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High throughput P2 laser scribing of Cu(In,Ga)Se_2 thin-film solar cells

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Materials Science & Technology



Flexible Solar Modules



- ▶ Bern University of Applied Sciences, BUAS
Institute for Applied Laser, Photonics and Surface Technologies ALPS
- ▶ www.ti.bfh.ch/alps



<http://appolo-fp7.eu>

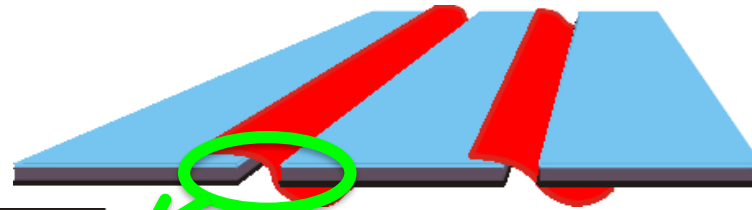
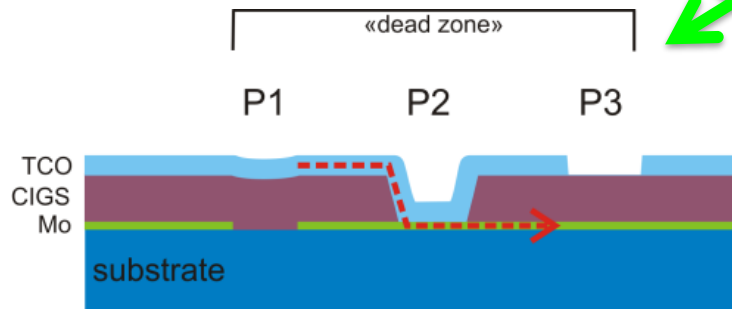
supported by



Outline

- ▶ **Introduction / Problem Statement**
- ▶ **Throughput optimization in scribing**
- ▶ **Experimental setup**
 - ▶ optical setup
 - ▶ process parameters
- ▶ **Scribing results**
 - ▶ morphological analysis
 - ▶ process robustness
 - ▶ electrical performance
- ▶ **Conclusions**
- ▶ **Outlook**

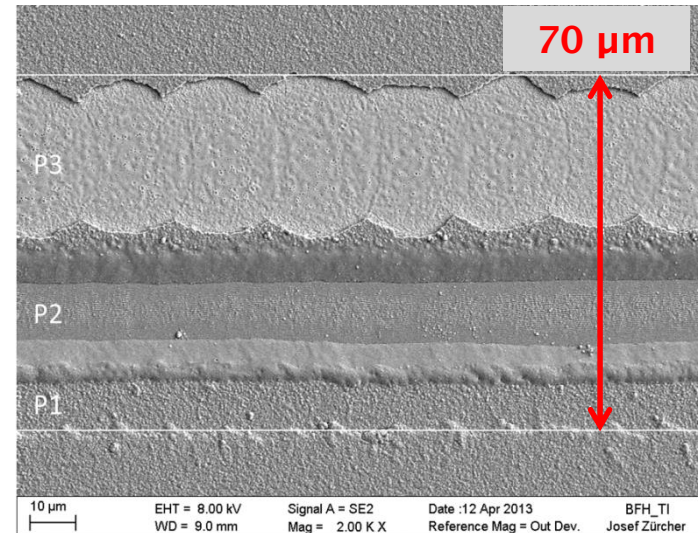
cell-to-cell interconnect



Module interconnection scheme

- P1 (removal of Mo back contact)
direct lift-off, through substrate
- P2 (selective removal of CIGS)
“classical” process, direct ablation
- P3 (selective removal of TCO)
induced lift-off process

Reference



All laser-scribed champion module
achieved certified 16.6% efficiency.

Burn, et al., Selective ablation of thin films in latest generation CIGS solar cells with picosecond pulses, Proc. of SPIE, Volume: 824, Art.-Nr: 824318, 2012

Burn et al., All Fiber laser scribing of Cu(In,Ga)Se₂ thin film solar cells, Physics Procedia, Vol 41, 706-715, 2013

Nishiwaki et al., A monolithically integrated high-efficiency Cu (In, Ga) Se₂ mini-module structured solely by laser. Progress in Photovoltaics: Research and Applications, 23(12), 1908-1915, 2015

