atmosphere (vertical path through atmosphere)
- AM 1.5 (Air Mass 1.5): light travelled 1.5 times the distance compared to AM 1

Introduction | Solar Spectrum and Radiation Types

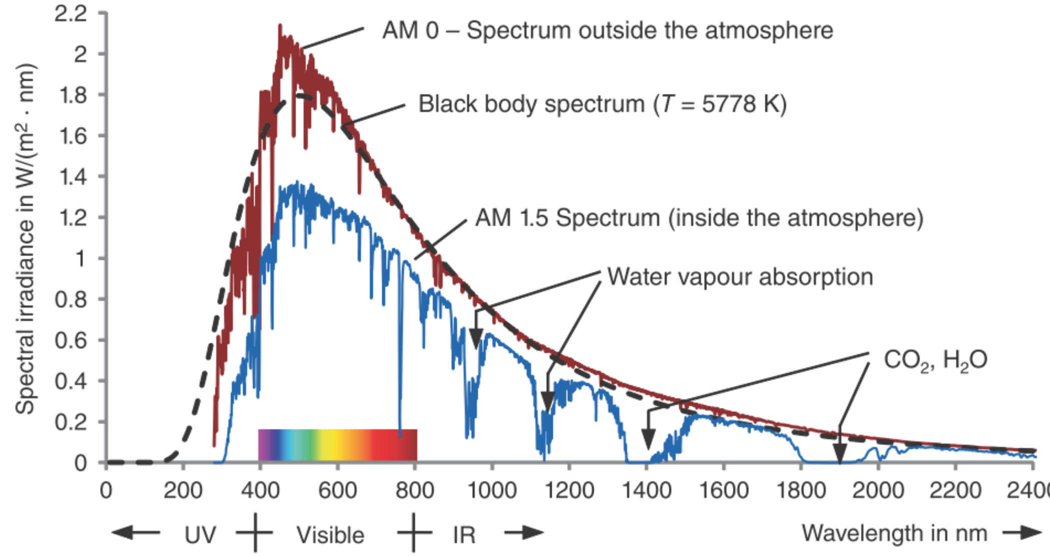
Losses:

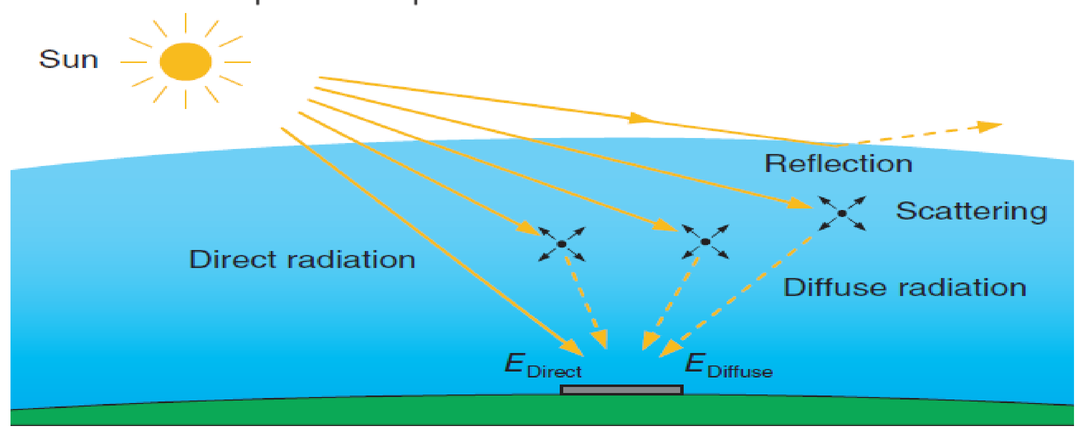
- Reflection at atmosphere
- Absorption of light
- Scattering

→ **Two types of radiation:**

- Direct
- Diffuse

→ $E_G = E_{Direct} + E_{Diffuse}$





Source:
Konrad Mertens, Photovoltaics – Fundamentals, Technology and Practice, Wiley 2014

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Physical Basics | Bohr's Atomic Model and Band Model

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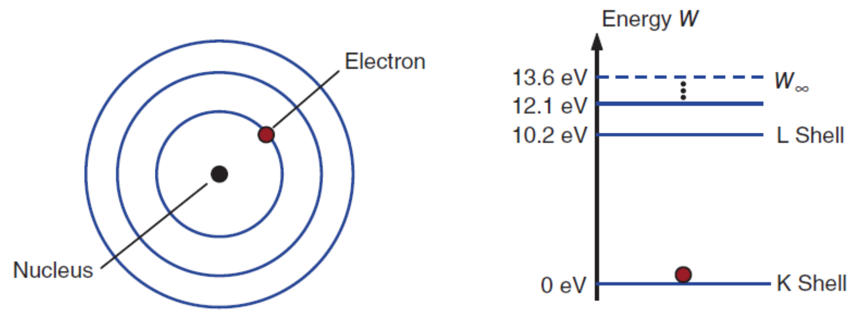
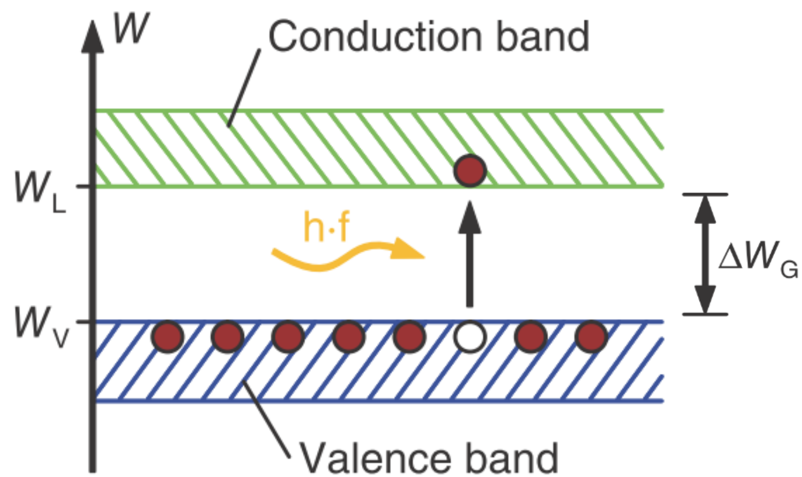
- **Ionizing energy**:
  separate electron from the atom
- **Photon**:
  light packet of particular wavelength
- **Absorption of light**:
  light particle hits electron and is absorbed. Released energy lifts electron from Valence band to Conduction band





