Photonics and Laser Material Processing for Solar Energy Systems at Fraunhofer ISE

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Fraunhofer Institute for Solar Energy Systems ISE

EPIC Online Technology Meeting on Solar Energy Systems

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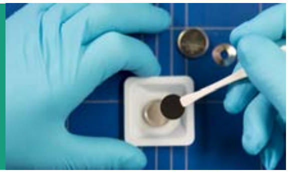
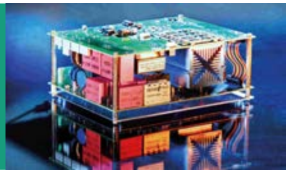
www.ise.fraunhofer.de

Fraunhofer ISE

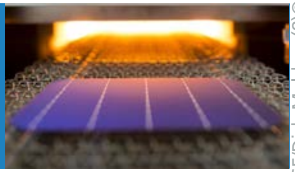
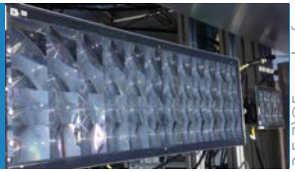
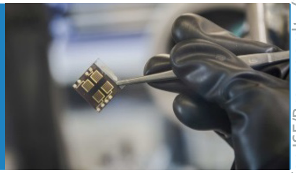
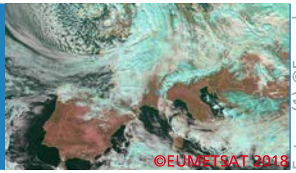
Fraunhofer ISE
Fields of Research

ISE: **I**nstitute for **S**olar **E**nergy Systems
Staff: ≈ 1200
Budget 2019: € 102.6 million (preliminary)
Established: 1981

ENERGY TECHNOLOGIES AND SYSTEMS
Prof. Dr. Hans-Martin Henning

- Energy Efficient Buildings 
- Solar Thermal Power Plants and Industrial Processes 
- Hydrogen Technologies and Electrical Energy Storage 
- Power Electronics, Grids and Smart Systems 

PHOTOVOLTAICS
Dr. Andreas Bett

- Silicon Photovoltaics 
- III-V and Concentrator Photovoltaics 
- Emerging Photovoltaic Technologies 
- Photovoltaic Modules and Power Plants 

Other Photonics Technologies @ ISE

Portofolio of Group Coating Technology and Systems CTS

Solutions based on functional vacuum coatings

- Solar thermal power generation
- Energy efficiency
- Photovoltaics
- Fuel cells and H_2 generation

thermal solar receiver tube and mirror

Colored PV modules

Facade with low-E glazing

Optically-switchable glazing

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Other Photonics Technologies @ ISE

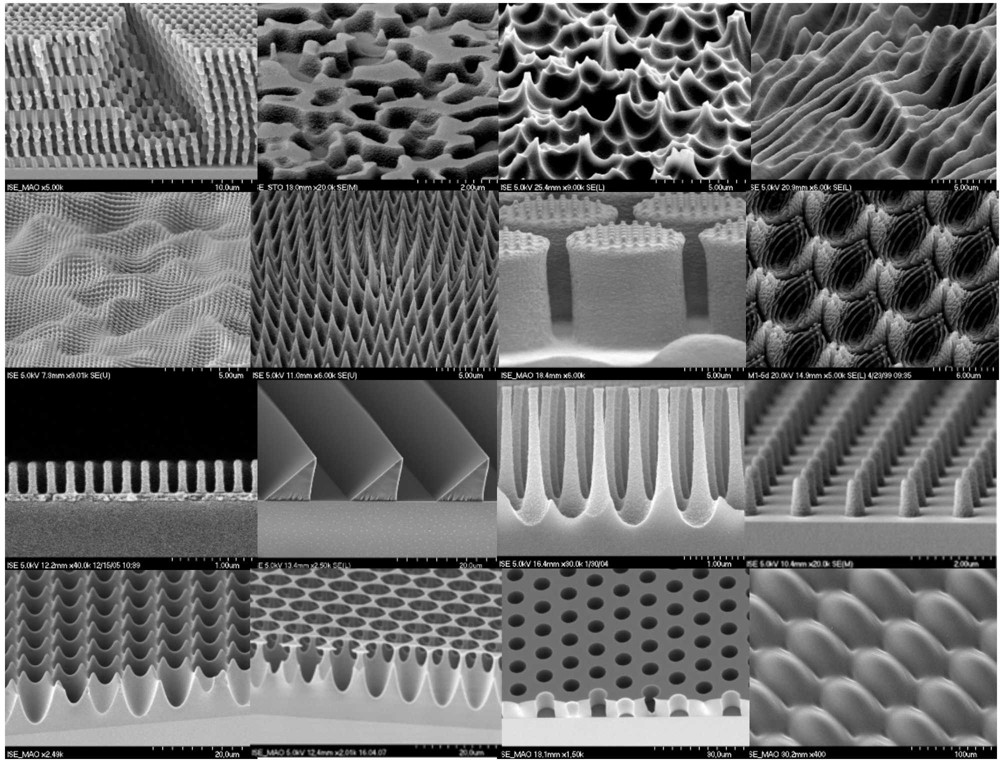
Fabrication of Photonic Structureswith Interference Lithography

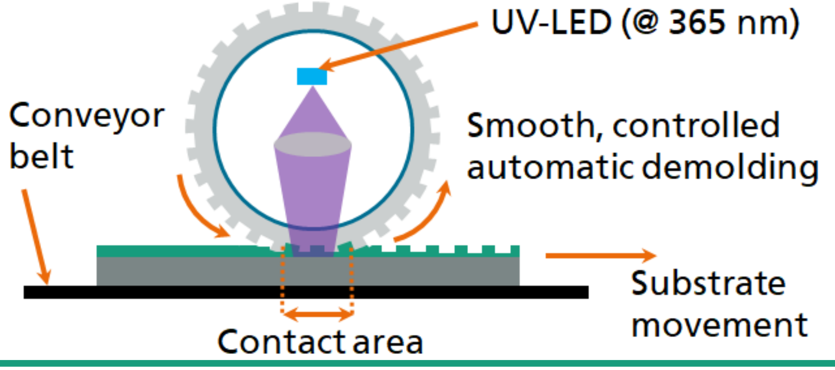
- Maximum substrate size: 1.2 x 1.2 m²
- Seamless structures over full area
- Exposure times:
  up to 5 h
- Optical path lengths:
  up to 20 m
- Acceptable instabilities: < 20 nm

→ Extreme stability requirements
for building and set-up

Other Photonics Technologies @ ISE
Nanoimprint Lithography

- UV-exposure throughout flexible stamp (e.g. PDMS)
- Imprinted area: 156 x 156 mm²
- Excellent adaptability to rough surfaces
- Homogeneous and low residual layer thickness (< 100 nm)
- Successfully tested on very thin wafer substrates (50 µm)





H. Hauser et al., IEEE Journal of Photovoltaics, 2 (2),114-122 (2012)

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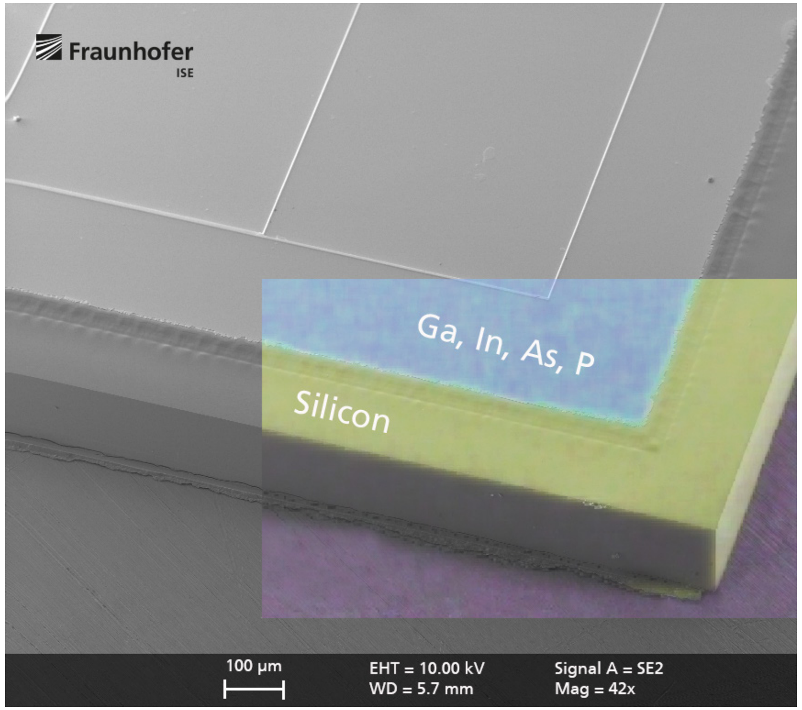
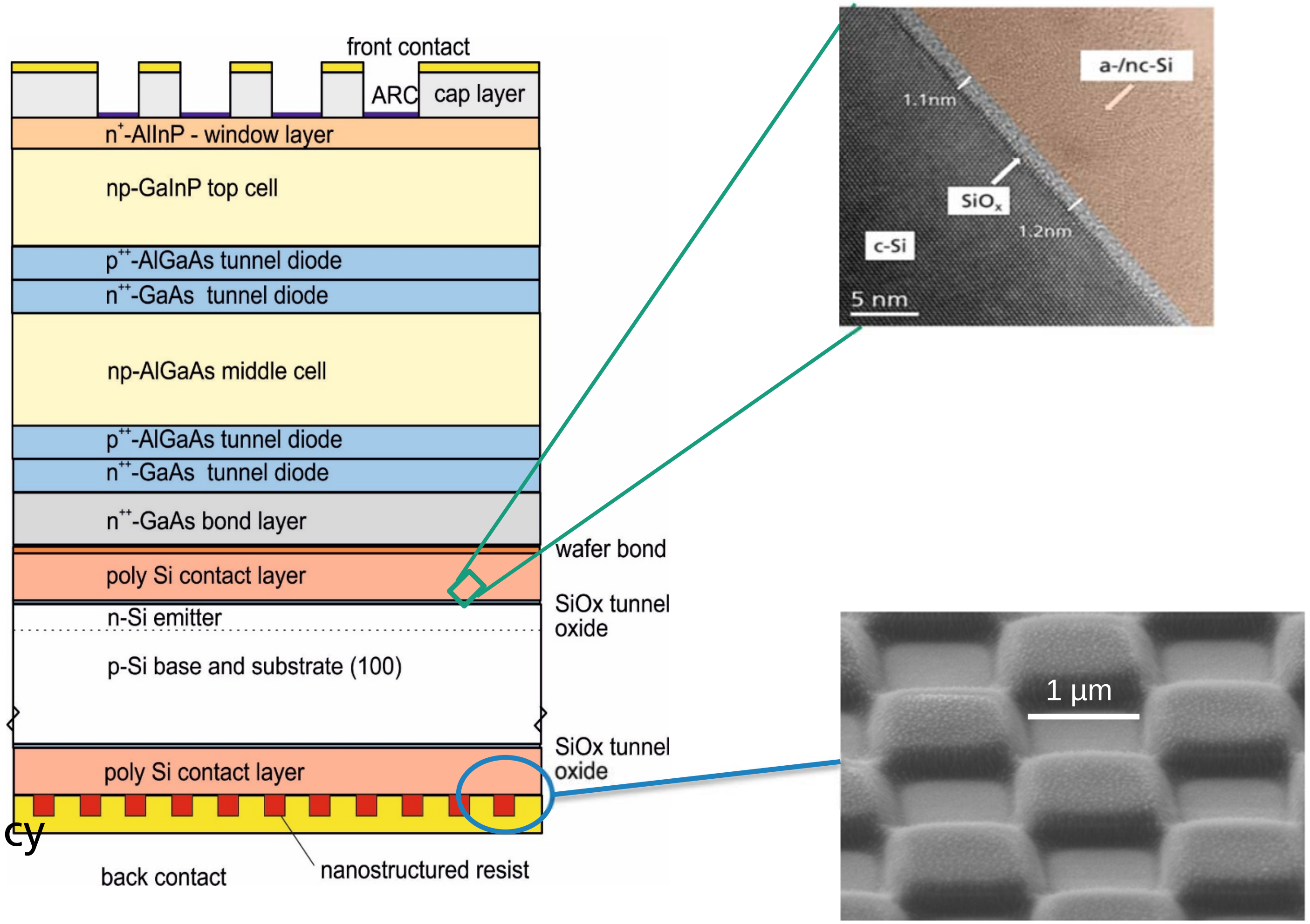
III-V/Si Triple-Junction Solar Cells (2-Terminal)

Rear Side TOPCon with Nanostructured Grating





4.8 µm of III-V material enable an efficiency increase from 26.7%* to 34.1% (AM1.5g)

* Best Si solar cell according to M.A. Green et al. „Solar cell efficiency tables (Version 55)", Prog. In PV, 2019

R. Cariou, Nature Energy (2018) doi:10.1038/s41560-018-0165-5

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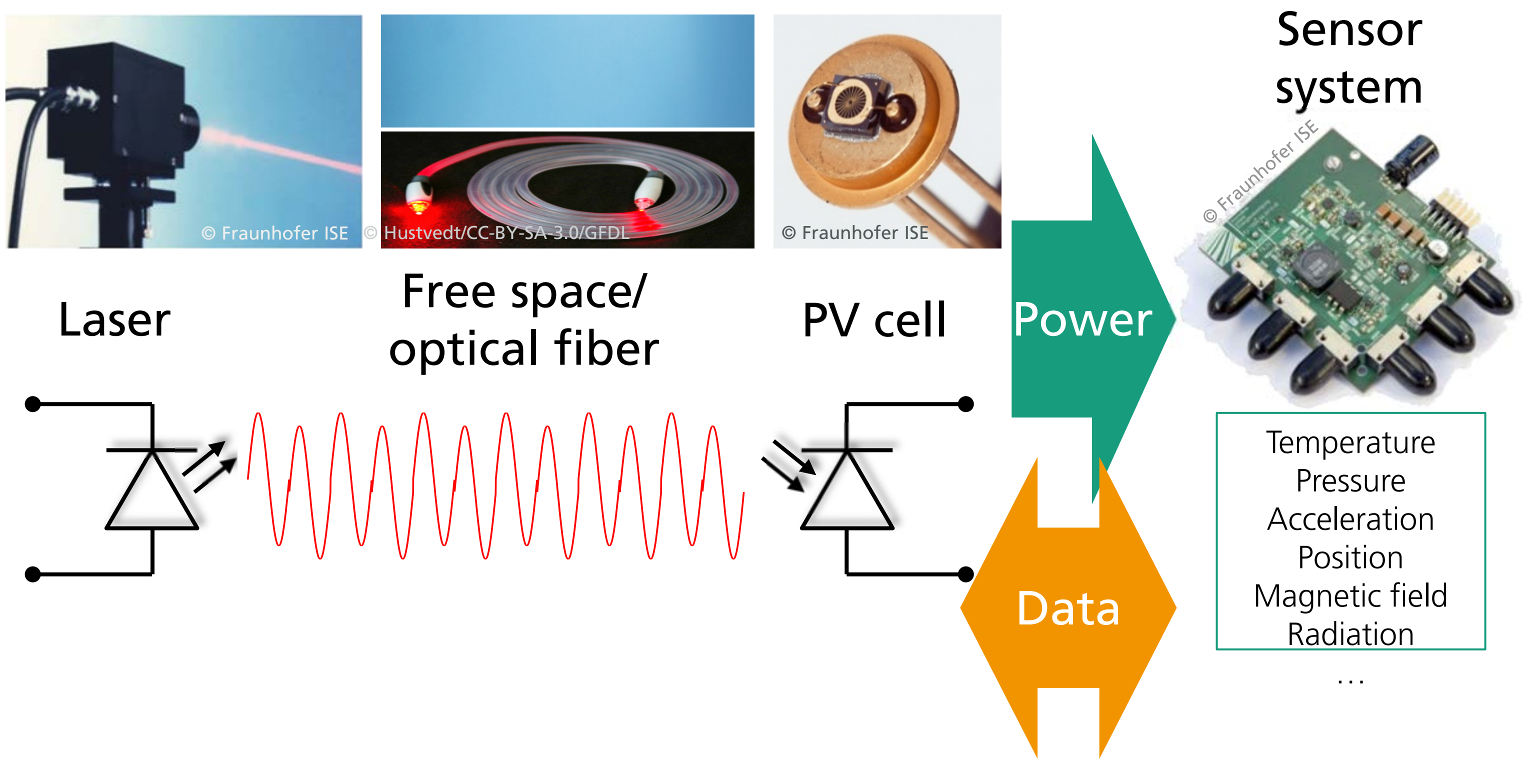
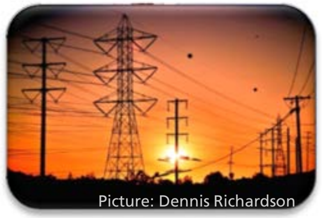
Other Photonics Technologies @ ISE

Optical Power Supply & Bidirectional Communication in Purely Optical Channel



Electromagnetic interference

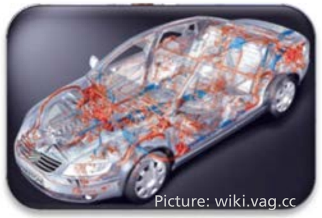
Wireless power



Galvanic isolation

Lightning protection

Explosion protection



Weight reduction

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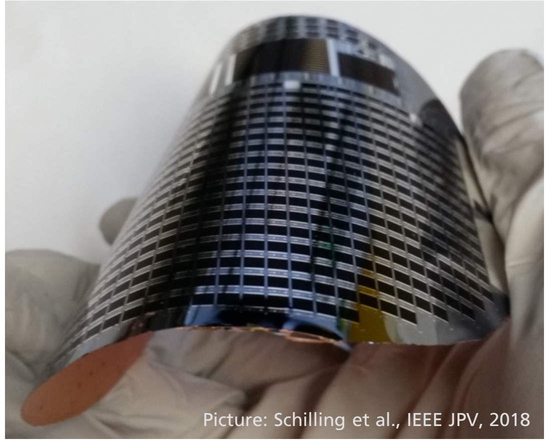
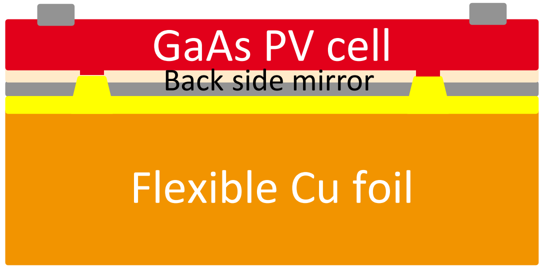
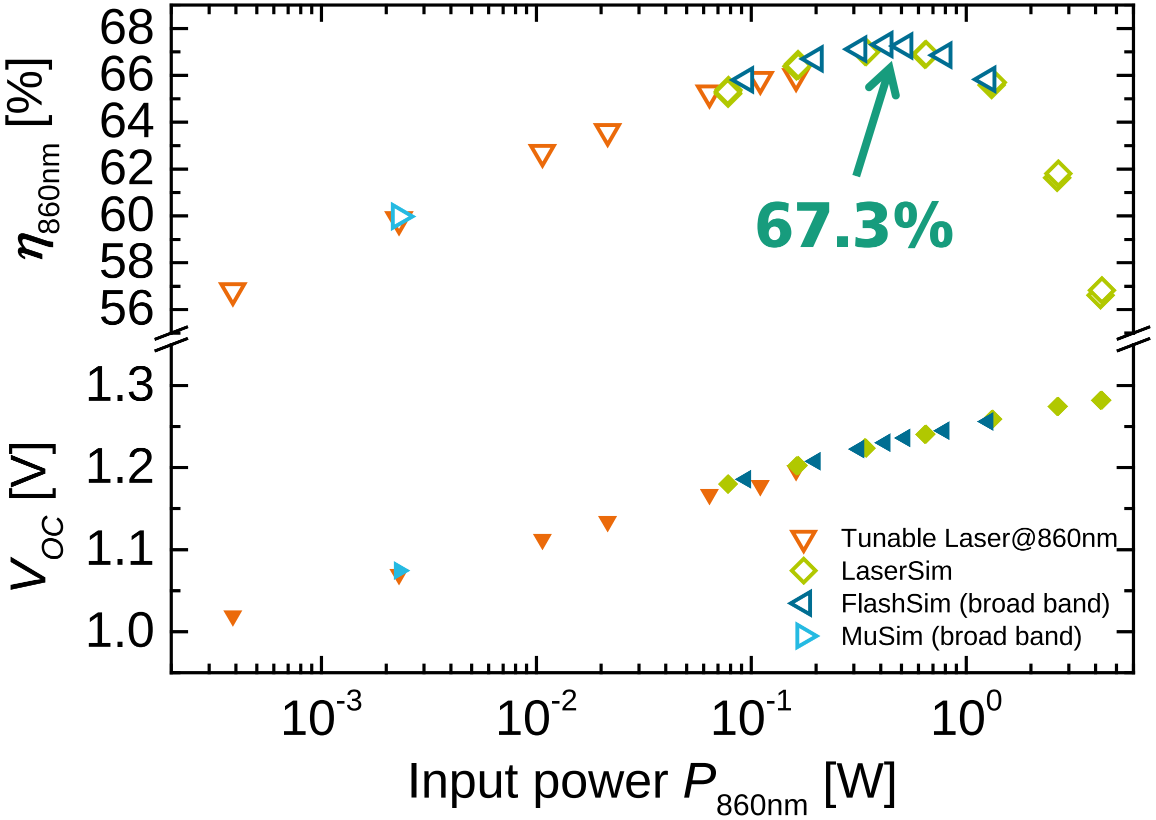
Other Photonics Technologies @ ISE

Photovoltaic Laser Power Converter: GaAs Cells under Monochromatic Light


Picture: Schilling et al., IEEE JPV, 2018



Single-junction GaAs



Schilling, et al., IEEE J Photov 8(1), 2018.
Helmers, et al., to be published.

