

TOPCon and beyond – What do western suppliers offer?

J. Rentsch, R. Preu, F. Clement, S. Rein,
M. Hofmann, A. Wolf, S. Lohmüller, D. Subasi,
S. Nold, F. Dimroth, M. Hermle, S. Glunz

Taiyang India Conference, Delhi, 10.04.2025

www.ise.fraunhofer.de

Fraunhofer Institute for Solar Energy Systems ISE

Carrying out Research for the Energy Transition since 1981

The Institute in Numbers

Institute Directors

Prof. Dr. Hans-Martin Henning

Prof. Dr. Andreas Bett

Staff around 1500

Budget 2023

Operation € 122,7 million

Investment € 20,1 million

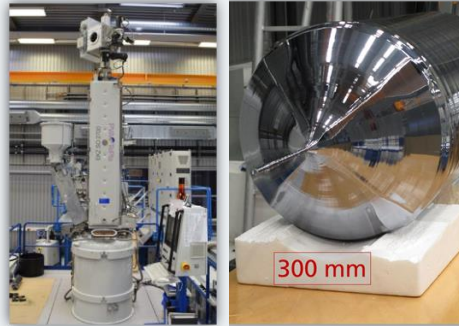
Total € 142,8 million



PV Pilot Facilities

Value Chain

Ingots & Wafer



Solar Cells



Modules



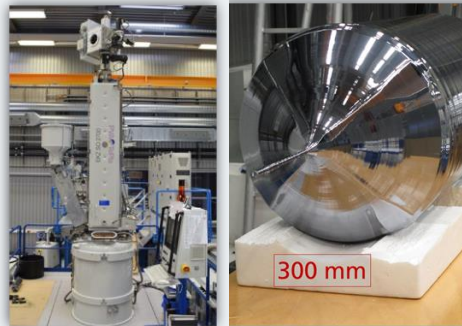
Industrial, automated tool platforms for large area (M10, G12) Wafers, Solar Cells and Modules



Pilot Facilities and Transfer Support Offerings

PV Value Chain & Transfer

Ingot & Wafer



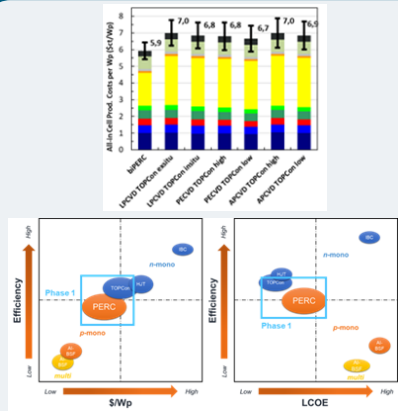
Solar Cells



Modules



Industrial, automated tool platforms for large area (M10, G12) Wafers, Solar Cells and Modules



Feasibility Stage



Concept and Basic Engineering



Training & RampUp Support



Operation

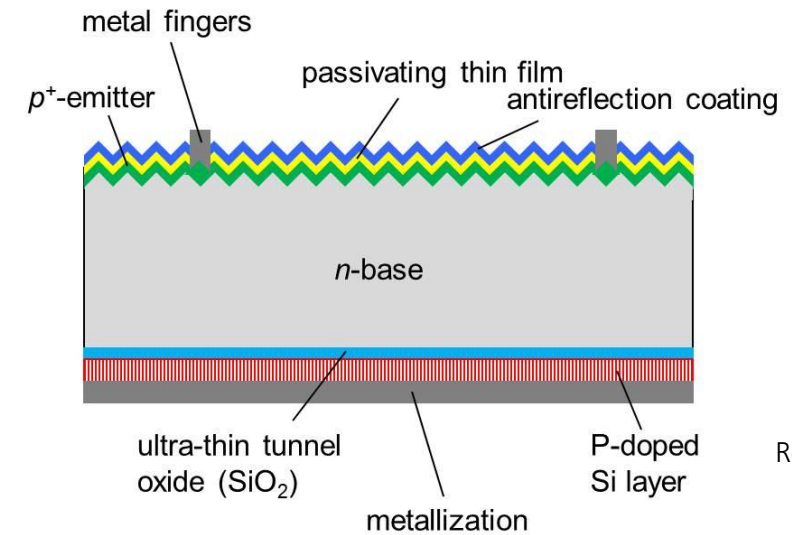


TOPCon Solar Cell Technology

Tunnel Oxide Passivating Contact (TOPCon)

History

- SIS Technology known from semiconductor industry^[1]
- Already suggested for solar cells in the 1980s^[2,3]
- Very likely implemented in Sunpower's Gen III IBC cells^[4]
- Hybrid cell structure suggested and term "TOPCon" coined by Fraunhofer ISE in 2013^[5]



Ref. [5]

Material, type area (cm ²)	V_{oc} [mV]	J_{sc} [mA/cm ²]	FF [%]	η [%]
n-type FZ-Si, HE, 10 x 10	712	41.2	82.8	24.3
n-type FZ-Si, SE, 2 x 2	718	42.5	82.8	25.3

HE: Homogeneous Emitter, SE: Selective Emitter

Ref. [6]

SIS Silicon Insulator Silicon, IBC Interdigitated Back Contact

[1] de Graaff HC, de Groot JG, IEEE TED, 1979

[2] R.J. Van Overstraeten, IEEE PVSC, 1981

[3] M.A. Green et al., Solar Cells, 1983

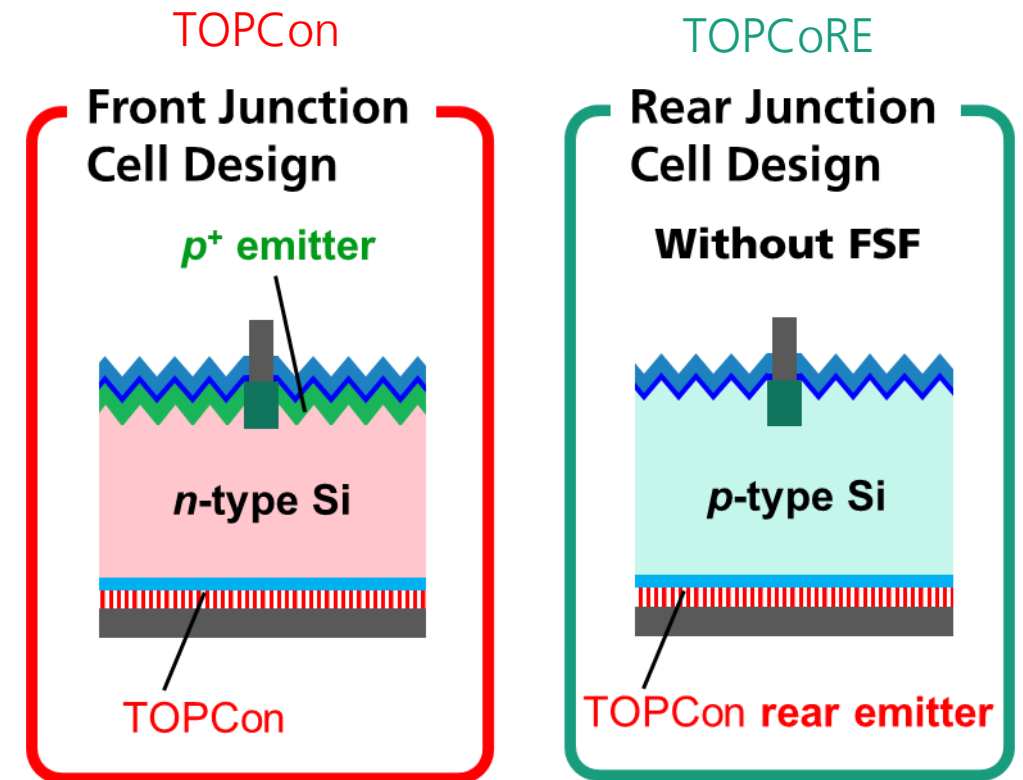
[4] J.P. Cousins et al., 35th IEEE PVSC, 2010

[5] Feldmann et al., 28th EUPVSEC; 2013

Tunnel Oxide Passivating Contact (TOPCon)

History

- SIS Technology known from semiconductor industry^[1]
- Already suggested for solar cells in the 1980s^[2,3]
- Very likely implemented in Sunpower's Gen III IBC cells^[4]
- Hybrid cell structure suggested and term "TOPCon" coined by Fraunhofer ISE in 2013^[5]
- Highest efficiency of 26.0% at Fraunhofer ISE obtained 2021 with p-type wafers^[6]



Design	V_{oc} (mV)	FF (%)	j_{sc} (mA/cm ²)	η (%)
TOPCon	724	83.1	42.9	25.8
TOPCoRE	732	84.3	42.1	26.0

