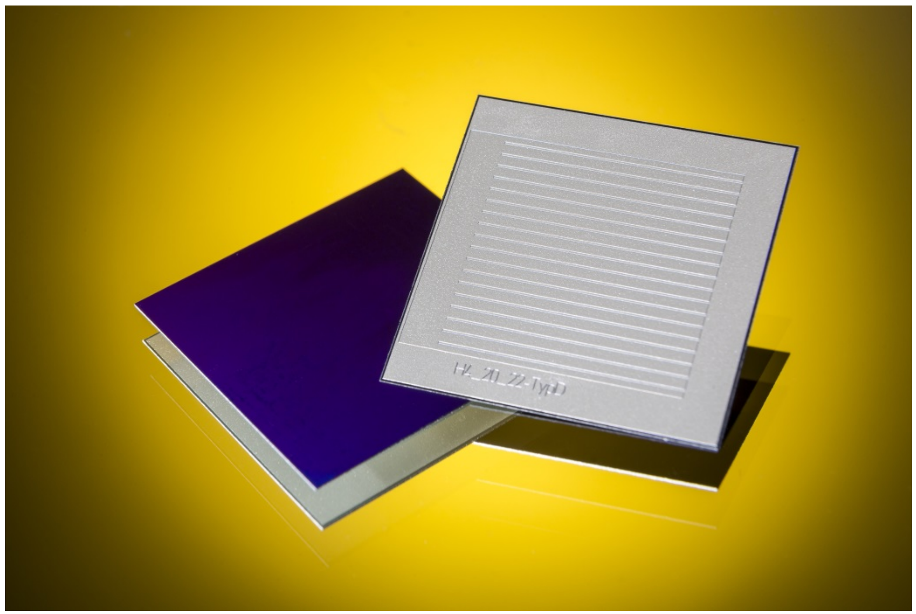
Towards 25 % efficient silicon BJBC solar cells with POLO junctions



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Heike Kohlenberg, Thomas Friedrich

2nd HERCULES workshop, Berlin, 11 October 2016

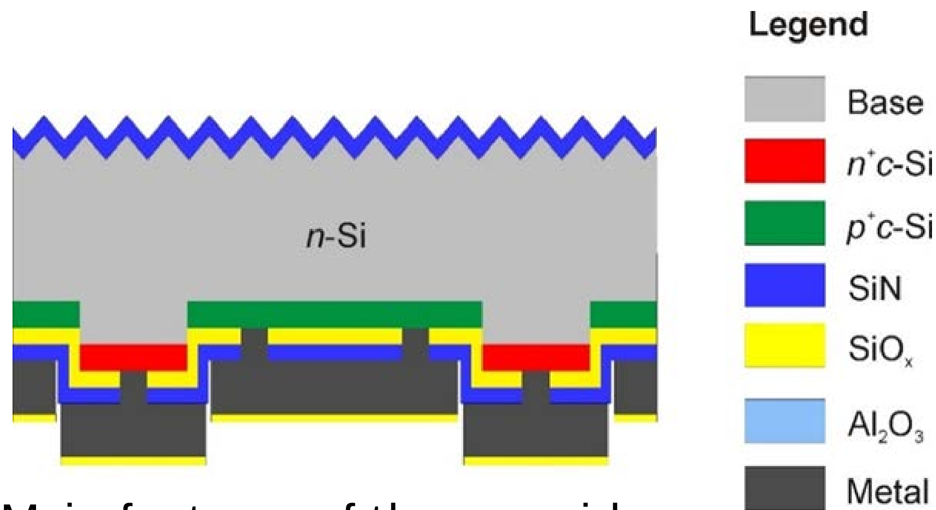
HERCULES main targets

1. Development of solar cells with efficiencies > 25 %
   - Back junction back contact solar (BJBC) cells with conventional junctions
   - Back junction back contact solar (POLO-BJBC) cells with carrier selective junctions

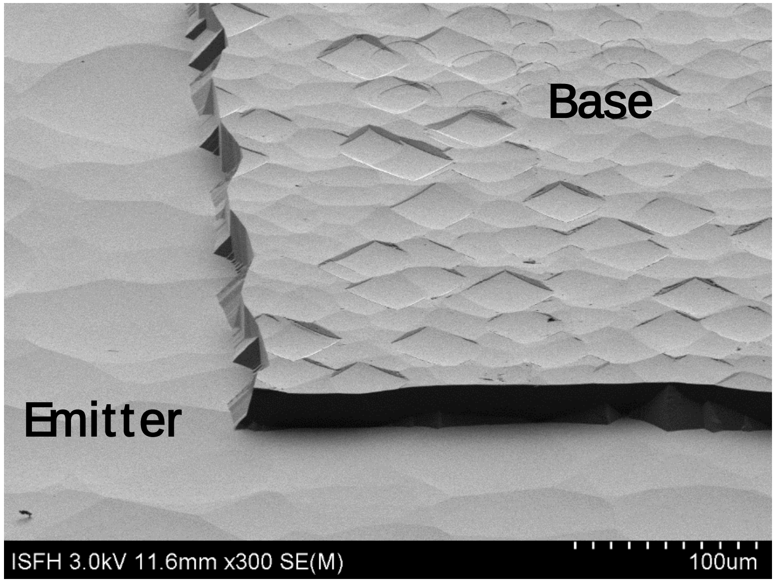
2. Development of modules with efficiencies > 21 %

3. Reduction of production complexity and costs
   - Development of cell fabrication processes using industrially feasible technologies

1. BJBC solar cells with conventional junctions: Main features



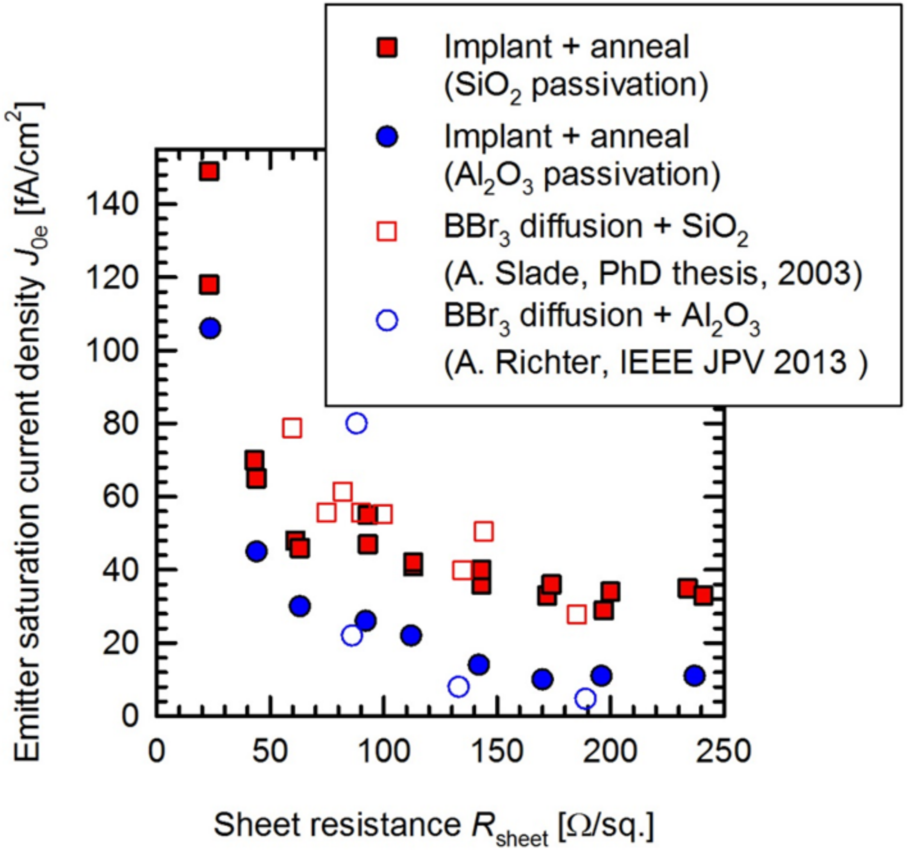
SEM image of the structured rear side of the cell



