HIGH EFFICIENCY CRYSTALLINE SILICON SOLAR CELLS

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Lecture KIT

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TODAY'S GOAL

1. Which leverage can be used to increase efficiency of silicon solar cells ?
2. How do different types of high efficiency silicon solar cells work ?

AGENDA

- Why high efficiencies?
- What is the efficiency limit for silicon solar cells?
- General strategy for high efficiencies
- Analyzing and fixing main losses in different solar cell types – the leaky bucket
- Future steps

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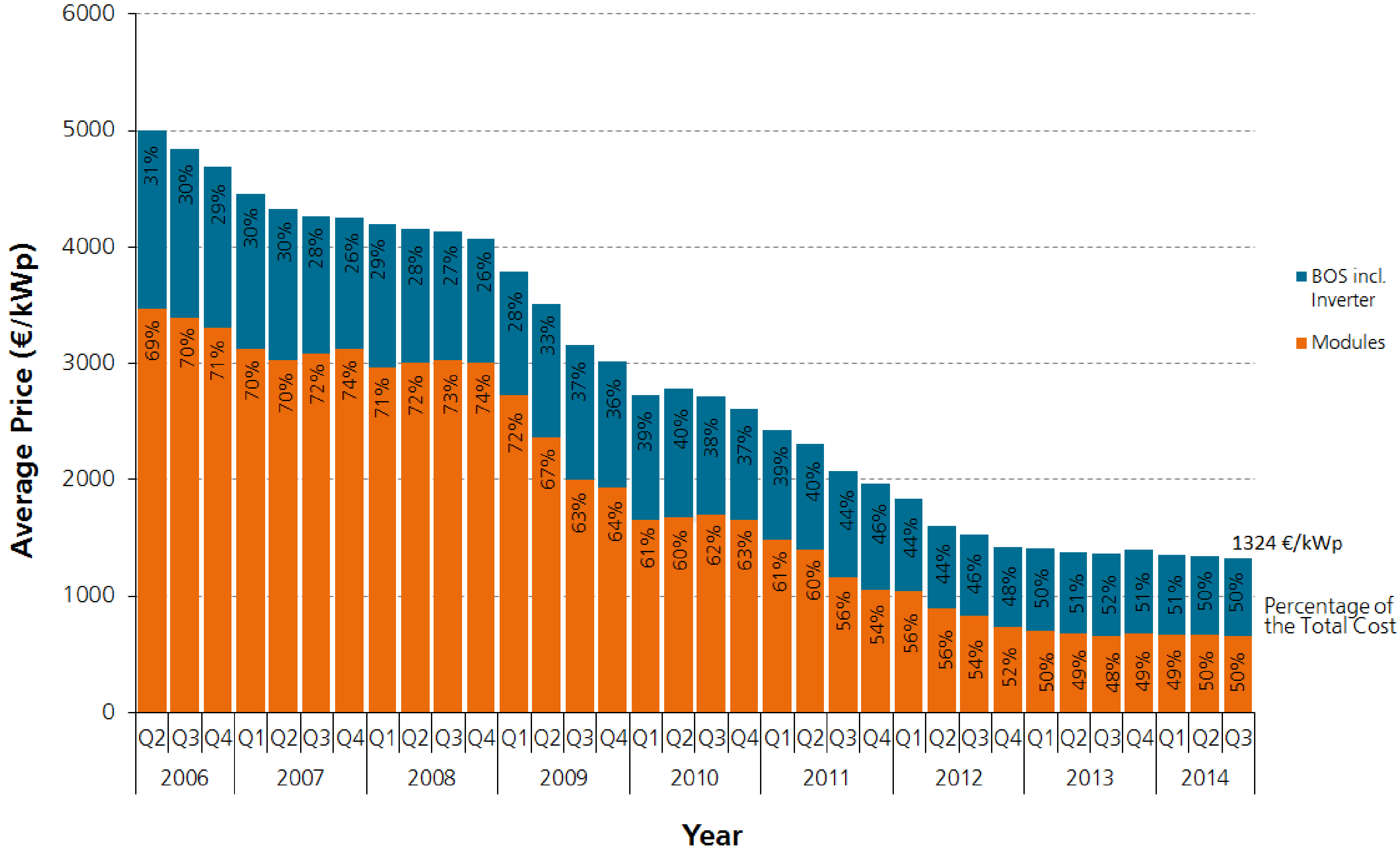
Dramatic Price Decrease
Average Price for German Rooftop Systems



Data: BSW-Solar. Graph: PSE AG 2014

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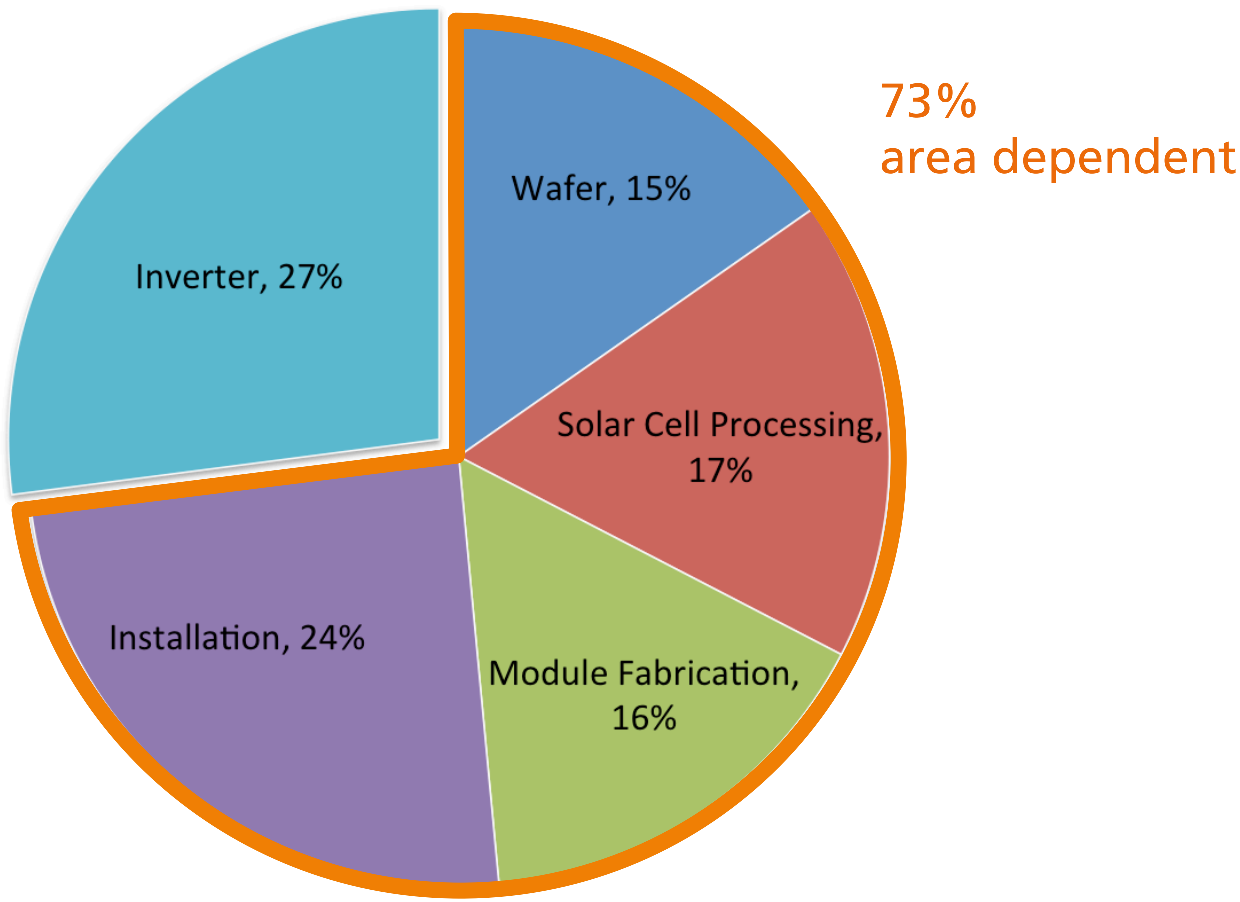
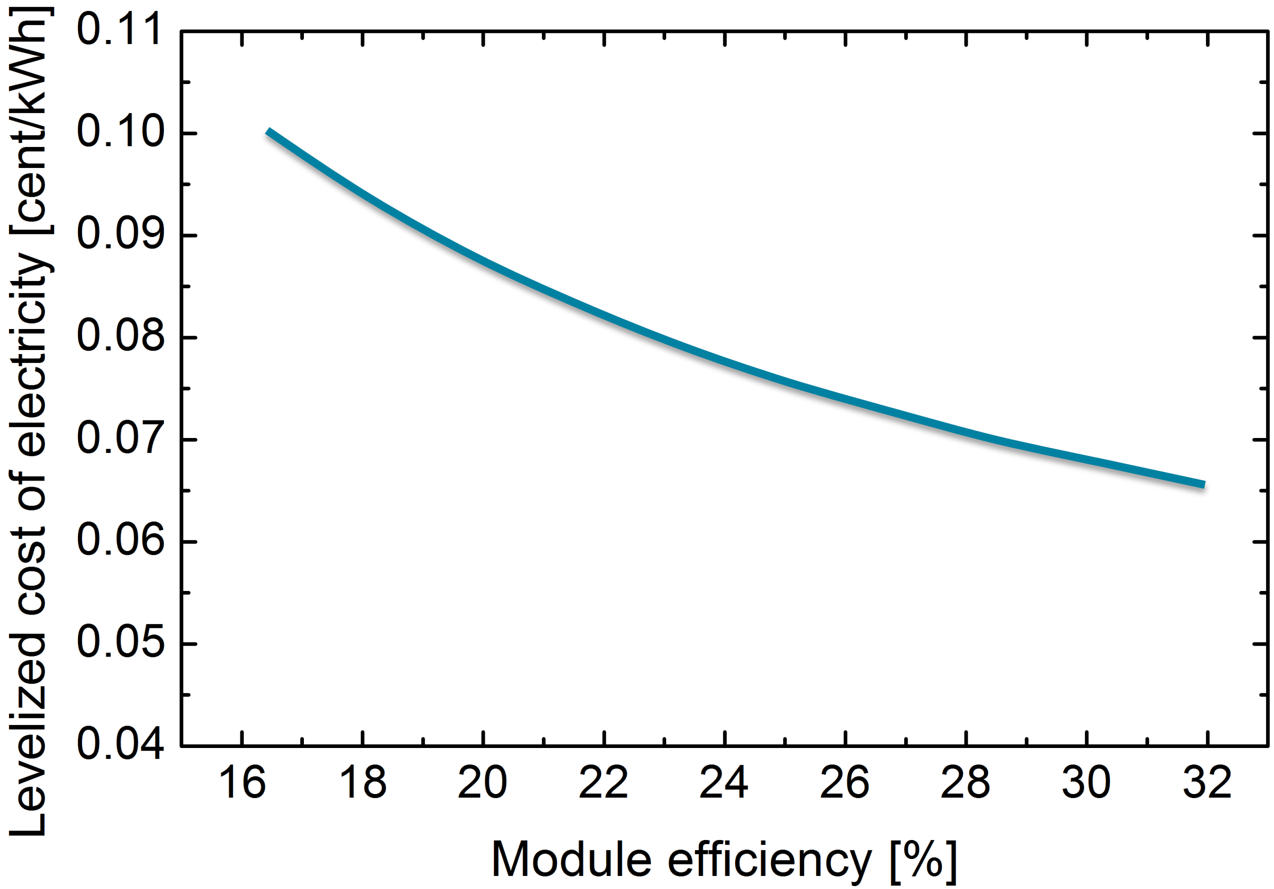
High Efficiencies for Cost Reduction
System Cost Structure



Total: ≈ 1.11 €/Wp

High Efficiencies for Cost Reduction
Levelized Cost of electricity



Why High Efficiencies?

- Higher efficiencies can decrease the specific costs of photovoltaic systems, because more output is generated from the same amount of input (land, materials, labor etc.)

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AGENDA

- Why high efficiencies?
- What is the efficiency limit for silicon solar cells?
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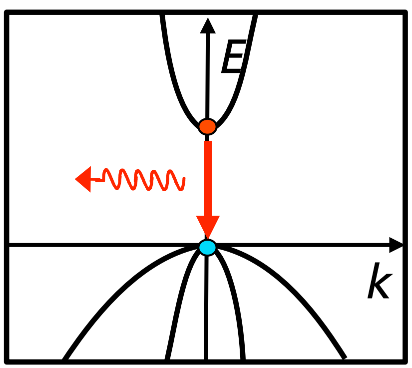
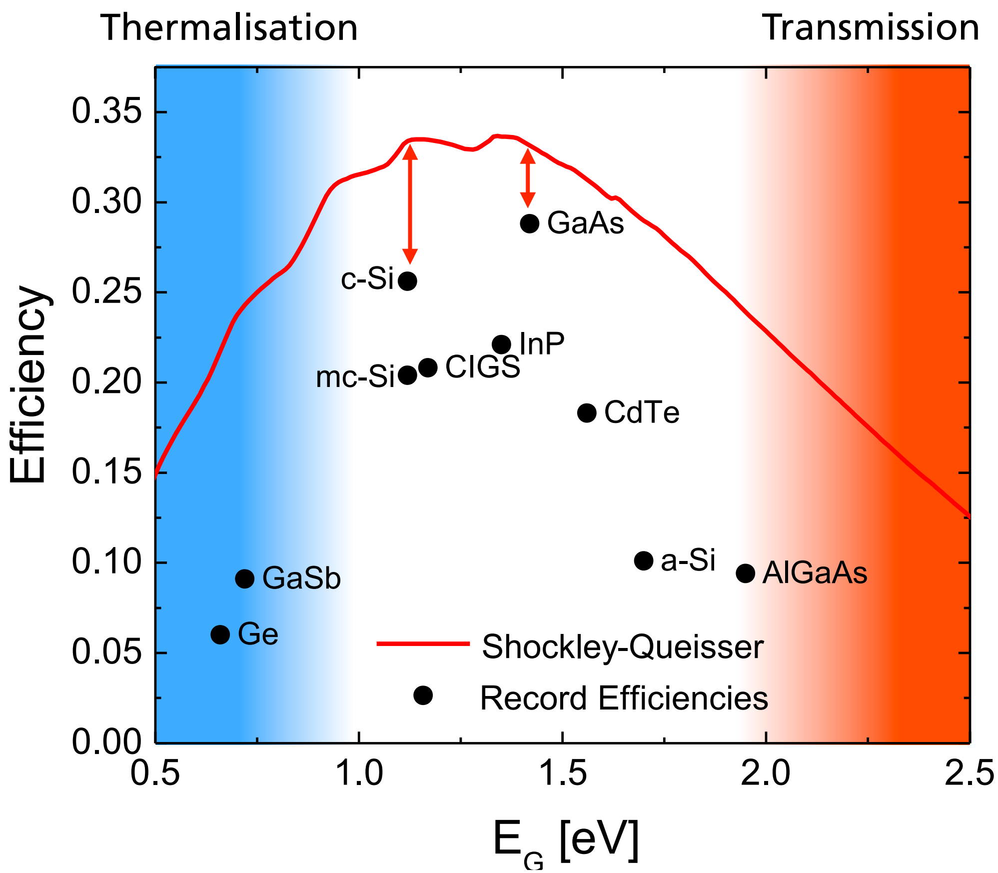
- Analyzing and fixing main losses in different solar cell types – the leaky bucket
- Future steps

What is the limit?
Detailed Balance and Radiative Recombination

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

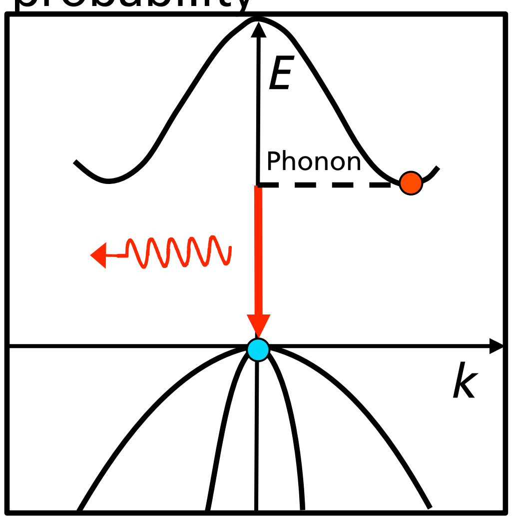


Radiative recombination in a direct semiconductor



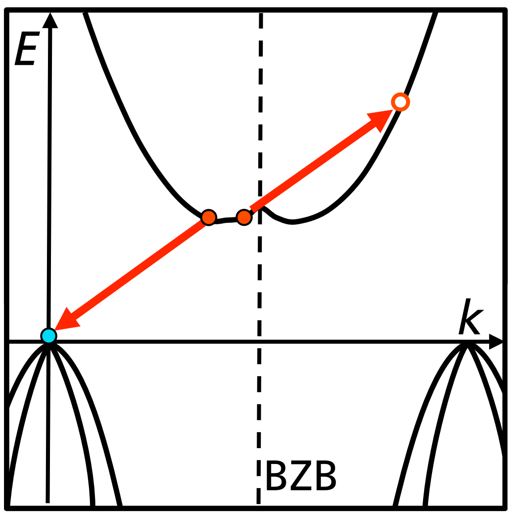
What is the Limit?
Reduced Radiative Recombination in Silicon

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



Radiative recombination in an indirect semiconductor

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



Auger recombination in an indirect semiconductor

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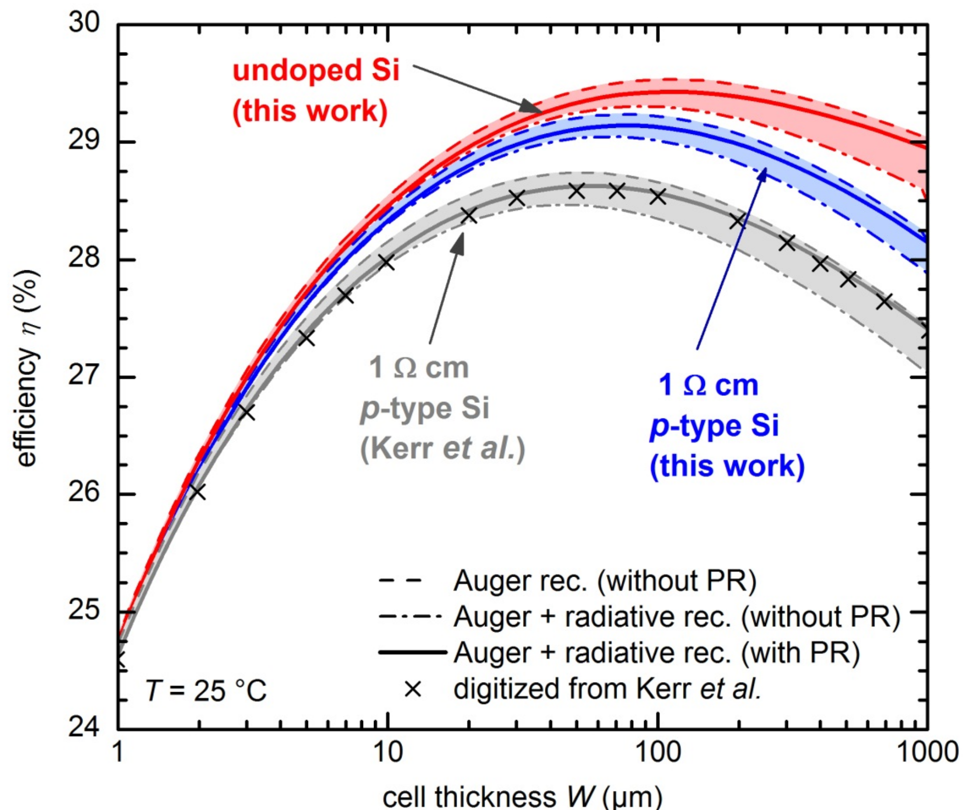
What is the limit?
Taking Auger Recombination into Account

- 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)

AGENDA

- Why high efficiencies?
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General Strategy
How to Achieve Highest Efficiencies?

