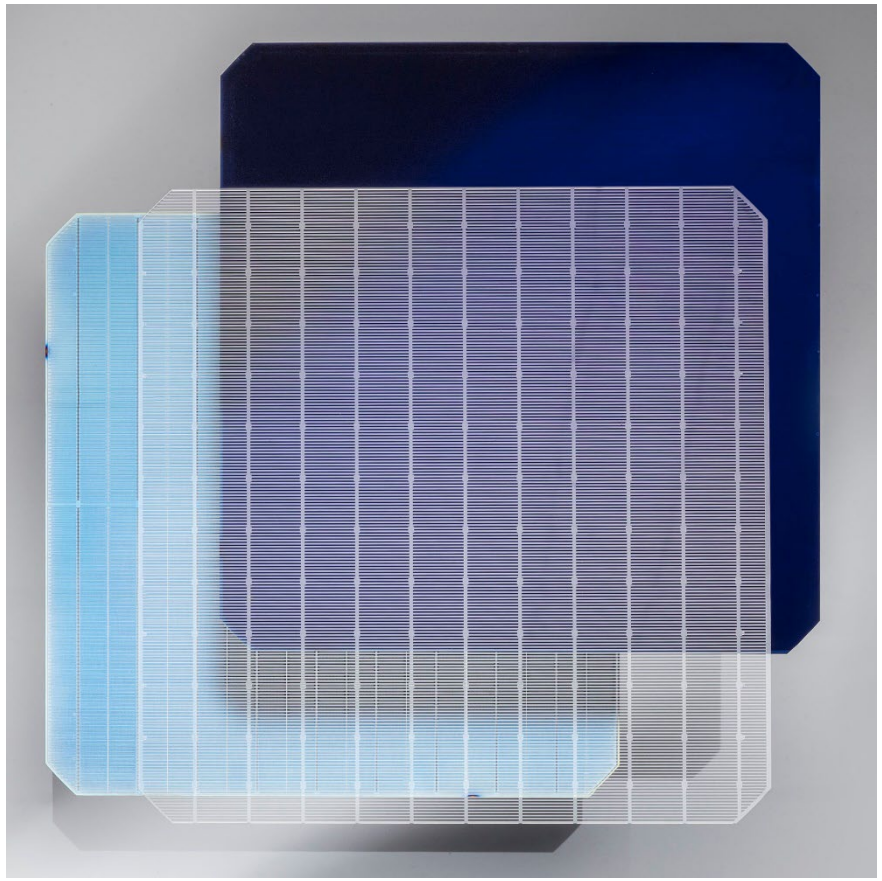


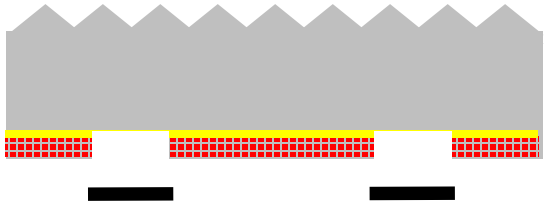
Status update on POLO IBC solar cells with glass shadow masks and perspectives beyond

T. Dullweber[1], Y. Larionova[1], P. Jäger[1], V. Mertens[1], R. Brendel[1,2], A. K. Dahle[3], Ö. Coskun[4], N. Töre Sen[4], E. Hoffmann[5], G. Gregory[5], M. Centazzo[5]

[1]Institute for Solar Energy Research Hamelin (ISFH), Germany
[2]Leibniz Universität Hannover, Germany
[3]NorSun AS, Norway
[4]Kalyon PV, Türkiye
[5]EnPV, Germany

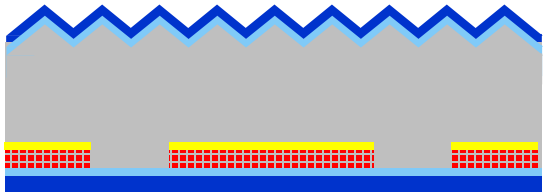
POLO IBC process flow with shadow mask

Texture &
rear polish

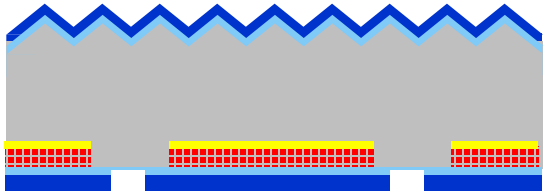


PECVD
SiO_xN_y/n-a-Si
w/ shadow mask

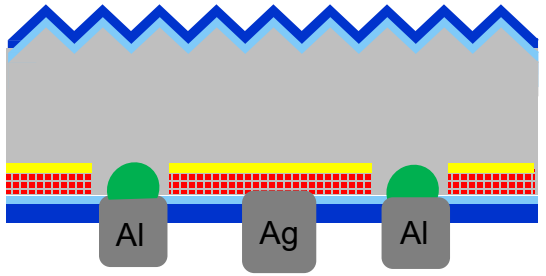
& Anneal



AlO_x/SiN
both sides



Laser contact opening



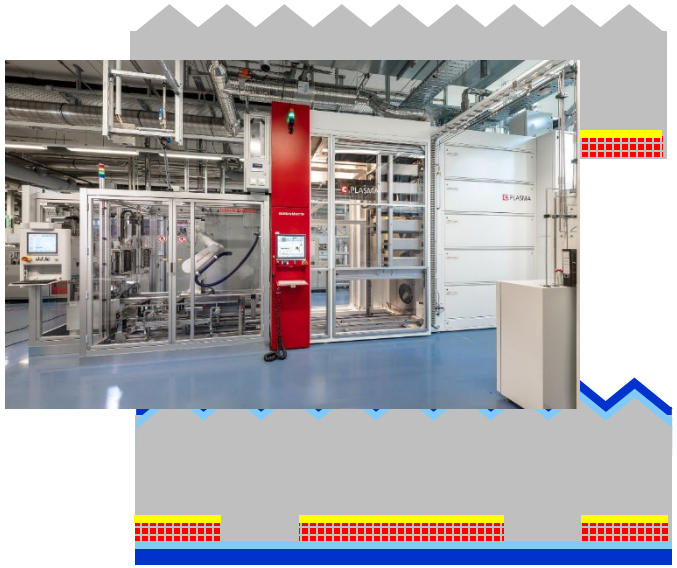
Ag and Al screen print
& firing

- Very lean POLO IBC process flow by ISFH[1,2]

[1] T. Dullweber et al., 8th WCPEC (2022), p. 35 - 39
[2] V. Mertens et al., 40th EUPVSEC (2023), p. 020015