Main features of the rear side:

- Interdigitated emitter and base regions situated on two height levels
- Conventional junctions fabricated by ion implantation into the crystalline silicon

1. BJBC solar cells with conventional junctions: Boron implantation in crystalline silicon



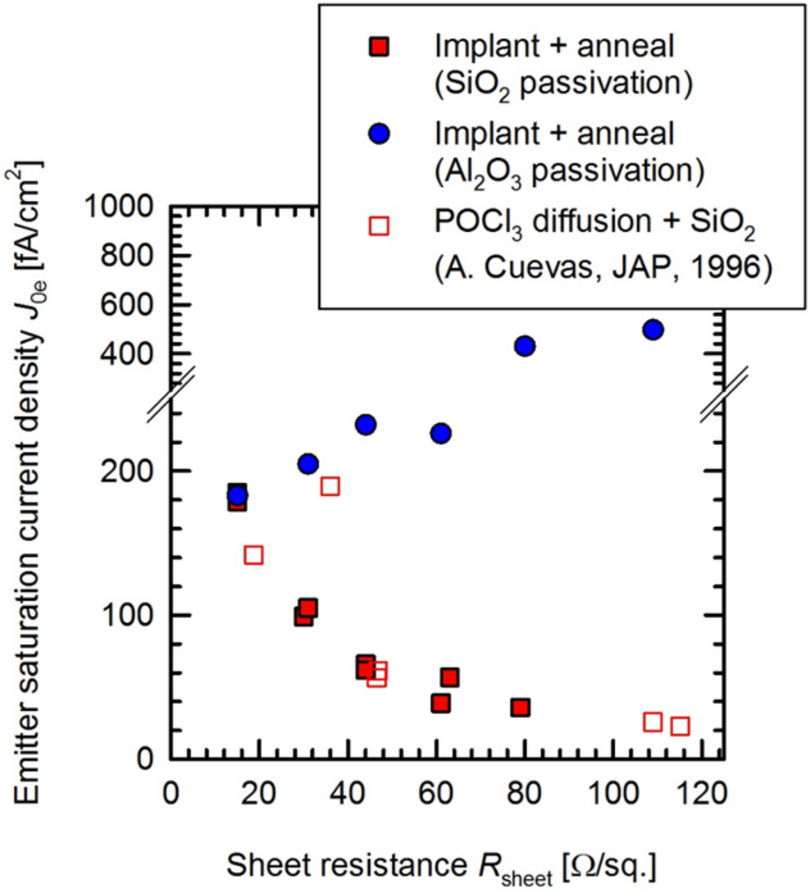
- Implant doses from $4 \cdot 10^{14}$ cm^{-2} to $6 \cdot 10^{15}$ cm^{-2} result in sheet resistivity ranging from 23 to 240 Ω/ sq.
- High temperature anneal process with in situ-oxidation

→ Recombination current densities as low as best literature data for boron diffusion

→ Very good passivation quality of the in-situ grown oxide

A. Merkle et al., Proc. of the 29st EUPVSEC, pp. 954-959 (2014).

1. BJBC solar cells with conventional junction: Phosphorus implantation in crystalline silicon



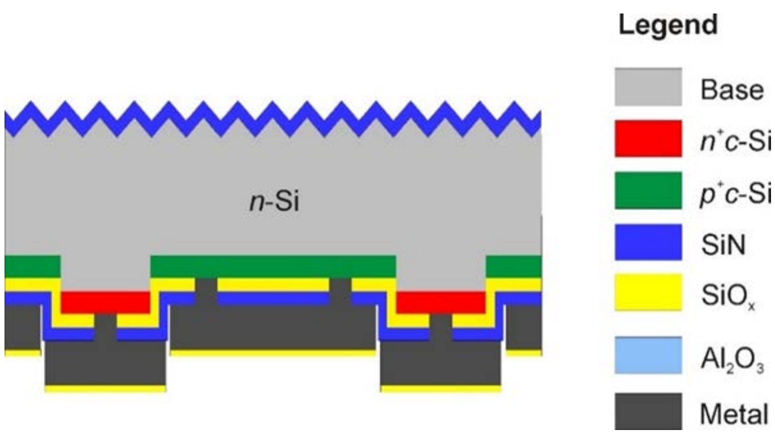
- Implant doses from $5 \cdot 10^{14}$ cm^{-2} to $5 \cdot 10^{15}$ cm^{-2} result in sheet resistivity ranging from 15 to 109 Ω/ sq.
- High temperature anneal process with in situ-oxidation

→ Recombination current densities as low as best literature data for Phosphorus diffusion

→ Very good passivation quality of the in-situ grown oxide

A. Merkle et al., Proc. of the 29st EUPVSEC, pp. 954-959 (2014).

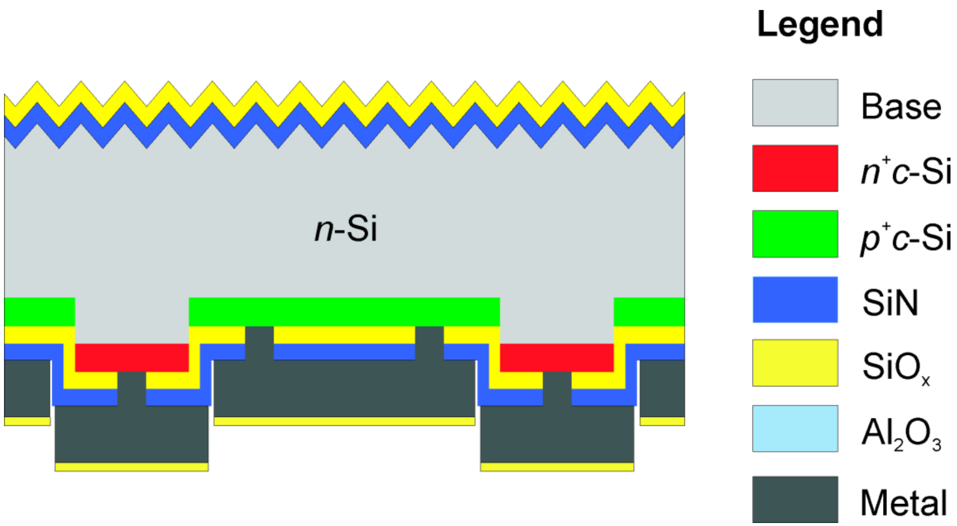
1. BJBC solar cells with conventional junctions: Cell process



