Bern University of Applied Sciences
Applied Laser, Photonics & Surface Technologies ALPS

Ps-processing of PV thin films

Salon EPMT Genève 2012
SLN workshop : Laser Micromachining.
07.06.2012, Palexpo

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ALPS - Applied Laser, Photonics and Surface Technologies

Overview

Introduction

- who we are
- optical fibers for pulse generation, amplification and transport

Picosecond laser in thin-film photovoltaics

- anatomy of a thin film solar cell
- PV thin film patterning – why and how
- picosecond laser in PV manufacturing – know your tool!
- three laser scribing processes in detail

Results and achievements

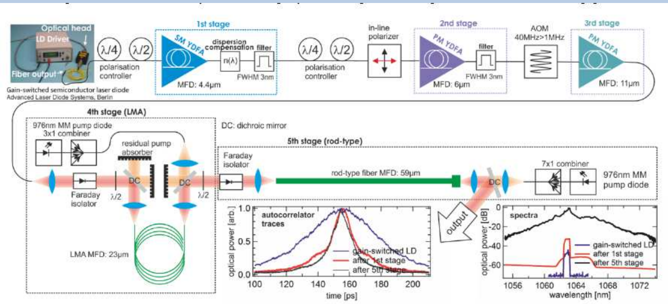
Conclusion and outlook

optical fiber group at BUAS – who we are

Competence center for optical fibers

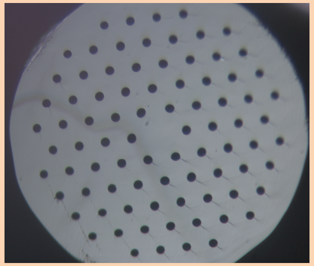
operated by the Institute for Applied Laser, Photonics and Surface Technologies (**ALPS**) at Bern University of Applied Sciences (BUAS) in Burgdorf together with the Institute of Applied Physics at the University of Bern.

development of fiber laser systems:
pulse generation and amplification

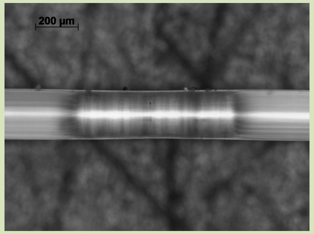


Ryser *et.al.*: 1064nm, 11ps, >10µJ, 1MHz

design and manufacturing of fibers:
calculation, material research & prototype production with own fiber drawing tower



fiber testing, coupling and splicing:
state-of-the art cleaving and splicing equipment, scattering analysis, pulse analysis for high power delivery fibers



Why fiber lasers and fiber delivery?

Fiber lasers are energy efficient

wall plug efficiencies of up to 30% can be achieved; this also allows air-cooling

Fiber lasers are low-cost

if the needed laser parameters are within the physical and technical limits of the fiber laser technology, a fiber-based laser source is most probably the cheapest solution. This is specially true for ultra-short pulsed lasers.

Fiber lasers are light and compact

fiber lasers can easily be integrated into production machines as they are very compact and do not need water cooling .

Fiber delivery is very convenient

major benefits for large machines, moving processing heads or very little available space. No free-space optics, thus no maintenance needed.

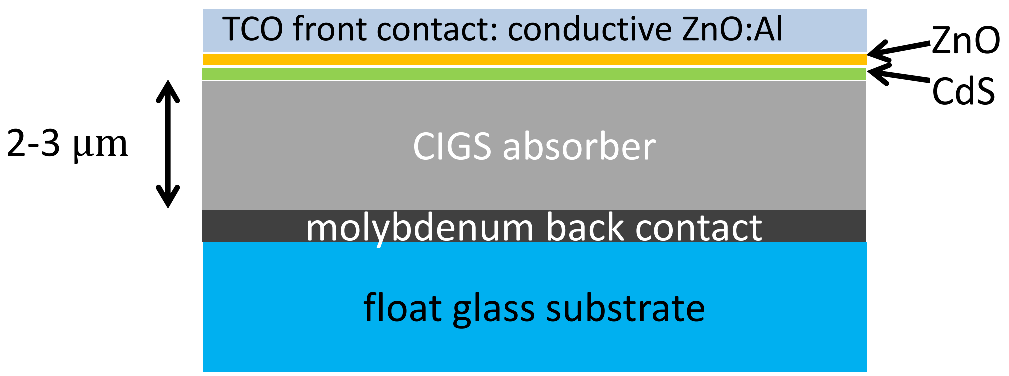
But: **various factors limit the maximum pulse energy and minimum pulse duration** for amplification and transport of ultrashort pulses in optical fibers.

We currently work on transporting **a few µJ at 50 ps over several meters of fiber**.

An interesting application in this parameter range is PV module patterning...

photovoltaic thin film structuring

Anatomy of a Cu(In.Ga)Se_2 or CIGS based solar cell

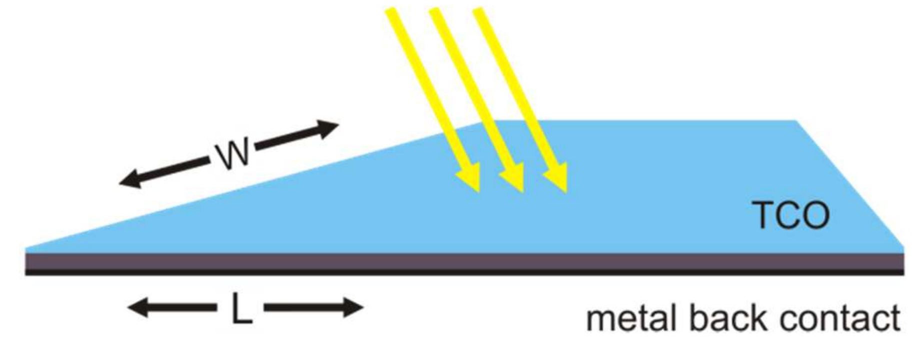


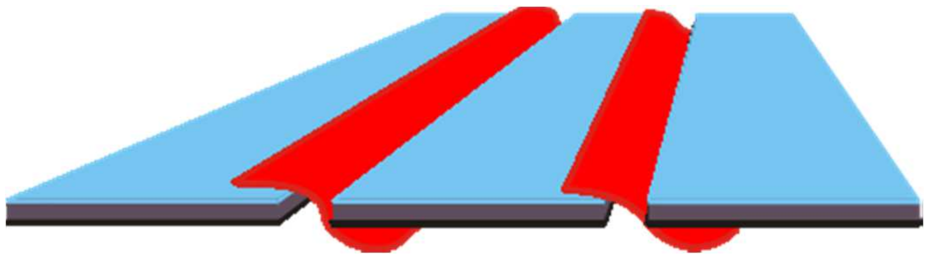
The full multi-layered stack consists of three main functional thin films:
a metallic back contact, the absorber material and the transparent front contact.

Three films – three very different problems for high precision laser structuring.

overall challenge: maintain reliability and precision at high throughput.

Why do we need solar module patterning?