Goals			Problems
■ Absorb all photons ■ Extract largest possible number of electron and holes	→	High Current	■ Optical losses ■ Recombination losses
■ Extract highest possible energy per electron-hole pair	→	High Voltage	■ Recombination losses ■ Resistive losses

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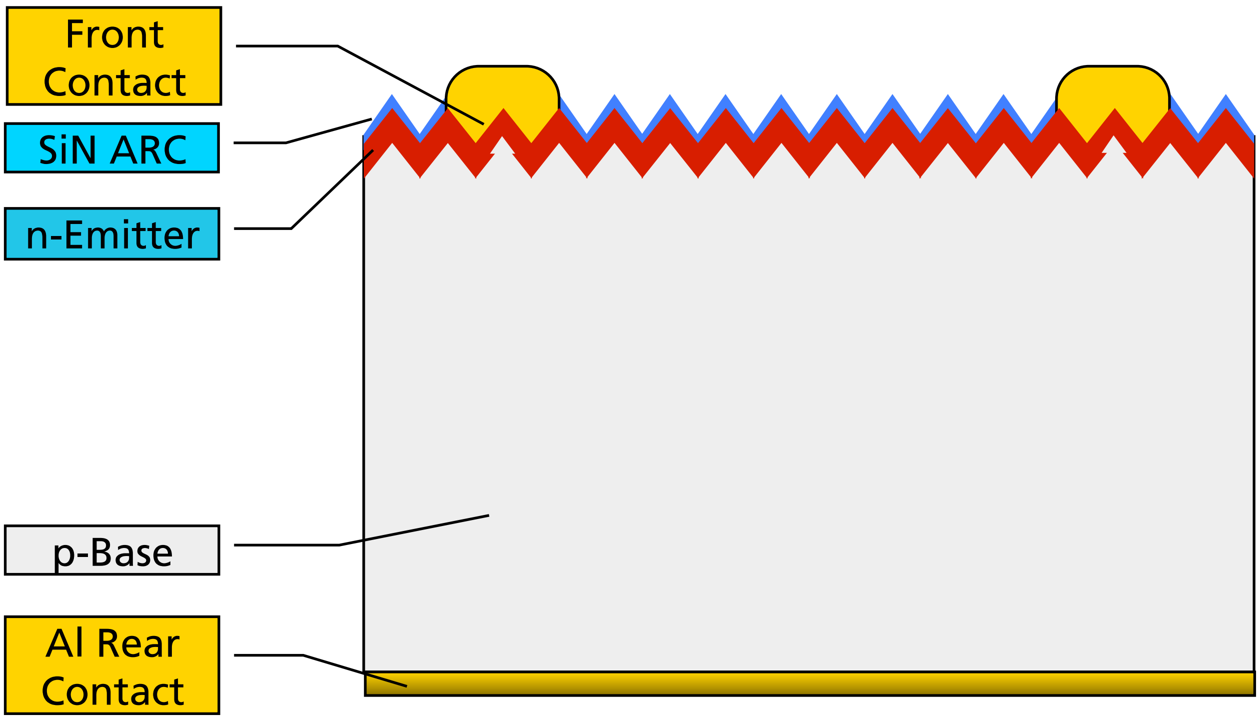
Simple Crystalline Silicon Solar Cell



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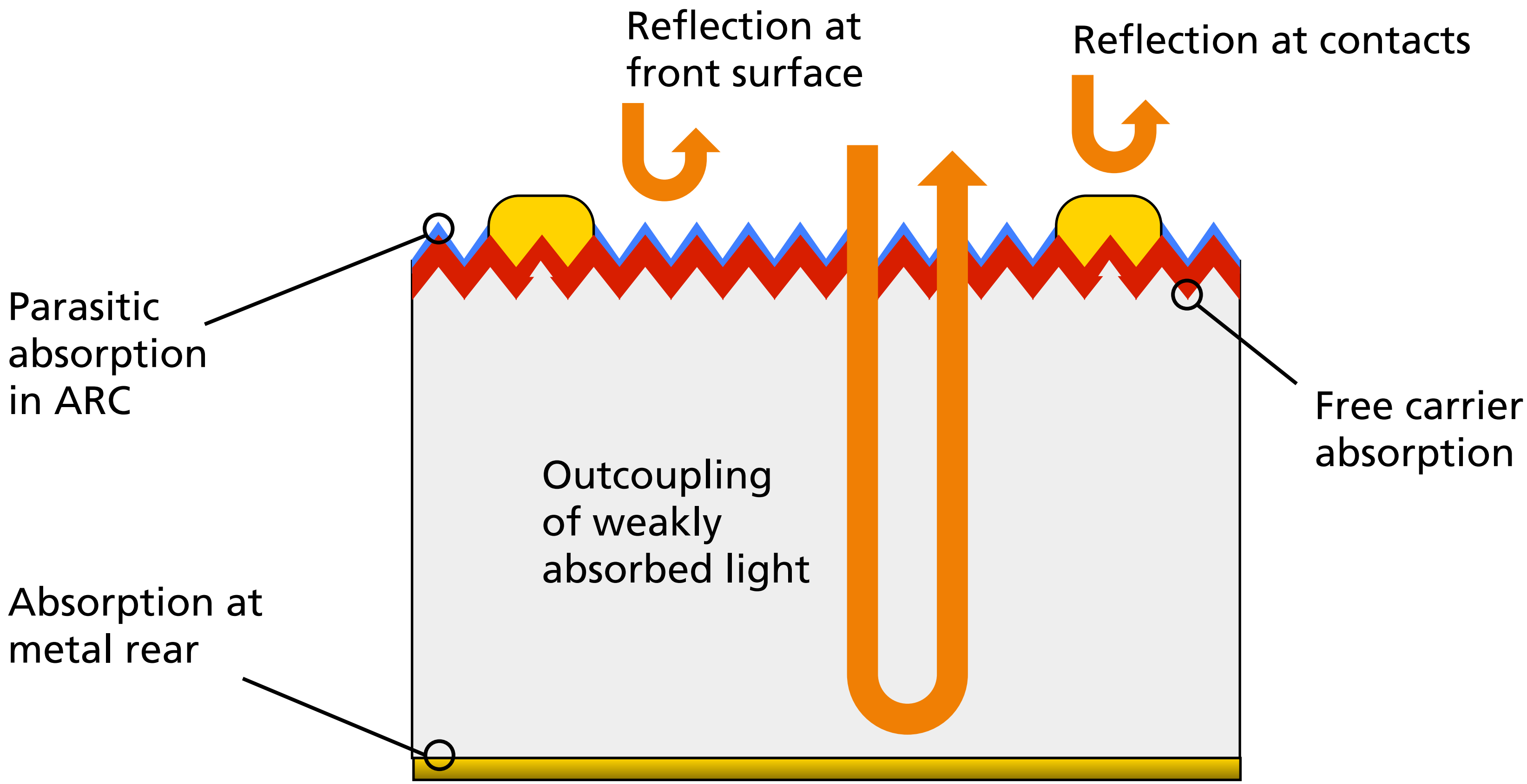
Simple Crystalline Silicon Solar Cell
Optical Losses



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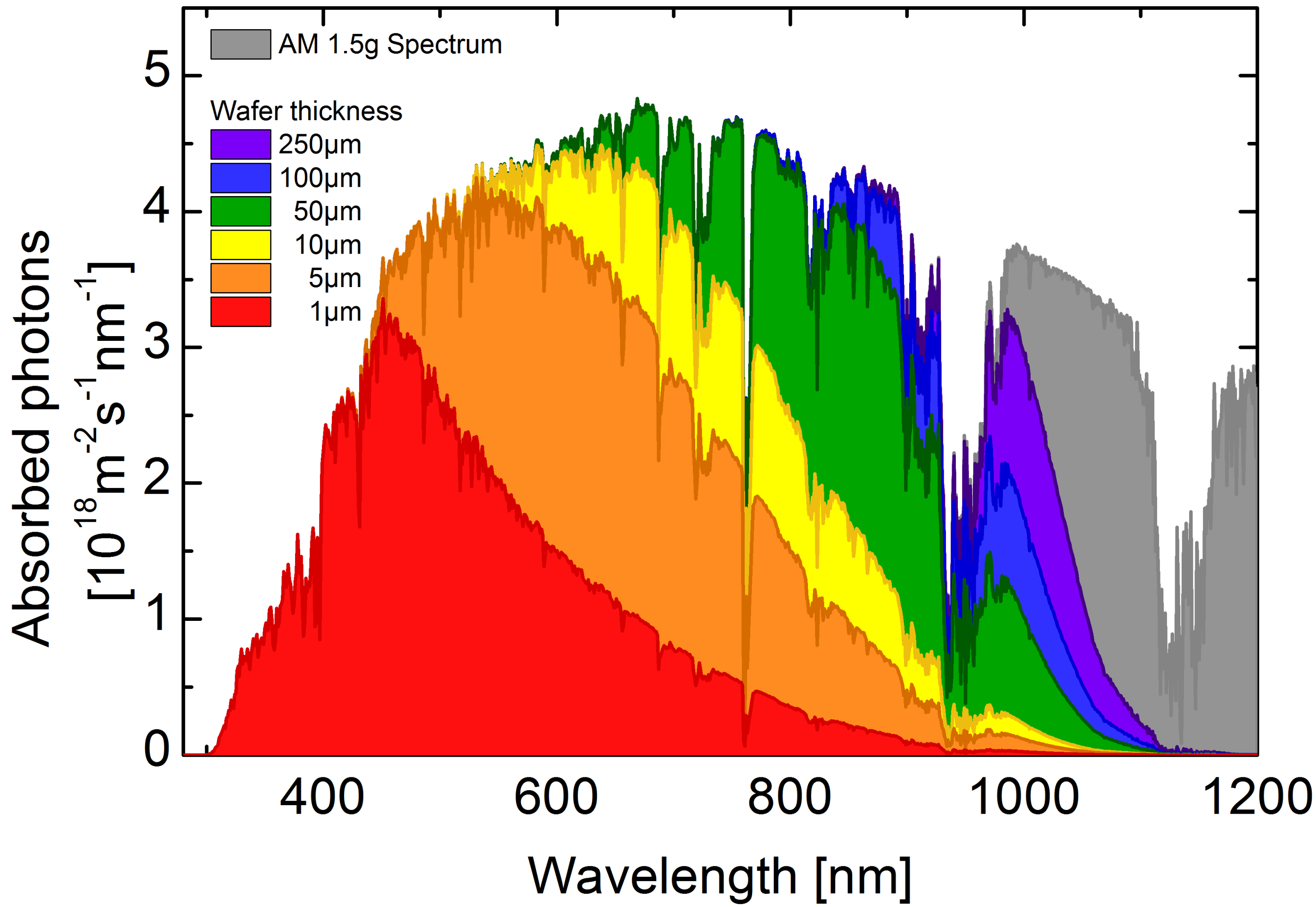
Incomplete Absorption
Challenge for Silicon Solar Cells



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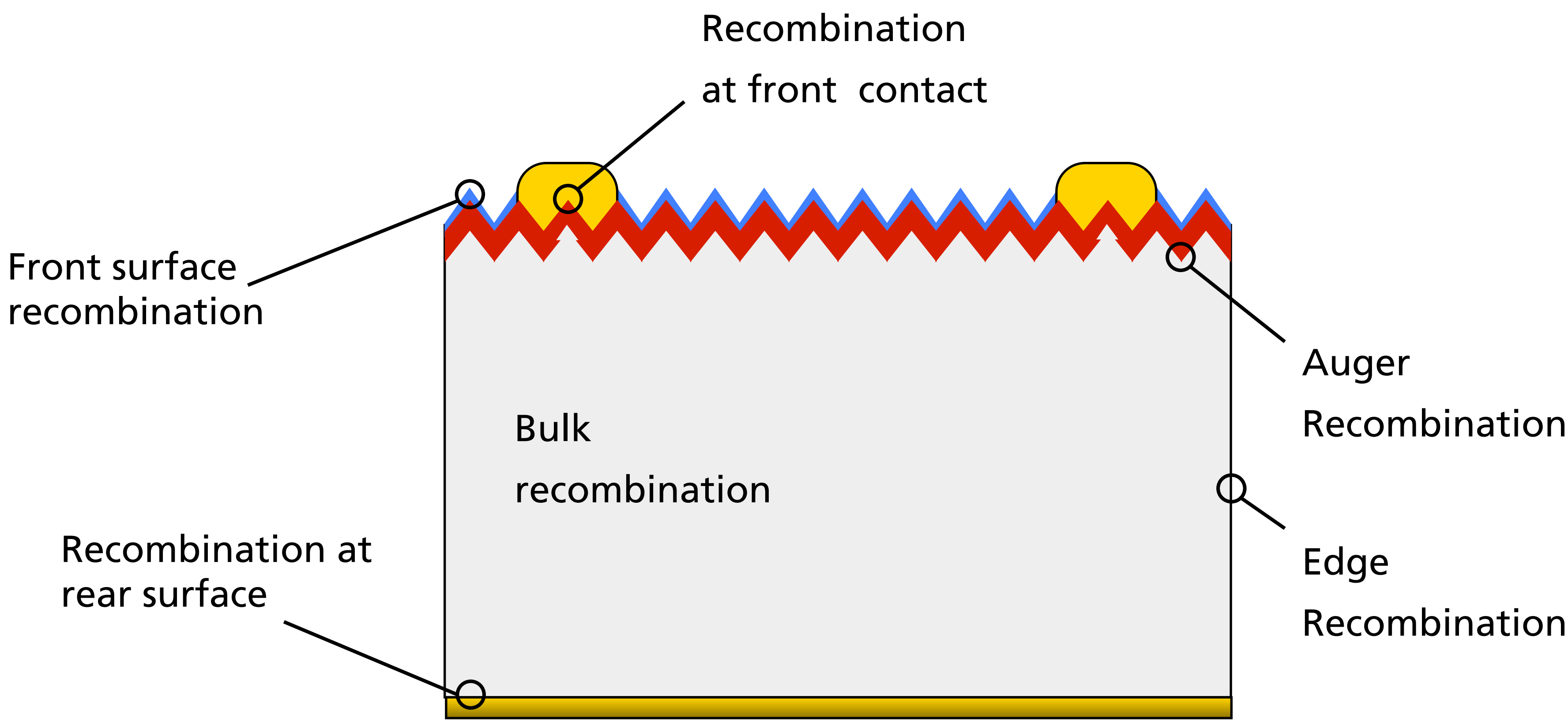
Simple Crystalline Silicon Solar Cell
Recombination Losses



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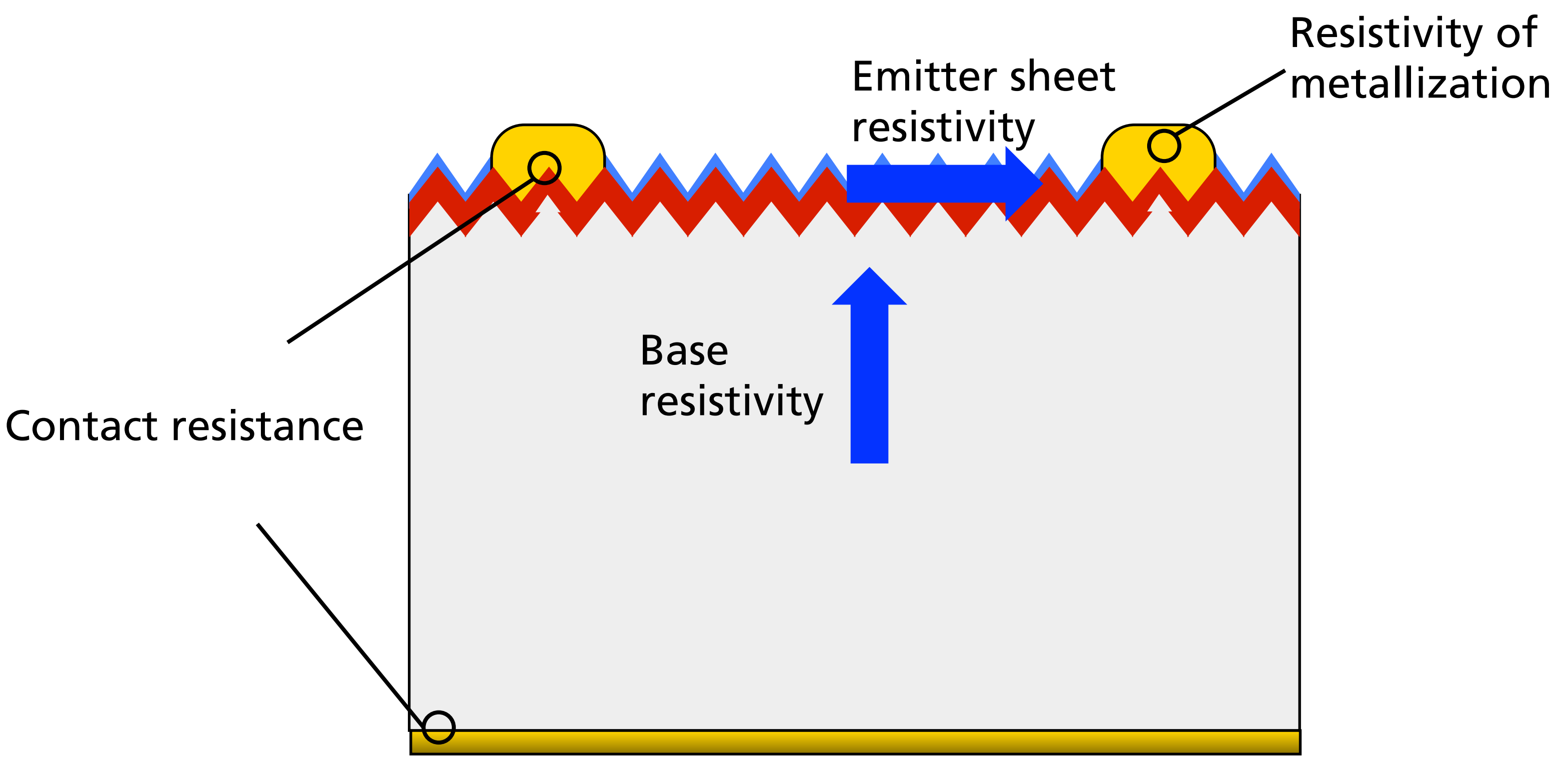
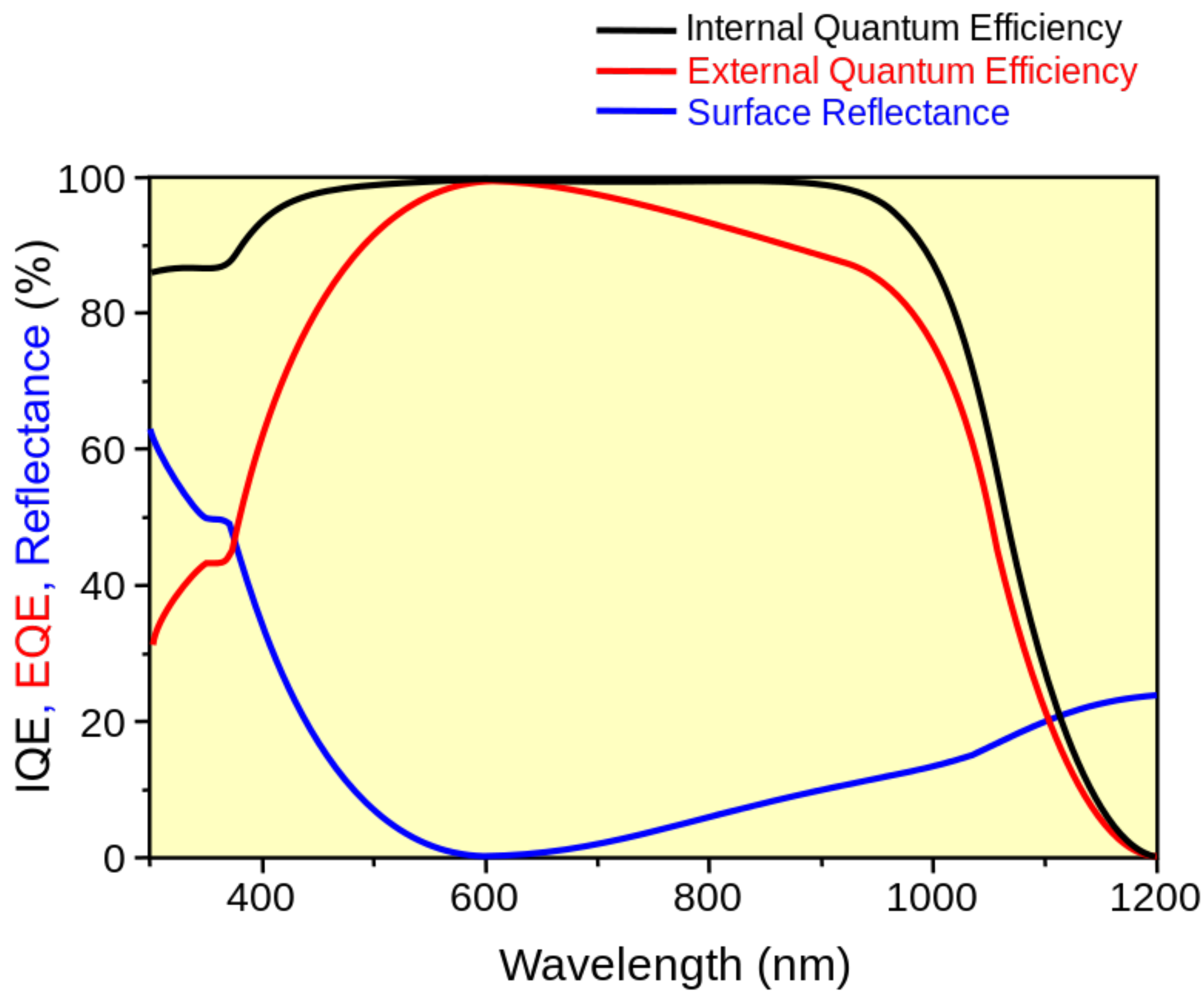
Simple Crystalline Silicon Solar Cell
Resistive losses



