# 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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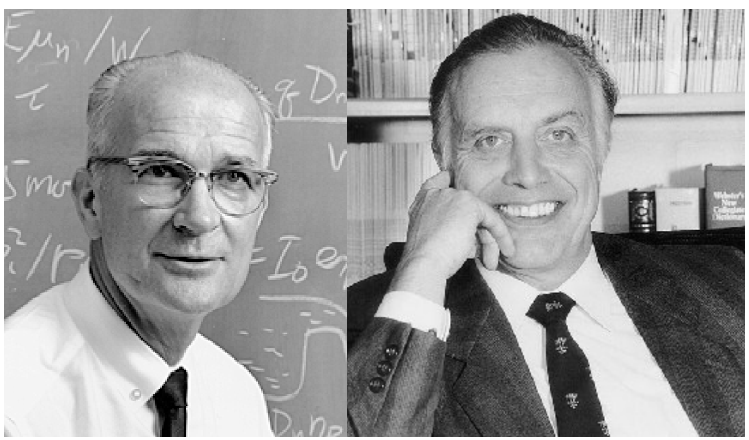
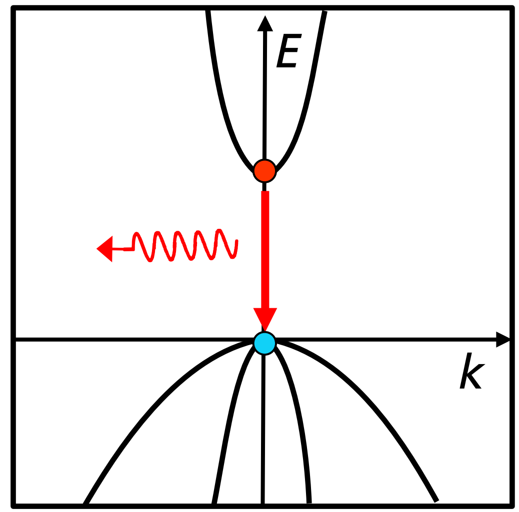
# What is the limit?
## Detailed Balance

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



W. Shockley & H. Queisser




Radiative recombination in a direct semiconductor



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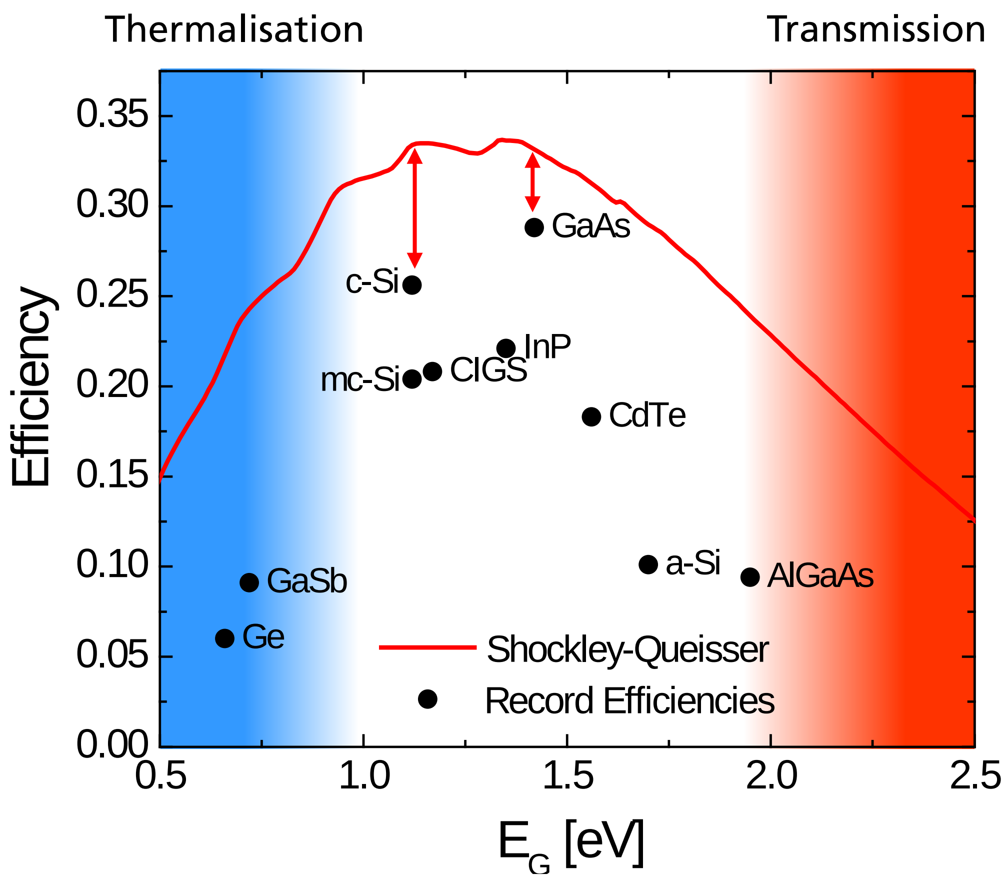
# What is the limit?
## Maximum Efficiency as a Function of Bandgap

- 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 ?



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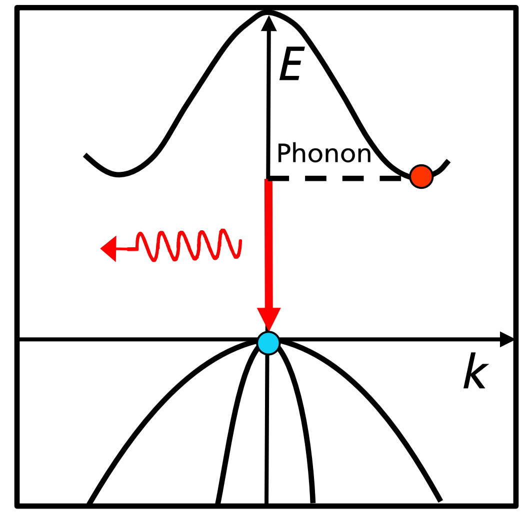
# What is the Limit?
## Other Recombination Channels

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

> lated using the principle of detailed balance.[9] It is this radiative recombination that determines the detailed balance limit for efficiency.[10] If radiative recombination is only a fraction $f_c$ of all the recombination, then the efficiency is substantially reduced below the detailed balance limit.

- But silicon is an indirect semiconductor
  → radiative recombination has a low probability




Radiative recombination in an indirect semiconductor



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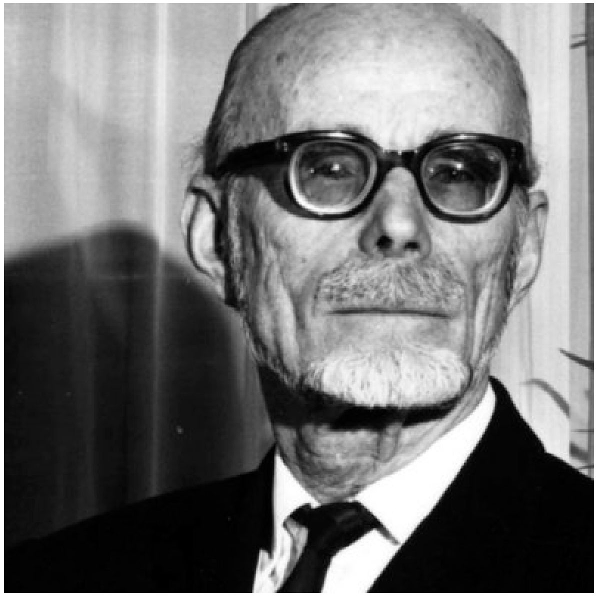
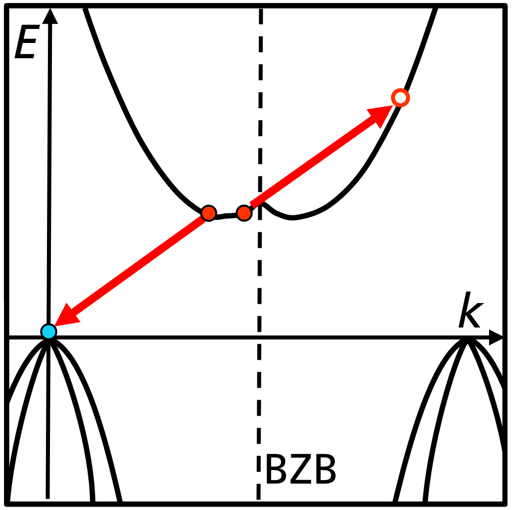
# What is the limit?
## Auger-Recombination

