Photovoltaic Efficiency

By Shaun Pacheco

Shockley-Queisser Limit

- Assumptions: perfect absorption with each photon creating an electron/hole pair
- Perfect collection of carriers and radiative recombination as the only allowed recombination mechanism.
  - Means every photogenerated electron travels to the collecting junction faster than it can recombine.
  - Number of generated electron/hole pairs equals the number of collected electron hole pairs.

Radiative Recombination

- An electron goes from the conduction band down to the valence band and excites a photon.

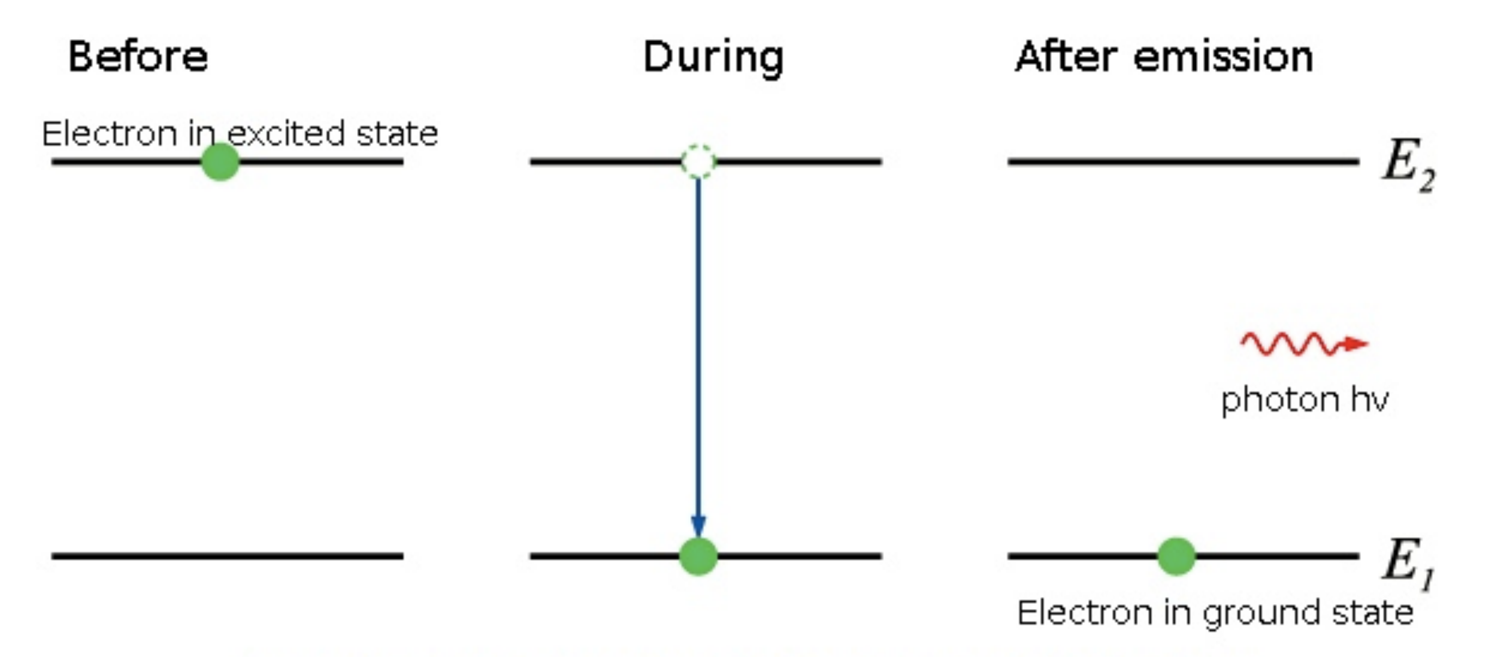
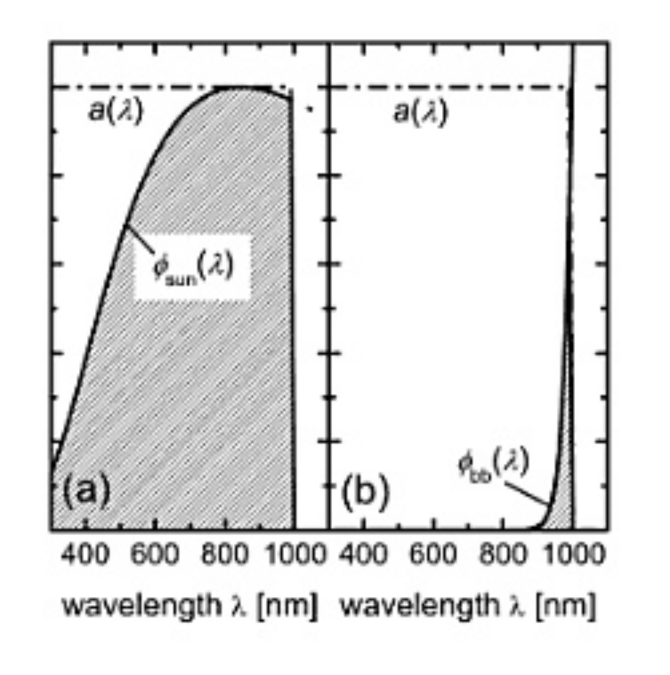