Photovoltaics Market Overview

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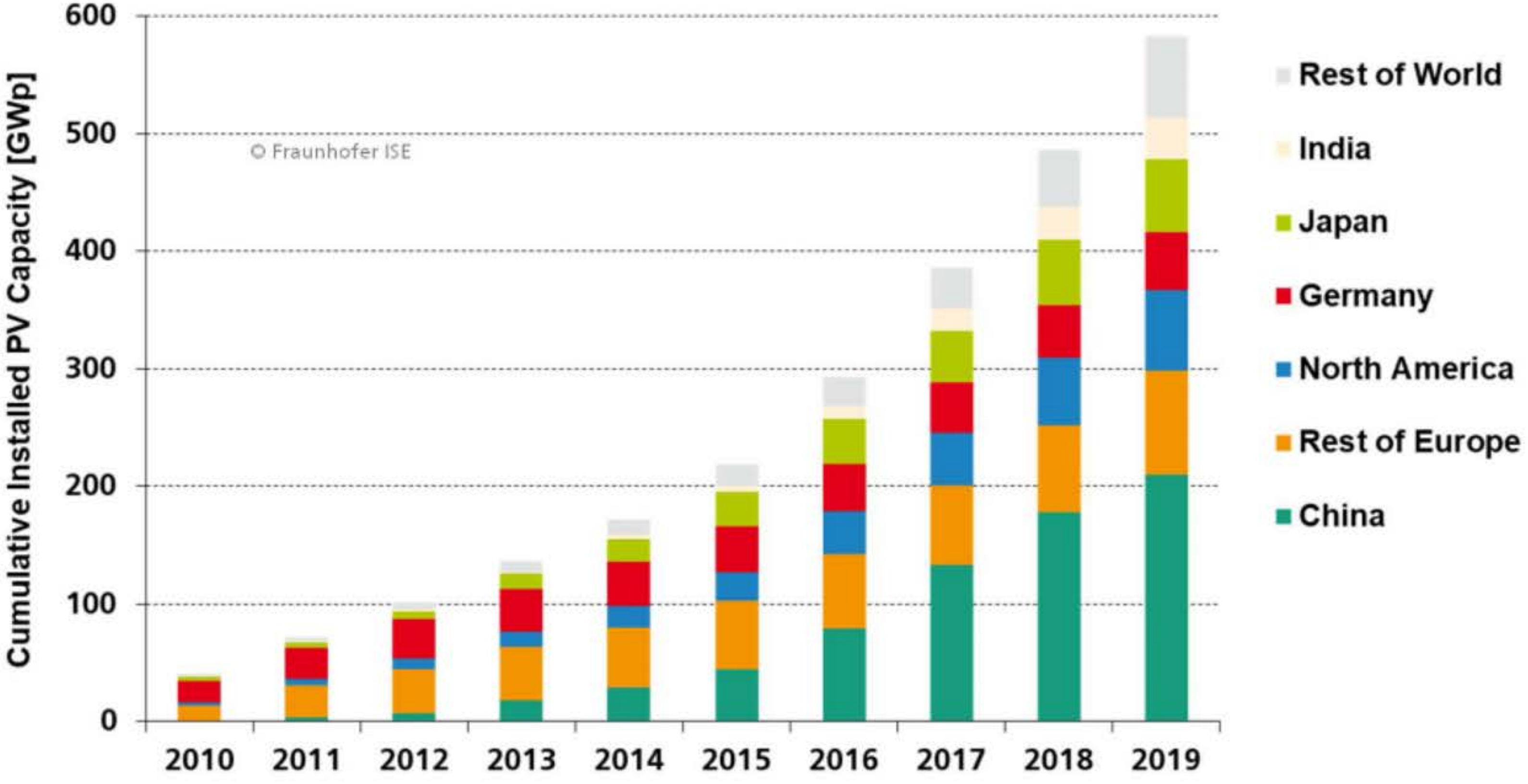
PV Production by Technology
Percentage of Global Annual Production

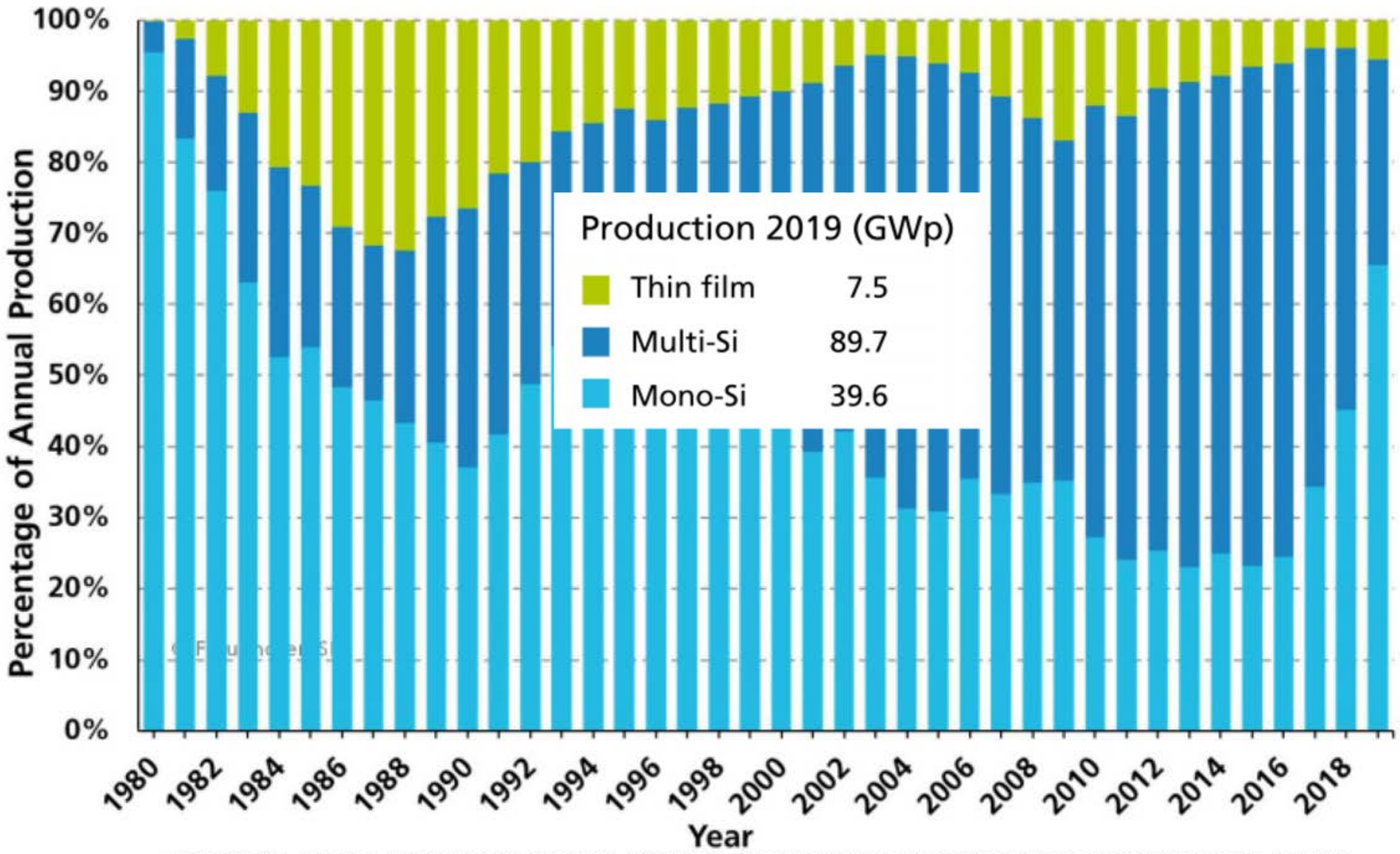


The share of off-grid installations decreased by time; from about 1% in year 2010 to about 0.6% in year 2019.

Data: IRENA 2020. Graph: PSE Projects GmbH 2020

Photovoltaics Market
Dominance of Wafer Based Solar Cells

- Wafer based crystalline silicon solar cells dominate > 90% of the production volume
- Thin-film technology with less than 5% market share



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE GmbH 2018

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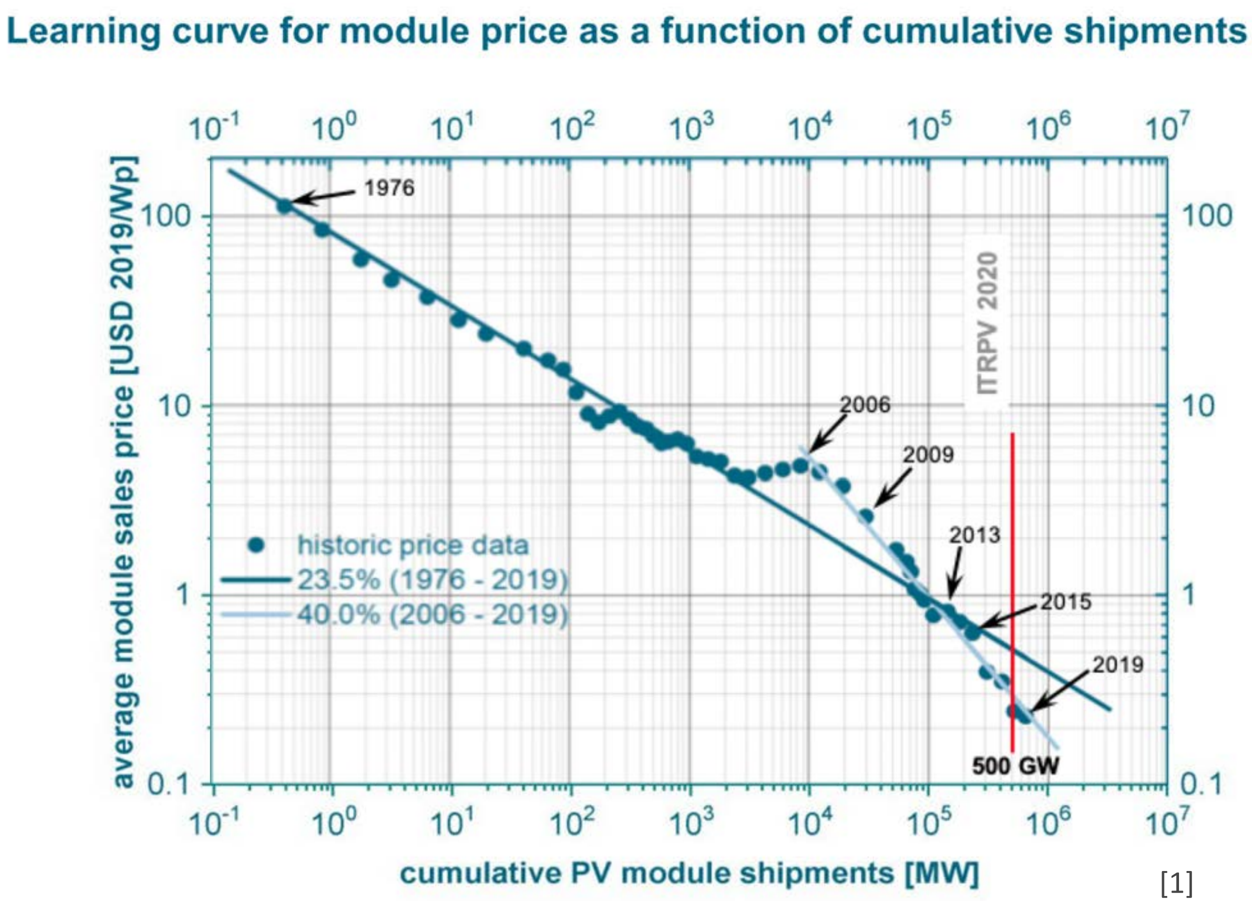
Photovoltaics Market

Price Learning Curve as Function of Cumulative Shipments – ‚Swanson's law'



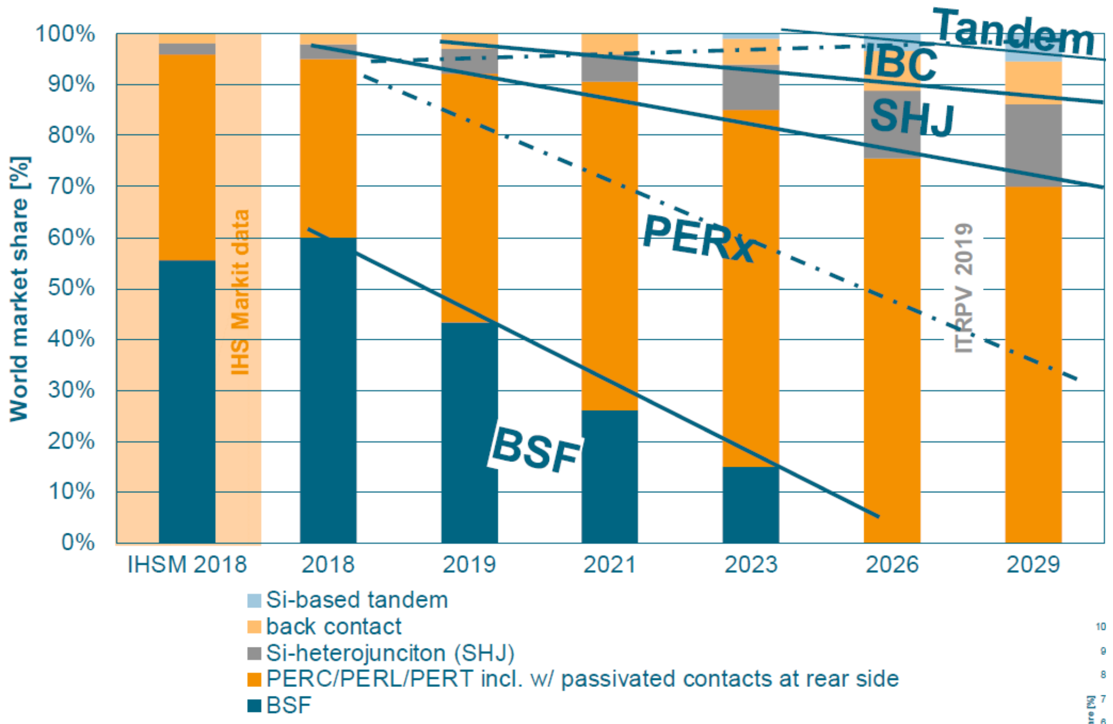
[1]

[1] VDMA, "International Technology Roadmap for Photovoltaic (ITRPV), 11th Edition," 2020

Photovoltaics Market
Device Type Trends

- Wafer based crystalline solar cells dominate > 90% of the production volume
- Thin Film technology with less than 5% market share
- PERC production in 2018 included around 1000 laser processing machines for laser contact opening alone

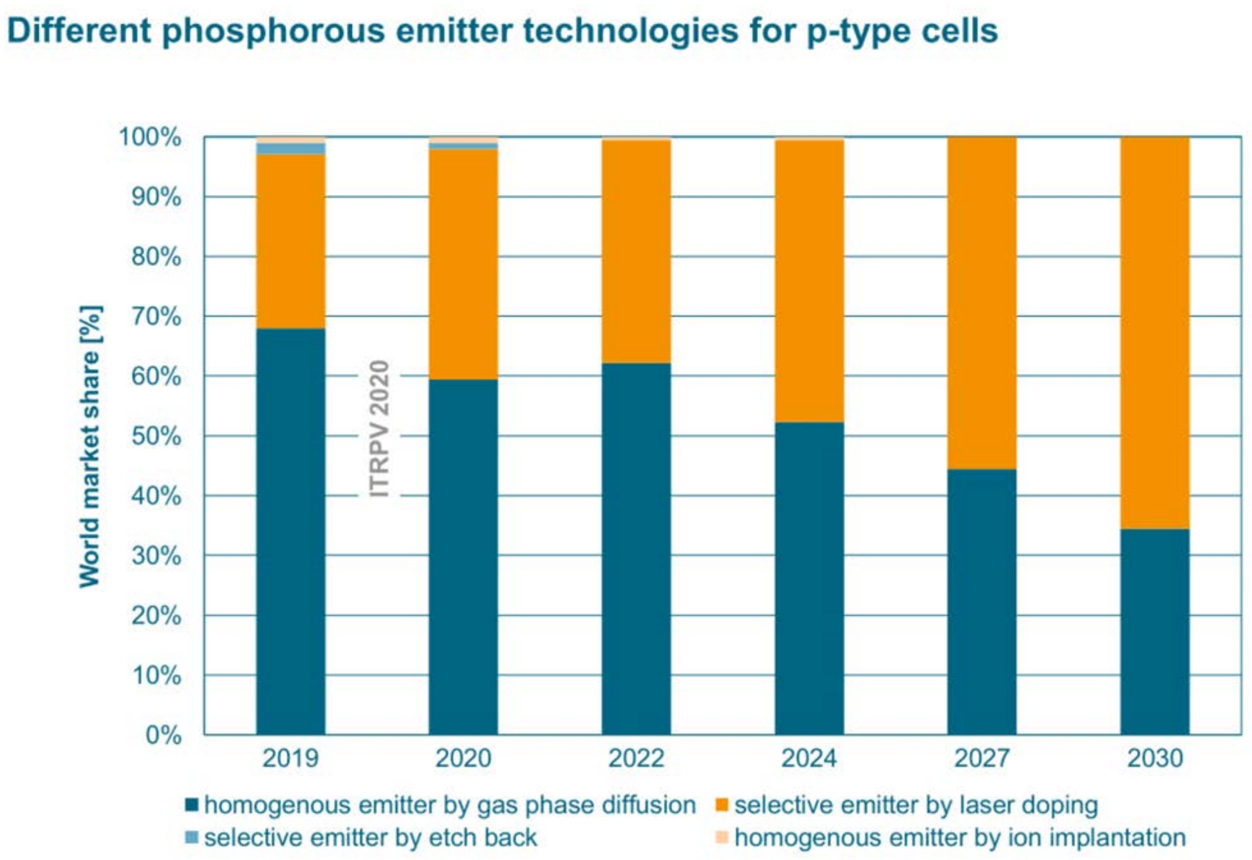
Trend: share of cell technologies



→ **PERx - technologies will dominate**
(2018 ITRPV data are close to IHS Markit)