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



Pierre Auger 1899 - 1993




Auger recombination in an indirect semiconductor

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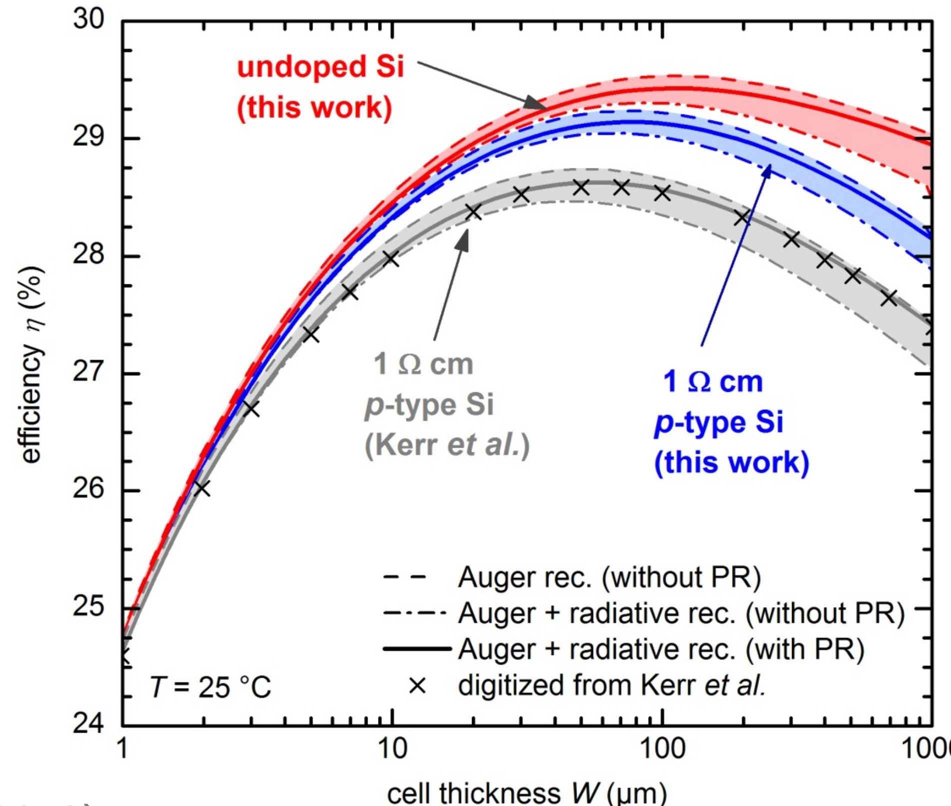
# What is the limit?
## Taking Auger Recombination into Account

- Shockley, Queisser (1961) = 33% (AM1.5)
- Theoretical efficiency limit for silicon (taking actual Auger model [1] into account) = 29.4%[2]

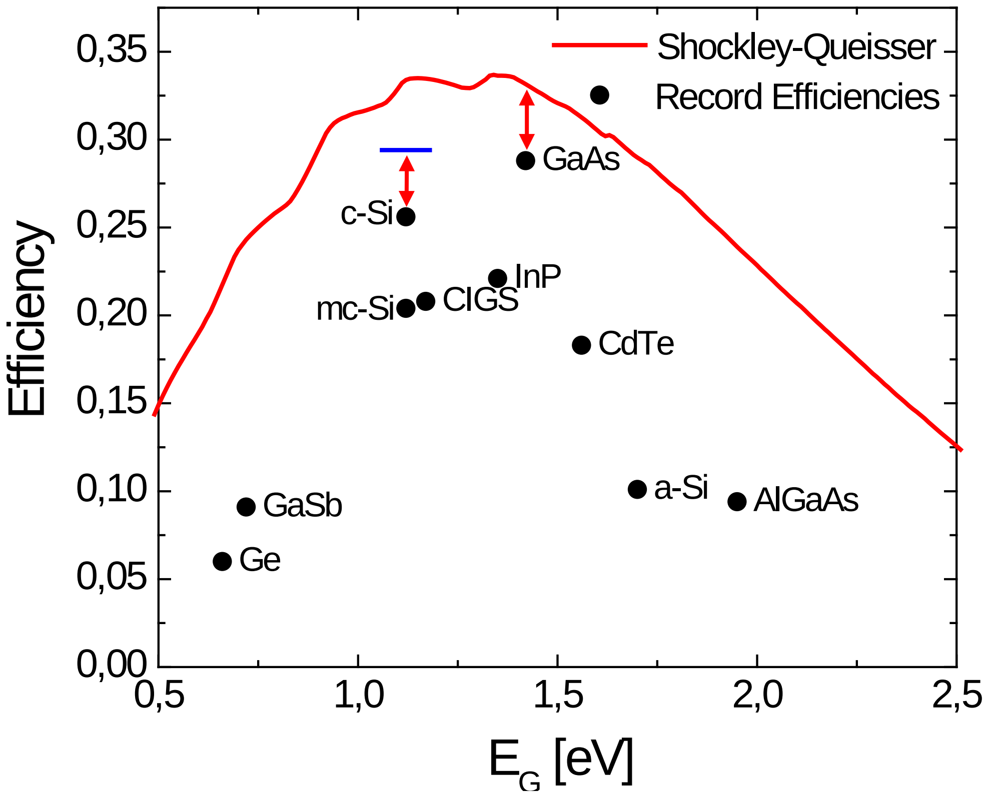



[1]Richter, Glunz *et al., Phys. Rev. B 86* (2013)

[2]Richter, Hermle, Glunz, *IEEE J. Photovolt.* (2013)

# 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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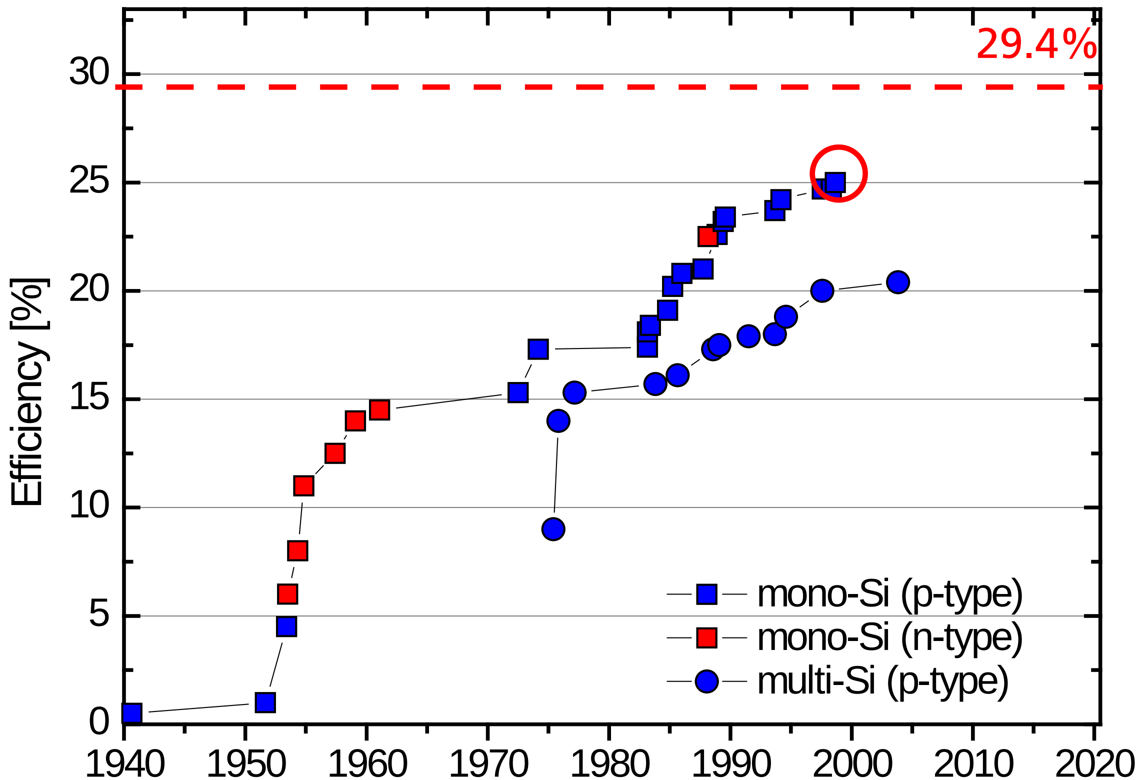
# Towards the Limit
## Small-area Record Values

