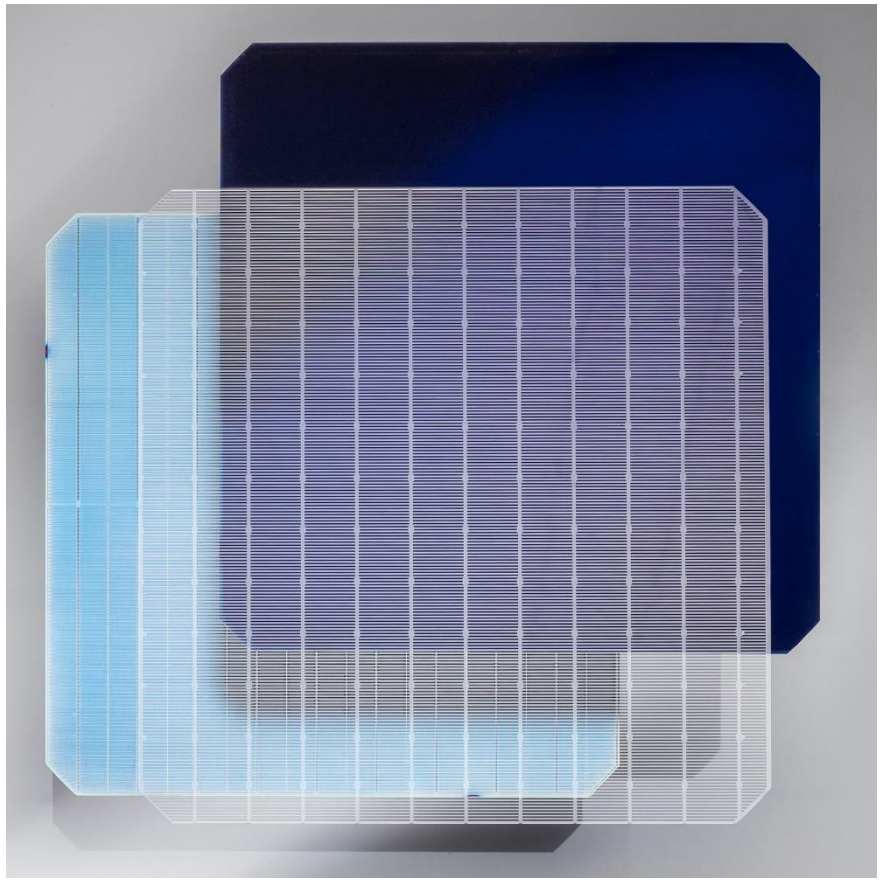


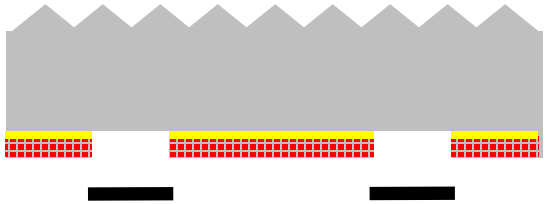
Optimized Ga-doped Cz wafers for POLO IBC solar cells with high efficiency and minimal LeTID degradation

T. Dullweber[1], V. Mertens[1], M. Winter[1], S. Schimanke[1], M. Ripke[1], S. Dorn[1], Y. Larionova[1], G. Lange[1], K. Bothe[1], J. Schmidt[1,2], R. Brendel[1,2], A. K. Dahle[3], Ö. Coskun[4], N. Töre Sen[4]