Figure 4.4: We have recombination of an EHP, and a photon is emitted

http://org.ntnu.no/solarcells/pages/Chap.4.php

Shockley-Queisser Limit

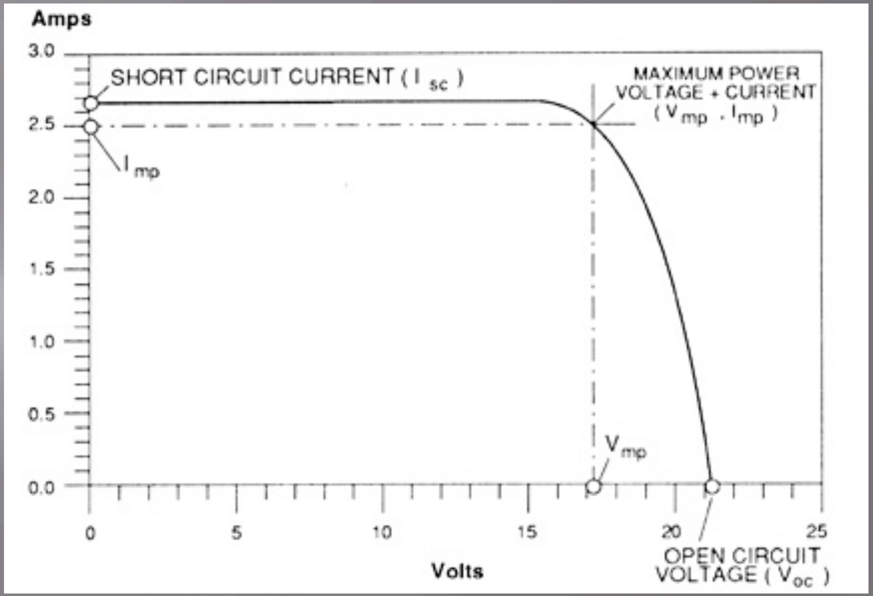
- No light below the band gap is absorbed.
- Every photon above the band gap is absorbed.
- During recombination, photons are emitted with the spectrum in (b).
- Emission must be caused by a recombination current.



http://books.google.com/books?id=73sN8kvgknIC&pg=PA14&lpg=PA14&dq=shockley+queisser+limit+assumptions&source=bl&ots=pLzDYkxiav&sig=RDl_hspcUwGz2R_cJzD8NSpV3t8&hl=en&ei=tbeyS-XwJYeQtgPMnomPAQ&sa=X&oi=book_result&ct=result&resnum=6&ved=0CB0Q6AEwBQ#v=onepage&q=shockley%20queisser%20limit%20assumptions&f=false

Shockley-Queisser Limit

- In thermodynamic equilibrium, the recombination current equals the photocurrent.
- Under voltage bias and illumination, there will be an exponential current/voltage curve.
- V_{OC} open circuit voltage: solar cell emits as many photons as it absorbs.
- I_{SC} short circuit current: photogenerated current under illumination



http://www.lettingchiboboshine.org.au/media/graph-1.jpg

Shockley-Queisser Limit

- The efficiency of a solar cell is given by:

$$\eta = \frac{V_m I_m}{P_{in}} = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

where V_m is the max voltage, I_m is the max current, P_{in} is the product of the irradiance of incident light with the area of the solar cell, and FF is the ratio of the max power to the open circuit voltage times the short circuit current