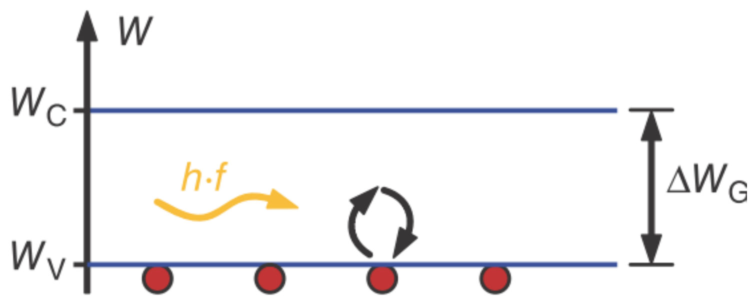
$$\Delta W_G = W_L - W_V = h \cdot f$$
$$\lambda = \frac{c_0}{f}$$

h = Planck's constant

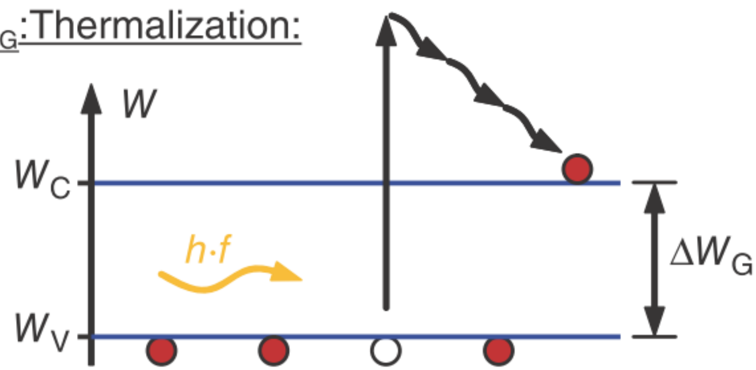
Source:
Konrad Mertens, Photovoltaics – Fundamentals, Technology and Practice, Wiley 2014

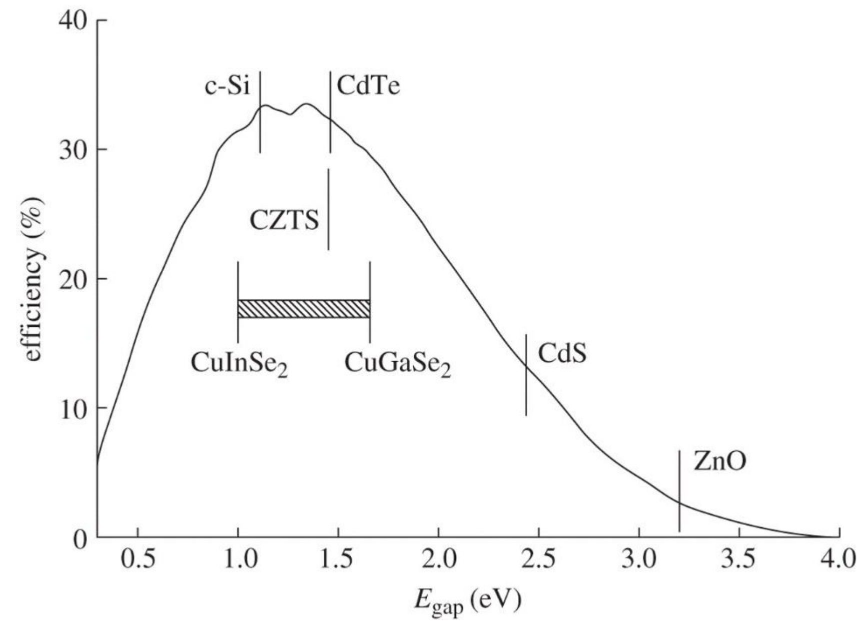
Physical Basics | Semiconductor Band Gap

$\lambda > \lambda_G$:Transmission:



$\lambda < \lambda_G$:Thermalization:





Source:
Konrad Mertens, Photovoltaics – Fundamentals, Technology and Practice, Wiley 2014