POLO IBC process flow with shadow mask

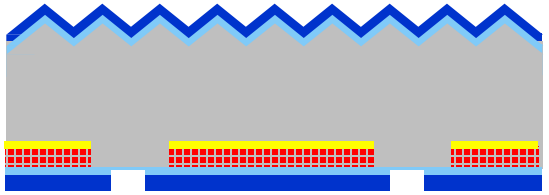
Texture &
rear polish



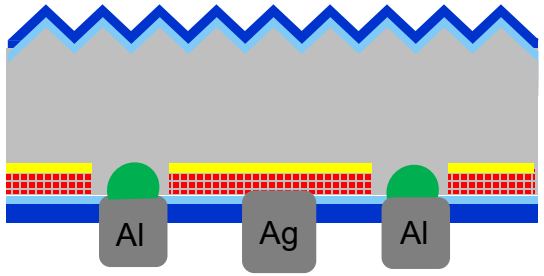
PECVD
SiO_xN_y/n-a-Si
w/ shadow mask

& Anneal

AlO_x/SiN
both sides



Laser contact opening



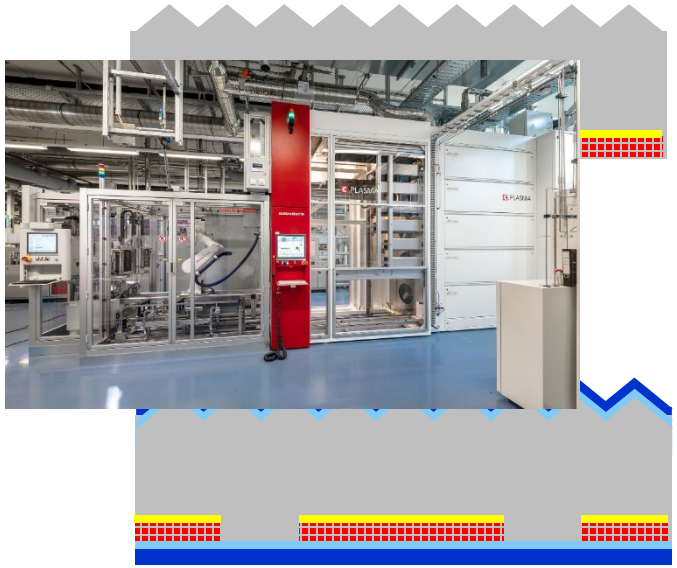
Ag and Al screen print
& firing

- Very lean POLO IBC process flow by ISFH[1,2]

[1] T. Dullweber et al., 8th WCPEC (2022), p. 35 - 39
[2] V. Mertens et al., 40th EUPVSEC (2023), p. 020015

POLO IBC process flow with shadow mask

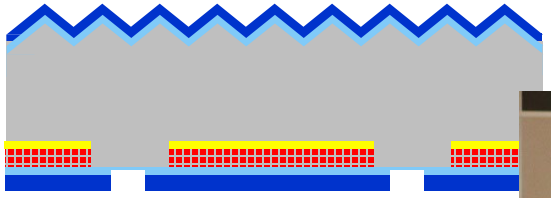
Texture &
rear polish

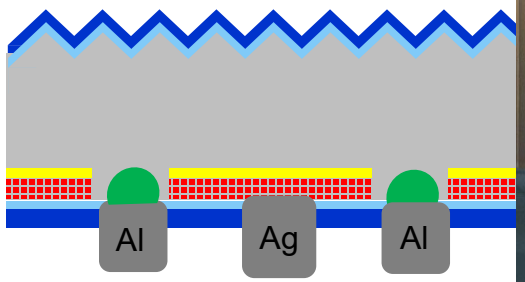


PECVD
SiO_xN_y/n-a-Si
w/ shadow mask

& Anneal

AlO_x/SiN
both sides





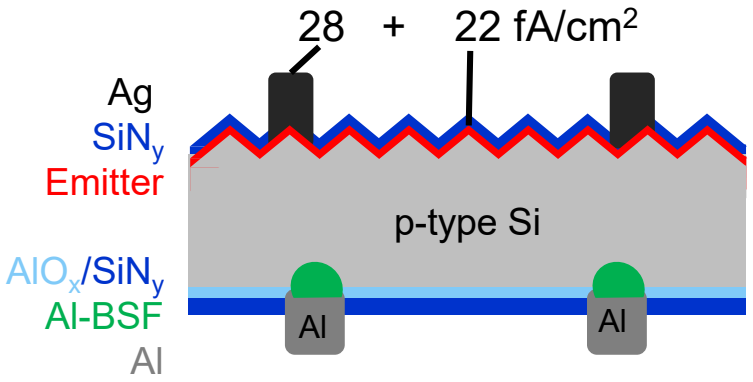
Laser contact opening

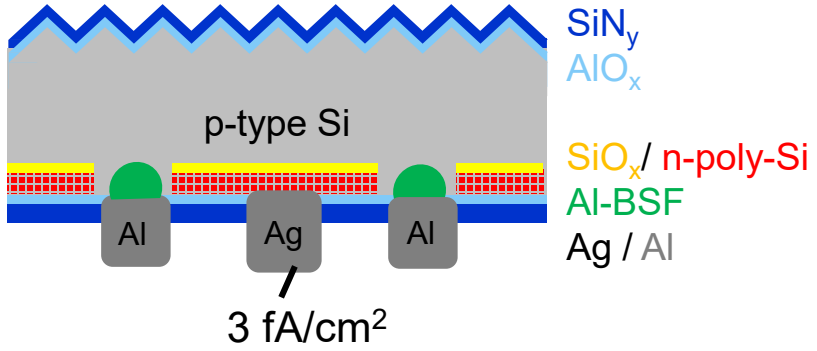
- Very lean POLO IBC process flow by ISFH[1,2]
- Technology cooperation started with Kalyon PV

[1] T. Dullweber et al., 8th WCPEC (2022), p. 35 - 39
[2] V. Mertens et al., 40th EUPVSEC (2023), p. 020015

Leibniz Universität Hannover

PERC+ vs. POLO IBC





V_{oc} = 697 / 690 mV
simulated / measured @ ISFH

733 / 716 mV
simulated / measured @ ISFH

η = 23.7 / 23.4%
simulated / measured @ ISFH

25.5 / 23.9%
simulated / measured @ ISFH

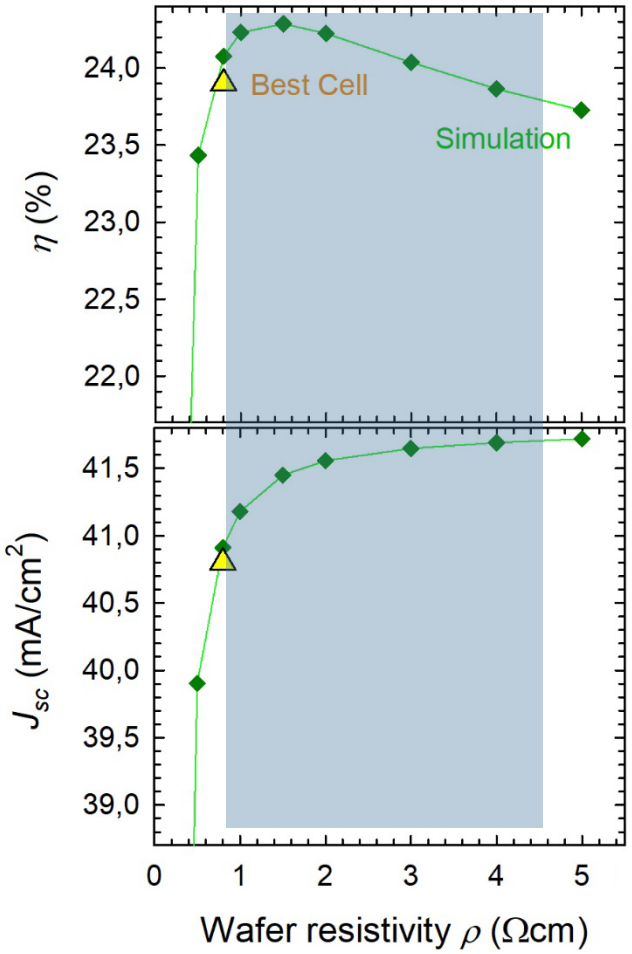
Ga wafer resistivity ρ = 0.4 – 0.8 Ω cm

?

