Challenges for Silicon Photovoltaics

Next steps in manufacturing and advanced technologies

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PVCellTech, Penang, Malaysia
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Silicon Photovoltaic – What´s Ongoing and Next?
The View of Fraunhofer ISE

- Cost reduction
  - Kerfless wafering
  - Ongoing production process optimisation
    - PID reduction on cell level
    - regeneration process for boron doped Cz
- Higher efficiencies
  - From bi-facial PERC to tandem cells
- Recycling
  - Close the value chain

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Kerfless Wafering Technologies

- Future cost reduction is mainly driven by:
  material cost saving and efficiency improvement

  ➔ The **EpiWafer** technology by **epitaxial growth process** provides low-cost material for highly efficient solar cell concepts

- Additional benefits of the EpiWafer concept:
  - low oxygen content and homogeneous dopant concentration
  - in-situ dopant control (p/n junction)
  - area and thickness variability

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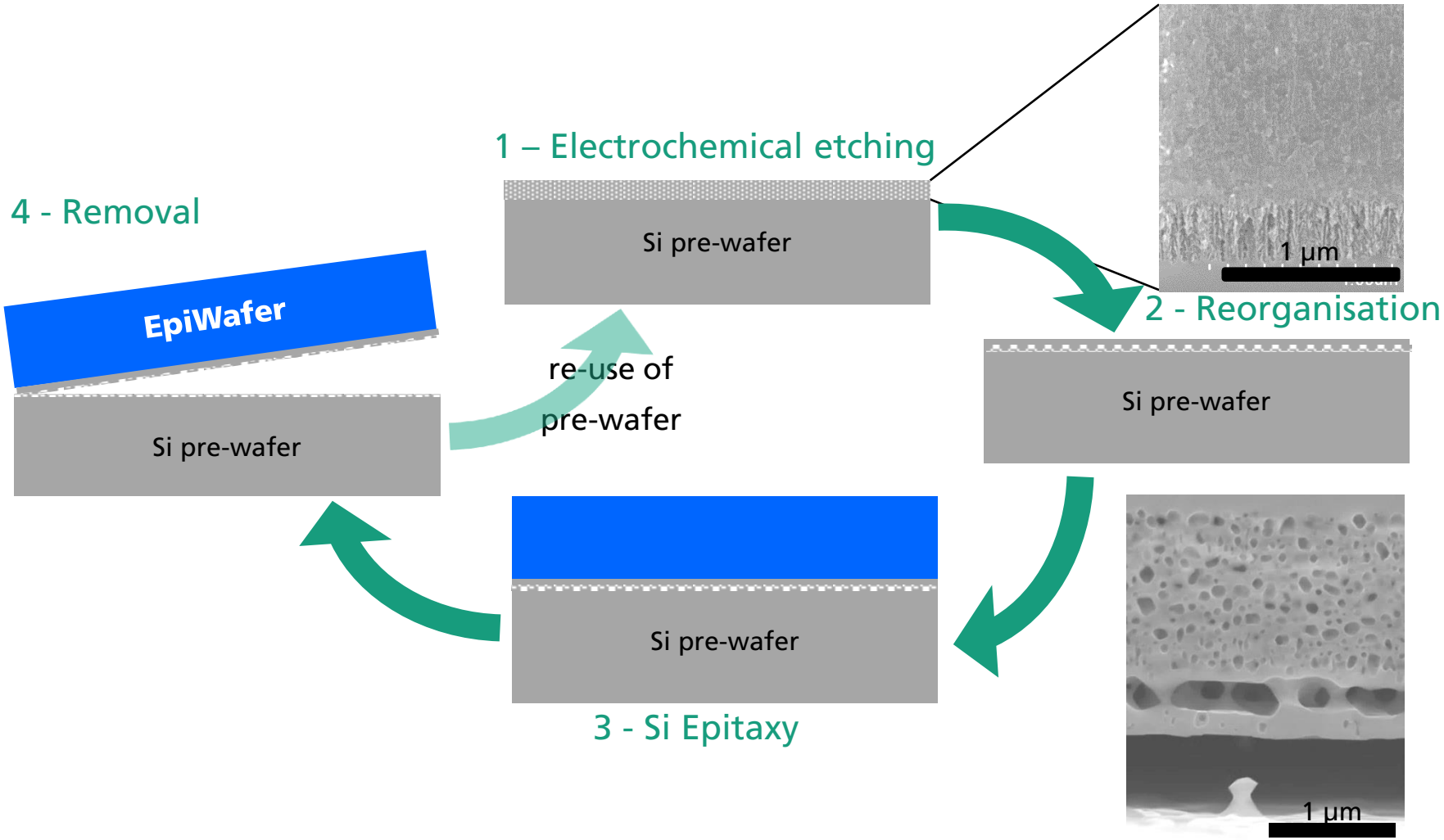
A Hot Topic: Kerfless Wafering, „EpiWafer“
A Disruptive Approach



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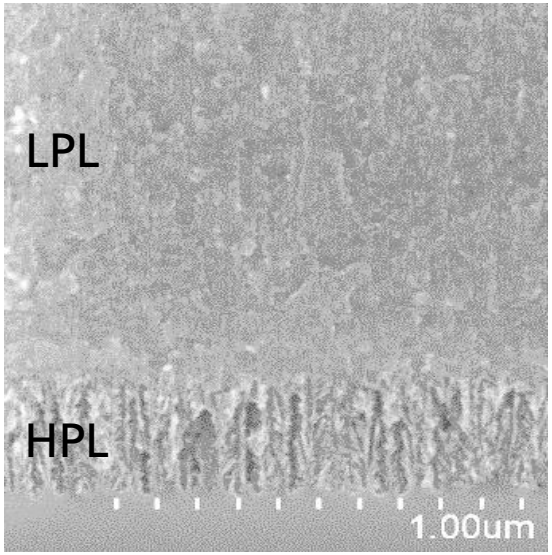
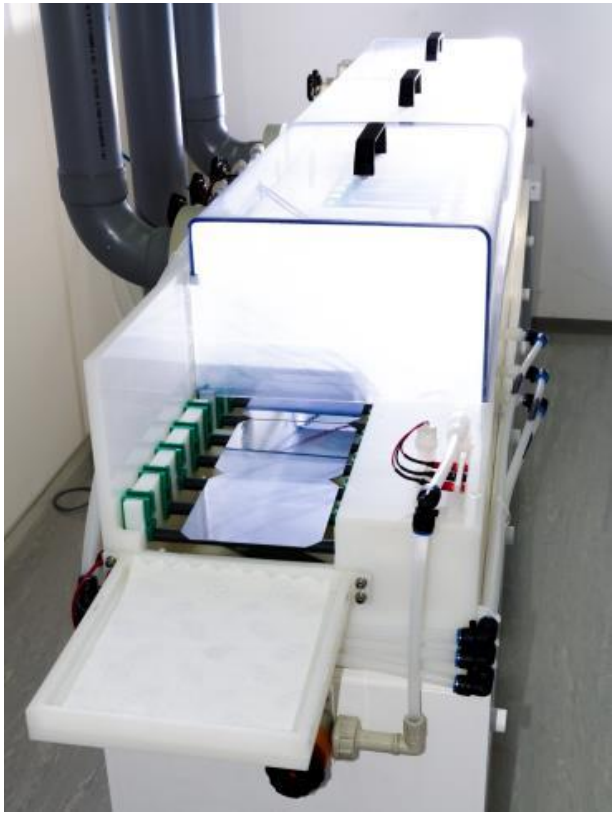
Kerfless „EpiWafer“
Inline-Porosification