<u>scaling effects</u>

one large solar cell

- low voltage
- high current density ~L
- high ohmic losses ~L
- full area is productive

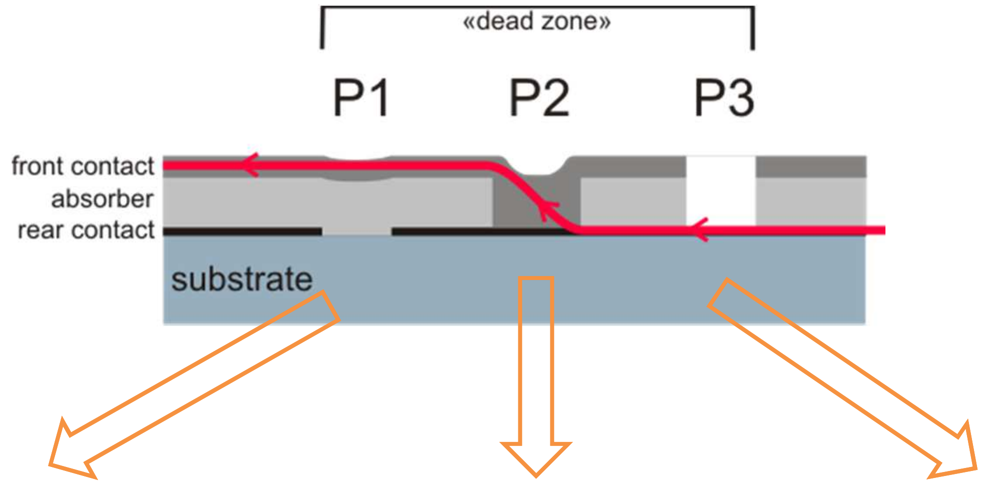
cell strips connected in series

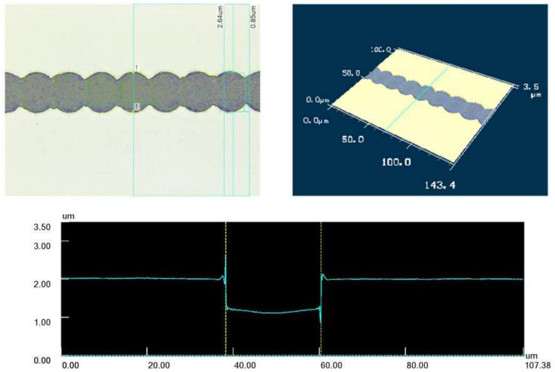
- high voltage
- low current density
- low ohmic losses
- reduced productive area

Need to find optimum between low current density and loss of productive area!

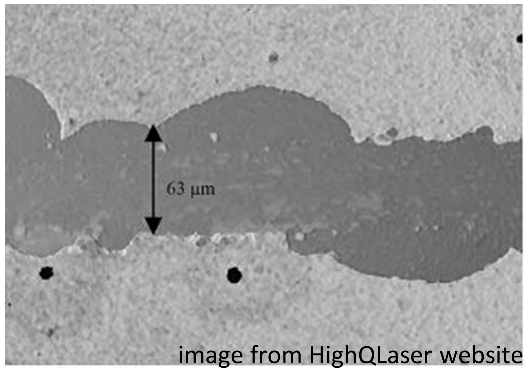
The outcome of this optimization process depends on the productive area loss per interconnect → build smallest possible interconnects.

"monolithic" interconnect from three scribes P1 to P3

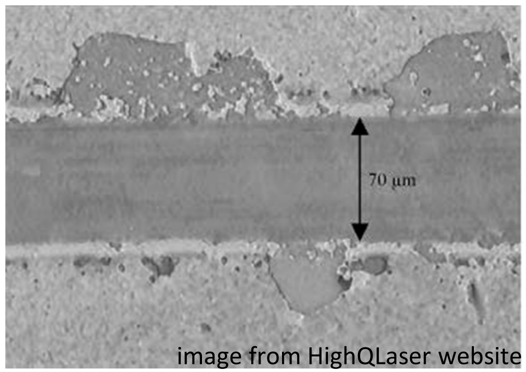




P1 – usually a laser process



mechanical P2 scribe, broadened by chipping



mechanical P3 scribe, broadened by chipping

dead-zone width can be up to 500 µm for mechanical scribing processes.

CTI project partners – CIGS all-laser scribing

solneva
swiss solar tools

Solneva SA, Aarberg, Switzerland
- Swiss Solar Tools
- Machine integration
- Industrial process know-how

EMPA
Materials Science & Technology

Empa. Laboratory for Thin Films and Photovoltaics, Dübendorf, Switzerland
- Thin film deposition
- PV materials expertise
- Standardized electrical testing procedures

onefive

onefive GmbH, Zürich
- development and building of the picosecond fiber laser source

Bern University of Applied Sciences
Engineering and Information Technology

Institute for Applied Laser, Photonics
and Surface Technologies

Bern University of Applied Sciences, ALPS, Burgdorf, Switzerland
- Laser delivery and process development
- Expertise in short and ultra-short pulse material processing
- Experimental work

Interconnection scheme

Molybdenum (Mo) layer grown on floatglass substrate (by DC sputtering)

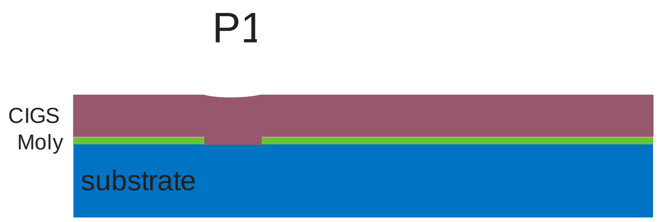
Interconnection scheme

P1 scribe removes the Moly layer completely and creates an isolating trench

...can be a layer-side or substrate-side process.

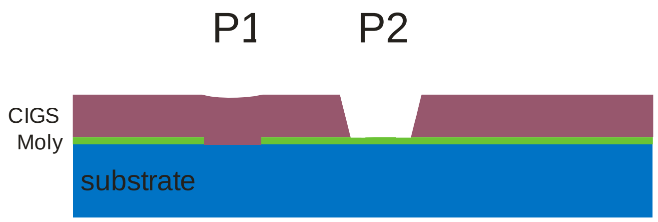
Interconnection scheme

CIGS absorber layer is deposited on P1 patterned Moly (co-evaporation)



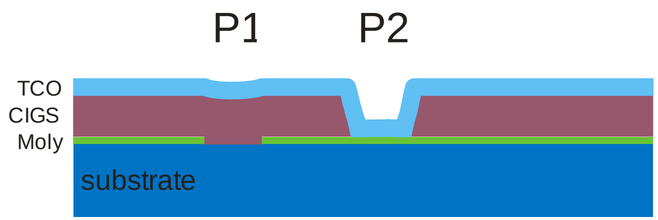
Interconnection scheme

P2 scribe removes the CIGS down to the Moly back contact



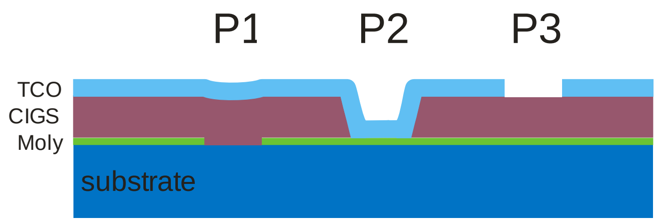
Interconnection scheme

TCO layer (i-ZnO/ZnO:Al bilayer grown by RF sputtering)

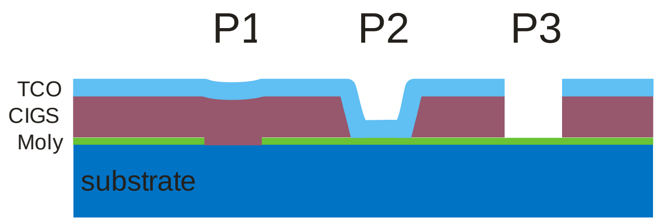


Interconnection scheme

P3 scribe creates an isolating trench in the TCO front contact

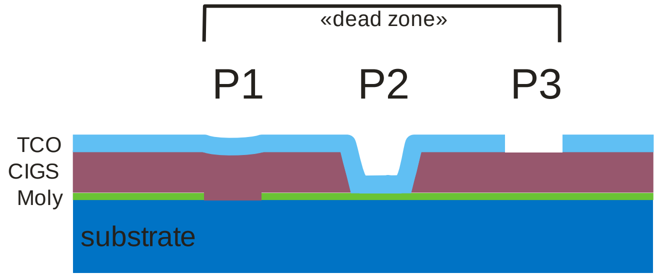


P3 scribe can also remove the whole layer stack down to the Moly



Interconnection scheme

non-productive area "dead zone" between the P1 and the P3 scribe, includes potential heat affected zone.