C. N. Kruse et al, Scientific Reports **11** (2021) 996
T. Dullweber et al., SOLMAT **212** (2020) 110586

C. N. Kruse et al, Scientific Reports **11** (2021) 996

POLO IBC Quokka 3 simulations

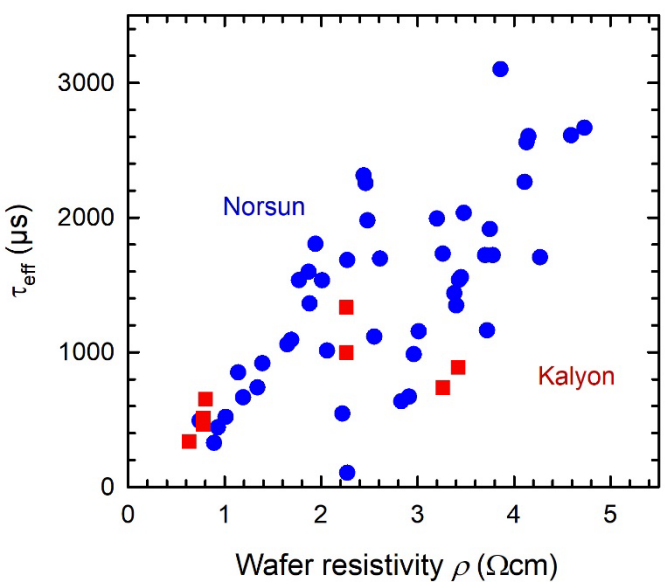


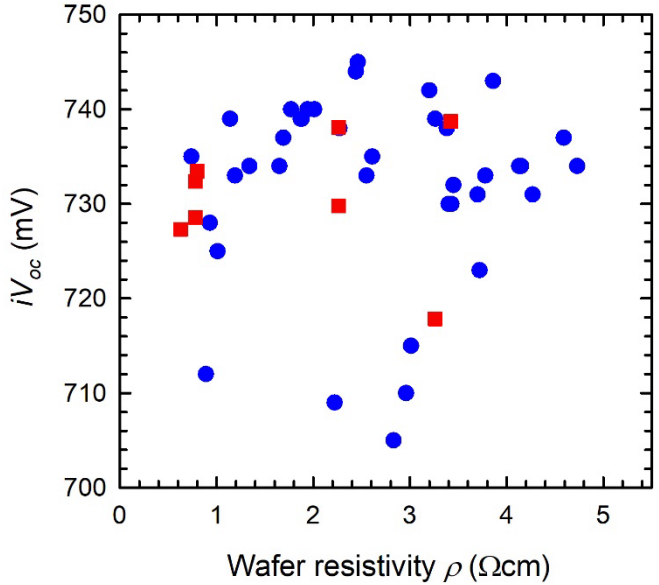
Cz Ingot at Kalyon PV

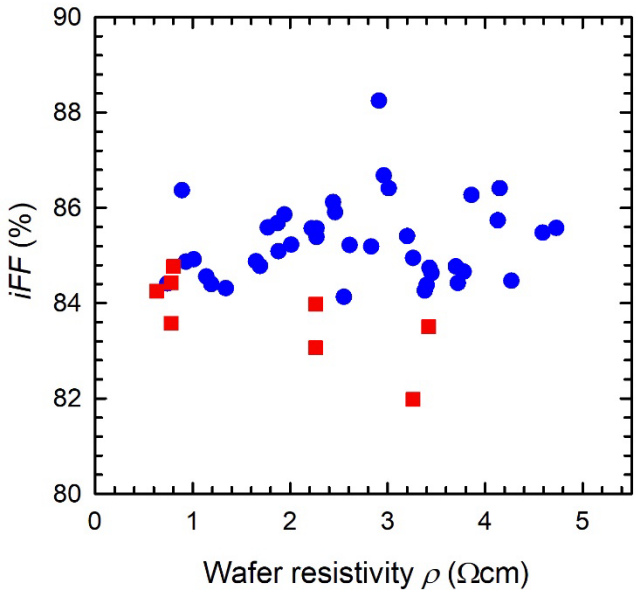
- Reference: 23.9% POLO IBC cell with 0.8 Ω cm Ga wafer measured at ISFH
- Quokka 3:
  - POLO IBC input parameters from [1]
  - τ_{bulk} vs. ρ assumes B-doped wafers after regeneration[2,3]
- Best POLO IBC efficiencies above 24% for wafer resistivity around 1.5 Ω cm
- Norsun and Kalyon did grow Ga ingots with 0.7 – 4.8 Ω cm

[1] V. Mertens et al., Sol. RRL 8 (2024) 23009196]
[2] D. C. Walter et al., Progr. Photovolt. Res. Appl. 24 (2016)
[3] N. E. Grant et al., Sol. RRL 5 (2021) 2000754

POLO IBC lifetime precursors



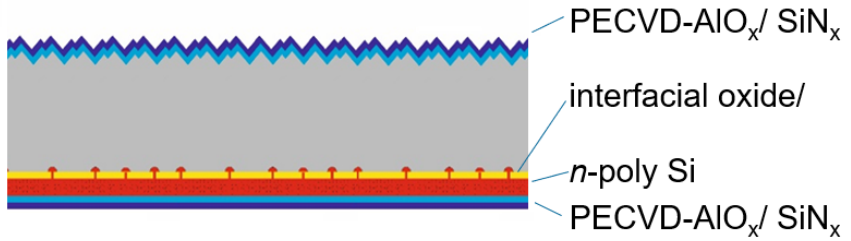




- τ_{eff} increases linearly with ρ up to 3.0 ms
- Implied efficiency $i\eta = iV_{oc} \times iFF \times J_{sc}$