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




ap = aperture area
da = designated area

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





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# Towards the Limit
## Small-area Record Values

- Small-area record cells
- Mono-Si:
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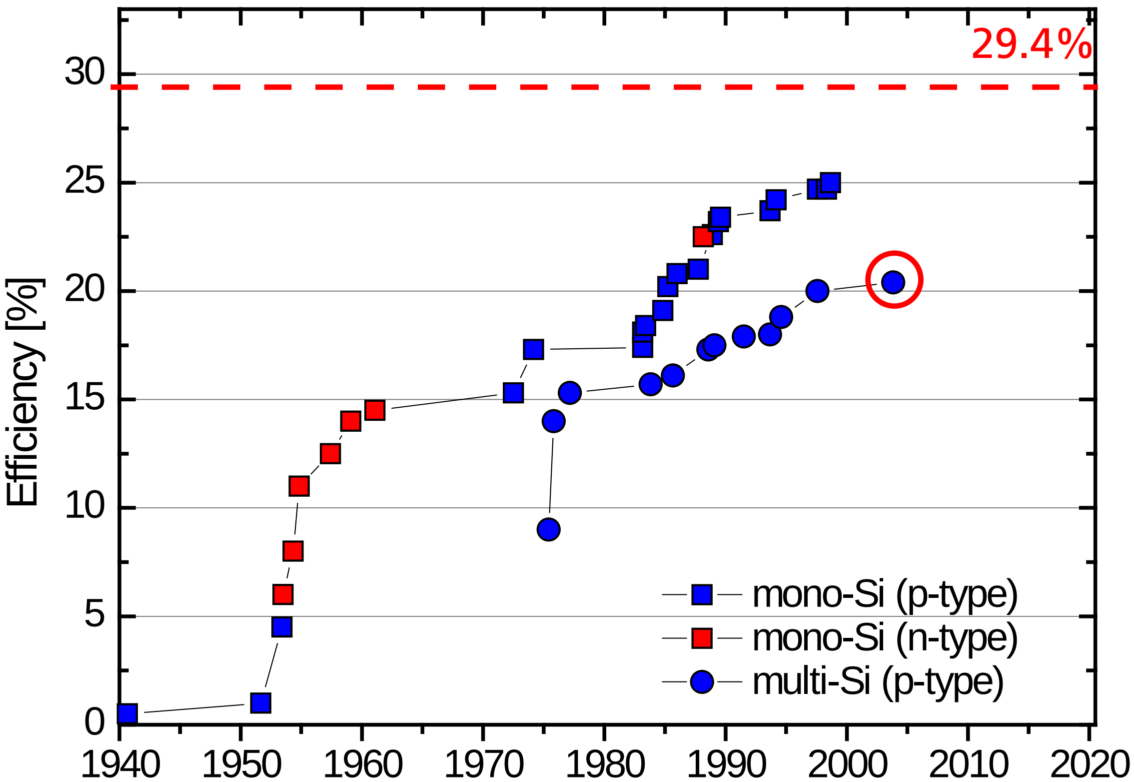
- Multi-Si:
  20.4% (ap)
  (LFC, ISE 2004)

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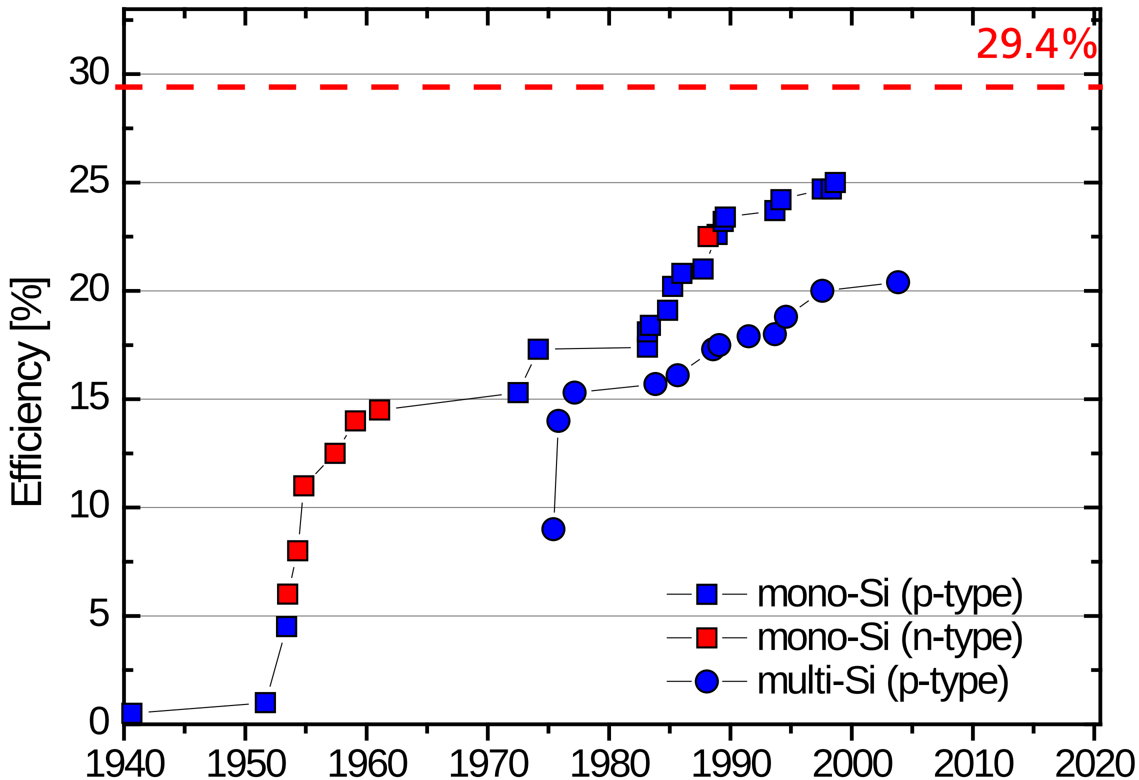
# Towards the Limit
## Small-area Record Values