<u>requirements for the laser processes</u>

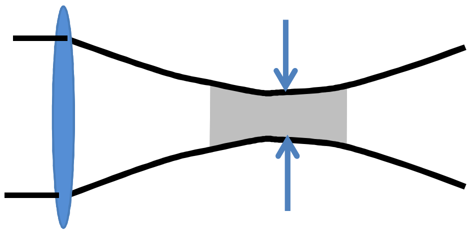
P1 complete removal, clean border, no cracks, no melt, no substrate damage substrate-side or layer-side processing possible

P2 high selectivity, no damage of Mo layer, melt and incomplete removal can be tolerated. only layer-side processing is possible

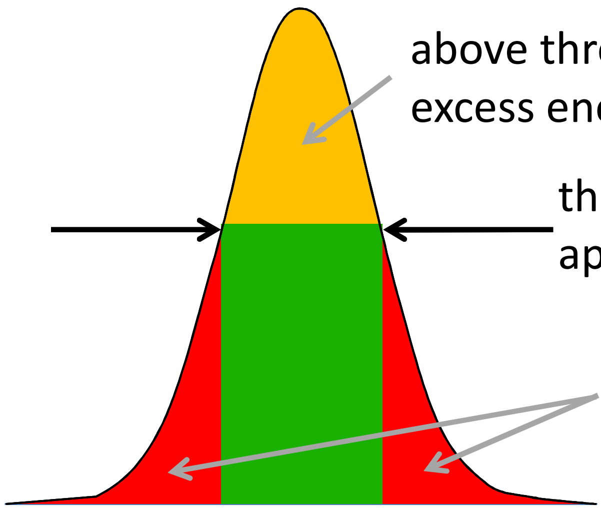
P3 high selectivity, complete removal, no melt. layer-side processing

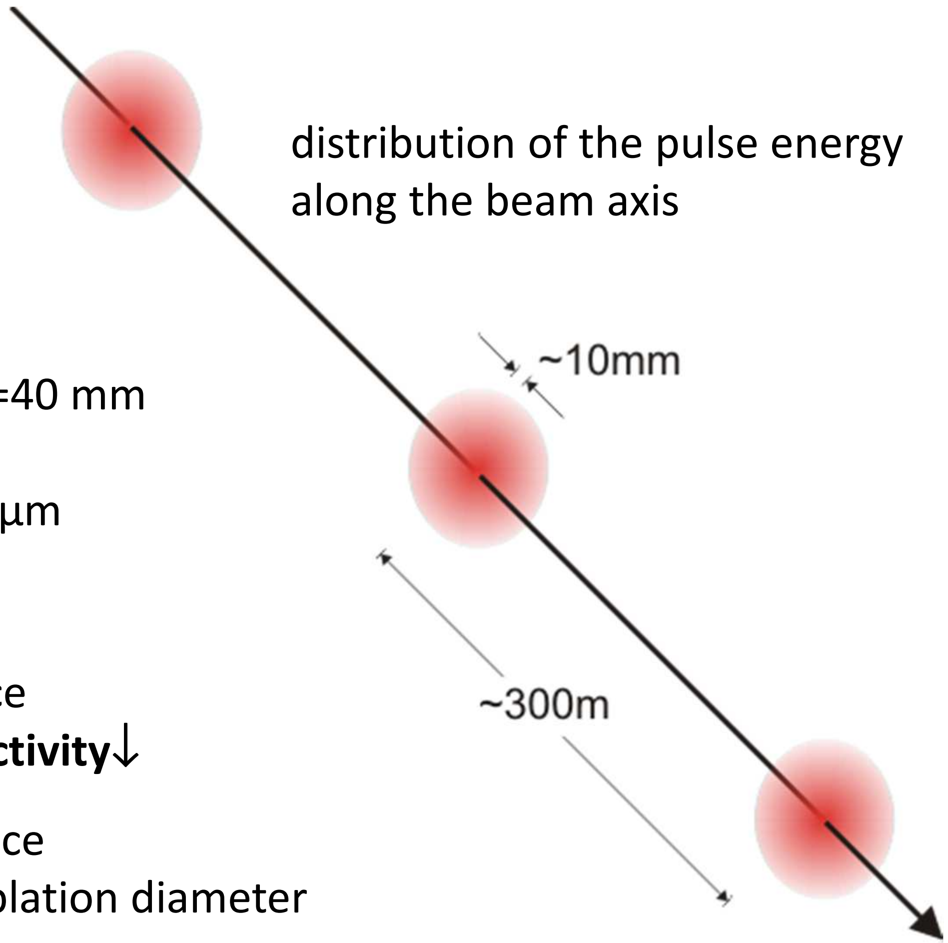
ps laser processing – know your tool!

Case:
wavelength: 1064 nm
pulse duration 30 ps
repetition rate: 1 MHz
beam: TEM_{00}, M^2=1



beam ø 4 mm, lens f =40 mm
spot ø 27 µm,
Rayleigh length ≈540 µm



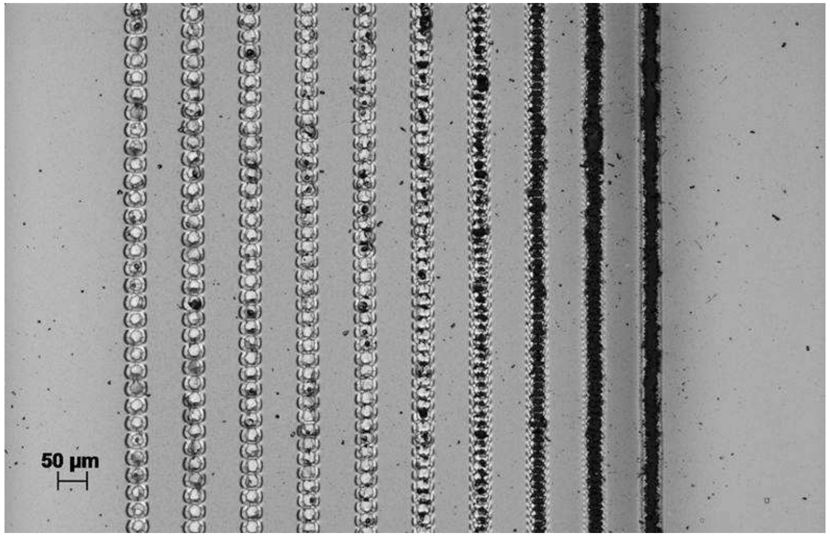


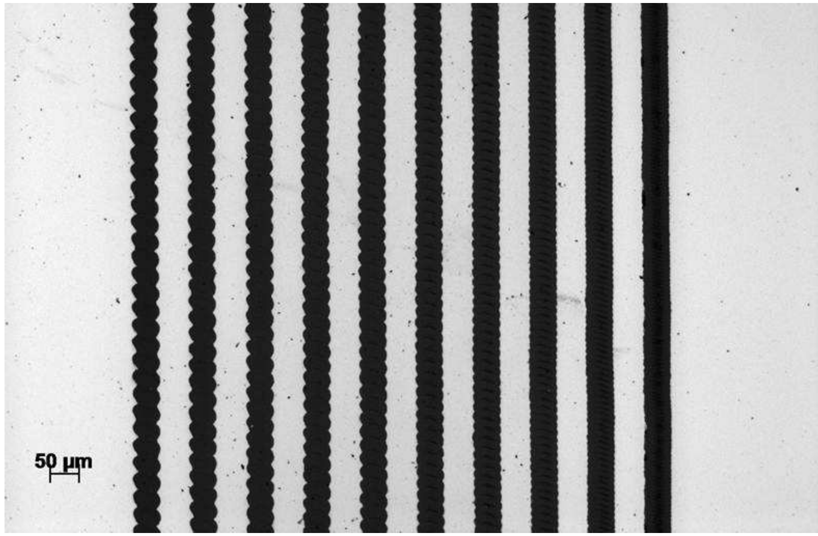
distribution of the pulse energy
along the beam axis

heat diffusion:
time needed to travel
1 µm typ. 2.5 ns (Moly)