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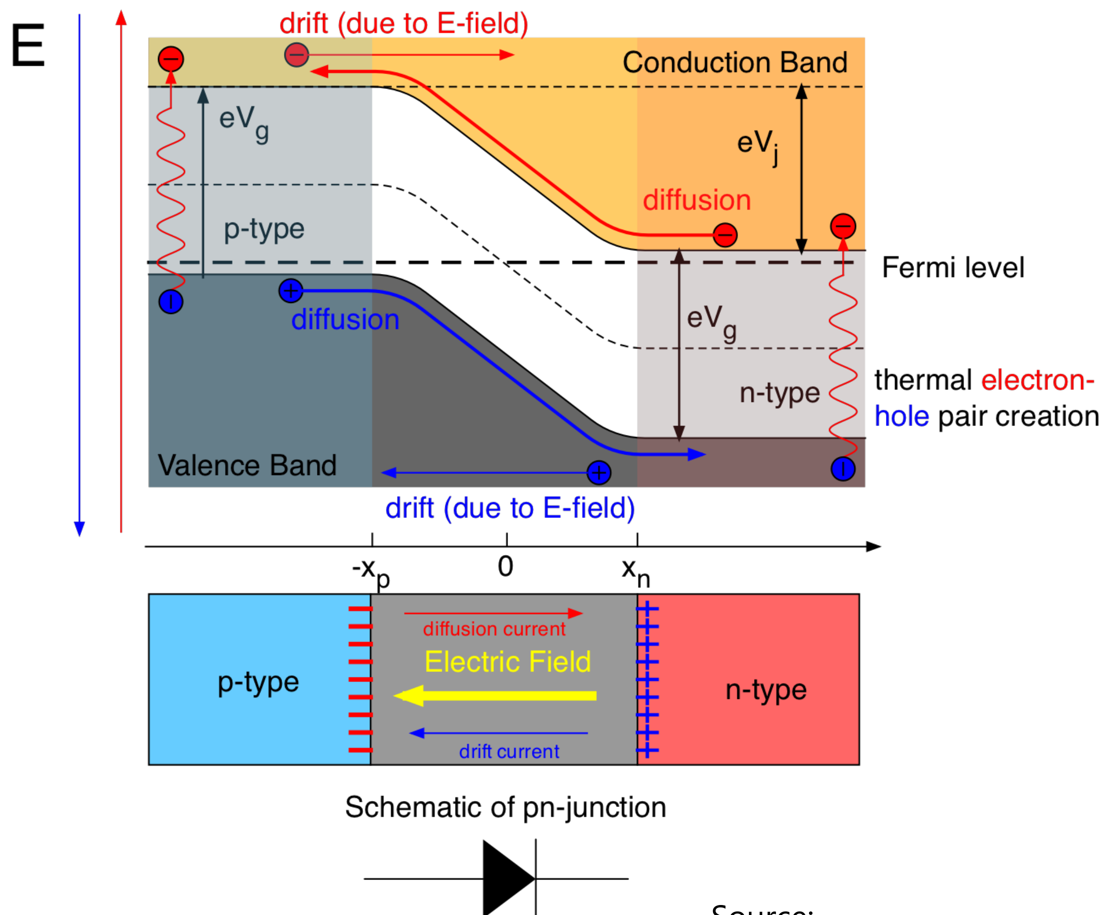
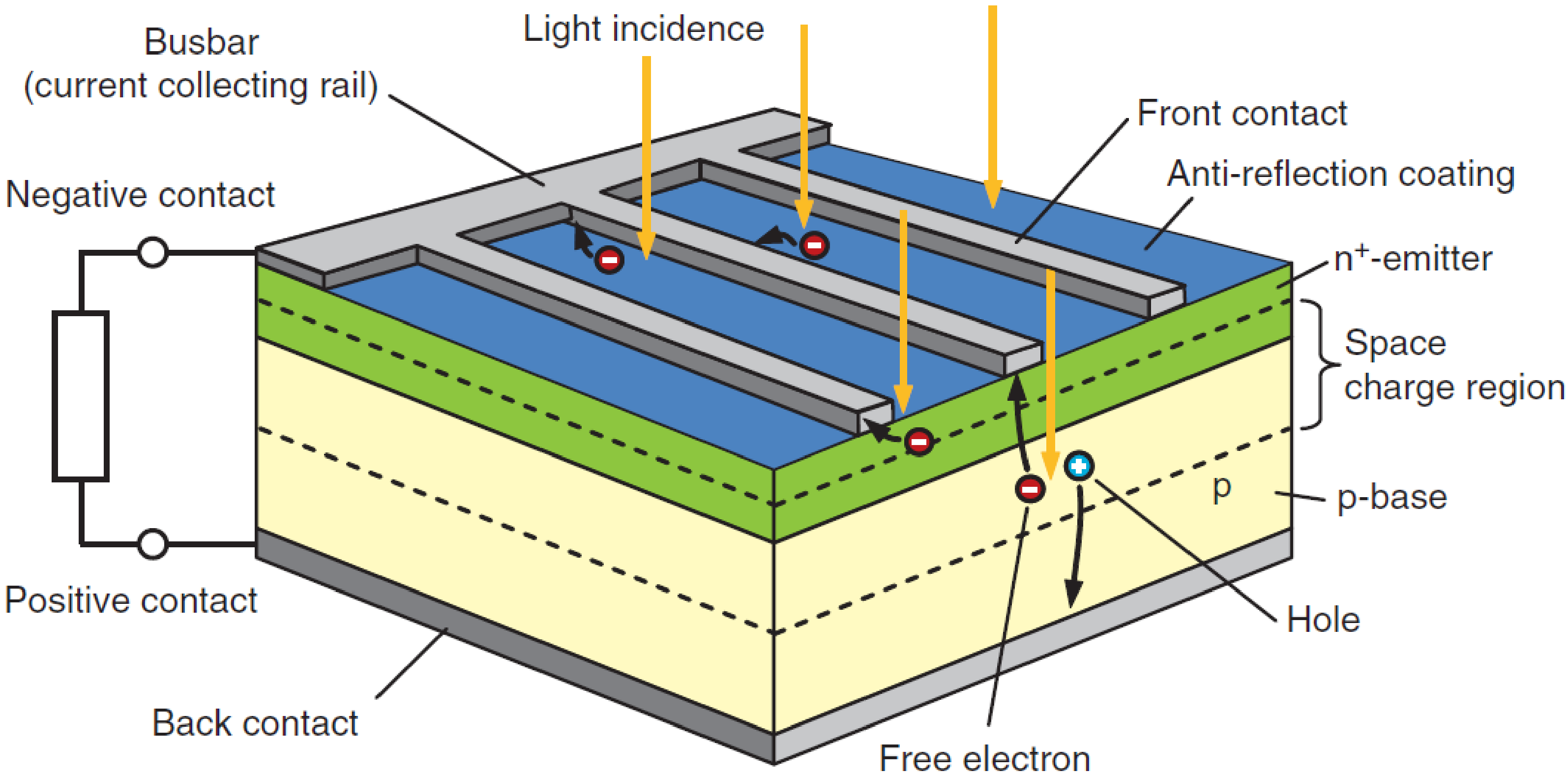
Function of Solar Cells | p-n junction