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

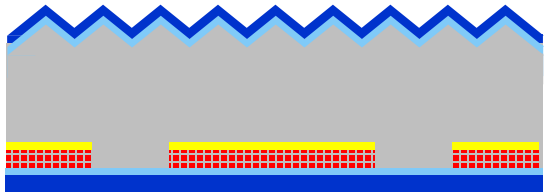
POLO IBC process flow with shadow mask

Texture &
rear polish

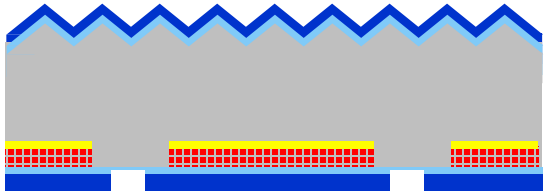


PECVD
SiO_xN_y/n-a-Si
w/ shadow mask

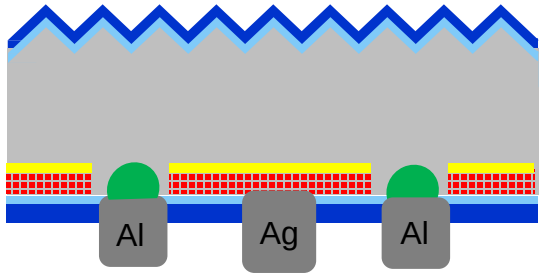
& Anneal



AlO_x/SiN
both sides



Laser contact opening



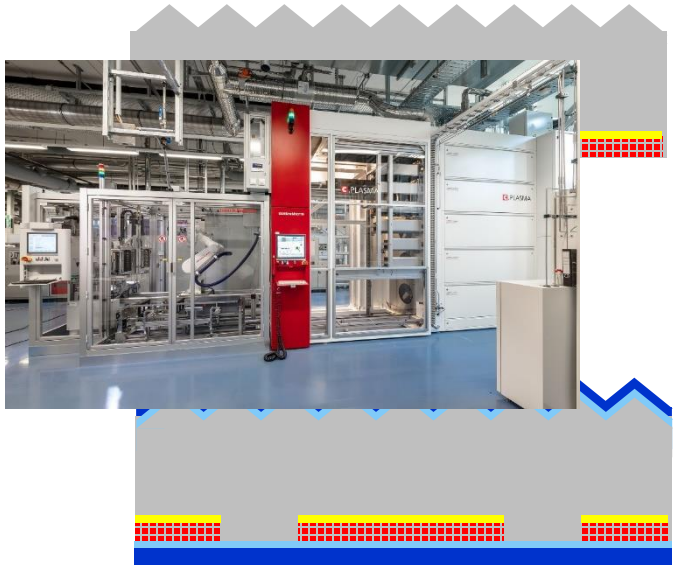
Ag and Al screen print
& firing

- 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

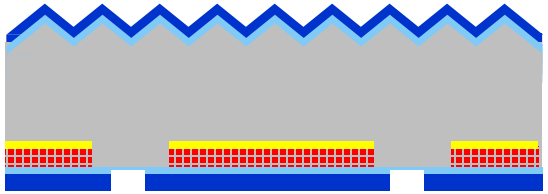
Texture &
rear polish



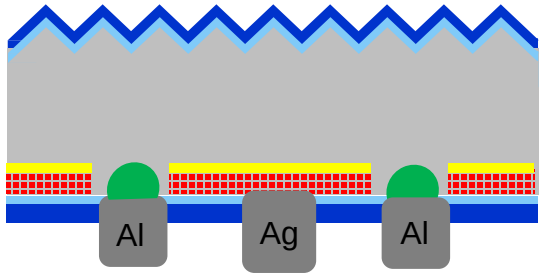
PECVD
SiO_xN_y/n-a-Si
w/ shadow mask

& Anneal

AlO_x/SiN
both sides



Laser contact opening



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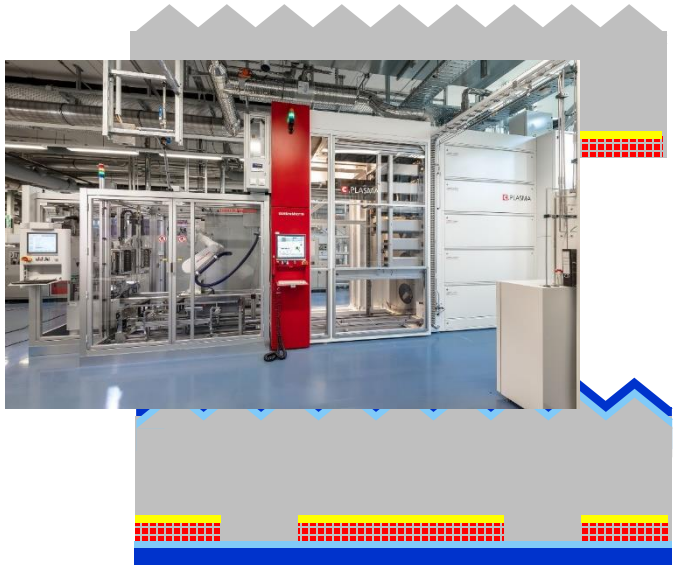
POLO IBC process flow with shadow mask

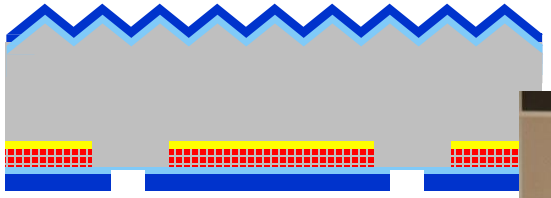
Texture &
rear polish

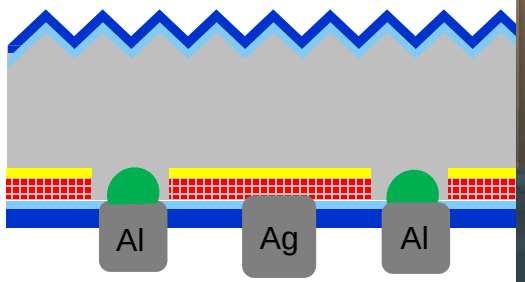


PECVD
SiO_xN_y/n-a-Si
w/ shadow mask

& Anneal

AlO_x/SiN
both sides



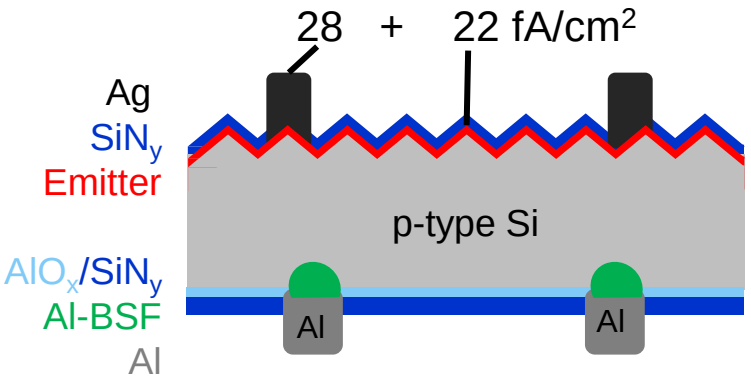


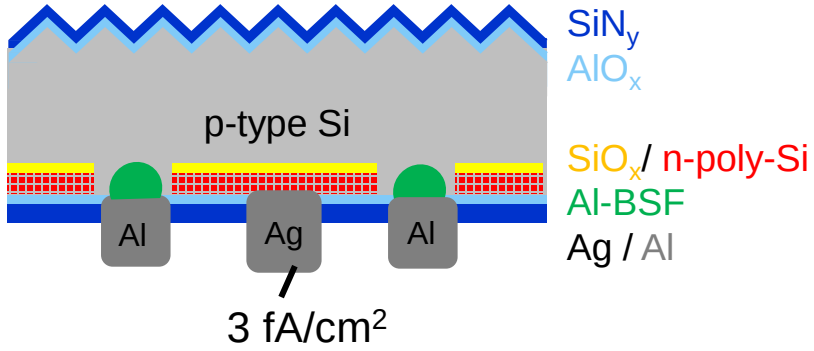
Laser contact opening

- 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

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

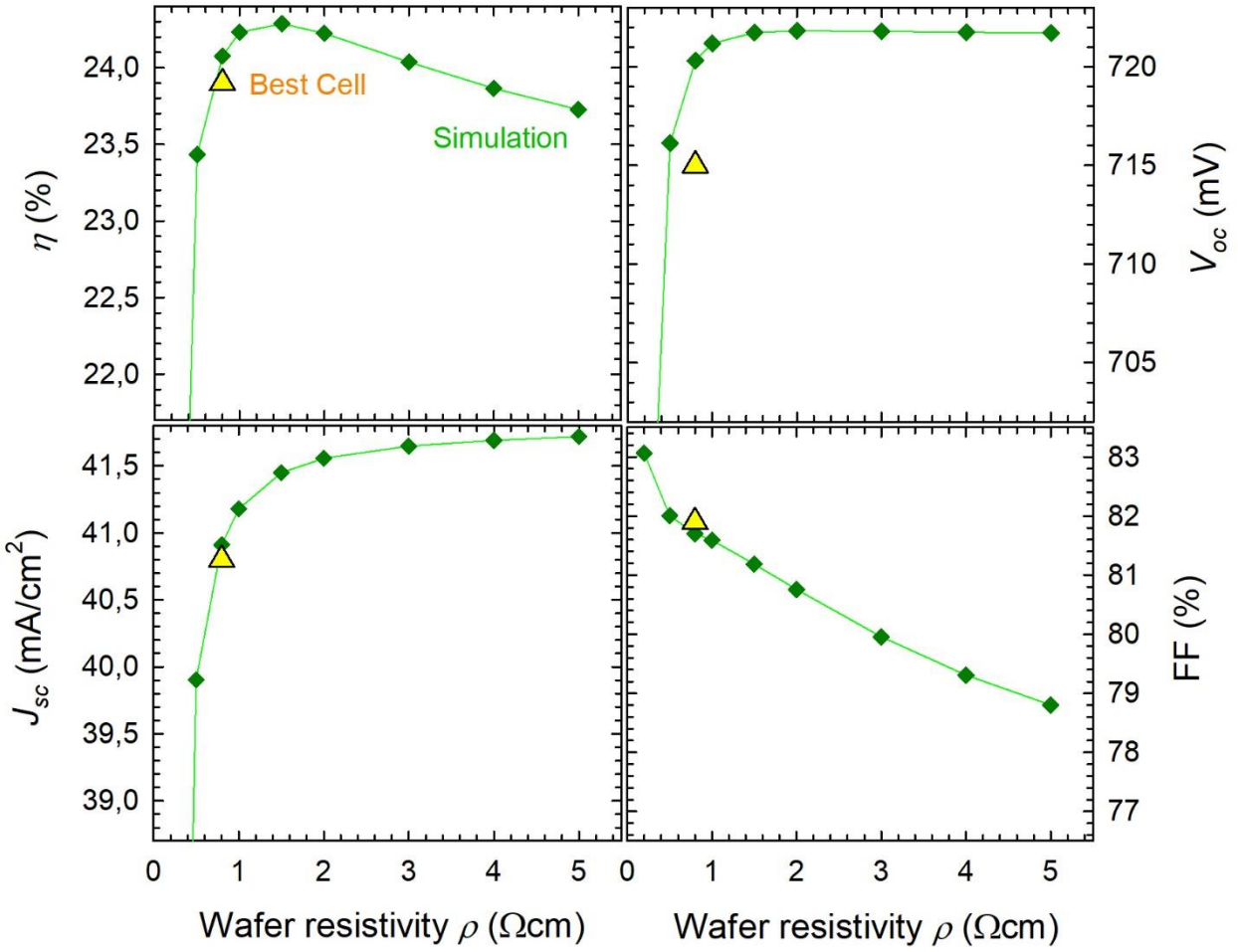
Ga wafer resistivity ρ = 0.4 – 0.8 Ω cm

?

