Conversion efficiency limit of solar cells

Modern Experiments in Physics Seminar

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Summary

Introduction

Introduction

Energy consumption boom: The industrial revolution (c. 1780 to 1840)
→ rapid growth ever since

- 1876: photoelectric effect in selenium (W. Adams)
- 1883: first selenium-based solar cells (C. Fritts) - <1%
- 1905: description of photoelectric effect (A. Einstein)
- 1918: first monocrystalline silicon growth (J. Czochralsky)
- 1954: first photovoltaic cell from silicon (Bell Labs) - 11%
- 1956: commercial availability of solar panels - 300$/W
- ’60s: recognition in space industry
- ’70s: widespread commercial use (energy crysis)

Photovoltaics

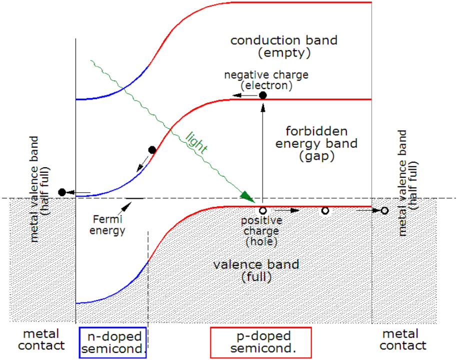

Figure: **Schematic figure of the photovoltaic process** *Current is generated upon excitation in semiconductors.*

Photovoltaic devices

- γ photon with $E \geq E_g$ is absorbed (here: in a semiconductor);
- an *electron* - *hole* pair (i.e. exciton) is generated;
- *electron*s and *hole*s get separated at the *p-n junction*;
- *electron*s are collected on the fingers of the bus;
- *hole*s are collected on the rear, through the base; ⇒ **electric current flows upon illumination**.

General design of traditional solar cells

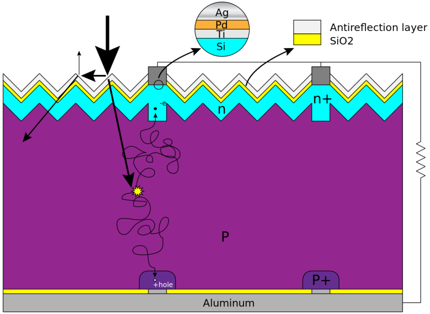

Figure: **Traditional structure of solar cells**
Single-junction solar cells based on a p-n junction.

Structure of solar cells (top-to-bottom)

- collector fingers and bus;
- antireflection layer(s);
- passivation layer (to prevent premature recombination);
- n-type (emitter) layer;
- p-type (base) layer;
- passivation layer;
- rare contact (collector);

Why silicon?

- *It's like pouring water into your shoes.*

Design considerations

Substrate material

- Default is silicon (abundant; existing technology);
- Non-optimal (too narrow band gap, indirect low absorption);

Cell thickness (single-junction

- Ideally ∼100 μm (light trapping, good passivation);
- Practically ∼200-500 μm is used;

Emitter

- less than 1 μm thick;
- ∼5 Ωcm (low V_{oc}, high resistance, but less defects);

Base

- 100-500 μm thickness;
- ∼1 Ωcm (low V_{oc}, high resistance, but less defects);

Grid

- ∼ 20-200 μm finger width;
- ∼ 1-5 mm spacing.

Limitations of Silicon-based solar cells

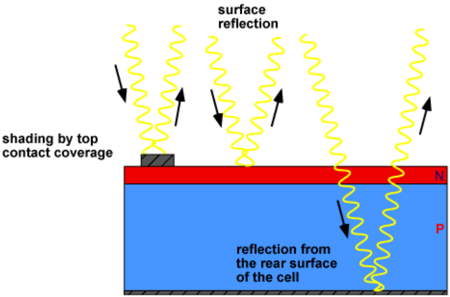

Figure: **Optical losses** *The three main source of optical loss in traditional solar cells.*

Optical losses

- shading (by fingers);
- reflectance at the surface (over 30% in Si);
- non-absorbed photons;
- transmission loss;
  ⇒ **low performance**.

Improving performance

- minimizing coverage;
- transparent conductive films collector;
- anti-reflection coating(s);
- surface texturing;
- increasing thickness (→lower collection probability);
- increasing optical path length (light trapping);
- *light concentration*.