- 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

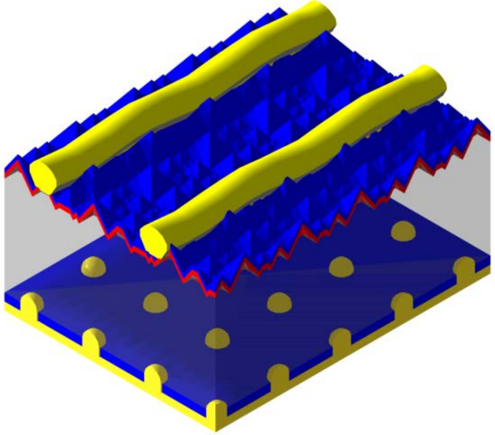



ap = aperture area
da = designated area

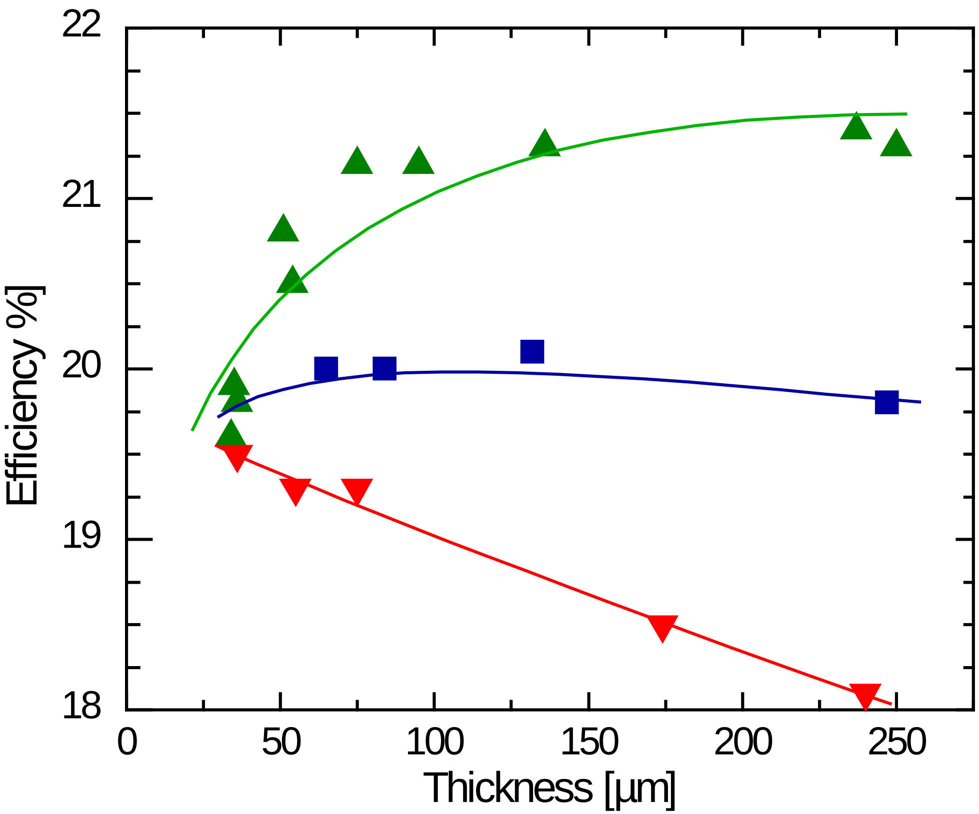
Data from M.A. Green, PIP 17, p.183 (2009)

# Towards the Limit
## Influence of Surface and Bulk Recombination

- Cells with excellent surface passivation
- Experimental thickness variation



Diffusion length
High (*L*$_b$>> 250 µm)
Medium (*L*$_b$≈ 250 µm)
Low (*L*$_b$<< 250 µm)




Glunz, *3rd Workshop on the Future Direction of Photovoltaics, Tokyo* (2007)



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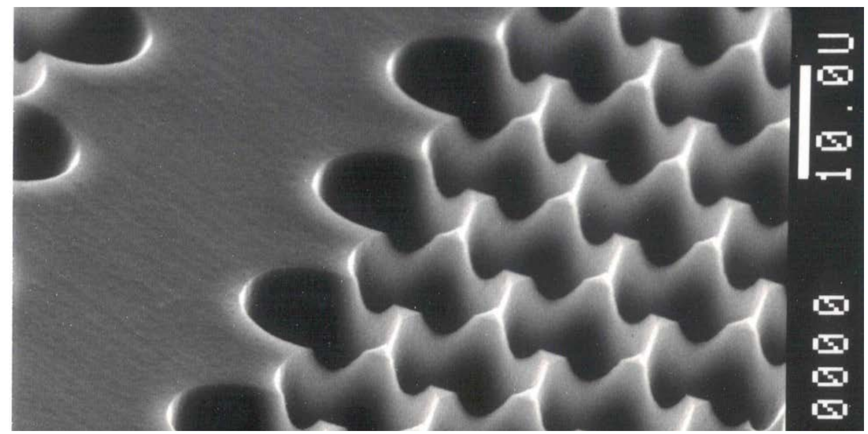
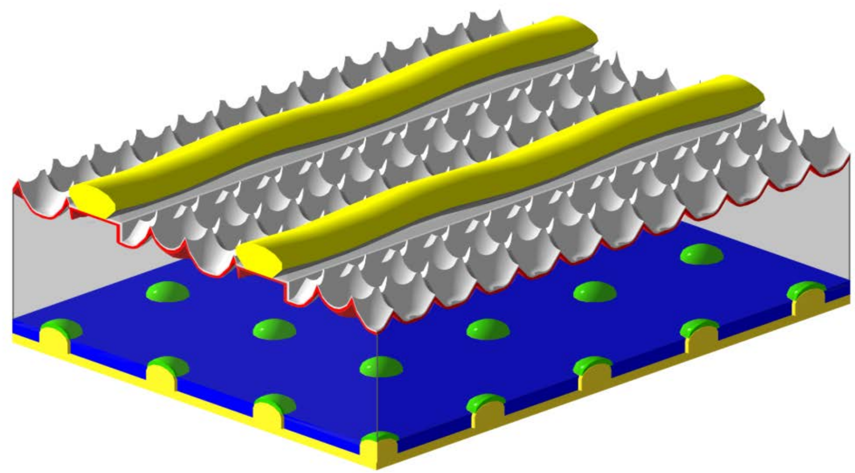
# Towards the Limit
## Multicrystalline Silicon

- *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%)

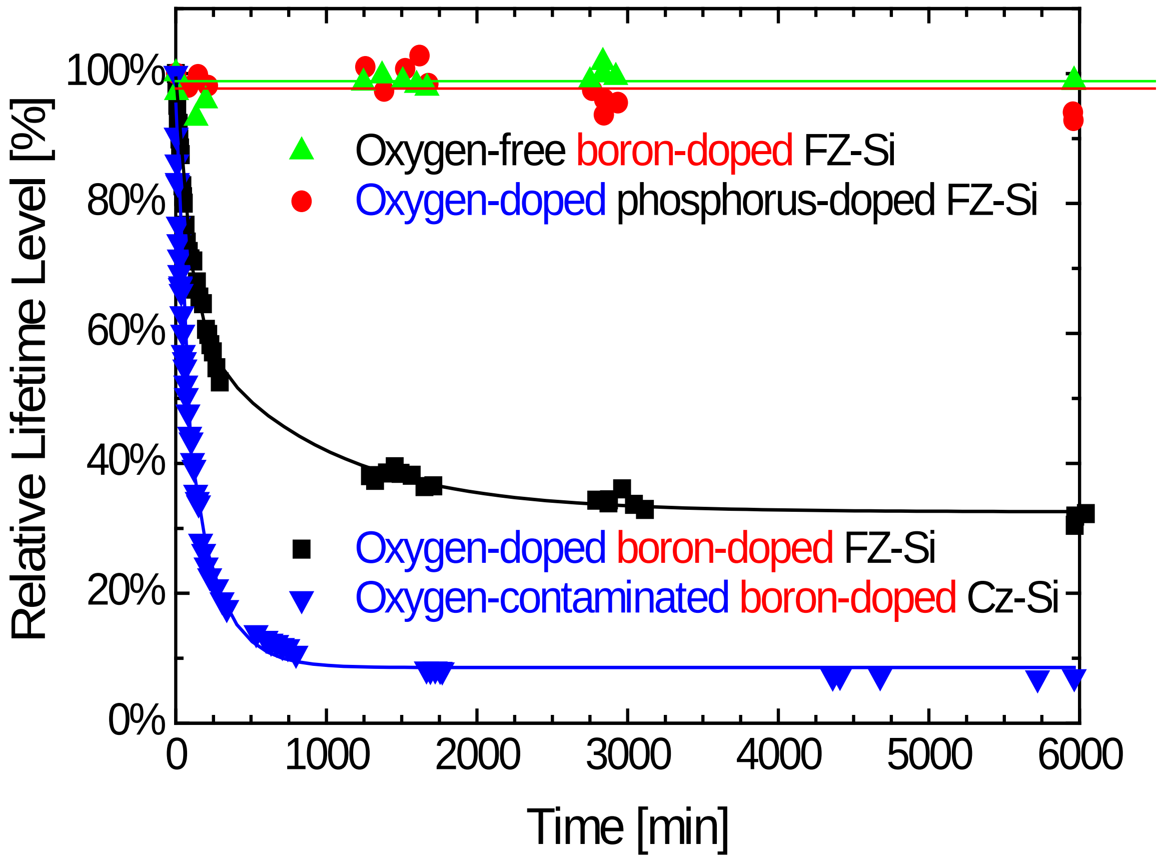




Schultz, Glunz, Willeke,
*Prog. Photovolt. 12* (2004)