- Rimless process on 156x156 mm²
- High (HPL) and Low Pororsity Layer (LPL) in one run



Inline-PorSi Equipment at ISE

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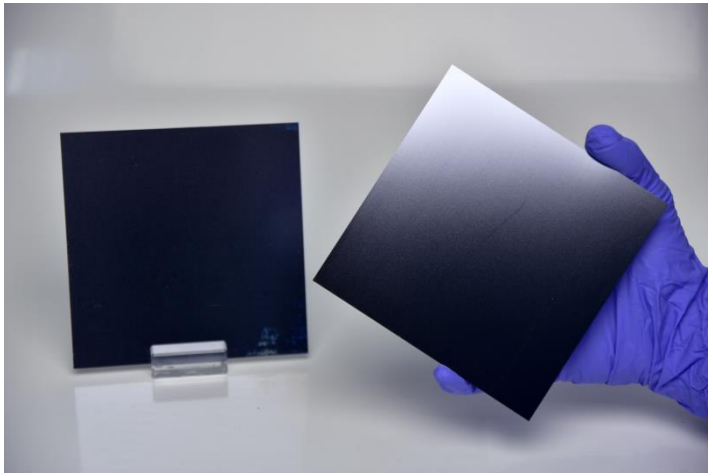
Kerfless „EpiWafer“
ProConCVD

- High throughput
  ~ 5 MW/a
- High speed growth
  3-5 µm/min
- EpiWafer^{plus} with p/n junction



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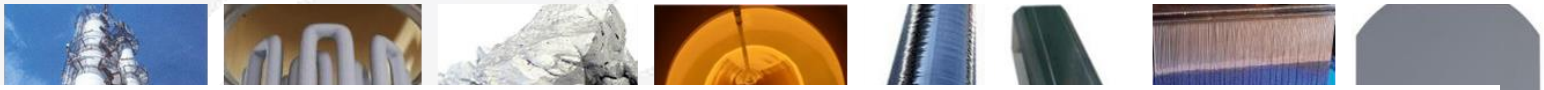
NexWafe – shortening the value chain by kerfless wafering

Conventional Cz



NexWafe

NEXWAFE GmbH Closes EUR 8 Million Financing

New funding to commission NexWafe's 5 MW EpiWafer production

Freiburg, Germany - December 11, 2017. NexWafe GmbH, a spinoff from the Fraunhofer ISE commercializing breakthrough technology for epitaxial fabrication of silicon wafers for photovoltaics, announced today the completion of Euro 8 million financing. The round was led by Saudi Aramco Energy Ventures (SAEV) and included Green Gateway Fund 2 (GGF2) advised by Wermuth Asset Management GmbH (WAM) and existing investor Lynwood (Schweiz) AG. Funds will be used for the commissioning of NexWafe's 5MW wafer production line in Freiburg, and for initial customer qualifications.

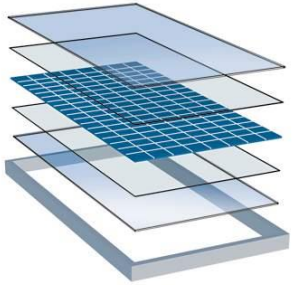
"NexWafe's technology provides superior quality monocrystalline wafers that are a drop-in replacement for current products, at dramatically reduced cost and with fewer processing steps and lower energy consumption," said Bruce Niven, Chief Investment Officer of SAEV. "We are

Drop-in, high-quality mono-crystalline EpiWafer

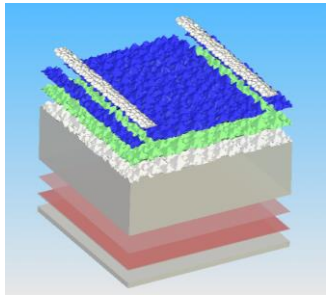
Potential Induced Degradation PID in Modules
Technical Solutions*

- System: grounding of the negative pole, regeneration at night, micro-inverter

- Module: alternative cover glass, encapsulation material, frameless module



- **Cell****: modification of the cell structure, use a thin diffusion barrier



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* H. Nagel et al., *Proc. 26th EU PVSEC* (2011) 3107.

**ISE Patents: EP 2 478 564 B1, CN102498573 B

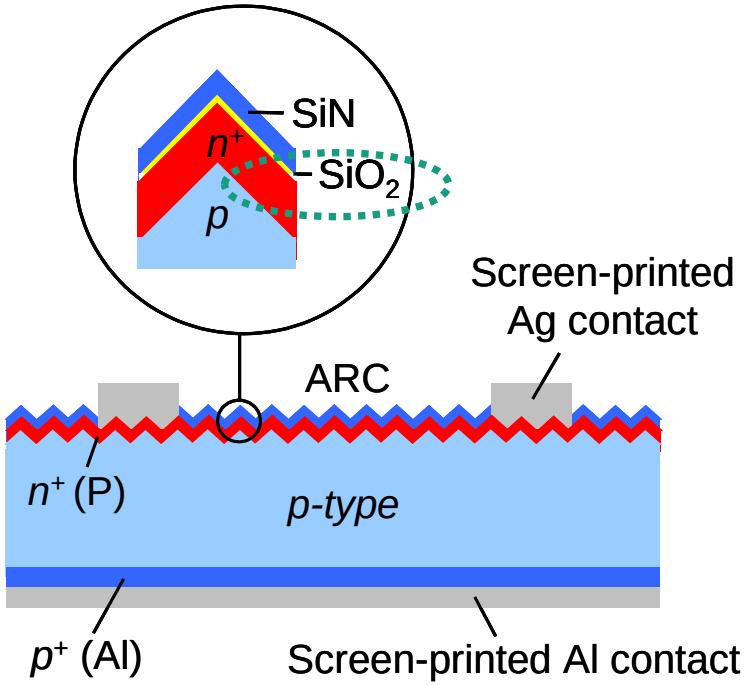
Inline Manufacturing of PID-s Resistant Solar Cells
Industrial Processing Sequence