P1 layer-side vs. substrate-side process

Micrographs of P1 scribes on a ~0.6 µm molybdenum layer

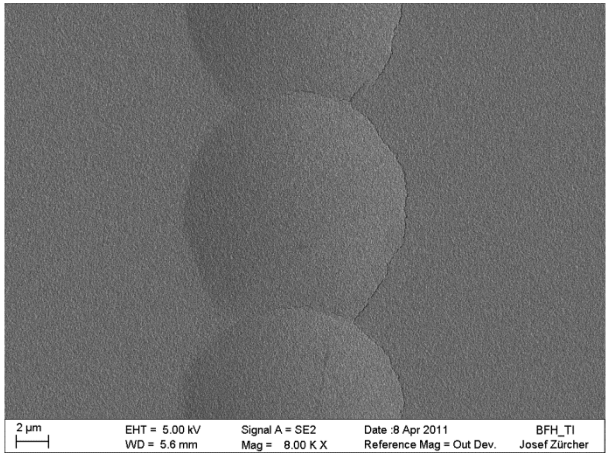




layer-side
1064 nm, 30 ps**, 40 µJ**
overlap 10% - 80 %

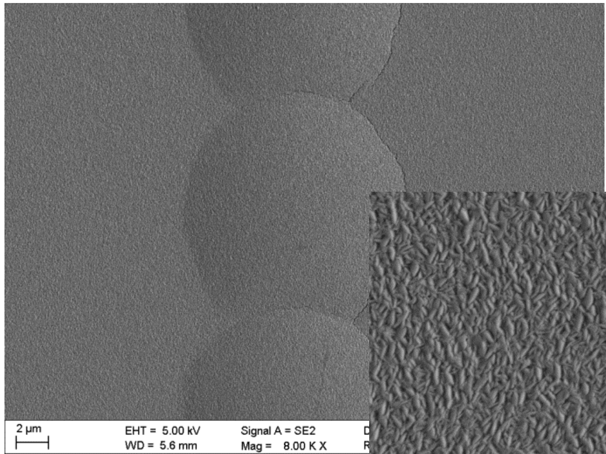
substrate-side
1064 nm, 30 ps, **4 µJ**
overlap 10% - 80 %

Substrate-side P1 process with picosecond pulsed laser

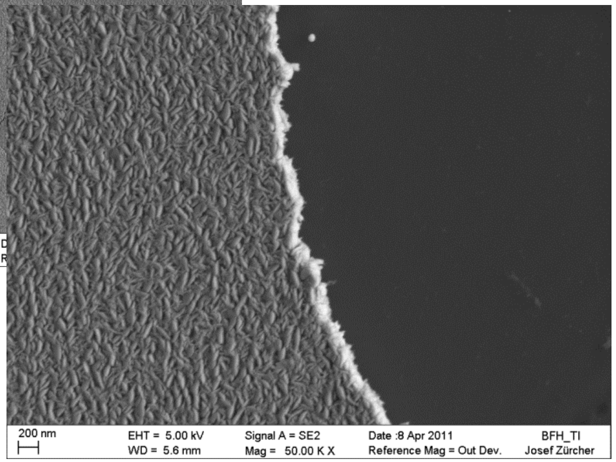


Electron micrograph of a P1 scribe made at 532 nm, 10 ps (below threshold)

Substrate-side P1 process with picosecond pulsed laser

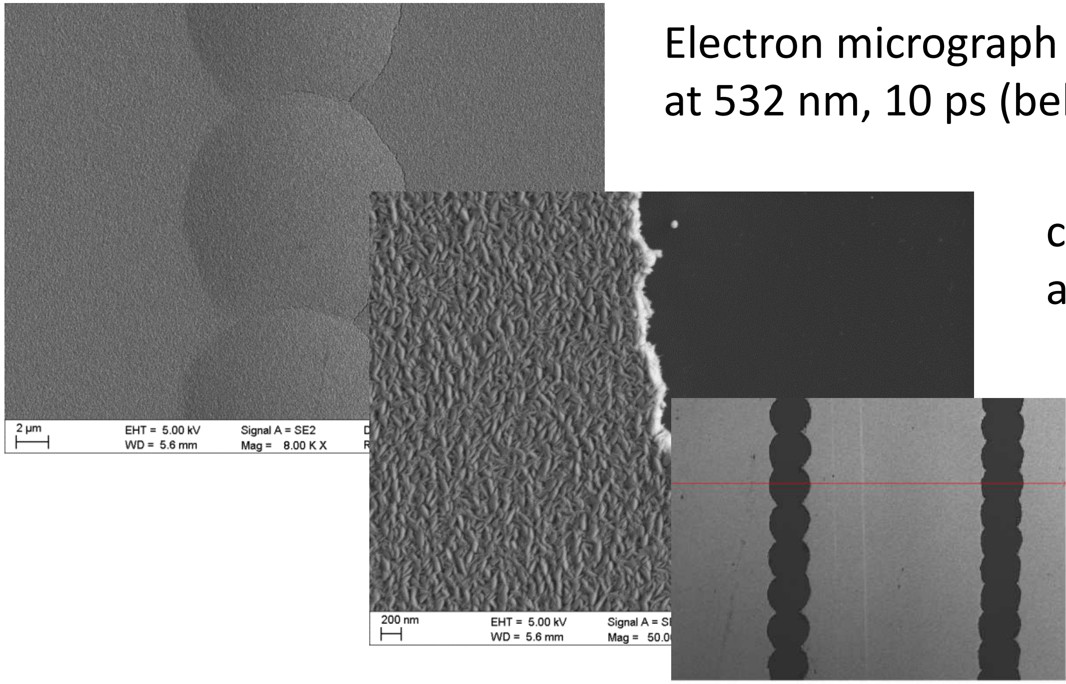


Electron micrograph of a P1 scribe made
at 532 nm, 10 ps (below threshold)



clean rupture of the moly
at pulse energies above threshold

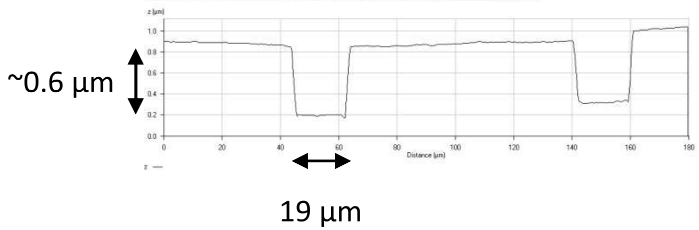
Substrate-side P1 process with picosecond pulsed laser



Electron micrograph of a P1 scribe made
at 532 nm, 10 ps (below threshold)

clean rupture of the moly
at pulse energies above threshold

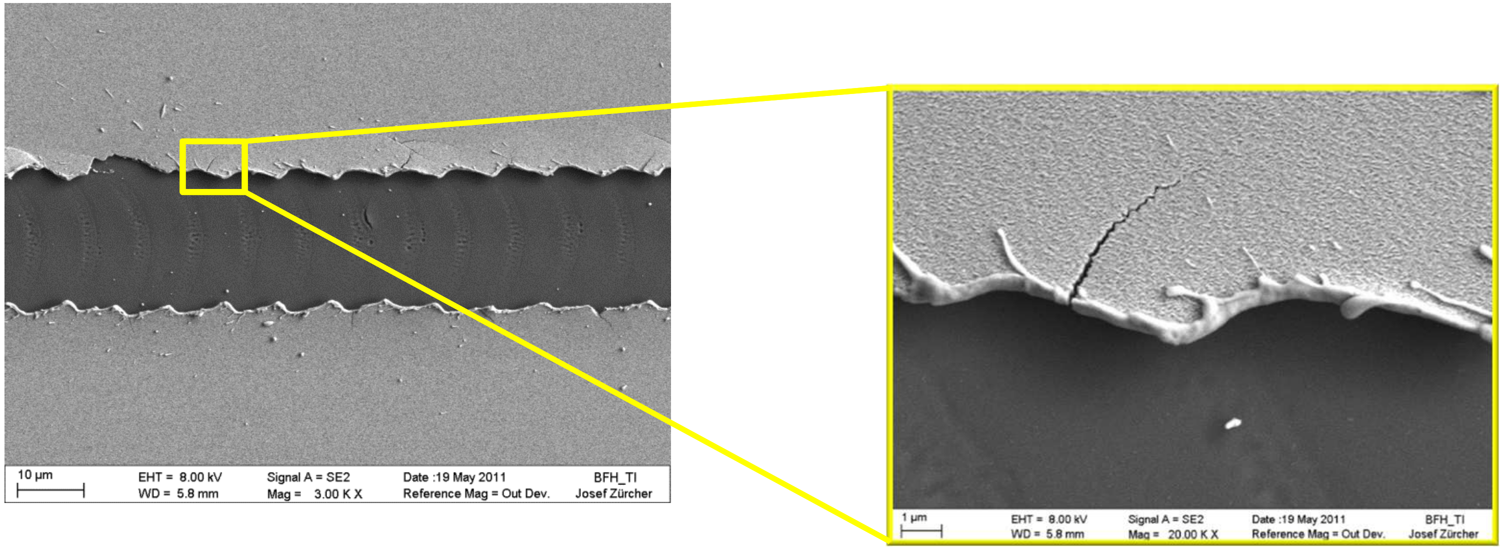
LSM height profile shows a
clean trench and sharp edges
scribe made at 1064 nm, 30 ps



Working P1 parameter combinations were found for all picosecond sources in this study (all wavelengths and all pulse durations).