Certified by Fraunhofer ISE Callab, designated area: 2x2 cm², cell thickness 245 μm

SIS Silicon Insulator Silicon, IBC Interdigitated Back Contact

[1] de Graaff HC, de Groot JG, IEEE TED, 1979

[2] R.J. Van Overstraeten, IEEE PVSC, 1981

[3] M.A. Green et al., Solar Cells, 1983

[4] J.P. Cousins et al., 35th IEEE PVSC, 2010

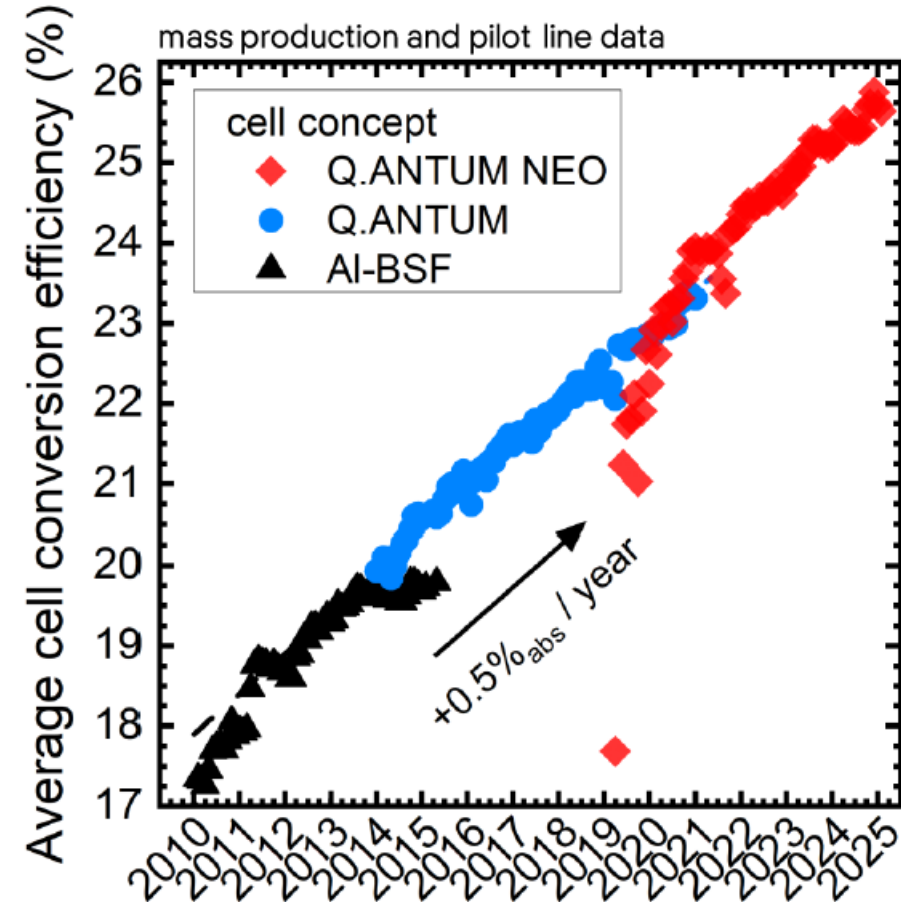
[5] Feldmann et al., 28th EUPVSEC; 2013

[6] A. Richter et al., Nature Energy, 2021

Tunnel Oxide Passivating Contact (TOPCon)

Industrial implementation

- Industrial implementation starting around 2016 by LG and Jolywood [1]
- Ongoing efficiency improvement demonstrated for example by Q-cells from 2019-2025 [5]
- Highest verified efficiency claimed so far:
 - 26.9% by Jinko M10 wafer, October 2023 [2]
 - 26.7% by Jolywood M10 wafer, April 2023 [3]
 - 26.6% by Trina G12R wafer, November 2024 [4]



[5] Fertig, F. et al., PV CellTech Europe (2025)

[1] <https://www.jolywood.com/en/history.html>

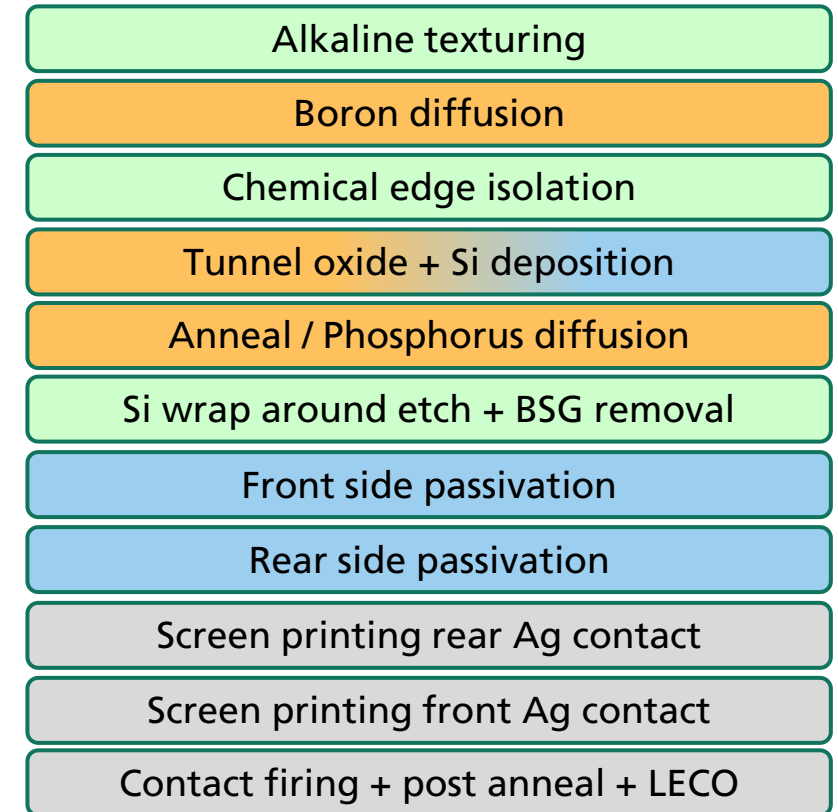
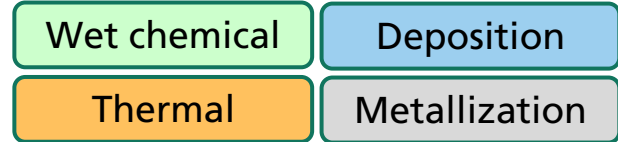
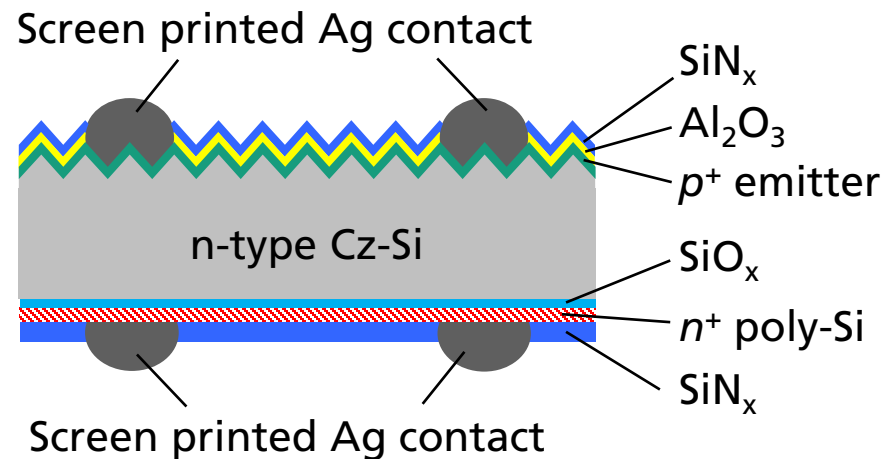
[2] <https://ir.jinkosolar.com/news-releases/news-release-details/jinkosolar-high-efficiency-n-type-monocrystalline-silicon-3>

[3] <https://www.pv-magazine.com/2023/04/12/jolywood-claims-26-7-efficiency-for-n-type-topcon-solar-cell/>

[4] <https://www.pv-magazine.com/2024/11/21/trina-solar-claims-record-breaking-efficiency-of-26-58-for-topcon-solar-cell/>