# 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]




[1] Glunz *et al.*, *WCPEC/EUPVSEC*, Vienna (1998)

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# July 1998, 2nd World Conference, Vienna

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

Prof. J. Schmid

The General Vice-Chairpersons

Dr. S. Bailey

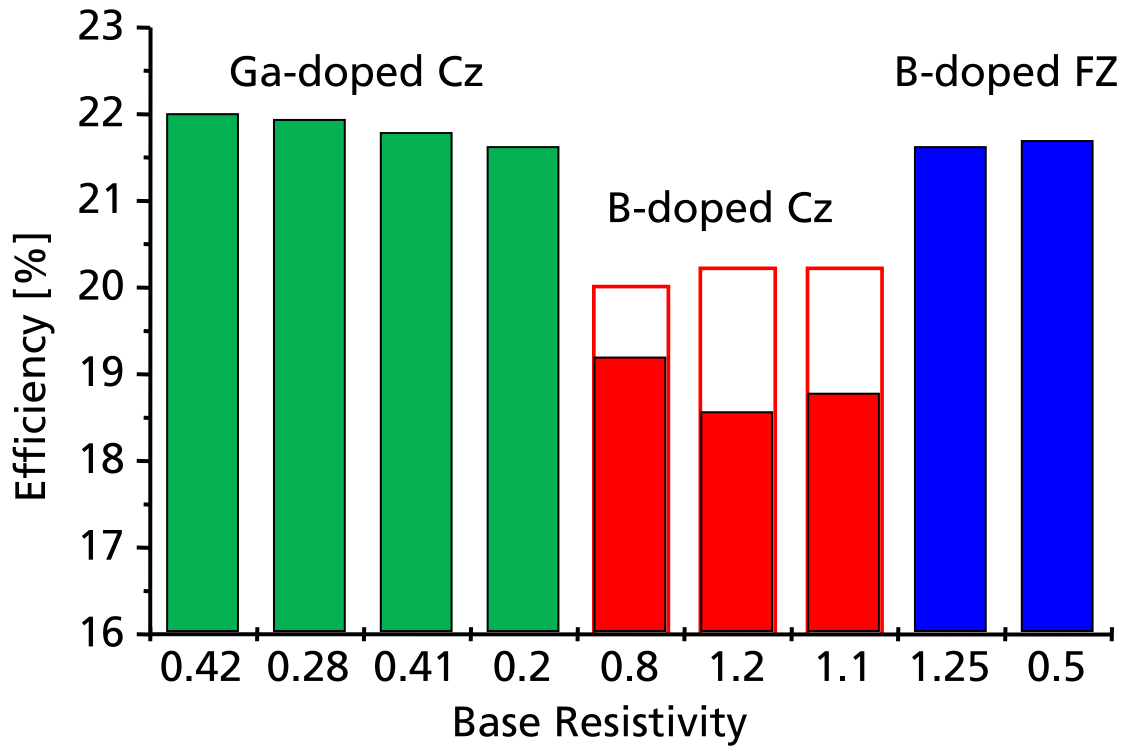
Prof. K. Kurokawa

# Towards the Limit
## Monocrystalline Silicon

- Additional bulk recombination in *p*-type Cz-grown silicon
- Light-induced degradation
- Metastable defect related to boron and oxygen[1]

→ Gallium–doped silicon[2]

→ *n*-type silicon




[1] Glunz *et al.*, *EUPVSEC*, Vienna (1998)
[2] Glunz *et al.*, *Progress Photovoltaics 7* (1999)





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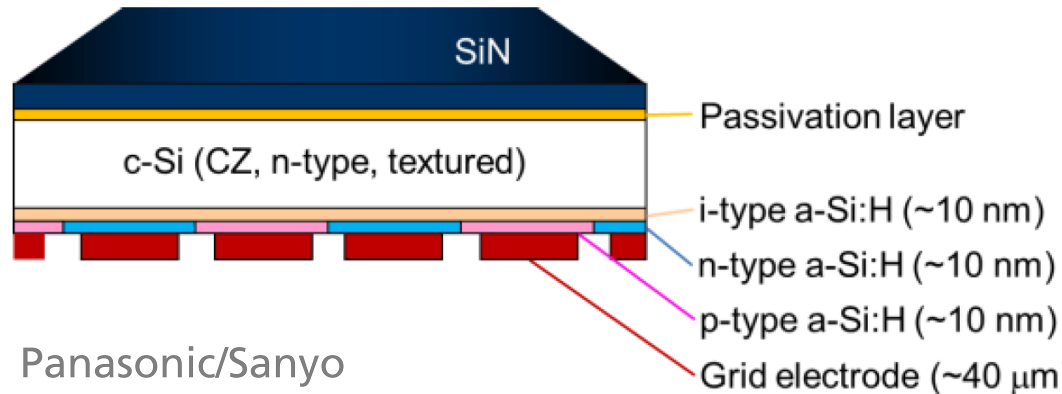
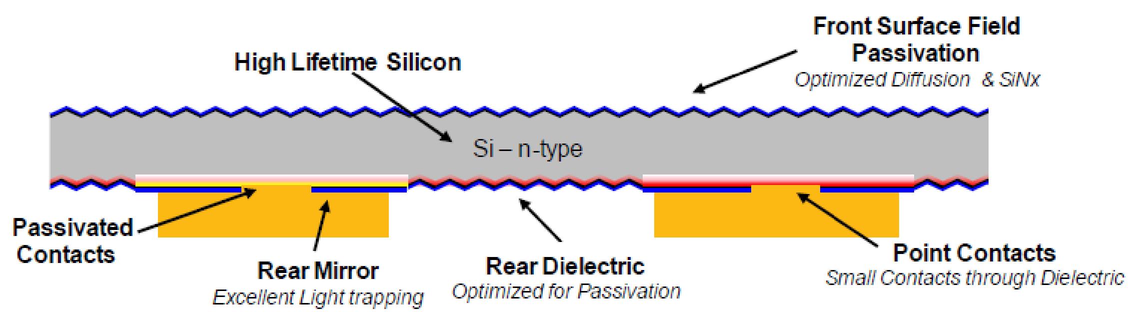
# Towards the Limit
## Large-area Record Cells

- Interdigitated back contact back junction solar cells
- Excellent contact passivation (a-Si/c-Si heterojunction, passivated contacts)
- Sanyo[1] (da=143.7 cm²) 25.6% ($V_{oc}$ = 740 mV)
- SunPower[2] (ap=121 cm²) 25.0% ($V_{oc}$ = 726 mV)
- Edge losses are getting crucial




