CRYSTALLINE SILICON SOLAR CELLS – TOWARDS THE LIMIT AND BEYOND

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CRYSTALLINE SILICON SOLAR CELLS – TOWARDS THE LIMIT AND BEYOND

- What is the limit?
  - Shockley-Queisser vs Auger

- Towards the limit
  - Recombination losses
    - Volume
    - Surfaces
    - Contacts
    - Recent results

- Beyond the limit
  - III/V on silicon
  - Perovskites on silicon
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What is the limit?

Detailed Balance

- Shockley und Queisser, 1961
- Detailed balance between sun and solar cell
- Assumption: Solar cell emits photons via radiative recombination

Radiative recombination in a direct semiconductor

W. Shockley & H. Queisser
What is the limit?

**Maximum Efficiency as a Function of Bandgap**

- **Max. Efficiency ~ 33%**
- **High thermalisation for low bandgaps**
- **High transmission for high bandgaps**
- **Silicon and GaAs are close to the optimum**
- **But: Record values of GaAs are closer to the limit.**
- **Is III/V-R&D better than silicon-R&D?**
What is the Limit?
Other Recombination Channels

- Assumption:
  Ideal solar cell: only radiative recombination
  (Shockley and Queisser, *J. Appl. Phys.* 1961)

  Radiative recombination in an indirect semiconductor

- But silicon is an indirect semiconductor
  → radiative recombination has a low probability
What is the limit?
Auger-Recombination

- In silicon solar cells Auger-recombination is the limiting intrinsic loss mechanism.

Pierre Auger 1899 - 1993

Auger recombination in an indirect semiconductor
What is the limit?
Taking Auger Recombination into Account

- Shockley, Queisser (1961) = 33% (AM1.5)
- Theoretical efficiency limit for silicon (taking actual Auger model into account) = 29.4%²

What is the limit?

Taking Auger Recombination into Account

- Shockley, Queisser (1961) = 33% (AM1.5)
- Theoretical efficiency limit for silicon (incl. Auger) = 29.4% \(^1\)
- Best silicon solar cells = 25.6% \(^2\)
- Corresponds to 87% of theoretical efficiency limit
- (GaAs = 87% 😊)

\(^1\)Richter, Hermle, Glunz, *IEEE J. Photovolt.* (2013)
\(^2\)Masuko et al., *IEEE-PVSC* (2014)
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Towards the Limit
Small-area Record Values

- Small-area record cells
- Mono-Si:
  25.0% (da)
  (PERL, UNSW 1999)

Data from M.A. Green, PIP 17, p.183 (2009)

ap = aperture area
da = designated area
Towards the Limit
Small-area Record Values

- Small-area record cells
- Mono-Si:
  25.0% (da)
  (PERL, UNSW 1999)
- Multi-Si:
  20.4% (ap)
  (LFC, ISE 2004)

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Towards the Limit
Small-area Record Values

- Small-area record cells
- Mono-Si:
  25.0% (da)
  (PERL, UNSW 1999)
- Multi-Si:
  20.4% (ap)
  (LFC, ISE 2004)
- Since 1974 nearly only records on p-type silicon
- Main progress:
  Reduction of recombination losses

ap = aperture area
da = designated area

Data from M.A. Green, PIP 17, p.183 (2009)
Towards the Limit
Influence of Surface and Bulk Recombination

- Cells with excellent surface passivation
- Experimental thickness variation

Diffusion length
- High \( (L_b \gg 250 \mu m) \)
- Medium \( (L_b \approx 250 \mu m) \)
- Low \( (L_b \ll 250 \mu m) \)

Towards the Limit
Multicrystalline Silicon

- Defect engineering during cell process
- Very thin wafers (99 µm) to reduce influence of volume recombination
- Plasma texture on front side
- World record on multicrystalline silicon (20.4%)

Towards the Limit

Monocrystalline Silicon

- Additional bulk recombination in $p$-type Cz-grown silicon
- Light-induced degradation
- Metastable defect related to boron and oxygen\(^1\)

\[\begin{align*}
\text{Relative Lifetime Level} & \quad [\%] \\
\text{Time} & \quad [\text{min}] \\
\end{align*}\]

\(^1\) Glunz et al., WCPEC/EUPVSEC, Vienna (1998)
On the occasion of the 2nd World Conference on Photovoltaic Solar Energy Conversion
6 – 10 July 1998, Vienna, Austria

S. W. Glunz, S. Rein, W. Warta, J. Knobloch, W. Wettling

have been selected by the official jury as the winners of the

Poster Award

for the topic Crystalline Silicon Solar Cells and Technologies.

This outstanding scientific poster was deemed to be a particularly valuable contribution to this
International Conference on Photovoltaic Energy Conversion.

The General Chairperson

The General Vice-Chairpersons

Prof. J. Schmid

Dr. S. Bailey

Prof. K. Kurokawa
Towards the Limit
Monocrystalline Silicon

- Additional bulk recombination in $p$-type Cz-grown silicon
- Light-induced degradation
- Metastable defect related to boron and oxygen
  - Gallium–doped silicon
  - $n$-type silicon

Graph showing efficiency vs base resistivity for different types of silicon:

- Ga-doped Cz
- B-doped Cz
- B-doped FZ

References:
2. Glunz et al., *Progress Photovoltaics* 7 (1999)
Towards the Limit
Large-area Record Cells

- Interdigitated back contact back junction solar cells
- Excellent contact passivation (a-Si/c-Si heterojunction, passivated contacts)
- Sanyo\(^1\) (da=143.7 cm\(^2\)) 25.6% (\(V_{oc} = 740\) mV)
- SunPower\(^2\) (ap=121 cm\(^2\)) 25.0% (\(V_{oc} = 726\) mV)
- Edge losses are getting crucial

\(^1\) Masuko et al., IEEE PVSC (2014)
\(^2\) Smith et al., IEEE PVSC (2014)
Towards the Limit
Large-area Record Cells

- Large-area (Sunpower, Sanyo/Panasonic)
- Extremely high lifetimes needed (>> 1 ms)
- Usage of $n$-type silicon to avoid light-induced degradation

![Graph showing efficiency trends over time for mono-Si (p-type) and mono-Si (n-type)]
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Beyond the Limit
Magic Antireflection Coatings (AAA-Coating®)

- Silicon Solar Cells with AAA-Coating®
  (amazingly active antireflection coating)
Beyond the Limit
Silicon Solar Cell

- Theoretical limit for $E_{g, \text{Si}}$: 33% (29.4% incl. Auger)
- Word record for silicon solar cells: 25.6%
Beyond the Limit
Multijunction Solar Cells

- Successfully realized with III/V-materials
Beyond the Limit
Multijunction Solar Cells

- Successfully realized with III/V-materials
- Tandem cells with Si bottom cell
  - III/V on Si
  - Silicon quantum dots
  - Perovskites

→ “Silicon Solar Cell 2.0”
Beyond the Limit
Silicon-based Multijunction Cells

- Top cells with high bandgap to utilize blue and visible light
- c-Si bottom cells for IR light
- Deposition by direct epitaxial growth or wafer bonding
Beyond the Limit
GaInP/GaAs/Si Solar Cells

- Efficient utilization of spectrum
- High efficiency
- Wafer bonfing
- But: Cell design optimized for concentration and AM1.5d
- More to come quite soon 😊

K. Derendorf et al., IEEE JPV (2013)

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Conclusion

- Crystalline silicon, the vital dinosaur, hunting record efficiencies. (pretty active for a first generation)
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- Coming soon: Crystalline silicon solar cells 2.0
- Let’s show Pierre A. what we can do!
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