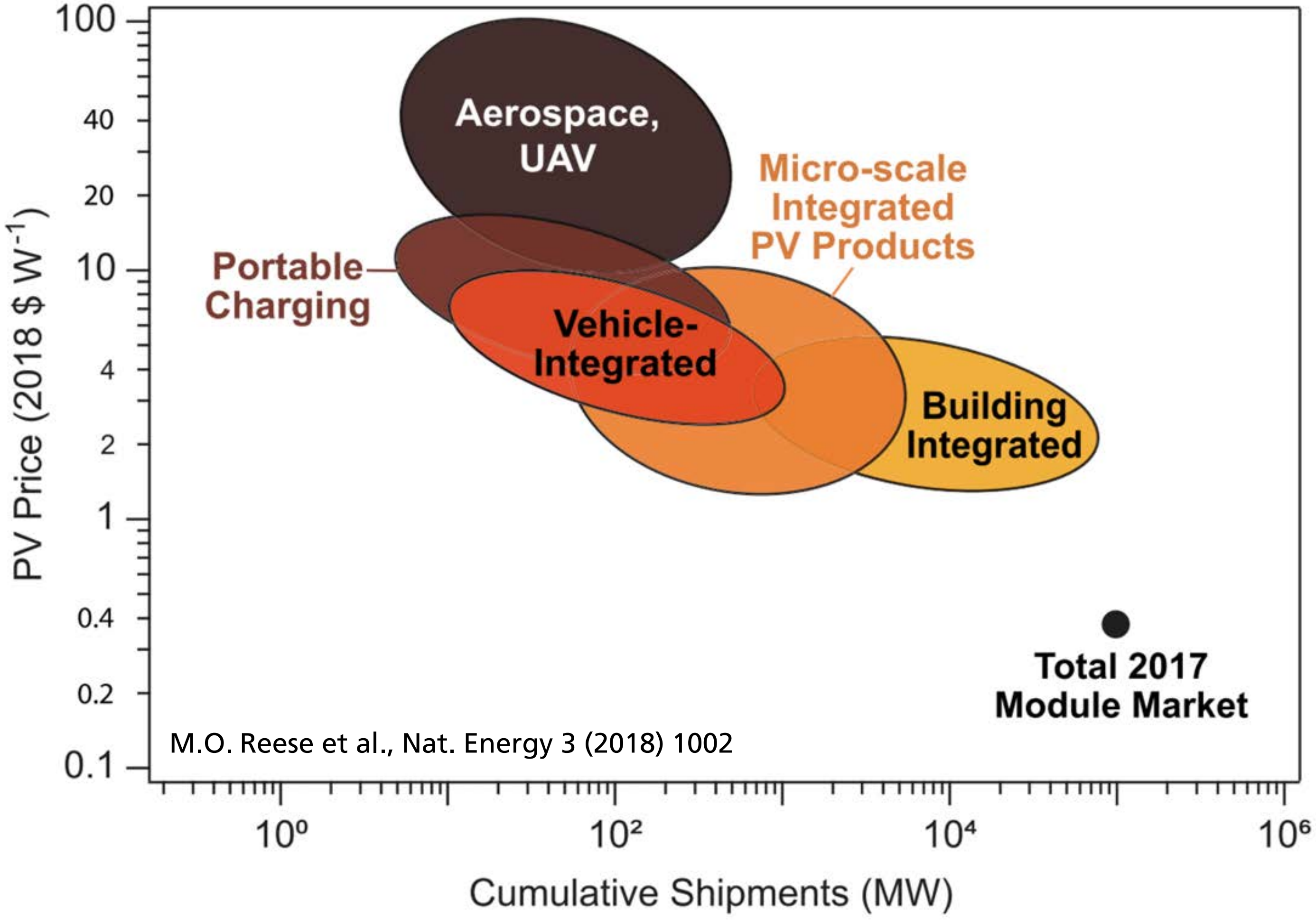
Photovoltaics Market
Widespread Adoption of Laser Doping in PERC Production Expected

- Second laser process that is due to increase market penetration after nanosecond laser contact opening is already the de facto standard for PERC solar cells



[1] VDMA, “International Technology Roadmap for Photovoltaic (ITRPV), 11th Edition,” 2020

Photovoltaics Market
Specialized Applications



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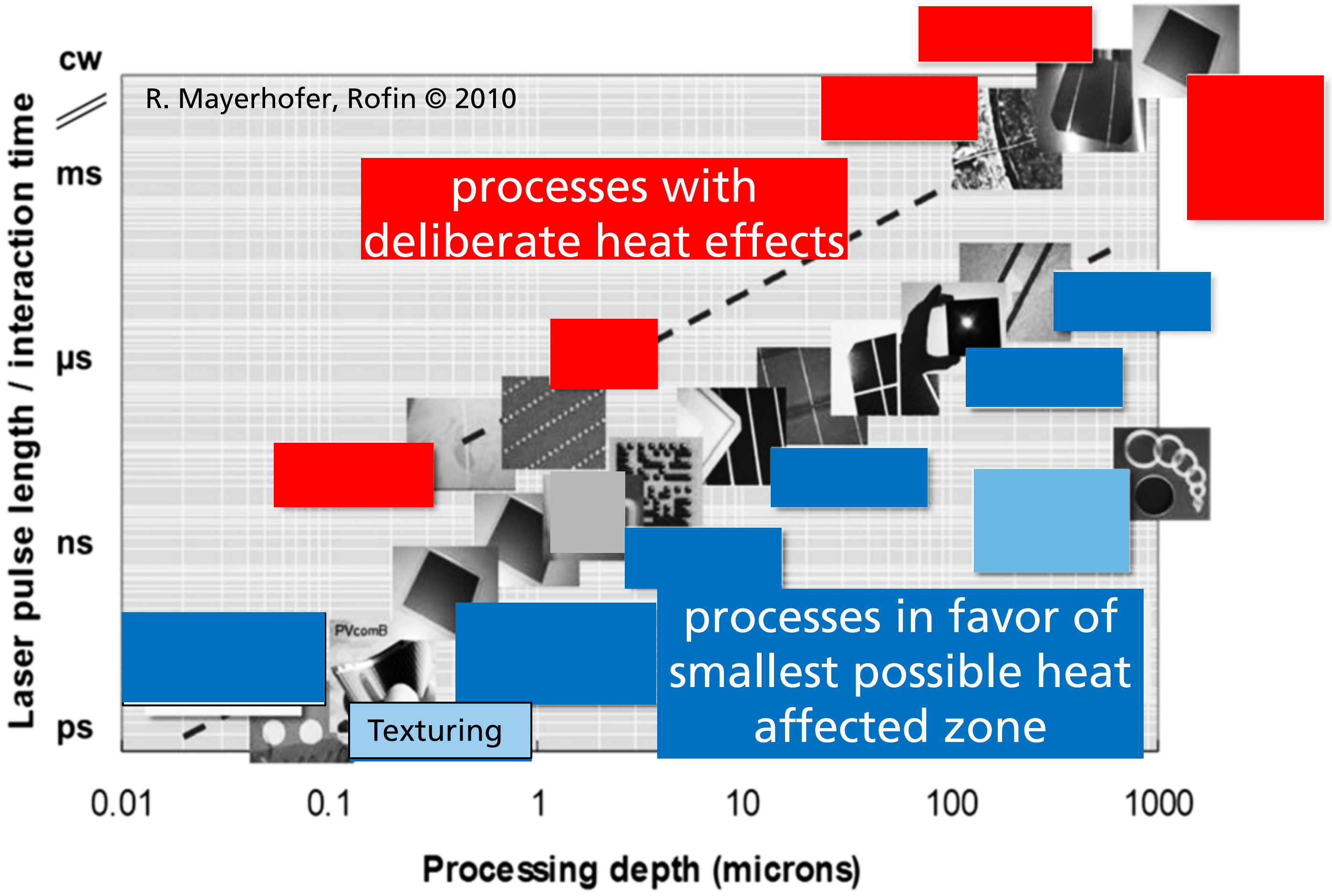
Laser Material Processing in Photovoltaic Manufacturing
Applications in Photovoltaics

- Many laser processes in PV production came and went
  - ~~Laser edge isolation~~
    → replaced by chemical etching
    → might reappear
  - ~~Via drilling~~
    → never mass adopted
  - Laser fired contacts (LFC) for PERC
    → replaced by
    laser contact opening (LCO)



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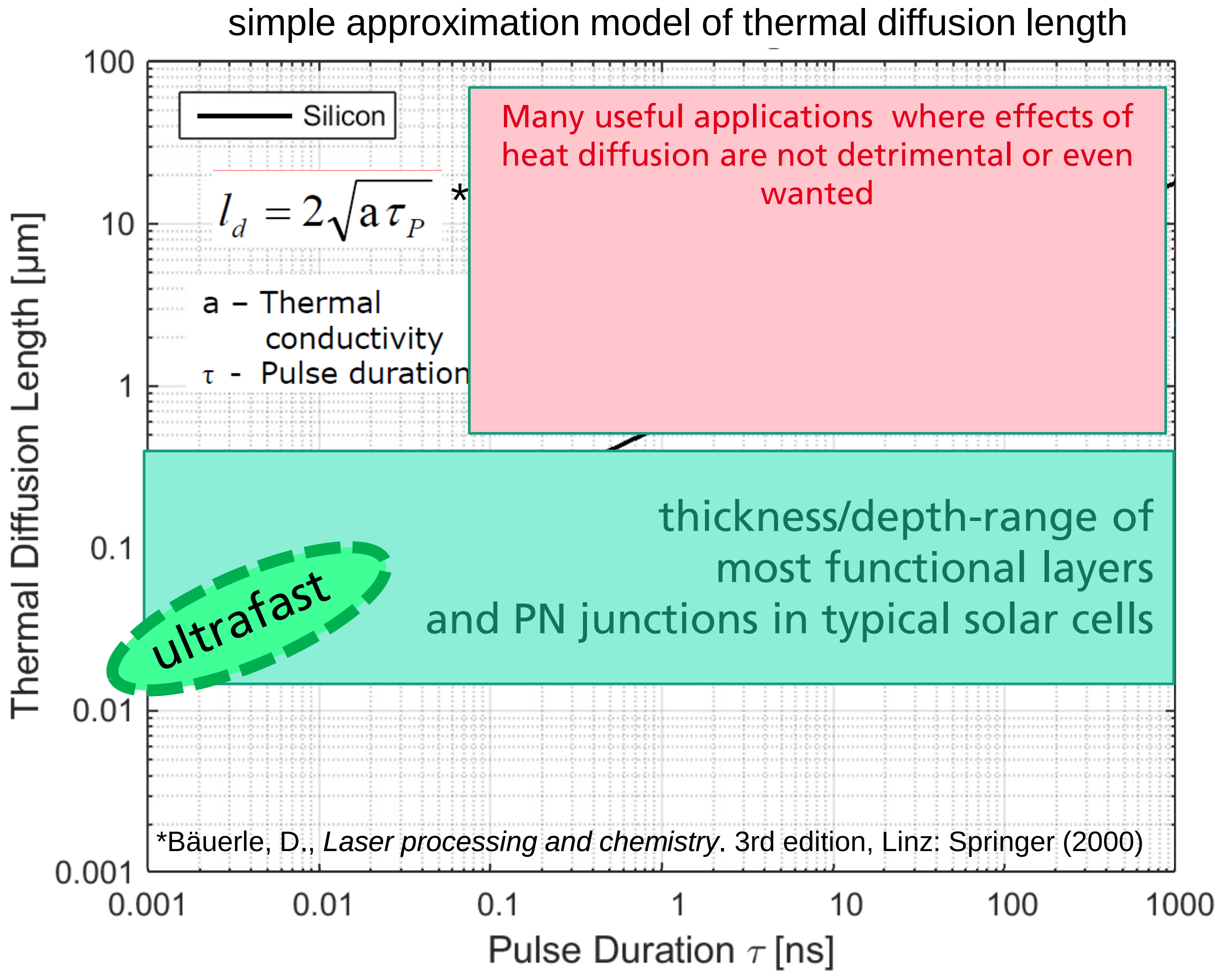
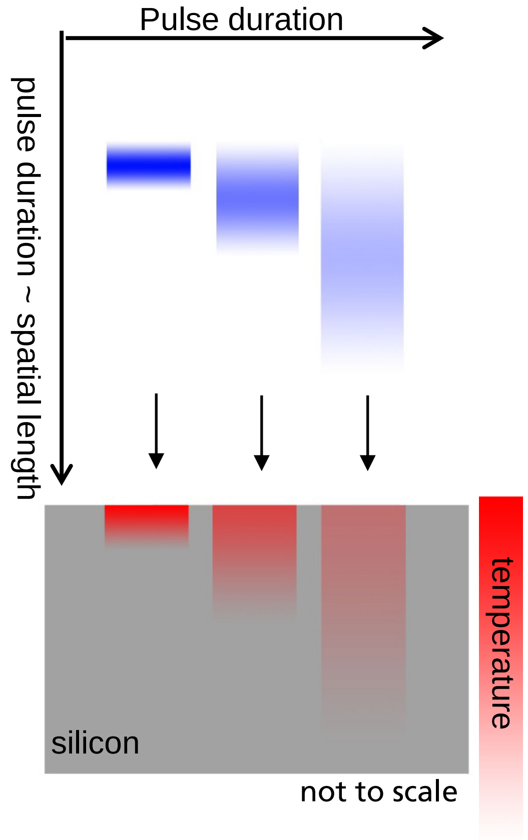
Laser Material Processing for Crystalline Silicon Solar Cells
- Background -

Laser Processes for Crystalline Silicon Solar Cells
Thermal Diffusion Length

- ultrashort laser pulses enable selective structuring without affecting underlying layers thermally





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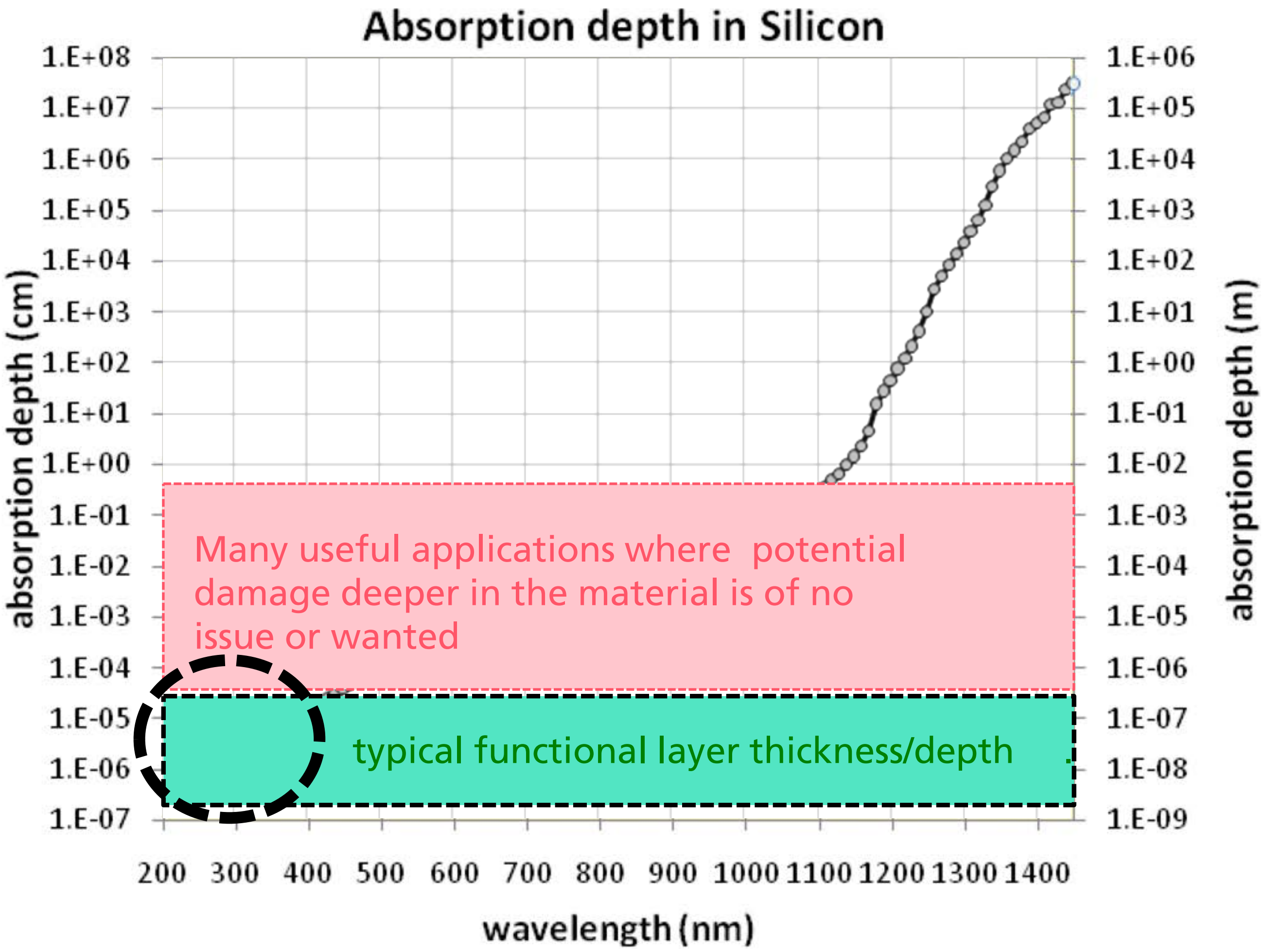
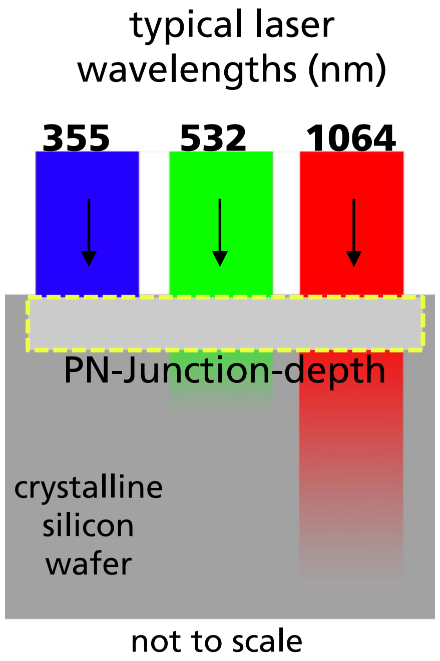
Laser Processes for Crystalline Silicon Solar Cells

Optical Absorption Depth

- ultrashort laser pulses enable selective structuring without affecting underlying layers thermally
- only UV provides small enough absorption depth to prevent defects in functional regions like PN-junction depths or passivated contact layer stacks





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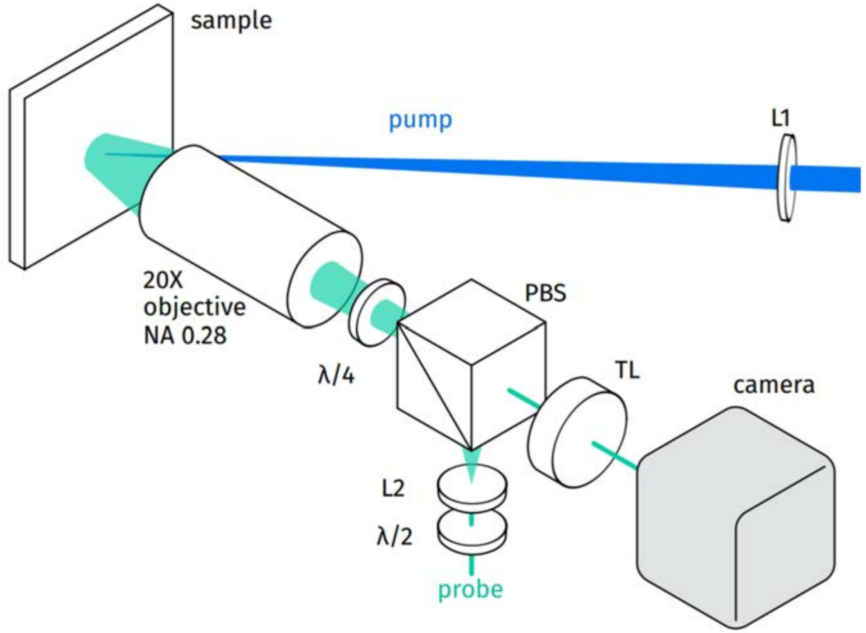
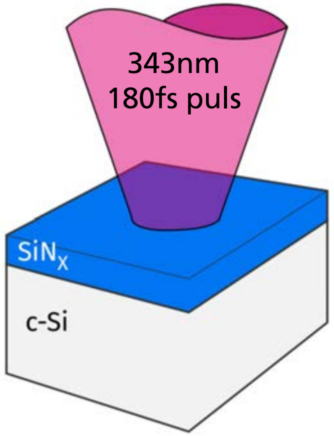
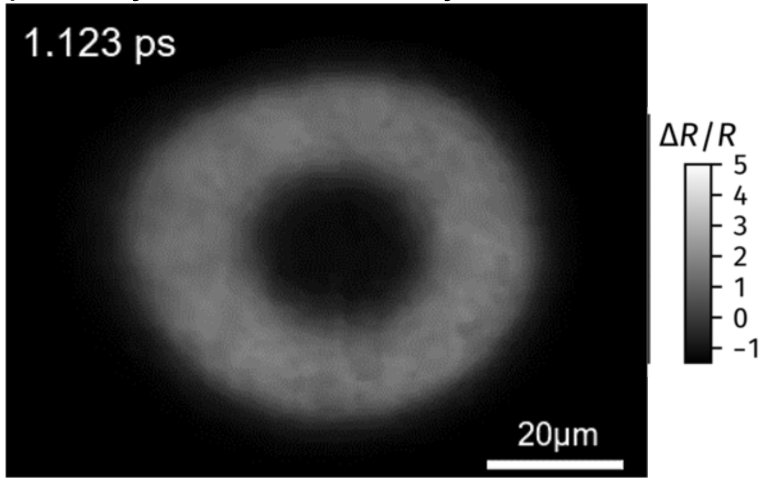
Laser Processes for Crystalline Silicon Solar Cells