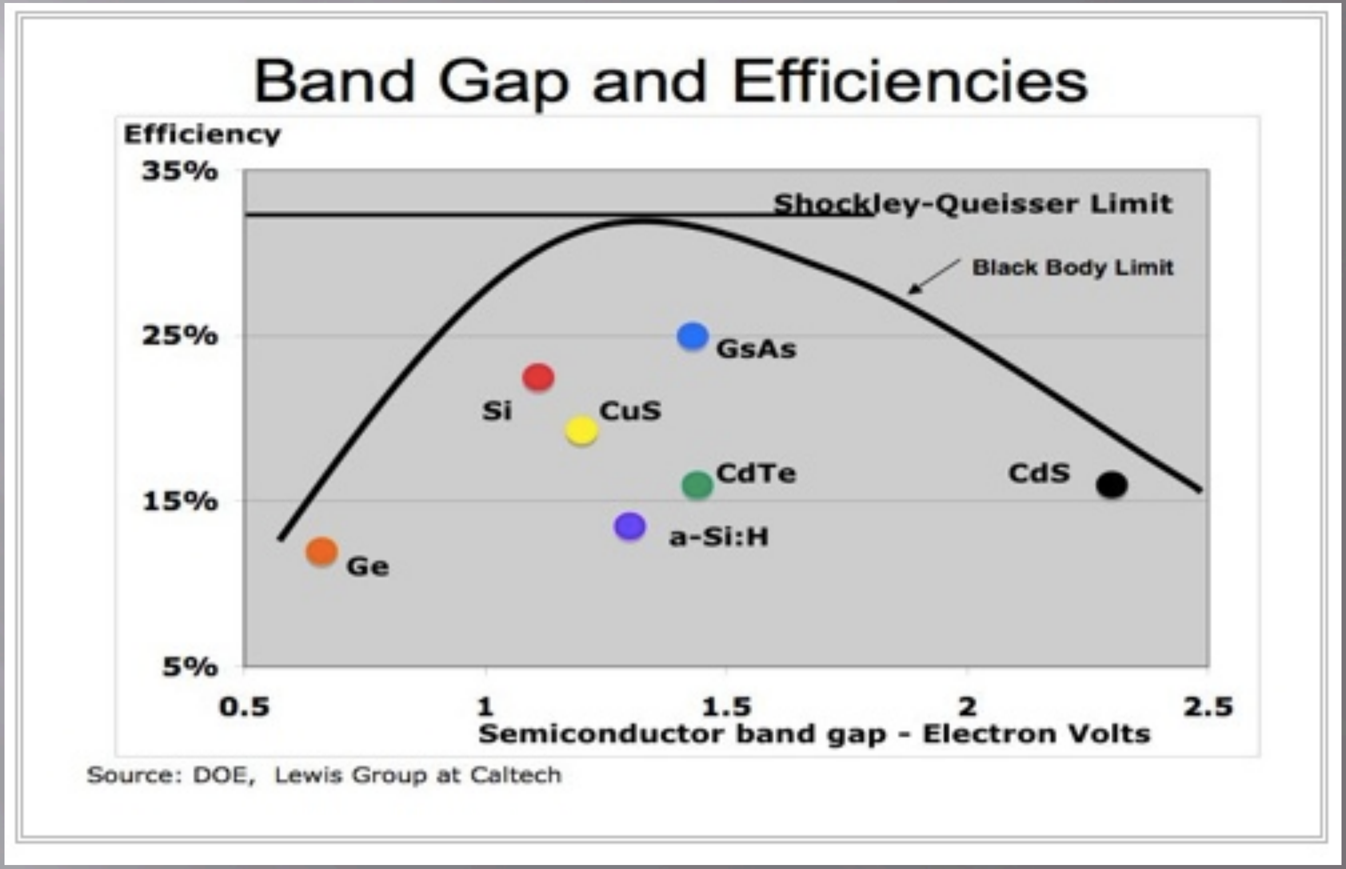
Theoretical Efficiency

- Based on the Shockley-Queisser Limit the theoretical efficiency of a solar cell with n junctions are:
  - 1 junction – 31%
  - 2 junctions – 43%
  - 3 junctions - 49%
  - Infinite junctions– 68%

http://mydocs.epri.com/docs/SEIG/1016279_Photovoltaic_White_Paper_1207.pdf

Band Gap Energies

- For single junction solar cells band gaps between 1.0 – 1.6 eV yield max results.