  = 740 mV × 86% × 42 mA/cm²

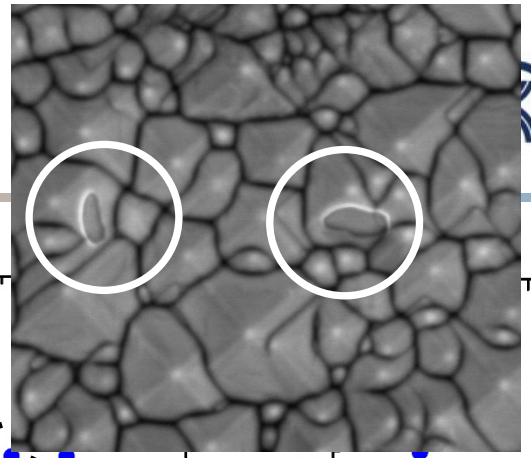
  = 26.7%

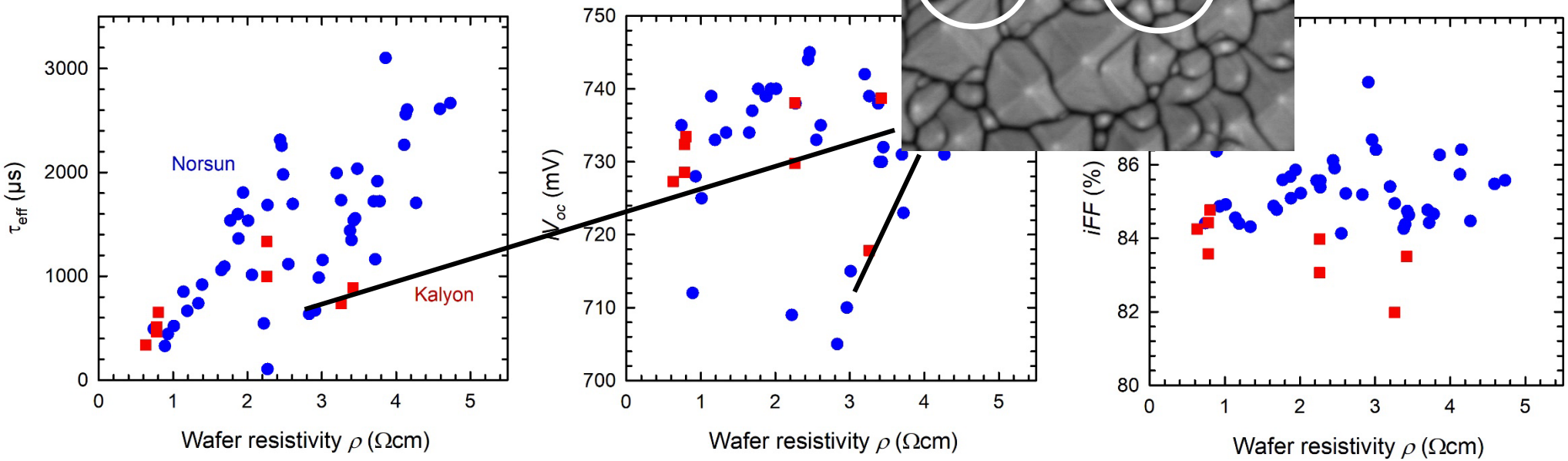


➡ Ga Cz wafers and industrial surface passivation support 25.5% POLO IBC potential

T. Dullweber et al., 41st EUPVSEC (2024), p. 020008

POLO IBC lifetime precursors

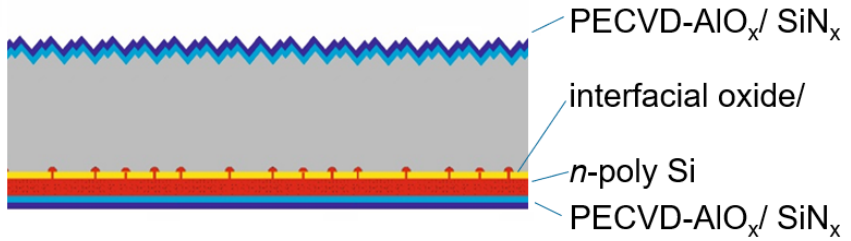




- τ_{eff} increases linearly with ρ up to 3.0 ms
- Implied efficiency $i\eta = iV_{oc} \times iFF \times J_{sc}$