- Photolithography-free
- Laser technology for patterning and contact opening
- Ion implantation for doping of the crystalline silicon
- Co-annealing with in-situ oxidation (only one high temperature step)
- Mask-free high throughput in-line metallization
- Self-aligned separation of contacts

1. *n*-type, Cz, 180 µm Si wafer
2. Damage etching and wet chemical cleaning
3. Phosphorus Implant
4. SiN_x deposition on the rear side
5. Laser patterning and damage etching
6. Boron Implant
7. Removal of the protective layer
8. Co-annealing with in-situ oxidation
9. SiN_x deposition on the rear side
10. Front oxide removal and texturing
11. SiN_x deposition on the front side
12. Laser contact opening
13. Metallization
14. Separation of contacts
15. Laser cutting of 24 cells from wafer

1. BJBC solar cell with conventional junctions: Best cell measurement and simulation



η [%]	23.71
V_{oc} [mV]	691
J_{sc} [mA/cm²]	41.74
FF [%]	82.17
A [cm²]	3.97*

* designated area
Independently measured at Fraunhofer CalLab

Quokka simulation

τ_{bulk} [ms]	1.4
η [%]	23.8
V_{oc} [mV]	698
J_{sc} [mA/cm²]	41.6
FF [%]	82.0

→ Overestimated V_{oc}, non considered edge recombinations

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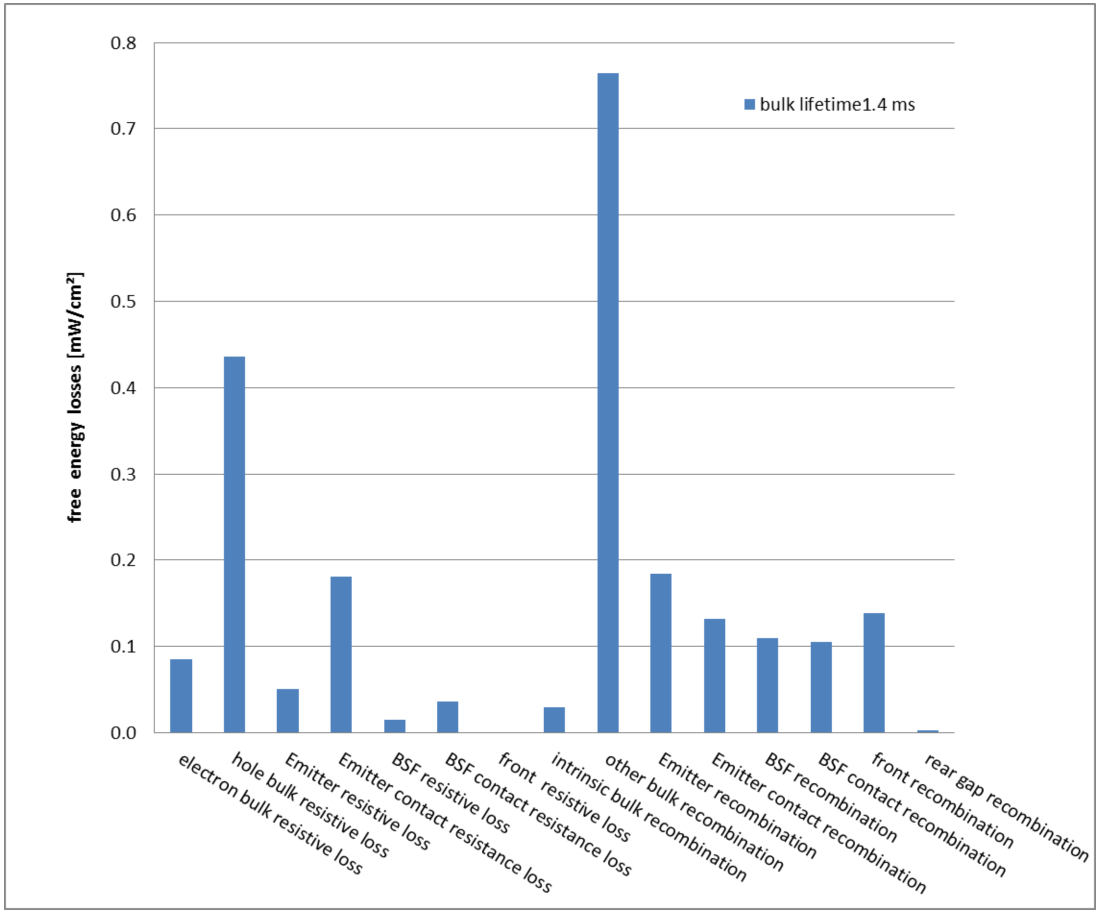
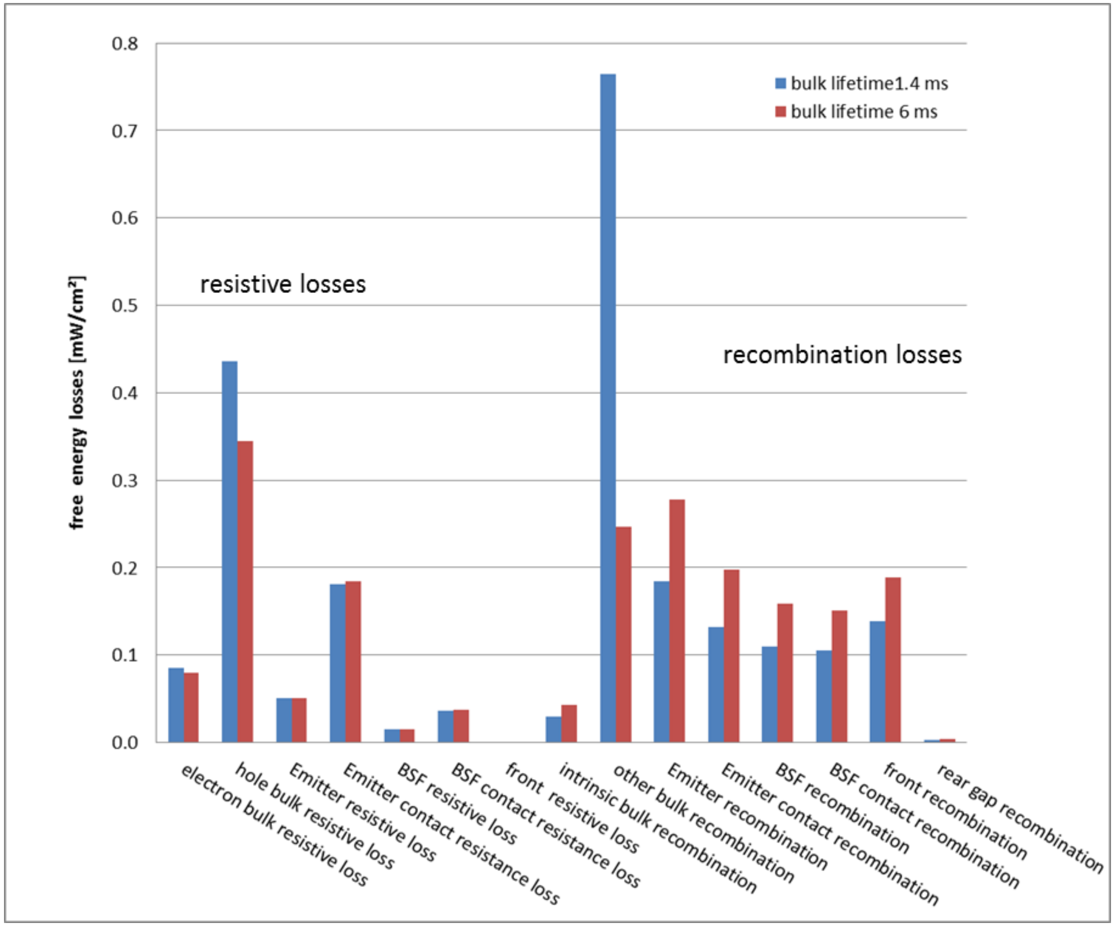
1. BJBC solar cell with conventional junctions: Best cell Quokka simulation - FELA analysis