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

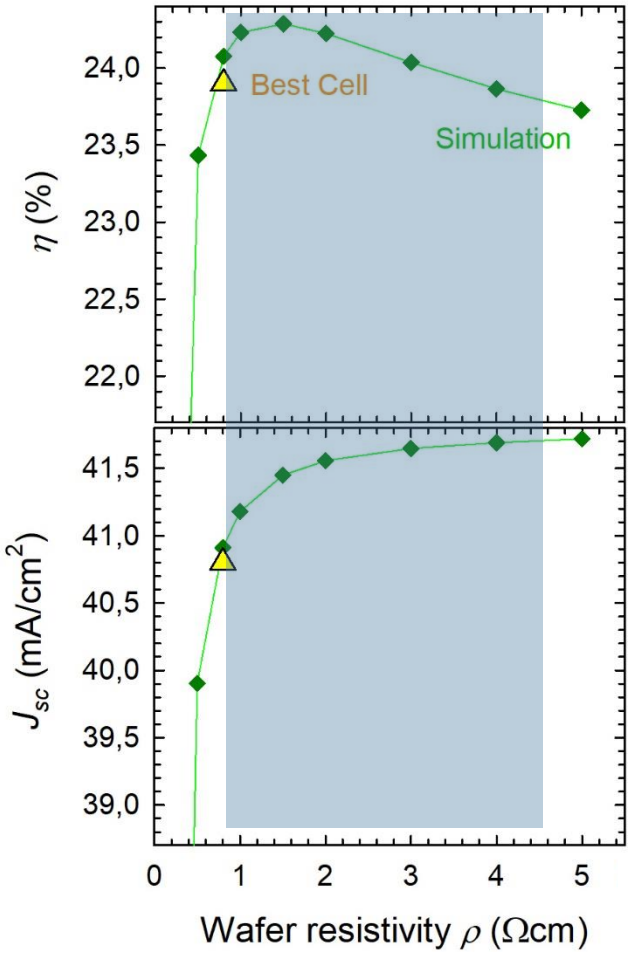
POLO IBC Quokka 3 simulations



- 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

[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 Quokka 3 simulations



Cz Ingot at Kalyon PV

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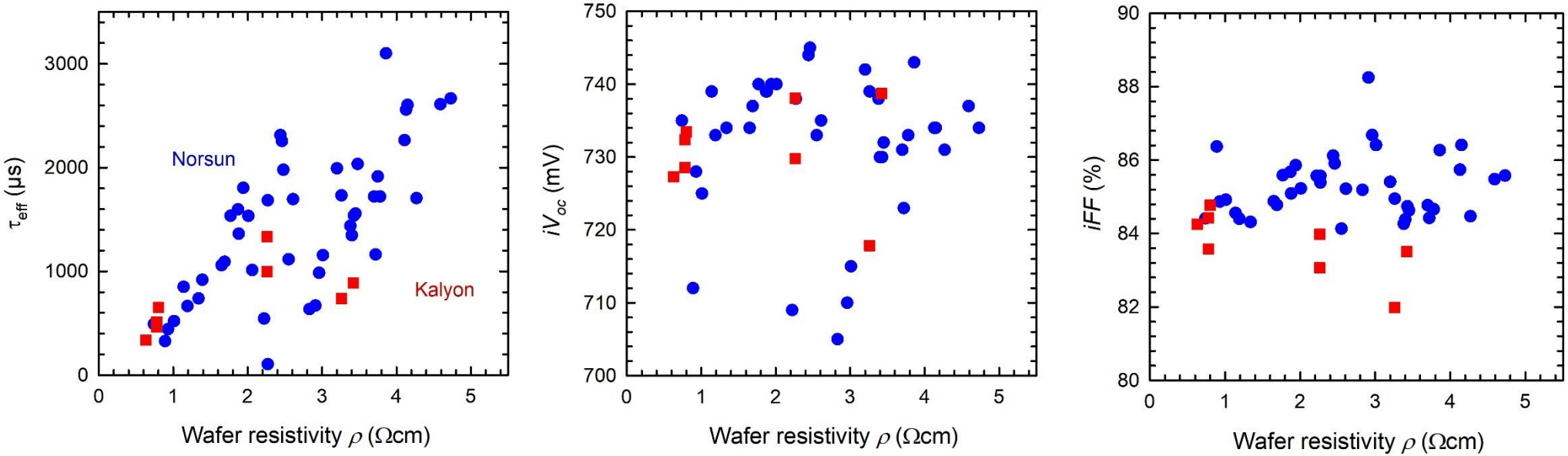
  - τ_{bulk} vs. ρ assumes B-doped wafers after regeneration[2,3]
- Best POLO IBC efficiencies above 24% for wafer resistivity around 1.5 Ω cm
- Norsun and Kalyon did grow Ga ingots with 0.7 – 4.8 Ω cm

[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

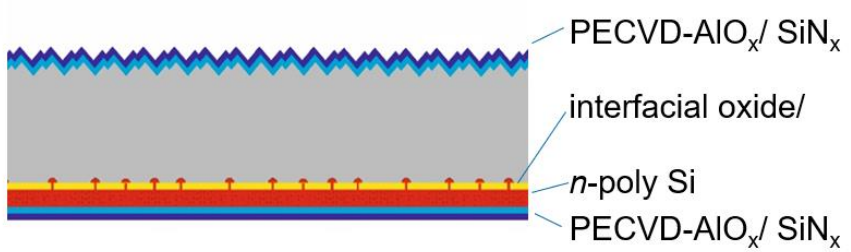
POLO IBC lifetime precursors



- τ_{eff} increases linearly with ρ up to 3.0 ms similar to [1]
- Implied efficiency $i\eta = iV_{oc} \times iFF \times J_{sc}$