TOPCon Cell Technology

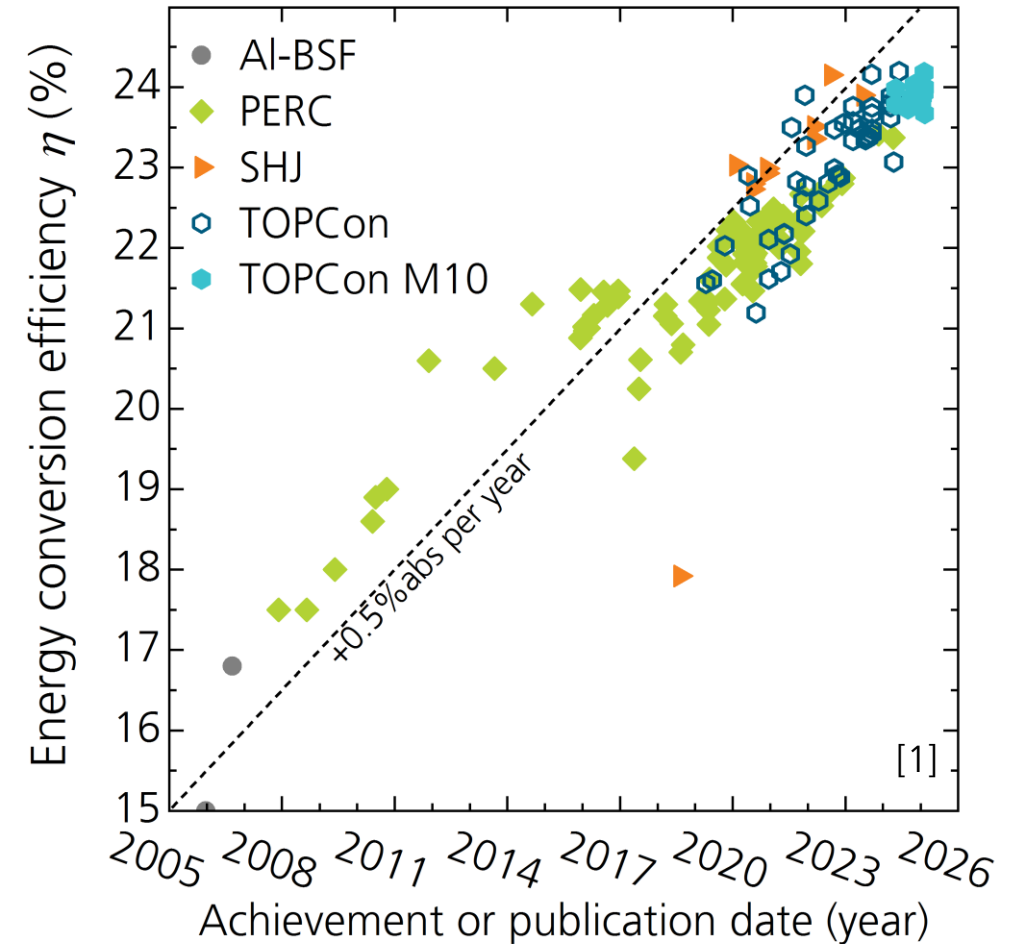
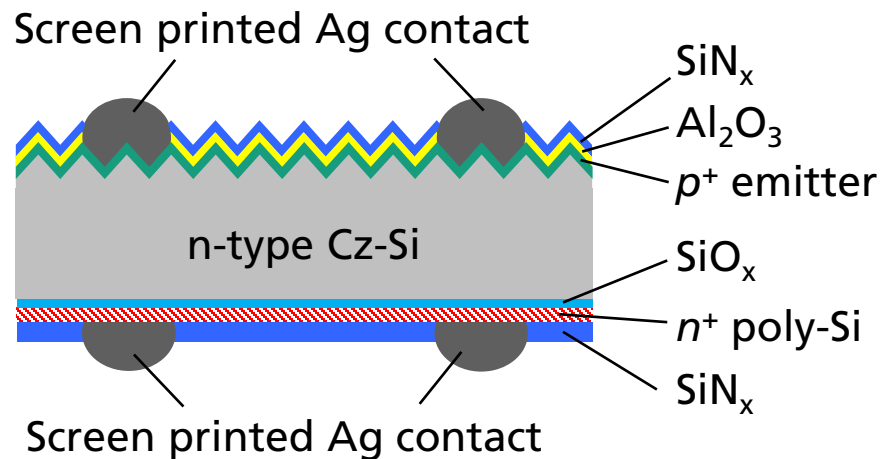
Generic Industrial Process Flow and Cell Structure



Industry-related solar cell process at ISE / PVTEC

Efficiency development

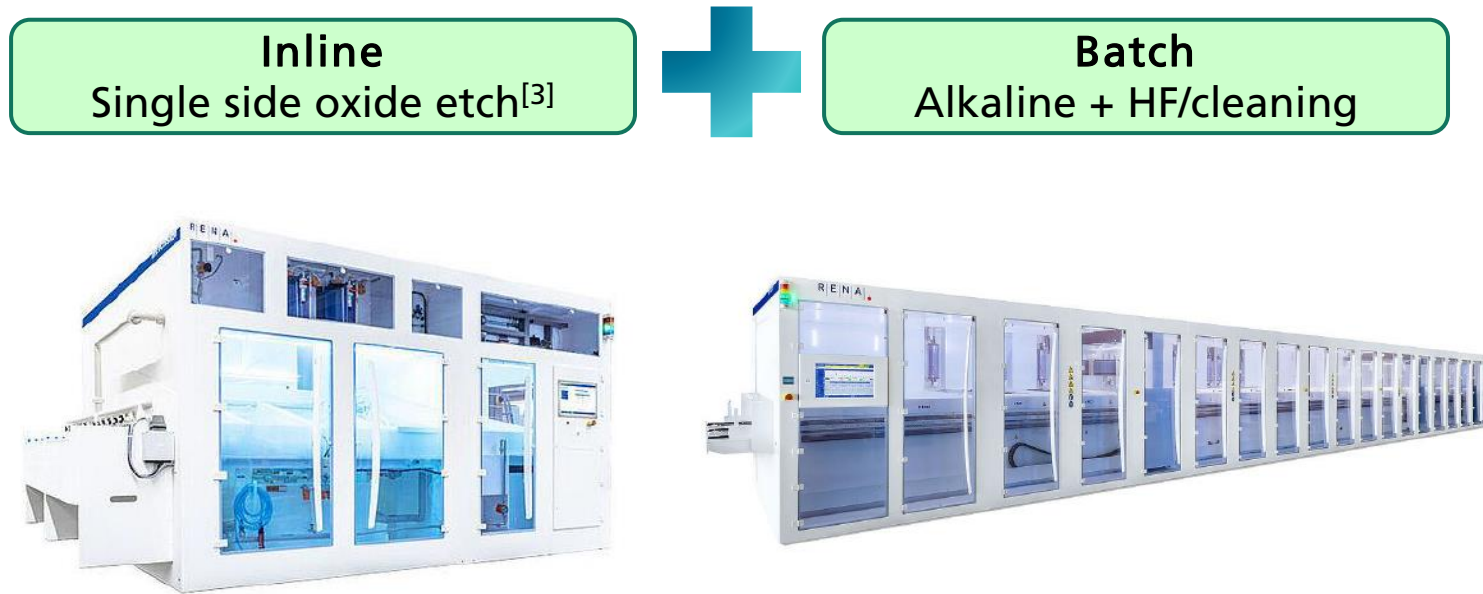
- Over 20 years industry-related solar cell development
- TOPCon baseline on large wafer size



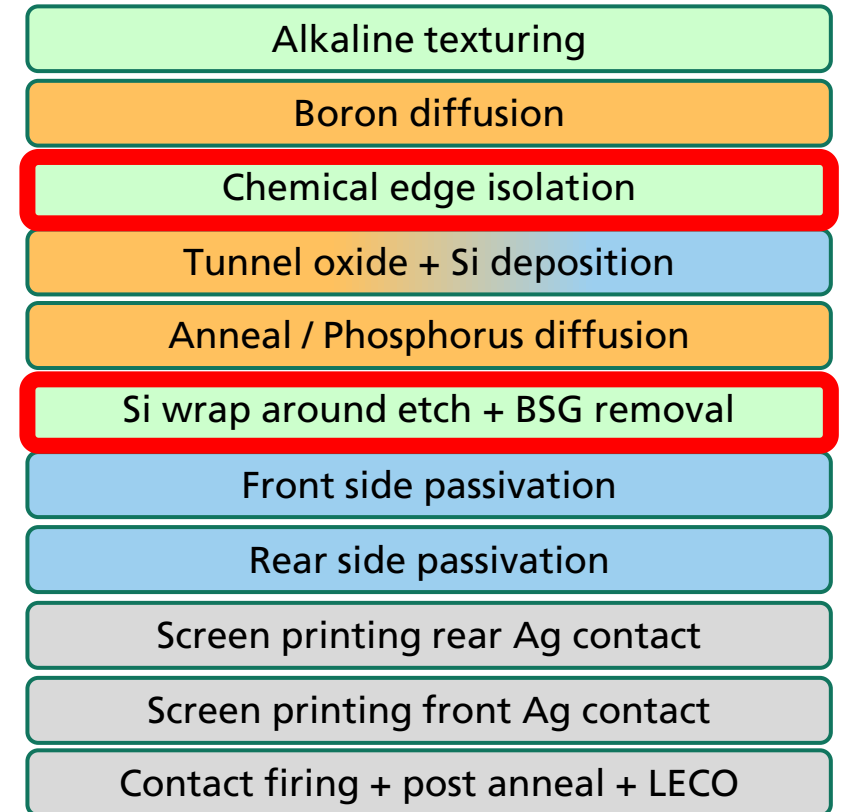
TOPCon Cell Technology

Chemical Edge Isolation and Si Wrap Around Etch

- Cluster process^[1,2] for high throughput processing



High Throughput of 15.000 wph (M10) with up to 40% OPEX reduction due to water and chemistry savings ^[4]