  $= 740\ \text{mV} \times 86\% \times 42\ \text{mA/cm}^2$

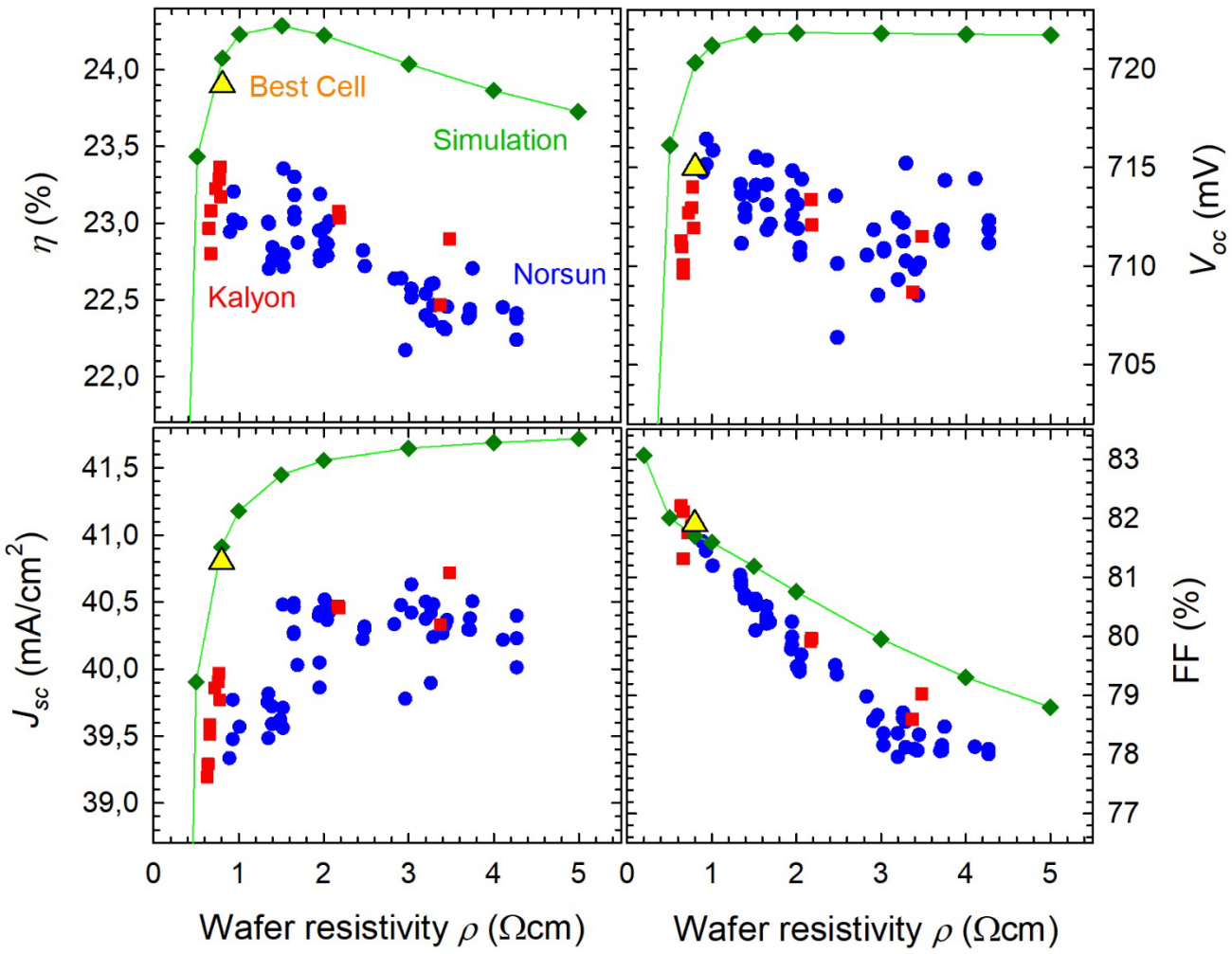
  $= 26.7\%$

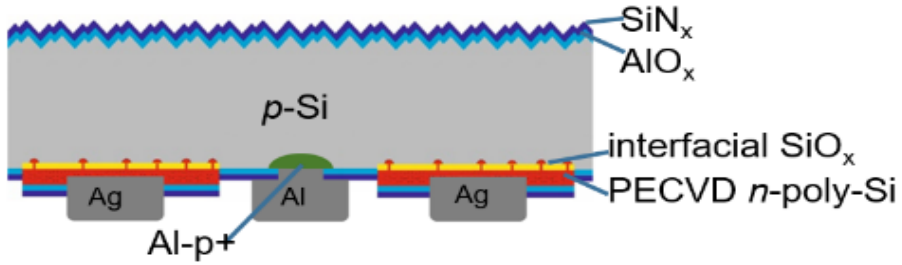


➡ Ga Cz wafers and industrial surface passivation support 25.5% POLO IBC potential

T. Dullweber et al., 41st EUPVSEC (2024), p. 020008

POLO IBC solar cell results



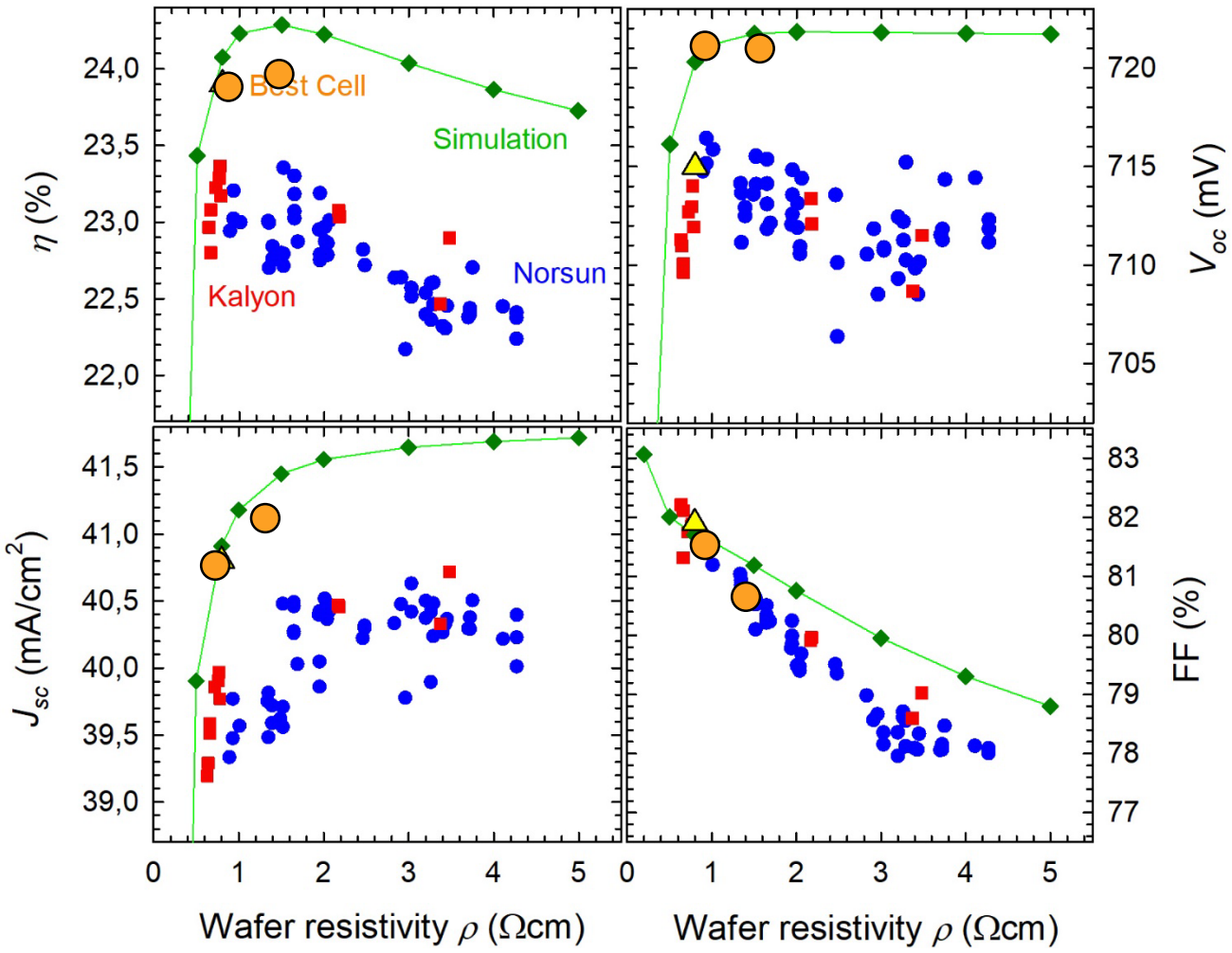


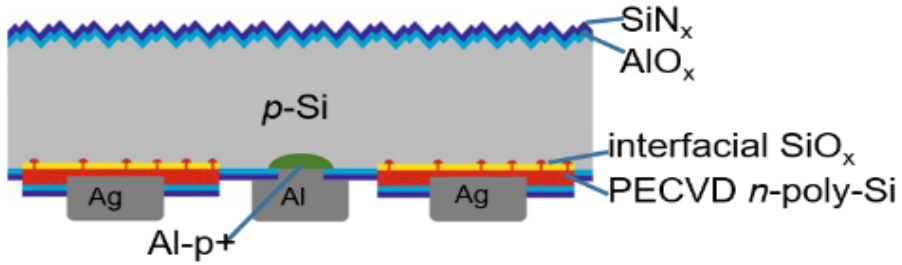
- J_{sc} and *FF* trends similar to Quokka 3 simulation
- Best POLO IBC efficiencies for

  1 Ωcm < ρ < 2 Ωcm
- η gap to best cell and simulations due to much lower J_{sc}. AlO_x/SiN blistering alloys Al „ghost“ contacts ?