Wafers:

Boron-doped Si, 0.5 - 2 Ωcm, 156 x 156 x 0.17 mm³

Process flow:

- texture and clean
- $POCl_3$ Diffusion
- rear side & PSG etch
- inline oxidation
- PECVD SiN
- screen-printing of front and rear contacts
- contact firing



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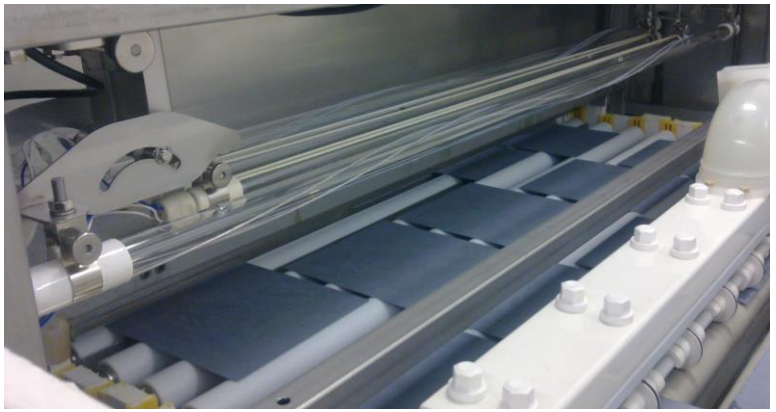
ISE Patents: EP 2 478 564 B1, CN102498573 B

Inline Process Integration

SiO_2 Formation by UltraViolet Light or Thermal Oxidation in Clean Air Environment

- UV lamp above an inline wafer transport system UV exposure time: 12 s
- Wafer temperature about 35°C
- Thickness of grown SiO_2: about 2 nm measured by ellipsometry on polished Si



- Infrared-heated walking-string furnace*
- Wafer T_{peak} = 820°C
- Thickness of grown SiO_2: about 3 to 4 nm measured by ellipsometry on polished Si

* D. Biro et al., Solar Energy Materials & Solar Cells 74 (2002) 35.

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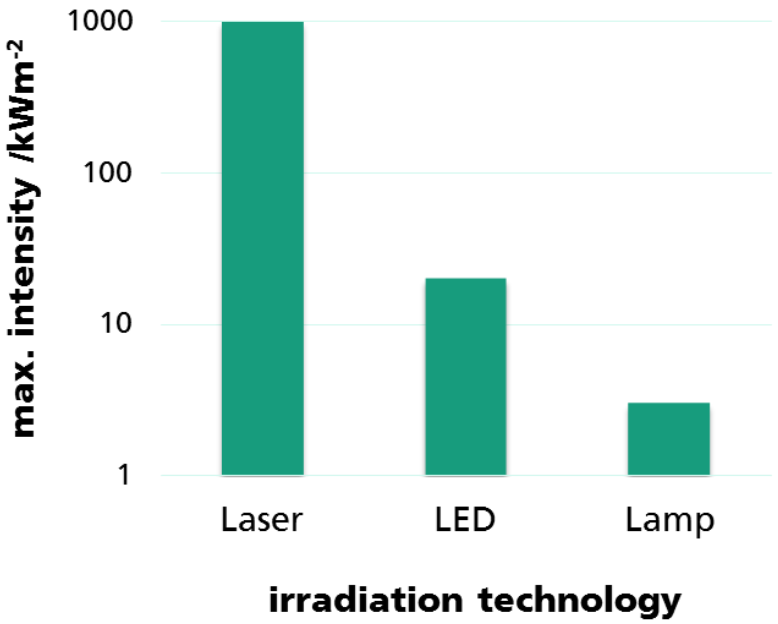
Light Induced Degradation LID

Prevention of BO-related LID – Importance for PERC

- Boron-doped Cz silicon suffers from carrier induced lifetime degradation
  - → efficiency of industrial PERC solar cells can degrade 1-2%$_{abs}$ *
- Prevention of BO-related LID by **regeneration** processes
  - → Ultra Fast Regeration (UFR) by *higher injection levels ⊿n and illumination intensity*
  - → use of high power lasers



* Ref: Wasmer, et al., SiliconPV 2017

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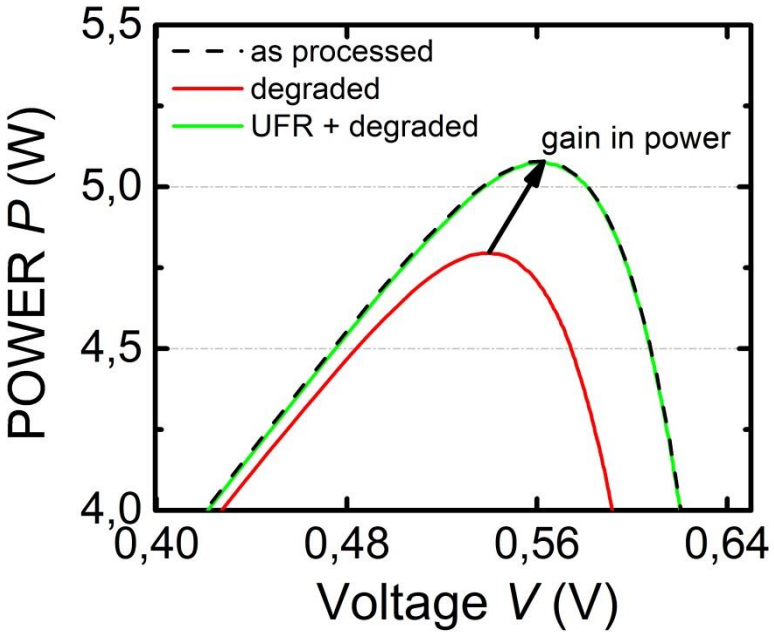
Ultrafast Regeneration Technology