EQE example



Source: Wikipedia http://en.wikipedia.org/wiki/Quantum_efficiency#mediaviewer/File:Solarcellige-en.svg

General Strategy for High Efficiencies

Reduce

1. optical,
2. recombination,
3. resistive

losses

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AGENDA

- Why high efficiencies?
- What is the efficiency limit for silicon solar cells?
- General strategy for high efficiencies
- Analyzing and fixing main losses in different solar cell types – the leaky bucket
- Future steps

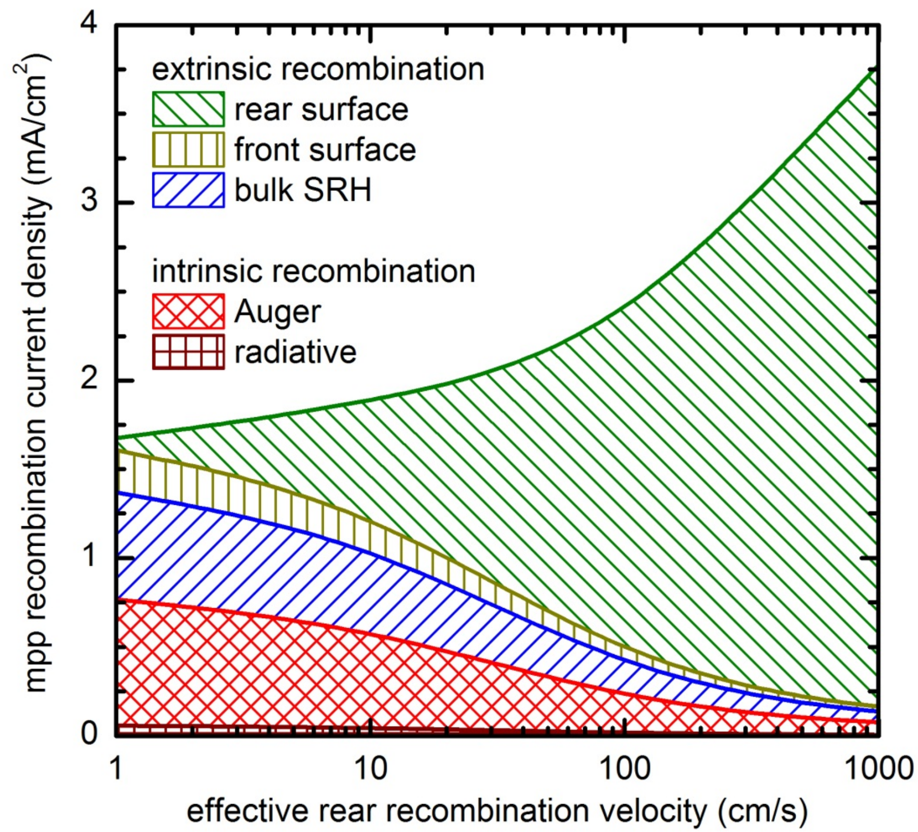
What is the main loss of my cell?
Fixing the leaky bucket

- To know what to tackle next you should know:
  What is my main loss?
- By reducing one recombination channel, the others can increase absolutely (not only relatively)

(S. Glunz, EUPVSEC 2012)

What is the main loss of my solar cell?
Recombination loss channels

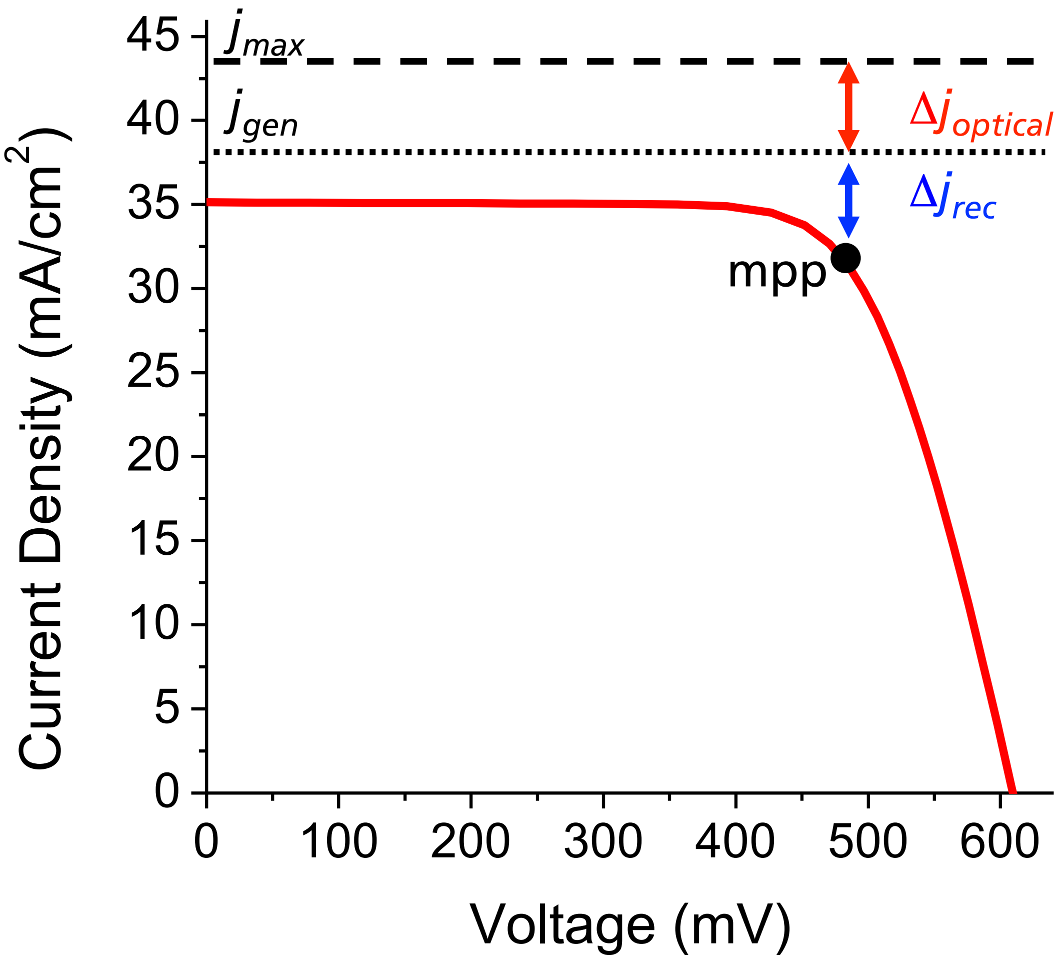
- Recombination loss at mpp in a *n*-type solar cell with varying rear surface recombination
- By reducing one recombination channel, the others can increase absolutely (not only relatively)



(A. Richter et al., Energy Procedia, SiliconPV 2012)

What is the main loss of my cell?
Analyzing loss currents

- j_{max} = Theoretical maximum for a certain wafer thickness
- j_{gen} = Generated photo-current in actual device
- Optical losses $= j_{max} - j_{gen}$
- Recombination losses at mpp $= j_{gen} - j_{mpp}$



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What is the main loss of my solar cell?
Analyzing loss currents – Modeling

Optical losses

- $j_{max,160\,\mu m}$ = Theoretical maximum for a 160 µm thick wafer (43.6 mA/cm²)
- j_{gen} = Generated photo-current in actual device (Raytracing simulation)

Recombination losses

- Numerical 2/3 dimensional simulation with *consistent* set of parameters
- Spatial integration of recombination currents at mpp
- Distinguishing losses in different regions of the cell:
  - Front Δj_{front} (Emitter, *IBC: FSF*)
  - Base, Auger $\Delta j_{Auger,\, base}$ (Undiffused region)
  - Base, SRH $\Delta j_{SRH,\, base}$ (Undiffused region)
  - Rear Δj_{rear} (BSF, *IBC: Rear Emitter + BSF*)

Resistive losses (taken into account but not shown)

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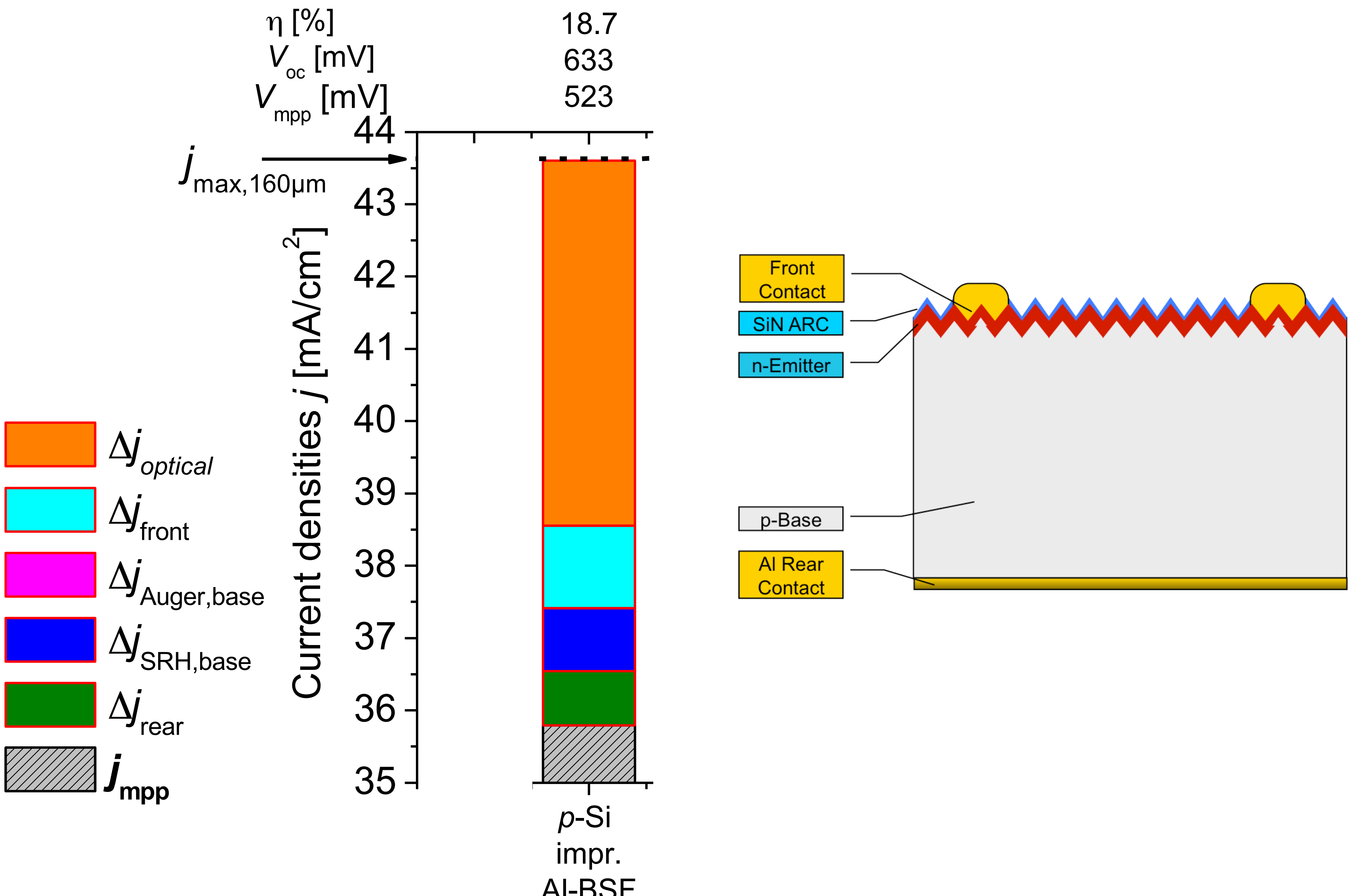
Al-BSF cell on p-type silicon



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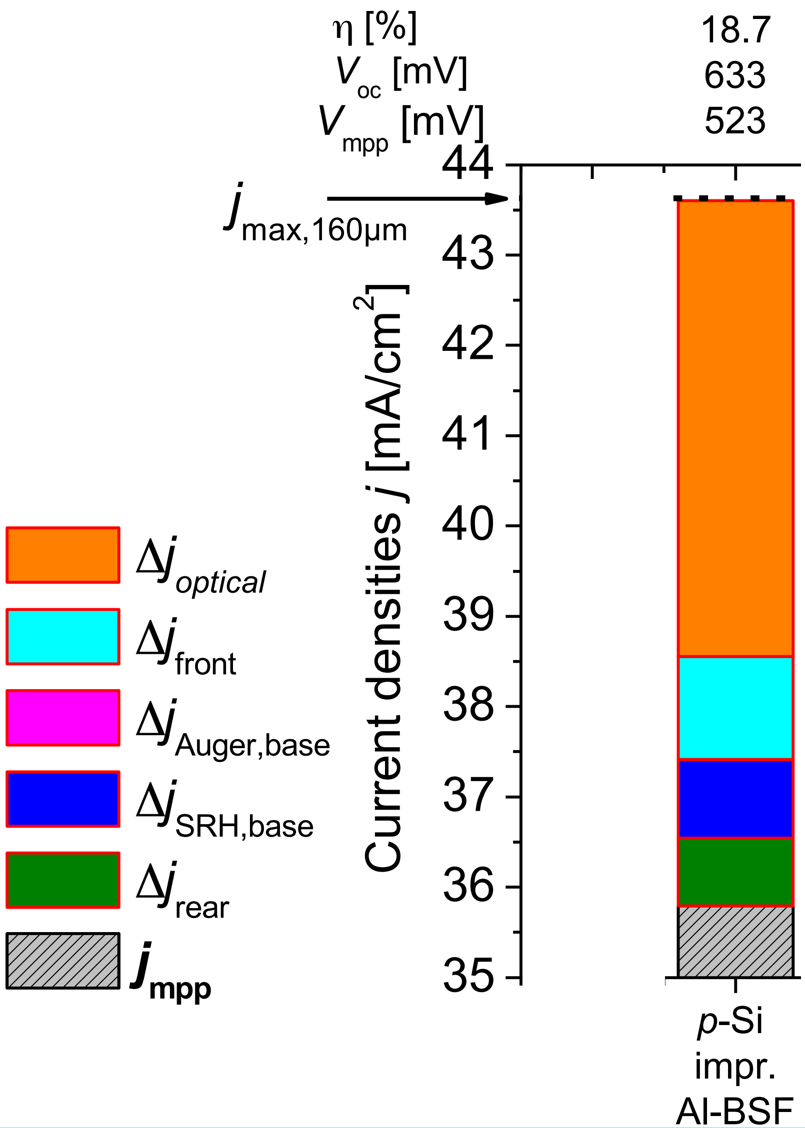
Al-BSF cell on p-type silicon



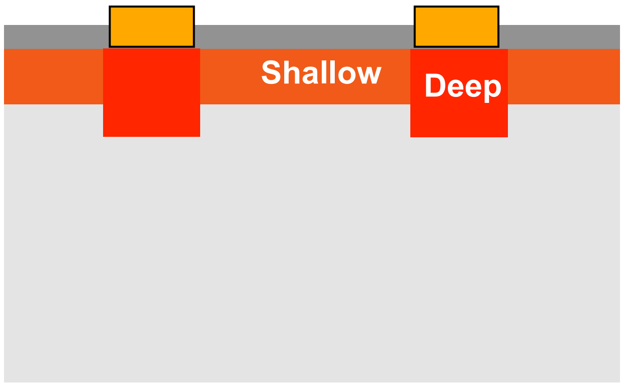
Main problem

- Recombination losses in emitter (=front) due to high doping concentration and insufficient surface passivation

Solution

→ Selective emitters or paste which are able to contact lowly doped emitters

Selective phosphorus emitters
Process technologies



- $\Delta\eta$ = 0.3% … 0.5%

Good overview:
G. Hahn et al.,
EU-PVSEC 2010, p. 1091

- Different technological options:
  - Laser over-doping from PSG
  - Chemical etch-back of heavy emitter diffusion
  - Implanted emitter
  - Diffusion through a thin oxide opened in the finger region
  - Selective laser doping from spray-on phosphorus coating
  - Printing of P-dope or phosphorus-doped silicon ink
  - Laser-chemical processing

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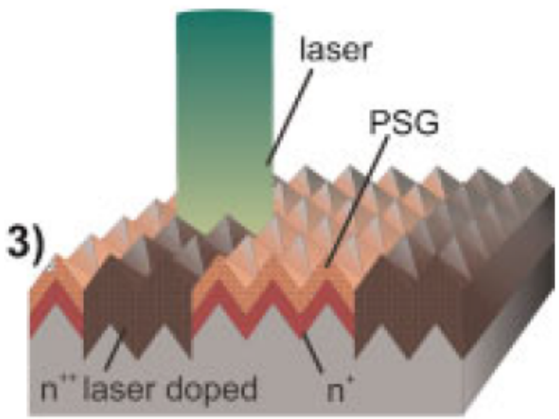
Selective phosphorus emitters
Process technologies

add-on
laser doping



Röder et al., Prog. Photovolt. 18, p. 505 (2010)