Panasonic/Sanyo
[1] Masuko *et al.*, *IEEE PVSC (2014)*




SunPower
[2] Smith *et al.*, *IEEE PVSC (2014)*



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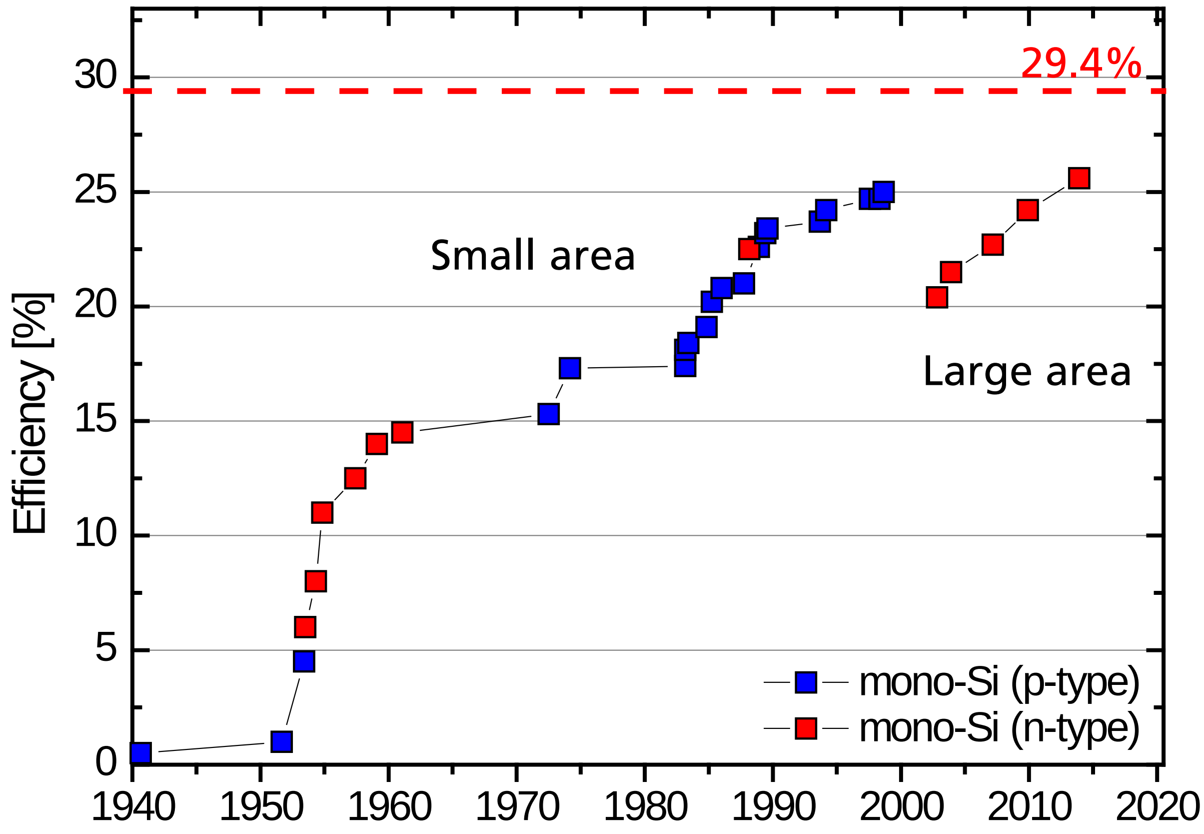
# Towards the Limit
## Large-area Record Cells

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



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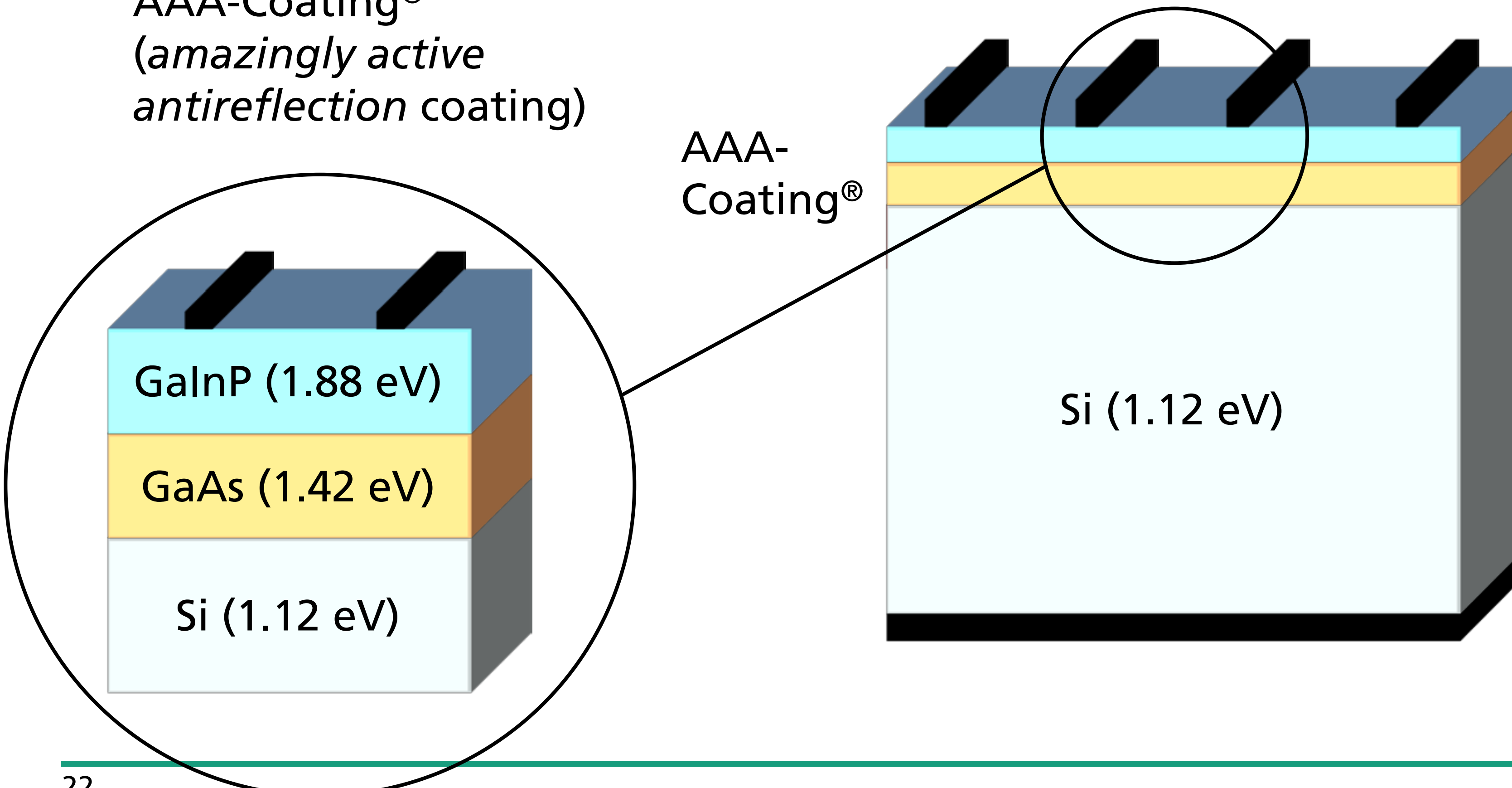
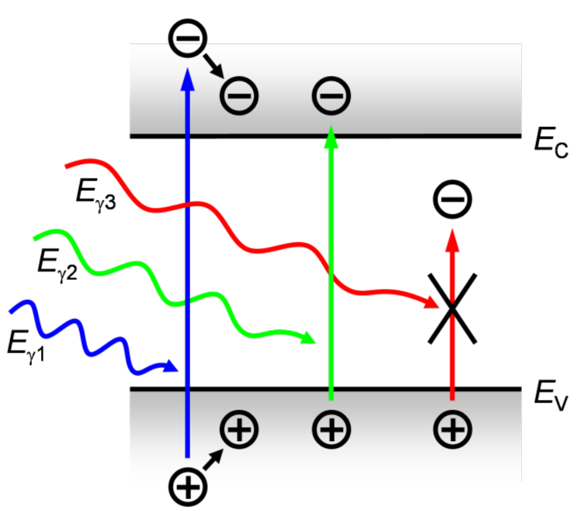
# Beyond the Limit
## Magic Antireflection Coatings (AAA-Coating®)