Prevention of BO-related LID – Importance for PERC



state	V_{oc} (mV)	J_{sc} (mA/cm²)	*FF* (%)	η (%)
as processed	666	39.8	80.2	21.25
degraded	644	39.2	79.6	20.08
UFR + degraded	665	39.7	80.3	21.20

➔ prevent up to 98% of the power loss caused by BO-LID in 4s process-time

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Ultrafast Regeneration Technology
In-Line Tool

- Robust and flexible laser irradiation
  - → Up to 98% regeneration completeness demonstrated in less than 4s irradiation time
- Fastest known in-line BO-regeneration process
- Very small footprint < 4 m²
- Single track belt speed of > 8000 mm/min

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THERMAL SYSTEMS

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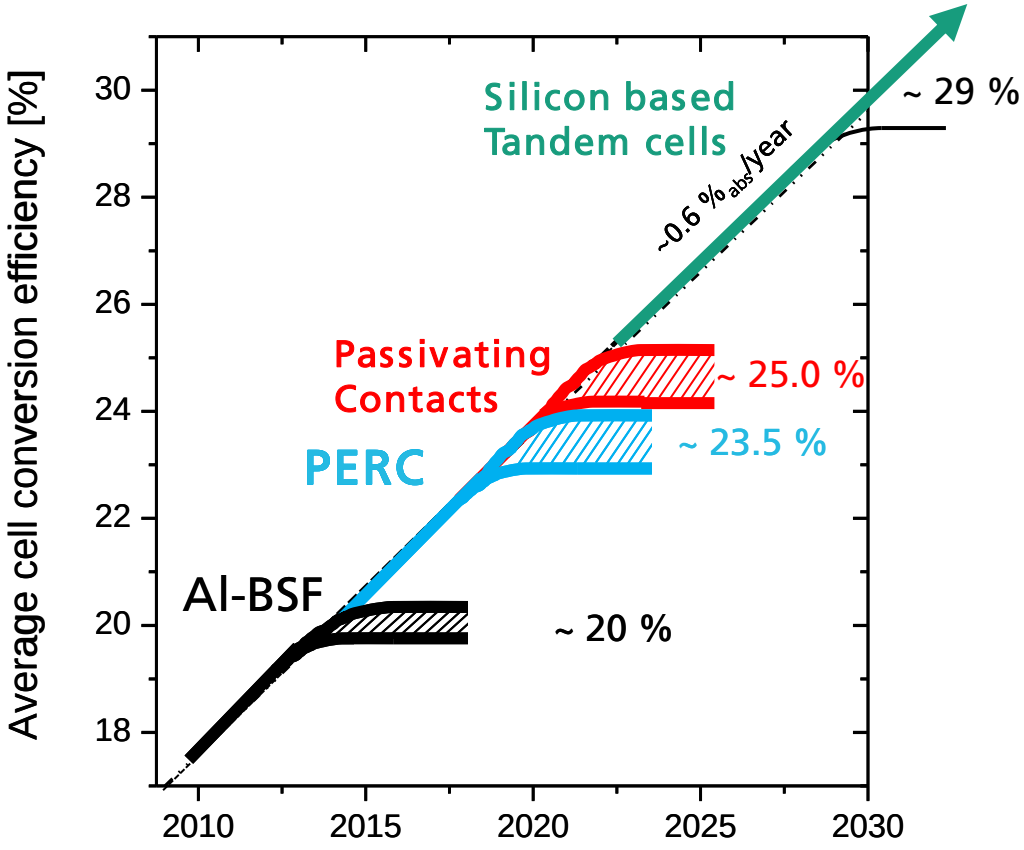
From Present to Future
PERC – What is the Limit?

- PERC efficiency will continuously increase due to evolutionary improvements
- Stagnation due to physical limitations **contact recombination** and **lateral current flow**

→ Passivating Contacts

→ Silicon based Tandem Cells



Source: Hermle PV Manufacturing in Europe, Brussels 2017

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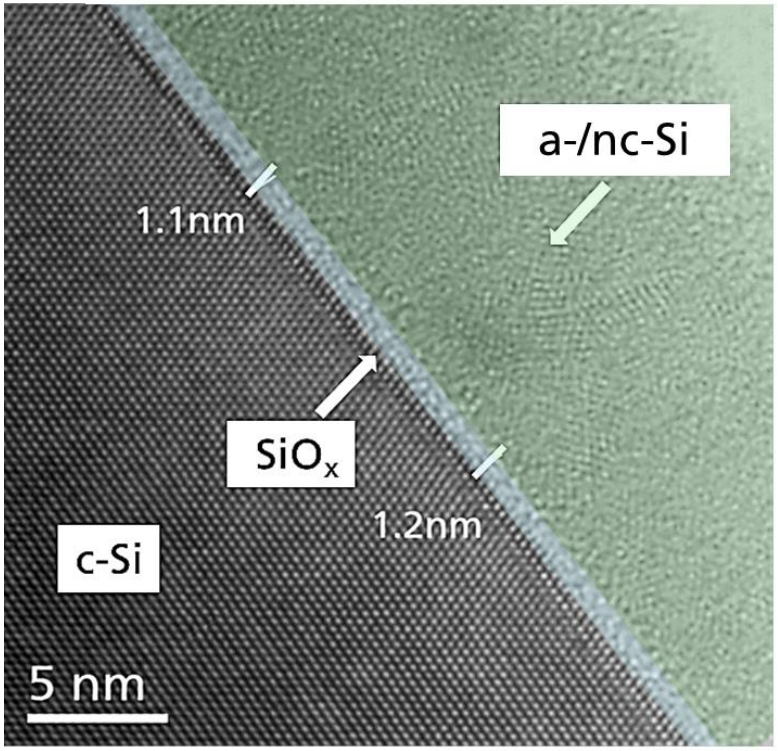
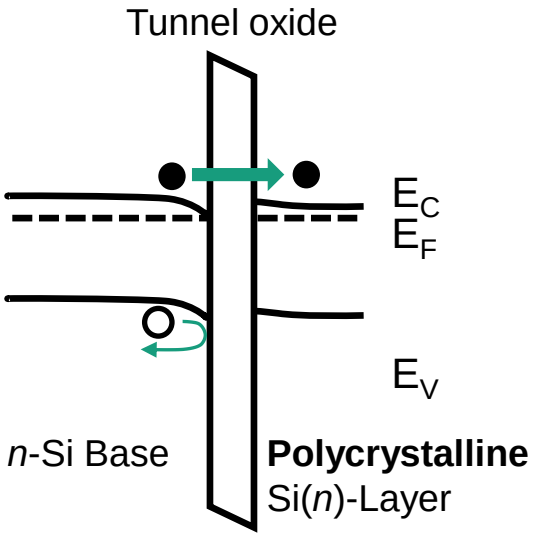
Passivating and Selective Contacts
High Temperature Approach