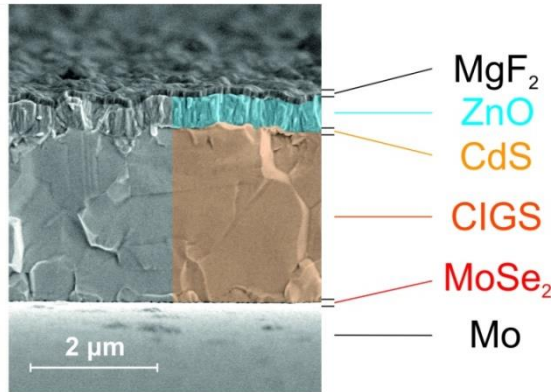
Sample material

Anatomy of a $\text{Cu}(\text{In,Ga})\text{Se}_2$ (CIGS) based solar cell

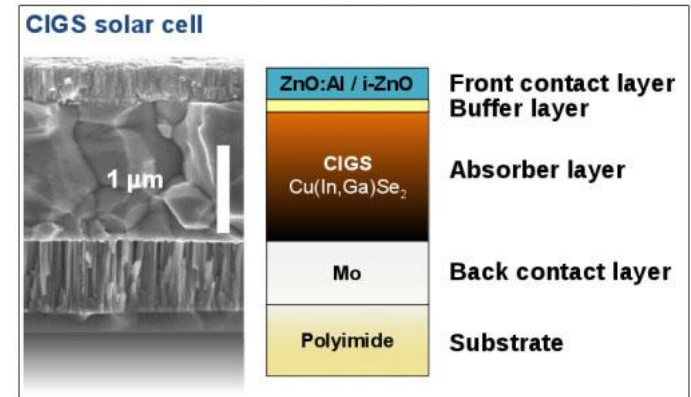
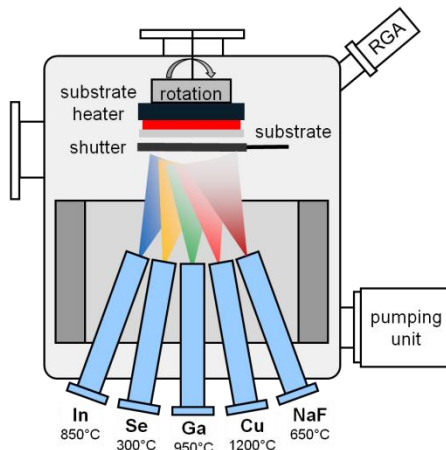


[R&D on glass]

Materials Science & Technology



[industrial on polyimide]



$\text{Cu}(\text{In,Ga})\text{Se}_2$ layer:

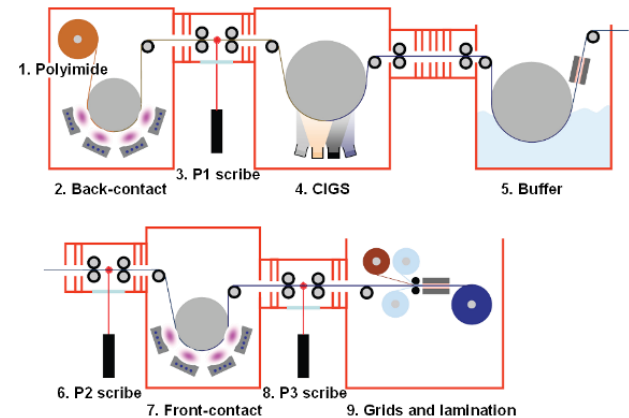
Low-temperature ($<500^\circ\text{C}$)
multistage co-evaporation
process with NaF post
deposition treatment.

Chirilă, Adrian, et al. "Highly efficient Cu (In, Ga) Se₂ solar cells grown on flexible polymer films." *Nature materials* 10.11 (2011): 857-861.

Industrial application of the scribing processes



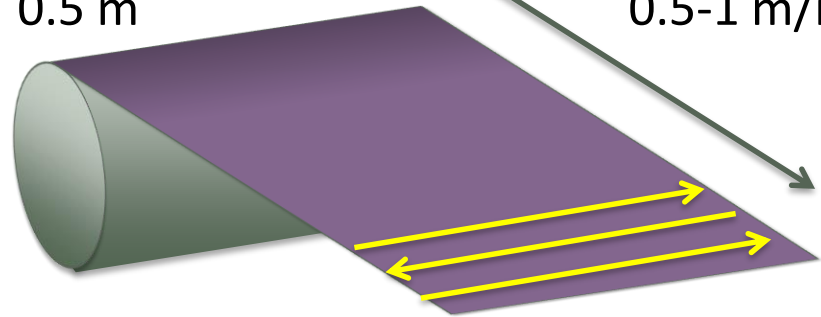
- ▶ APPOLO (FP7 project)
«Hub of Application Laboratories
for Equipment Assessment in
Laser Based Manufacturing»
- ▶ Assessment of laser equipment
and processes for **industrial
applications**



- ▶ our scenario:
 - roll-to-roll production
 - all in-line
- ▶ scribing velocity 1-2 m/s

roll width
0.5 m

substrate velocity
0.5-1 m/min



cross-web scribing
cell height 5-10 mm

Scribing Setup at BUAS-ALPS



*additional IPG green 1 ns laser and scanner head currently only used for marking

Demands on laser source

Typical laser process parameters at 100 kHz pulse repetition frequency and achieved scribing velocities (typical values).