  = 740 mV × 86% × 42 mA/cm²

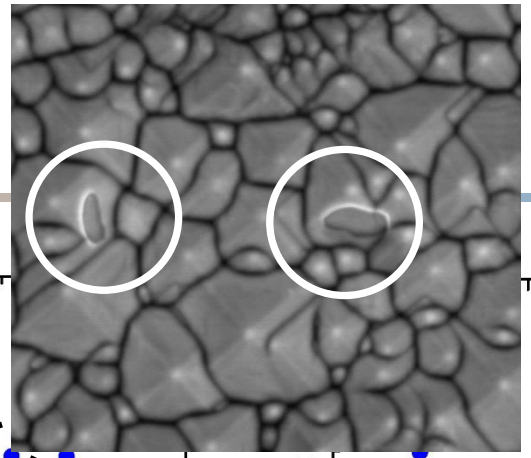
  = 26.7%

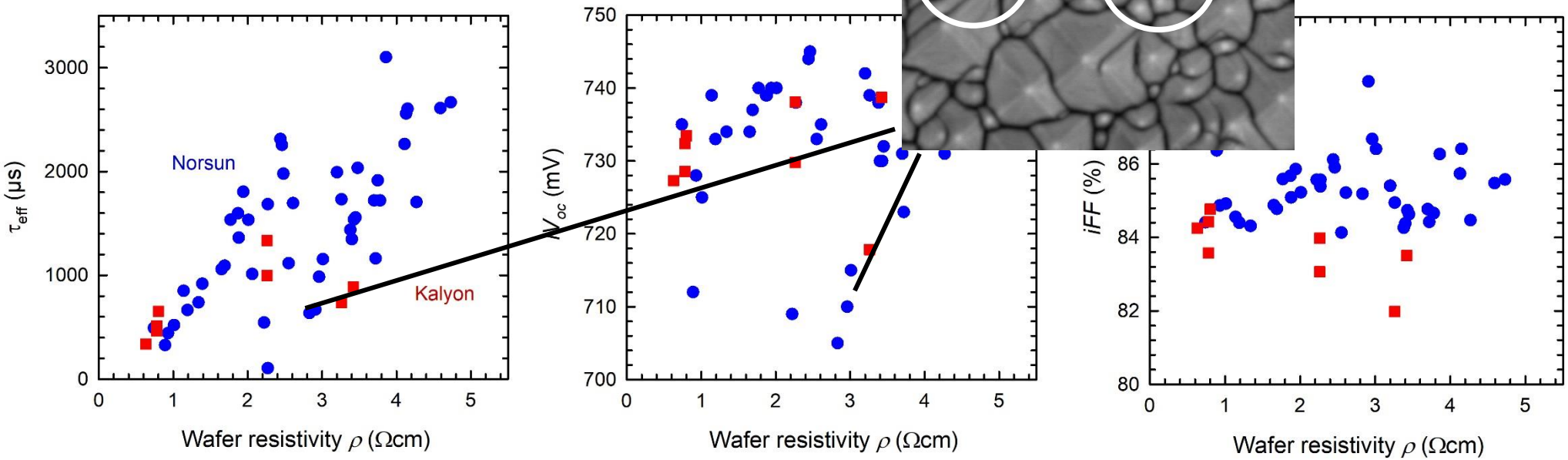


➡ Ga Cz wafers and industrial surface passivation support 25.5% POLO IBC potential

[1] N. E. Grant et al., Sol. RRL 5 (2021) 2000754

POLO IBC lifetime precursors





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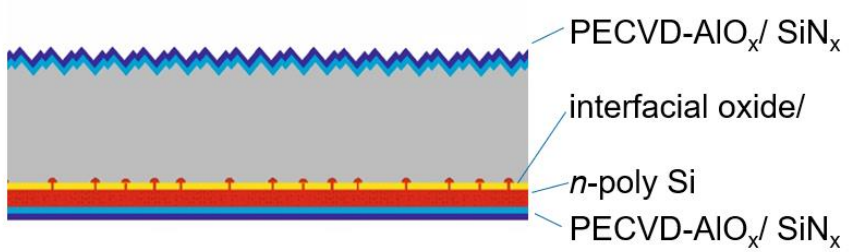

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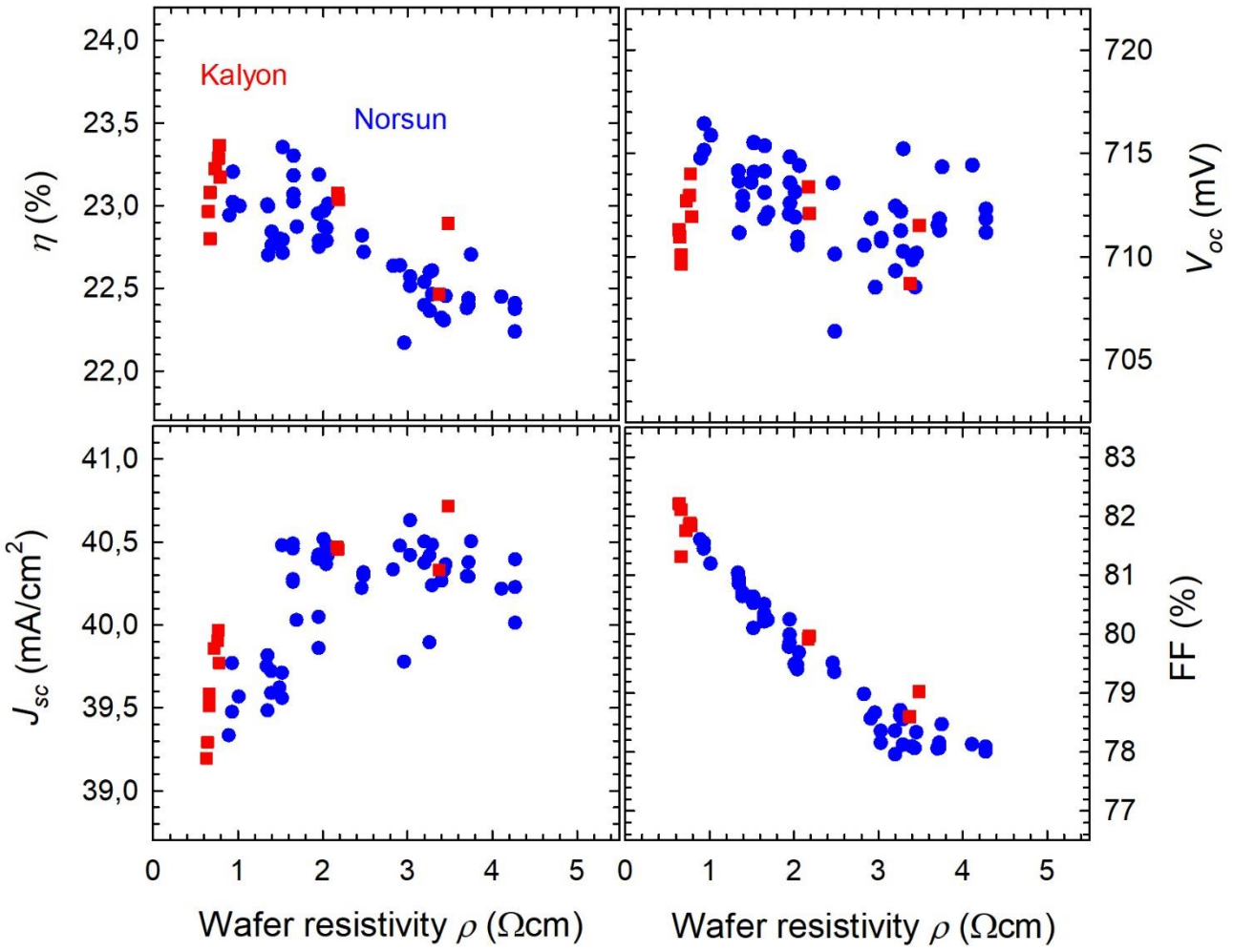
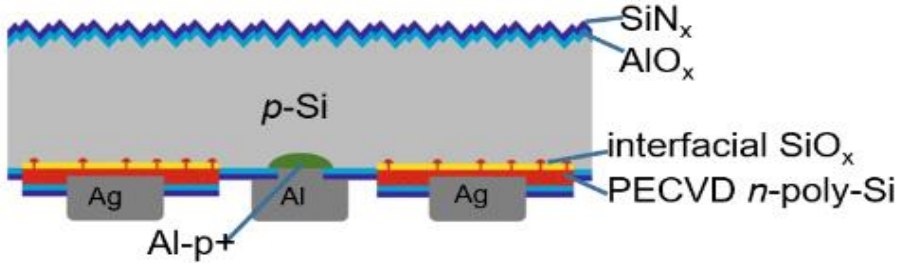
[1] N. E. Grant et al., Sol. RRL 5 (2021) 2000754