TOPCon Structure





Post, IEEE Transactions on Electron Devices (1992)

F. Feldmann et al., *SOLMAT 120* (2014)

U. Römer, et al. IEEE Journal of Photovoltaics (2015)

D. Yan Solar Energy Materials and Solar Cells (2015)

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Passivating and Selective Contacts
High Temperature Approach: ISE Records

Material	Area	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
n-type Mono	4 cm² (da)	724	42.9	83.1	25.8* A)
n-type Multi	4 cm² (ap)	674	41.1	80.5	22.3* B)
n-type Mono	100 cm² (ap)	713	41.4	83.1	24.5* C)

* confirmed by Fraunhofer ISE Callab

- ➔ **TOPCon PECVD process scalable**
- ➔ TOPCon PECVD process transferred to industrial equipment J_0 ~ 0-3 fA/cm² , ρ_c~ 3 mΩcm²

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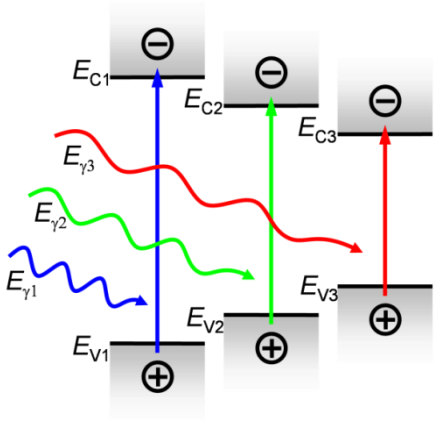
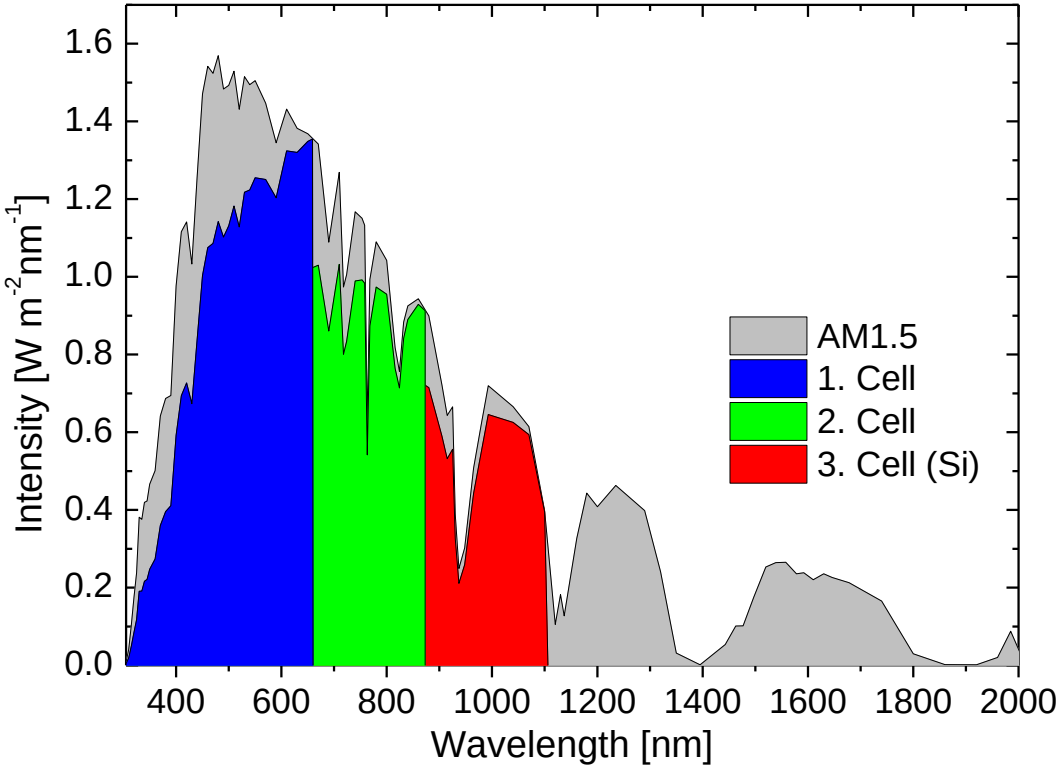
A) A. Richter et al, EUPVSEC, Amsterdam, 2017
B) J. Benick et al, EUPVSEC, Amsterdam, 2017
C) F. Feldmann et al, EUPVSEC, Amsterdam, 2017

Future
Beyond the Single-Junction Limit



- Tandem cells with silicon as bottom cell
  - Perovskite top cell
  - III/V top cell