Scribing process	Wavelength [nm]	Pulse repetition frequency [kHz]	Pulse energy [μ J]	Pulse duration [ps]	Velocity [mm/s]
P1	1064	100	up to 15	<200	1500
P2	1064	100	~3.0	<100	66
P3	532	100	<1.0	<50	1500

for the moment only:

- neglect all problems related to process scaling (heat accumulation etc.)
- assume process scalability with no loss of process/optics efficiency

Naive power scaling:

P1: 1.0 W/(m/s) [necessary power per additional 1m/s scribing speed]

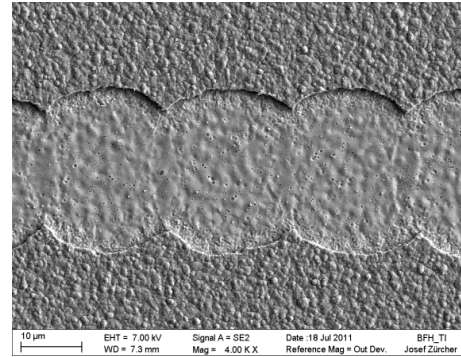
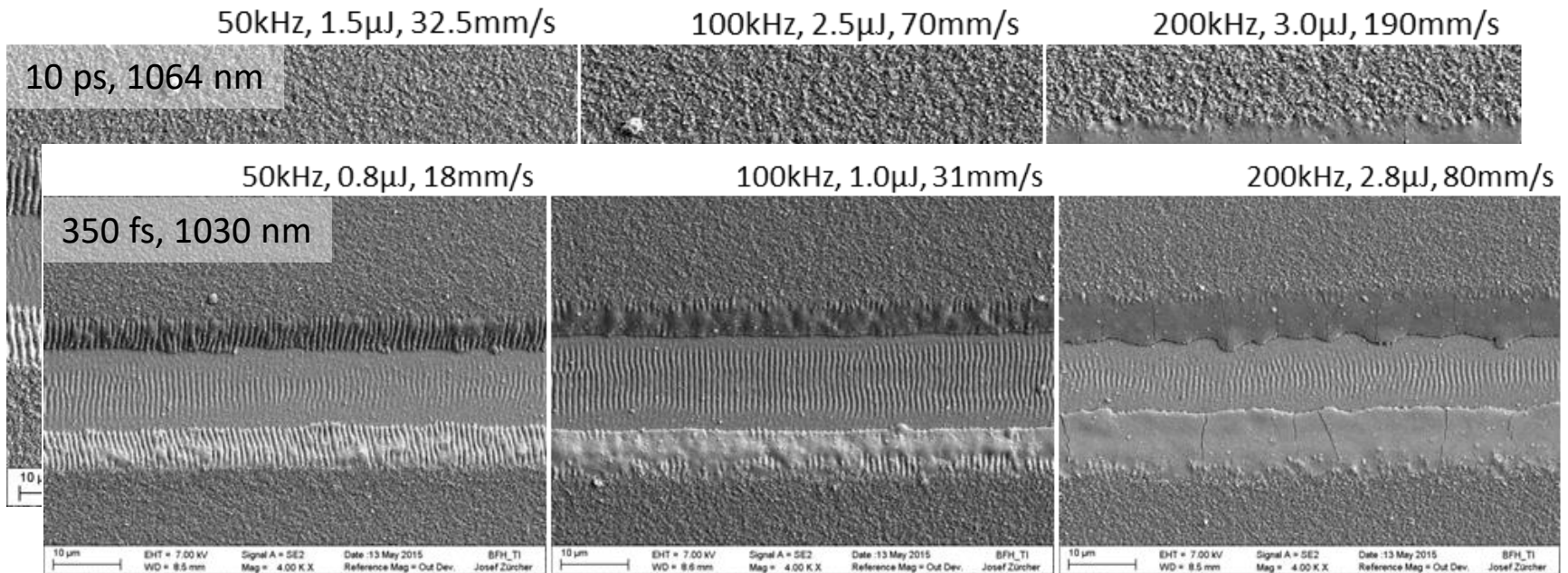
P2: 4.5 W/(m/s)  **P2 is most demanding**

P3: 0.1 W/(m/s) or an equivalent of about 0.2 W/(m/s) at 1064 nm.