- Different technological options:
  - Laser over-doping from PSG
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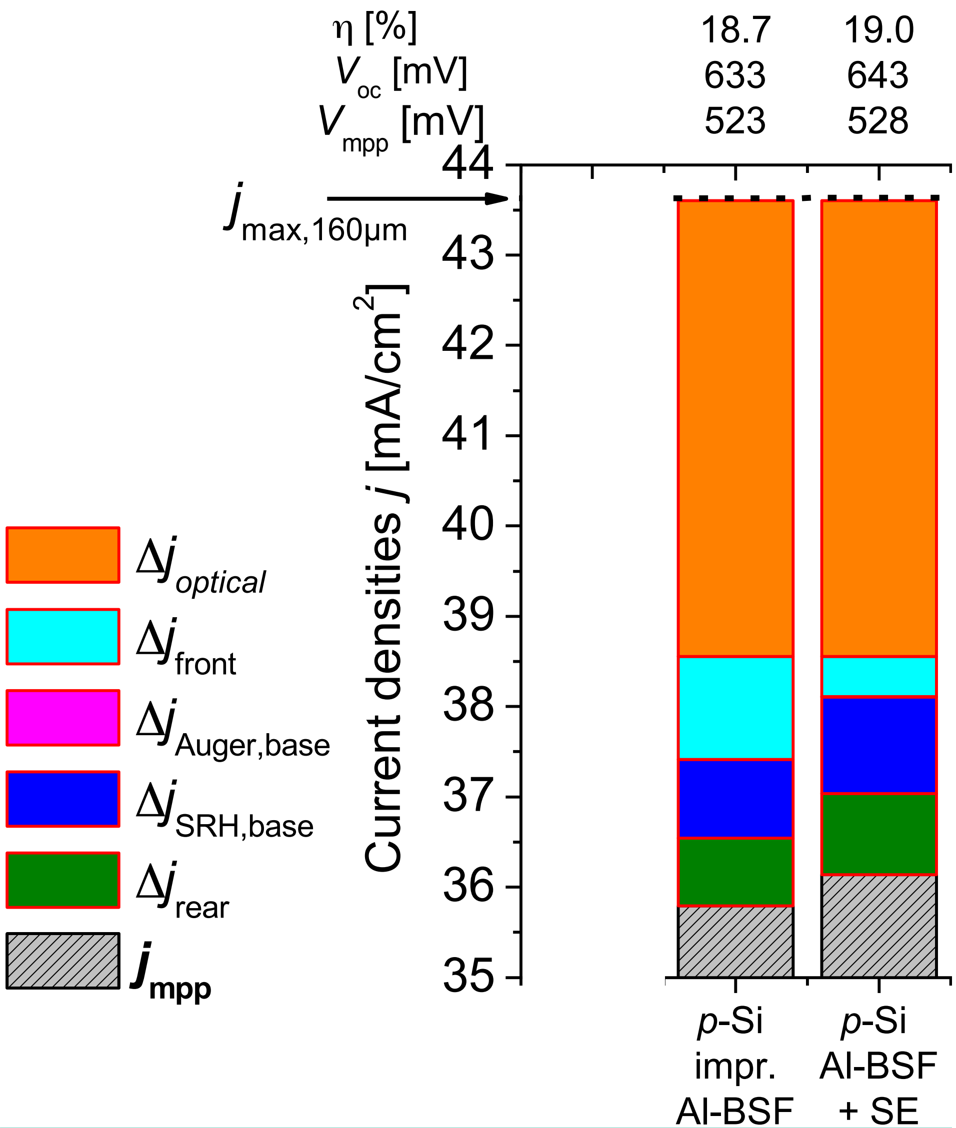
  - Implanted emitter
  - Diffusion through a thin oxide opened in the finger region
  - Selective laser doping from spray-on phosphorus coating
  - Printing of P-dope or phosphorus-doped silicon ink
  - Laser-chemical processing

Al-BSF cell on p-type silicon with selective emitter



- Better blue response
- Lower j_{oe}
- Strong reduction of Δj_{front}

Next Main problem:

- Base and rear recombination

Solution

→ Substituting Al-BSF by dielectric rear passivation

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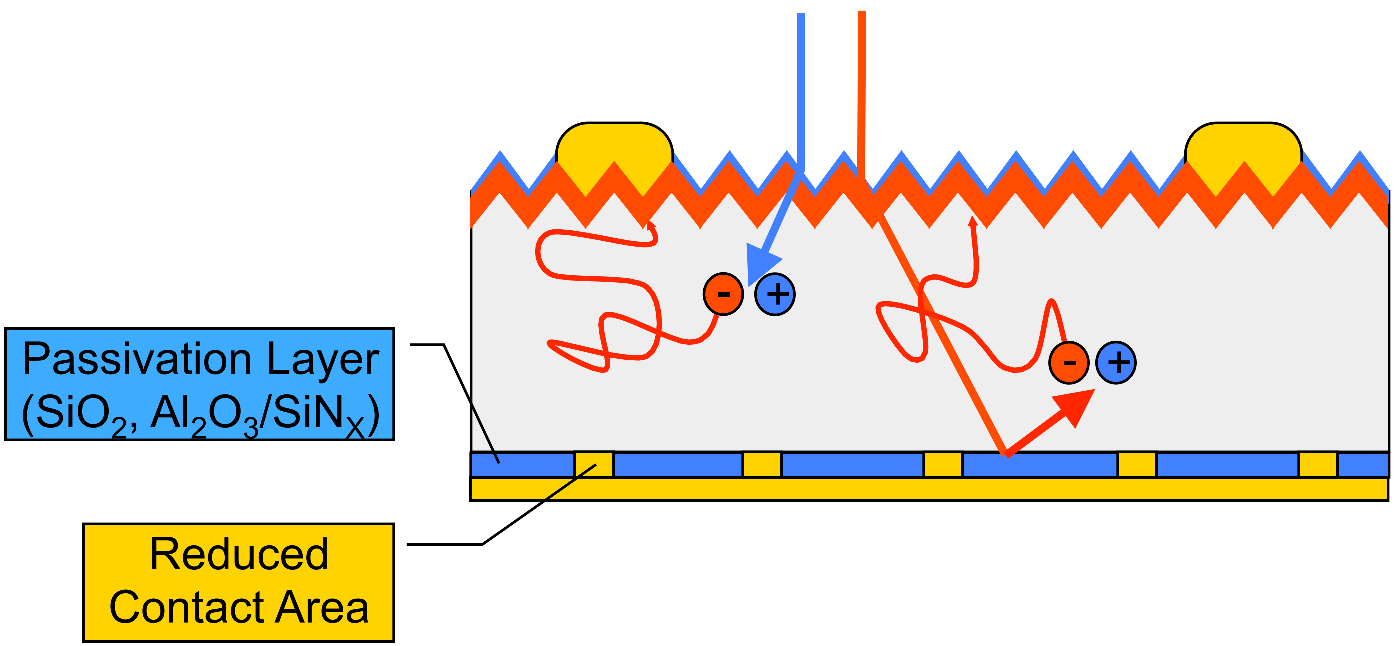
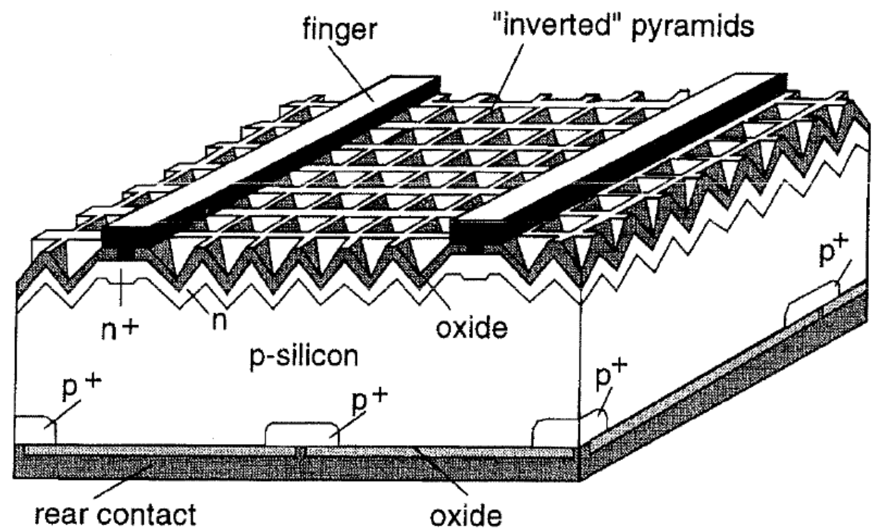
High-efficiency cells with dielectrically passivated rear
Optical and electrical rear reflector

- Reduction of rear recombination
- Better internal reflection



High-efficiency cells with dielectrically passivated rear
Optical and electrical rear reflector

- Reduction of rear recombination
- Better internal reflection
- Early world record with complex photo-lithographic processing



Company	Technology	Material	Area [cm²]	Efficiency
UNSW J.Zhao, APL **73** 1998	PERL	p-type FZ	4	25.0 %

(M. Hermle, EUPVSEC 2014)

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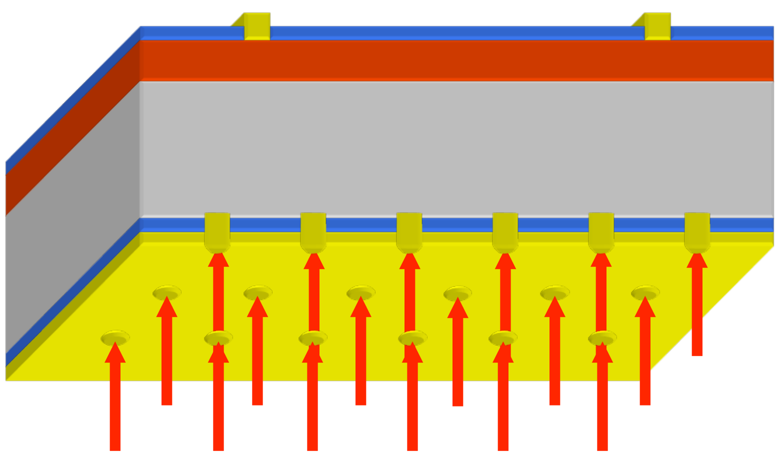
High-efficiency cells with dielectrically passivated rear

p-Type partial rear contact PRC

- Two additional process steps
  - Dielectric passivation
  - Local contact opening (LCO) or Laser fired contact (LFC)
- Can be used for **mc** und **Cz** silicon



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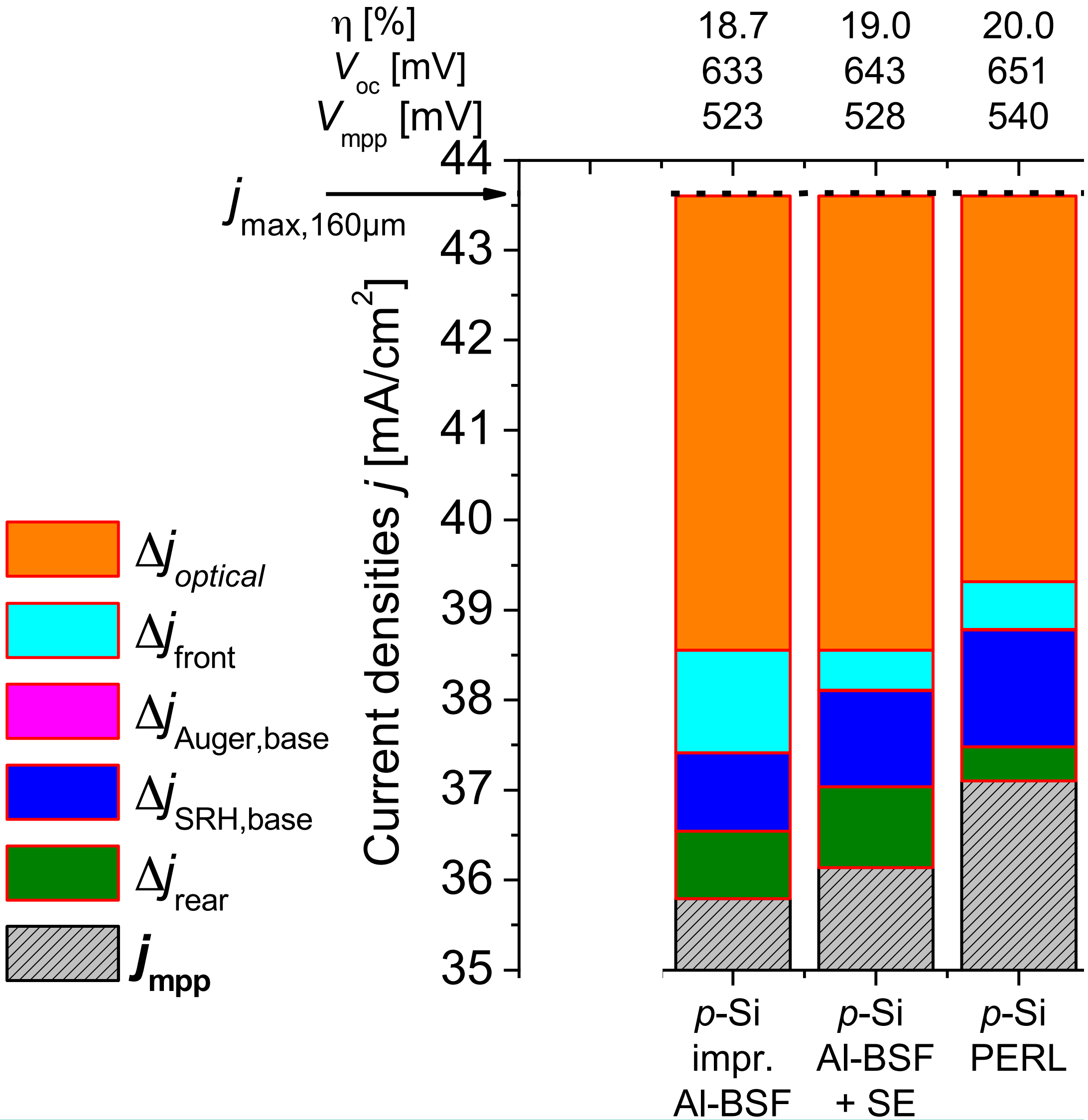
High-efficiency cells with dielectrically passivated rear



- Strong reduction of Δj_{rear}
- Better internal reflection → lower $\Delta j_{optical}$

High-efficiency cells with dielectrically passivated rear

p-Type PRC

	Mat-erial	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]	Comment
Q-Cells	mc	655	39,5	79,1	19,5	LFC for point contact P. Engelhart, EUPVSEC 2011
Gintech	mc	652	39,4	79,3	19,5	LCO for point contact Y.K.Chiou, Silicon PV 2014
Trina	Cz	662	39,1	79,4	20,5	P. Verlinden, Silicon PV 2014
Solar-world	Cz	672	39,2	79,3	20.9	High lifetime mono material G. Fischer, Silicon PV 2014
Schott	Cz	665	39,9	80,5	21,3	Electro plated front side A.Metz, SOLMAT 120 2014
ISFH	Cz	661	39,8	80,7	21,2	5 BB with dual print H.Hannebauer, PSS RRL 2014
ISE	MCz				21,3	Al-Foil LFC & Ni/Cu plated *GridTOUCH* measured A.Brand 2DO.2.5 and M. Graf 2CO.2.6

(M. Hermle, EUPVSEC 2014)

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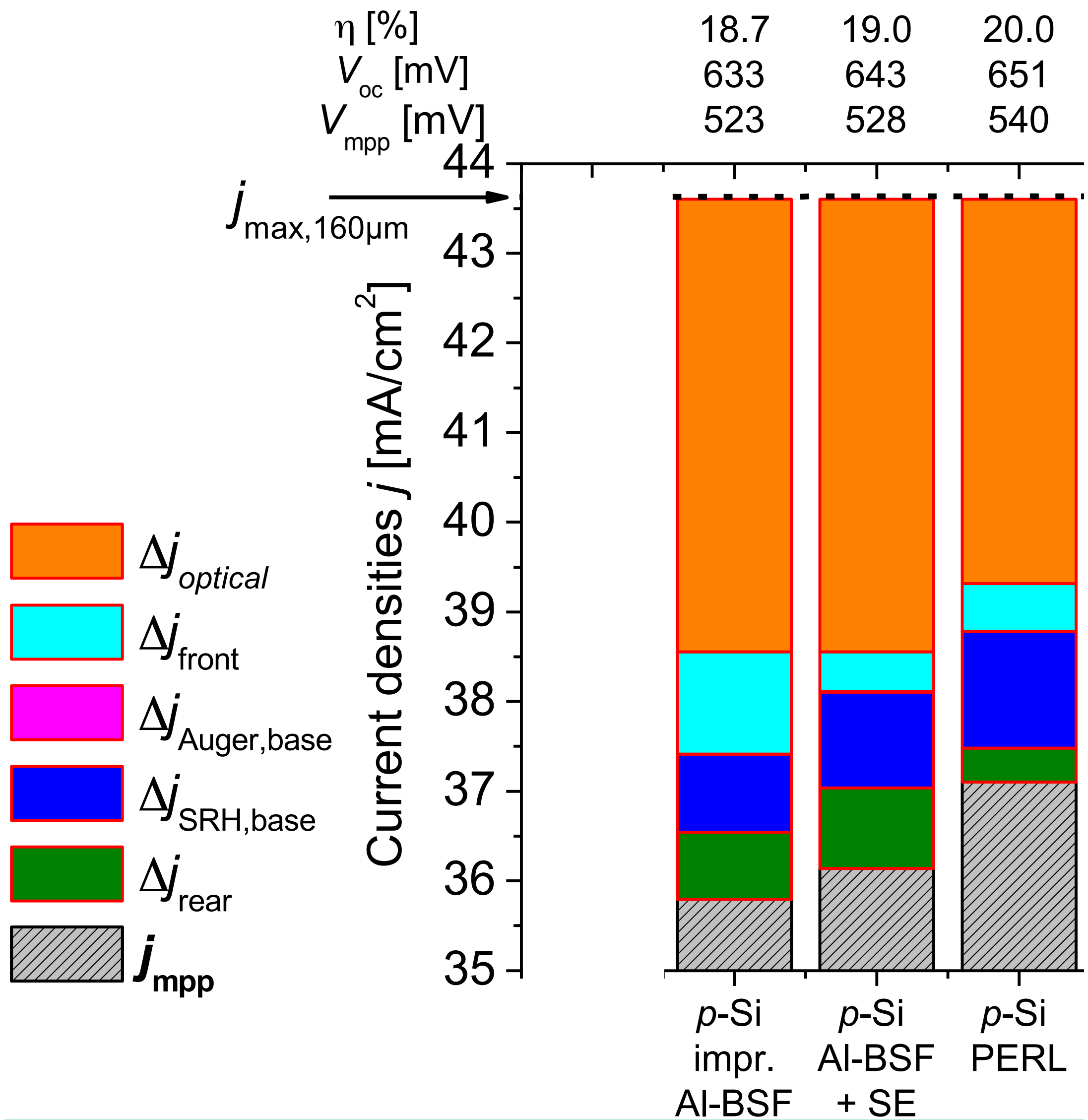
High-efficiency cells with dielectrically passivated rear



- Strong reduction of Δj_{rear}
- Better internal reflection → lower $\Delta j_{optical}$