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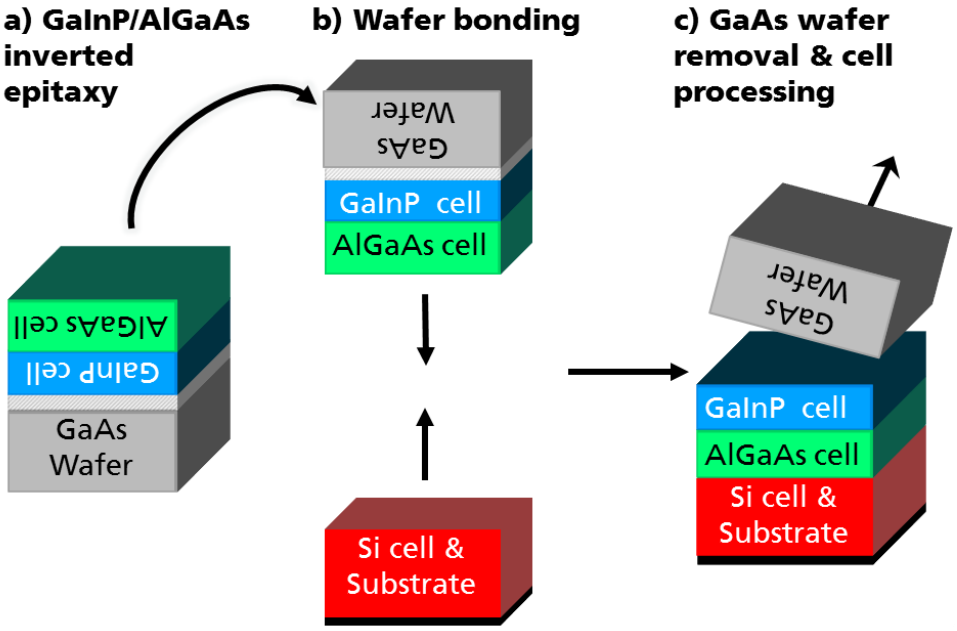
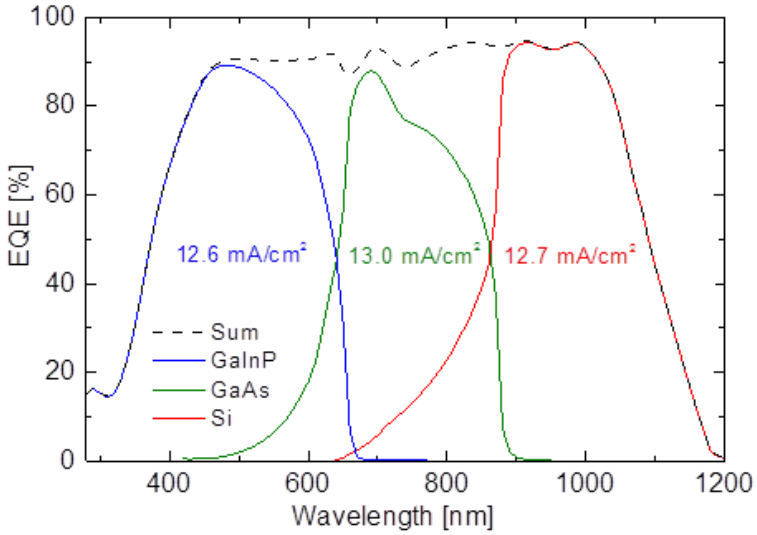
Assembling of Silicon and III-V Solar Cell
Surface Activated Wafer Bonding

Process flow





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R. Cariou, J. Benick, P. Beutel, N. Razek, Ch. Flötgen, M. Hermle, D. Lackner, S. Glunz, A.W. Bett, M. Wimplinger, F. Dimroth, IEEE JPV. 7, No. 1, January 2017, p. 367-373

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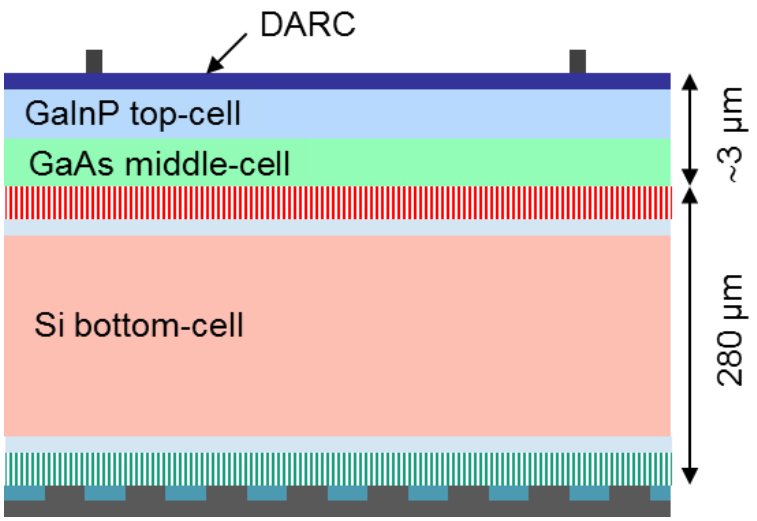
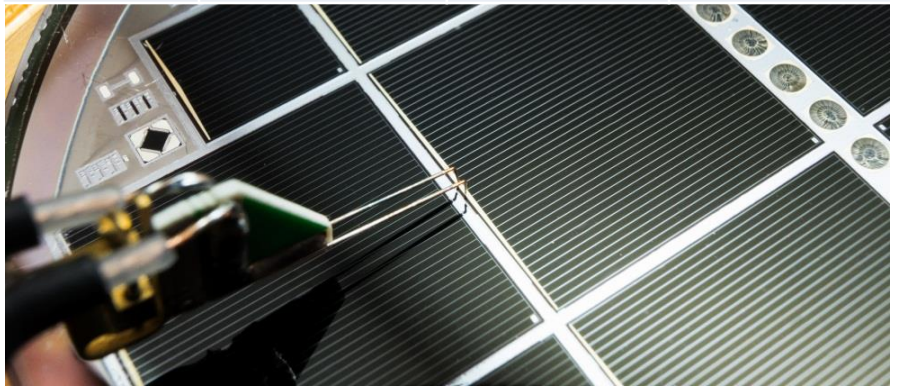
Results of III-V//Si Solar Cells

Efficiency: **33.3%**

→ World record efficiency



V_{oc} [V]	J_{sc} [mA/cm²]	*FF* [%]	η [%]
Gen 1			
3.046	11.7	87.5	31.3
Gen 2			
3.125	11.6	86.5	31.4
Gen 3			
3.127	**12.7**	83.8	**33.3**