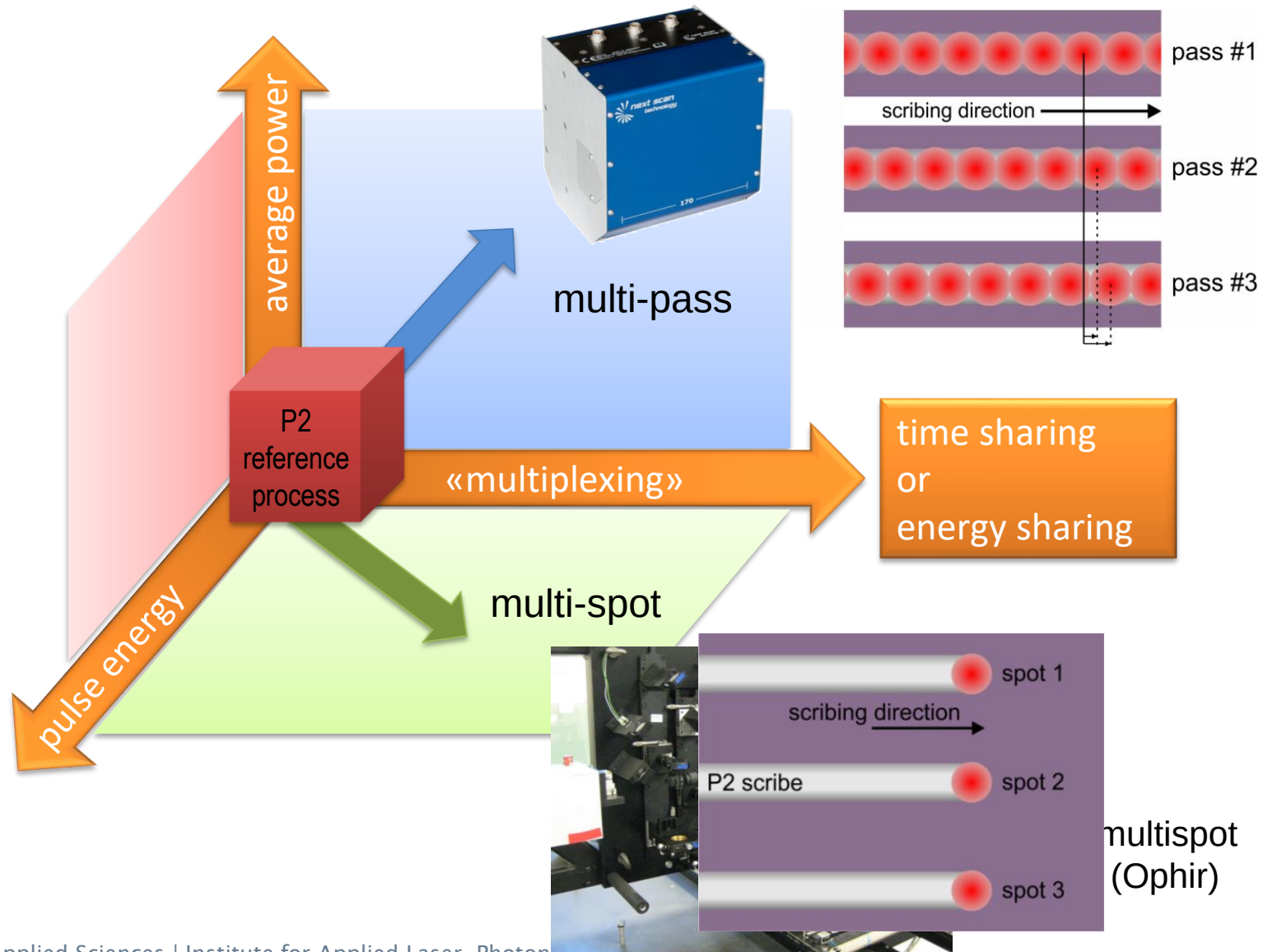
Our scenario: **target scribing velocity 1-2 m/s**

Scaling approaches – increase pulse frequency

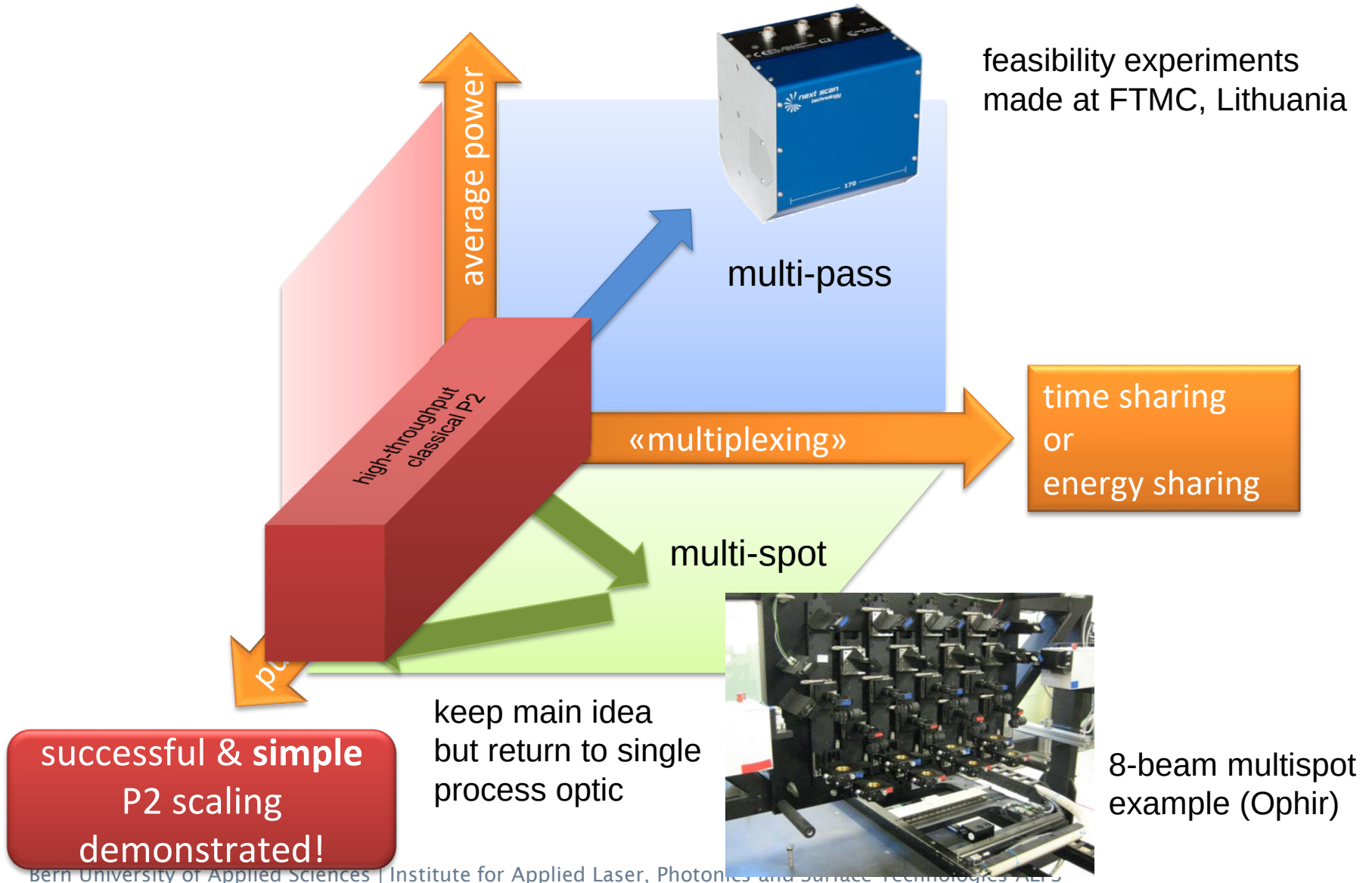
- ▶ works well for low overlap P1 and P3 processes:
- ▶ problems occur for high overlap P2:
- ▶ heat accumulation leads to melting of CIGS material
- ▶ Mo exposure threshold increases when material is hot
→ layer selectivity is lost above 200 kHz and Mo gets damaged