→ Cell efficiency limited by:

- bulk resistive losses
- bulk recombination losses

1. BJBC solar cell with conventional junctions: Quokka simulation - FELA analysis

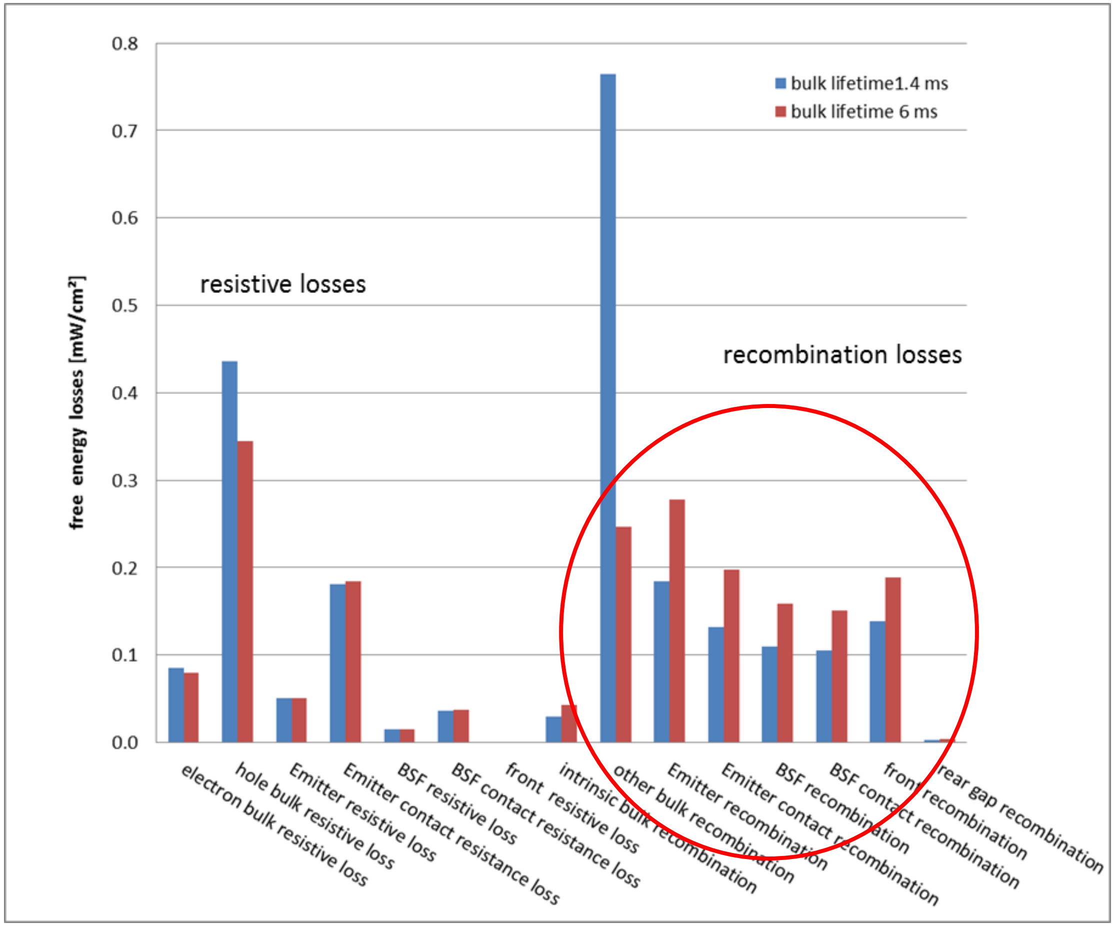


Quokka simulation

τ_{eff} [ms]	1.4	6
η [%]	23.8	24.4
V_{oc} [mV]	698	703
J_{sc} [mA/cm²]	41.6	41.9
FF [%]	82.0	83.0

→ Higher material quality reduces bulk recombination and improves cell efficiency