[1] K. Krieg et al., EUPVSEC 2024

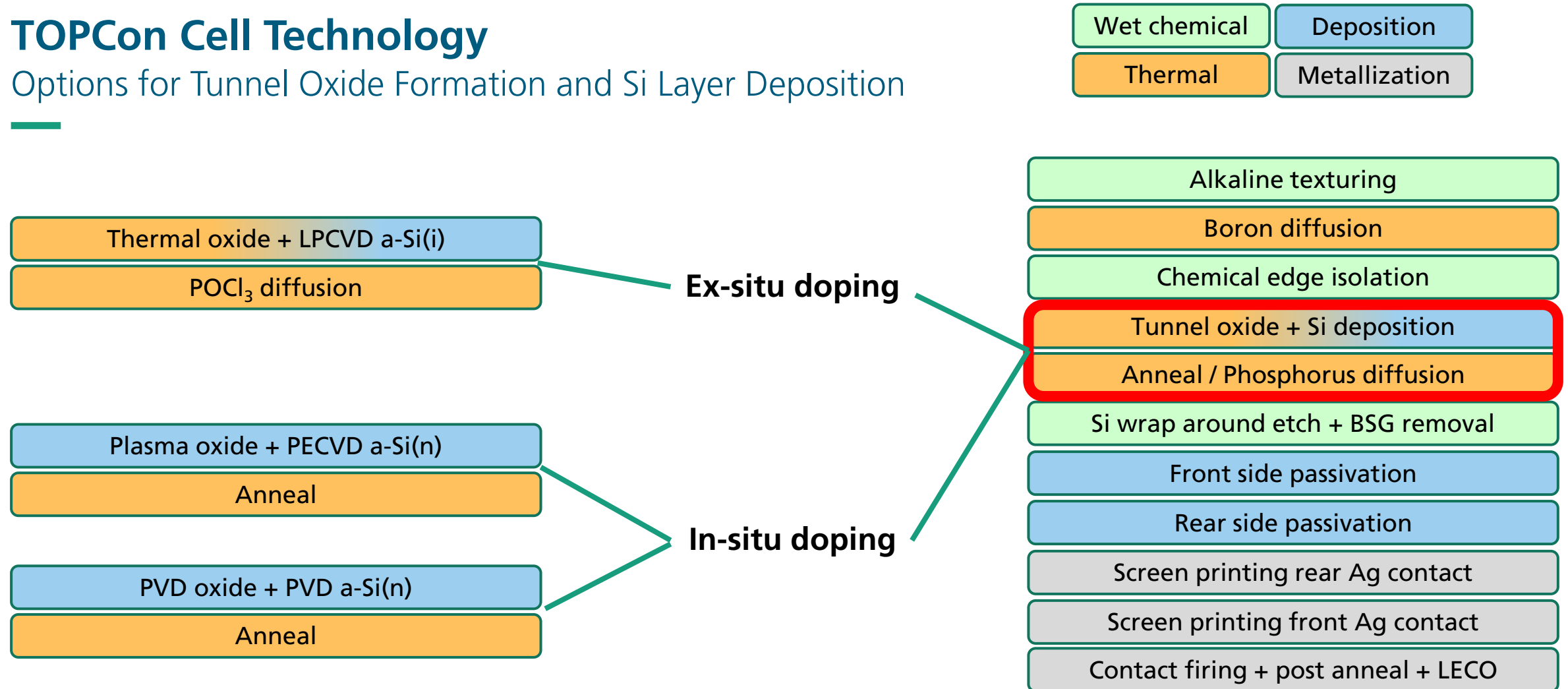
[2] J. Vollmer et al., EUPVSEC 2024

[3] Patents DE10313127 and WO2011047894A1

[4] Brunner, D. et.al, PVCellTech 2025

TOPCon Cell Technology

Options for Tunnel Oxide Formation and Si Layer Deposition



TOPCon Cell Technology

PVD Tunnel Oxide Formation and PVD Si Layer Deposition

Safer Operation

- No toxic phosphine (PH_3)
- No highly inflammable silane (SiH_4)
- Other eliminated gases: CH_4 , N_2O
- No dust in exhaust → no fire hazard



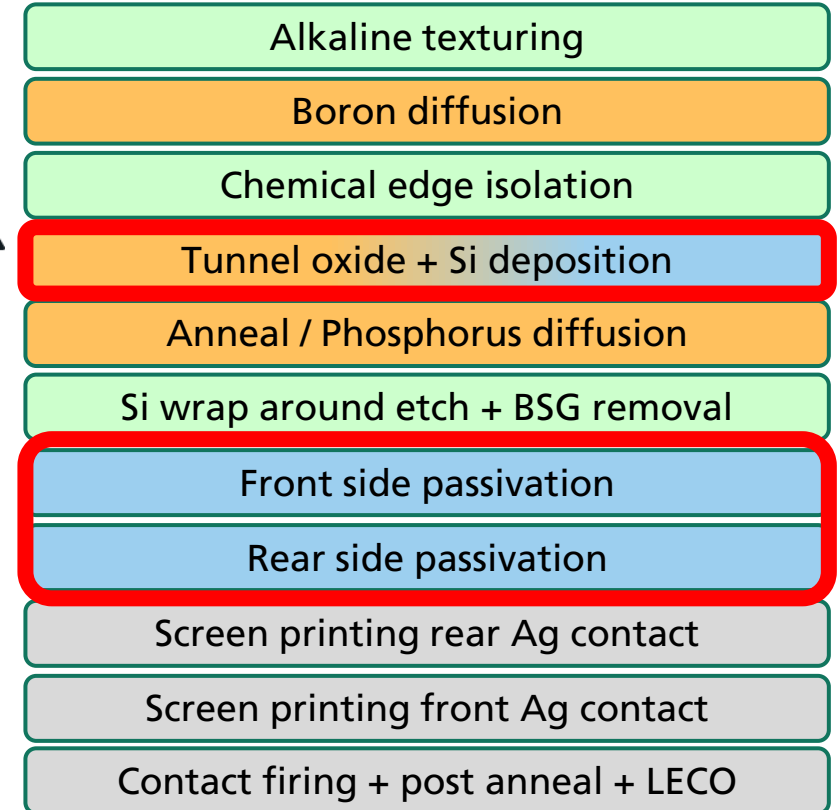
Leaner, faster permit process

Significant savings in

- OPEX for SiH_4 , PH_3 , NH_3 , CH_4 , N_2O
- Facility costs for gas bunkers, piping, gas detectors
- Cleanroom area
- OPEX for operation and maintenance
- Building insurance