T. Dullweber et al., 41st EUPVSEC (2024), p. 020008

POLO IBC solar cell results



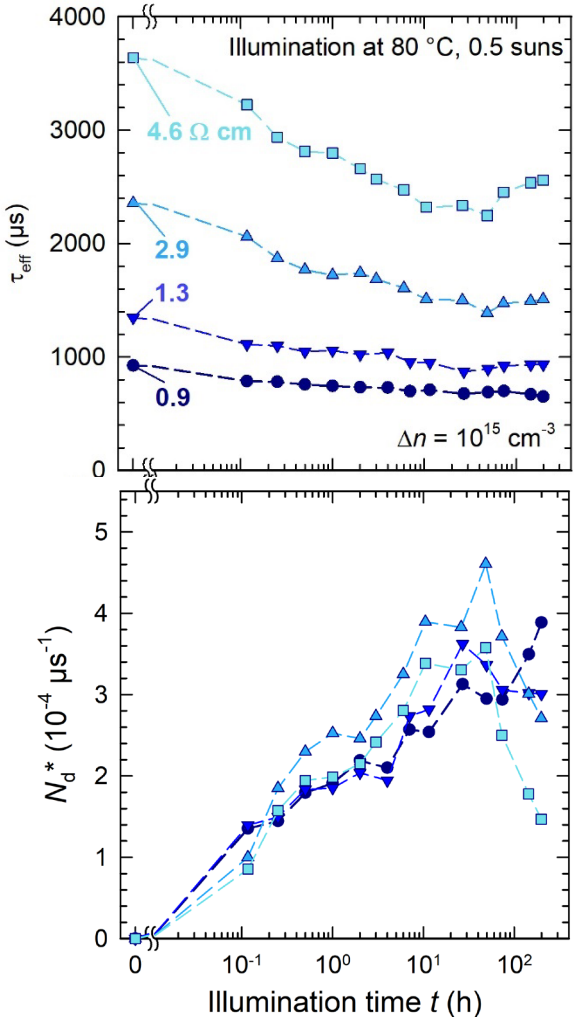


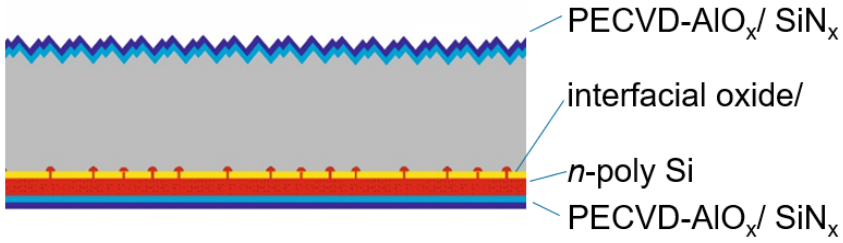
- J_{sc} and *FF* trends similar to Quokka 3 simulation
- Best POLO IBC efficiencies for

  1 Ωcm < ρ < 2 Ωcm
- η gap to best cell and simulations due to much lower J_{sc}. AlO_x/SiN blistering alloys Al „ghost“ contacts ?

T. Dullweber et al., 41st EUPVSEC (2024), p. 020008

LeTID at 80 °C, 0.5 suns with POLO IBC test wafers and cells





- Effective LeTID defect concentration calculated as

$$N_{\mathrm{d}}^{*}(t) = \frac{1}{\tau_{\mathrm{d}}(t)} - \frac{1}{\tau_{0}}$$

- N_d does not dependent on Ga doping concentration
- Confirms hypothesis of recent publication[1] now with more statistics [2]
- LeTID of POLO IBC cells relatively small (<4% relative) [2]
- LeTID could be further reduced by lower firing cool down rate[2,3]

[1] F. Maischner et al, SOLMAT 260 (2023) 112451
[2] T. Dullweber et al., 41st EUPVSEC (2024), p. 020008