Schematic of pn-junction

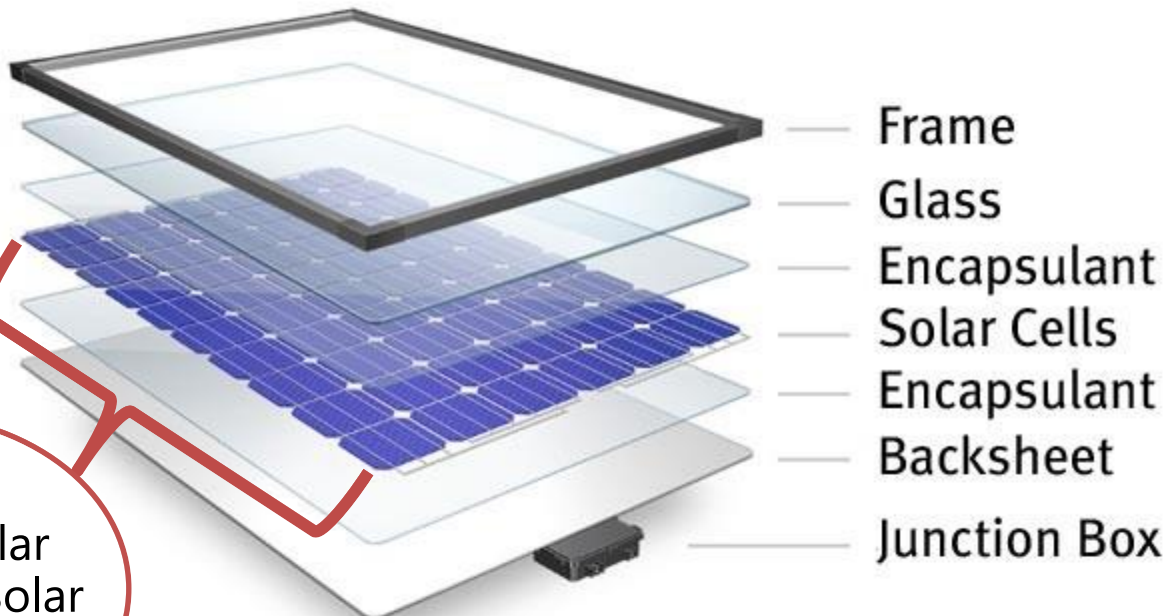
Source:
http://wanda.fiu.edu/teaching/courses/Modern_lab_manual/_images/pn-junction_energy.png

Function of Solar Cells | Method of Function



Source:
Konrad Mertens, Photovoltaics – Fundamentals, Technology and Practice, Wiley 2014

Function of Solar Cells | Solar Panel Construction



Multiple Solar Cells in one Solar Panel

Source: http://www.dupont.com/content/en_us/home/products-and-services/solar-photovoltaic-materials/what-makes-up-solar-panel/_jcr_content/thumbnail.img.jpg/1435680366722.jpg

Function of Solar Cells | Characteristic Curve

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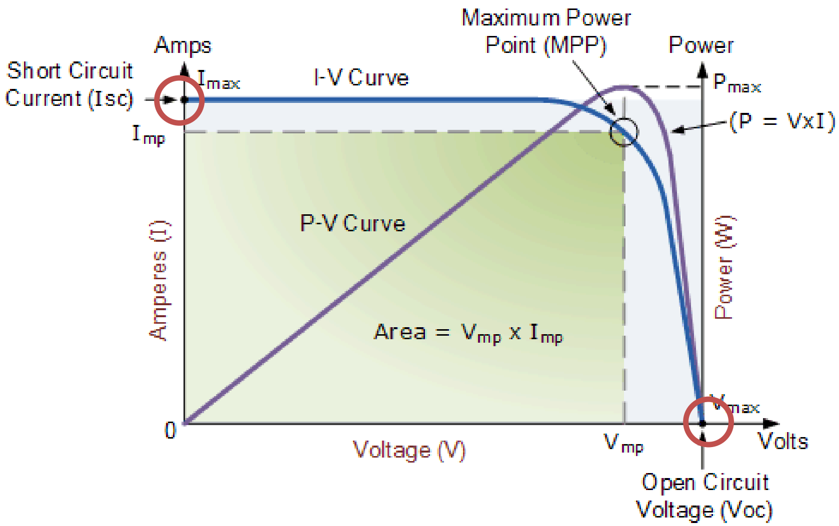