1. BJBC solar cell with conventional junctions: Quokka simulation - FELA analysis

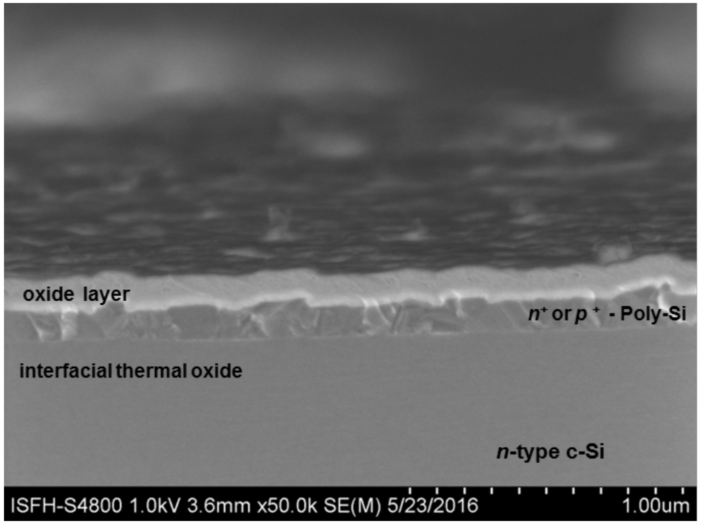


→ For cell efficiencies >25 % recombination losses have to be strongly reduced

Carrier selective junctions

Carrier selective junctions at ISFH: Polysilicon on oxide junctions

Polysilicon on **o**xide - POLO - junctions

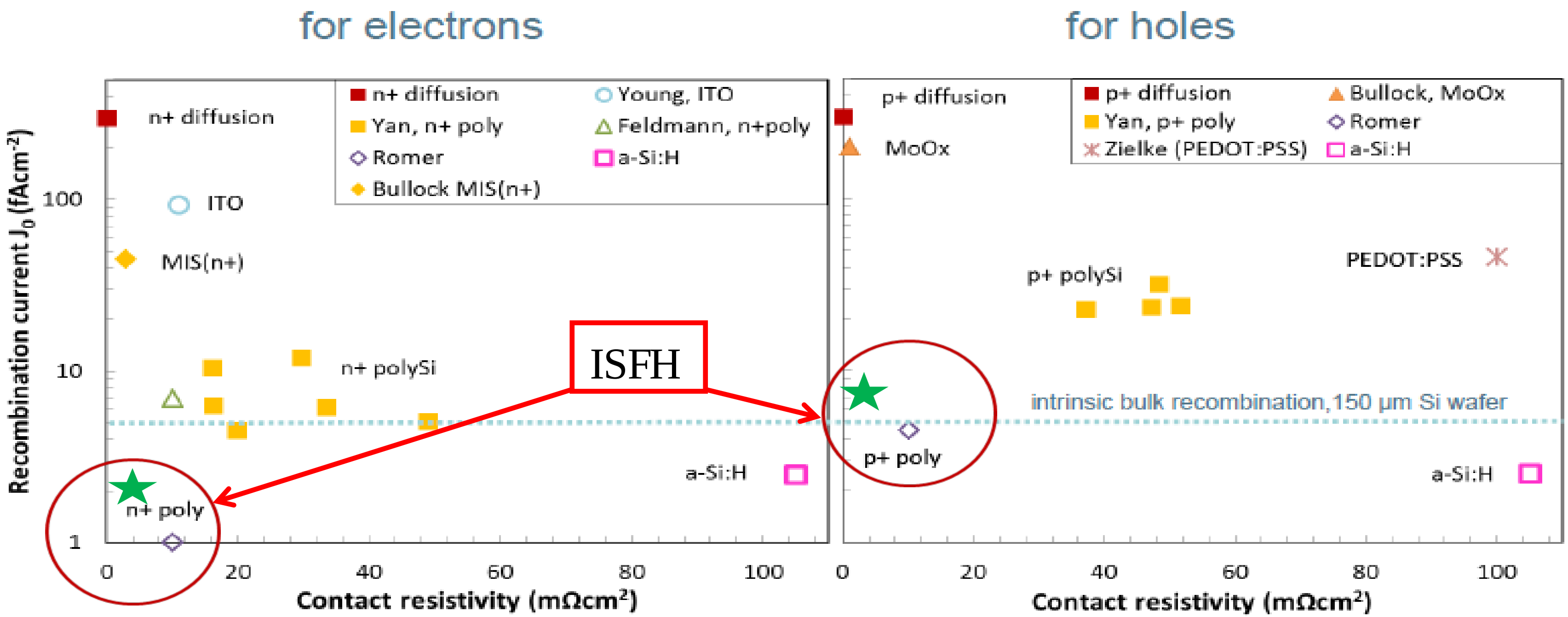


SEM image of a POLO-junction with an oxide protection layer on the top

Main features:

- Thermally or wet chemically grown interfacial oxide
- LPCVD Polysilicon layer
- Phosphorus or Boron doping of the polysilicon layer by ion implantation

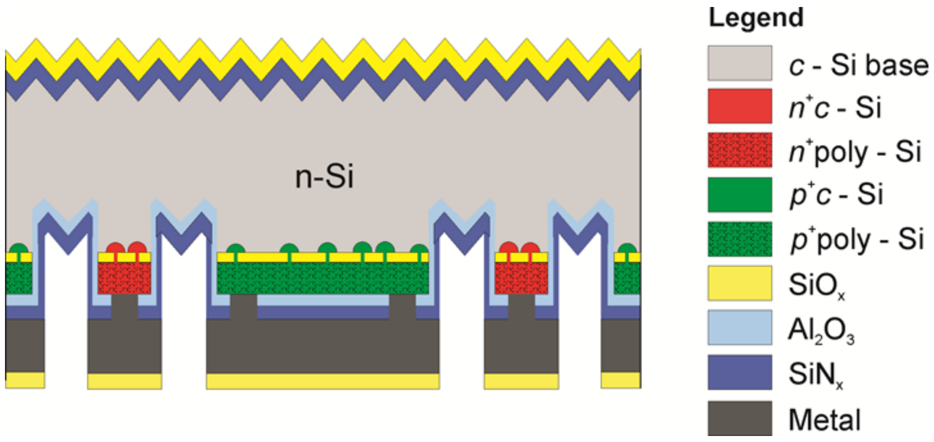
Carrier selective junctions: POLO junctions



ISFH achieved with POLO junctions simultaneously very low J_0 and ρ_c values

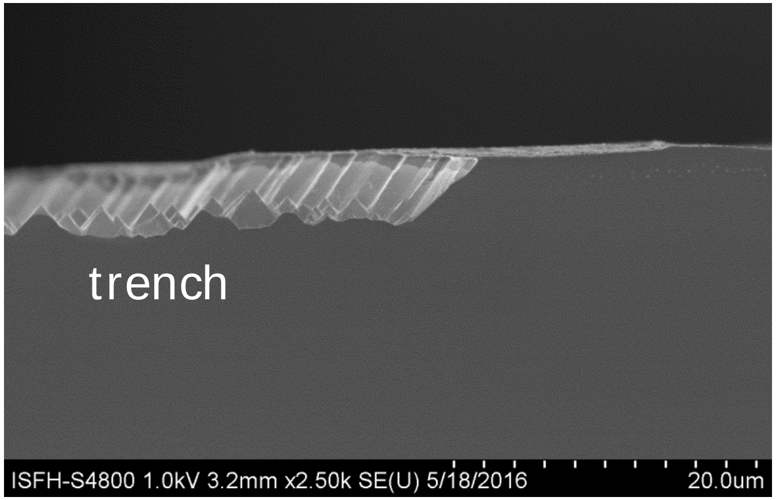
A. Cuevas et al., Proc. of the 41st IEEE PVSC, pp. 1-6 (2015).
U. Römer *et al*, IEEE Journal of Photovoltaics **5** (2), pp. 507-514 (2015)
M. Rienäcker *et al.*, DOI: 10.1109/ JPHOTOV.2016.2614123

2. BJBC cells with carrier selective junctions: Main features of the POLO-BJBC cell



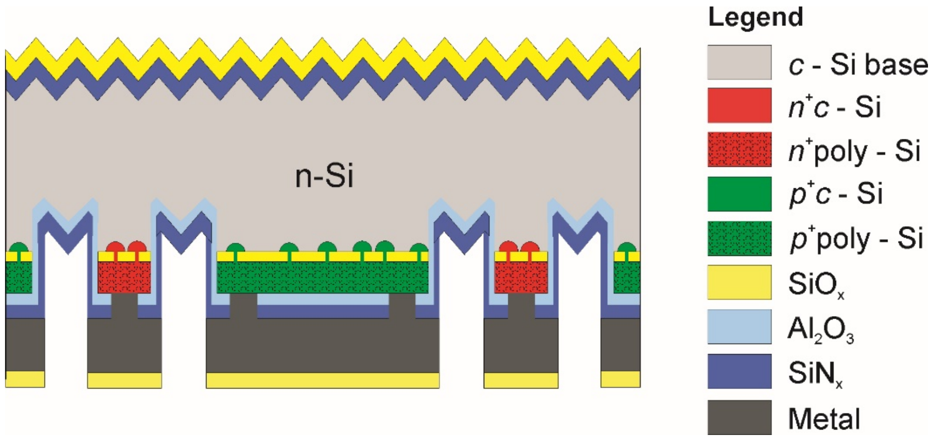
Main features of the rear side:

- Interdigitated emitter and base regions separated by textured trenches
- Ion implanted POLO junctions for both polarities