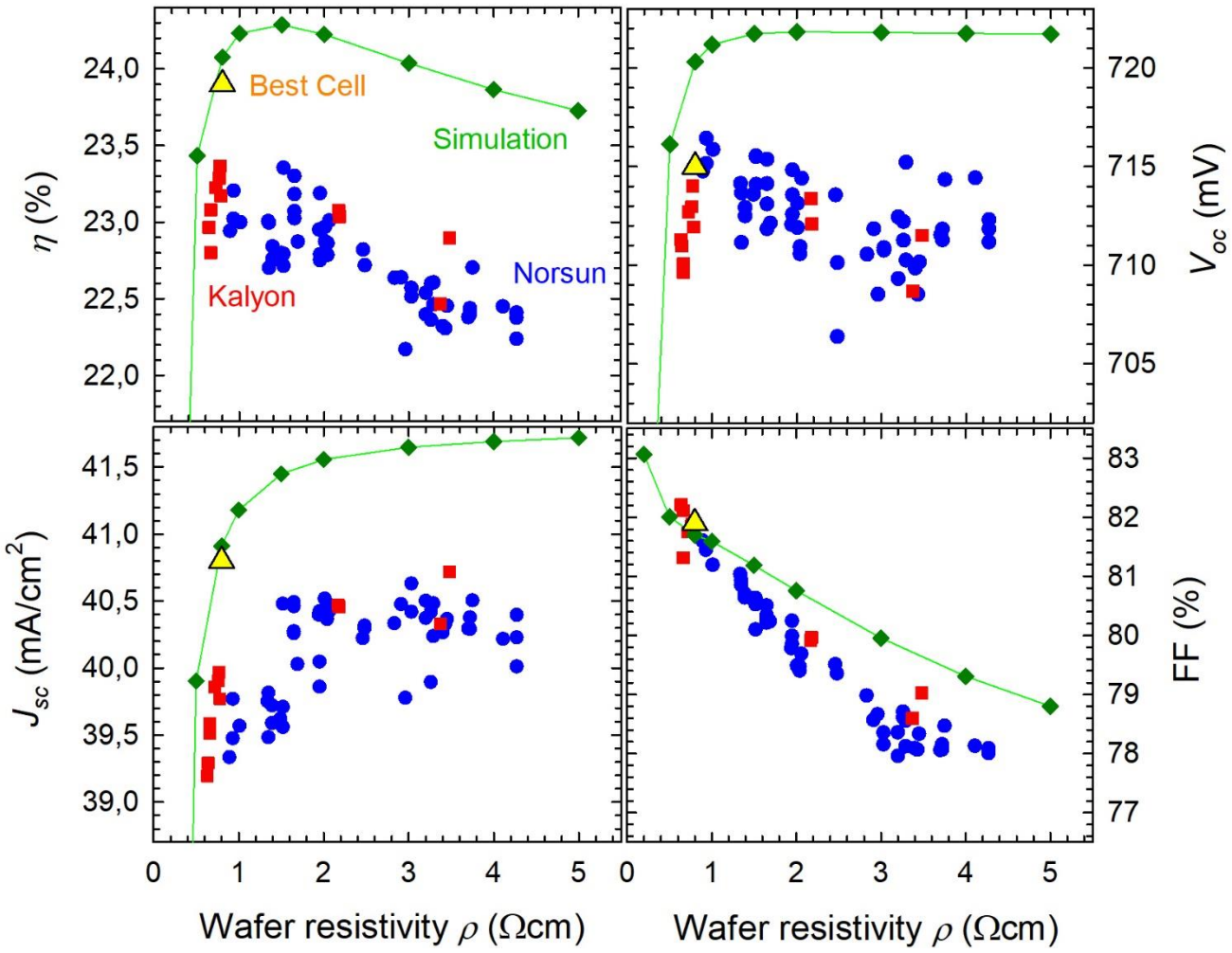
POLO IBC solar cell results

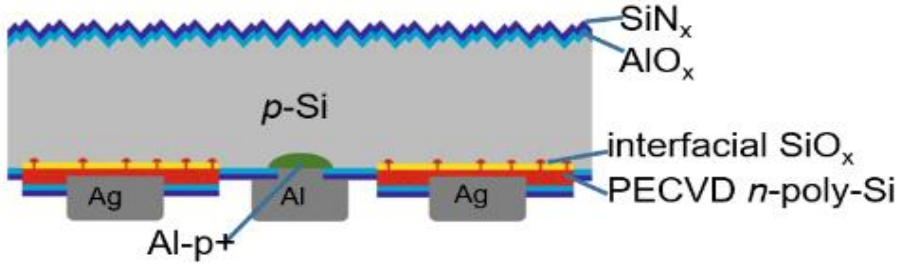




- With increasing Cz wafer resistivity
  - J_{sc} increases by 1 mA/cm²
  - *FF* decreases by 5% abs.
- Best POLO IBC efficiencies of 23.4% for 1 Ω cm < ρ < 2 Ω cm