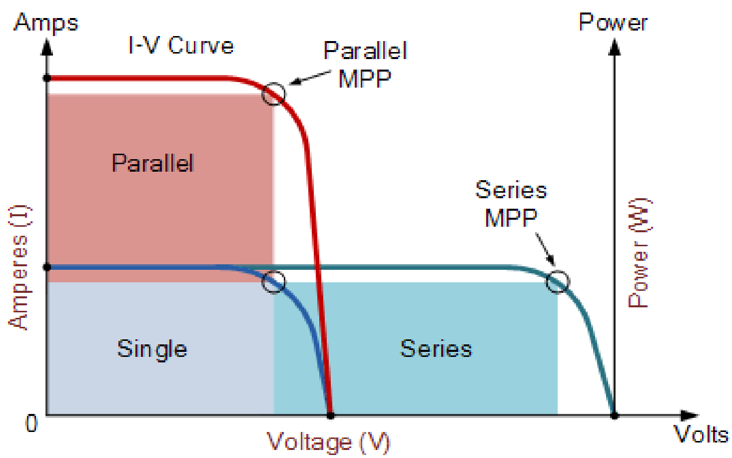

Source: http://www.alternative-energy-tutorials.com/energy-articles/solar-cell-i-v-characteristic.html

- Load Resistance determines operating point:
  - R = 0 → I_{SC}
  - R = ∞ → V_{OC}
- Maximum Power Point (MPP):

$$P_{MPP} = I_{MPP} \cdot V_{MPP}$$

- Fill Factor (FF):

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} = \frac{P_{MPP}}{V_{OC} \cdot I_{SC}}$$

  - Si-Cells: 0.75 – 0.85
  - Thin Film: 0.6 – 0.75
  - Measure for Quality

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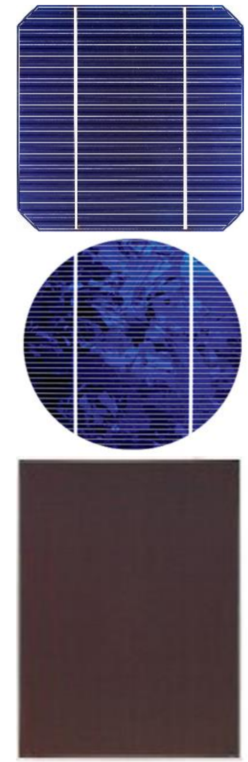
Cell Technologies | Cell Types

η_{max}

- **Thick Film (150 – 250 µm)**
  - Monocrystalline (1st Gen Cells) ~ 20 %
  - Polycrystalline (1st Gen Cells) ~ 16 %
- **Thin Film (< 10 µm)**
  - Amorphous Silicon (2nd Gen Cells) ~ 10 %
  - Cadmium-Telluride (2nd Gen Cells) ~ 10 %
  - CIGS ($CuIn_xGa_{(1-x)}Se_2$)* (2nd Gen Cells) ~ 15 %
  - **Emerging: Perovskite (3rd Gen Cells)**
- **Multi-Layer**



*Copper-Indium-Gallium-Selenide

Cell Technologies | Comparison of Cell Types

	Mono	Poly	Thin	CIGS
Generation	1st Gen		2nd Gen	
Efficiency	14 – 20 %	12 – 16 %	6 – 10 %	13 – 15 %
Low light performance	Losses (diffuse)		Low losses	
Thermal behavior	High temperature losses		Low losses	
Cost (1 = lowest)	3	2	1	4
Long-term test	Very high Performance, stable	High Performance, stable	Average Performance	Low Performance (in winter higher)
Durability	High	High	Lower	Not tested yet
Weight	↑		↓	
Failure vulnerability	↓↓		↓	

↑ = High, ↓ = Low, ↓↓ = Very low

Source: http://www.solaranlagen-portal.com/solarmodule/systeme/vergleich

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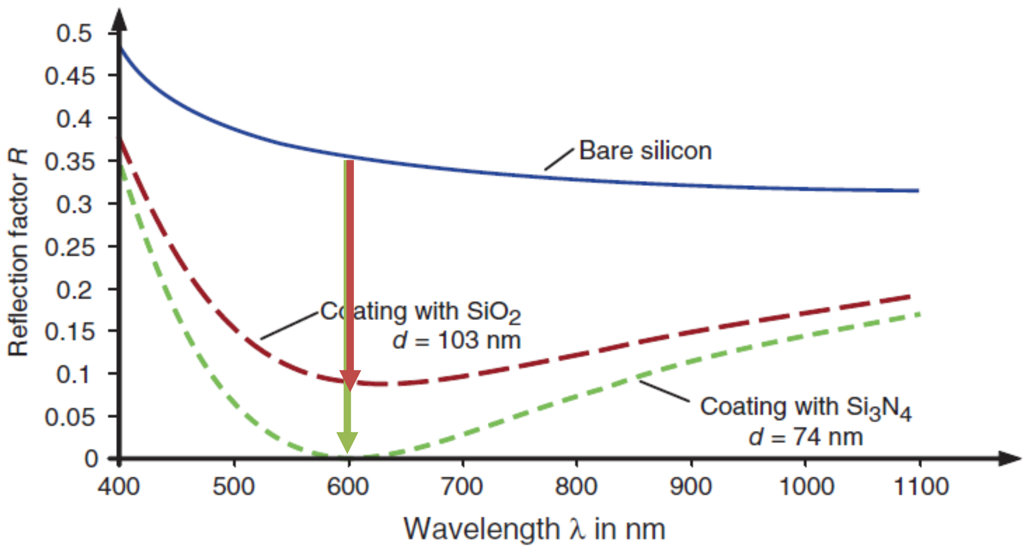
Anti-Reflection Coating