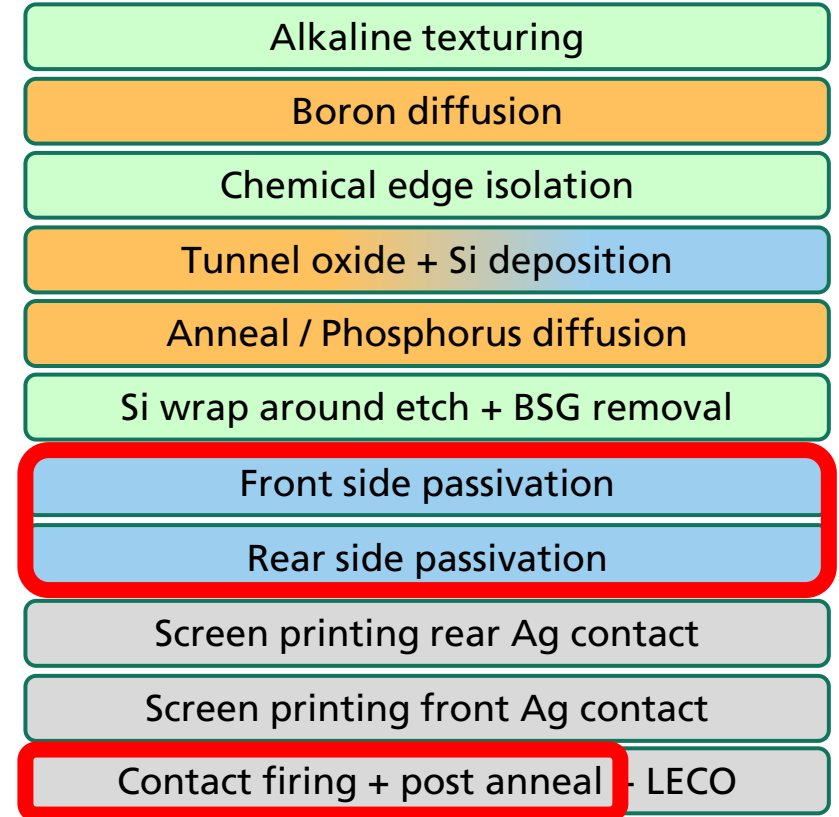
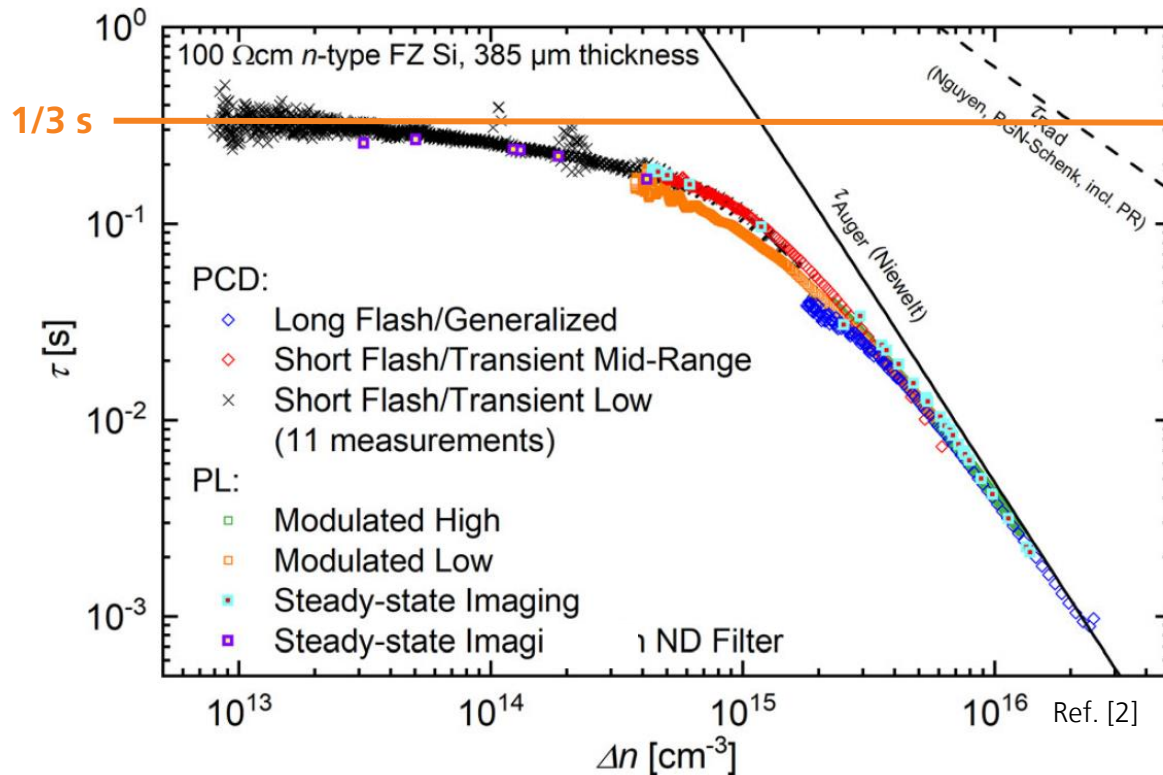
Throughput 19.200 wph (M10)



TOPCon Cell Technology

Hydrogen Management

- Multiple processes influence hydrogen concentration and distribution^[1]
- Hydrogenation essential to achieve excellent passivation^[2,3]



[1] B. Hammann et al., submitted for SiliconPV 2025

[2] B. Steinhauser et al., Sol. RRL, 2021

[3] European patent EP3050124

TOPCon Cell Technology

Laser Enhanced Contact Optimization (LECO)





- First LECO^[1,2] application to TOPCon cells reported by ISE^[3]

Received: 14 February 2022 | Revised: 4 May 2022 | Accepted: 6 June 2022
DOI: 10.1002/pip.3598

RESEARCH ARTICLE

PHOTOVOLTAICS WILEY

Laser-enhanced contact optimization on iTOPCon solar cells

Tobias Fellmeth¹ | Hannes Höffler¹ | Sebastian Mack¹  | Eve Krassowski²  |
Katrin Krieg¹ | Bishal Kafle¹  | Johannes Greulich¹ 

¹Fraunhofer ISE, Freiburg, Germany

²Cell Engineering GmbH, Kabelsketal, Germany

Correspondence

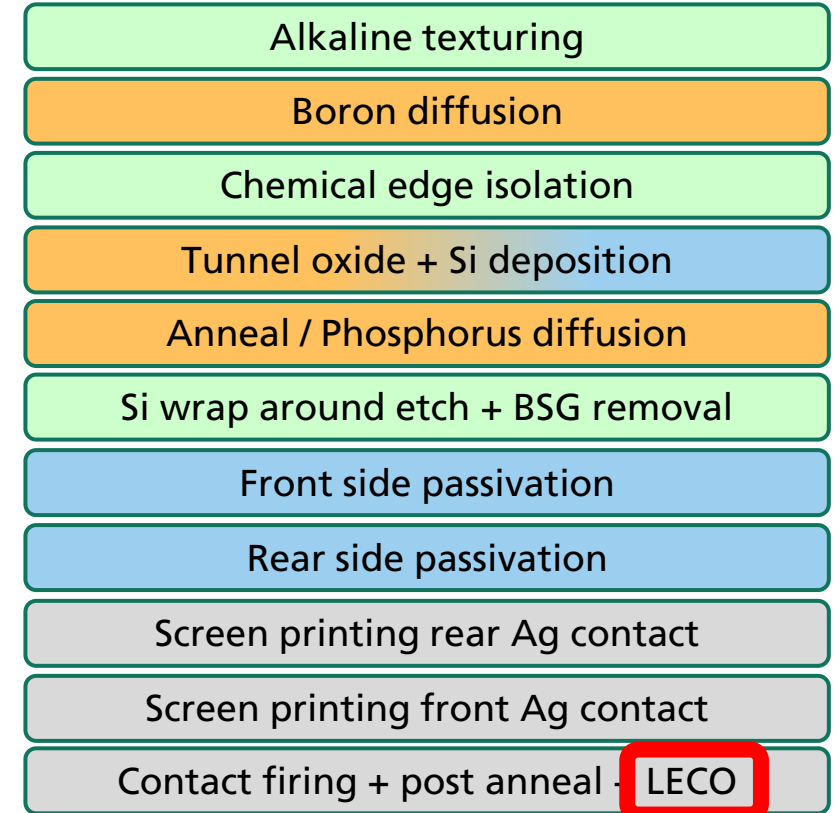
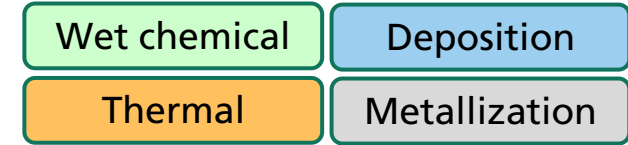
Tobias Fellmeth, Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstrasse 2, Freiburg 79110, Germany.
Email: tobias.fellmeth@ise.fraunhofer.de

Funding information

Bundesministerium für Wirtschaft und Klimaschutz, Grant/Award Numbers: 03EE1065A, 03EE1055B