POLO IBC efficiency roadmap to 25%

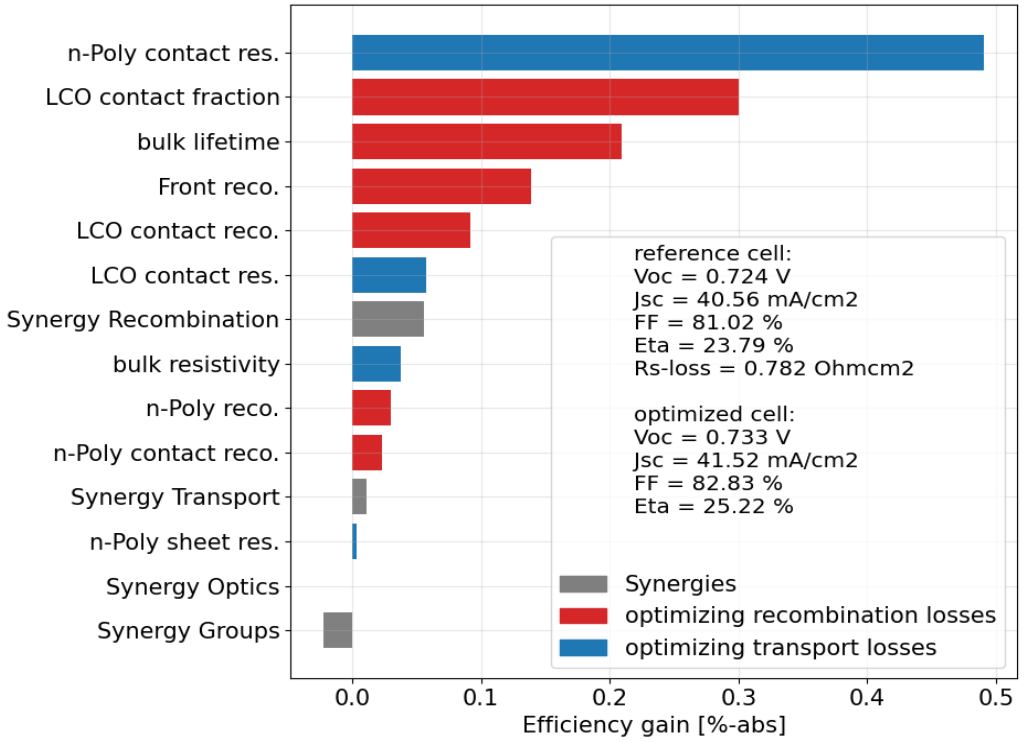
23.9%: best POLO IBC cell

+ 0.5%: reducing Ag to n-poly Rc

+ 0.3%: reducing LCO area and $J_{0,Al\text{-}BSF}$

+ 0.3%: optimized BB and Pad design

25.0% near-term efficiency potential



➡ Recombination at LCO Al-BSF contact limits POLO IBC efficiency < 25.5%

V. Mertens et al., Sol. RRL 8 (2024) 23009196

POLO² IBC efficiency potential > 26%

23.9%: best POLO IBC cell

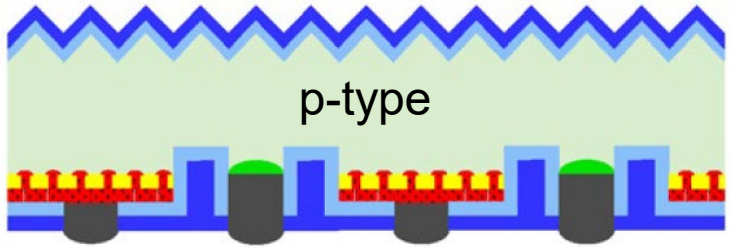
+ 0.5%: reducing Ag to n-poly Rc

+ 0.3%: reducing LCO area and $J_{0,Al\text{-}BSF}$

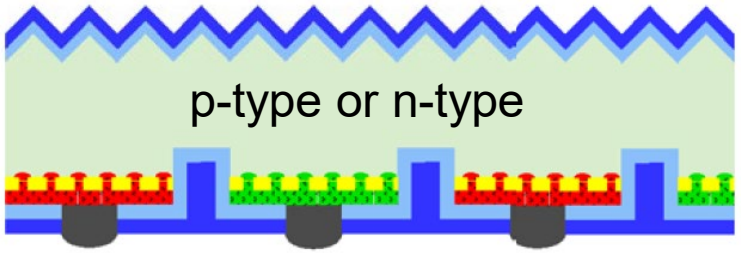
+ 0.3%: optimized BB and Pad design

25.0% near-term efficiency potential

POLO IBC



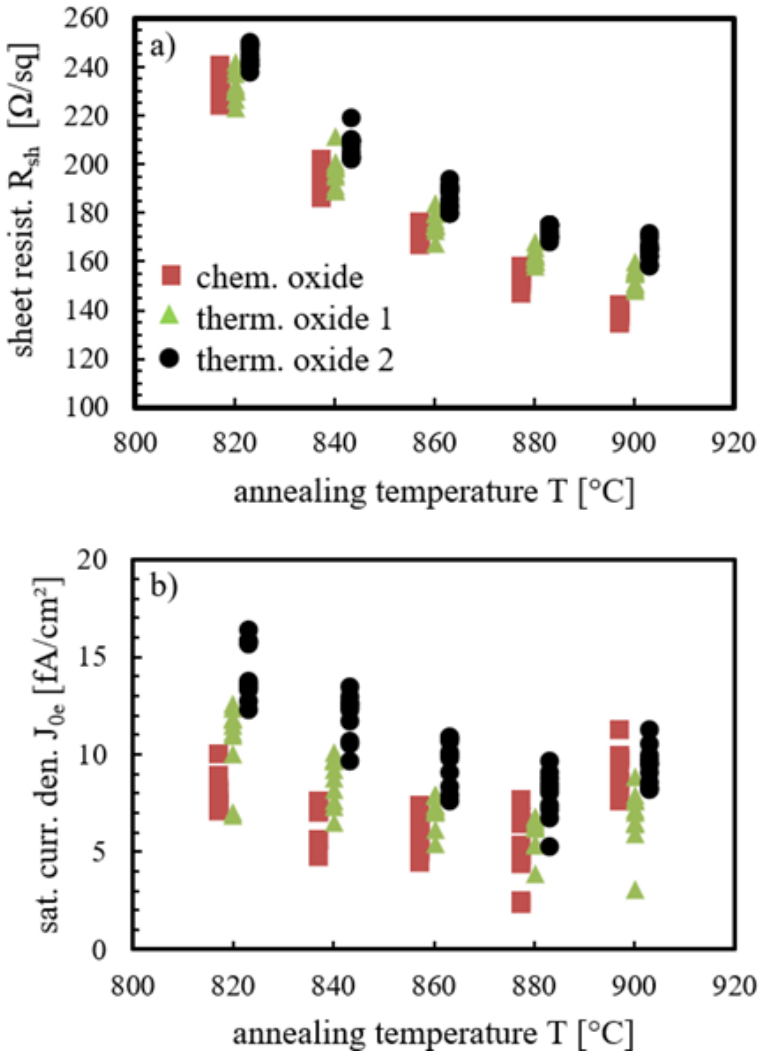
POLO² IBC



➡ Recombination at LCO Al-BSF contact limits POLO IBC efficiency < 25.5%

➡ For > 26%, Al-BSF contact to be replaced by passivating SiO_x/p-poly-Si contact => POLO² IBC

Industrial passivating SiO_x/p-poly-Si contact

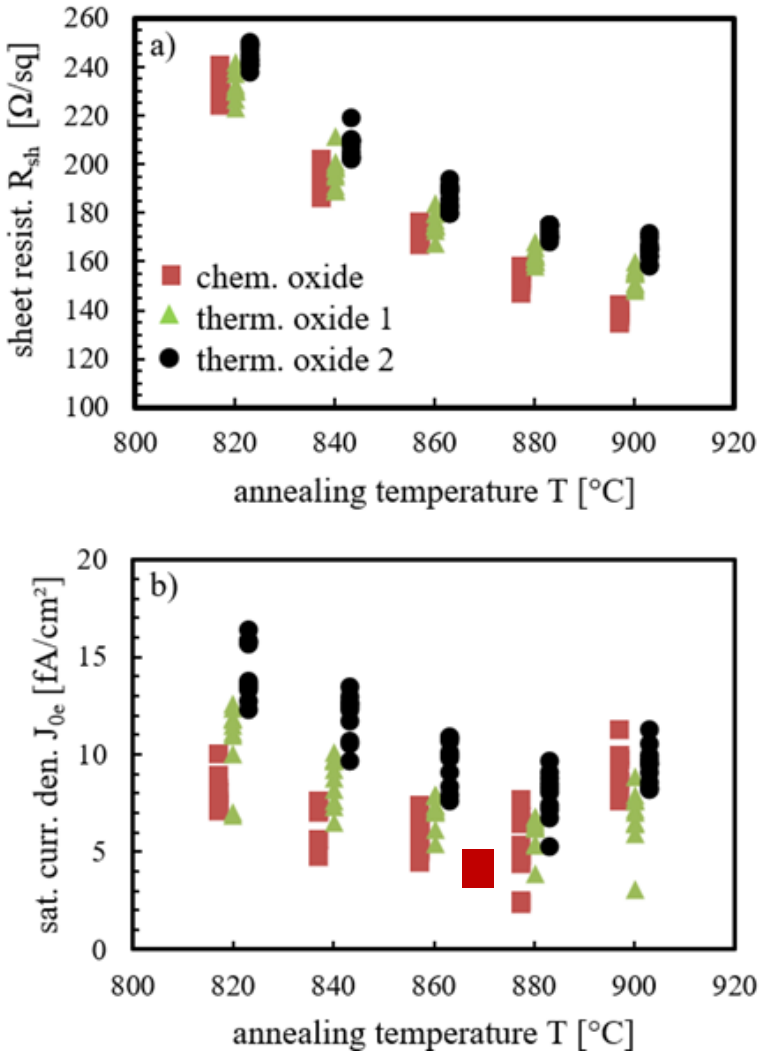


- Wet chemical oxide deposited in industrial wet bench
- In-situ boron-doped p-poly-Si deposited in industrial LPCVD tool
- Best $J_{0,p\text{-}poly}$ = 2.3 fA/cm² for R_{sheet} = 160 Ω/sq