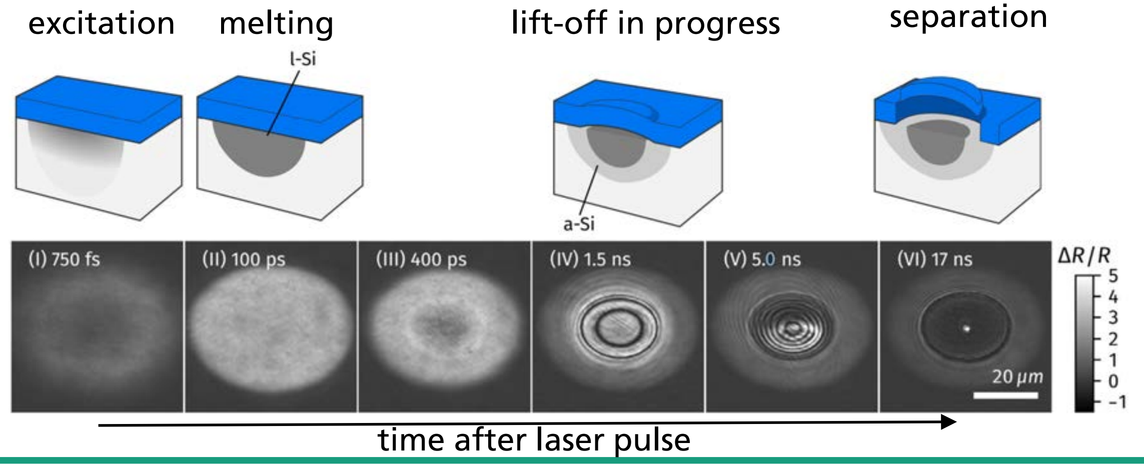
Dynamic Analysis of Thin-Film laser ablation via Pump-Probe Microscopy





Temporal dynamics of SiNx layer ablation on silic





- Thousands of single images combined deliver a slow motion of the dynamics with an effective framerate of 10^{13}
- Provides insight into process dynamics like material removal and resolidification velocities

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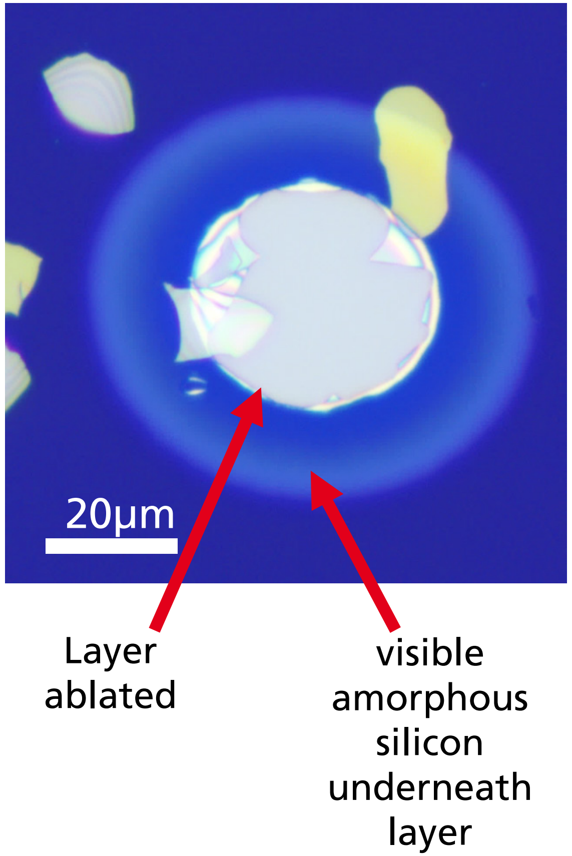
Laser Ablation of Dielectric Layers on Crystalline Silicon

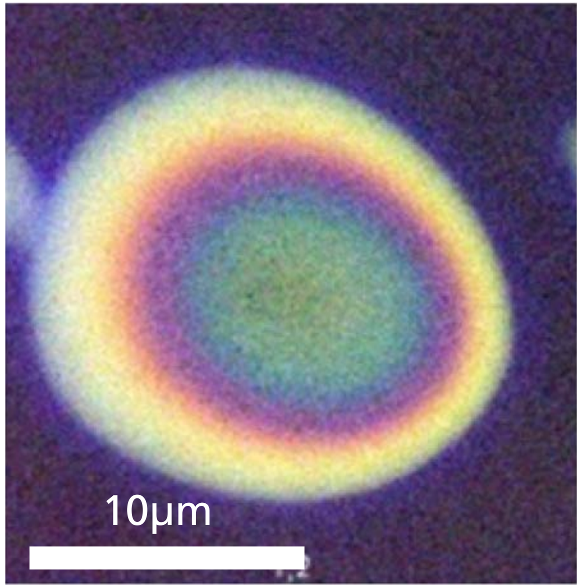
Amorphization of Surface

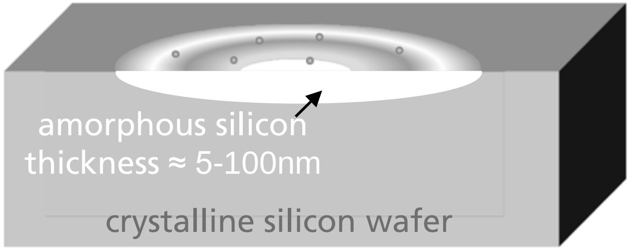
- Highly selective layer ablation without much melting possible with ultrashort pulse lasers
- Cooling rate of molten silicon too fast to recrystallize properly, amorphous silicon remains
- Amorphization also occurs when irradiating bare silicon with ultrashort laser pulses

Optical microscopy image of 70nm SiN_x ablated by 180fs pulse with λ=343nm



Optical microscopy image of planar silicon irradiated by 10ps laser pulse, λ=355nm





not to scale

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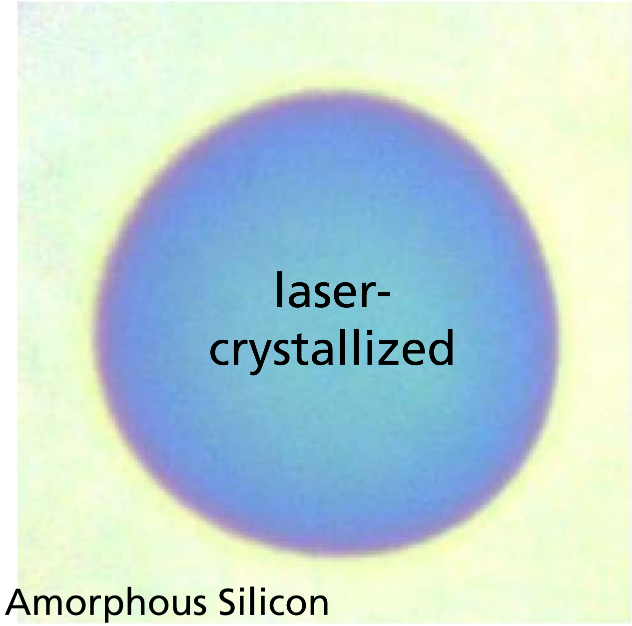
Laser Ablation of Dielectric Layers on Crystalline Silicon

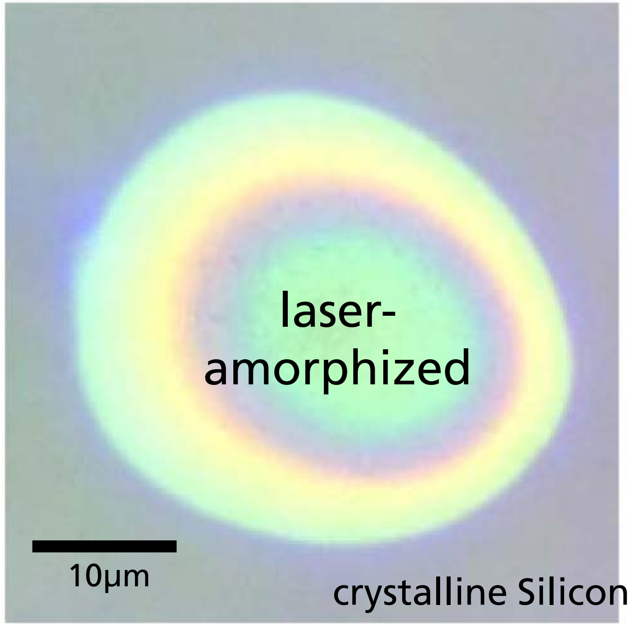
Amorphization vs Crystallization – a matter of pulse duration

- Highly selective layer ablation without much melting possible with ultrashort pulse lasers
- Cooling rate of molten silicon too fast to recrystallize properly, amorphous silicon remains
- Amorphization also occurs when irradiating bare silicon with ultrashort laser pulses
- Pump-Probe reflectometry reveals process dynamics
- Residual crystallinity of silicon drastically affected by laser process dynamics

Crystallizing using nanosecond laser pulse



Amorphization using picosecond laser pulse



Optical microscopy images

How to achieve ultra-short pulse layer ablation without amorphization?

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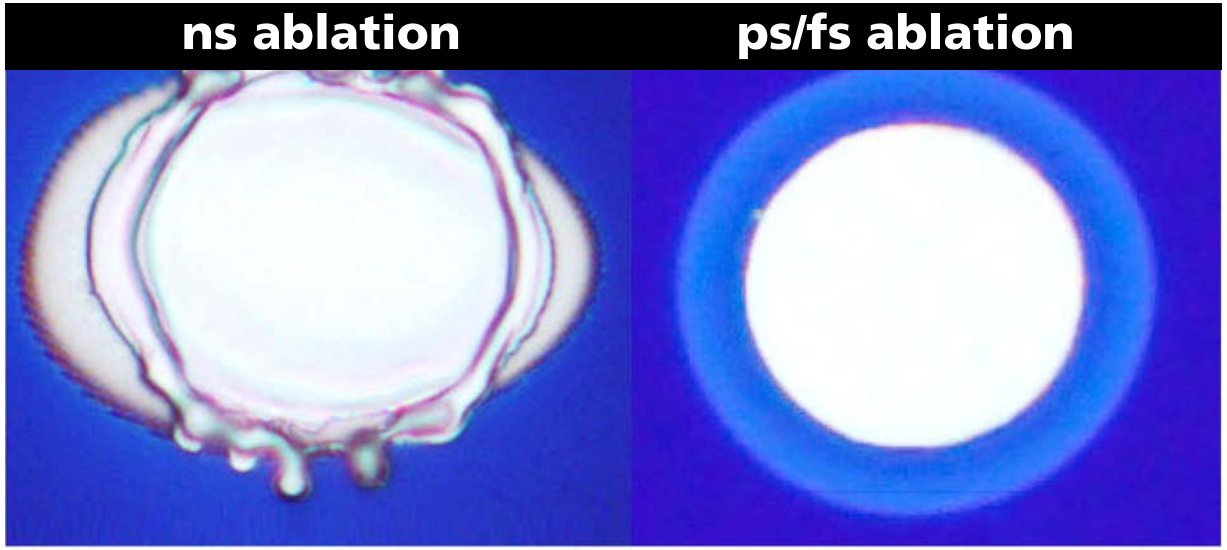
Laser Ablation of Dielectric Layers on Crystalline Silicon

Which Is The Best Process?

Is this always going to be a compromise?

- No amorphization
- Large heat affected zone and melt ejection



examples for selective layer ablation of transparent SiNx on planar silicon wafer

- Residual surface and surrounding area amorphous
- Very shallow *heat affected zone* of <100nm

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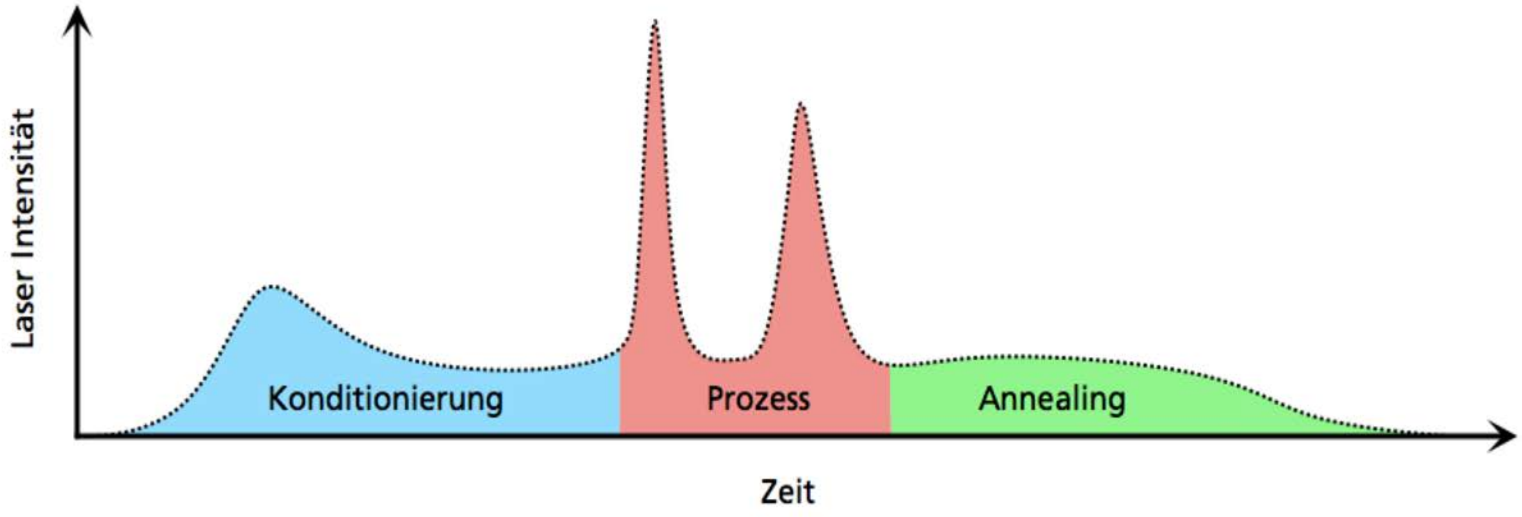
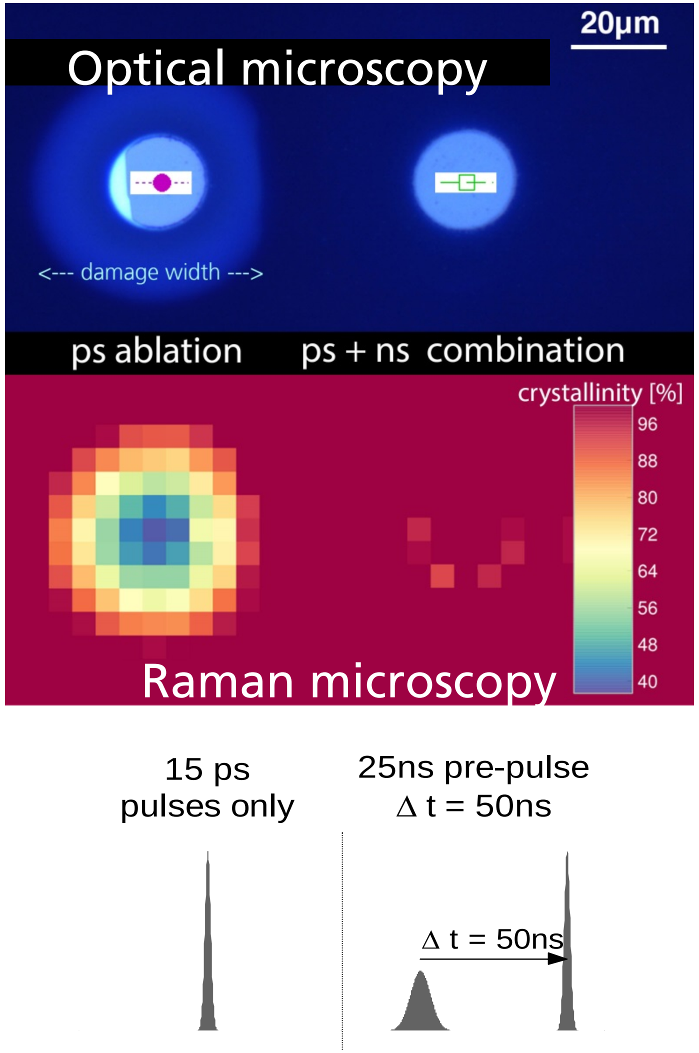
Laser Ablation of Dielectric Layers on Crystalline Silicon
Temporal Pulse Shaping

- Pre-Heating or post-annealing the material can yield a process without amorphization
- A whole new processing regime opening up with temporal pulse shaping

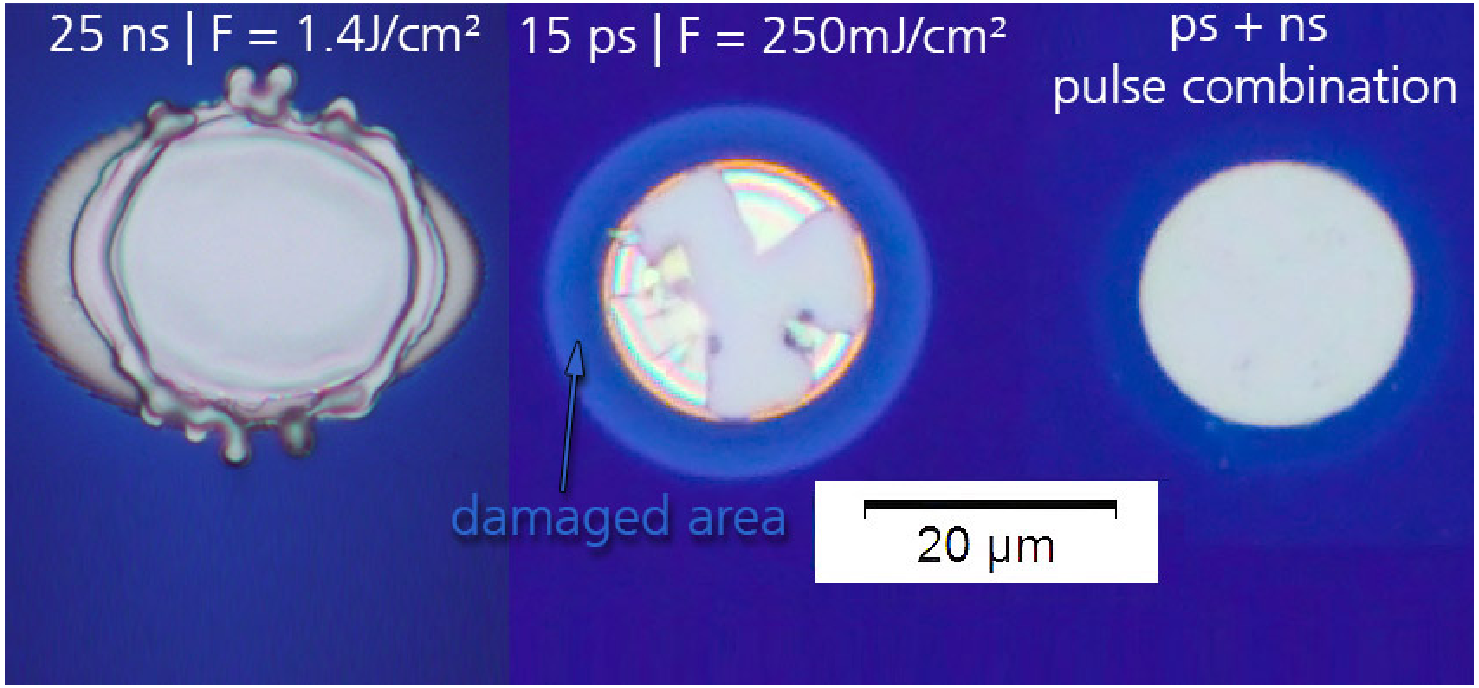




Brand et al. In *Proc. SPIE 8473, Laser Material Processing for Solar Energy*, 8473:84730D-84730D – 10, 2012.