Next main problem

- Bulk dominates recombination
- Lifetime limited by light-induced degradation

Solution

→ Reducing O_i or substituting B

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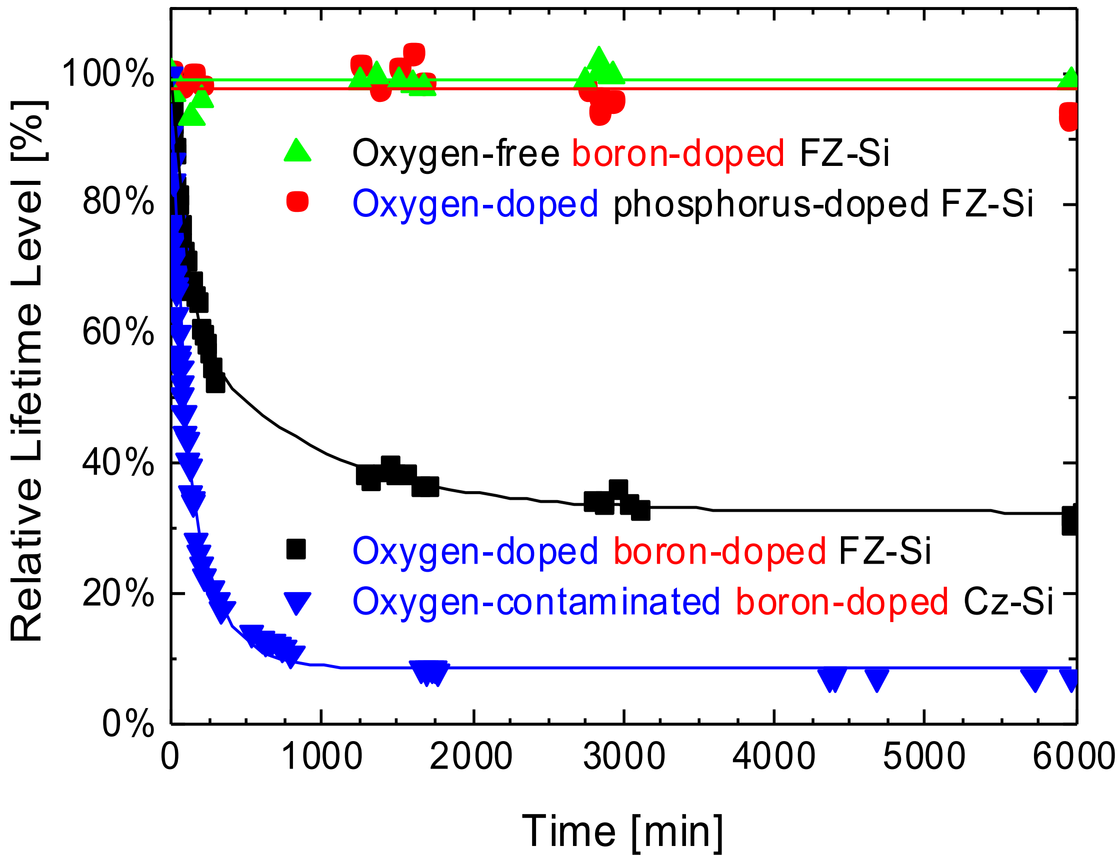
Reduced Minority Carrier Lifetime in Silicon
Boron – Oxygen Complexes

- 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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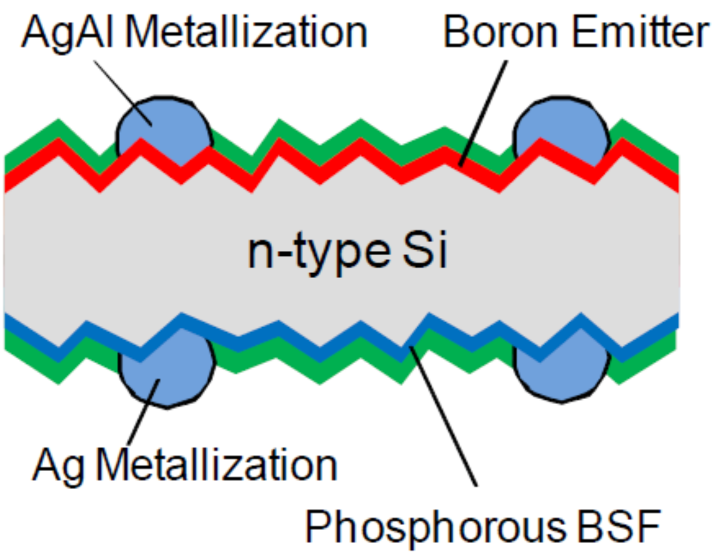
P-BSF cell on *n*-type silicon
Bosch

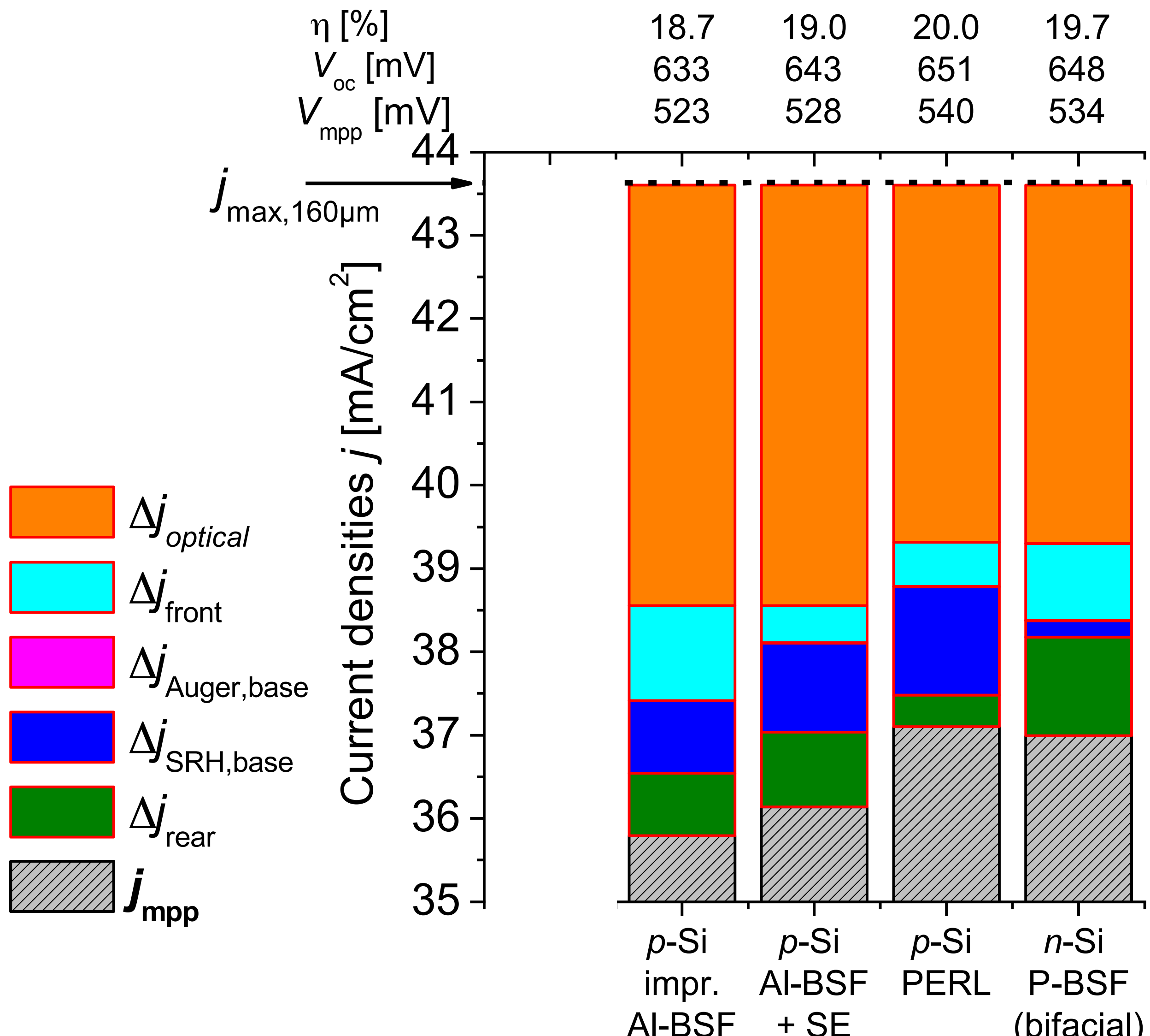
- Bifacial cell structure
- Reduced efficiency in comparison to mono-facial solar cell
- Higher yearly yield possible



Chuck	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
Gold coated	**648**	**39.1**	**79.5**	**20.1**
Black coated	**647**	**38.7**	**79.4**	**19.9**

Böscke et al., IEEE PVSC 2012

P-BSF cell on *n*-type silicon



- Strong reduction of Δj_{base}

Next main problem

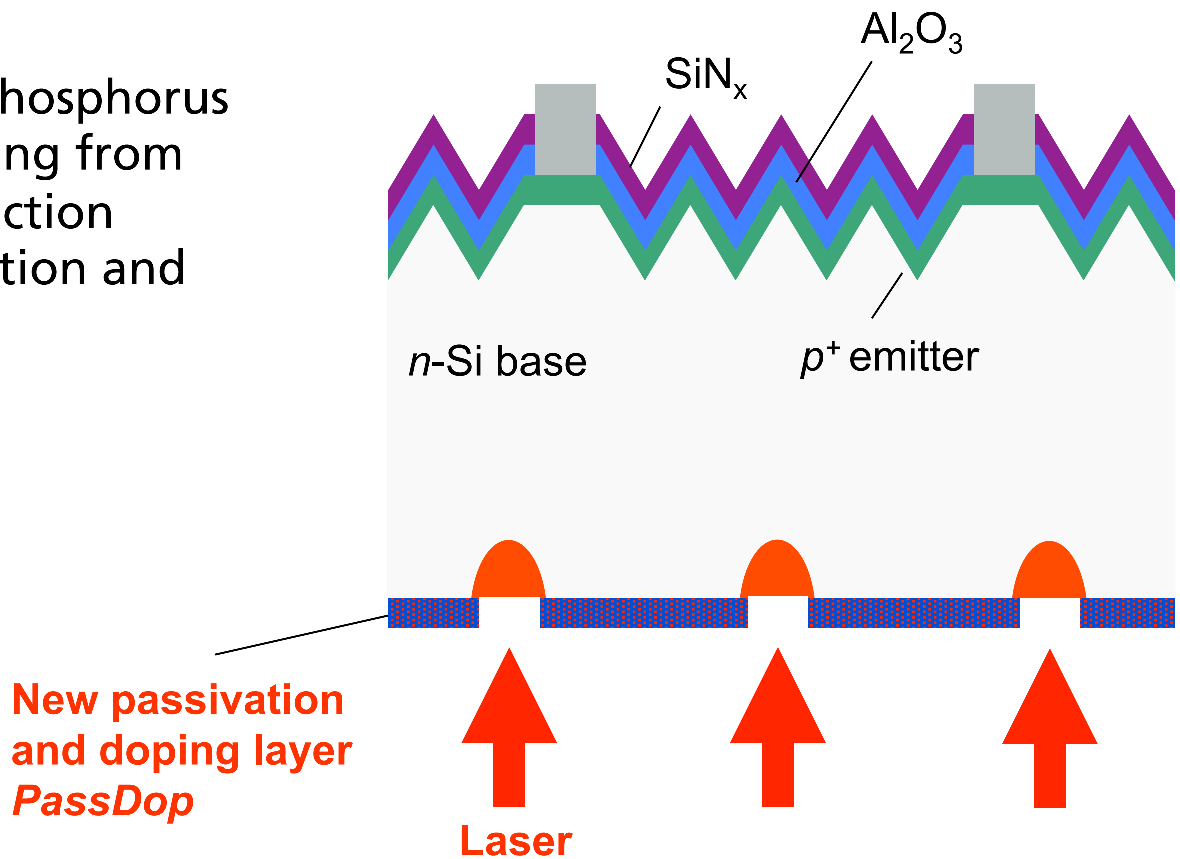
- Rear dominates recombination

Solution

→ Introduction of dielectric rear surface passivation

PERL on *n*-type silicon
Towards industrial high-efficiency cells

- Substitution of local phosphorus diffusion by laser doping from innovative double-function *PassDop* layer (passivation and doping)



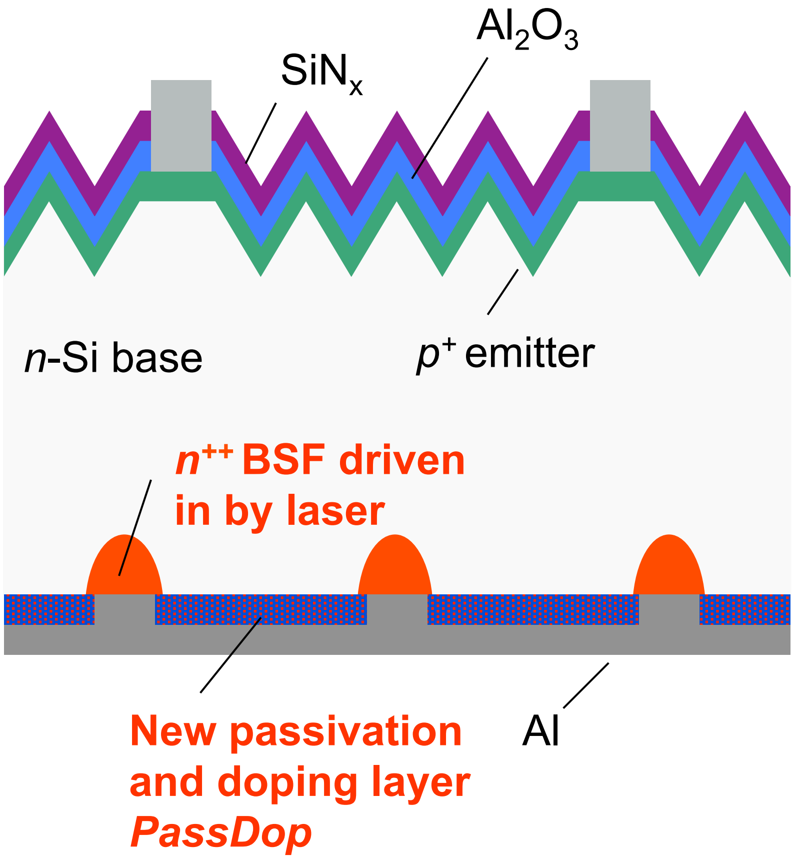
D. Suwito et al., IEEE TED (2010)

PERL on *n*-type silicon
Towards industrial high-efficiency cells

- Substitution of local phosphorus diffusion by laser doping from innovative double-function *PassDop* layer (passivation and doping)
- Excellent results with evaporated front contacts

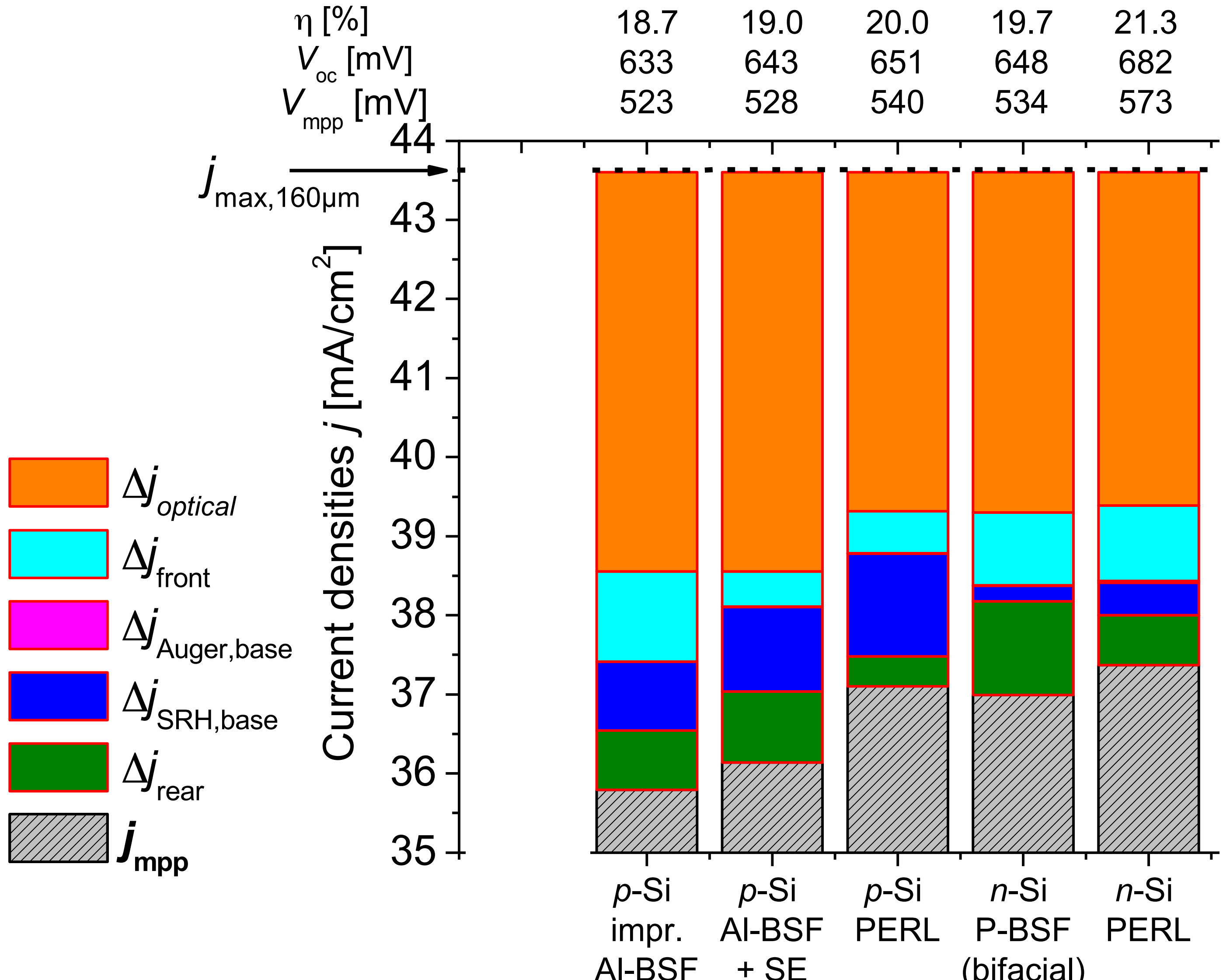
	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
Best cell	**701**	**39.8**	**80.1**	**22.4***

*Confirmed at Fraunhofer ISE CalLab



D. Suwito et al., IEEE TED (2010)

PERL cells on *n*-type silicon



- Recombination losses already quite low

Next main problem

- optical losses

Solution

→ Back contact solar cells

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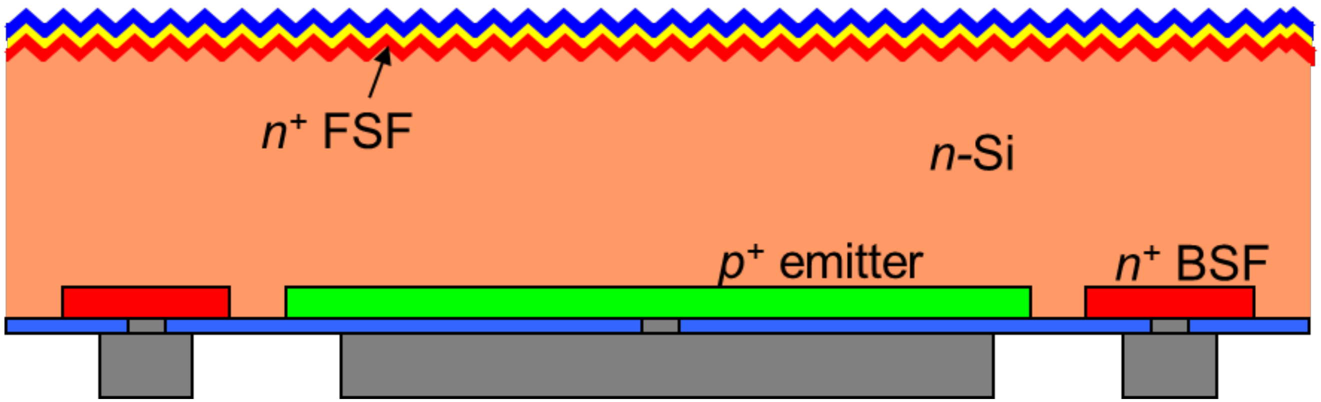
Solar Cell Concept to Close the Gap
n-Type BJBC– without “passivated contacts”