E. Hoffmann et al., 41st EUPVSEC (2024), p. 020020

Leibniz Universität Hannover

Industrial passivating SiO_x/p-poly-Si contact



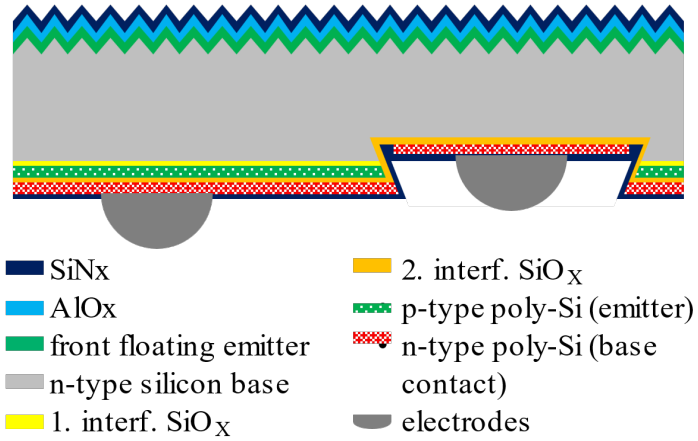
- Wet chemical oxide deposited in industrial wet bench

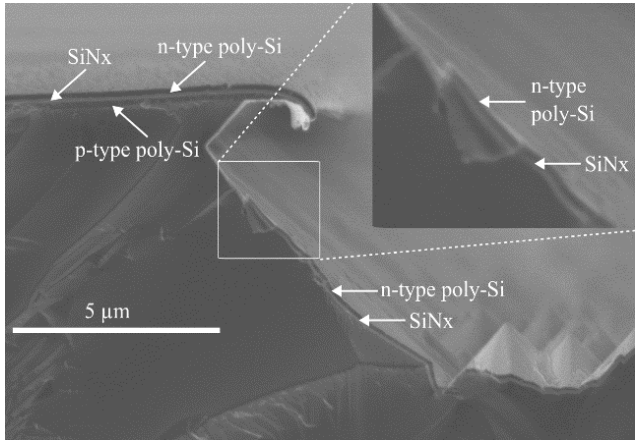
- In-situ boron-doped p-poly-Si deposited in industrial LPCVD tool

- Best $J_{0,p\text{-}poly}$ = 2.3 fA/cm² for R_{sheet} = 160 Ω/sq
- Optimized p-poly recipe with reduced spread 4 ± 0.5 fA/cm²

E. Hoffmann et al., 41st EUPVSEC (2024), p. 020020

SABC cell development with EnPV

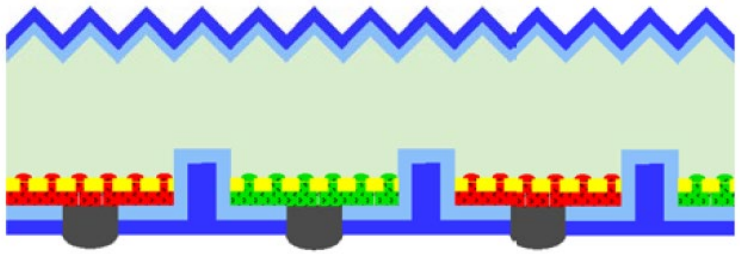




- Novel **S**elf **A**ligned I**BC** cell design „SABC“ by EnPV jointly developed at ISFH
- SiO_x/p-poly-Si deposition see previous slide
- SABC design utilizes undercut from chemical etching to separate sputtered n-poly layer polarities
- First SABC cell protoype obtains 20.2% efficiency which is subject to continuous improvement
- EnPV targets SABC commercialization with industrial partners

E. Hoffmann et al., 41st EUPVSEC (2024), p. 020020

Industrial POLO^2 IBC solar cell development at ISFH



- In 2018, ISFH developed a 26.1% lab-type POLO^2 IBC cell with poly-Si layer doping by ion implantation[1]
- Now, ISFH starts to develop an industrial POLO^2 IBC process flow including
  - Full-area SiO_x/p-poly-Si deposition, see previous slide
  - Full-area SiO_x/n-poly-Si deposition (LPCVD or PECVD)
  - Laser-structuring and etching of both poly-Si layers
  - Patent pending
- First test structure and IBC cell results very promising
- Industry partners are welcome to join us !

[1]F. Haase et al., Sol. Energy Mat. Sol. Cells 186 (2018),pp. 184–193

ISFH SolarTeC: Replacing old M2 wafer size tools with new state-of-the-art M10 tools

- Funding provided by
  State of Lower Saxony and
  Federal Ministry of Economics

Status 2024: Up to 15 years old tools for M2

- Inline and Batch Wet Chemistry from 2011, M2
- Diffusion Furnace from 2010, M2
- LPCVD Furnace from 2015, M2
- PECVD from 2022, M2 – G12
- Screen Printing from 2016, M2

Throughput ca. 100 Wafer / h

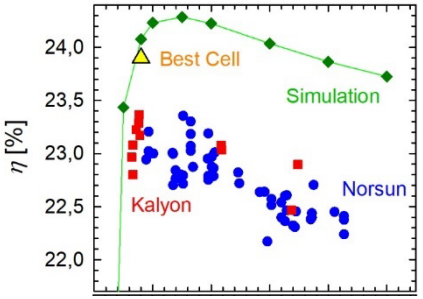
Rebuilding till 2026: New tools for ≥ M10 wafer size

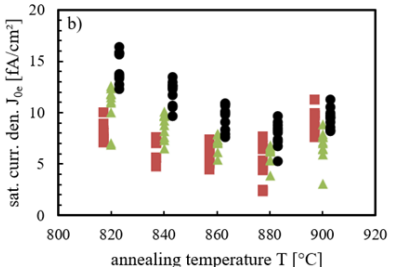
- Inline and Batch Wet Chemistry: New, ≥ M10
- Diffusion Furnace : New, ≥ M10
- LPCVD Furnace: New, ≥ M10
- PECVD : New Graphite boats, ≥ M10
- Screen Printing : New, ≥ M10

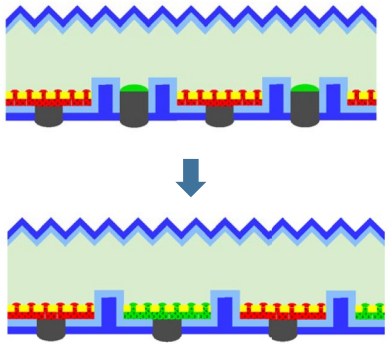
Throughput ≥ 300 Wafer / h

Summary

- Calculated POLO IBC implied efficiency $i\eta = iV_{oc} \times iFF \times J_{sc}$ = 26.7%
- Best POLO IBC efficiencies for 1.0 Ωcm < ρ < 2.0 Ωcm
- Best POLO IBC cell presently with 23.9%. 25% efficient POLO IBC cells targeted by optimizing Ag and Al metallization
- Maximum LeTID of POLO IBC cells < 4%rel. LeTID N_d does not depend on Ga doping concentration
- In-situ doped LPCVD p-poly passivating contact with $J_{0,p\text{-}poly}$ = 2.3 fA/cm²
- Two different industrial POLO² IBC cell designs in development at ISFH
- From 2026, POLO² IBC cells on M10 wafer size at ISFH SolarTeC







Acknowledgements

- Funding was provided by the European Union of the IBC4EU project, the German Federal Ministry for Economic Affairs and Climate Action of the Olivia project, by the State of Lower Saxony and by our industry partners.

- **Thank you for your attention !**

IBC4 EU

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

State of Lower Saxony, Gemany

kalyon PV

EnPV

NorSun

centrotherm

R|E|N|A

Leibniz Universität Hannover