Laser Ablation of Dielectric Layers on Crystalline Silicon
Temporal Pulse Shaping – Pre-Heating

- Pre-Heating or post-annealing the material can yield a process without amorphization
- A whole new processing regime opening up with temporal pulse shaping
- Nanosecond pre-pulse temporarily increases absorption coefficient for VIS and NIR radiation
- Best of short and ultrashort pulse machining possible in 'one process'



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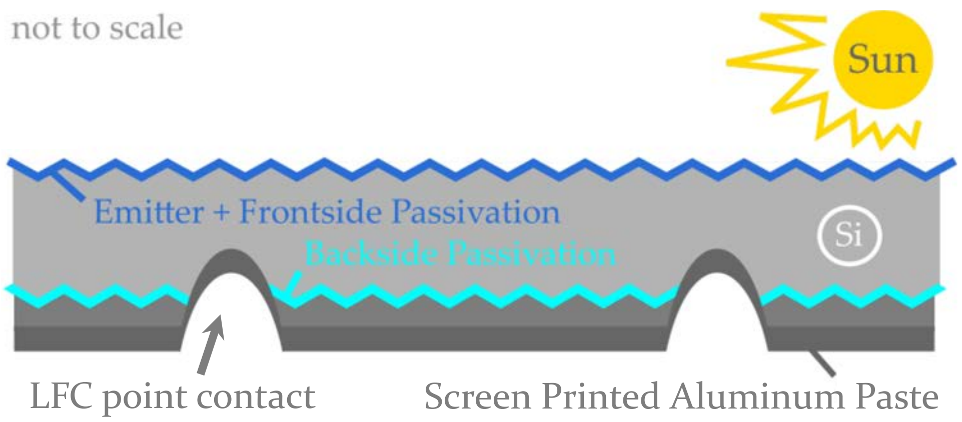
Selection of Laser Processes for Crystalline Silicon Solar Cells

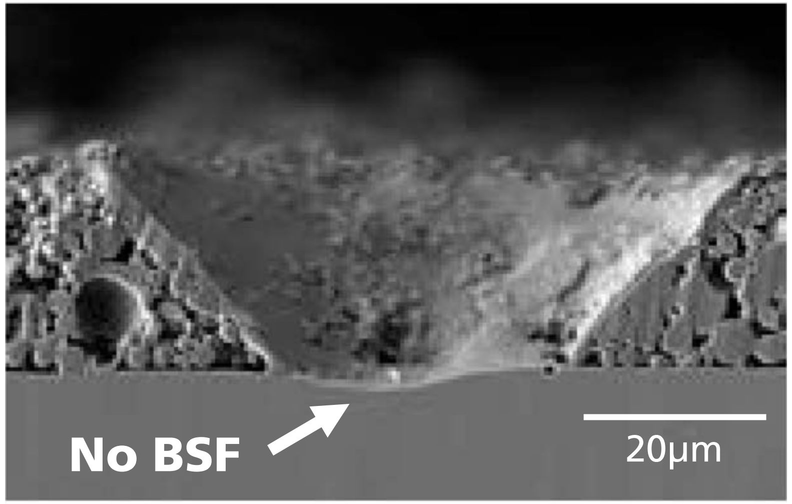
Laser Fired Contacts (LFC) [1]
Of Screen Printed Aluminium Rear Side



- First industrial PERC Module by *Q Cells* featured LFC process invented at Fraunhofer ISE [1]
- Screen printed layer is shot through the passivation
- Advantages of lasers in production processes
  - Reliable + cost effective
  - High flexibility
  - Easy application
  - Contactless

	V_{oc} [V]	J_{sc} [A]	*FF* [%]	η [%]	*A* [cm^2]
Solar Cell	0.652	9.46	76.7	19.50	243

PV parameters of *Q Cells* large-area solar cell world record.[2]



Source: Innovation Award Laser Technology 2014

[1] E. Schneiderlöchner, R. Preu, R. Lüdemann, and S. W. Glunz, "Laser-fired rear contacts for crystalline silicon solar cells," *Prog. Photovolt: Res. Appl.*, vol. 10, no. 1, pp. 29–34, Jan. 2002, doi: 10.1002/pip.422.

[2] P. Engelhart *et al.*, "R D pilot-line production of multi-crystalline Si solar cells with top efficiencies exceeding 19%," in *2011 37th IEEE Photovoltaic Specialists Conference*, 2011, pp. 001919–001923, doi: 10.1109/PVSC.2011.6186327.

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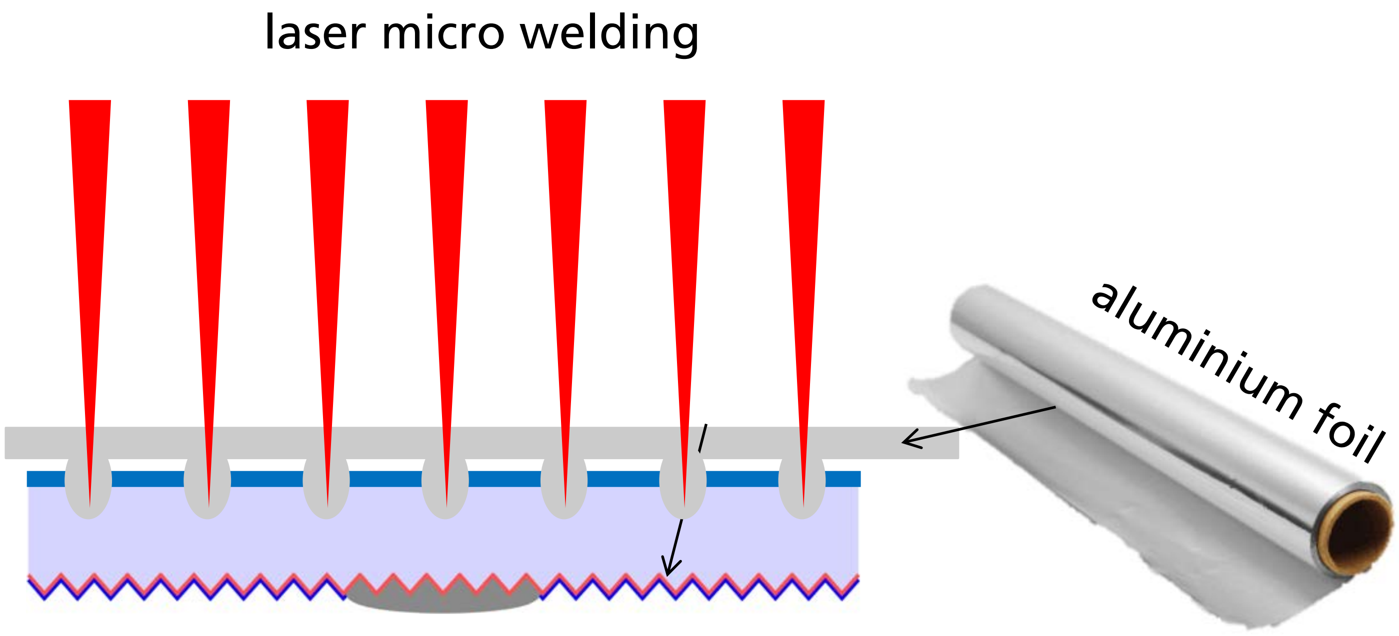
Laser Fired Contacts using Aluminium Foil (FOLMET)
Process Animation

- Passivated Emitter and Rear Cell (PERC) p-type [1]
- Positioning of aluminium foil at the rear side
- Laser fired contacts (LFC) [2] for electrical contact and fixation
- Cutting the foil at the edge of the wafer



[1] Blakers, Applied Physic Letters 55, 1989
[2] E. Schneiderlöchner, EU PVSEC, 2001, Munich

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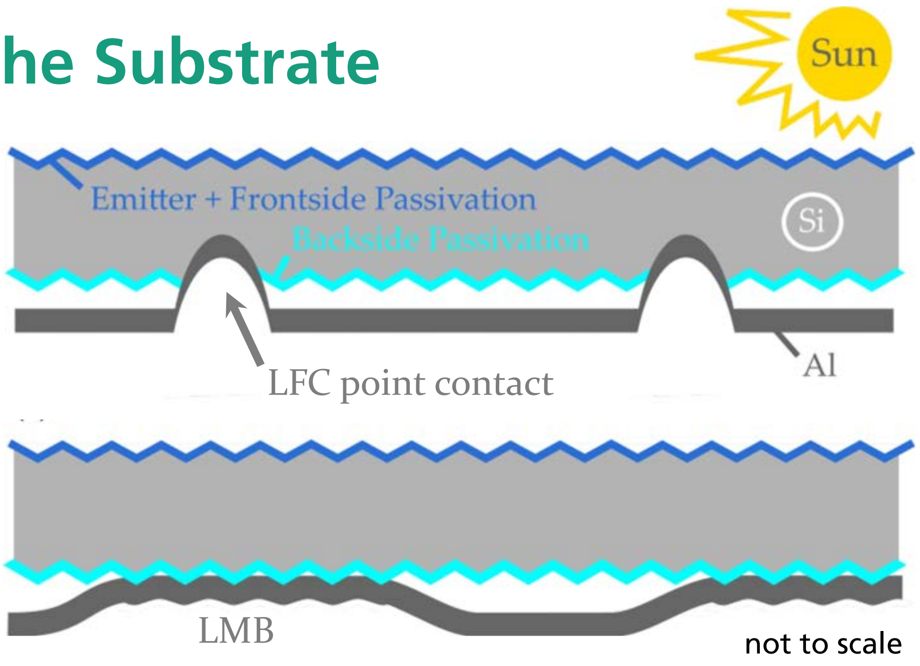
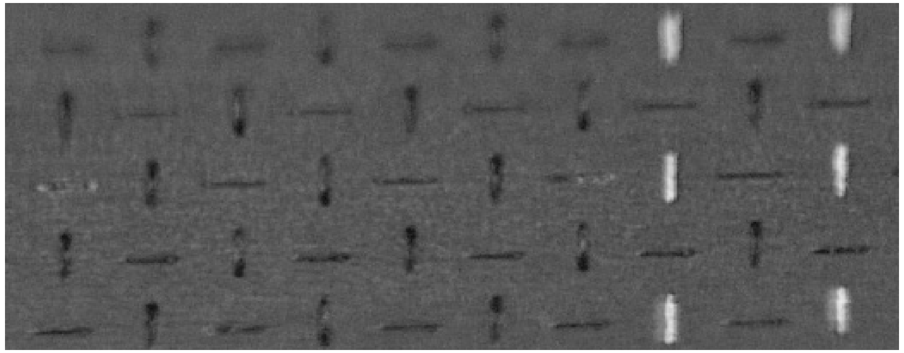
Laser Metal Bonding (LMB)
Adhesion of Aluminium Foil without Affecting the Substrate

- No melting of the substrate material
- Non penetrating, non-ablative → particle free
- Optimization via finite element simulations
- Tunable air-gap between aluminium and substrate for superior optical reflection
- Cost efficient CW Laser source





In situ photo of the LMB process, showing a tilted view on the backside aluminum foil surface [5]

[5] O. John, "Laser Metal Bonding (LMB) - Low Impact Joining of ThinAluminum Foil to Silicon and Silicon Nitride Surfaces,"Procedia CIRP,to be published

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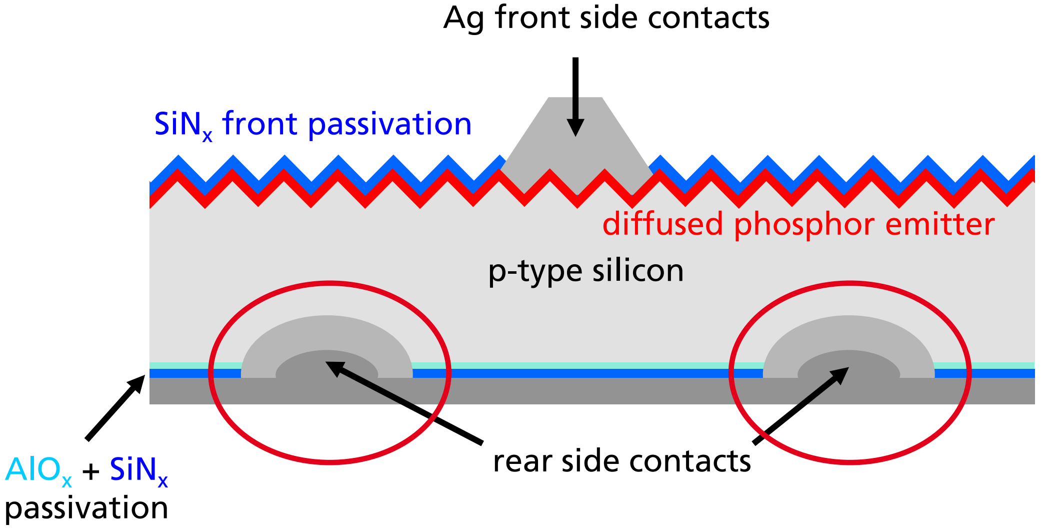
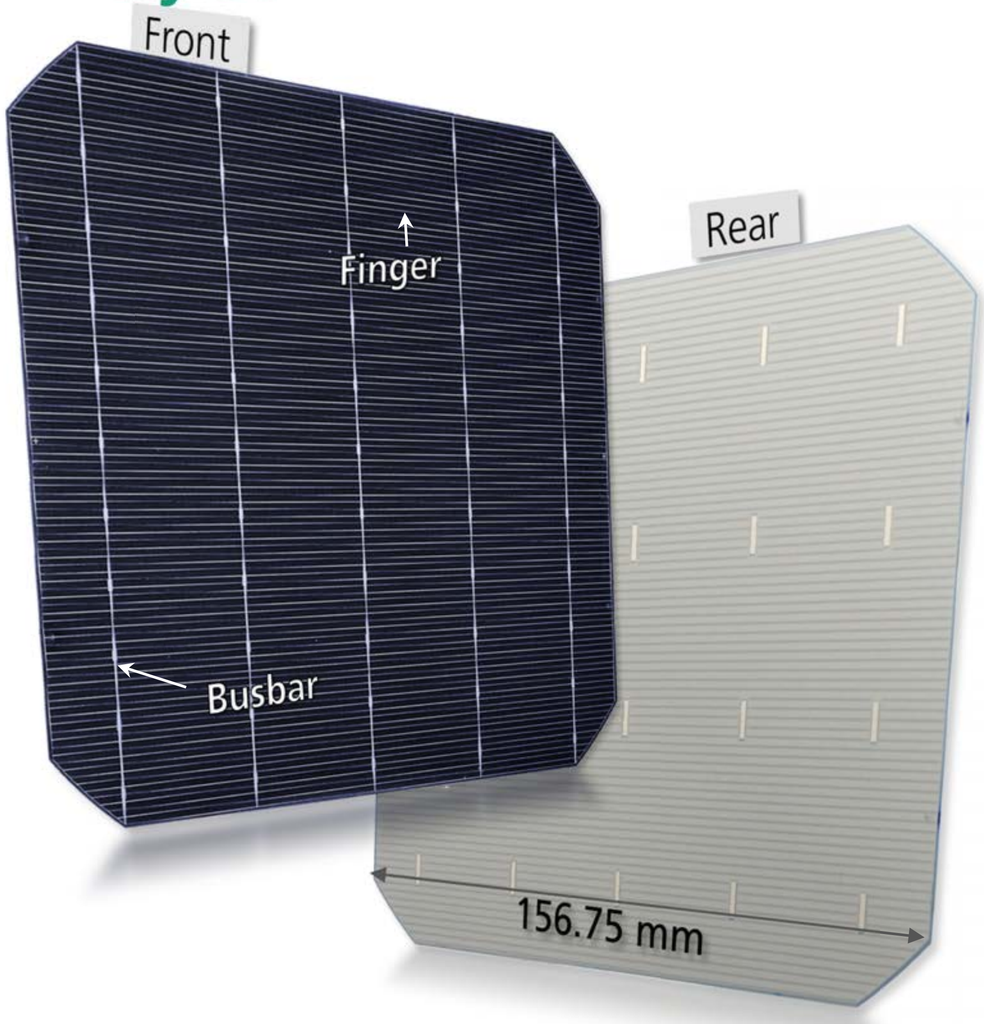
Laser Contact Opening (LCO)

For Local Rear Side Aluminium Contacts of Industry Standard PERC Solar Cells





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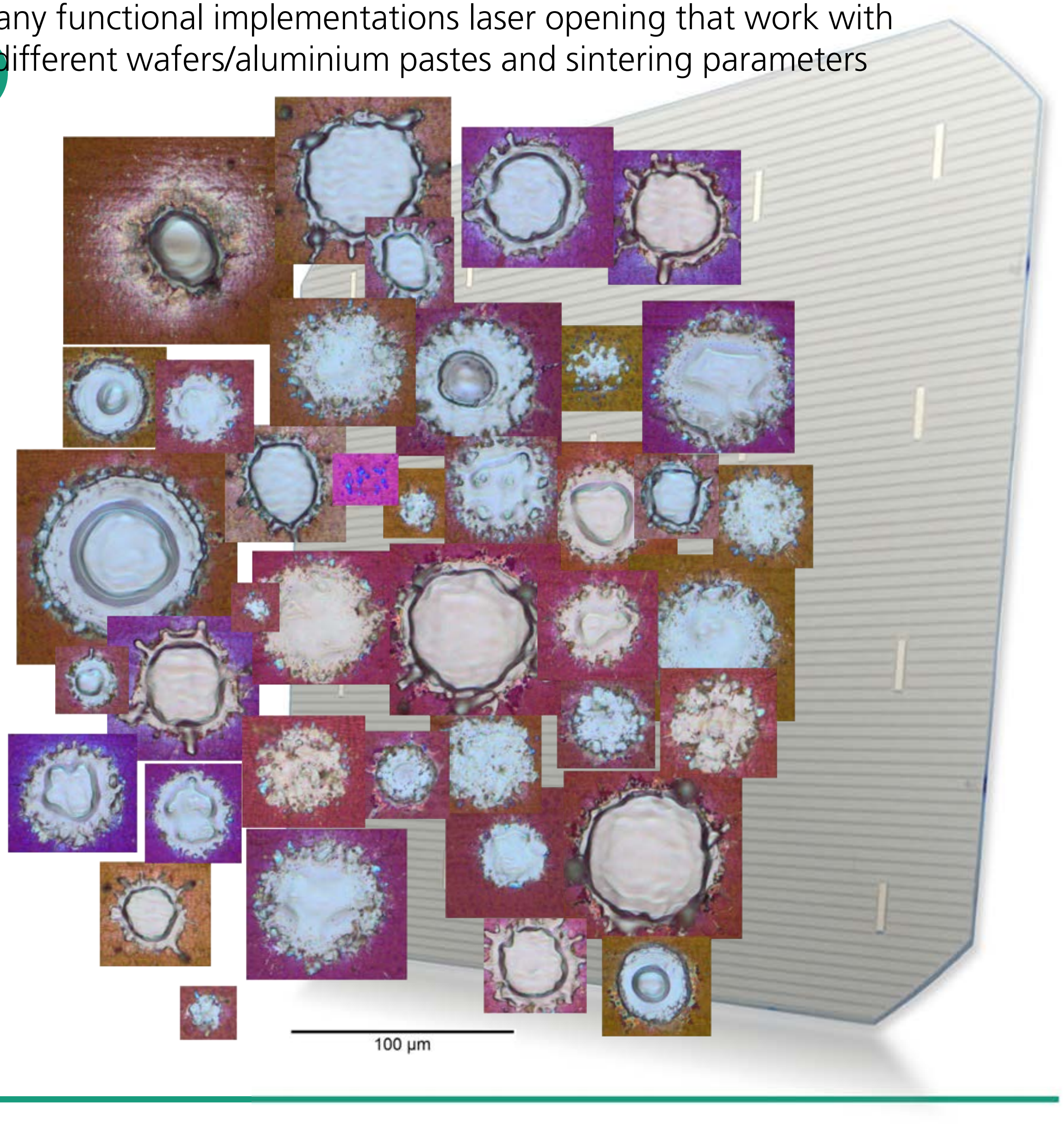
Laser Contact Opening (LCO)

For local rear side contacts (p-type PERC)

many functional implementations laser opening that work with different wafers/aluminium pastes and sintering parameters

- LCO PERC makes up more than 50% of world wide production of standard cells (both sides connected)
- Contact firing eliminates (most) laser damage
- Laser parameters and geometry range widely by manufacturer
- Process mostly implemented using IR laser with <100 ns pulse duration
  but also 15ps with 532nm wavelength
- Dot-Geometry Spacing ≈ 0.5mm
  → Galvo-scanners limit process speed
- Optimal combination of wafer surface, layer type, aluminium paste an sintering profile needed