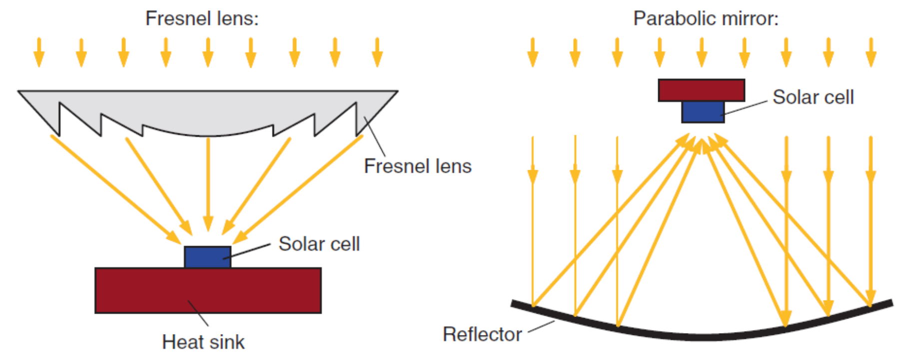
- Reduction of reflection increases efficiency
- With certain coatings and specific wavelengths: Reflection → 0

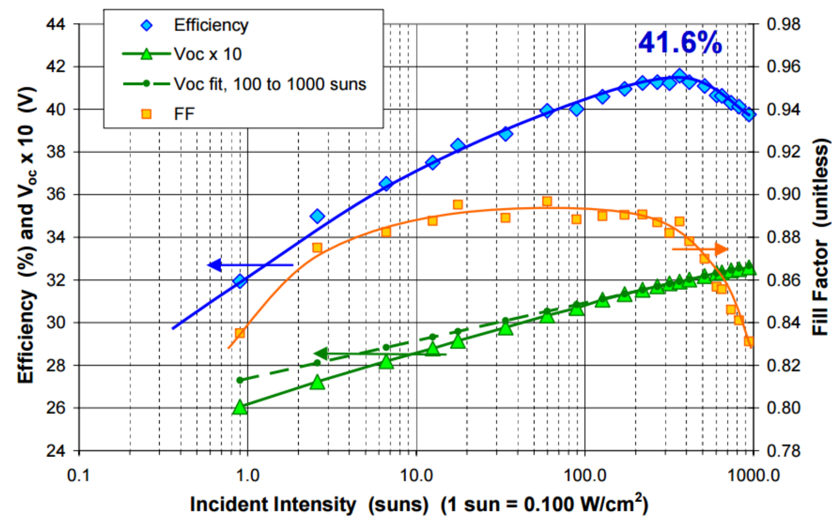
Source:
Konrad Mertens, Photovoltaics – Fundamentals, Technology and Practice, Wiley 2014

Efficiency Improvement | Radiation Bundling

Radiation Bundling

- Reduction of solar cell area
- Cell curve moves up
  → higher efficiency
- Efficiency increase not continuously!
  → Electrical losses increase as well
- Resistance rise with square of operating current
  → Heat sink needed
- Record: 43.5 % efficiency
  (concentration factor: 418(!))





Source:
Mertens, Konrad: Photovoltaics – Fundamentals, Technology and Practice, Wiley 2014

King, Richard R.: Raising the Efficiency Ceiling in Multijunction Solar Cells, Spectrolab, Inc., 2009

Efficiency Improvement | Multi-Layer Cells

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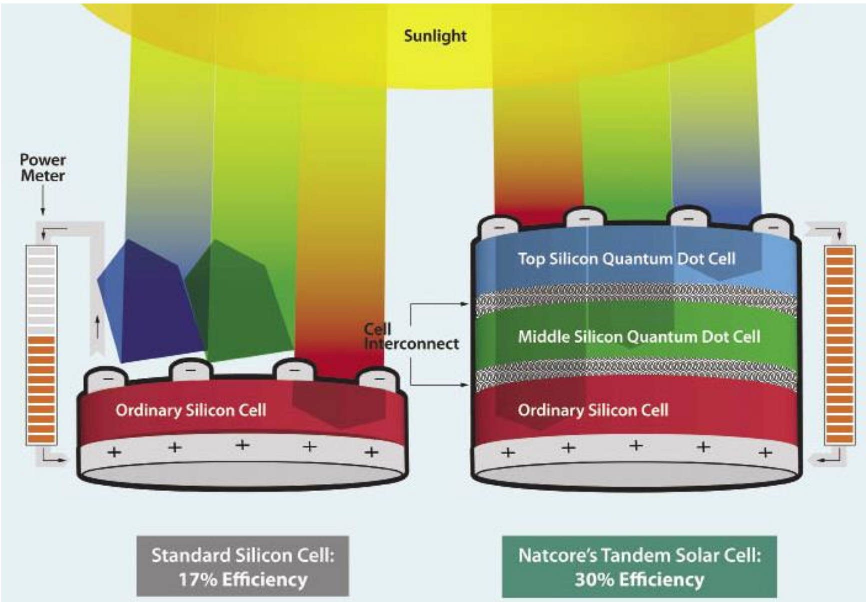
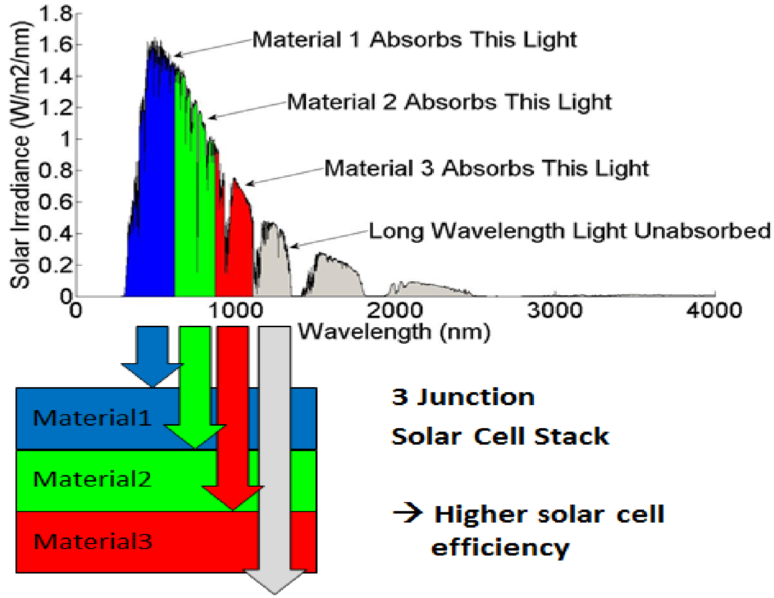
Multi-Layer Cells