POLO IBC solar cell results

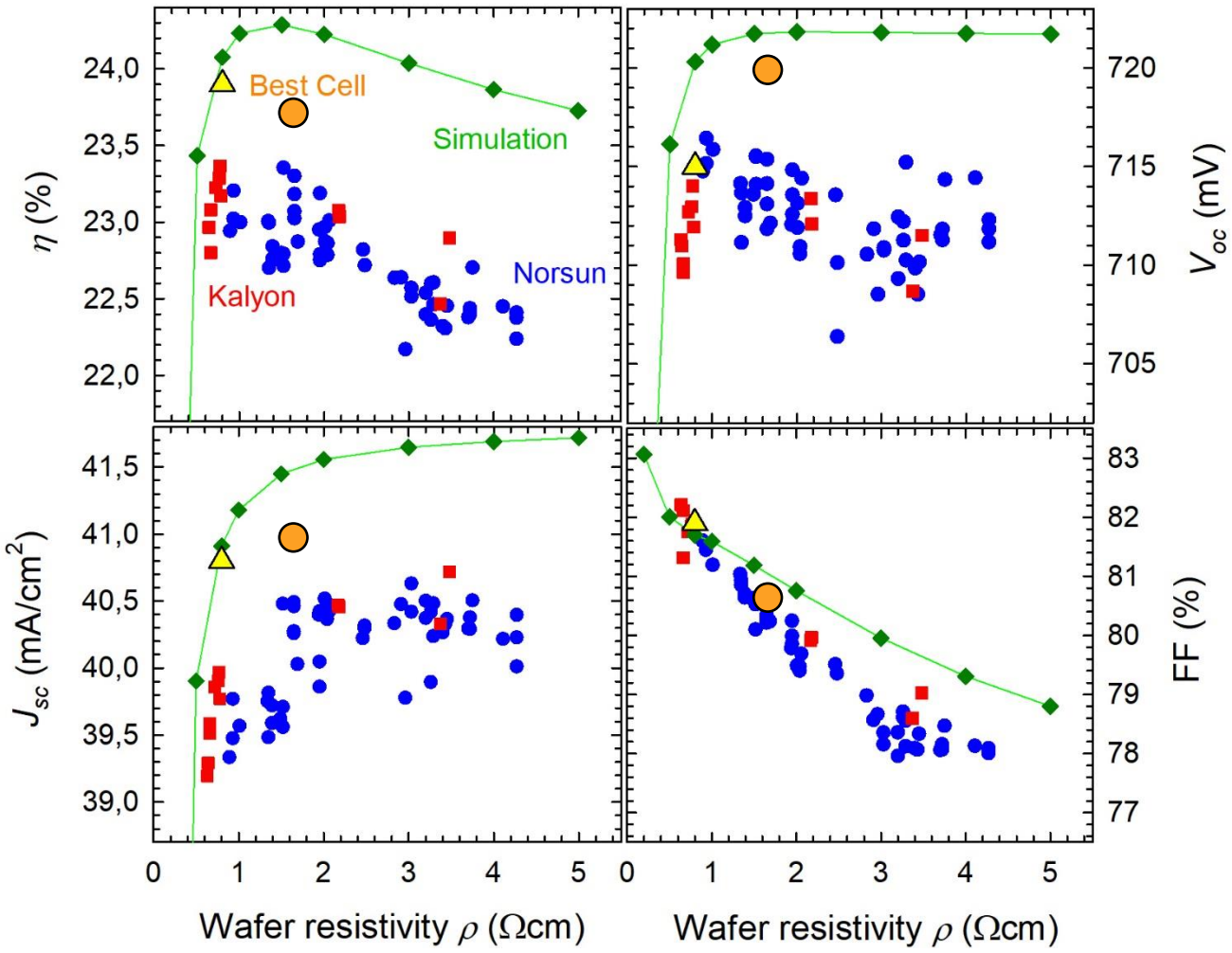


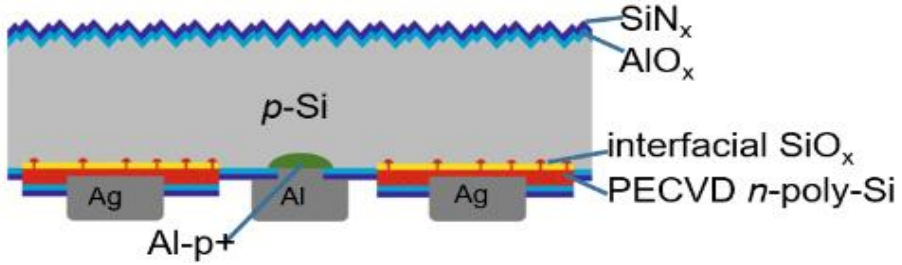


- J_{sc} and *FF* trends similar to Quokka 3 simulation
- Best POLO IBC efficiencies for

  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 ?

POLO IBC solar cell results





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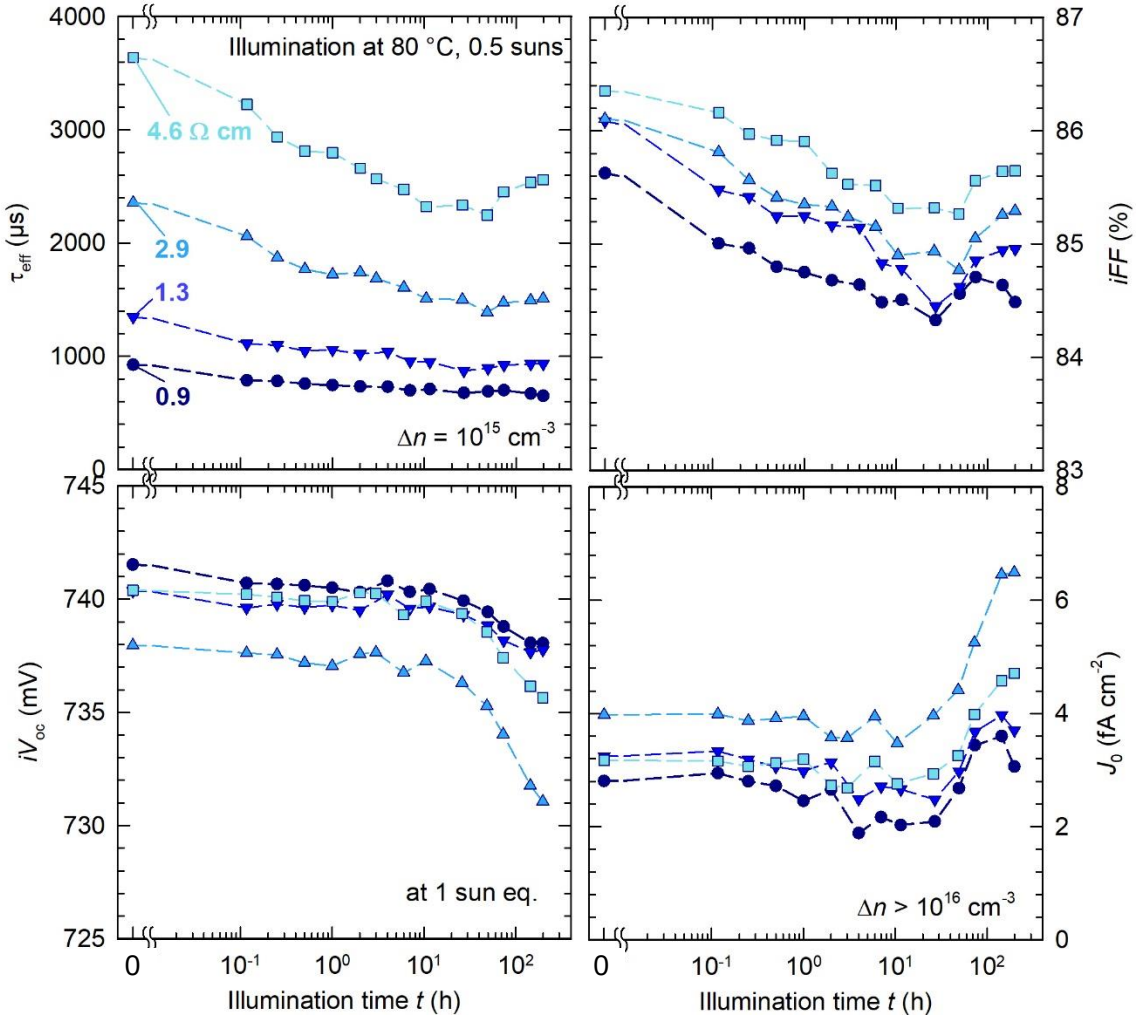
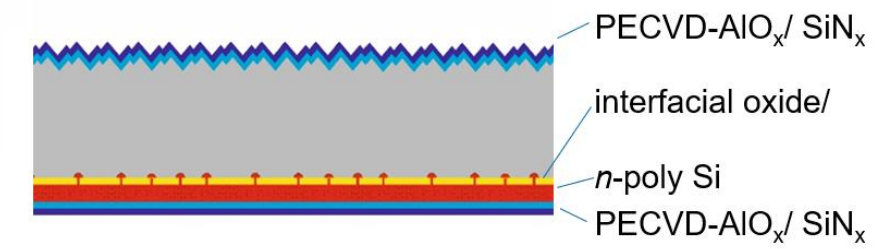
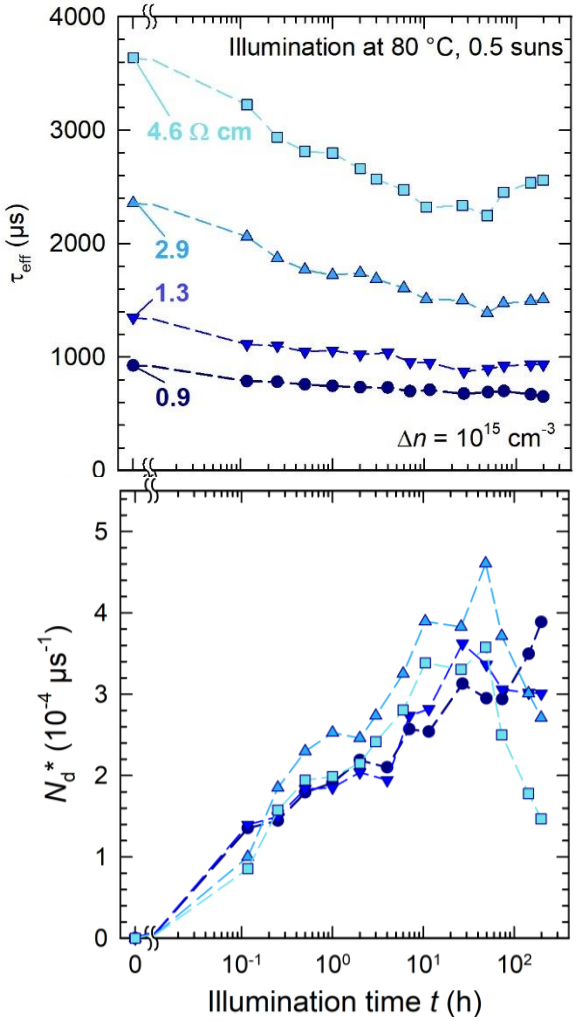
LeTID at 80 °C, 0.5 suns with POLO IBC lifetime precursors