P2 scribing process throughput scaling

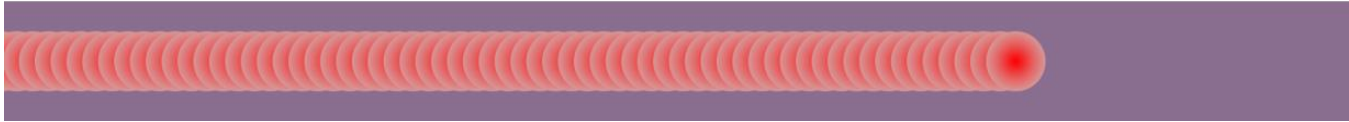


P2 scribing process throughput scaling

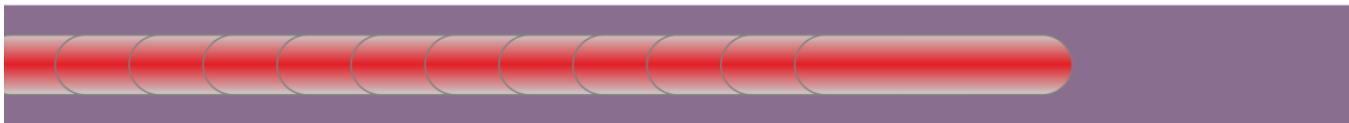


Process area scaling approach

- ▶ start from reference P2 process parameters



- ▶ keep pulse repetition frequency, pulse-to-pulse overlap and fluence constant
- ▶ replace round focal spot by a line focus element with high aspect ratio
- ▶ increase pulse energy to conserve fluence

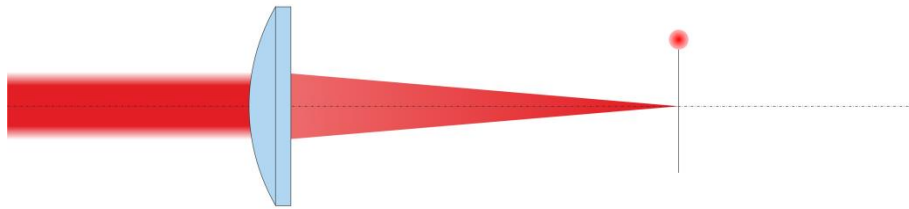
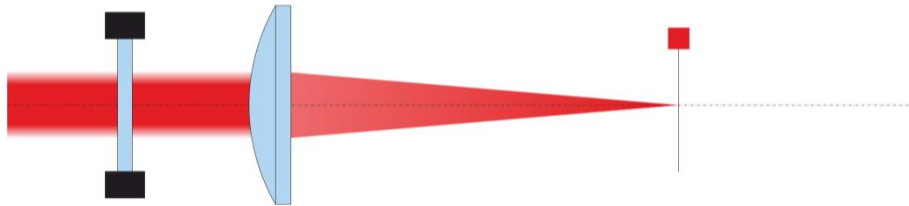


- ▶ → scribing velocity proportional to laser pulse energy

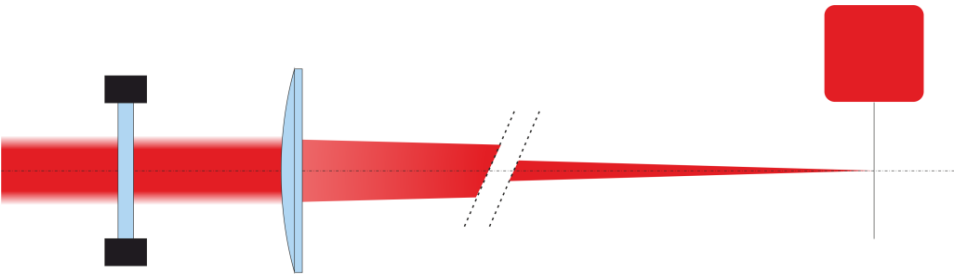
elliptical Gaussian spots were used for scribing before:

▮ Huber, H. P., et al. "High speed structuring of CIS thin-film solar cells with picosecond laser ablation." *SPIE LASE*, 2009.

optical realization



refractive square top hat
beam shaping lens



large flat top square in the
focus of a low power lens

focusing of the square profile
into a line by a cylinder lens

Linear spot properties

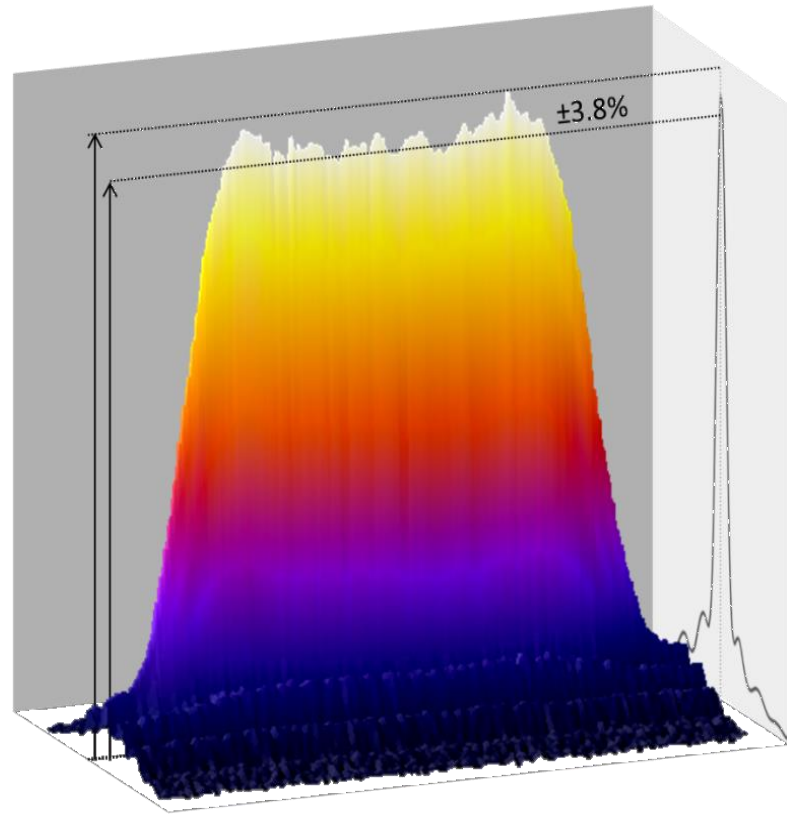
Typical dimensions

line width ($1/e^2$): $60\text{ }\mu\text{m}$

line length ($1/e^2$): $1600\text{ }\mu\text{m}$

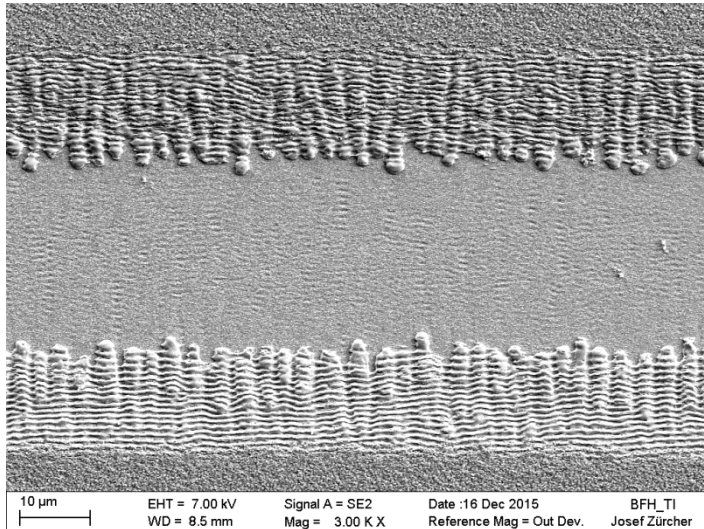
exposed Mo width: $25\text{ }\mu\text{m}$
(after about 40 pulses)