SEM image of a textured trench

2. BJBC solar cells with POLO junctions: POLO-BJBC cell process

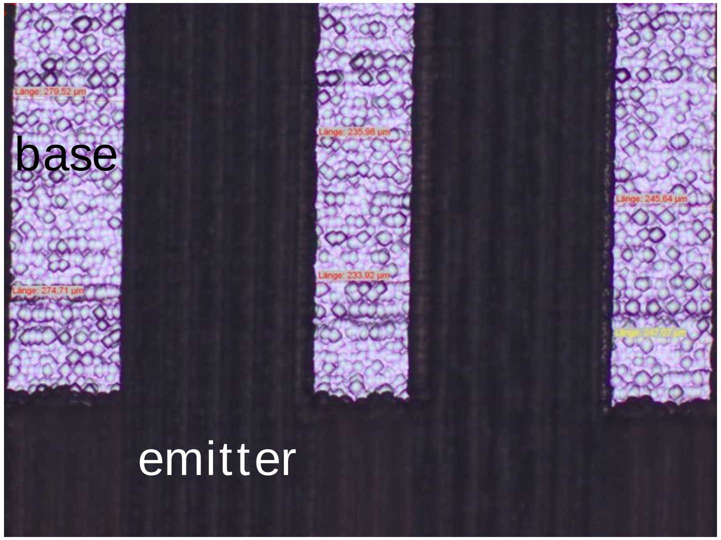


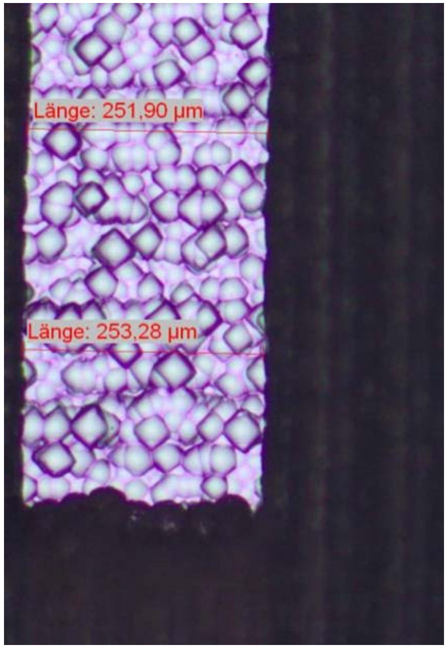
1. *n*- type Si, Cz, 180 µm wafer
2. Damage etching and wet chemical cleaning
3. Oxidation (growth of an interfacial oxide)
4. LPCVD amorphous-Si deposition
5. CVD SiO$_x$ deposition on the rear side
6. Inkjet patterning and wet chemical etching
7. Phosphorus Implantation
8. Removal of the protective layer
9. Boron Implantation
10. Co-annealing and oxidation
11. Inkjet patterning and wet chemical etching
12. Texturing of the front side and trenches
13. SiN$_x$ deposition on the front side
14. Rear side passivation
15. Laser contact opening
16. Metallization
17. Separation of contacts
18. Laser cutting of 20 cells from wafer

- Photolithography-free
- Inkjet and laser technology for patterning and contact opening
- Ion implantation for doping of the polysilicon layer
- Co-annealing and oxidation
- Mask-free high throughput in-line metallization
- Self-aligned separation of contacts

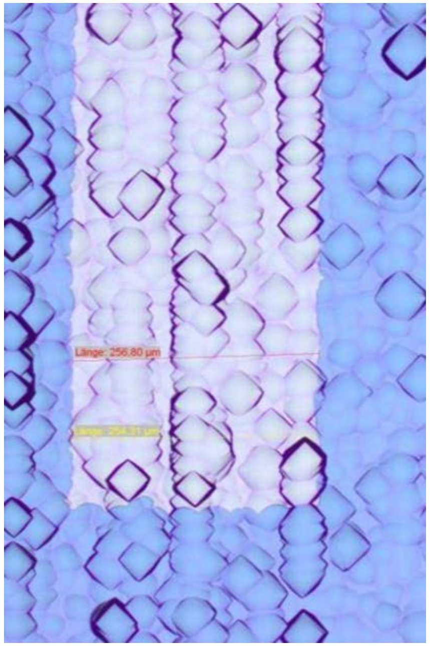
2. BJBC solar cells with carrier selective junctions: Inkjet patterning of the rear side

After inkjet printing of the implant mask before P implantation





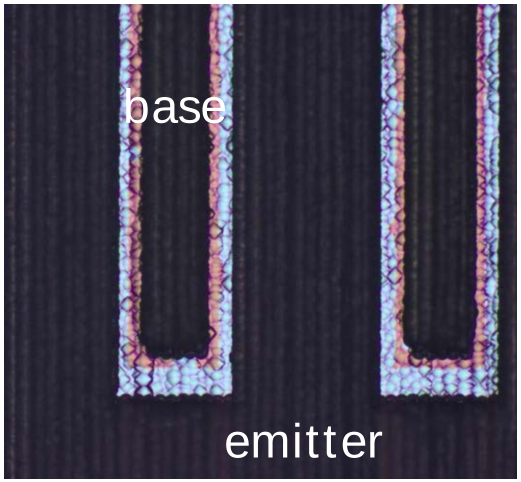
After stripping of the wax and HF-etching of the BSF regions



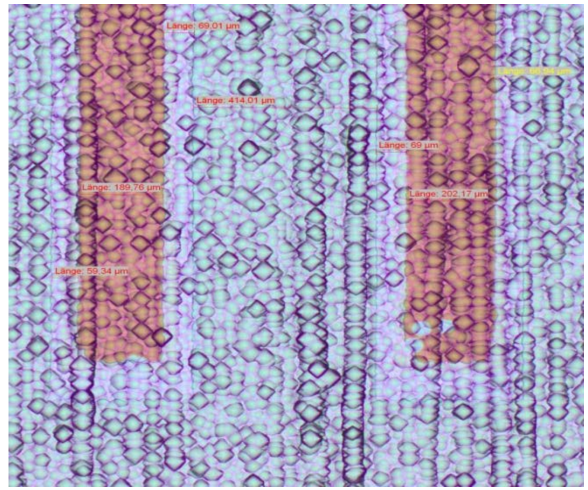
Good definition of the emitter and BSF regions