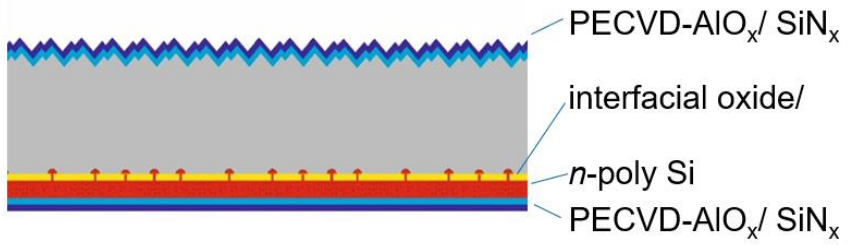




- LeTID slightly degrades τ_{bulk} and *iFF*
- iV_{oc} stable till 10 h
- $J_{0,surface}$ slightly increases due to degradation of surface passivation after 100 h

LeTID at 80 °C, 0.5 suns with POLO IBC lifetime precursors





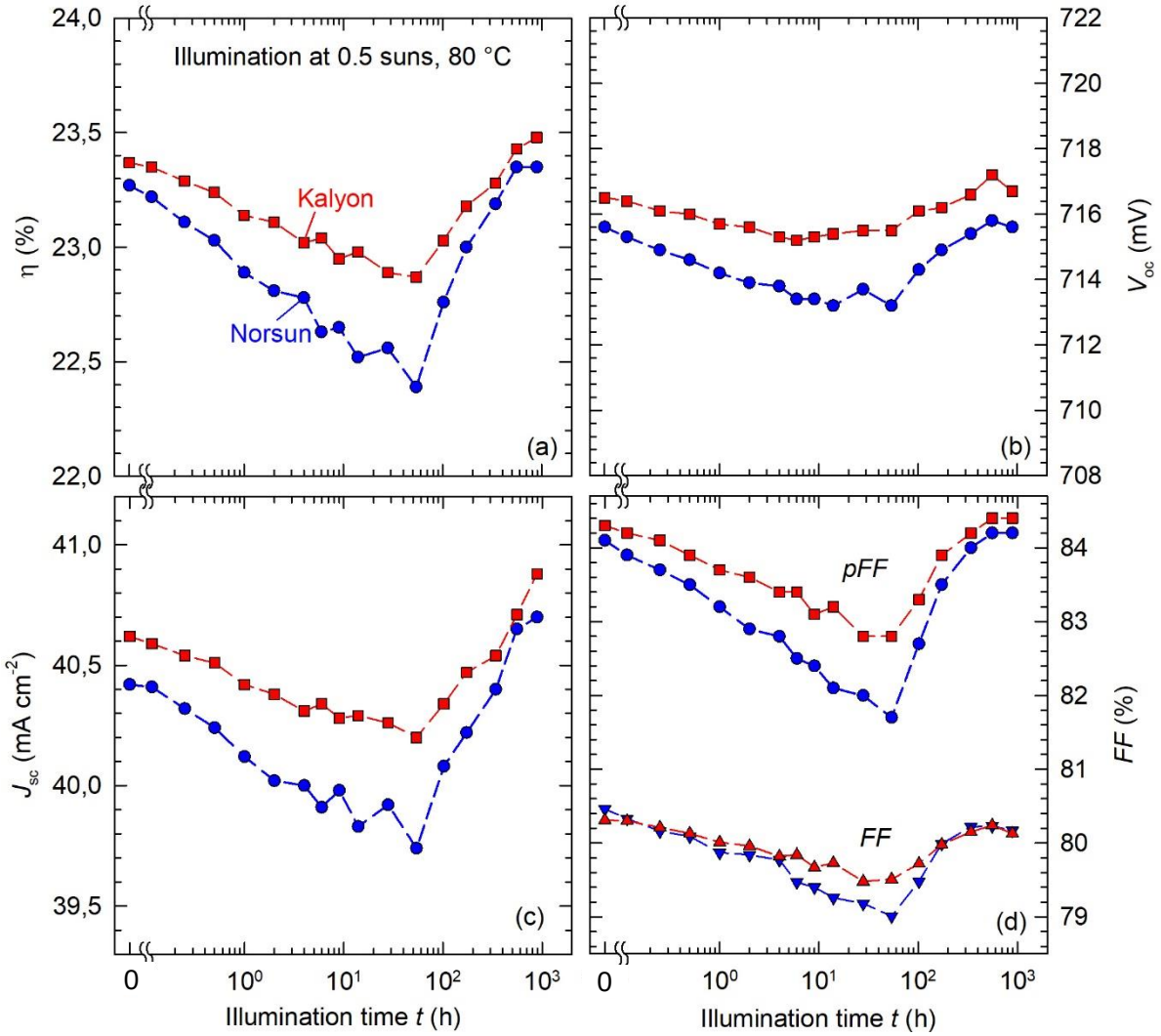
- Effective LeTID defect concentration calculated as