Substrate-side P1 process with nanosecond pulsed laser

typical scribe made on 0.6 µm moly at 1550 nm, 3.2 ns pulse duration



<u>Characteristics</u>

- Separation of Mo layer and substrate at the scribe edge
- small cracks are often found
- molten Mo at the scribe edge forms small burrs

There are indications that ns processes may work better on samples of other manufacturers. [Witte et. al. *EU PV Sec Proceedings*, Frankfurt (2011)]

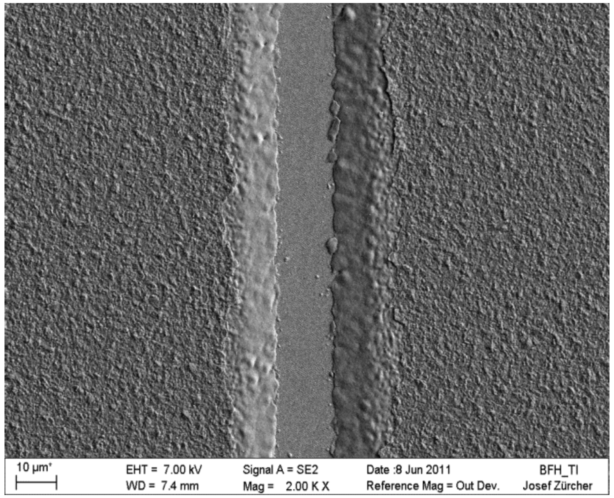
P2 process (picosecond laser)

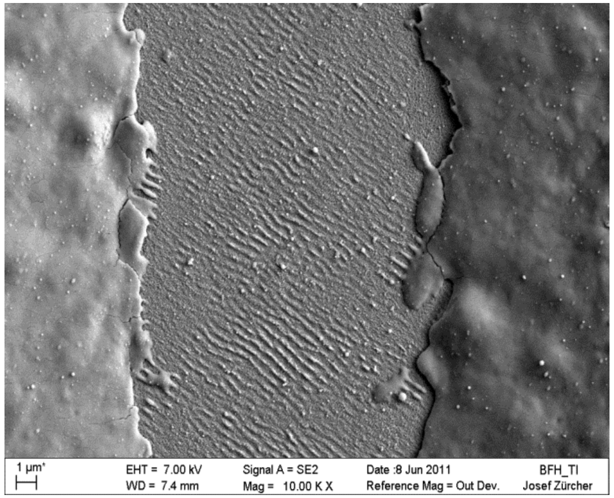
⚠ **There is no 'cold direct ablation' of CIGS – even 10 ps pulses produce melt**

CIGS is a <u>volume absorber</u> by design!

<u>P2 quality criteria for process selection</u>

- Mo back-contact integrity
- width of the exposed Mo-film *vs.* width of the molten CIGS zone
- height and profile of the
- cracks and bubbles in the molten CIGS

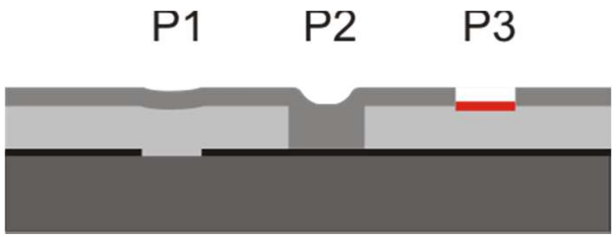




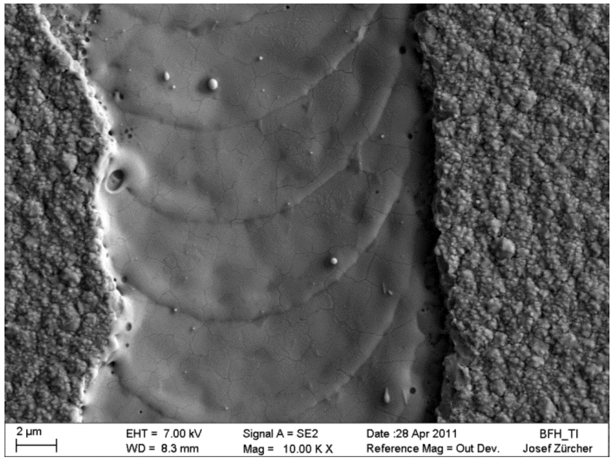
optimized P2 scribe example for 532 nm, 30 ps, ω_0=20 µm
→ fully exposed Mo, clean trench, undamaged Mo

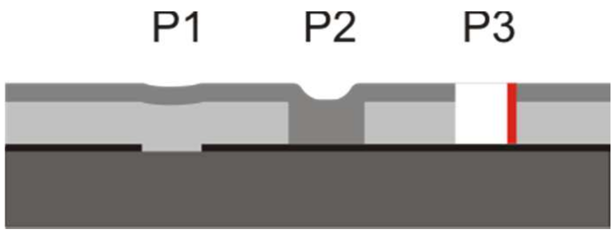
P3 process

P3 is the most critical process with respect to $Cu_{1-x}Se$ short formation

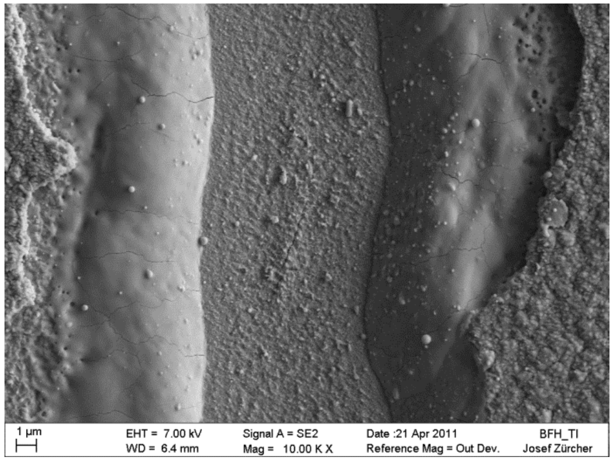


horizontal short formation



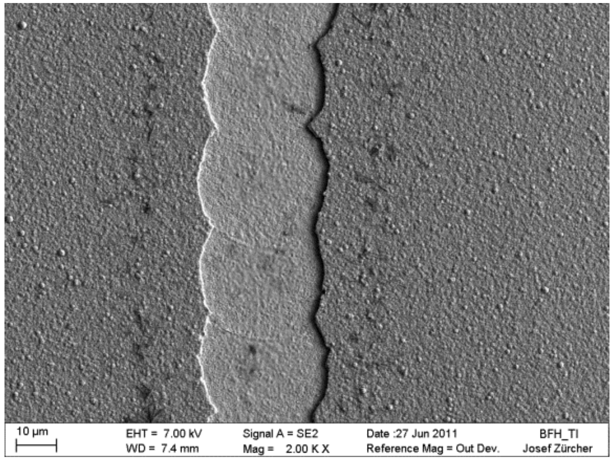


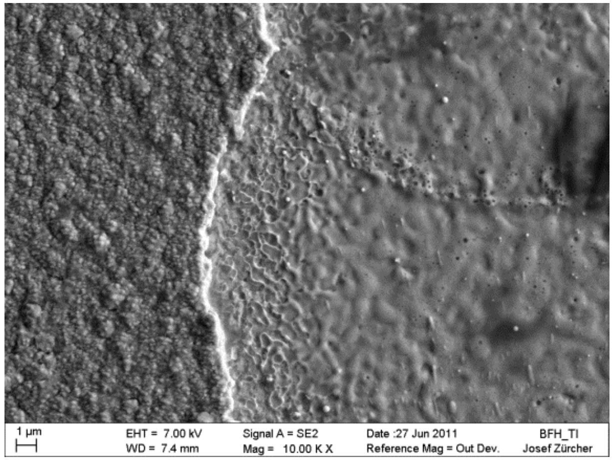
vertical short formation for alternative P3