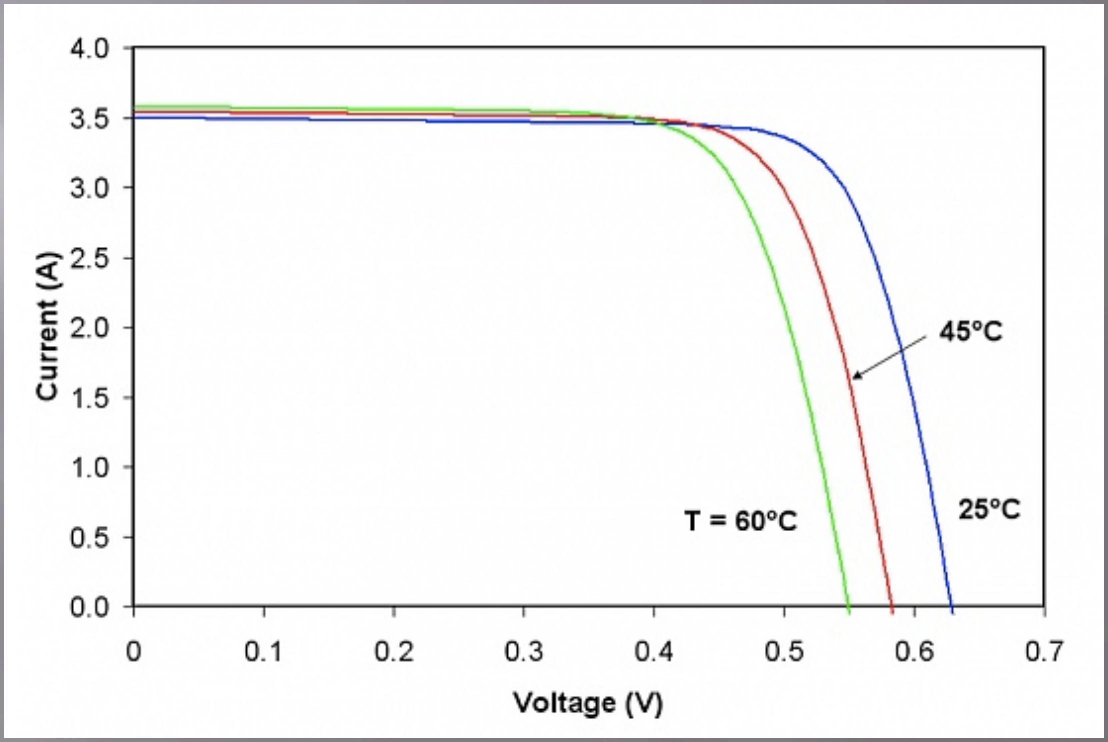


Why Silicon?

- It has the appropriate band gap energy.
- Silicon fabrication technology is well developed as a result of its pervasiveness in the semiconductor electronics industry.
- Relatively easy to make a semiconductor.
- Silicon constitutes about 26% of the Earth's crust.

Temperature of Solar Cell

- A general rule of thumb is that the efficiency of a solar cell decreases with 0.5% for every 1°C (1.8 °F) above 25 °C (77 °F).



http://www.solarpower2day.net/solar-cells/efficiency/

Concentrators

- Sunlight is focused onto a PV cell by mirrors or lenses to generate more power per unit of cell surface area

http://www.seco.cpa.state.tx.us/Images/re_pv-concentrator.jpg

http://www.greenlaunches.com/entry_images/1108/05/solfocus-concentrating-solar-pv.jpg

Concentrators

- AM0 = 1.358 kW/m^2 is the solar radiation from space.
- Used in order to justify high costs of multi-junction cells.
- In order to maintain high efficiency, concentrators must track the sun.