- Large volume production by Sunpower since more than 10 years



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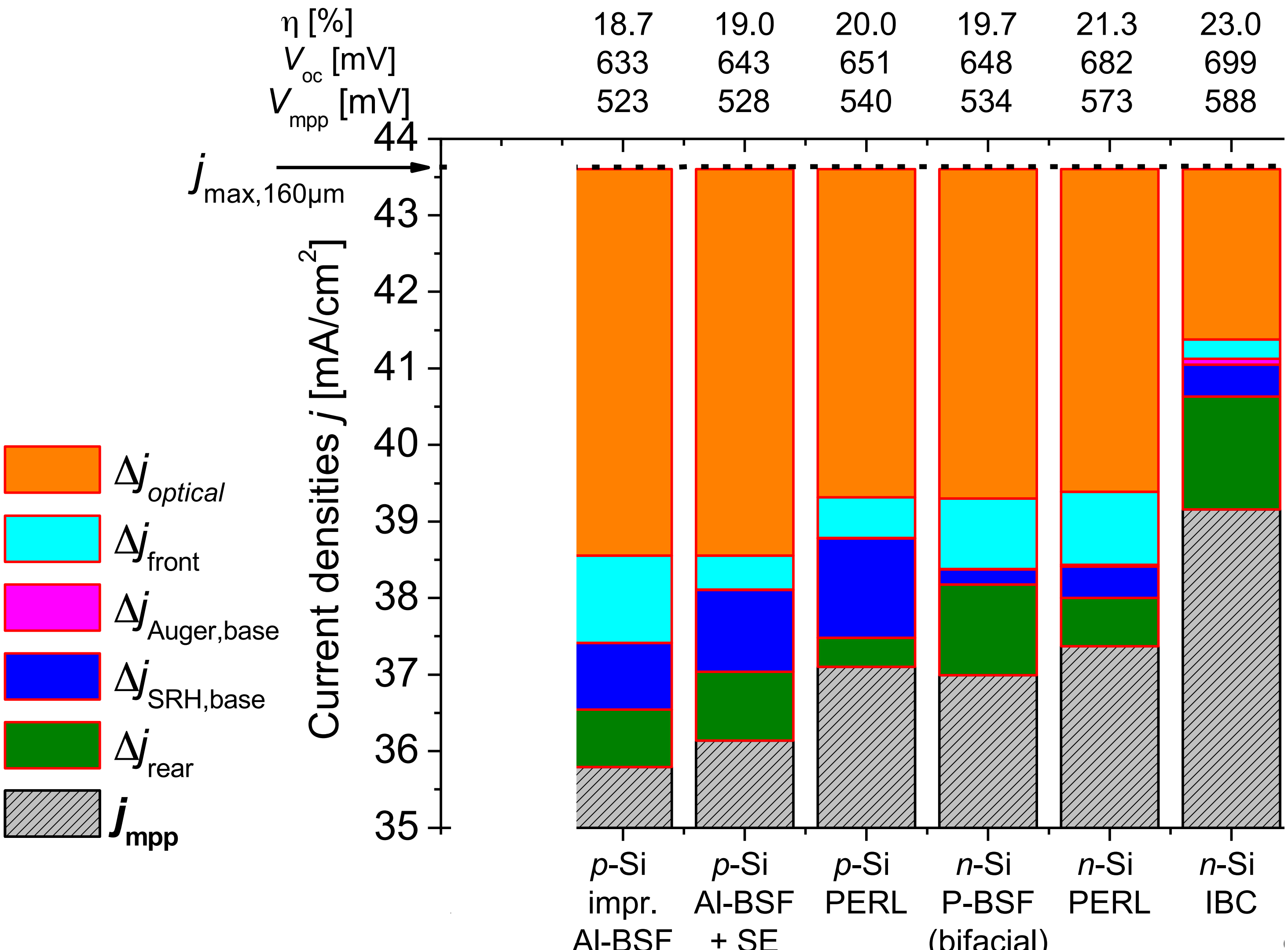
IBC cell on n-type silicon



- Big optical gain

Next main problem

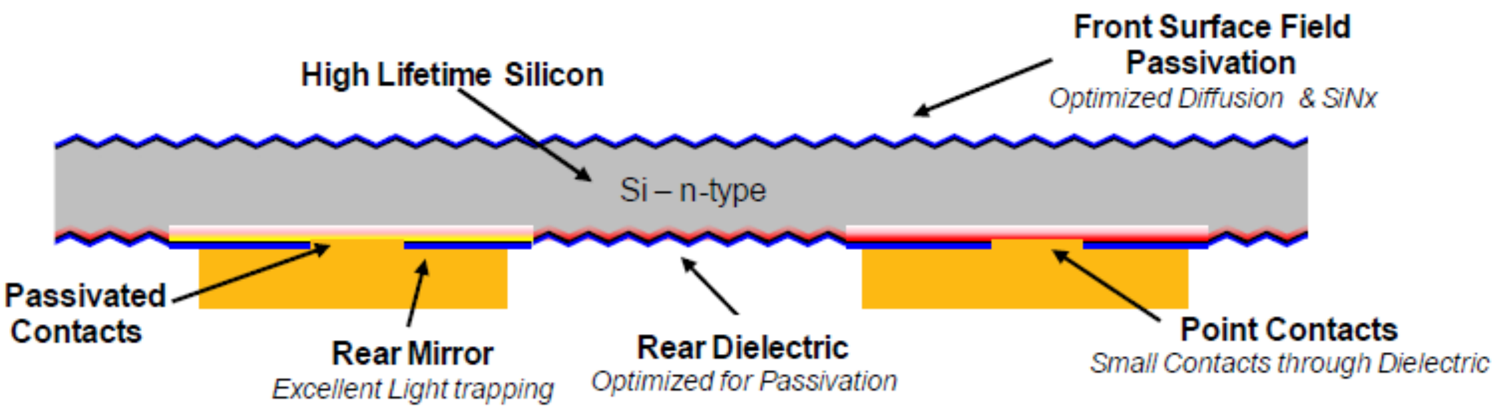
- Rear recombination especially contact recombination

Solution

→ Passivated contacts

Towards the Limit
IBC cell with passivated contacts on n-type silicon

- Interdigitated back contact back junction solar cells
- Excellent contact passivation
- SunPower[2] (ap=121 cm^2) 25.0% (V_{oc} = 726 mV)
- Edge losses are getting crucial



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

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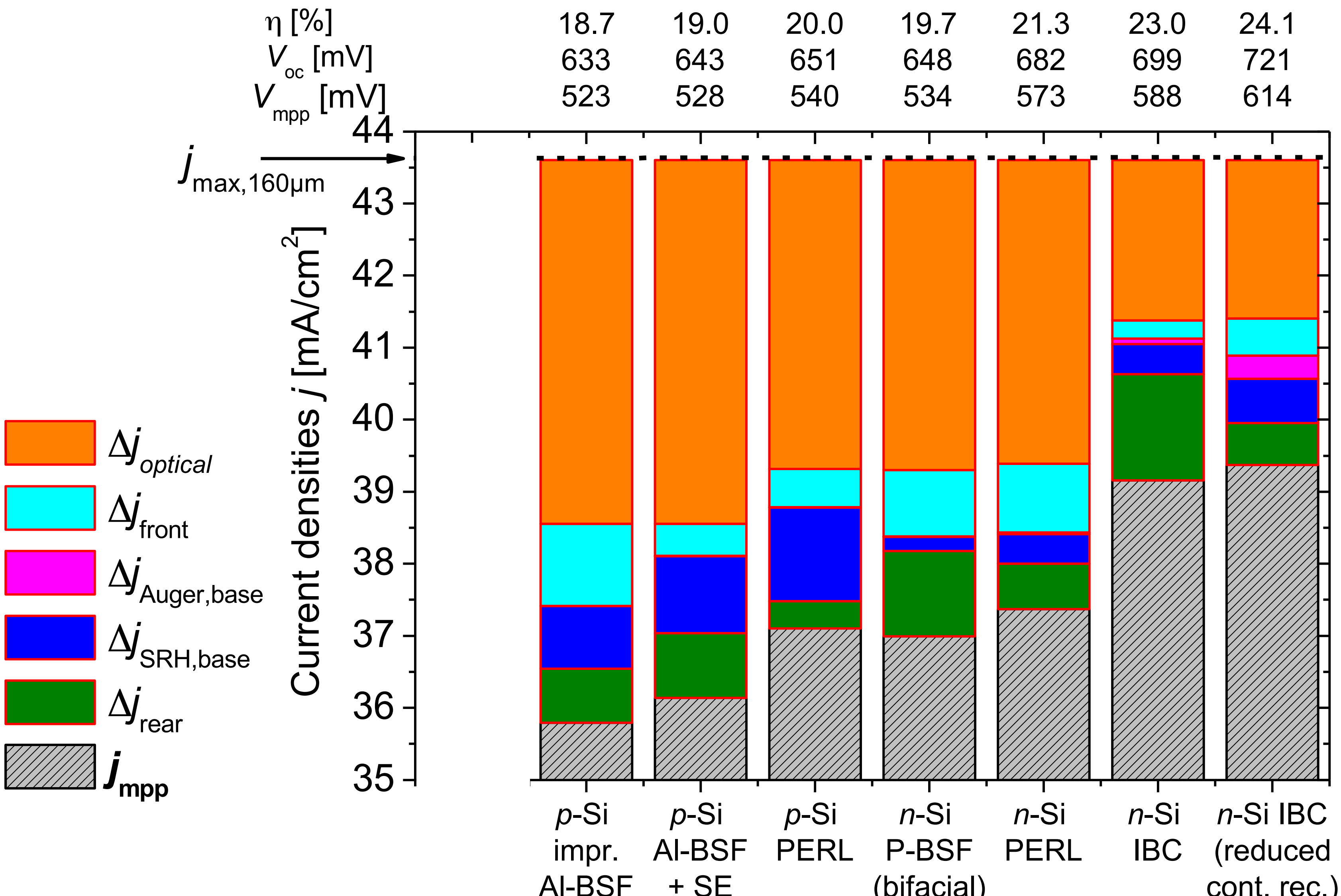
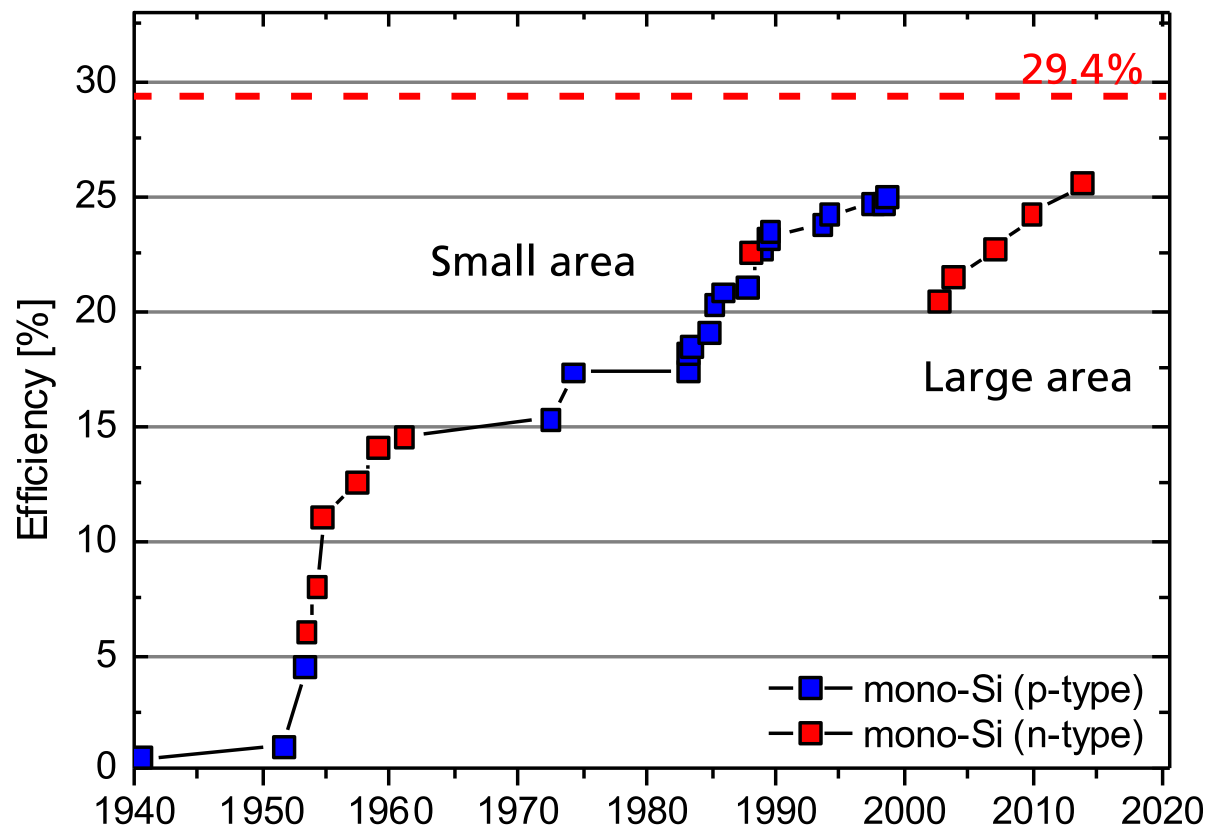
IBC cell with passivated contacts on *n*-type silicon



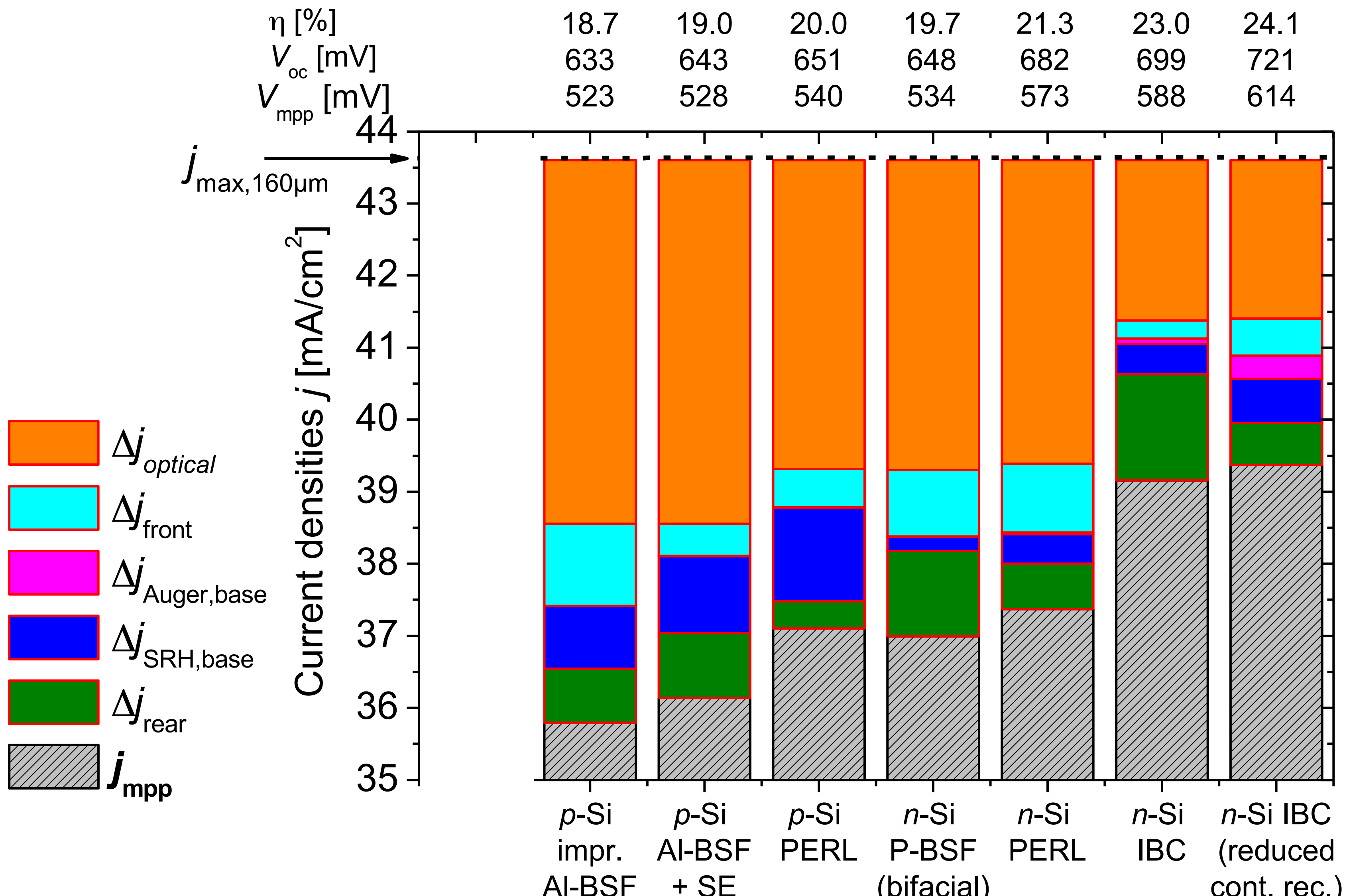
Towards the Limit
Large-area Record Cells

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



(S. Glunz, EUPVSEC 2014)

IBC cell with passivated contacts on n-type silicon



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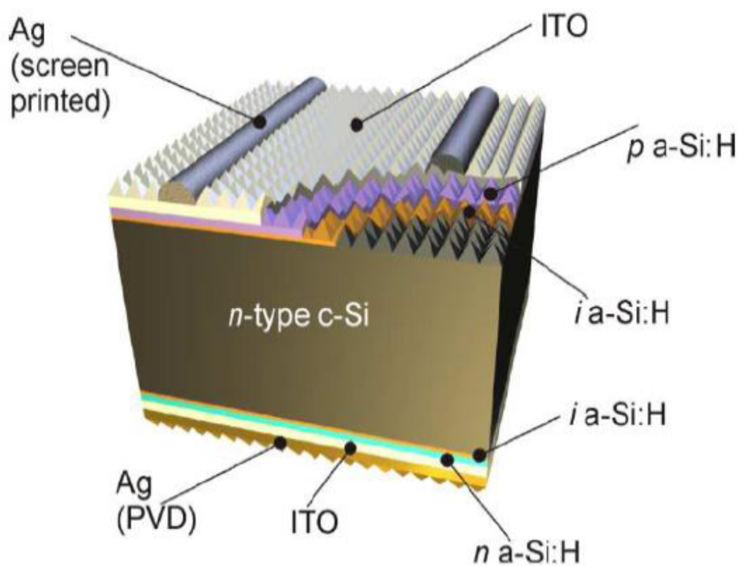
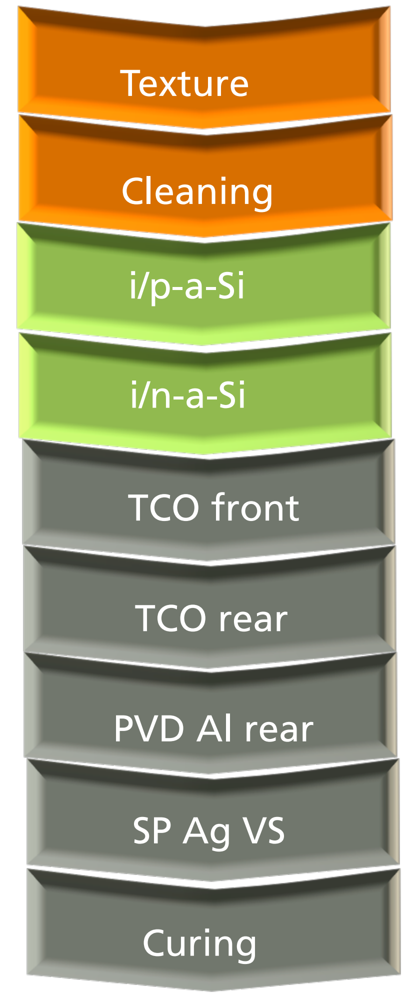
n-Type Heterojunction
A “simple” cell structure

- Lean process flow
- Highly efficient carrier selective contacts
- High V_{oc} and low T_k
- High efficiencies for thin wafers





from: D.Bätzner Silicon PV 2014

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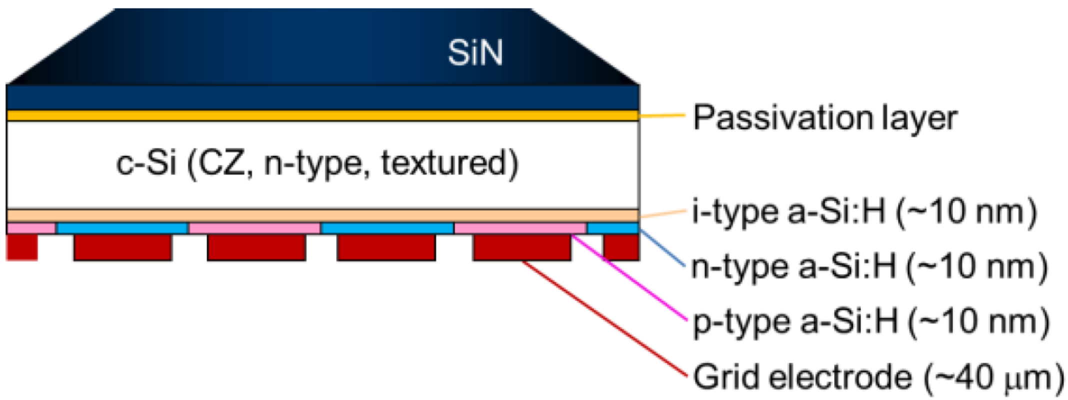
n-Type Heterojunction
A "simple" cell structure

	Area [cm²]	**V_{oc}** [mV]	**J_{sc}** [mA/cm²]	**FF** [%]	**η** [%]	**Comment**
Silevo	239	**739**	39,9	80,5	**23,1**	Tunnel oxide passivation J.Heng 40th IEEE PVSC 2014
R&R	239	**736**	38,6	81,3	**23,1**	Smart wire no BB GridTOUCH measured D.Bätzner, Silicon PV 2014
Choshu	239	**733**	37,3	81,8	**22,3**	Rear Emitter cell J. Nakamura, nPV Workshop 2013
CEA-INES	105	**730**	38,7	78,8	**22,3**	PJ. Riberon, Silicon PV 2014
Kaneka	171	**738**	40	81,9	**24,2**	Copper plated front grid JL. Hernandez, EUPVSC 2013
Panasonic	101.8	**750**	39,5	83,2	**24,7**	98 µm thin wafer M. Taguchi, IEEE JPV 2013

(M. Hermle, EUPVSEC 2014)

Towards the Limit
Hetero BCBJ Record Cell

- Interdigitated back contact back junction solar cells
- Excellent contact passivation (a-Si/c-Si heterojunction)
- Sanyo[1] (da=143.7 cm^2) 25.6% (V_{oc} = 740 mV)



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

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Fighting against losses

- *Improving the front side*: Selective emitters
- *Improving the rear*: Dielectric passivation and point contacts
- *Improving the base*: Transition to n-type silicon
- *Reducing the optical losses*: Rear contact cells
- *Getting rid of the last (?) recombination:* Passivated contacts

What next ?