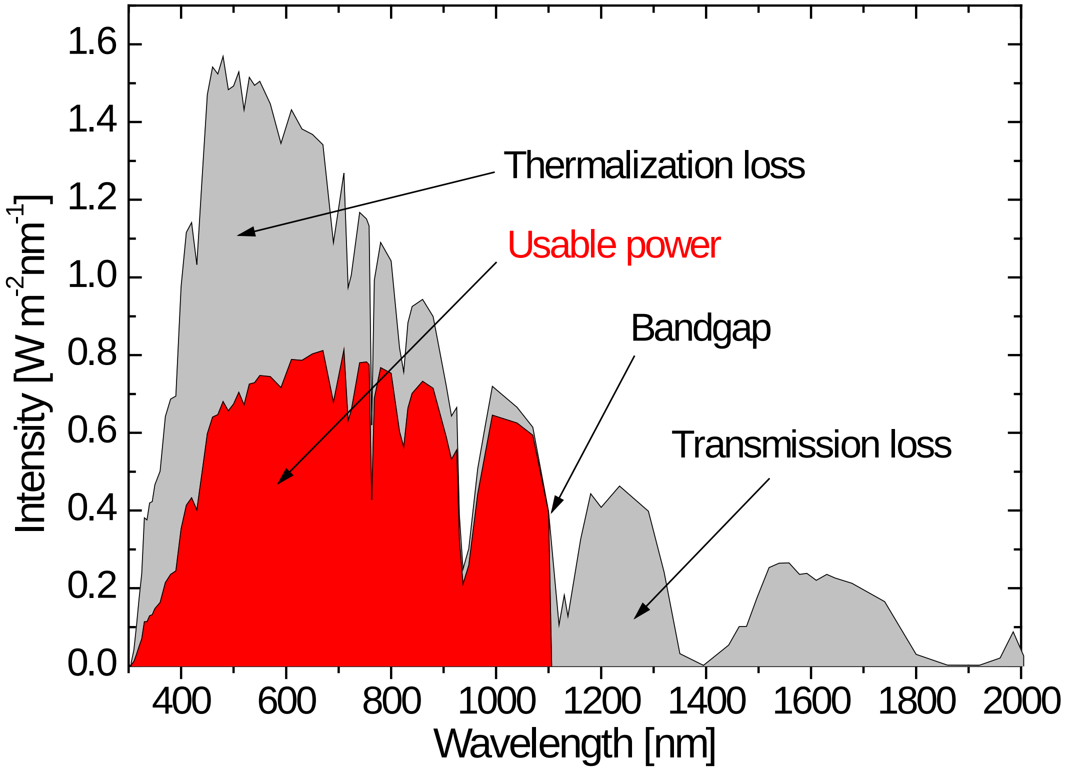
- Silicon Solar Cells with AAA-Coating® (*amazingly active antireflection* coating)



# Beyond the Limit
## Silicon Solar Cell

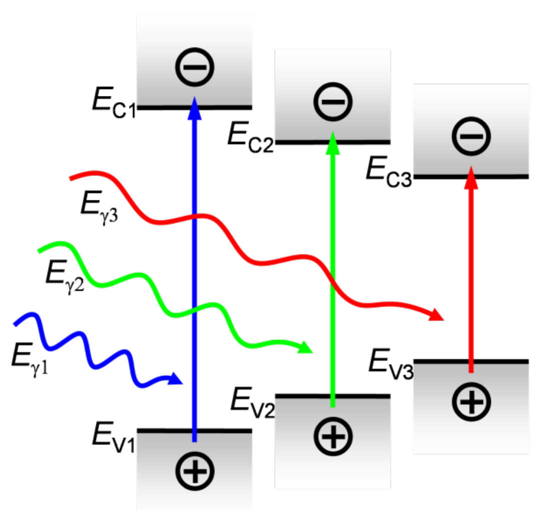
- Theoretical limit for $E_{g,Si}$: 33% (29.4% incl. Auger)
- Word record for silicon solar cells: 25.6%