flat top profile along the line
Gaussian-like lateral profile

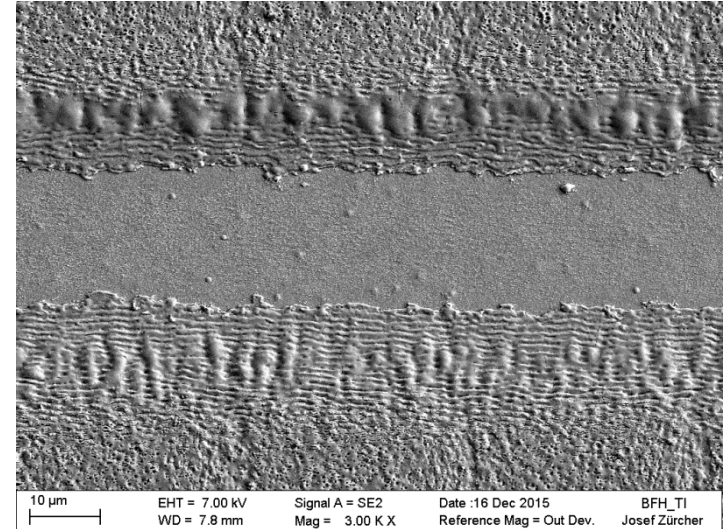


Scribing results

Glass substrate, 4.0 W@10kHz
scribing velocity 425 mm/s

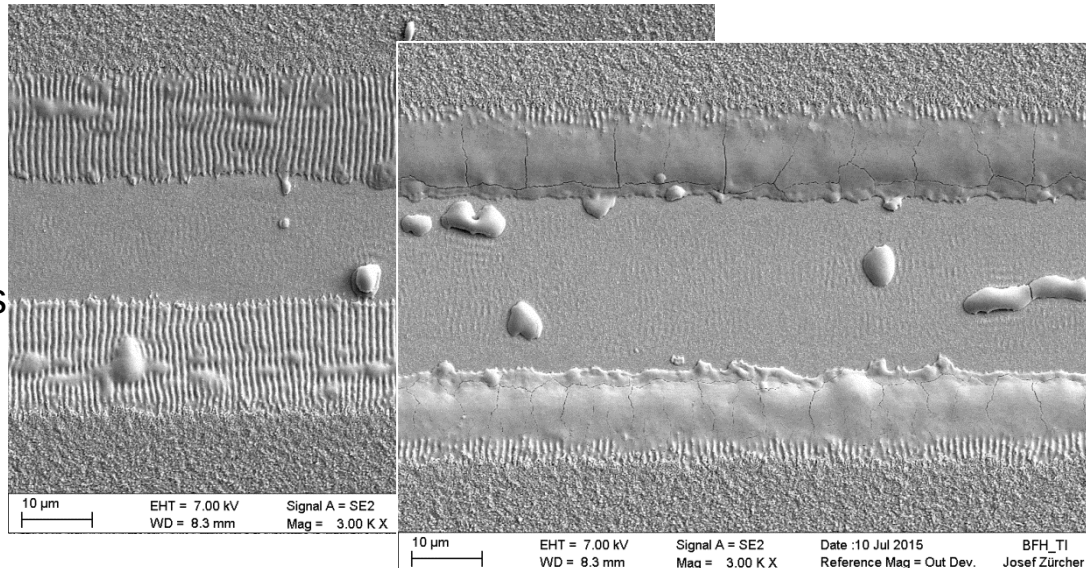


Polyimide substrate, 2.5 W@10kHz
scribing velocity 380 mm/s



Atlantic 60W

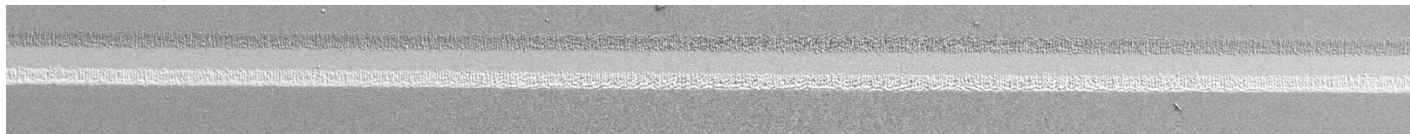
6.4 W@40kHz
velocity 1200 mm/s



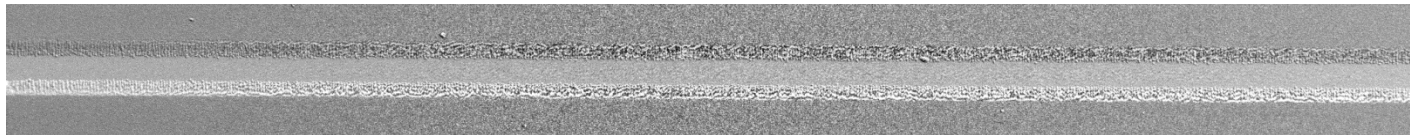
10.7 W@67kHz
velocity **1720 mm/s**

Robustness in velocity/overlap

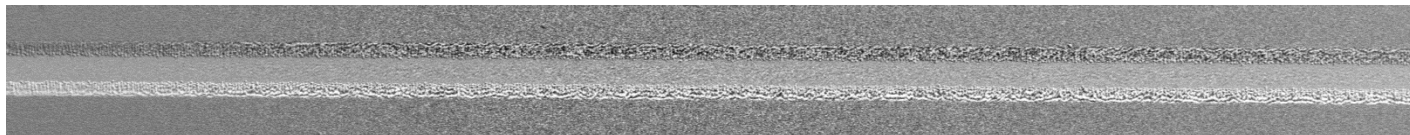
- ▶ flat top profile leads to excellent layer selectivity of the process
- ▶ a stable process can be maintained over a wide velocity range