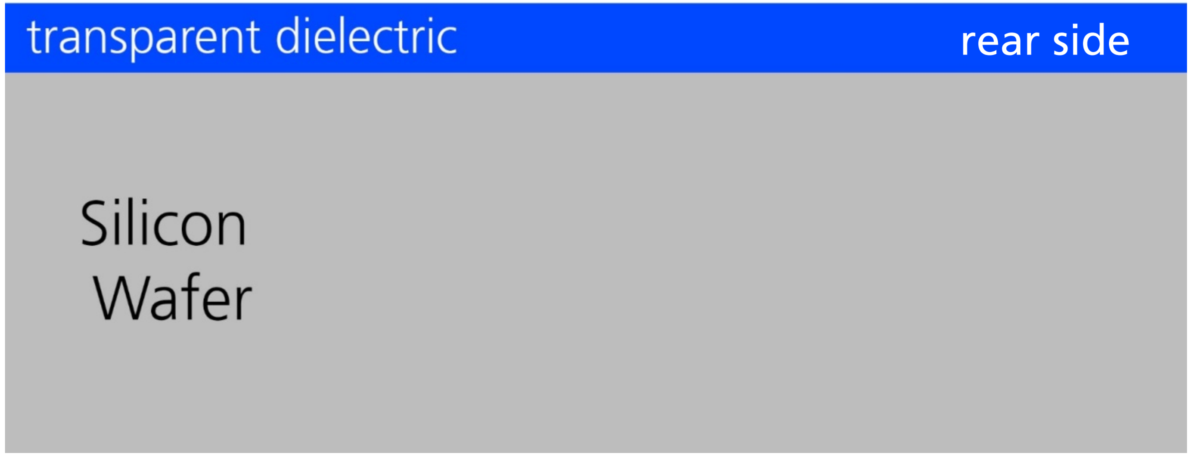


Laser Contact Opening (LCO)

For local rear side contacts (p-type PERC)

p-type c-Si wafer

front end processes



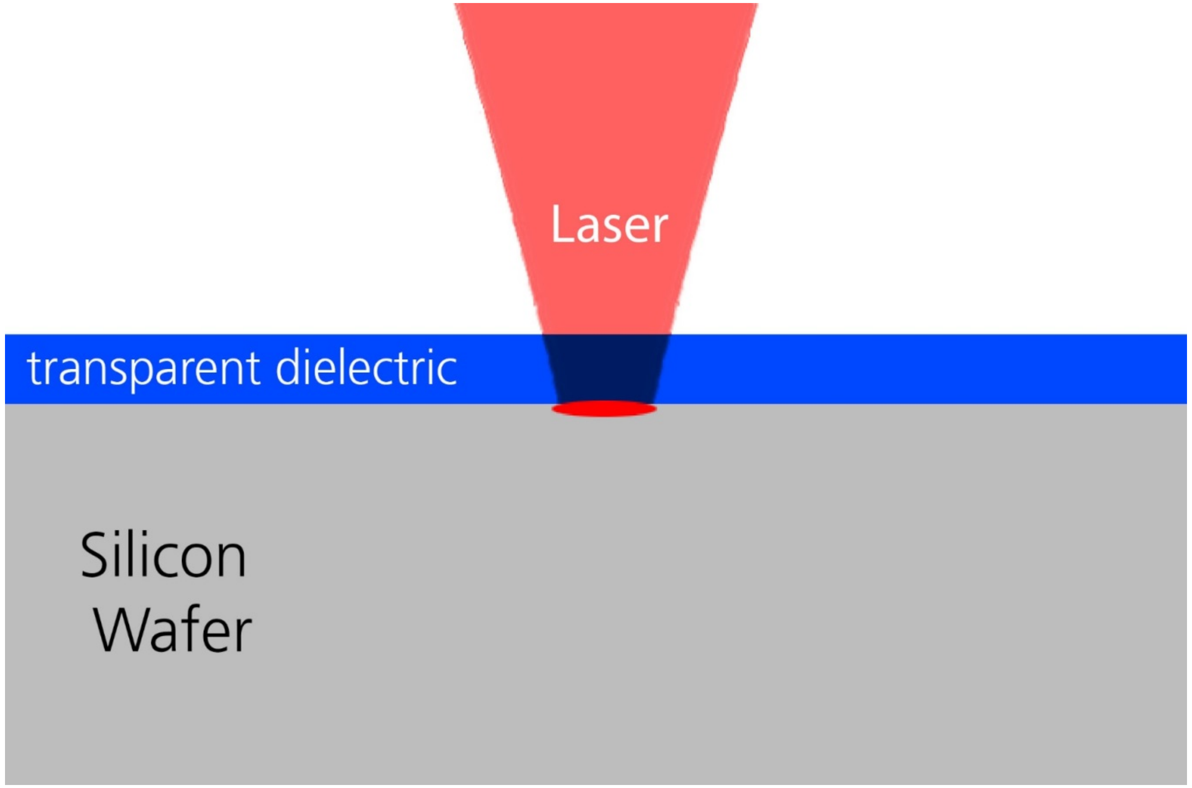
not to scale

Laser Contact Opening (LCO)

For local rear side contacts (p-type PERC)

Process flow

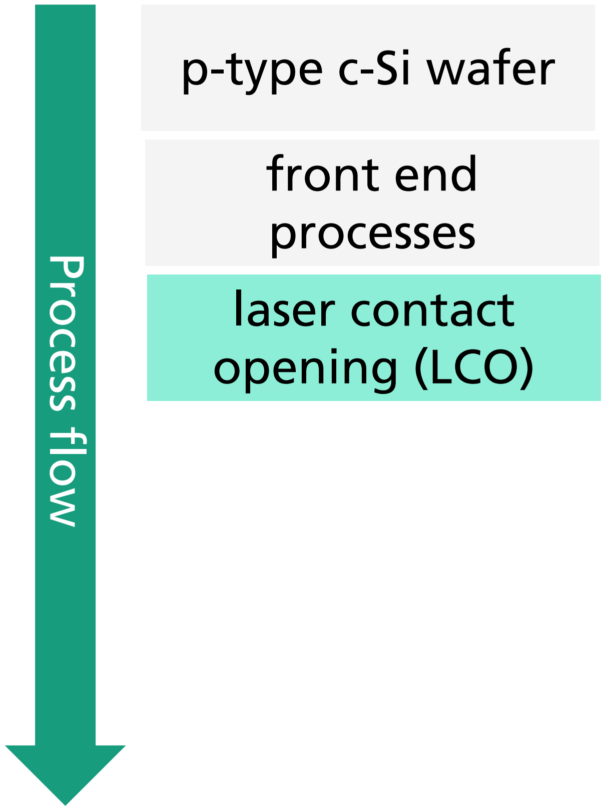
- p-type c-Si wafer
- front end processes
- laser contact opening (LCO)



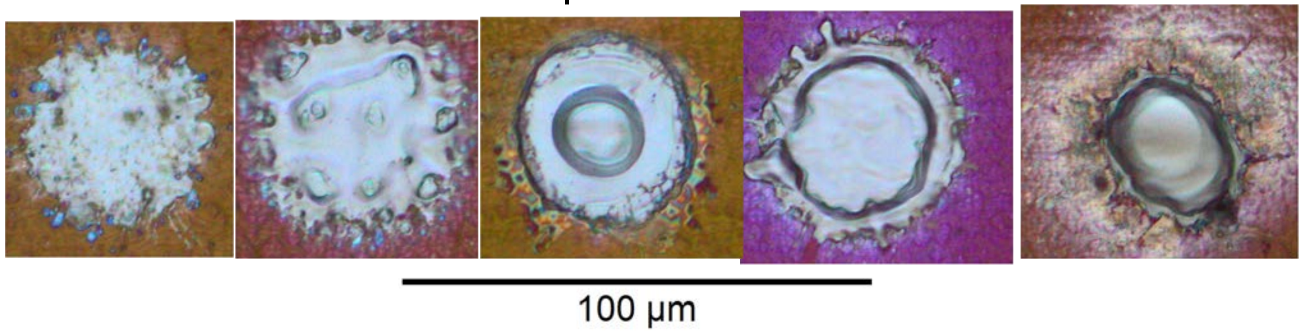
not to scale

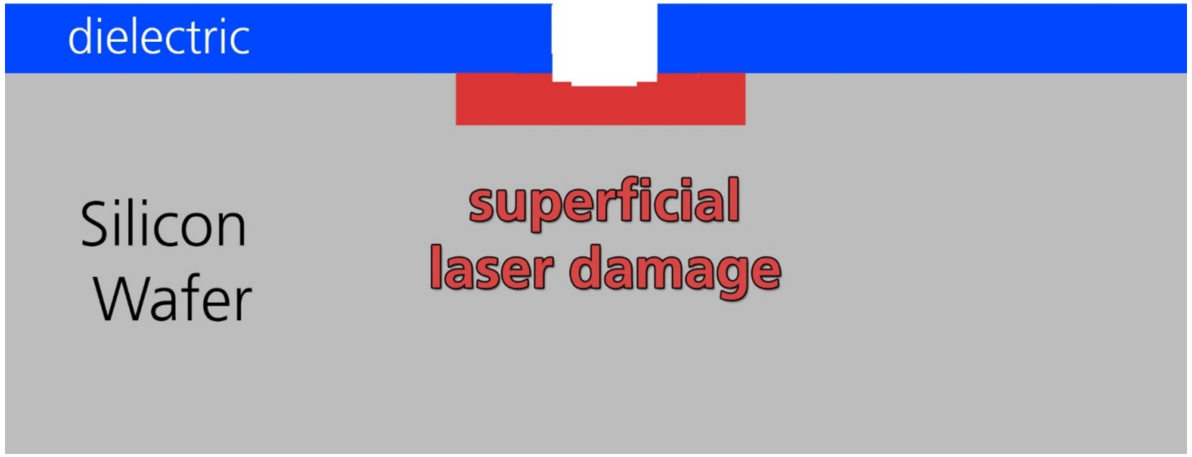
Laser Contact Opening (LCO)

For local rear side contacts (p-type PERC)



Example LCO-Dots





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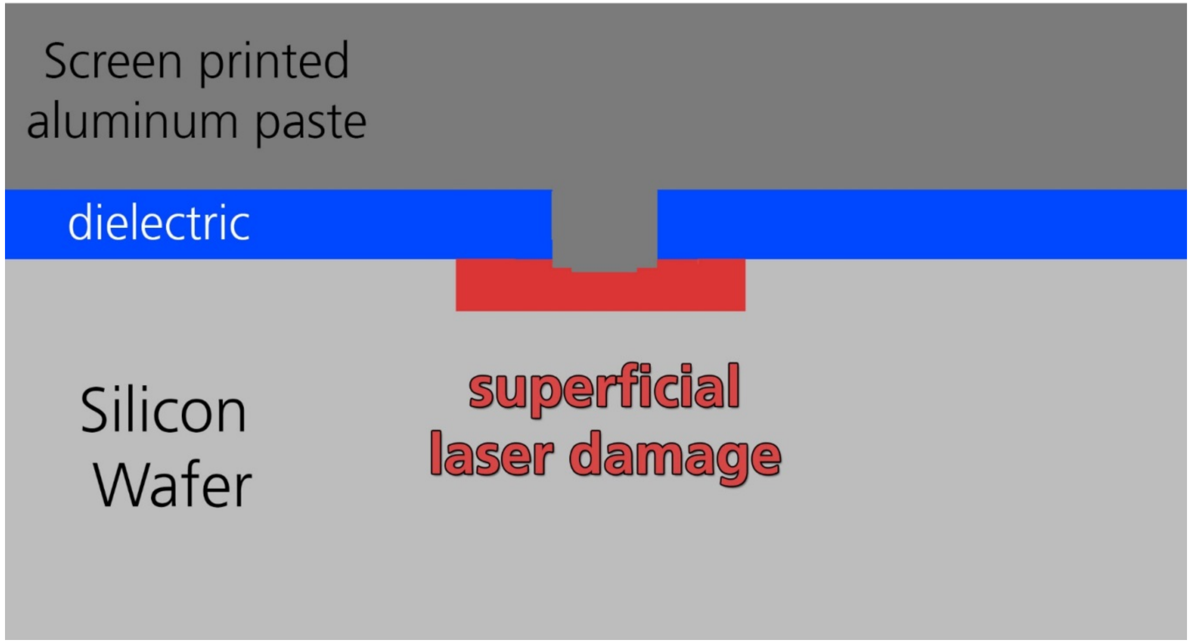
Laser Contact Opening (LCO)

For local rear side contacts (p-type PERC)

Process flow

- p-type c-Si wafer
- front end processes
- laser contact opening (LCO)
- screen printing of aluminum paste



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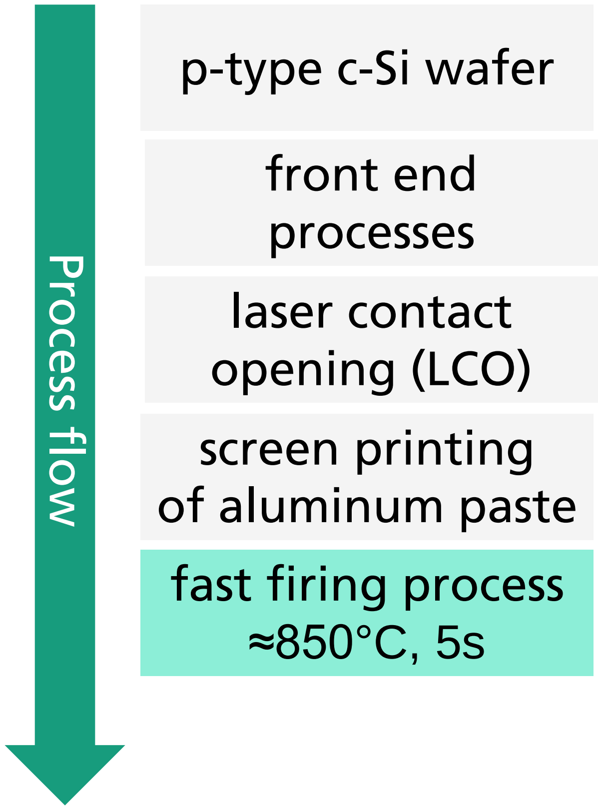
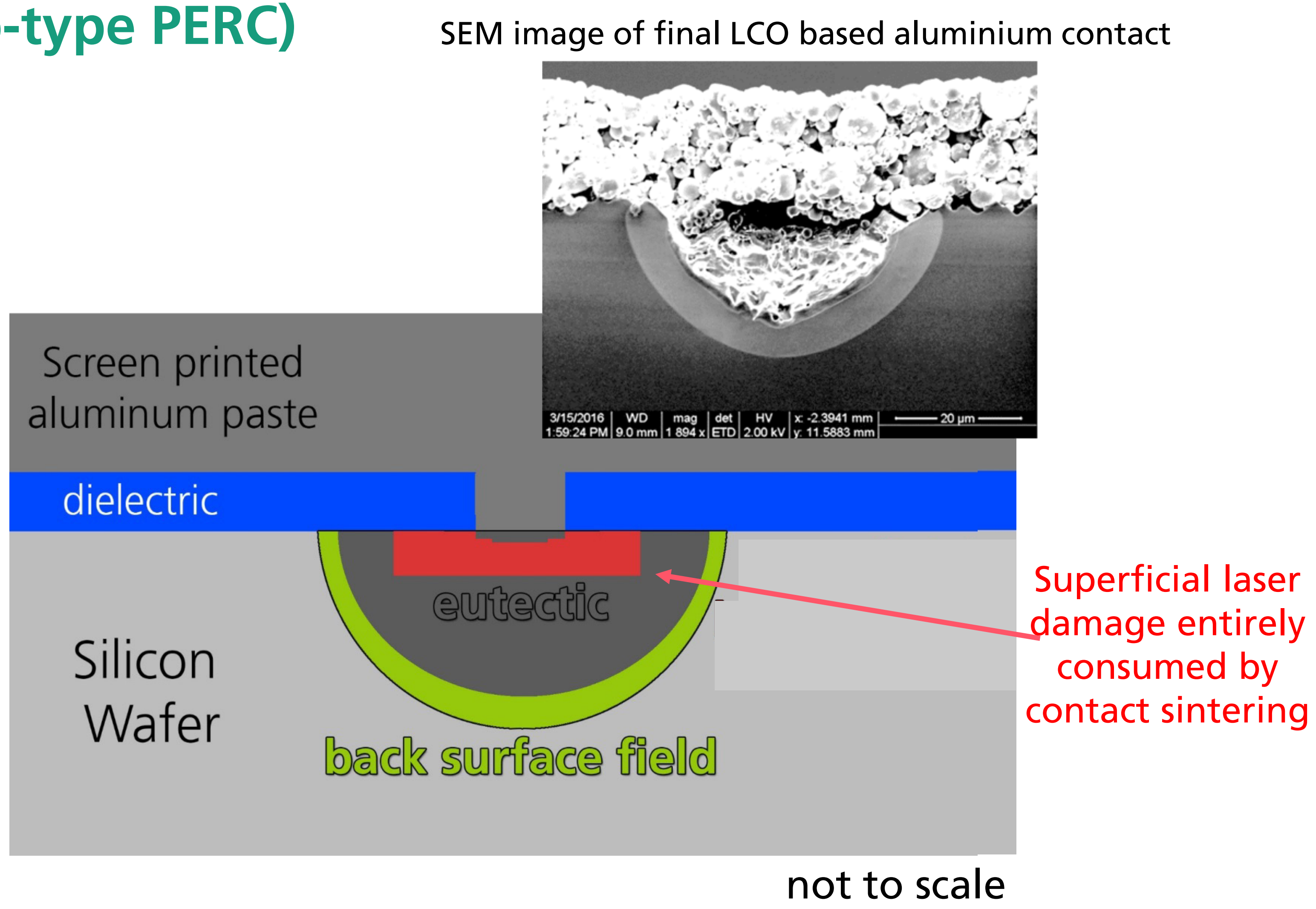
Laser Contact Opening (LCO)

For local rear side contacts (p-type PERC)



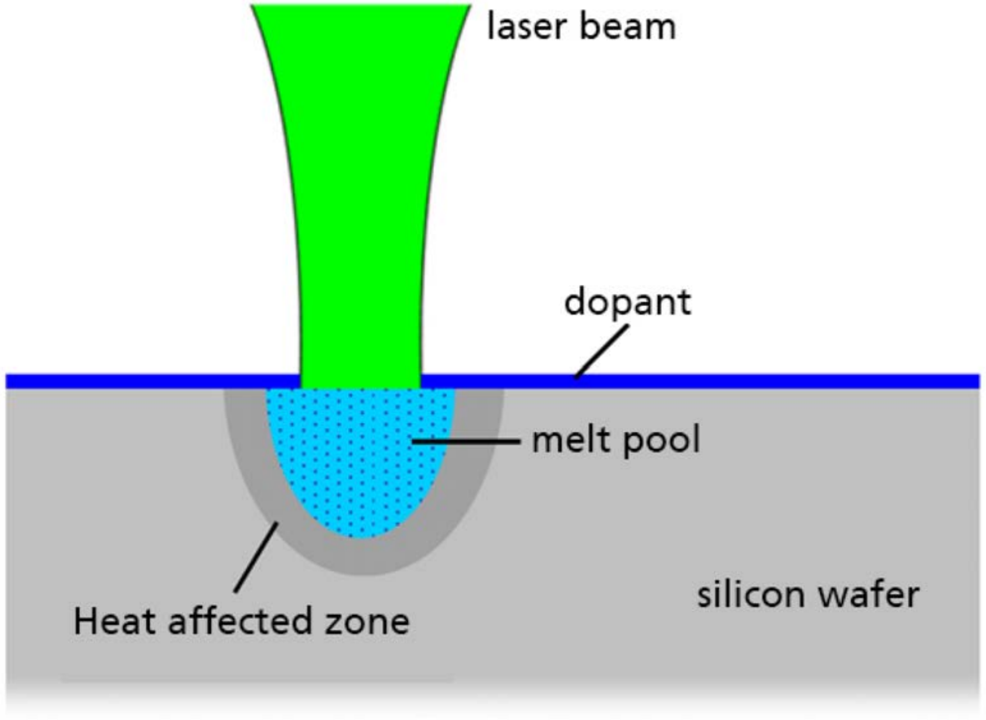


Laser Doped Selective Emitter (LDSE)