2. BJBC solar cells with carrier selective junctions: Inkjet patterning of the trenches

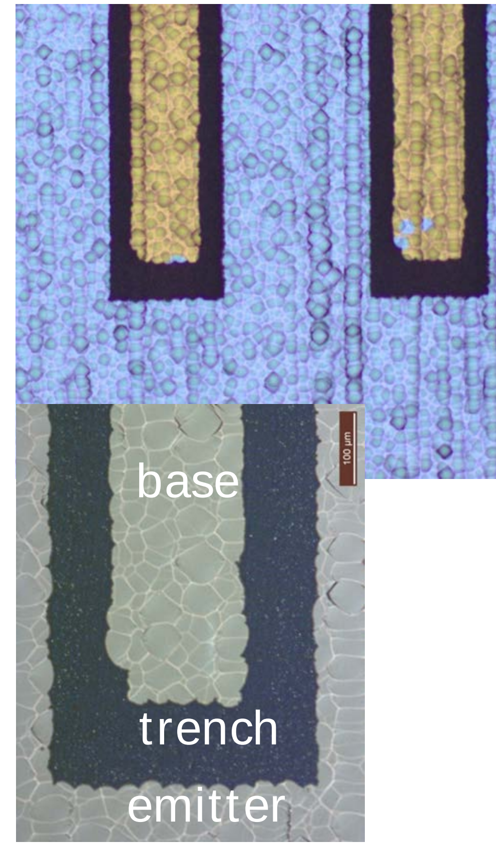
After inkjet printing



After stripping of the wax



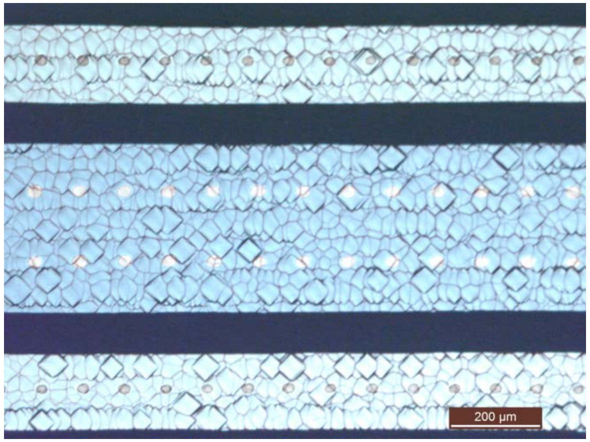
After texture of the trenches

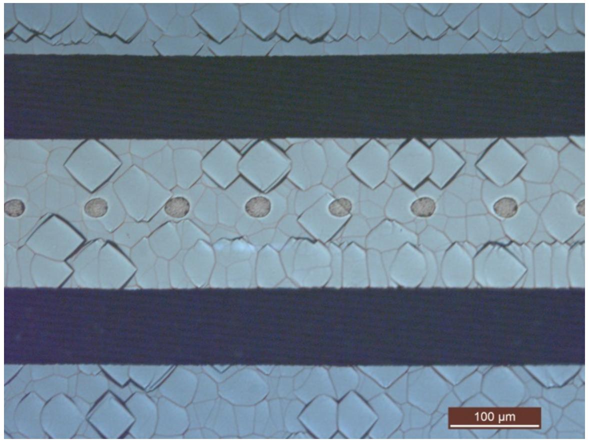


- Good alignment of the trench mask
- Complete separation of the emitter and BSF regions by textured trenches

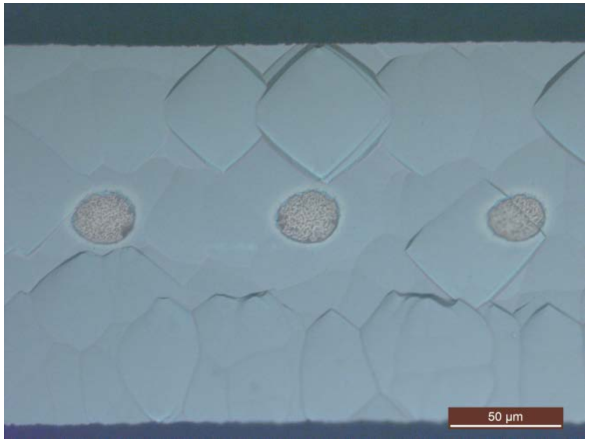
2. BJBC solar cells with carrier selective junctions: Laser contact opening

Microscope images of laser contact openings (LCO) on emitter and BSF





- Laser used: ~10 ps pulselength,
  355 nm wavelength
- Very good alignment even for narrow BSF regions
- Complete opening of the dielectrical layer



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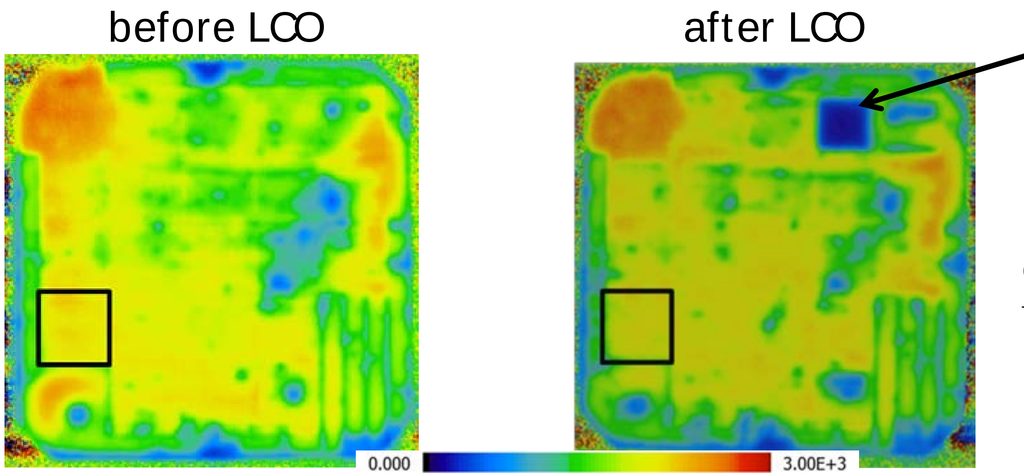
2. BJBC solar cells with carrier selective junctions: Laser contact opening

Dynamic Infrared Lifetime Mappings (ILM) at 0.33 suns



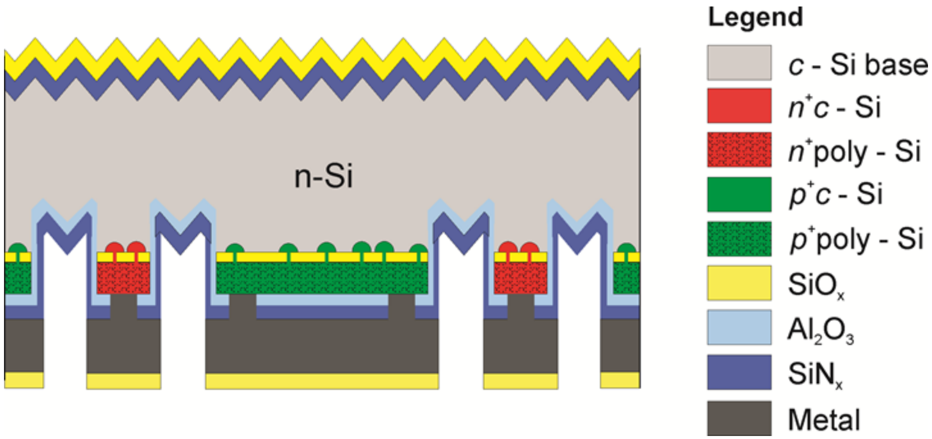
$\tau_{eff} = 2$ ms $\tau_{eff} = 1.9$ ms

→ No significative damage of the poly-silicon layer by laser contact opening

From injection dependent ILM measurements (J_{sc}=41.5 mA/cm²)

	$V_{oc, implied}$ [mV]	$pFF_{implied}$ [%]	$\eta_{implied}$ [%]
Before LCO	740	85.5	26.3
After LCO	738	85.1	26.1