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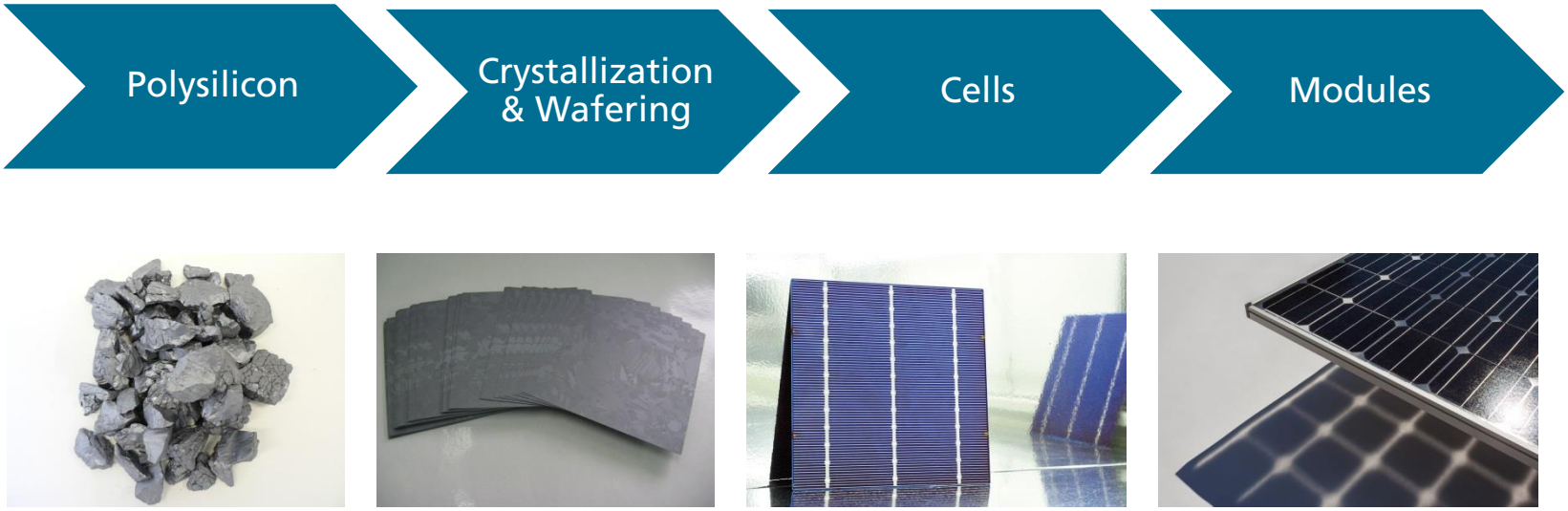
Silicon Module Production Sequence

From Quartz to Power



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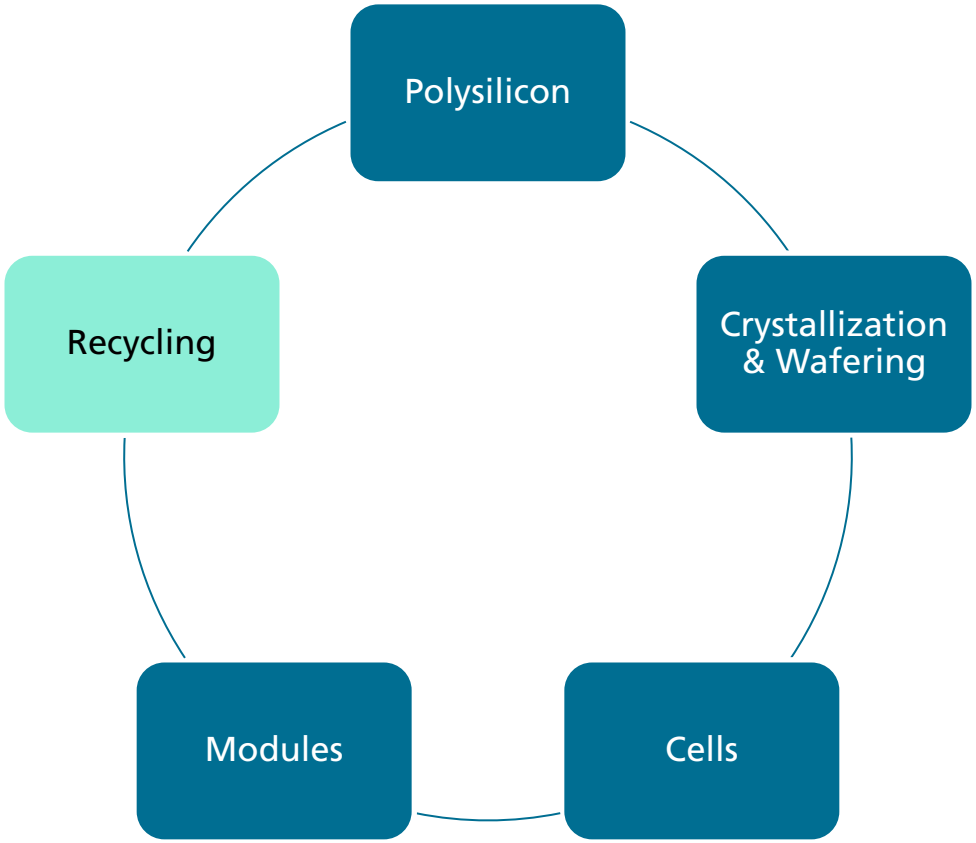
Silicon Module Production Sequence