Overdoping to reduce contact resistance and recombination

- Laser induced melting to drive in dopant atoms

→ Is becoming attractive again as front side limits cell performance



U. Jäger, Dissertation 2012

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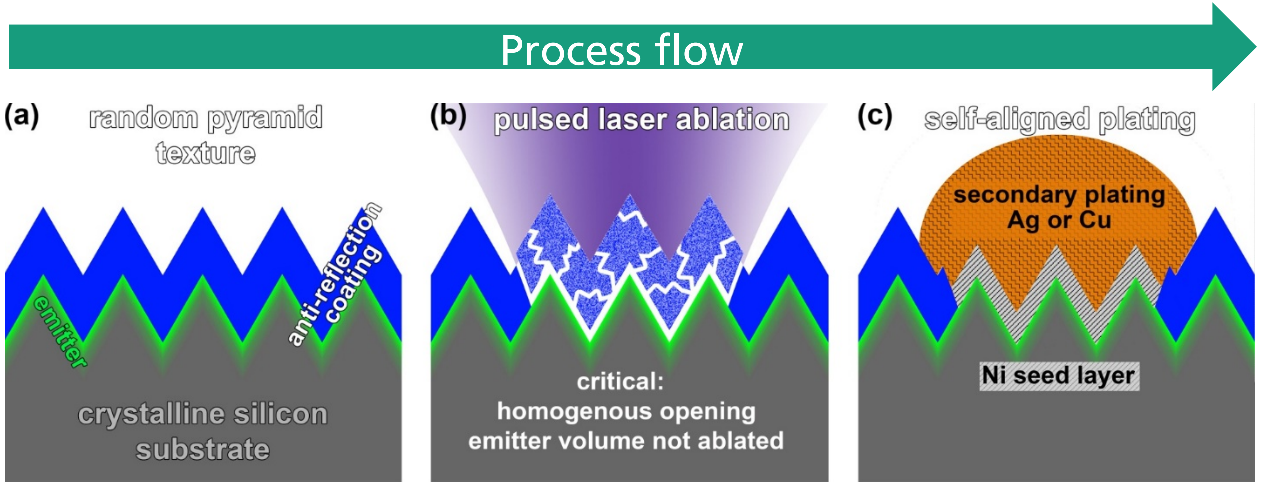
Laser Ablation of Dielectric Layers for Ni-Cu Plated Contacts

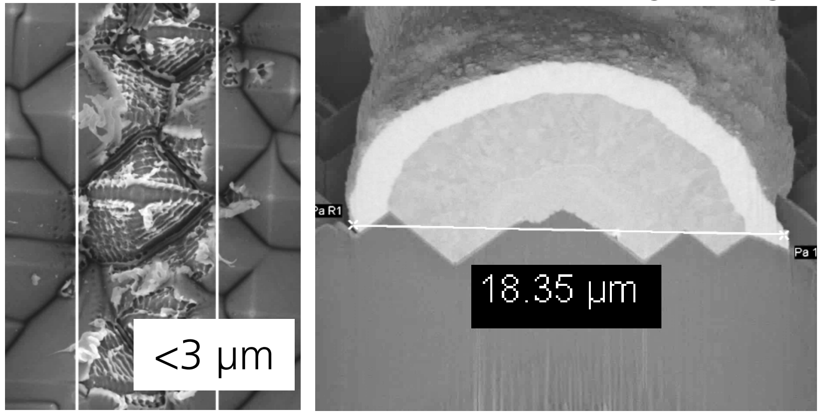
Enabling Silver-free Contacts

- Small contact openings less than 20µm optical width
- Excellent adhesion of plated contacs [1]
- Very small contact resistance on high efficiency emitters [2]
- Typical laser requirements:
  - Ultrashort pulse duration
  - UV wavelength
  - Diffraction limited spot size



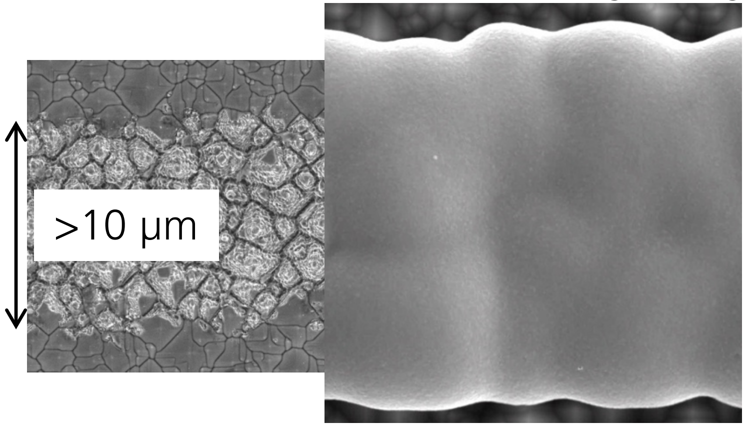
Lab Process

After Laser Ablation After Ni-Cu/Ag Plating



Industrial Process

After Laser Ablation After Ni-Cu/Ag Plating



[1] Mondon et al., EUPVSEC 2014
[2] Kluska et al., SiliconPV 2015

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Laser Ablation of Dielectric Layers for Ni-Cu Plated Contacts

Significat Cost Reduction vs Screen-Printing on TOPCon Solar Cells

- Process compatible with both sides
- Ultra shallow laser ablation damage <70nm on TOPCon® allows for cheaper amorphous silicon deposition

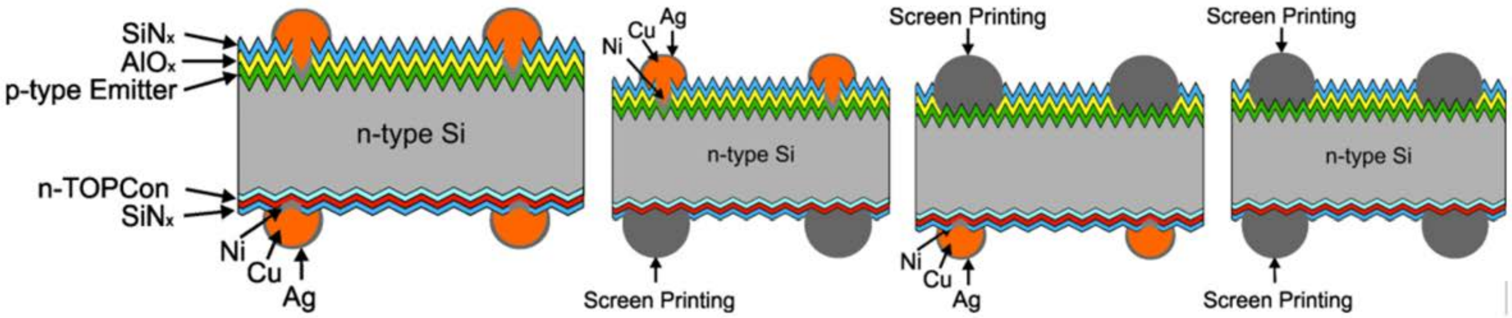
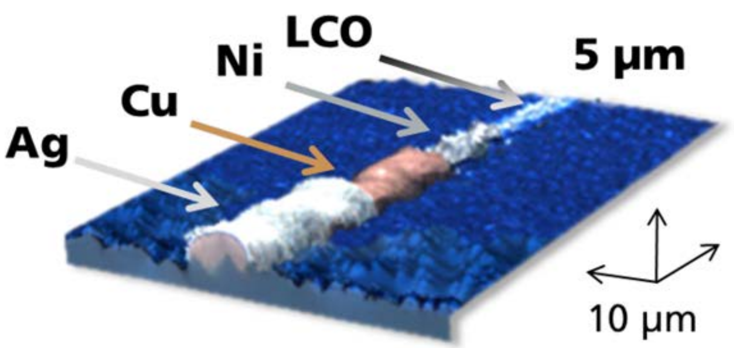
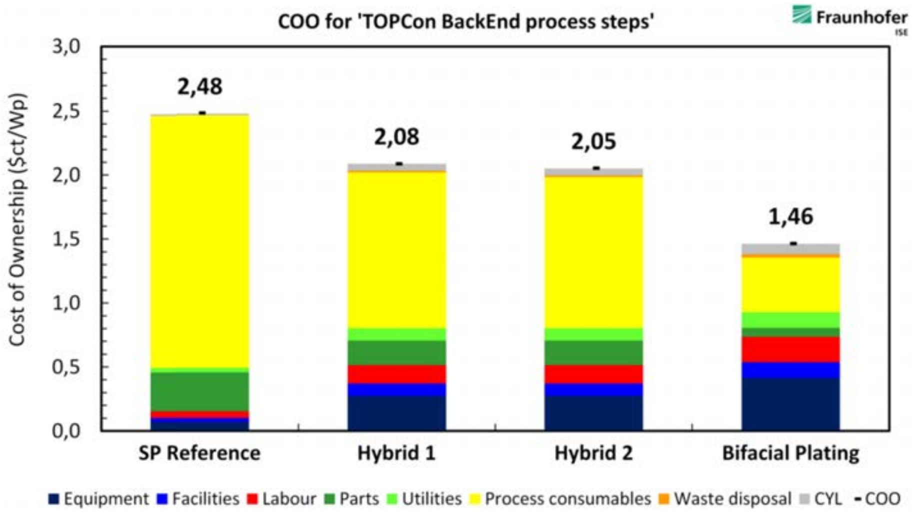
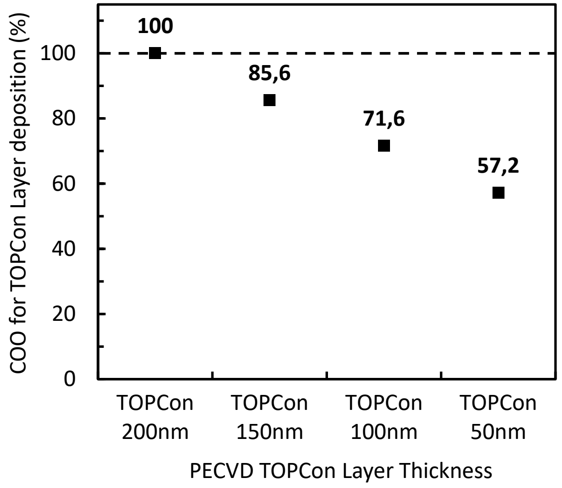


Figure 4 Schematics of i- TOPCon solar cells with bifacially plated Ni/Cu/Ag contacts (left), hybride designs (Hybrid 1 mid-left, Hybrid 2 mid-right) of plated or screen printed contacts (right).







S. Kluska et al., Photovoltaics International Volume 44, June 1, 2020

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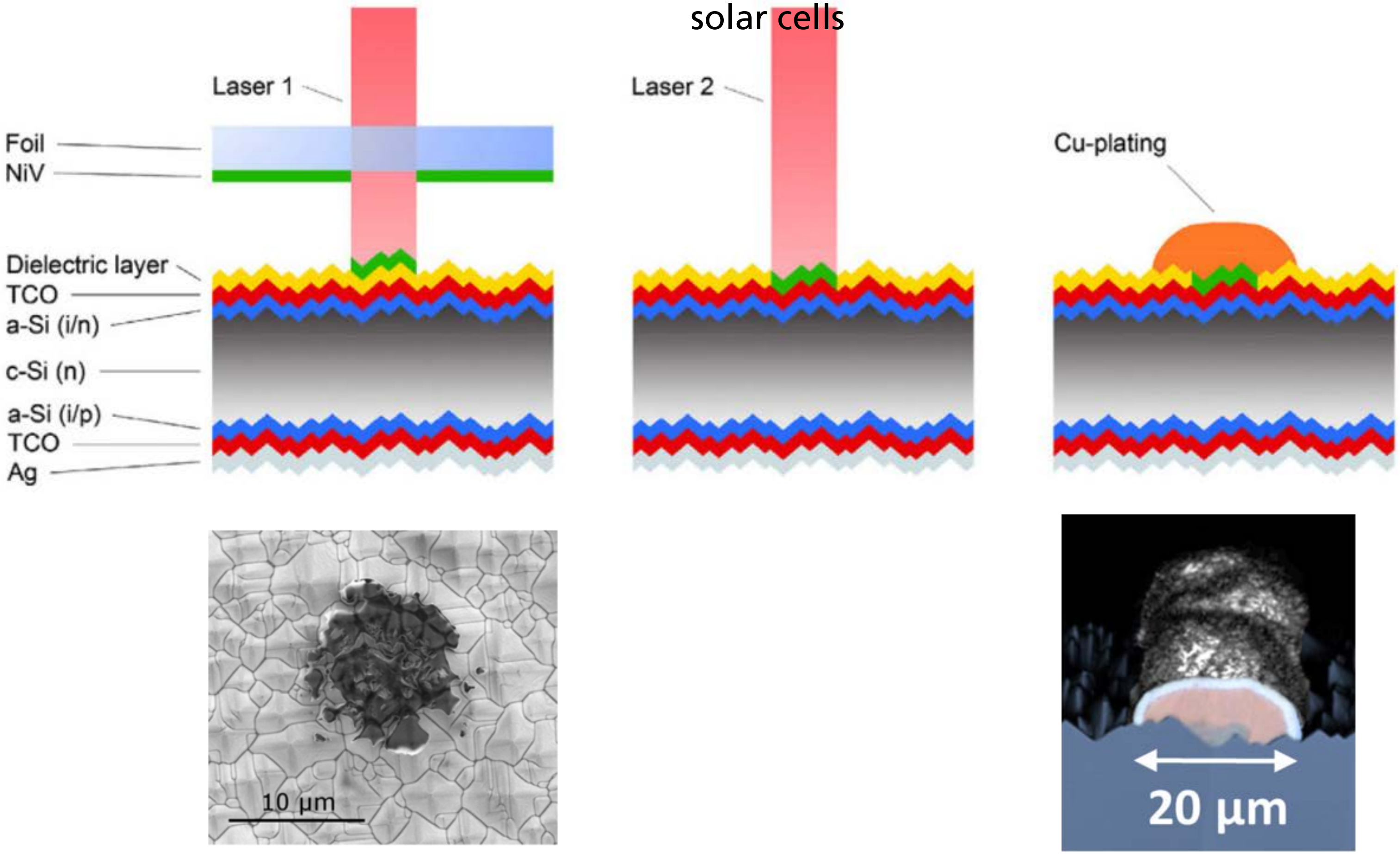
Generative Laser Processes

Laser Induced Forward Transfer (LIFT) + Laser Selective Heating (LSH)

- Laser *'Printing'* from thin layers on transparent foil
- almost arbitrary choice of materials
- Spot diameters down to a few µm possible at high throughput
- Roll to roll process
- Selective heating & sintering of metal layers

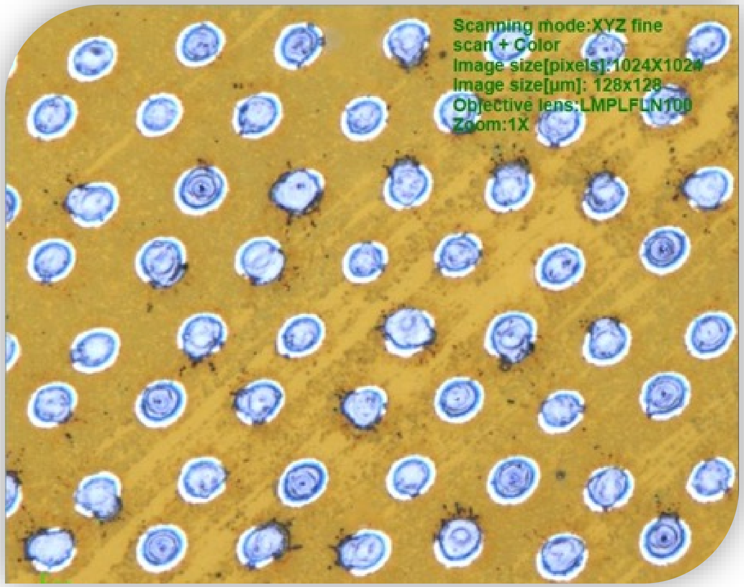
Example: LIFT + plating for auto aligned electrode generation on solar cells



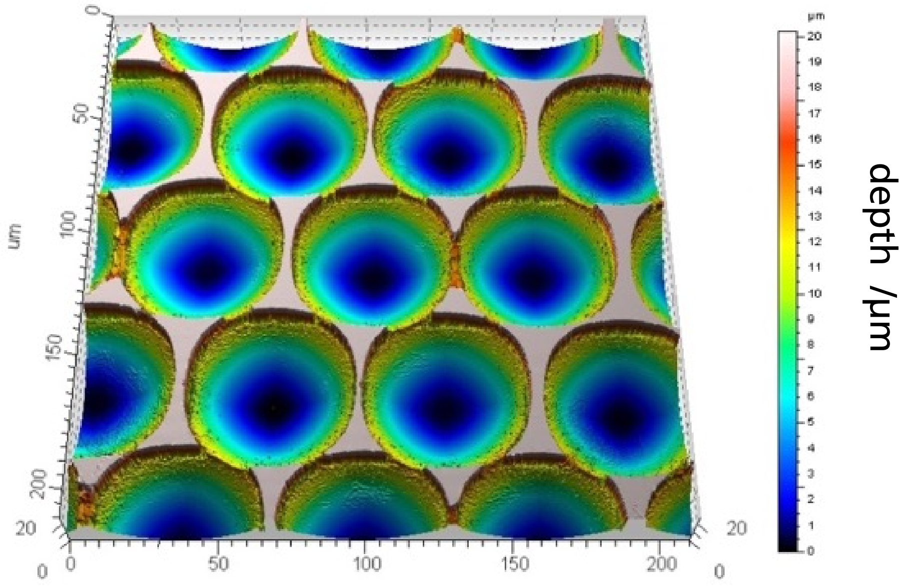
A. Rodofili et al., Solar RRL 2017

Surface Texturing of Semiconductors

Ablation of Dielectric Layer + Etching



wetchemical
etching



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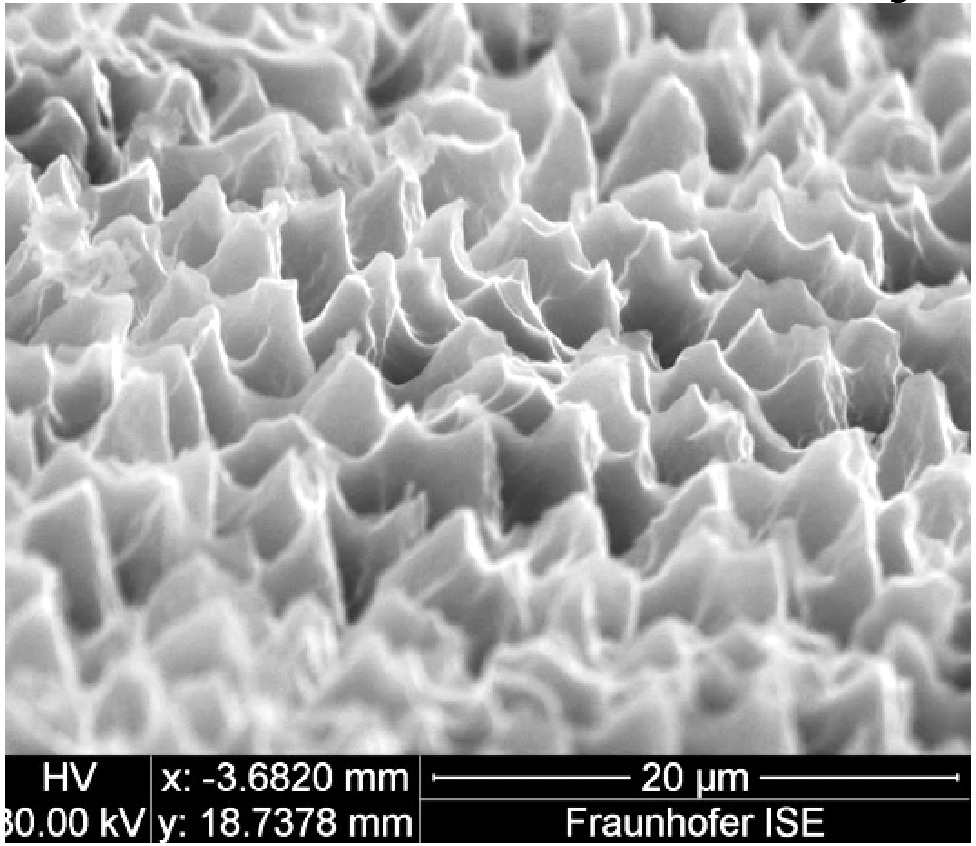
Surface Texturing of Semiconductors