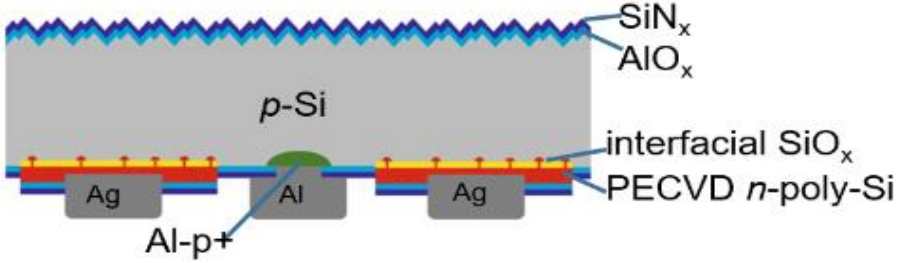
$$N_{\mathrm{d}}^{*}(t) = \frac{1}{\tau_{\mathrm{d}(t)}} - \frac{1}{\tau_{0}}$$

- N_d does not dependent on Ga doping concentration
- Confirms hypothesis of recent publication[1] now with more statistics

[1] F. Maischner et al, SOLMAT 260 (2023) 112451

LeTID at 80 °C and 0.5 suns of POLO IBC cells





- Maximum LeTID extent relatively small (<4% relative)
- LeTID affects mainly J_{sc} and *pFF*
- Full recovery of all IV parameters after 1000 h illumination
- LeTID norm test[1] n.a. to cells, no fail criteria
- LeTID could be further reduced by lower firing cool down rate[2,3]

[1] Module test norm IEC TS 63342
[2] F. Maischner et al., SOLMAT 262 (2023) 112529
[3] M. Winter et al., IEEE JPV 13 (6), p. 849-857 (2023)

POLO IBC efficiency roadmap to 25%

23.9%: best POLO IBC cell

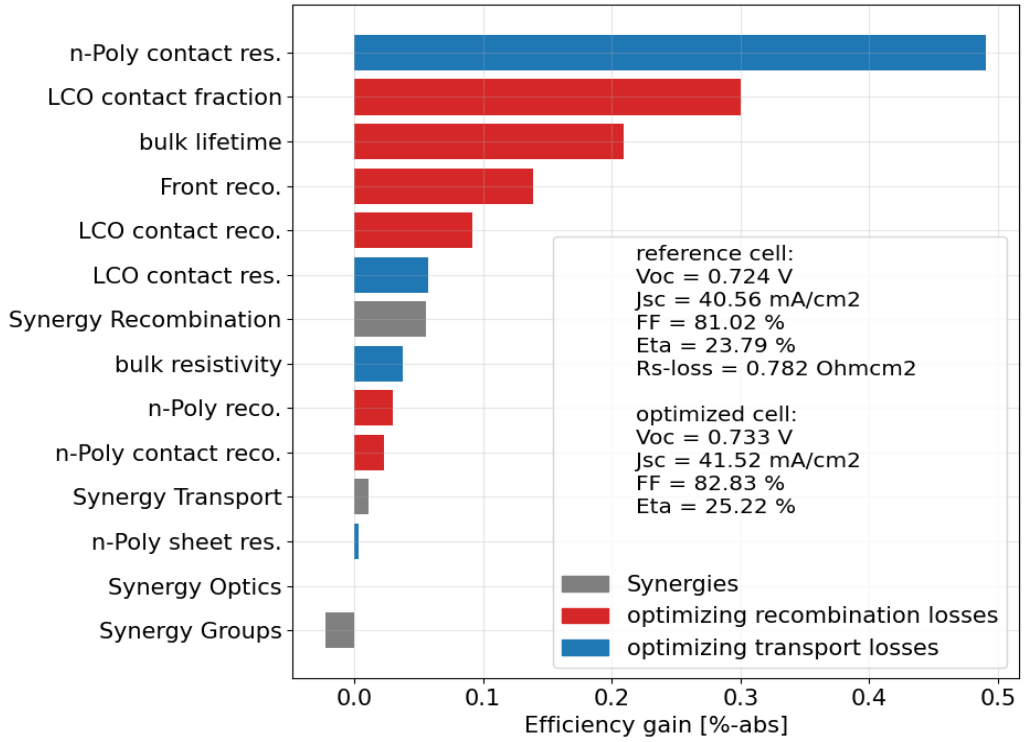
+ 0.5%: reducing Ag to n-poly Rc

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

+ 0.3%: optimized BB and Pad design

+ 0.2%: 1.5 Ω cm Ga-doped Cz wafers

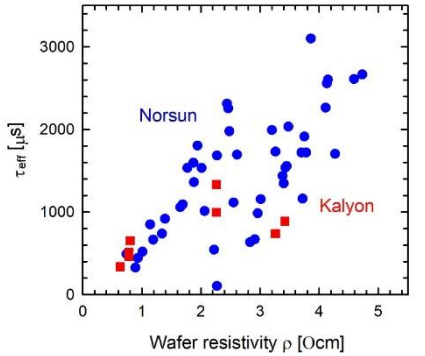
➡ 25.1% near-term efficiency potential

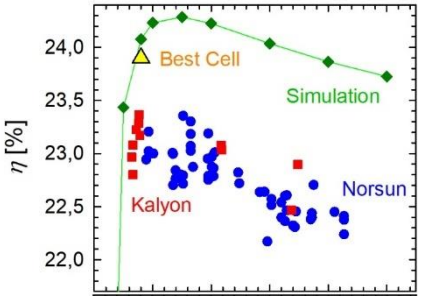


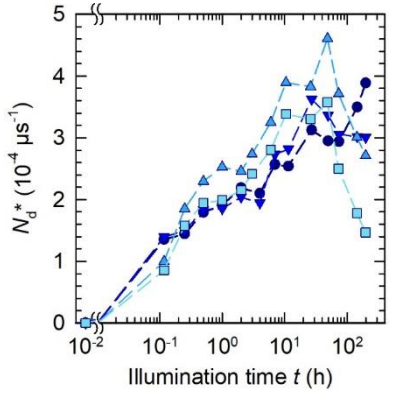
V. Mertens et al., Sol. RRL 8 (2024) 23009196

Summary

- τ_{eff} increases linearly with higher ρ up to 3.0 ms
- Calculated implied efficiency $i\eta = iV_{oc} \times iFF \times J_{sc}$ = 26.7% for wide range of ρ
- Best POLO IBC efficiencies for 1.0 Ωcm < ρ < 2.0 Ωcm
- Best POLO IBC cell with 23.9%. 0.5% η gap in this study due to lower J_{sc}. AlO_x/SiN blistering alloys Al „ghost“ contacts ?
- 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







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, and by the State of Lower Saxony.

- **Thank you for your attention !**

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