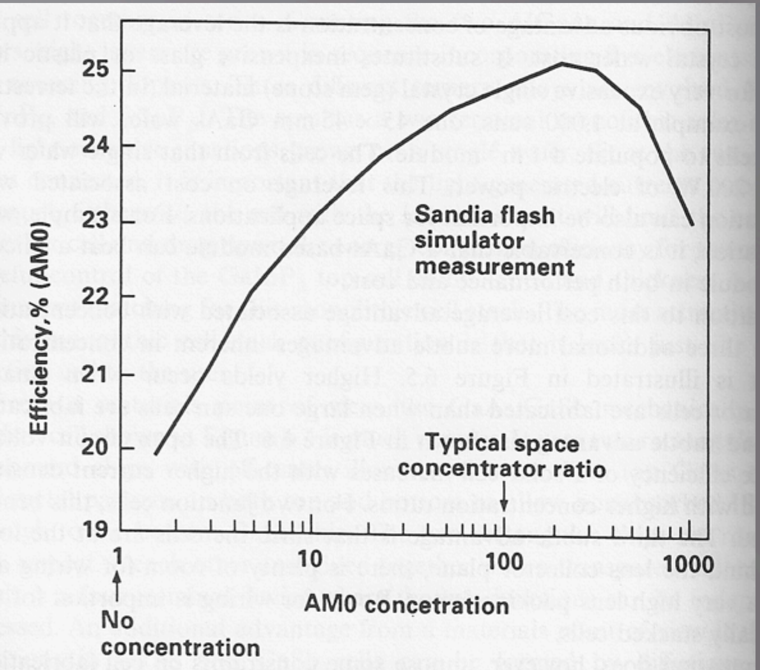
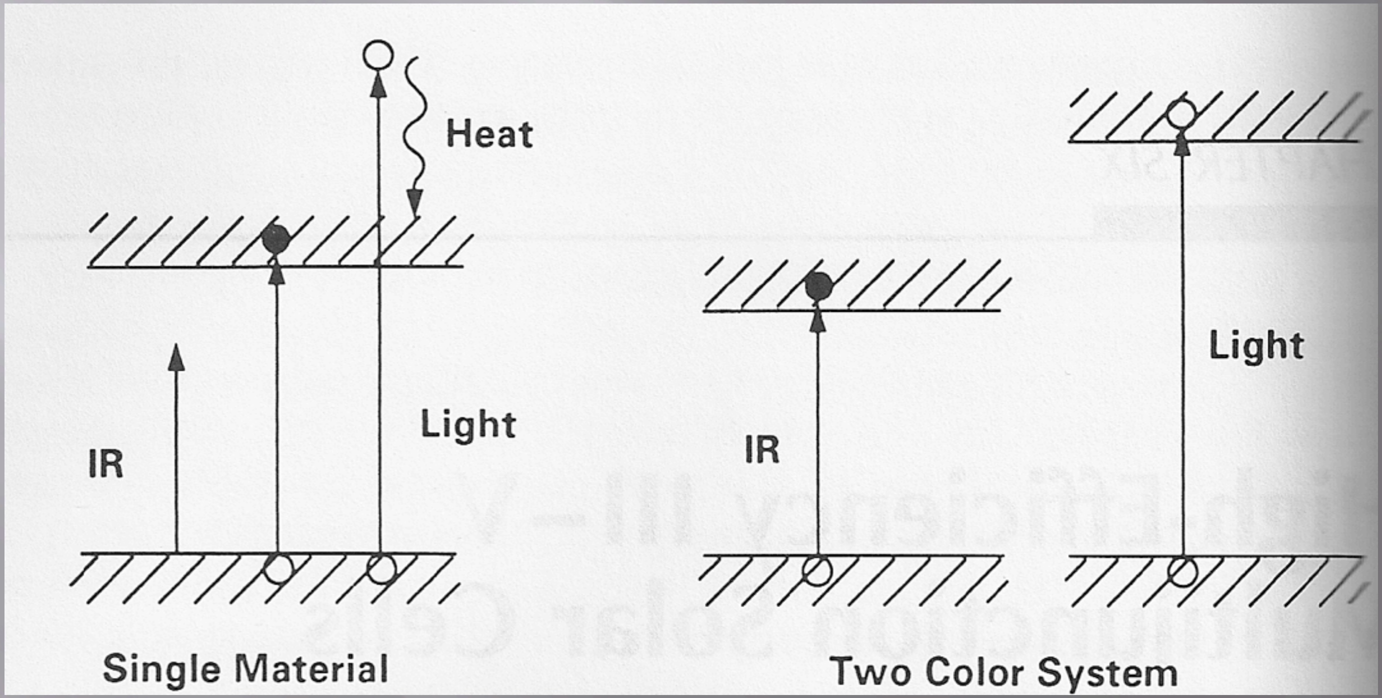


FIGURE 6.6 Efficiency versus concentration ratio for GaAs cells.

Solar Cells and Their Applications (Wiley Series in Microwave and Optical Engineering). New York: Wiley-Interscience, 1995. Print. 150.