P3 process

induced ablation process: pulse energy absorbed in the CIGS top layer and powers a TCO lift-off process





532 nm, 30 ps

scribe characteristics
- complete removal of the TCO
- clean, brittle fracture of the TCO at the scribe border
- molten CIGS mainly in the center

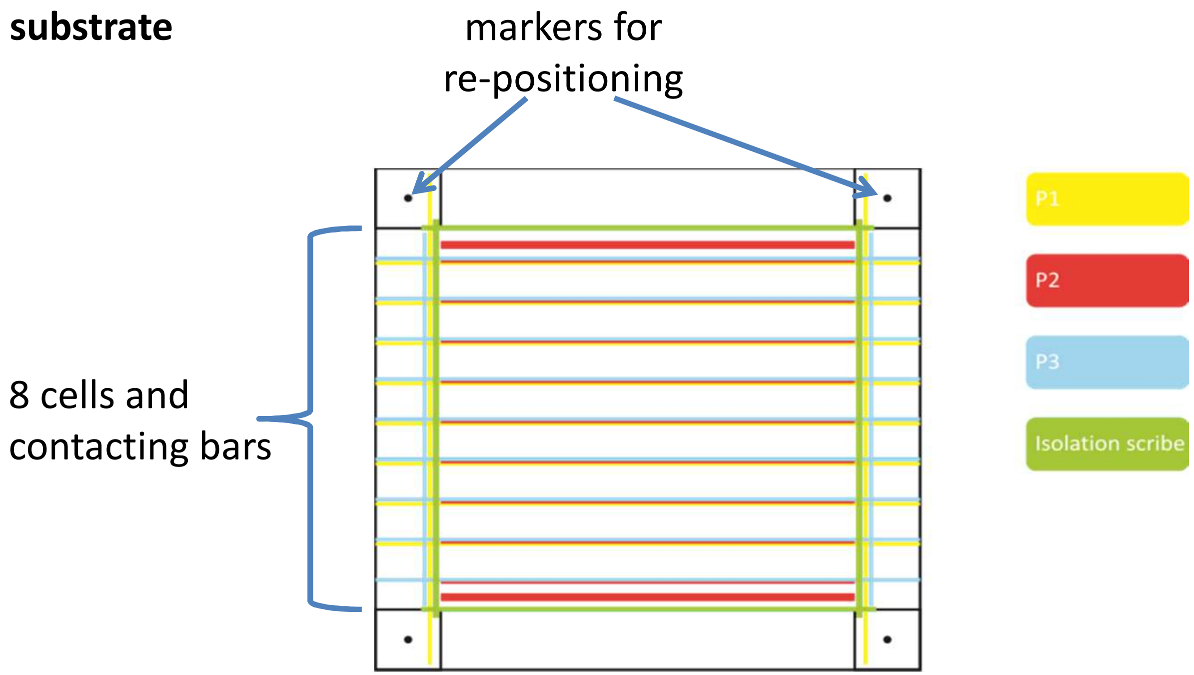
Functional 8-cell mini-module

Functional mini-modules were produced with variable scribe-to-scribe distance between 70 µm and 150 µm.

laser parameters

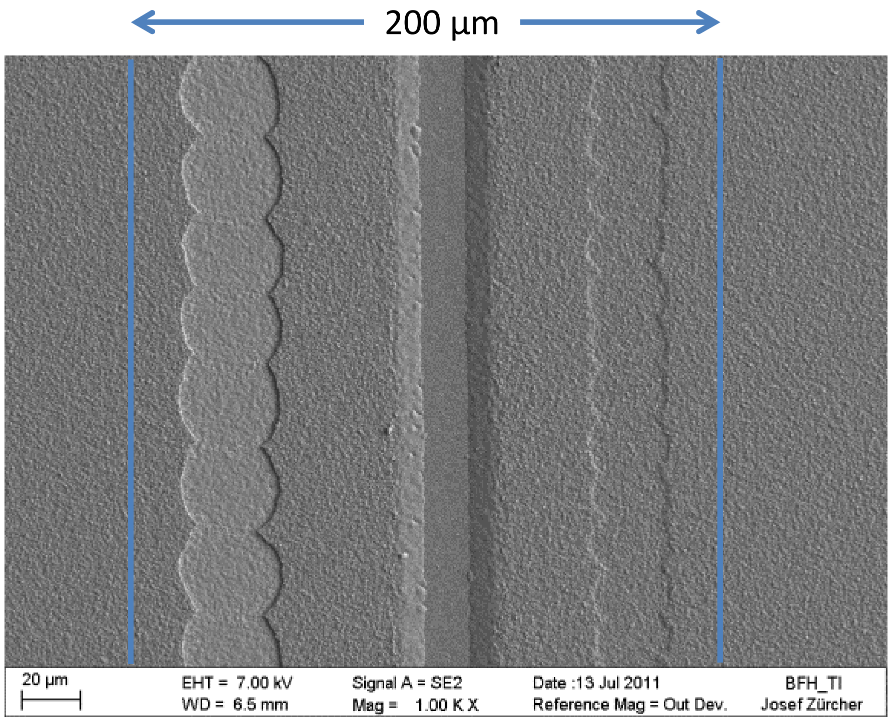
	λ / nm	τ / ps	w_0 / mm
P1	1064	50	17
P2	532	30	20
P3	532	30	20

Scribing pattern on a 50 x 50 m² float glass substrate



low dead zone

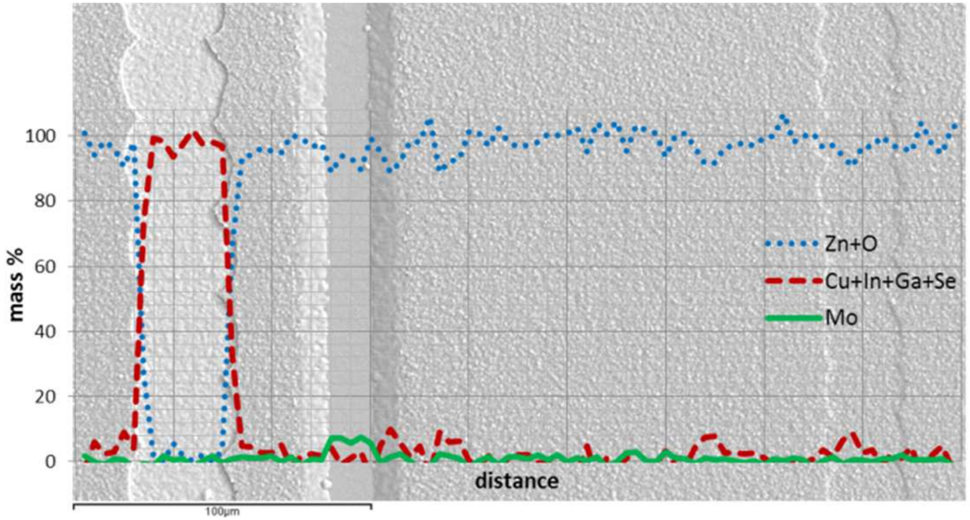
A dead zone of <200 µm was realized on an entire functional mini module.
No negative effect on electrical performance of the interconnections was observed.