Surface texturing

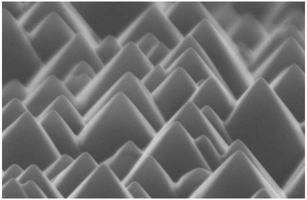

Figure: **Random pyramids (etched)**

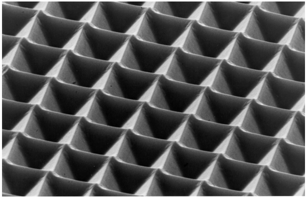

Figure: **Inverted pyramids (etched)**

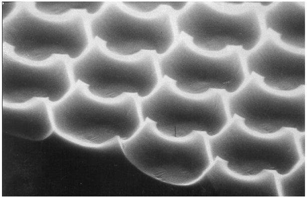

Figure: **Honeycomb (photolithographic)**

Electrical losses

Thermalization

- resistive loss;
- surface or bulk recombination (quantum efficiency);
- low energy photon/excess energy absorption (phonon excitation);

Extraction losses

- re-absorption (charge carrier separation efficiency);
- resistive loss (conduction efficiency);
- contact resistance (charge carrier collection efficiency);

Thickness optimization

- thick absorbers → maximise absorption;
- thin absorbers → maximise current collection;
- thin = thinner than diffusion length or drift length;
  ⇒ **balance between absorptivity and diffusion/drift length**
- cost factor.

Thermodynamic efficiency limit

1961: William Shockley and Hans-Joachim Queisser

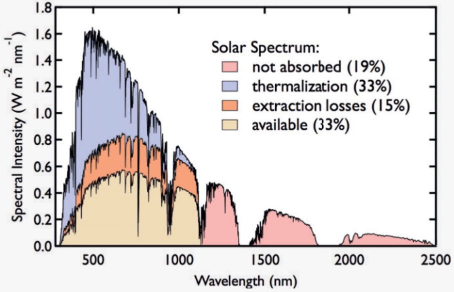

Figure: **SQ limit** *Sources of losses and the maximum convertible portion of the solar spectrum.*

Shockley-Queisser limit

- radiative efficiency (quantum energy conversion);
- relaxation to band edges;
- below-bandgap photons;
- extraction losses;
- only radiative recombination;
- black-body radiation (NOCT);
- impedance matching (optimal load resistance);

  $\Rightarrow$ **33.16% efficiency under *AM1.5* at 1.34 eV**.

Tandem solar cells and concentrator cells

Tandem cells

How to overcome the Shockley-Queisser limit?

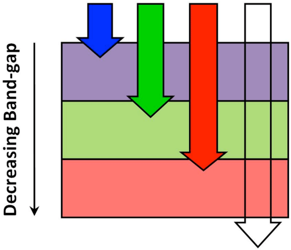

Figure: **Schematic drawing of a tandem cell** *Each layer absorbs a different section of the spectrum.*

Working principle

- multiple bandgaps → response to a broader range of wavelengths;
- bandgaps have to be optimized for each case;
- carrier collection is increasingly complicated;
- lattice-matching, current-matching, and high performance opto-electronic properties are required;
  $\Rightarrow$ 33.16% efficiency limit **can easily be outperformed**.

Tandem cells

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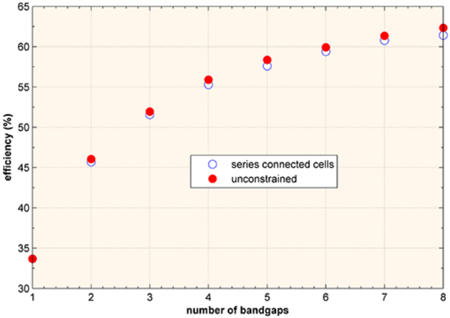

Figure: **Efficiency of a tandem cell** *Each added MJC potentially improves efficiency.*

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Tandem cells

How to achieve matching properties?

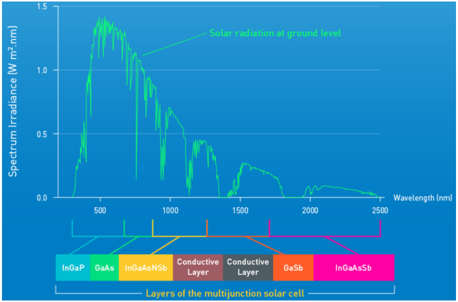

Figure: **Practical structure of a tandem cell** *A proper selection of compound semiconductors can cover the solar spectrum.*

GaAs-based compounds

- over 99% spectrum coverage;
- mechanical and electrical compatibility;
- combination of thin layers (light trapping needed);
- can be further improved by concentrated light (CPV);
- one of many development directions;
  ⇒ currently **39.5% efficiency** under 1-sun illumiation.