From Quartz to Power – New: The Circle Economy



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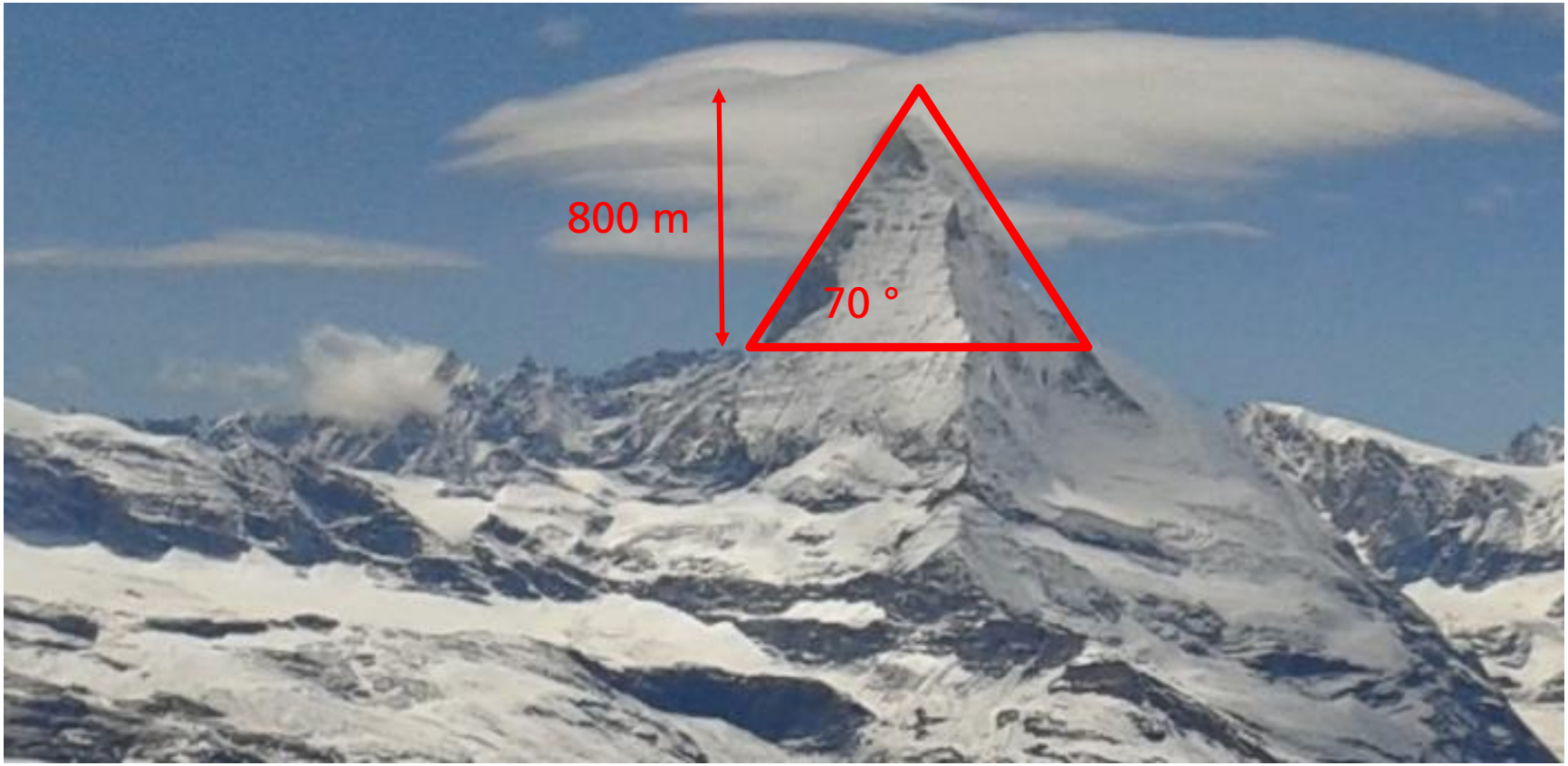
Recycling



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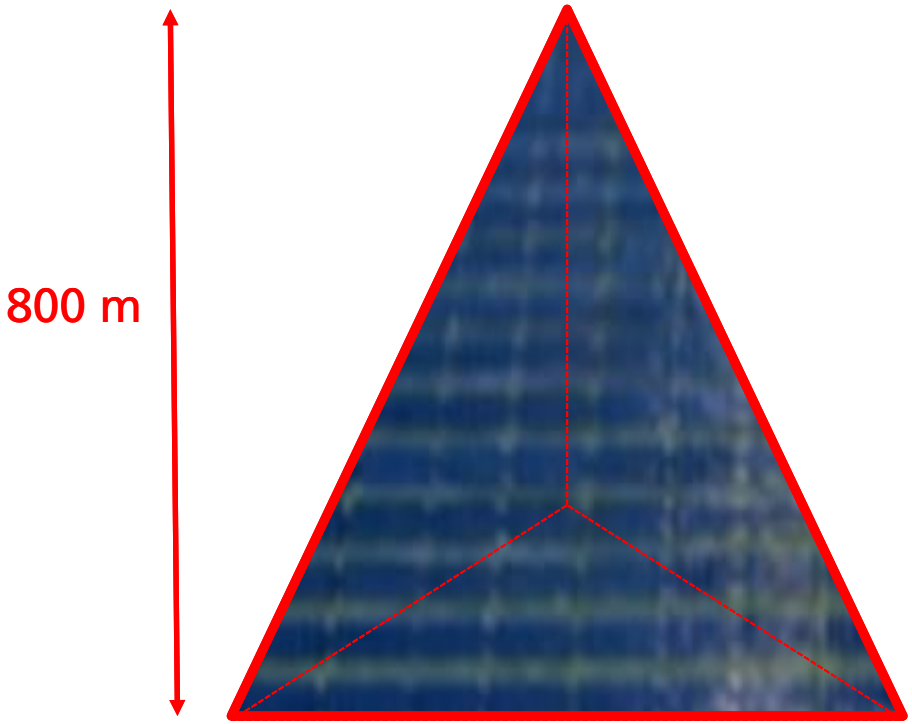
Recycling



Modul:
300 Wp, 1.67*1.0*0.033 m³, 18 kg

→ 212 GW
→ 1272 Gt

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Sustainability and Recycling
Recycling of End-of-Life Modules

Re-use of the raw materials for manufacturing of new modules

Development of a robust, low cost process for the recycling of end-of-life PV-modules

- extraction of silver, copper, tin
- extraction and refinement of silicon
- separation of the low-iron front glass and re-use for the manufacturing of new solar glass

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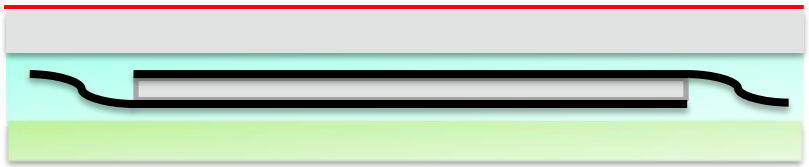
Module by Design for easier Recyling Processes

TPEdge Module

laminated module with backsheet, framed

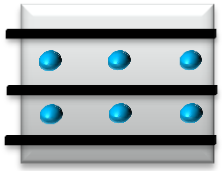


laminated module with rear glass (no seal, no frame)

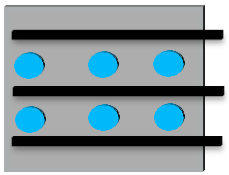
TPEdge* module build-up with thermoplastic sealing,
no laminate, no frame

side view

top view



rear view



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*ISE Patent: CN102396077A

TPEdge Modul in Operation

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Conclusions

- Fraunhofer ISE addresses with R&D:
  - near term needs of industry
    → transfer process know-how
  - develop next generation technologies
    → material: EpiWafer
    → cell: selective contacts and passivation, tandems
    → module: TPEdge
    → recycling technologies
- We work in tandem with industries or we spin-out companies

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Thank you for your attention!

Coloured photovoltaic modules made at Fraunhofer ISE

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