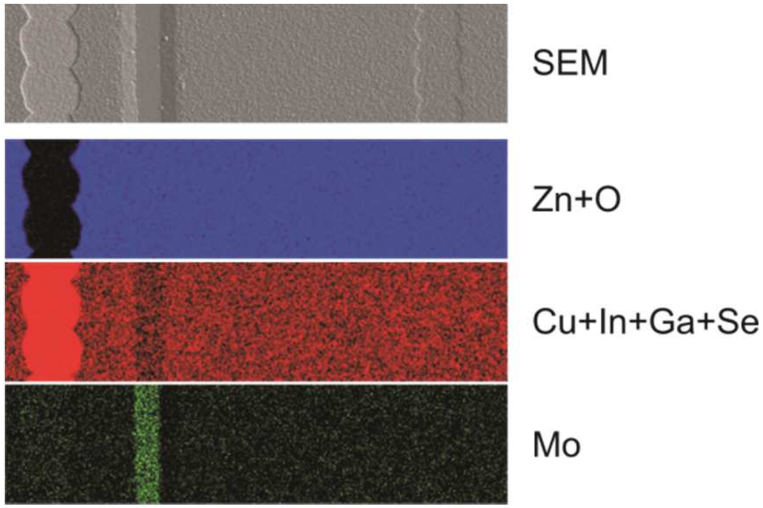


A further reduction of the dead zone width by 40% could be achieved without changing the beam parameters.
Less than 2% module dead area should be possible.

EDX analysis

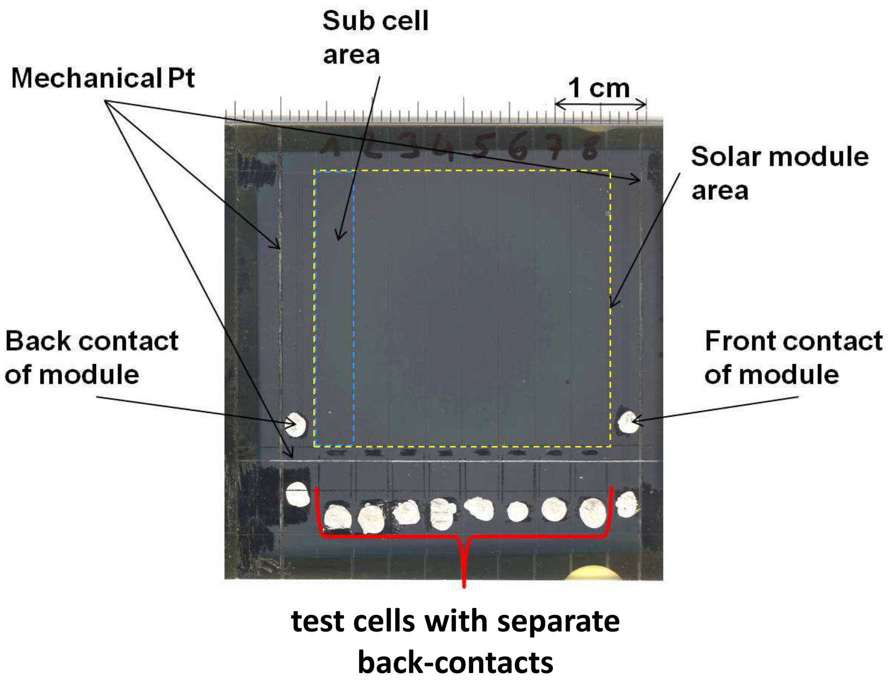
Energy dispersive X-ray line profiles and material mapping of the scribe region.
Analysis made on the finished module.





Line profile and maps show the characteristic fingerprint of an interconnect.

Electrical performance of the functional module



Analysis by means of illuminated current voltage (JV) characteristics at the EMPA laboratory according to the international standard IEC 60904-1, AM1.5G irradiation spectrum and 1000 Wm^{-2} irradiation intensity; constant temperature 25°C.

Compare the electrical performance of the single cell with the module performance.

Results from previous study:
Module efficiency is 16 percent (relative) lower than the single cell efficiency.

New results from the current study comprising 30+ modules in total will be available soon.

Conclusion

- Overview on the activities of the fiber group at BUAS and the **competence center optical fibers Bern – Burgdorf**.

- Fiber lasers are reliable and practical tools. Often they can replace bulkier and much more expensive laser systems. **This includes applications in the picosecond pulse duration regime up to several µJ pulse energy**.

- We developed laser scribing processes for thin-film solar module patterning. The **scribing quality and reliability benefit from ps laser processing.**

- An **increase in precision** and a reduction of the dead zone to less than 200 µm has been demonstrated for a full mini-module.

- Solar module patterning shows optimum results with 30-50 ps pulse length. This range is **accessible for fiber lasers**. Together with our CTI project partners we work on the integration of fiber laser, laser delivery into an industrial machine.

Thank you for your attention!

Acknowledgment
This study was financed in parts by the Swiss Commission for Technology and Innovation CTI.

EMPA Materials Science & Technology

solneva swiss solar tools

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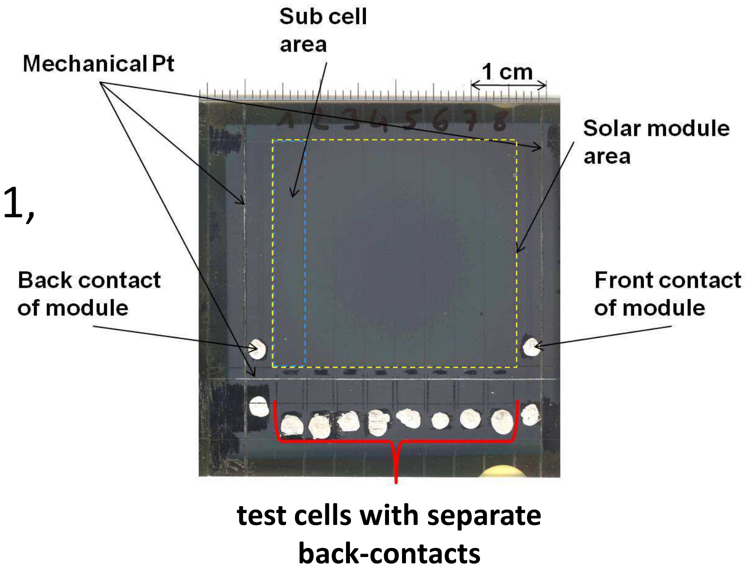
Bern University of Applied Sciences
Engineering and Information Technology

Institute for Applied Laser, Photonics
and Surface Technologies

Backup Slides

Electrical performance

Analysis by means of illuminated current voltage (JV) characteristics at the EMPA laboratory according to the international standard IEC 60904-1, AM1.5G irradiation spectrum and 1000 Wm^{-2} irradiation intensity; constant temperature 25°C.

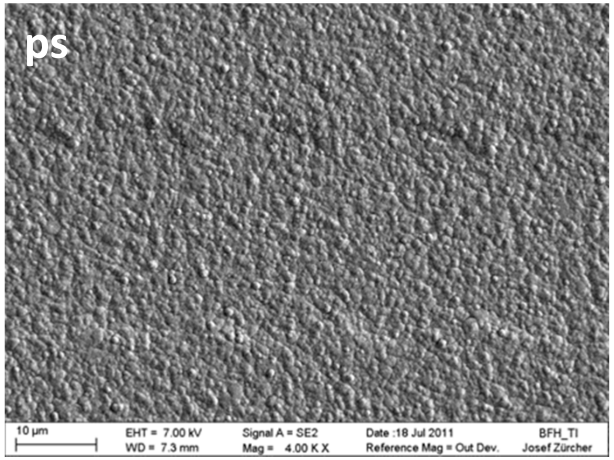


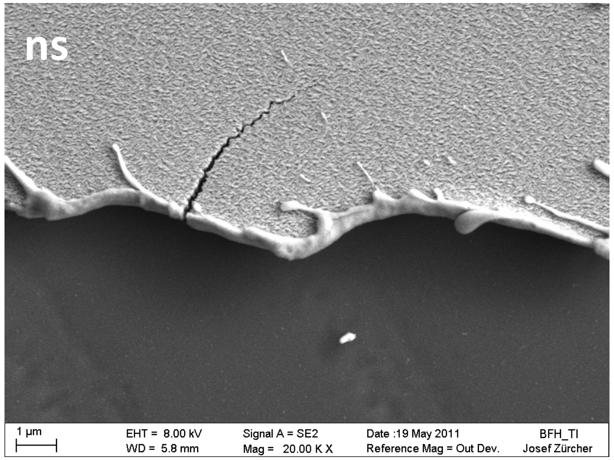
View of the test module after mechanical re-scribing

<u>Module performance *vs.* cell performance</u>

Module efficiency is 16 percent (relative) lower than the single cell efficiency.