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AGENDA

- Why high efficiencies?
- What is the efficiency limit for silicon solar cells?
- General strategy for high efficiencies
- Analyzing and fixing main losses in different solar cell types – the leaky bucket
- Future steps

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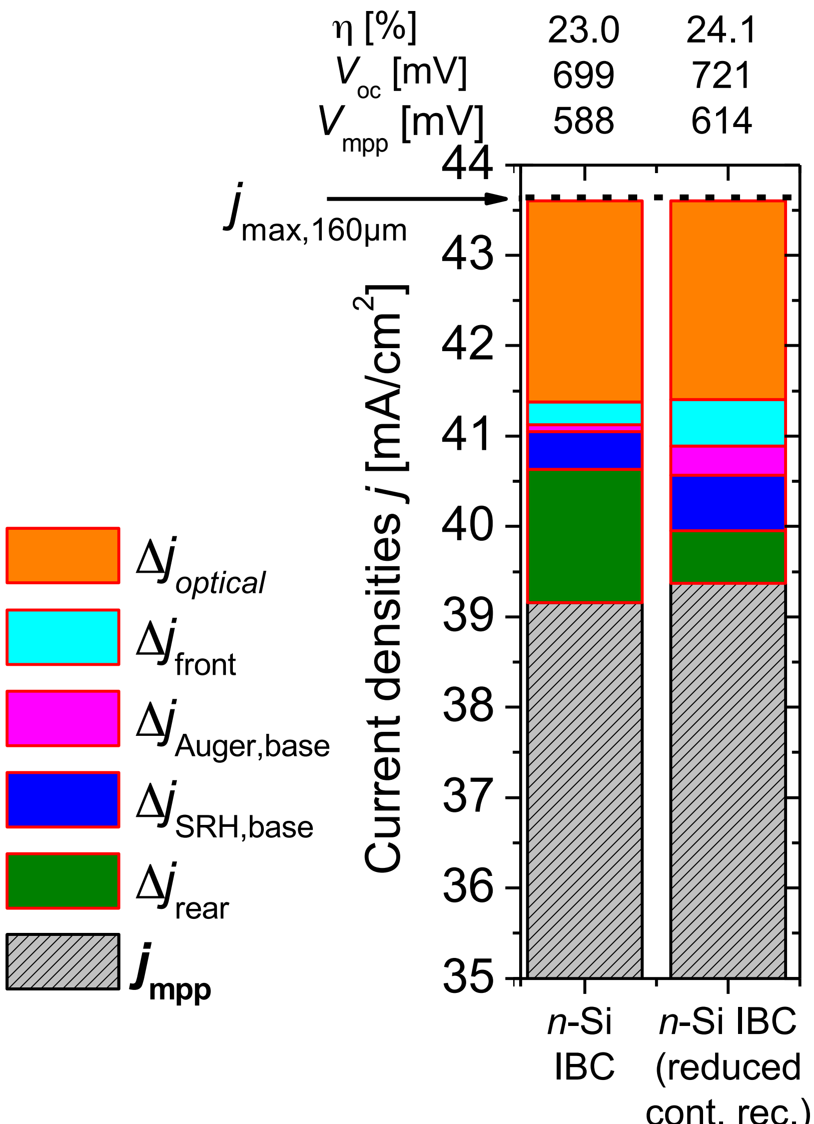
What limits the IBC cell with passivated contacts?



Next main problems

- Volume recombination (Auger and SRH)
- Surface recombination

Solution

→ Thinner wafer

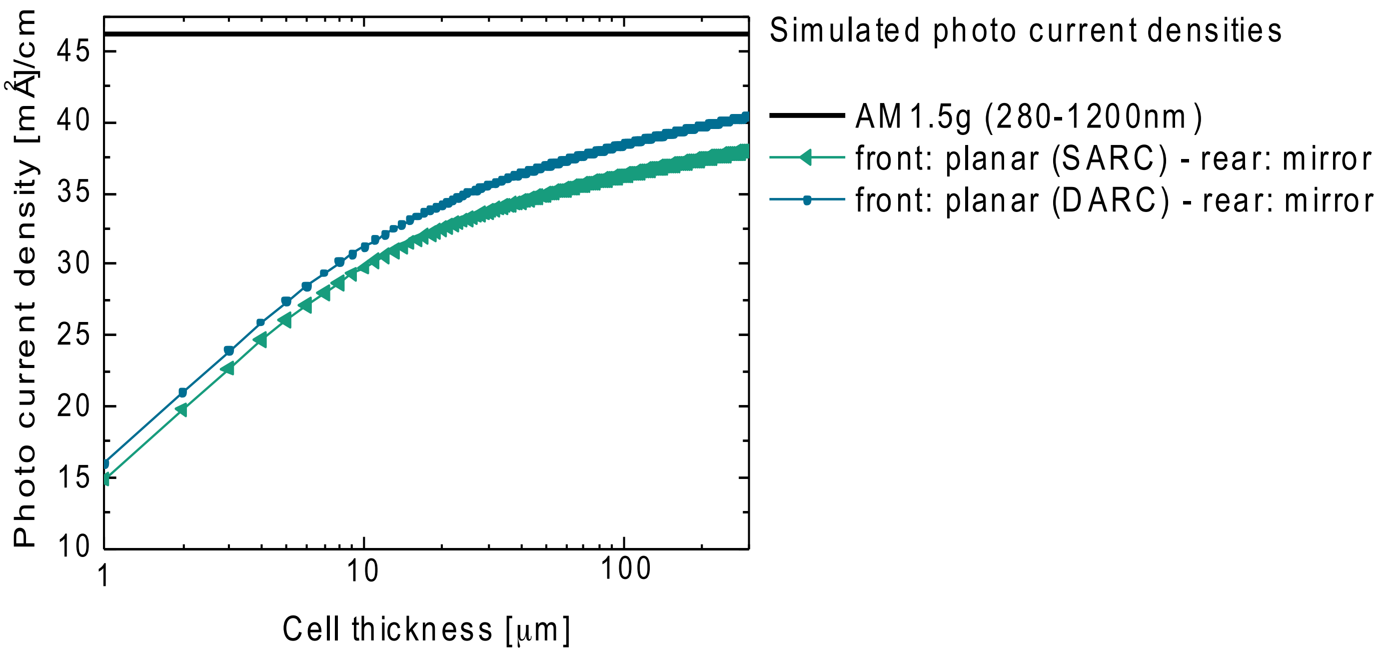
→ Flat silicon surfaces

Electrically thin, but optically thick solar cells

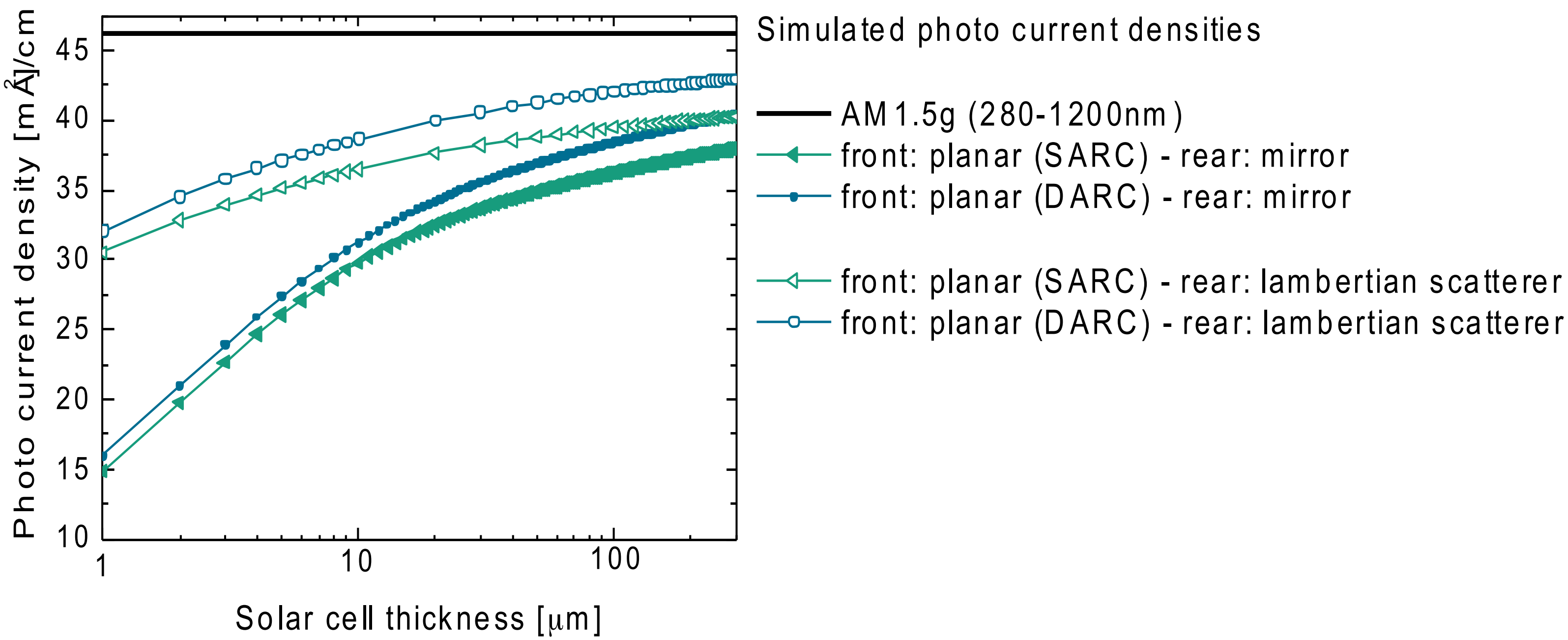
with

Electrically flat, but optically rough surfaces

Increasing Light Absorption
Flat Surfaces

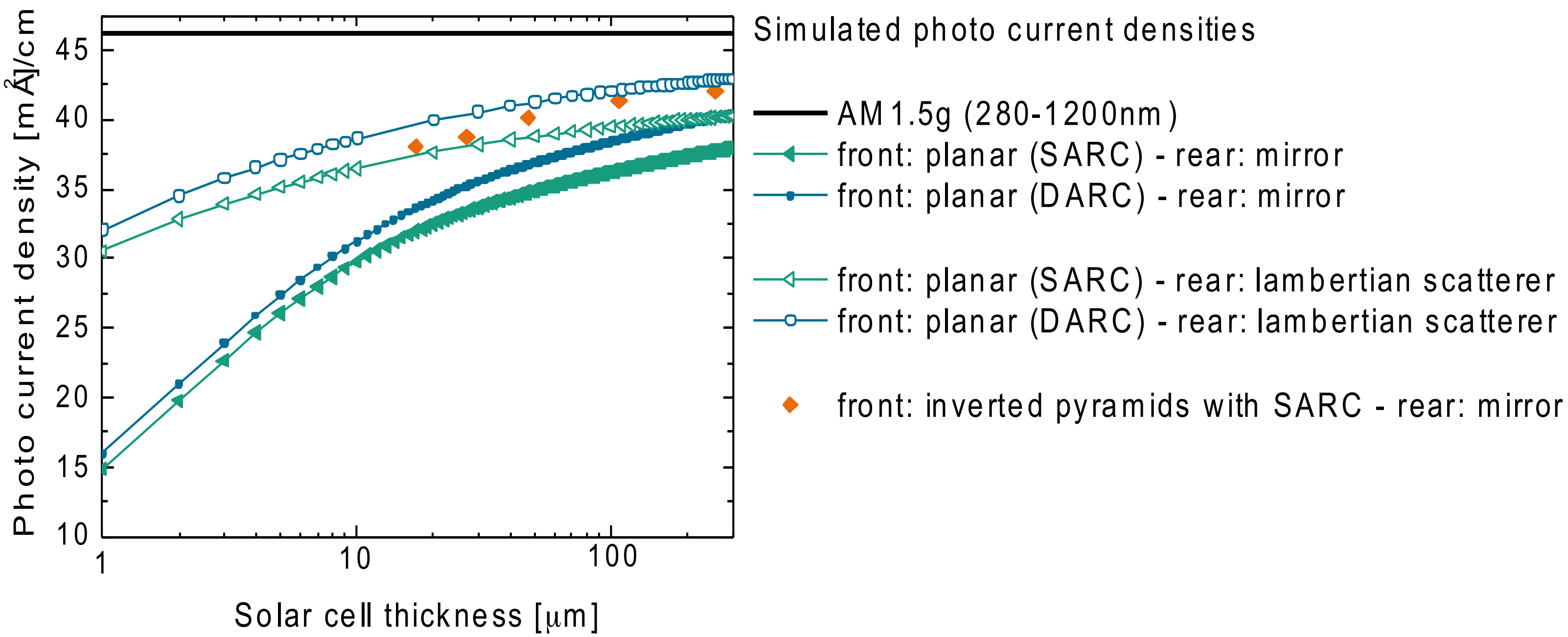


Increasing Light Absorption
Scattering Rear Surfaces



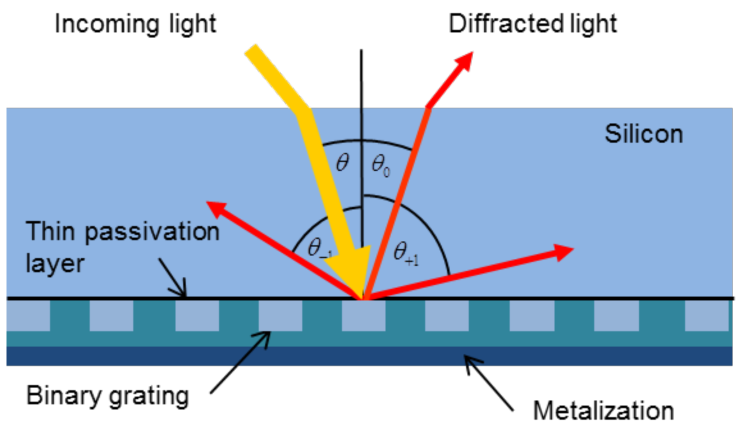
Increasing Light Absorption

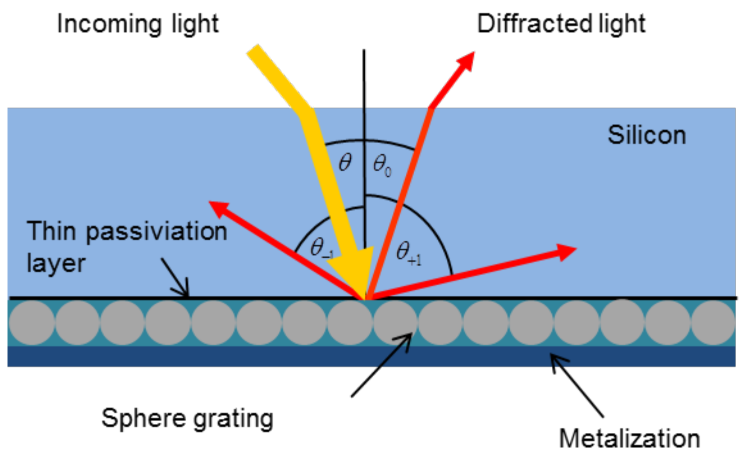
Scattering Rear compares to Pyramid Front



Electrically flat and optically rough dielectric rear
Hexagonal sphere gratings and nano-imprinted gratings

- Diffractive rear side structures: sphere gratings and nano-imprinted gratings
- Thin passivation layer separates silicon bulk and optical rear side structure