Abstract

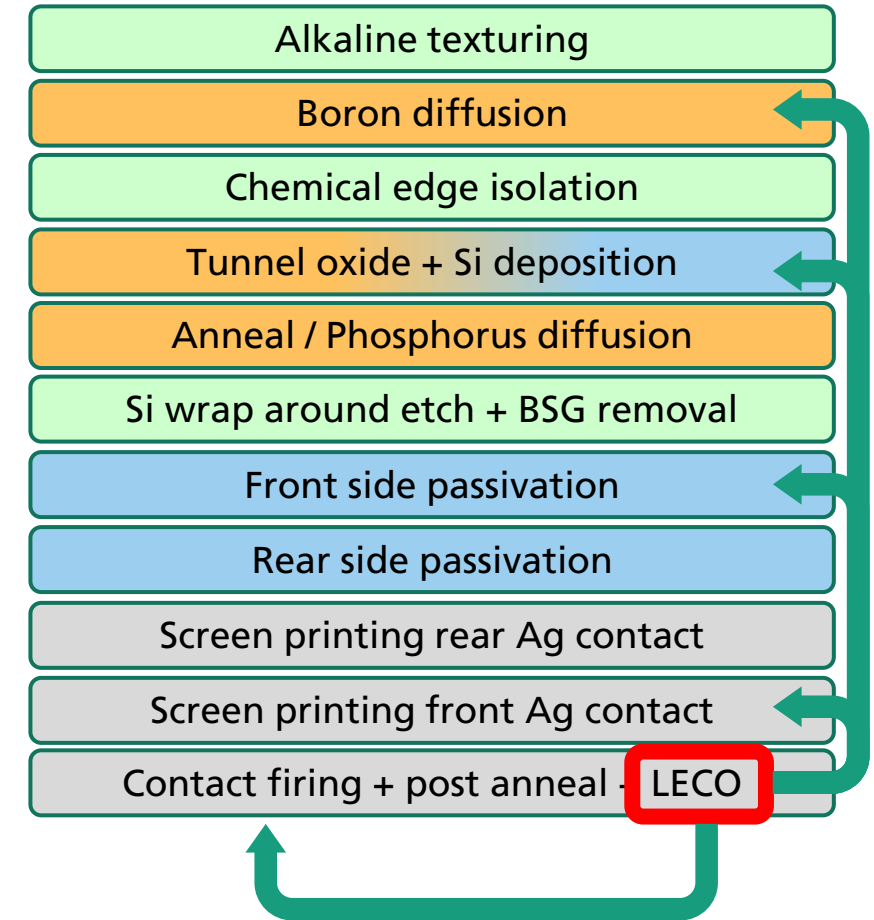
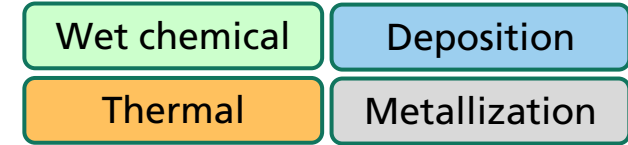
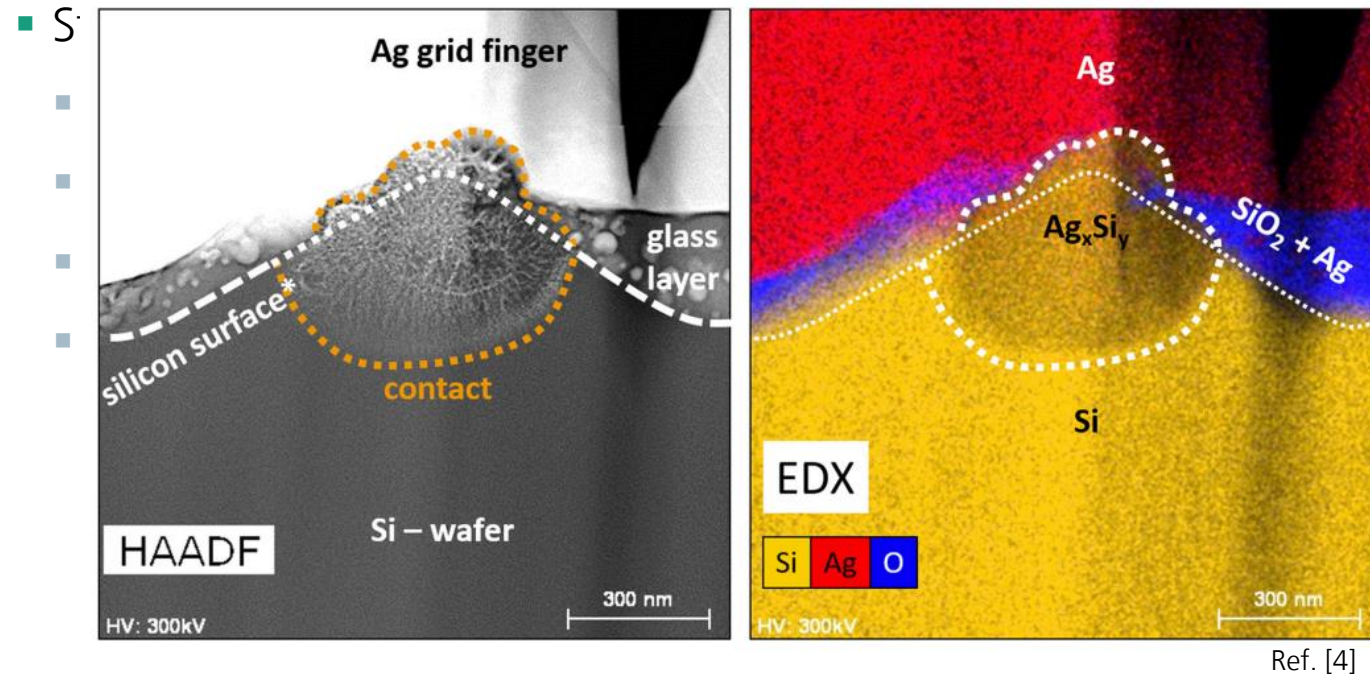
The authors present their work on laser-enhanced contact optimization (LECO) on iTOPCon solar cells. LECO improves the metal-semiconductor contact resistivity ρ_c on the boron emitter and the n-TOPCon side from an underfired (thermal budget too low) state of 2.9 and 14.1 m Ω cm² to an enhanced state of 1.8 and 2.9 m Ω cm². Therefore, it enables the reduction of the optimal peak firing temperature, which leads to a decrease of metal induced recombination mainly on the boron emitter side and to minor degree on the n-TOPCon side, as shown in this work. Ultimately, LECO improves iTOPCon solar cells conversion efficiency by 0.6%_{abs} compared with the optimal fired, untreated reference. Submitting those cells to 140°C and 2 suns equivalent irradiation for more than 4 h shows no impact on the conversion efficiency or any sign of light and elevated temperature-induced degradation (LeTID). Confirmed by ISE CaLab, LECO improved iTOPCon solar cells reach 23.8% and 24.1% conversion efficiency on industrial typical wafer formats and processes.



TOPCon Cell Technology

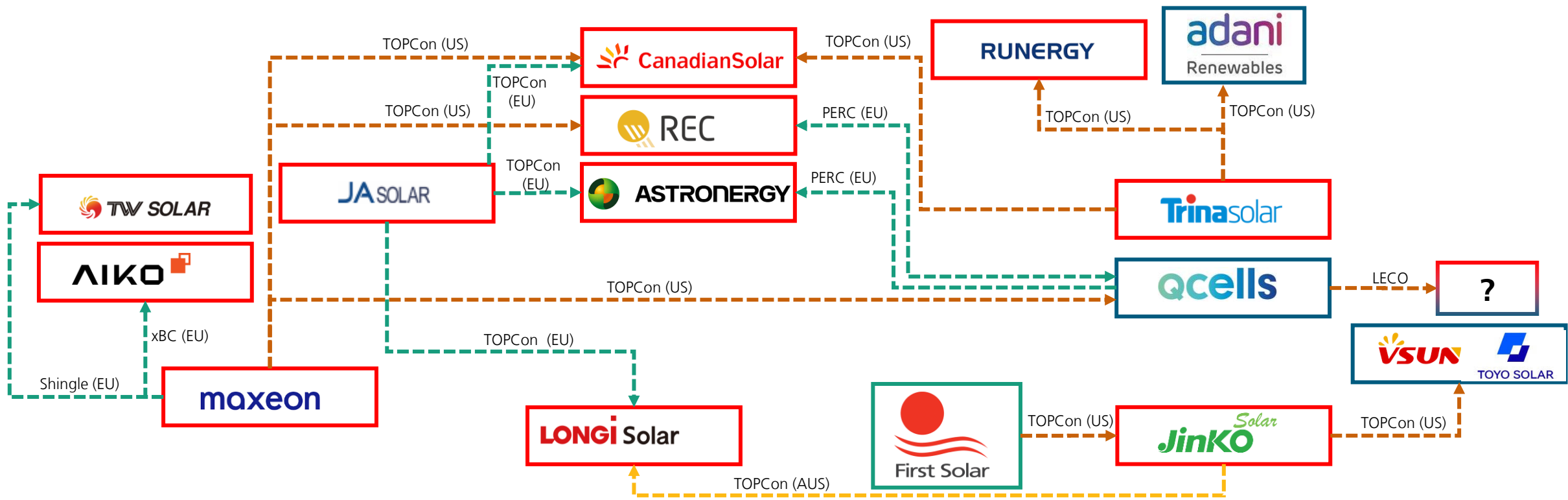
Laser Enhanced Contact Optimization (LECO)