2. BJBC solar cell with carrier selective junctions: Best POLO-BJBC cell



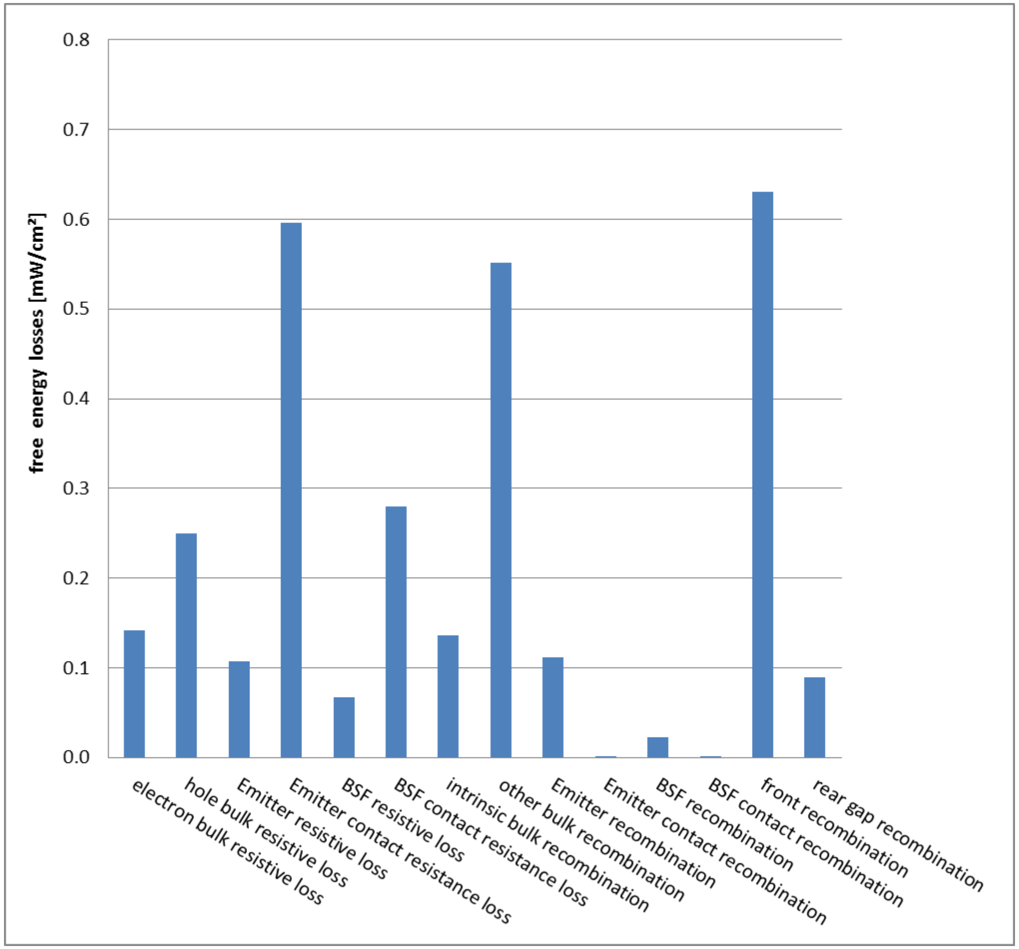
η [%]	24.25
V_{oc} [mV]	727
J_{sc} [mA/cm²]	41.57
FF [%]	80.23
A [cm²]	3.97*

* designated area
Independently measured at Fraunhofer CalLab

Quokka simulation

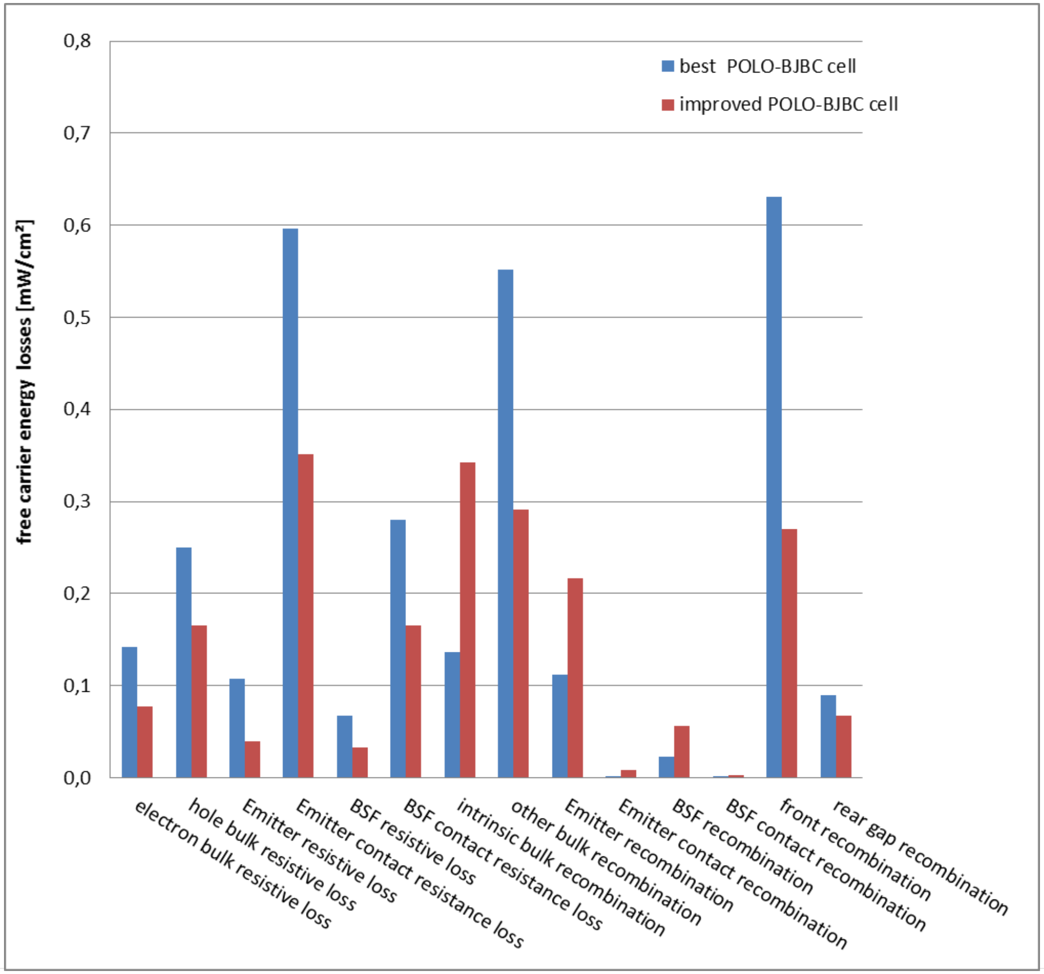
η [%]	24.4
V_{oc} [mV]	731
J_{sc} [mA/cm²]	41.7
FF [%]	80.0

2. BJBC solar cell with carrier selective junctions: Best cell Quokka simulation - FELA analysis



→ contact recombinations are strongly reduced by the POLO junctions

2. BJBC solar cell with carrier selective junctions: Best cell Quokka simulation - FELA analysis



→ Further improvements
$J_{0,front}$ 10 → 2 fA/cm^2
τ_{bulk} 6 → 20 ms
optimized emitter contacts
yield a cell efficiency of 26%

Conclusions

1. For BJBC solar cells with conventional junctions, we developed a photolithography-free process based on ion implantation and laser technology.

   → Best independently confirmed cell efficiency: 23.7 %

2. We developed the POLO-BJBC solar cell with carrier selective junctions for both polarities.

   → Best independently confirmed cell efficiency: 24.25 %

3. Further developments of this cell can lead to cell efficiencies > 26 %

We thank

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- David Sylla, Tobias Neubert, Frank Heinemeyer, Jan Hensen and Nadine Wehmeier (ISFH)

for their contributions to the fabrication of the solar cells.

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Thank you for your attention !