Multijunction Cells

- Takes advantage different band gaps for different materials



Solar Cells and Their Applications (Wiley Series in Microwave and Optical Engineering). New York: Wiley-Interscience, 1995. Print. 144.

Multijunction Cells

- Max Efficiency of 43.5% when Eg1 = 1.6-1.7 eV Eg2 = 0.9-1.0 eV

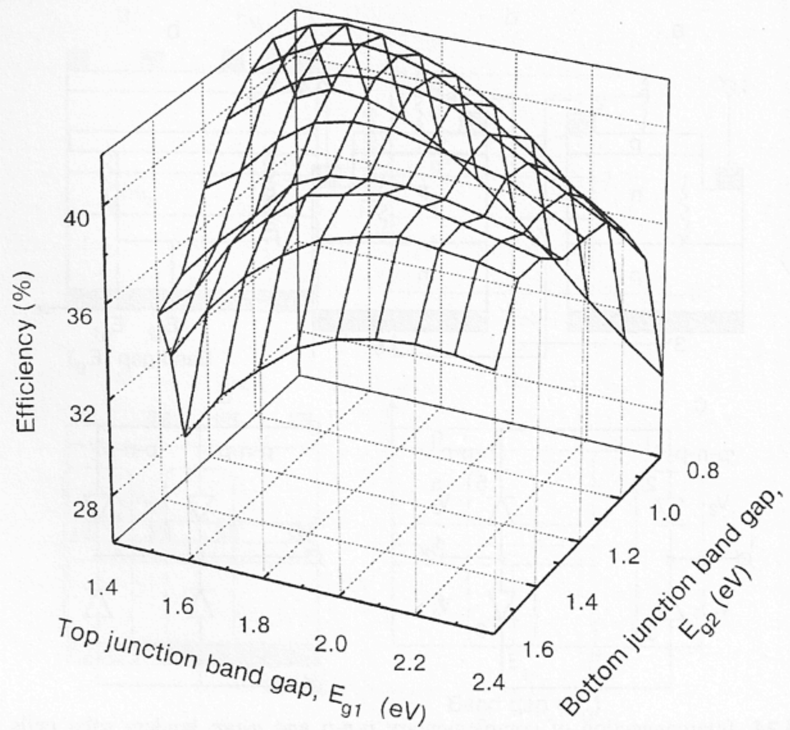
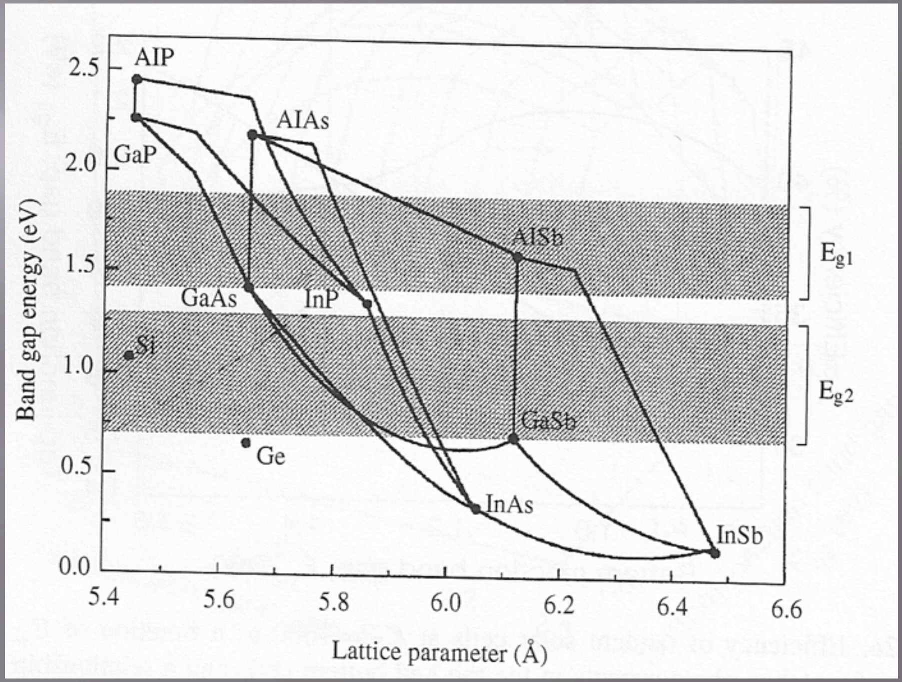