- First LECO^[1,2] application to TOPCon cells reported by ISE^[3]
- Game changing by partly decoupling contact properties ρ_c and J_0
- Formation of nano-sized “current fired contacts” on front side^[4]



TOPCon Cell Technology

IP battle on technology heats up



- Thorough analysis of the patent situation is complex
 - different implementation routes, cell designs and module implementations
 - location of production and market relevant
- Situation similar for other technologies like hetero-junction, back-contact and Perovskite-silicon tandem

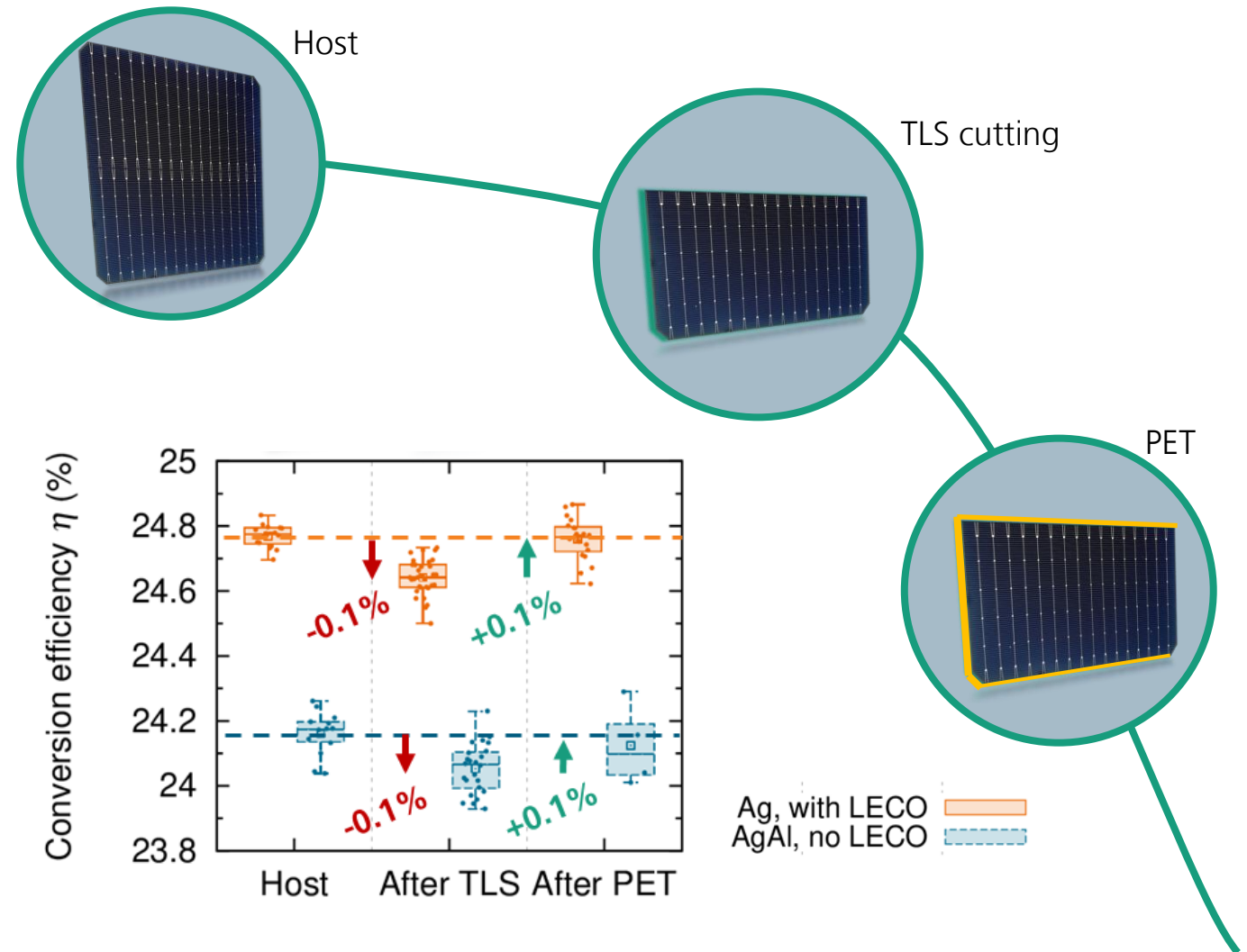
Ref. modified from FirstSolar Earnings Report Q3/24, Oct. 29th 2024

Passivated Edge Technology (PET) developed at Fraunhofer ISE

Cell Cutting and Edge Passivation

Example: Half Cell Cutting

- Host cell with half cut layout
- Cut into cell half
 - Increased ratio of edge to cell area
 - Edge recombination due to cut edges^[1,2]
- Edge passivation by PET^[3-6]
 - ALD Al₂O₃ layer
 - Annealing
- Full Efficiency recovery with PET^[7]

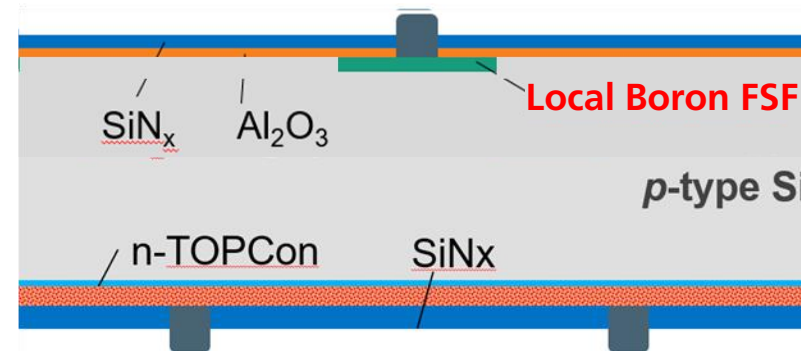


What's next in TOPCon development?

TOPCoRE and TOPCon²

TOPCoRE with Local Boron FSF

- Wafer can reach lifetimes of n-type [2]
 - But more susceptible to impurities (e.g. Fe)
- Wafer ~10% cheaper than n-type [1]
- Reducing the FSF to a local FSF increases efficiency by ~0.2%
- Less patent coverage



What's next in TOPCon development?

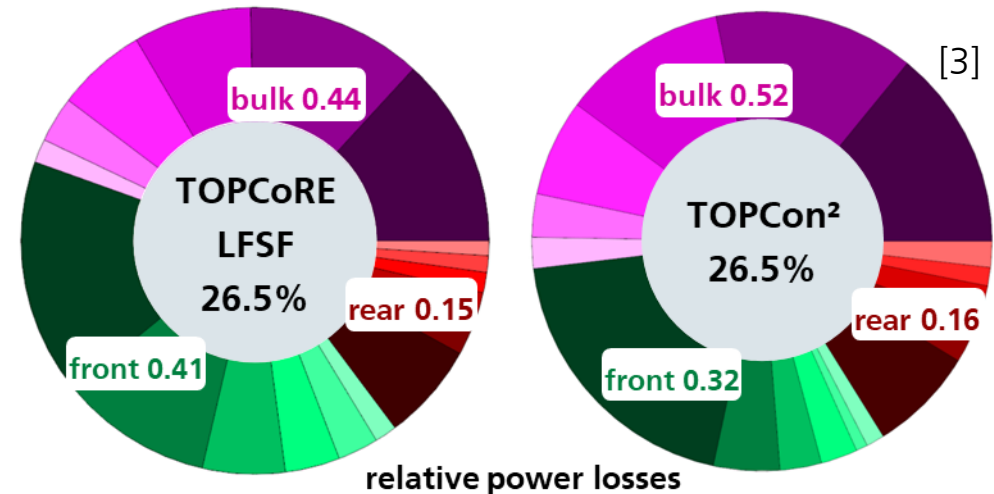
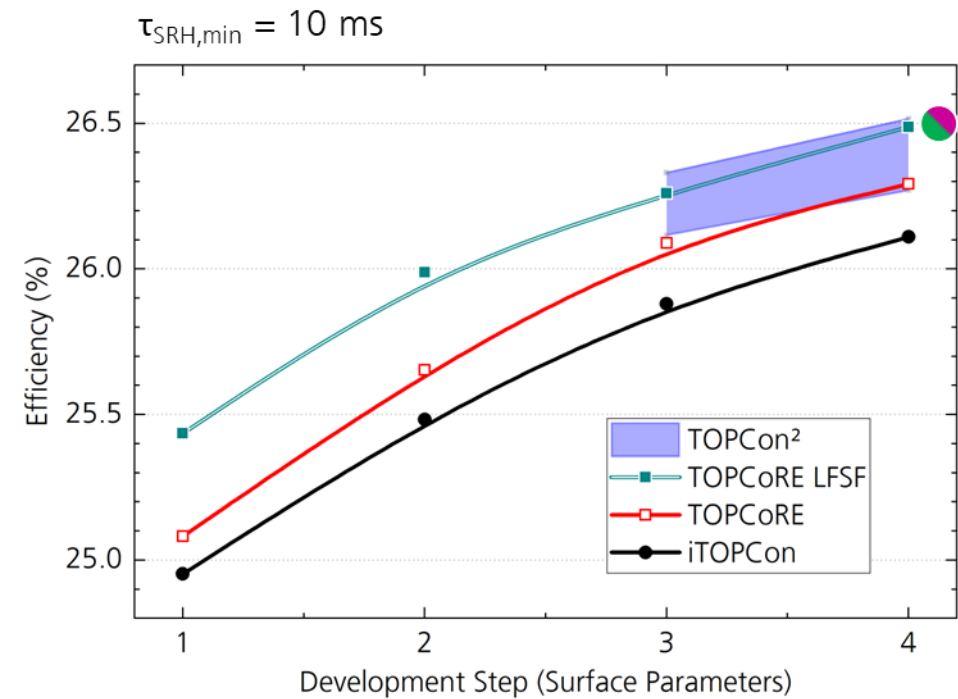
TOPCoRE and TOPCon²