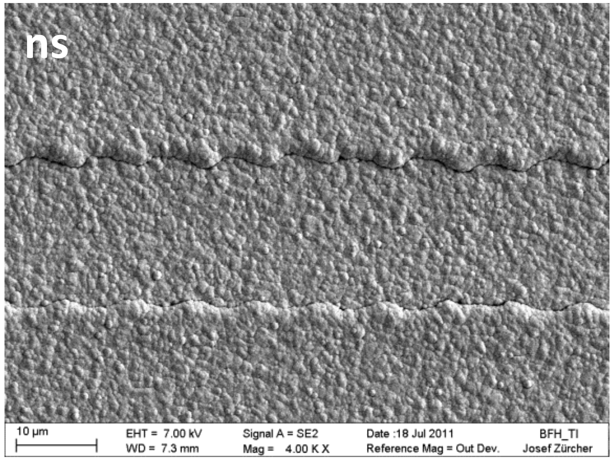
picosecond *vs*. nanosecond P1 scribing quality

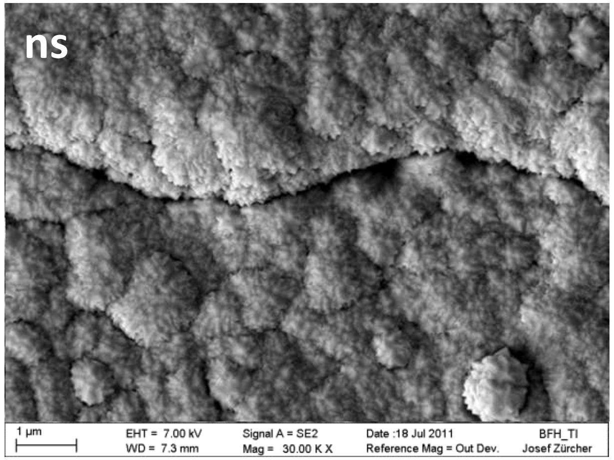




ns P1 scribe border detail

SEM images of the finished mini-modules

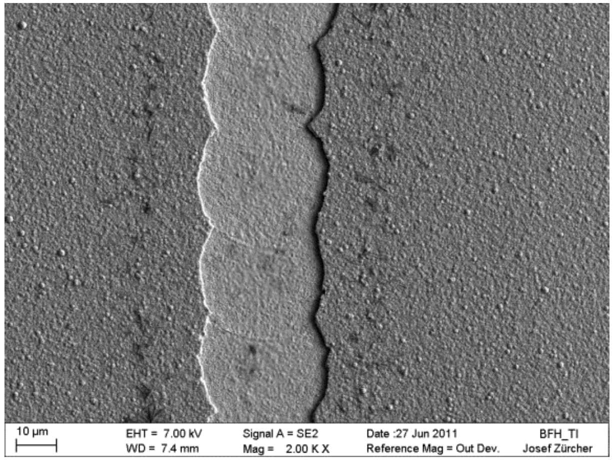


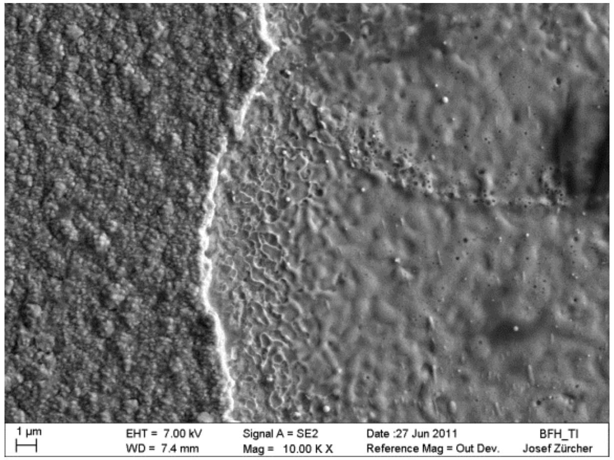


detail of the same sample after the remaining process steps.

P3 process (picosecond laser)

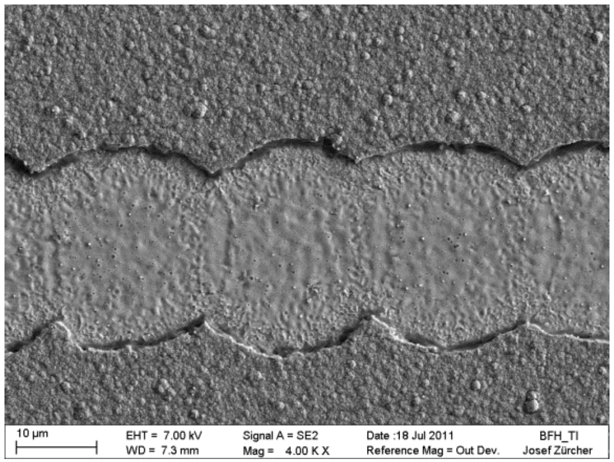
induced ablation process: pulse energy absorbed in the CIGS top layer and powers a TCO lift-off process

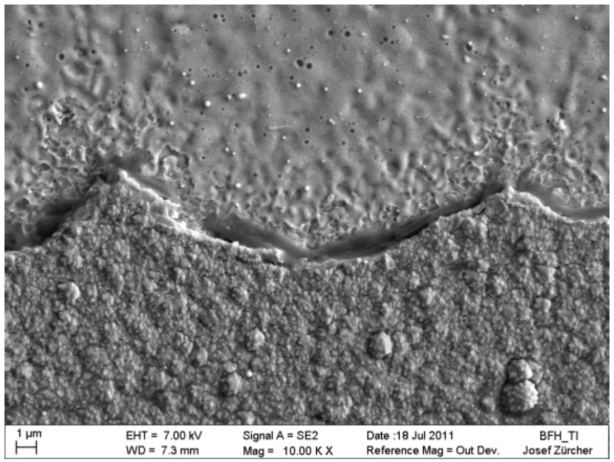




532 nm, 30 ps

a similar process can be realized with nanosecond pulses

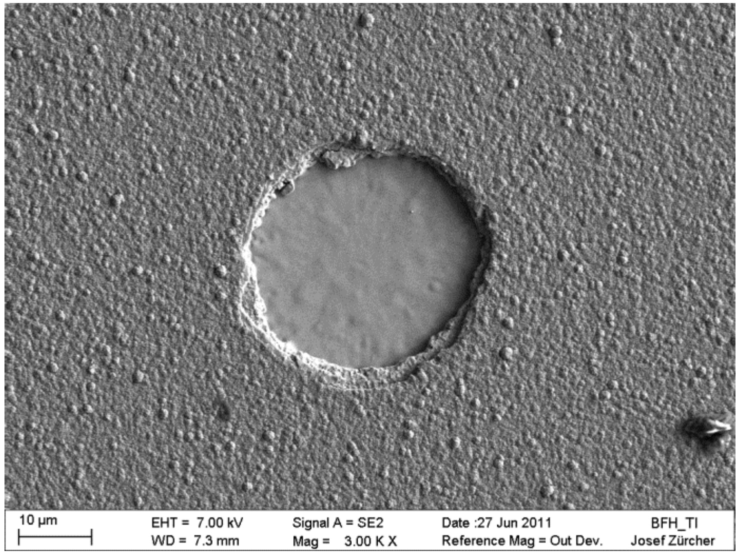




532 nm, 1.5 ns

Special cases

Effect of a single pulse 1064 nm, τ=10 ns on a Mo/CIGS/ZnO stack



Potential for an alternative P2 process.

Laser sources

basic requirements to our laser sources:
- good beam quality, $M^2 < 1.5$
- near Gaussian beam profile

ps lasers	wavelength		
pulse length	355 nm	532 nm	1064 nm
10 ps	➨	➨	➨
30 ps	➨	➨	➨
50 ps	➨	➨	➨

ns lasers	wavelength		
	532 nm	1064 nm	1550 nm
pulse length	1.5 ns	10 ns, 25 ns	3.2 ns

Optical setup as simple as possible – no beam shaping optics.