Texturing via direct Ablation (and etching)

- Achieves very small reflectance <2% for the visible spectrum (silicon) or below depending on material and treatment
- Ultrashort pulse laserablation with large overlap
  → laser-induced periodic surface structures (LIPSS)
- KOH etching

silicon wafer surface with laser texture + etching



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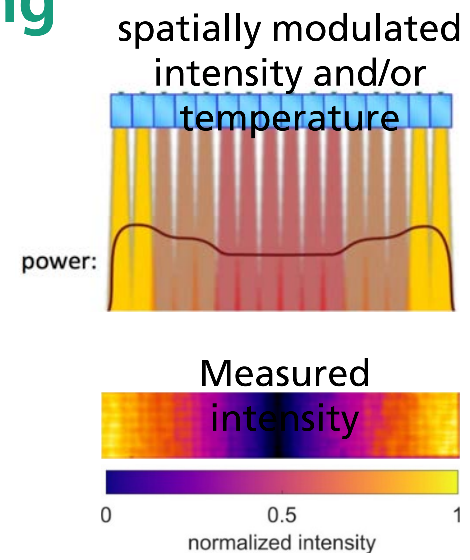
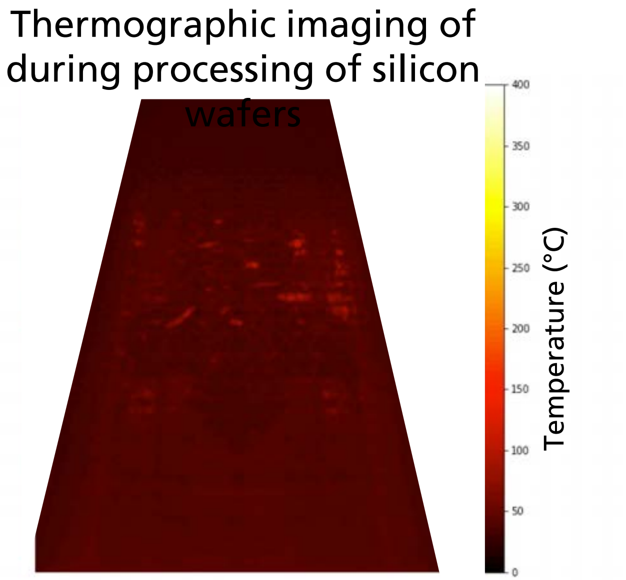
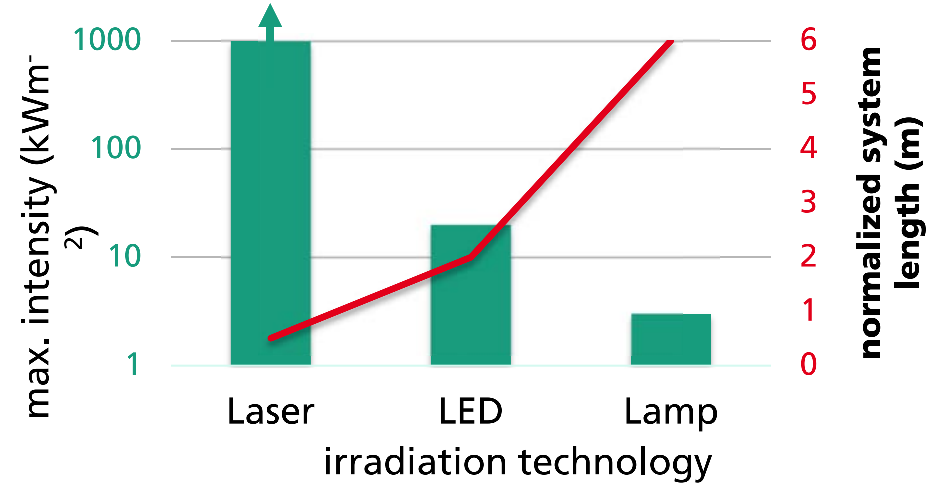
Large Area Inline Laser Irradiation
Annealing, Sintering, Defect Engineering

- Smaller Footprint and better energy efficiency compared to competing heating technologies
- Flexibility for either homogeneous illumination or homogeneous temperature distribution
- Rapid temperature processing with ramps up to 400K/s inline and >1000K/s in stationary systems
- Much simpler optical temperature control due to narrow band irradiation
- Maximum temperatures well above comparable technologies
- Potentially replacing RTP and oven systems at much better cost of ownership and process quality







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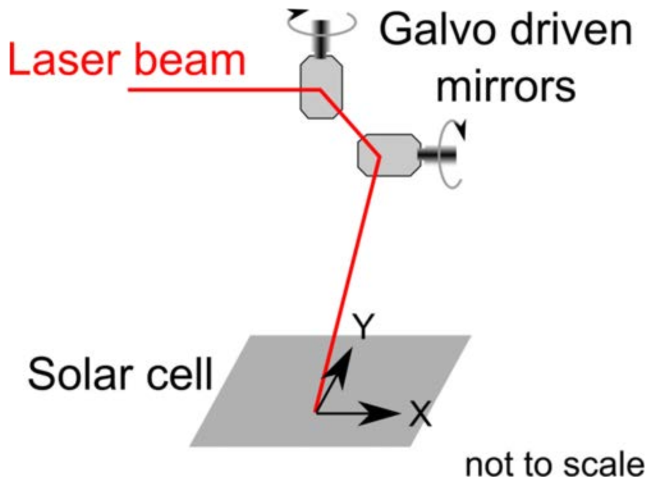
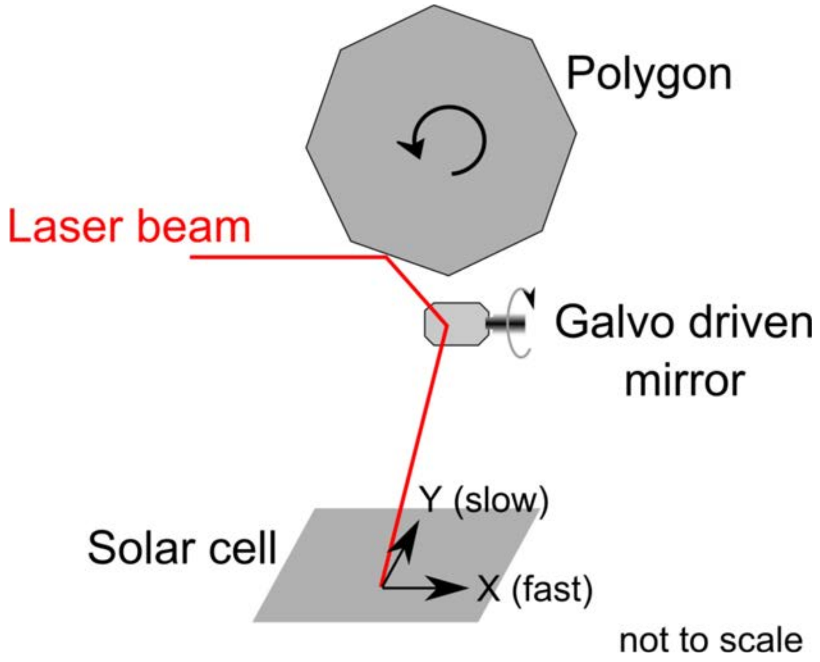
Laser Tools Development
"Ultrafast" Laser Processing Speed



Common galvanometer scanner

Scanning speed for both axis at focal length ≈ 350mm
$v_{scan} \leq 50$ m/s



Scanning speed for fast axis at focal length ≈ 350mm
$v_{scan} \geq 1500$ m/s

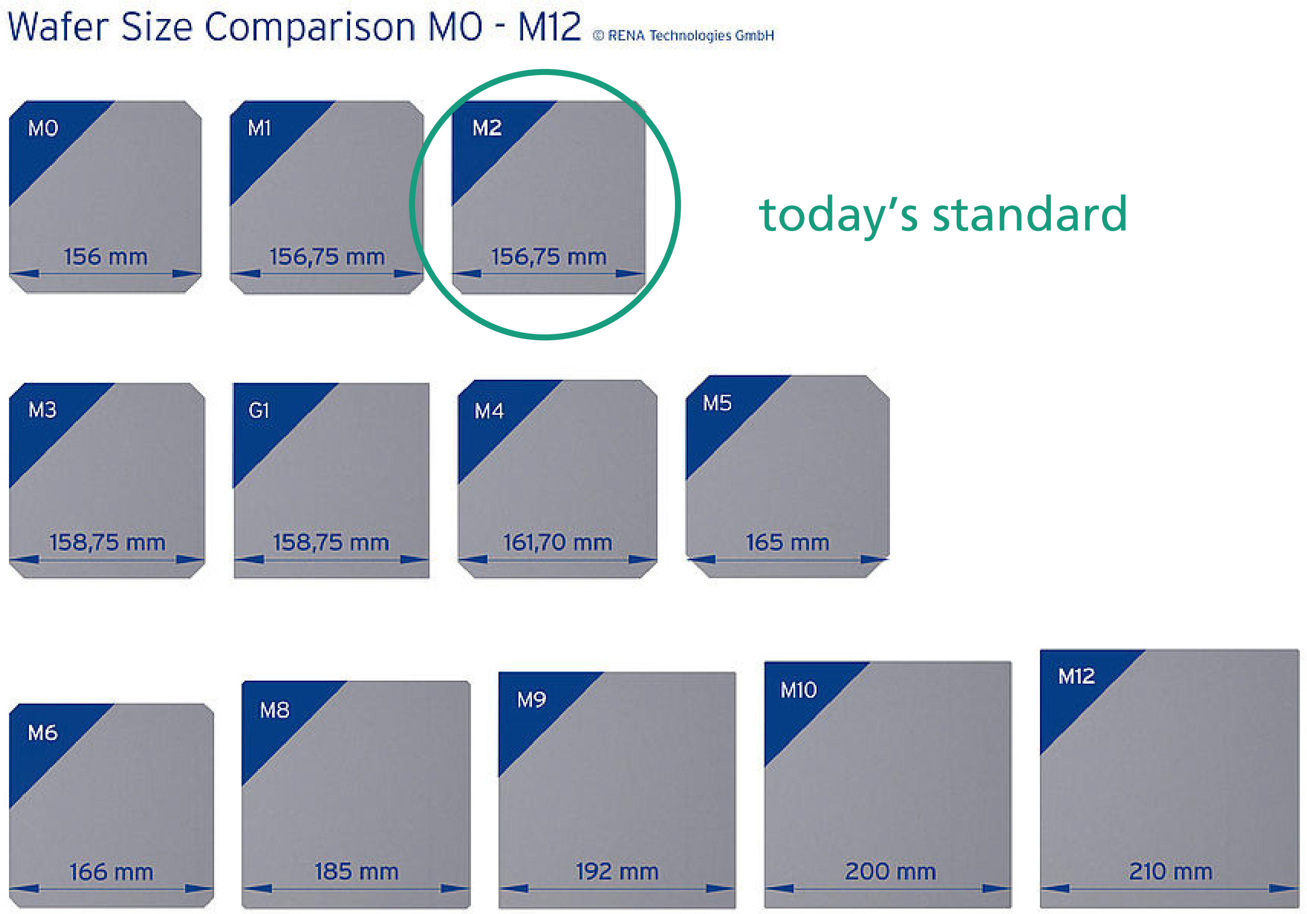
Laser Material Processing for Solar Cell Production

Increasing Lens Requirements

- Wafer size will increase up to 30%
- Minimum required feature sizes will remain the same or go down to 10µm

→ Larger NA f-theta lenses needed depending on process

- Demand for 'perfect' lenses with diffraction limited performance across field of view will go up
- Number of UV processes likely to increase due to material properties



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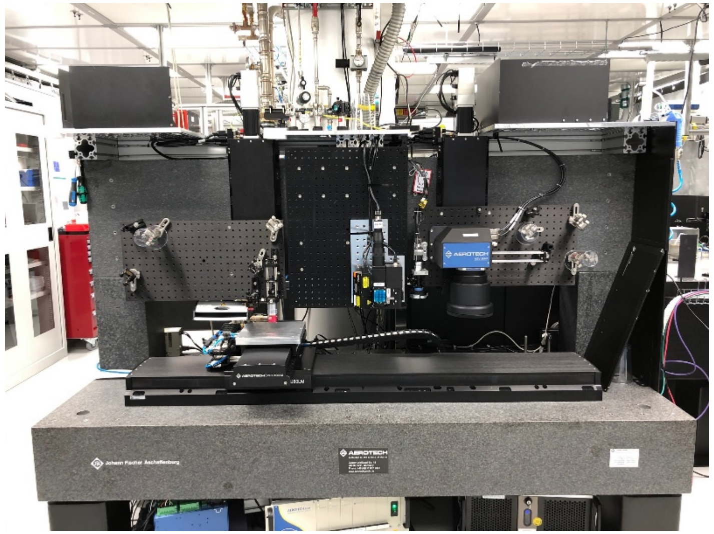
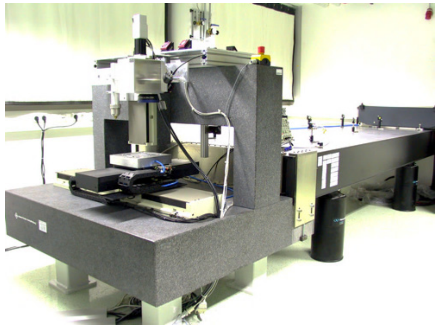
Laser Material Processing Infrastructure & Equipment

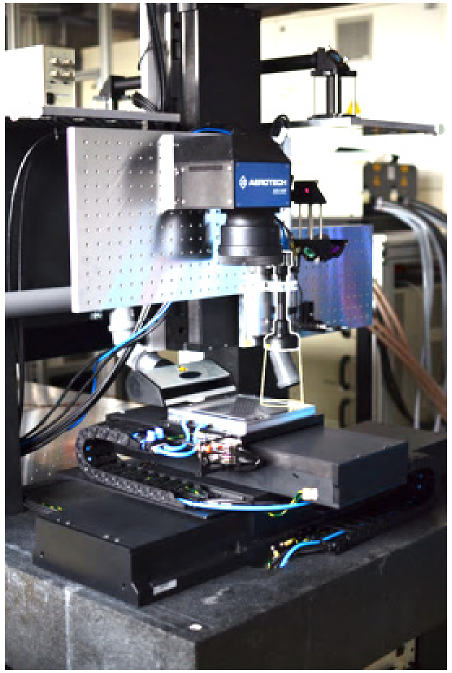
Laser-Material-Processing @ Fraunhofer ISE

Laboratories & Equipment

- > 200m² laser class 4 lab space with XYZ stages and beam delivery up to 1500m/s







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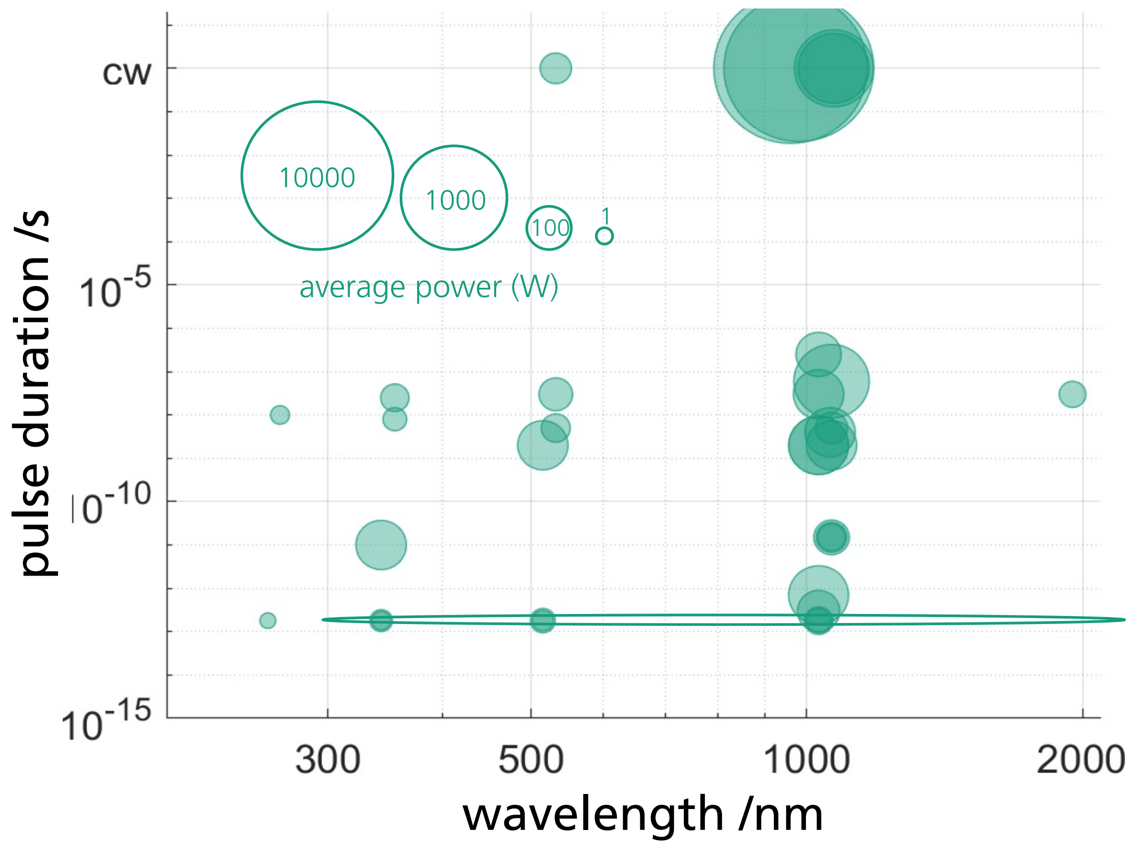
Laser-Material-Processing @ Fraunhofer ISE
Laboratories & Equipment

- > 200m² laser class 4 lab space with XYZ stages and beam delivery up to 1500m/s
- More than laser 25 beam sources for material processing
  - Pulse durations from >180fs to cw
  - Wavelengths from 250nm to 2000nm
  - Average power 1W to >10kW

laser beam sources for material processing @ISE



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Laser-Material-Processing @ Fraunhofer ISE

Laboratories & Equipment

- > 200m² laser class 4 lab space with XYZ stages and beam delivery up to 1500m/s
- More than laser 25 beam sources for material processing
  - Pulse durations from >180fs to cw
  - Wavelengths from 250nm to 3000nm
  - Average power 1W to >10kW
- Laser class 1 processing machines from prototypes to fully automated production class tools

Keep in mind: several thousand square meters of laboratory with pre- and post-processing and characterization of solar cells, fuel cells and other devices related to solar energy systems

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Great News – New Production of High-End Solar Cells in Europe

MEYER BURGER

“Meyer Burger Technology Ltd aims to transform itself from a supplier of production equipment to a technologically leading manufacturer of solar cells and modules…

…

establishing an own large-scale cell and module production in Germany”

19.06.2020 www.meyerburger.com

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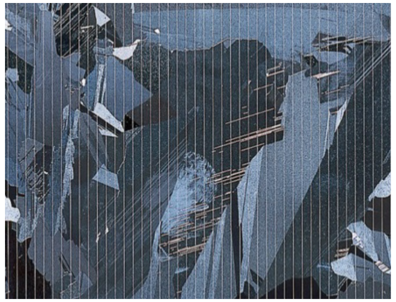
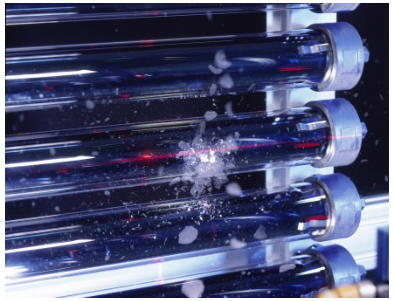
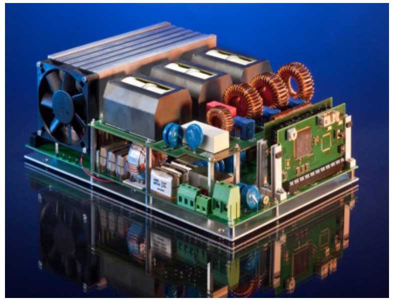
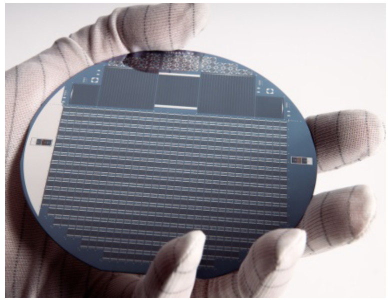
Thank you for your Attention!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