TOPCoRE with Local Boron FSF

- Wafer can reach lifetimes of n-type [2]
 - But more susceptible to impurities (e.g. Fe)
- Wafer ~10% cheaper than n-type [1]
- Reducing the FSF to a local FSF increases efficiency by ~0.2%
- Less patent coverage

TOPCon² (local p-TOPCon)

- Improve the front contact recombination further by exchanging the local FSF by a front TOPCon layer



[1] www.energytrend.com/solar-price.html

[2] J. Horzel *et al.*, SolarRRL, 2022, doi: 10.1002/solr.202200613

[3] N. Wörke *et al.*, SiliconPV 2025

What's next in TOPCon development?

TOPCoRE and TOPCon²

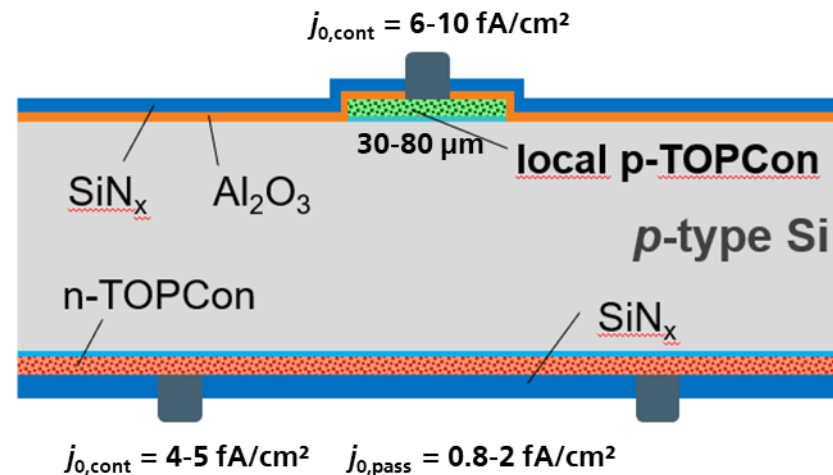
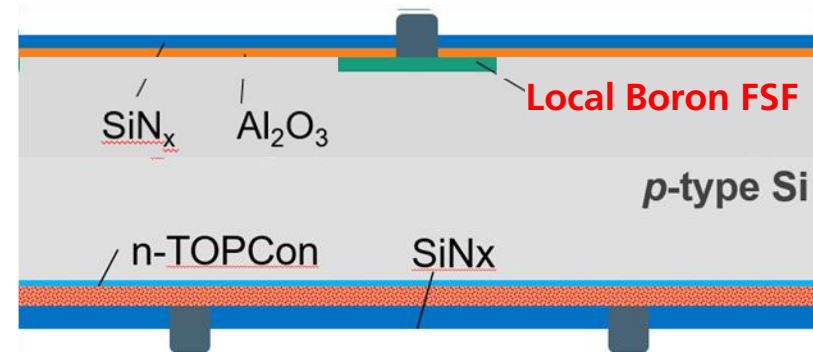
TOPCoRE with Local Boron FSF

- Wafer can reach lifetimes of n-type [2]
 - But more susceptible to impurities (e.g. Fe)
- Wafer ~10% cheaper than n-type [1]
- Reducing the FSF to a local FSF increases efficiency by ~0.2%
- Less patent coverage

TOPCon² (local p-TOPCon)

- Improve the front contact recombination further by exchanging the local FSF by a front TOPCon layer

TOPCon² as bottom cell allows smooth transition into the Si-Perovskite Tandem future !

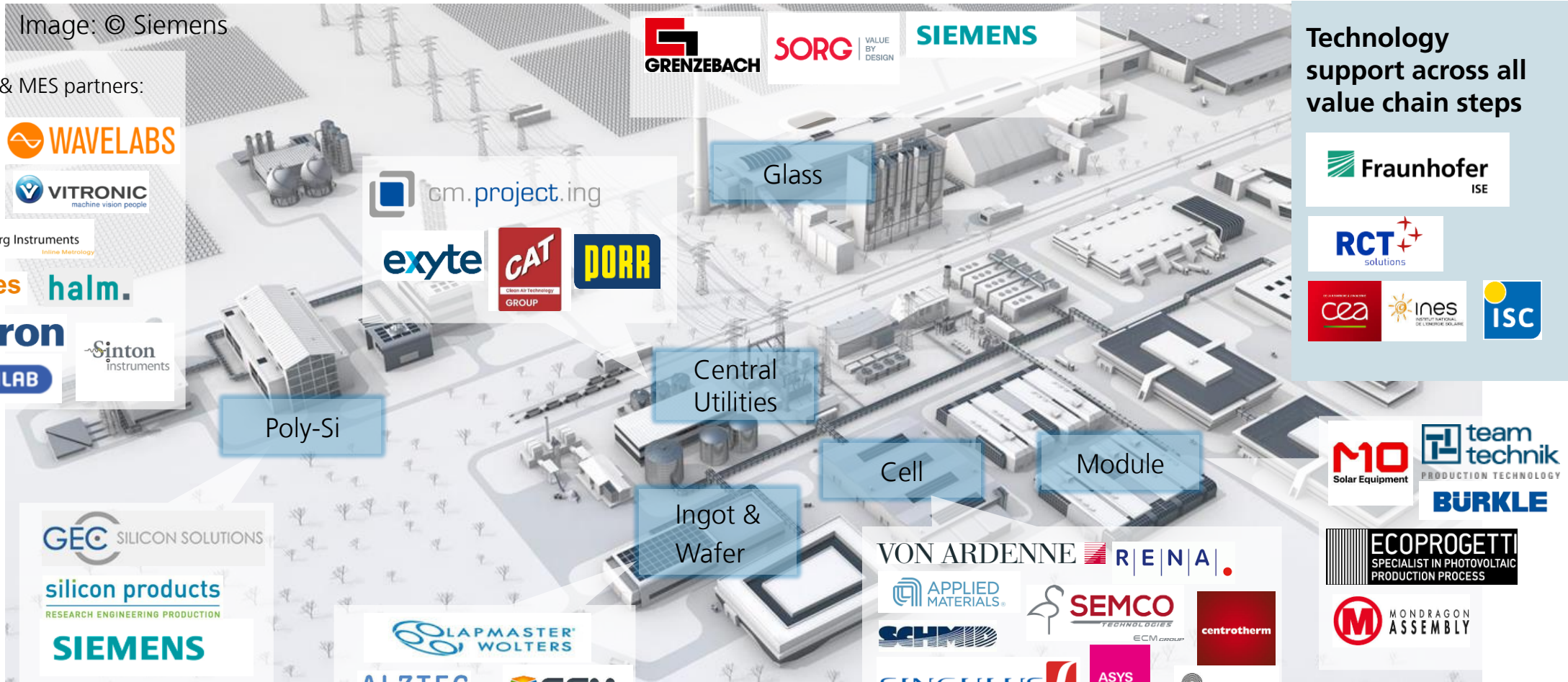


Creating a Fully Integrated PV Ecosystem

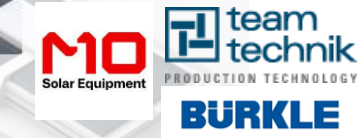
Partner Network

Image: © Siemens

Metrology & MES partners:



Technology support across all value chain steps





Supported by:



Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

Thank you for your attention

jochen.rentsch@ise.fraunhofer.de