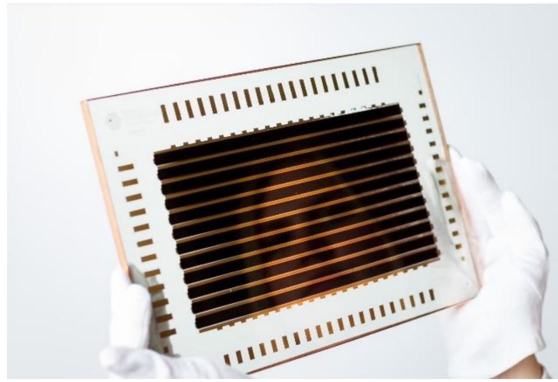
Source:
http://www.solarpowerworldonline.com/2011/10/solar-cells-without-the-silicon/

http://www.sj-solar.com/technology/

Efficiency Improvement | Perovskite

New Materials: Perovskite

- Thin film cells (stand-alone or in multi-layer cells)
- Very fast efficiency improvement
  (2006: 2.2 % → 2014: 20.1 %)
- $CH_3NH_3PbX_3$ where
  $X = I^- \ (Iodine), Br^- \ (Bromine) \ or \ Cl^- \ (Chlorine)$
- Anode/Cathode material defines bandgap
  → not tuned to one wavelength
  → higher efficiency
- Low energy input in processing compared to Si
  → Low material/manufacturing costs
- Flexible | Light-weight | Semi-Transparent



Source:
Dyakonov, Prof. Dr. Vladimir, Perowskit-Halbleiter erobern die (Dünnschicht-) Photovoltaik, ZAE Bayern, 2014

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Outlook | Smart Grids

Source: http://www.tonex.com/training-courses/smart-grid-training-for-non-engineers/

- Decentralisation of energy supply
- Efficiency of high importance (decrease of required place and costs)
- Photovoltaics is a big and important part in future concepts (smart grid)

