8.4 Summary

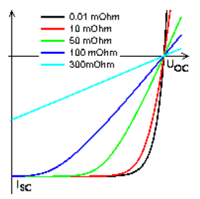
8.4.1 Summary to: 8 Solar Cells

A solar cell converts light power into electrical power. It's overriding parameter is the over-all conversion efficiency η

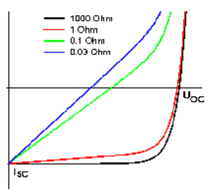
- Any solar cell is essentially a large -area junction, usually of the **pn**-type.
- It's essential parameter are the short-circuit current I_{SC}, the open-circuit voltage U_{OC} and the fill factor **FF**
- For optimal efficiency the bandgap E_g should be matched to the solar spectrum; we need around **1.5 eV**.
- Maximum efficiency from the *semiconductor physics* point of view is achieved if all light with energy **>=** E_g produces minority carriers and all of these carrier are swept out as diode reverse current and
- Maximum efficiency from the *module systems* point of view is achieved if the semiconductor part is **OK**, only very little light is reflected by the solar cell module, series resistances and shunt resistances can be neglected, and everything is uniform and homogeneous

The equivalent circuit diagram with the basic equation has is all!

- Series and shunt resistances, unavoidable for large areas, are of overwhelming importance for solar cells with η **<≈ 10 %**



Effect of series resistance



Effect of shunt resistance

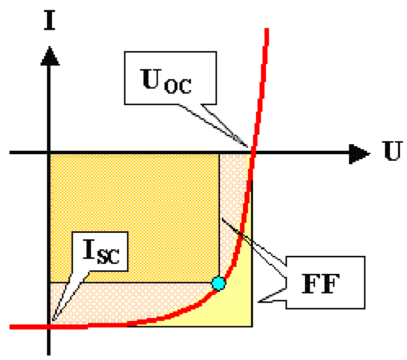
Switching solar cells with individual characteristics in series and / or in parallel causes all kinds of problems.

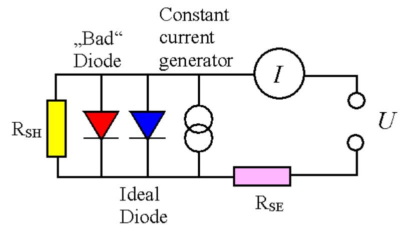
- Worse: Any inhomogeneous solar cell (e.g. **mc-Si** solar cells) consists of *locally* different solar cells "somehow" connected internally
- Optimizing solar cells with respect to "money" thus provides exciting science and engineering!

Important "raw" numbers.

- **Maximum η Si solar cell ≈ 25 %**
- **Maximum sun power ≈ 1 kW / m²**
- **Maximum commercial solar cell power ≈ 200 W / m².**
- **Yearly average commercial solar cell power ≈ 25 W / m².**

Solar cell science and technology centers exclusively on *money* and *saving the earth*!

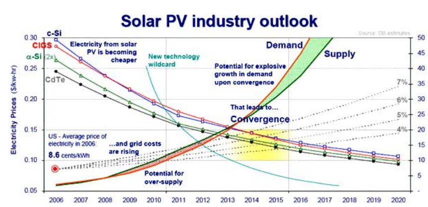




$$I = I_1 \cdot \left(\exp \frac{eU_{eff}}{kT} - 1 \right) + I_2 \cdot \left(\exp \frac{eU_{eff}}{nkT} - 1 \right) + \frac{U_{eff}}{R_{SH}} - I_{Ph}$$

"Ideal" Diode "Bad" Diode

$$\eta = \text{const} \cdot U_{OC} \cdot I_{SC} \cdot FF$$



Courtesy Deutsche Bank

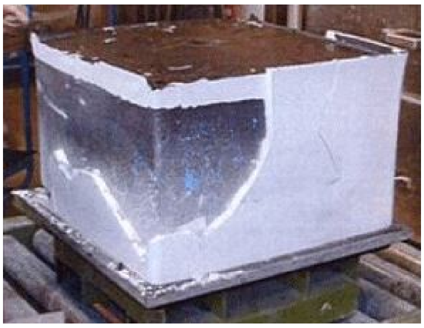
- There are many competing solar cell technologies and materials.
    - Bulk single-crystal and **mc Si** vs. thin film **Si (a-Si:H, µc-Si:H. ..**
    - Other thin-film semiconductors:**CIGS, CdTe, ...**.
    - Exotica: **TiO_2**- electrolyte ("Grätzel cell"), organic semiconductors, "Nano" materials, ...