Final efficiency limit of solar cells

Final thermodynamic efficiency limit

Infinite-stack efficiency limit

- 1981: Alexis de Vos and Herman Pauwels
- Apprixination as a Carnot heat engine (Chambadal–Novikov–Curzon–Ahlborn efficiency).
- Stacking single-junction silicon cells infinitely:
  - Band gaps ranging from infinity (the first cell) to 0;
  - $V_{cell,i} \approx V_{oc,i} \approx 0.95E_{g,i}$;
  - 6000K blackbody radiation coming from all directions;
  - 300K selective black body heat sinks.

  $\leftrightarrow$ the stack **emits radiation** as it has **non-zero temperature**!
- *Maximum theoretical efficiency* = **86.8%**.
- *MTE under 1-sun radiation* = **68.7%**.

Further optimization?

- Not possible.

Final thermodynamic efficiency limit

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Outlook

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Maximizing performance

- # of bandgaps increases ⇒ efficiency potentially increases.
- In reality, semiconductor materials do not exist to allow for any specific bandgap and of high quality.
- Higher efficiency means higher power-to-area ratio.
- Practically LCOE is desired to be minimal.
- One size does not fit all ⇒ different applications require different approaches.
- Already the cheapest energy source since 2020.
- Solar panels are mostly recyclable cost-effectively.

Outlook

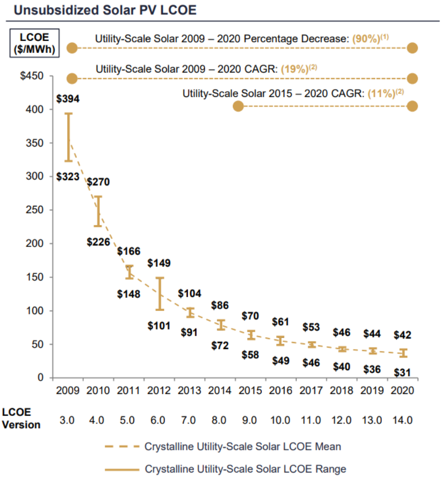

Figure: **Levelized cost of energy** *Since 2020 solar energy has the lowest LCOE out of all possible energy sources.*

Outlook

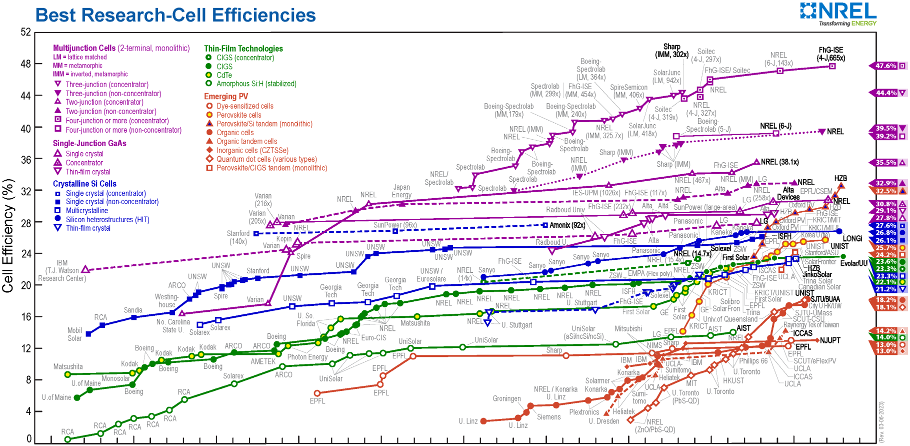

Figure: **State of the art** *Historical improvement of solar cell efficiencies using different approaches.*

References

Literature:

1. Bhattacharya, S., John, S. *"Beyond 30% Conversion Efficiency in Silicon Solar Cells: A Numerical Demonstration"*. Sci Rep 9, 12482, 2019.
2. C.B.Honsberg and S.G.Bowden, *“Photovoltaics Education Website”*, www.pveducation.org, 2019.
3. De Vos, A. *"Detailed balance limit of the efficiency of tandem solar cells"*. Journal of Physics D: Applied Physics. 13 (5): 839–846, 1980.
4. William Shockley and Hans J. Queisser *"Detailed Balance Limit of Efficiency of p-n Junction Solar Cells"*. Journal of Applied Physics. 32 (3): 510–519., 1961
5. Lumb, M. P., Mack, S., Schmieder, K. J., González *"GaSb-Based Solar Cells for Full Solar Spectrum Energy Harvesting"*. Adv. Energy Mater., 7, 1700345., 2017

Other sources:

1. *Image Courtesy of National Renewable Energy Laboratory (NREL).*
2. *Image Courtesy of The School of Photovoltaic Renewable Energy Engineering, University of New South Wales.*

Thank you
for your attention!