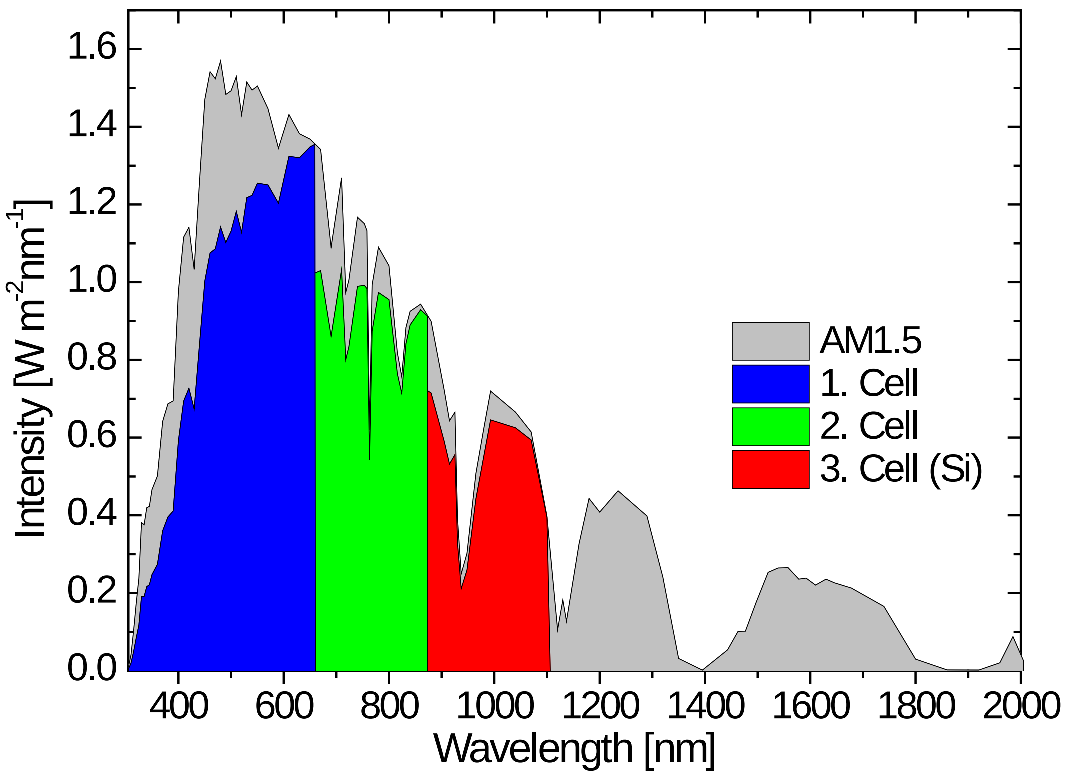


# Beyond the Limit
## Multijunction Solar Cells

- Succesfully realized with III/V-materials







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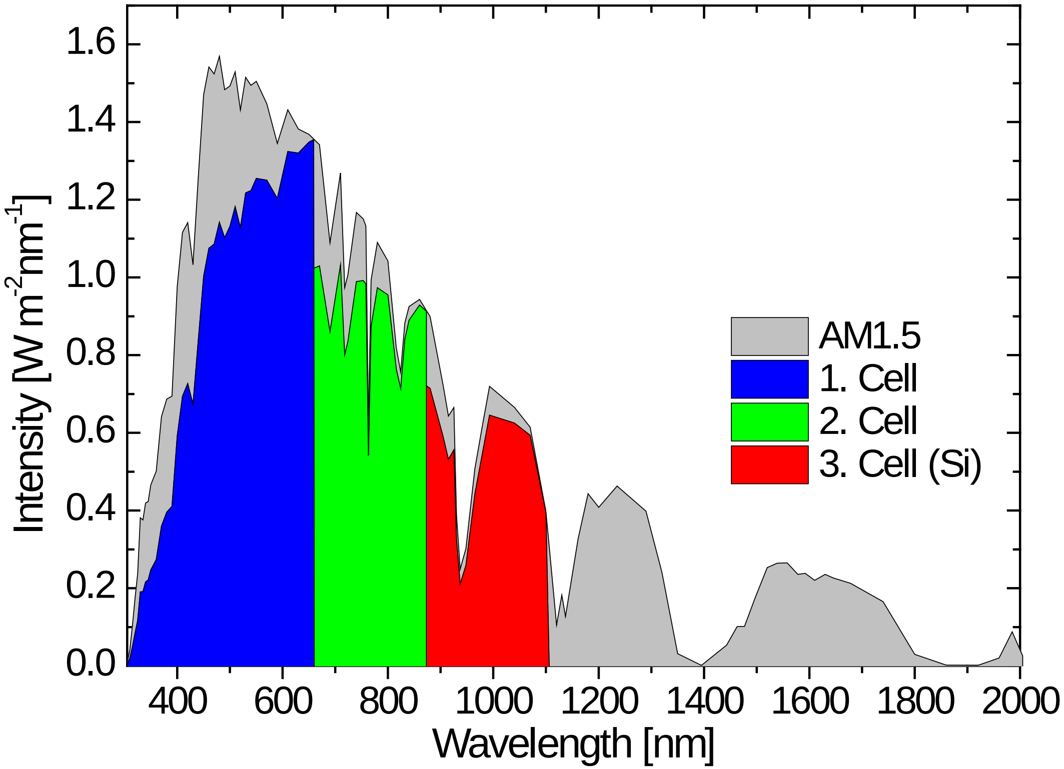
# Beyond the Limit
## Multijunction Solar Cells

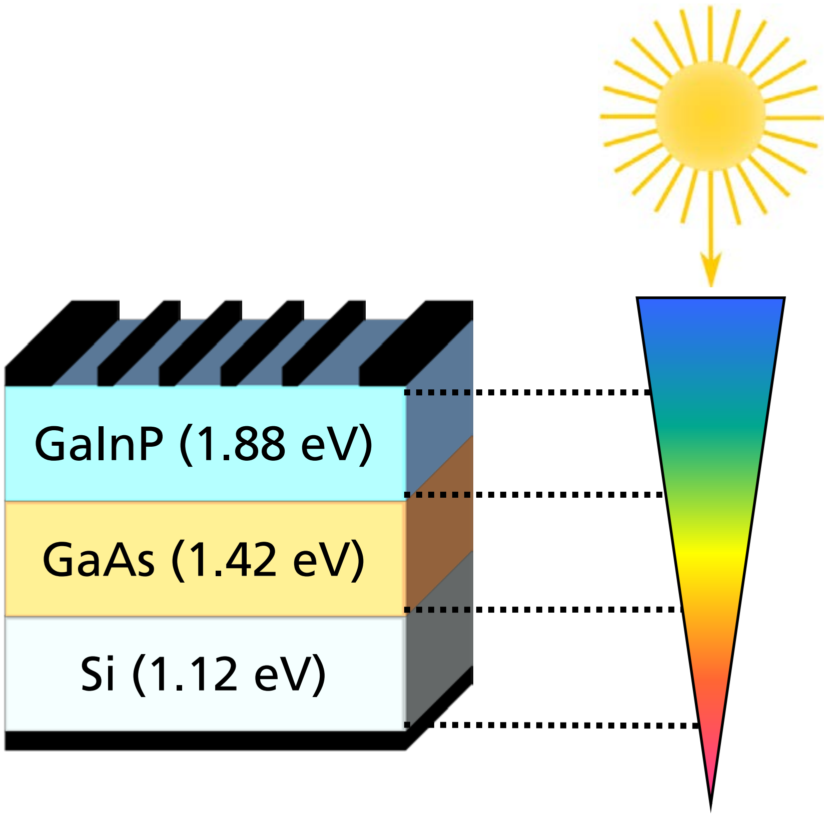
- Succesfully realized with III/V-materials
- Tandem cells with Si bottom cell
  - III/V on Si
  - Silicon quantum dots
  - Perovskites

→ "Silicon Solar Cell **2.0**"



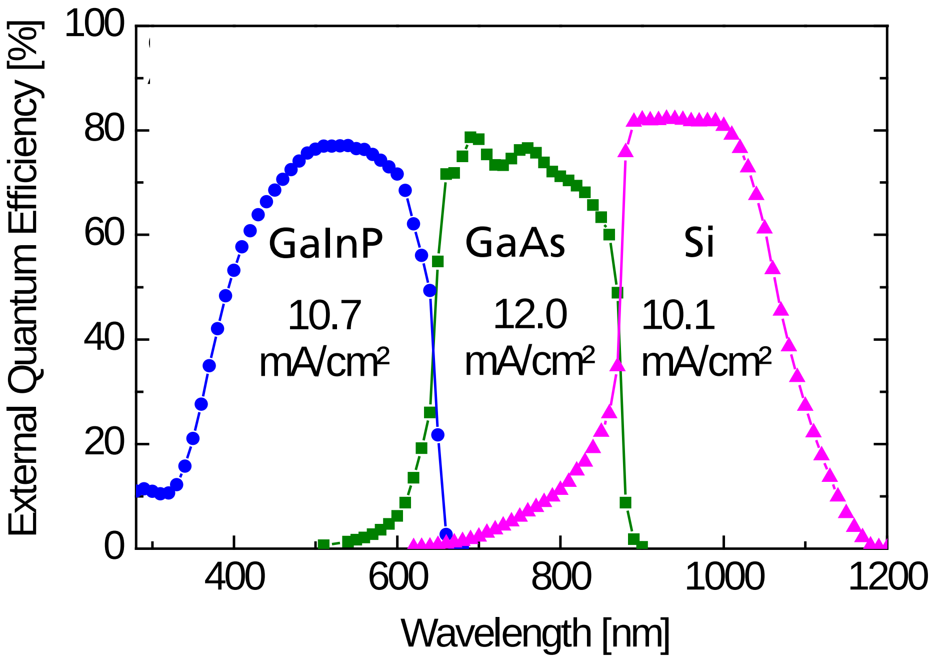
# Beyond the Limit
## Silicon-based Multijunction Cells

- 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 ☺




| $C$ [suns] | $V_{oc}$ [V] | $J_{sc}$ [mA/cm$^2$] | $FF$ [%] | $\eta$ [%] |
|---|---|---|---|---|
| **1** | **2.89** | **10.1** | **87.8** | **25.6** |
| **112** | **3.40** | **1129** | **88.3** | **30.2** |

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

S. Essig, *PhD Thesis* (2014)

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# Conclusion

- Crystalline silicon, the vital dinosaur, hunting record efficiencies.
  (pretty active for a first generation)






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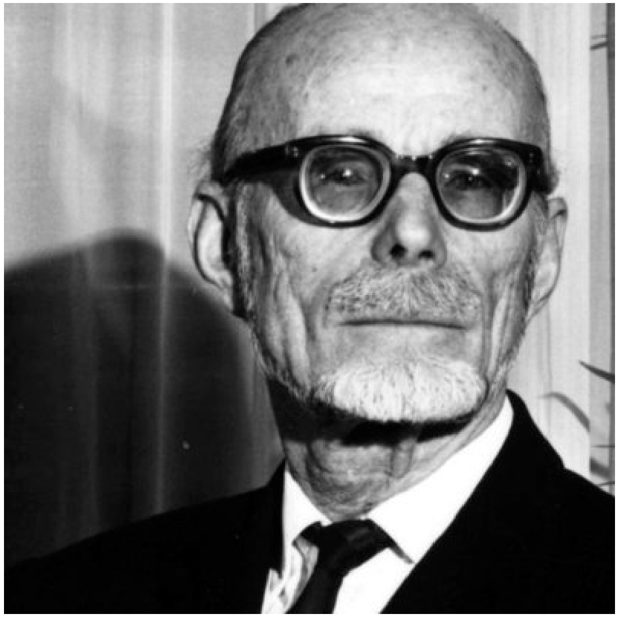
# Conclusion

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







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# Conclusion

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