Figure 3.25. Spatial representation of the calculated efficiency for tandem solar cells as a function of E_{g1} and E_{g2} at AM 2.3, $K_S = 1000$ [12]

Andreev, V. M., V. A. Grilikhes, and V. D. Rumyantev. *Photovoltaic Conversion of Concentrated Sunlight. New York, NY: Wiley, 1997. Print. 126.*

Multijunction Cells

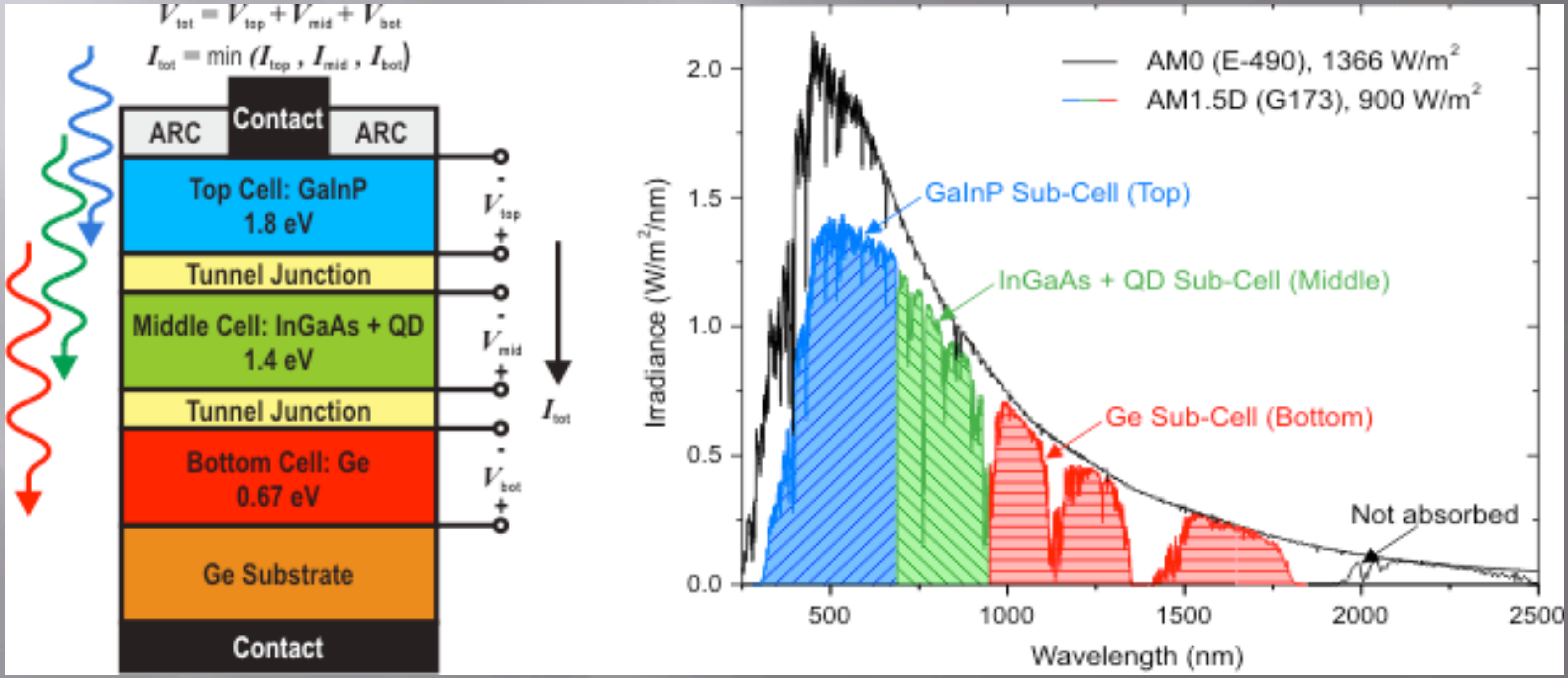
- Mismatch in the crystal lattice creates defects where recombination centers occur decreases V_{OC}.
- Work at NREL showed that lattice mismatching as low as ±0.01% causes significant degradation of photovoltaic quality.