Outlook | Innovations

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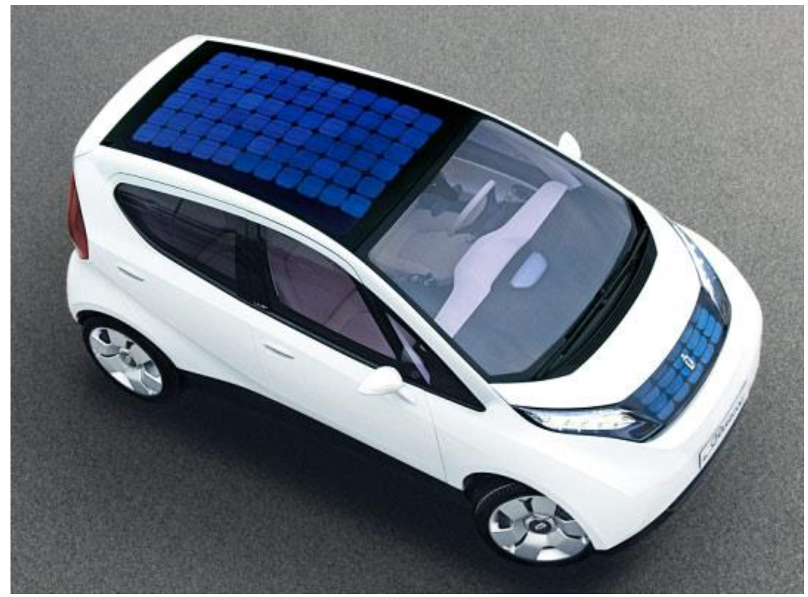
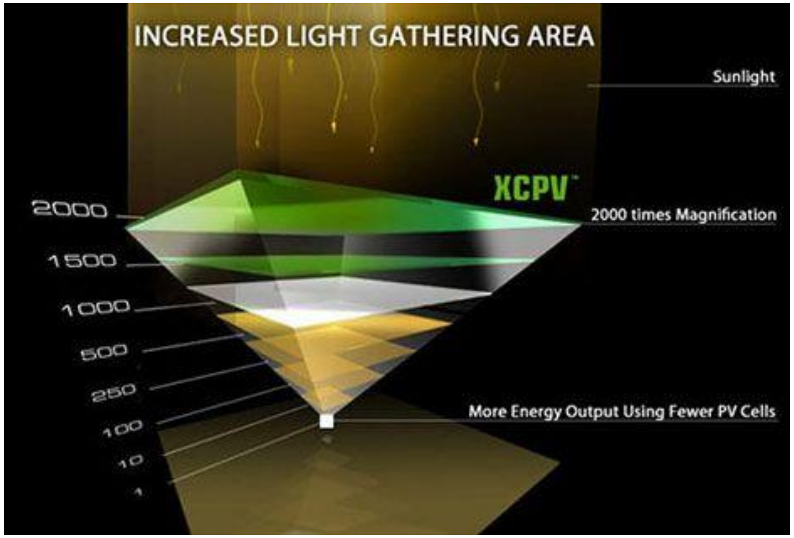
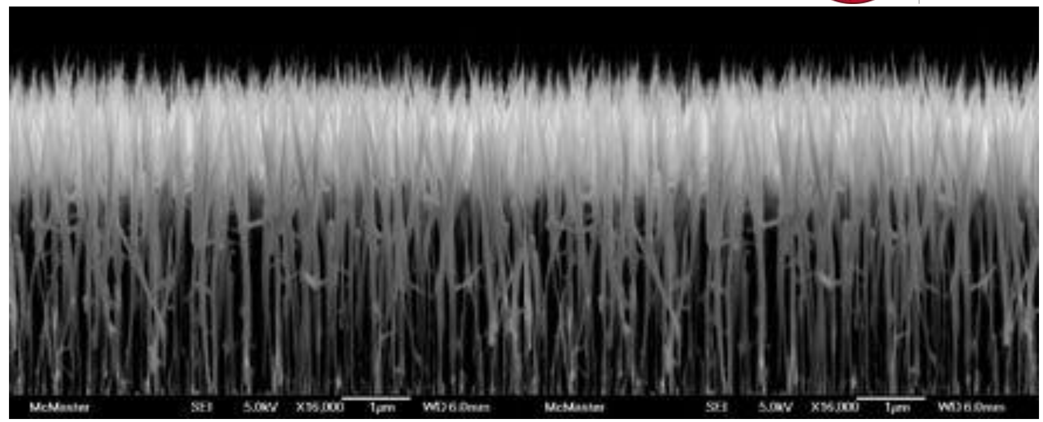
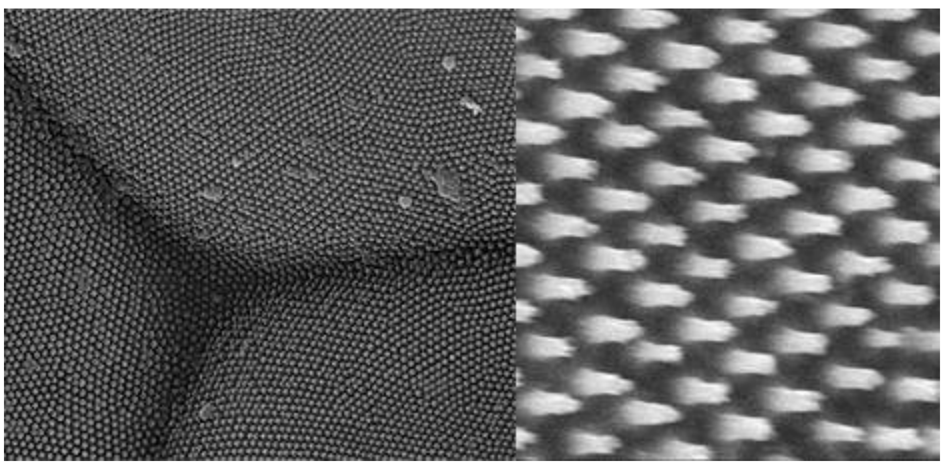
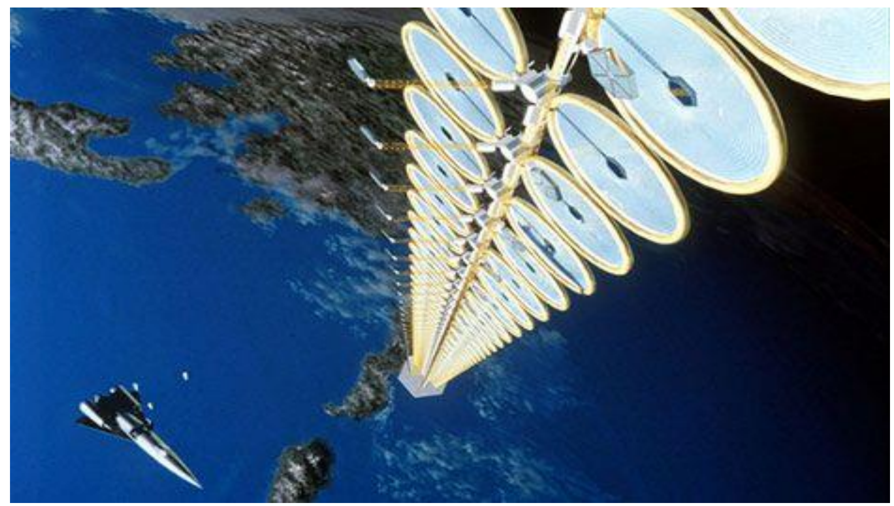


Outlook | Innovations









Source: http://www.scientificamerican.com/article/farming-solar-energy-in-space/

Thank You

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Questions?