- Bulk **Si** solar cells are made from (cheap) single crystalline wafers (cut squarish) or from square multicrystalline (***mc***) wafers. They account for about **85 %** of the installed solar power at present (**2008**).
    - A yearly production of **1 GW_{peak}** means about **10^7 m^2=10 km^2** **pn**-junction of good quality and much more
    - Consider ⇒

    A big problem is cranking up world wide **Si** production by **30 % - 40 %** per year.

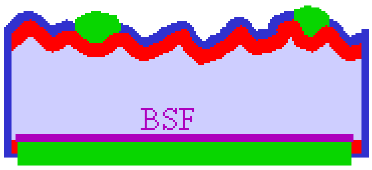
Processing Time	**1s / solar cell**
Cost Decrease	**5 % / a**
Efficiency Increase	**20 % in 2012 ?**
Key Material Supply	**30 % /a more Si**
Industry Growth Rates > 30 % for many years	**Supply capital and people**

- ***mc*** wafers are produced by **Si** casting. Problems are
    - Expansion upon crystallization.
    - Reaction with walls of mold
    - Columnar grain growth required
    - **300 kg** ingots are routinely cast in **2007**; liquid encapsulation and precise temperature control are essential

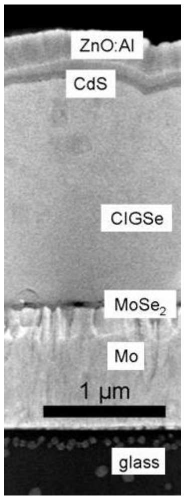


- Sawing the ingot into **mc-Si** wafers with as little losses as possible and with wafer thicknesses of **< 300 µm**, while straight-forward, is "high-tech".
    - Saw damage is removed by a chemical etch.

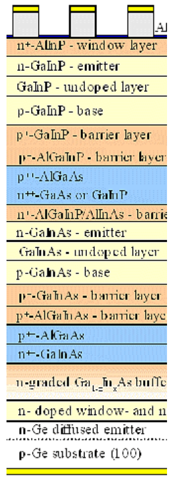
- Processing, simple in principle, has to meet the conditions above and is highly specialized. Essential processes are:
    - Diffusion, edge isolation, passivation, screen printing contacts and sintering contacts.
    - Essential device features are back surface field, gettering of impurity atoms, **H**-passivation of grain boundaries and other defects.



- Thin film solar cells need to meet some key requirements:
  - Process-compatible and cheap substrate ⇒ large area deposition.
  - Suitable direct band gap ⇒ high absorption coefficients f
  - Insensitivity to "defects"
  - Technology for junction and good ohmic contacts.
- Major contenders in (or close) to production are:
  - Amorphous **Si**.
  - Nanocrystalline thin film **Si**.
  - Polycrystalline thin film **Si**.
  - The **$CuIn_xGa_{1-x}Se_2$** or "**CIGS**" family.
  - The **CdTe** solar cell.
  - May others in **R&D**
  - The present "high potentials" are **CdTe** and **CIGS**.



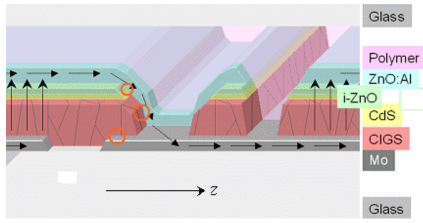
CIGS



Multi junction

- High-efficiency multi-junction solar cells may find applications as "concentrator cells" at the focus point of a large mirror or lens that tracks the sun.

- **CIGS** and most other thin film solar cells have high internal resistances and need to be switches in series after about **1 cm** for high performance
  - This must be done automatically and in-situ as part of the production process.
  - A whole new technology needs to be developed for thin film solar cell mass production
- The race between bulk **Si** solar cells and thin film technologies is open in **2008**; the winning technologies are to be determined.



- Solar cells have a bright future!

Exercise 8.4-1
All Quick Questions to 8