Andreev, V. M., V. A. Grilikhes, and V. D. Rumyantev. *Photovoltaic Conversion of Concentrated Sunlight. New York, NY: Wiley, 1997. Print. 128.*

Multijunction Cells

- The thickness of the cells vary in order to match currents.



http://sunlab.site.uottawa.ca/research/Content/MjCellSpectra.gif

Current Record Holder

- Spectrolab converted 41.6%of concentrated sunlight into electricity with a germanium wafer.
- All told, a tiny cell just 0.3174 square centimeters turned the sunlight equivalent of nearly 364 suns into 4.805 watts.
- Those cells cost 40 cents per watt, according to the manufacturer.

http://www.scientificamerican.com/blog/post.cfm?id=new-solar-cell-efficiency-record-se-2009-08-27

Thin Films

- Most popular materials for low-cost, low-efficiency cells are:
  - Gallium arsenide (GaAs)
  - copper indium gallium selenide (CIGS),
  - cadmium telluride (CdTe),
  - amorphous silicon and
  - micromorphous silicon.
- Low cost due to significantly less material needed for solar cell.

http://solar.calfinder.com/blog/wp-content/uploads/2009/08/thin-film-solar.jpg

Gallium Arsenide

- The GaAs bandgap is 1.43 eV.
- Only a few microns thick.
- Relatively insensitive to heat.
- Single crystal GaAs has high cost.
- GaAs cells are used primarily in concentrator systems, in which a typical concentrator cell measures only about 0.25 cm^2 in area but can produce ample power at high concentrations.

https://www1.eere.energy.gov/solar/tf_single_crystalline.html

CdTe

- CdTe absorbs sunlight at close to the ideal wavelength, capturing energy at shorter wavelengths than is possible with silicon panels.
- First Solar have manufacturing costs less than $1 per watt in the near future. This will allow it to compete with coal-burning electricity on the grid.
- Cadmium is abundant.
- Tellerium rare, but available as a byproduct of copper and lead smelting

http://www.treehugger.com/files/2008/08/cheaper-solar-panels-first-solar.php
http://www.treehugger.com/files/2008/02/making_solar_po.php

CIGS

- The copper indium gallium diselenide (CIGS) thin-film solar cell recently reached 19.9% efficiency, setting a new world record for this type of cell.

Measured Efficiency

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m2) at 25°C

Classification	Efficiency (%)
Si (crystalline)	25.0
Si (thin film)	16.7
GaAs (thin film)	26.1
CIGS (cell)	19.4
CdTe (cell)	16.7
Si (amorphous)	9.5
Dye sensitised	10.4
Organic Polymer	5.15
GaInP/GaAs/Ge	32.0
GaAs/CIS (thin film)	25.8

http://159.226.64.60/fckeditor/UserFiles/File/tyndc/reference/19909584825552.pdf

Measured Efficiency

Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m2) at a cell temperature of 25°C

Classification	Efficiency (%)
Si (crystalline)	22.9
Si (thin-film polycrystalline)	15.5
CIGS	13.5
CdTe	10.9
Amorphous Silicon	10.4

http://159.226.64.60/fckeditor/UserFiles/File/tyndc/reference/19909584825552.pdf

Sources

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- Kirchartz, and Thomas. "Generalized detailed balance theory ... - Google Books." *Google Books. N.p., n.d. Web. 31 Mar. 2010. <http://books.google.com/books?id=73sN8kvgknIC&pg=PA14&lpg=PA14&dq=shockley+queisser+limit+assumptions&source=bl&ots=pLzDYkxiav&sig=RDl_hspcUwGz2R_cJzD8NSpV3t8&hl=en&ei=tbeyS-XwJYeQtgPMnomPAQ&sa=X&oi=book_result&ct=result&resnum=6&ved=0CB0Q6AEwBQ#v=onepage&q=shockley%20queisser%20limit%20assumptions&f=false>*
- Record Makes Thin-Film Solar Cell Competitive with Silicon Efficiency." *National Renewable Energy Laboratory. N.p., n.d. Web. 30 Mar. 2010. <www.nrel.gov/news/press/2008/574.html >.*
- "Solar Cell Efficiency Tables (Version 33)." *Wiley InterScience. N.p., n.d. Web. 30 Mar. 2010. <159.226.64.60/fckeditor/UserFiles/File/tyndc/reference/19909584825552.pdf >.*
- *Solar Cells and Their Applications (Wiley Series in Microwave and Optical Engineering). New York: Wiley-Interscience, 1995. Print.*