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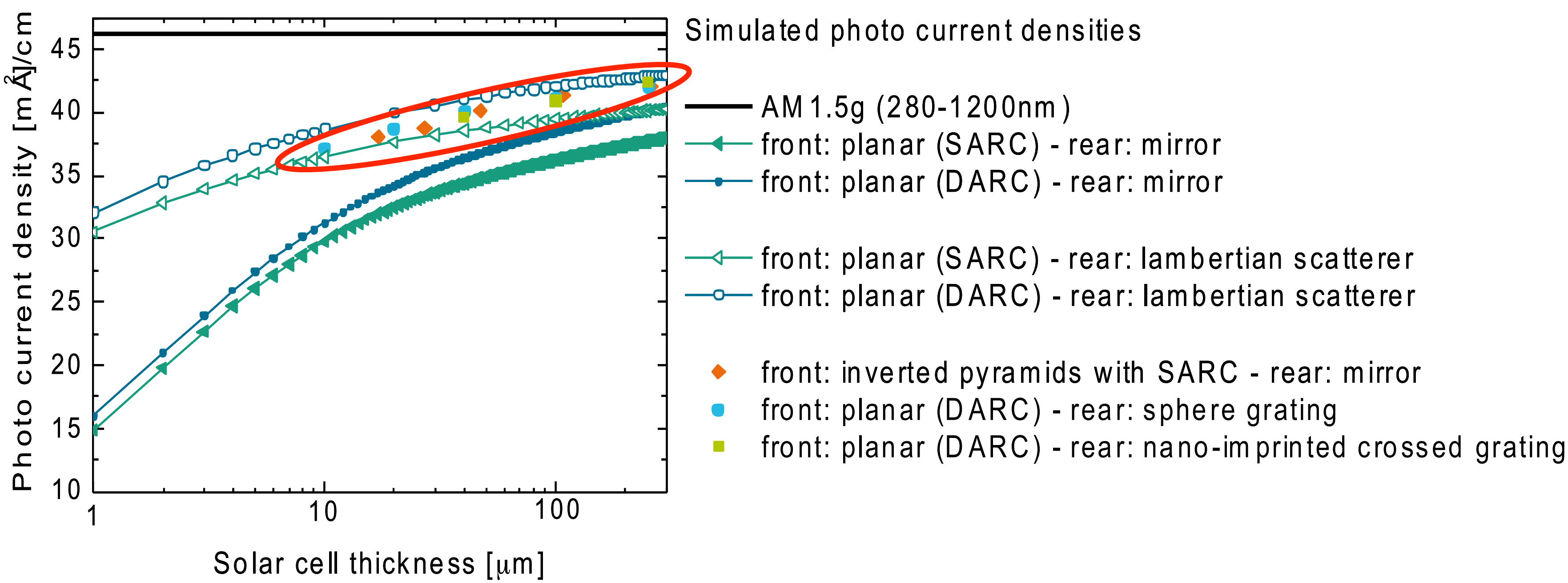
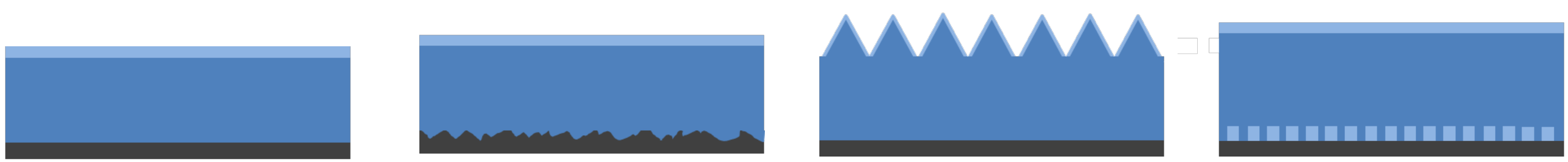
Increasing Light Absorption
Diffractive Rear Surfaces

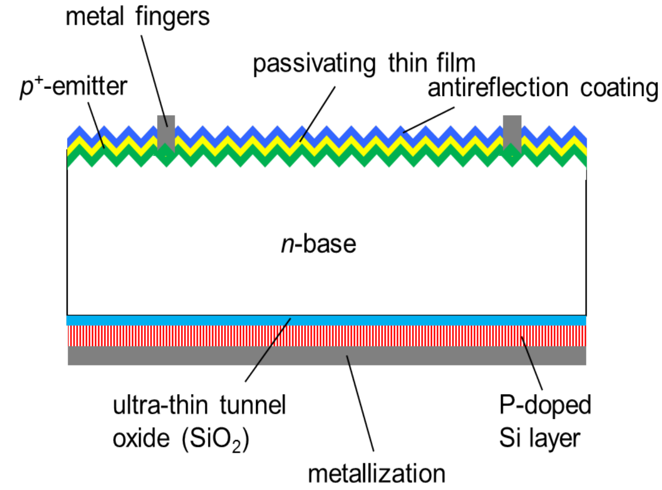




Increased Light Absorption with Diffractive Rear Side

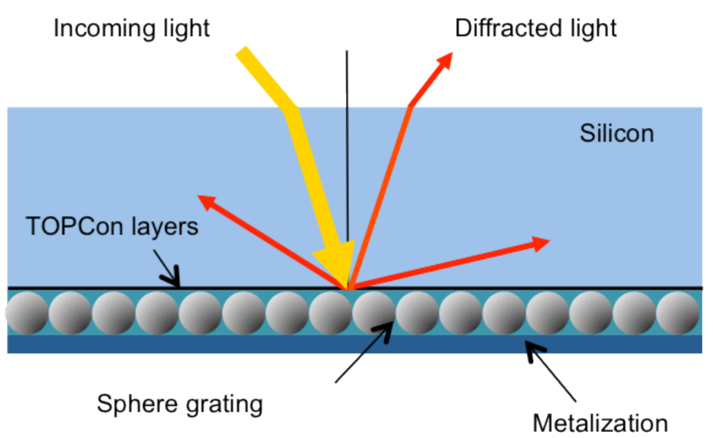
Starting from Our Best Solar Cell

- **T**unnel **O**xide **P**assivated **Con**tacts (TOPCon): η = 24.4% demonstrated[1]



F. Feldmann et *al*., SOLMAT, Vol. 120, 2014, 270–274

- Improving of light trapping of TOPCon cell by rear side sphere grating



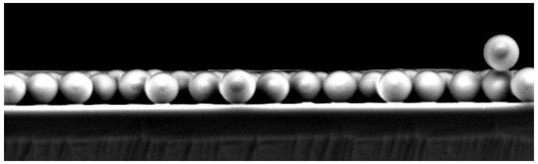
[1] F. Feldmann et *al*., SOLMAT, *Tunnel oxide passivated contacts as an alternative to partial rear contacts,* Article in Press

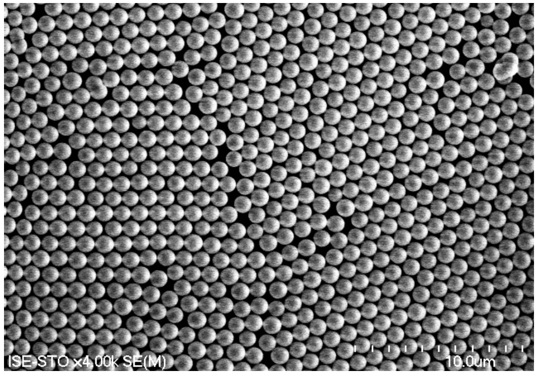
Increased Light Absorption with Diffractive Rear Side
Fabrication of Sphere Gratings

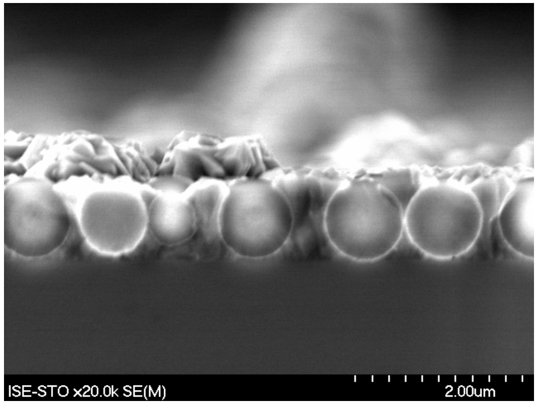
- Step 1: Spin coating of SiO_2-spheres on TOPCon surface

- Step 2: Infiltration with silicon by APCVD-process

- Implied $\mathbf{V_{OC} \approx 720\ mV}$ after whole process chain (TOPCon + sphere grating + APCVD)







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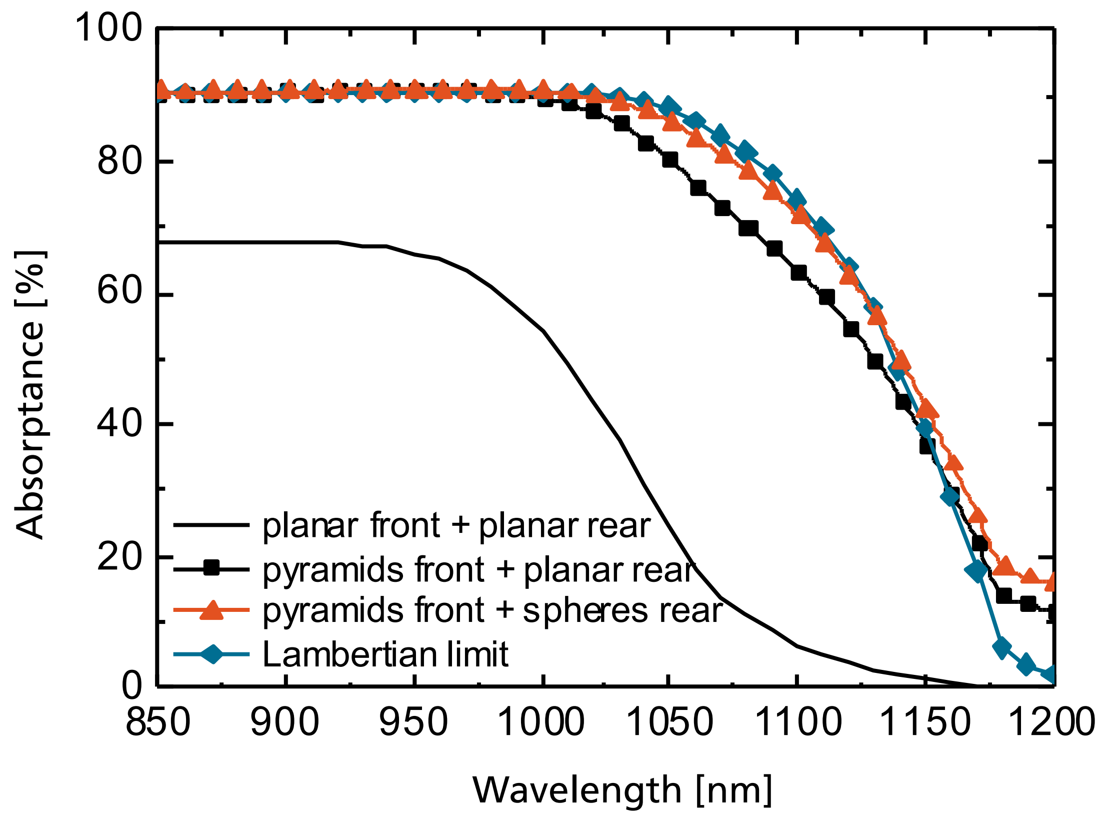
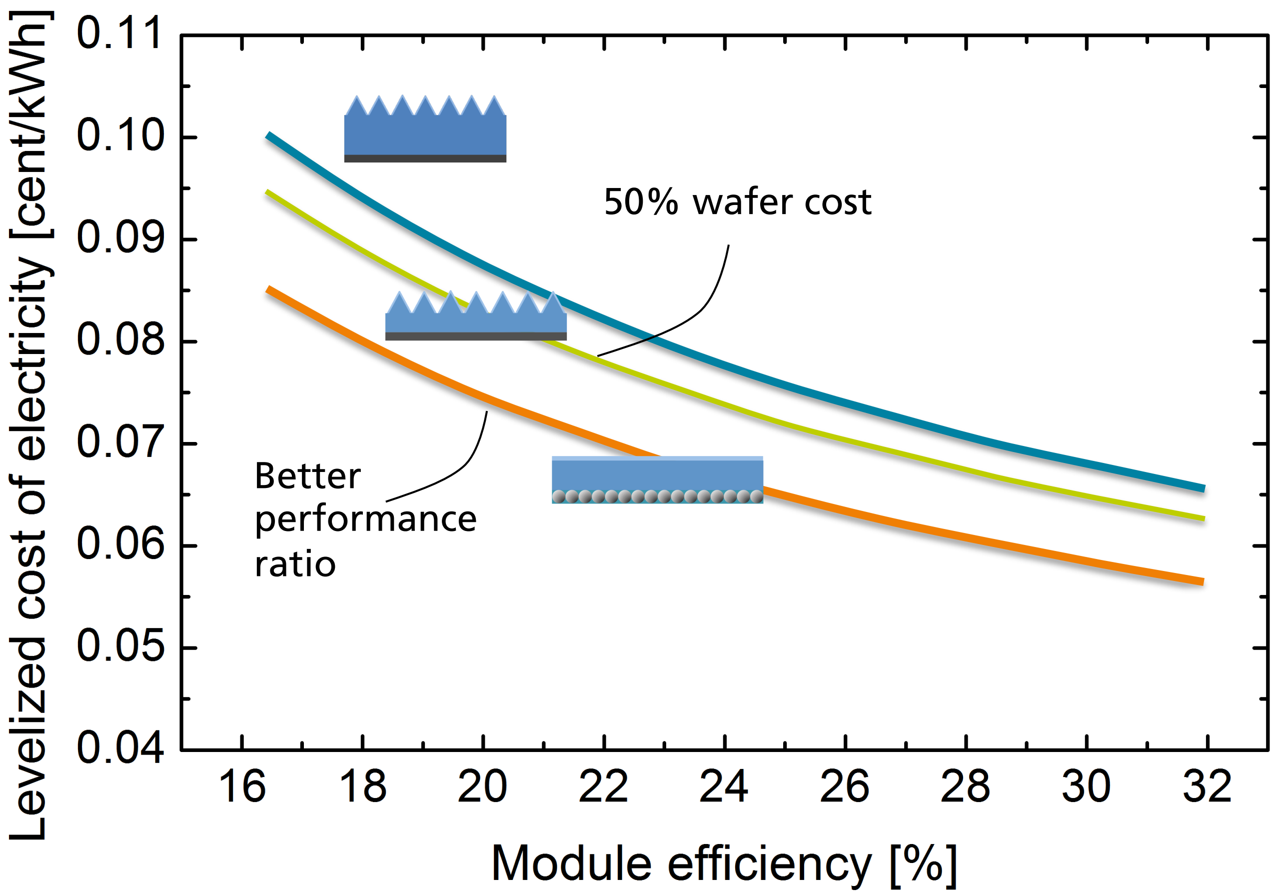
Increased Light Absorption with Diffractive Rear Side
Absorption Enhancement with Sphere Gratings

- Mirror behind all samples
- Sphere grating
- ➔ Absorption very close to Lambertian limit
- ➔ ~0.4 mA/cm² enhancement compared to front pyramids alone



How Nanophotonics drive Competitiveness
Cost Calculations



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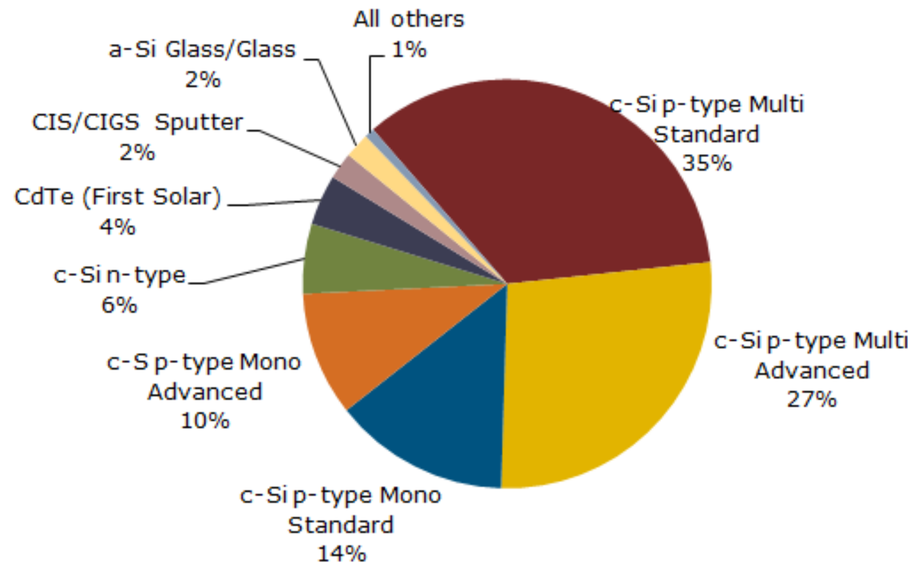
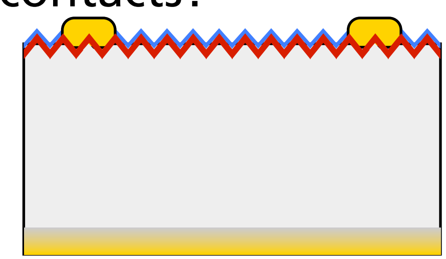
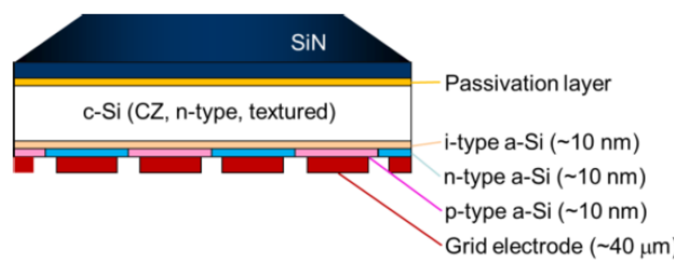
Highly Efficient Solar Cells with Low Complexity
State-of-the-Art Silicon Solar Cell

- Current reality in PV
- 91 % silicon
- **62 %** multi crystalline p-type silicon
  - > 90 % Al-BSF cells



Will there be a transition to the more complex n-type BJBC with passivated contacts?

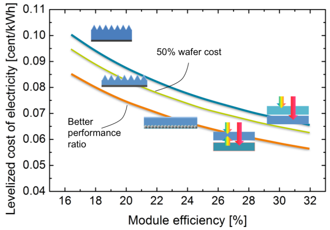




http://www.solarbuzz.com/news/recent-findings/multicrystalline-silicon-modules-dominate-solar-pv-industry-2014

 (M. Hermle, EUPVSEC 2014)

Conclusion & Outlook

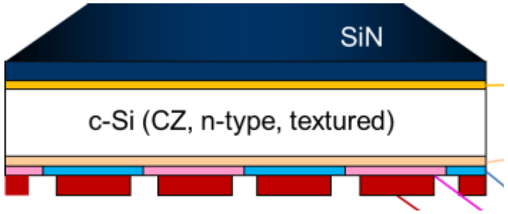


- Lower specific system costs main motivation for higher efficiencies

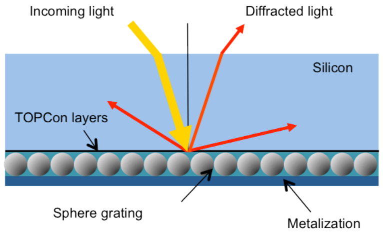
- Auger recombination limits efficiency to 29.4%

- General strategy for high efficiencies:
  Reduce optical, recombination and resistive losses

- Current world record of 25.6% is achieved with hetero-junction, inter-digitated back contact solar ce



- To be tackled next
  - Electrically thin, but optically thick solar cells with electrically flat, but optically rough surfaces
  - Highly efficient solar cells with low complexity



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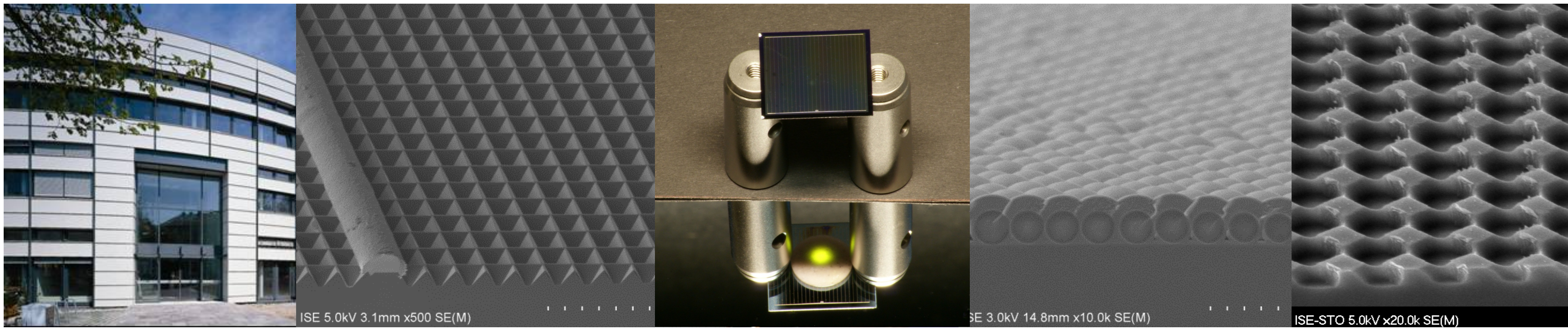
Thank you for your attention!

and many colleagues at Fraunhofer ISE for input



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