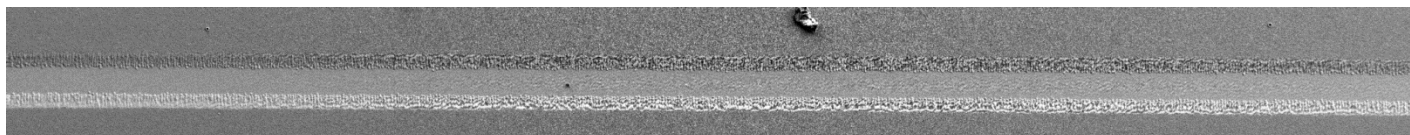
350 mm/s



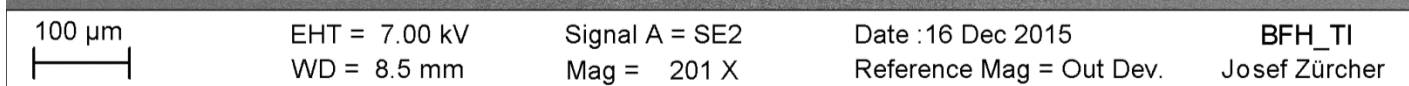
375 mm/s



400 mm/s



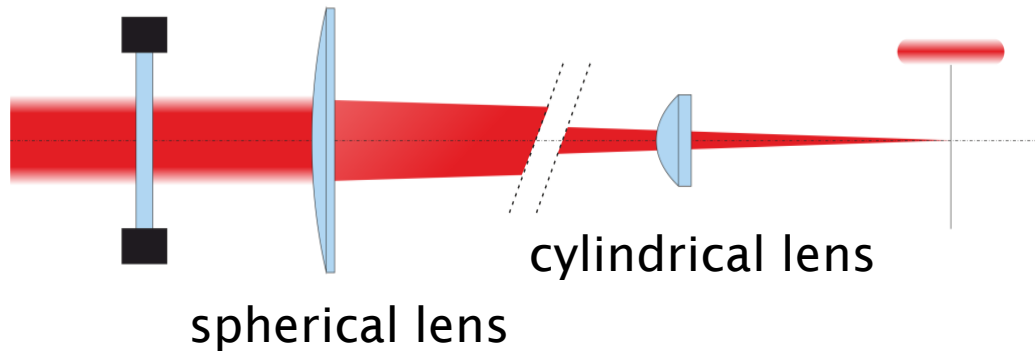
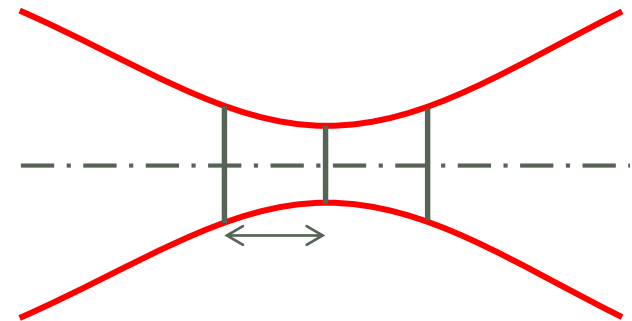
425 mm/s



Genki XP, P2 on glass substrate, 4.0 W@10kHz

Long working range in z-direction

- ▶ typical focal lengths spherical lens $f=1000$ mm, cylindrical lens $f=50$ mm
- ▶ NA in lateral direction $\gg$ NA in line direction
- ▶ for the line spot the fluence at $z \pm z_R$ drops only to approximately $\frac{1}{\sqrt{2}}$ of the comparable symmetrical Gaussian spot.



Robustness in focus position



$\Delta z = 250\mu\text{m}$ per line



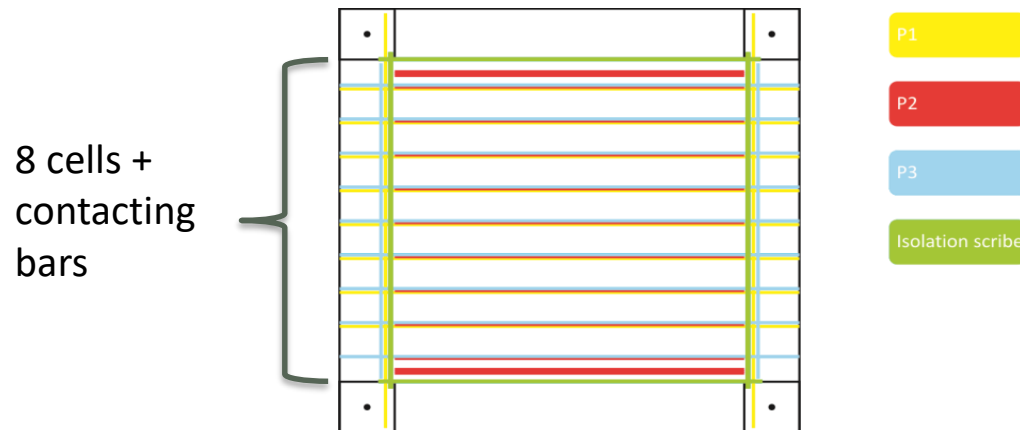
$\Delta z = 500\mu\text{m}$ per line



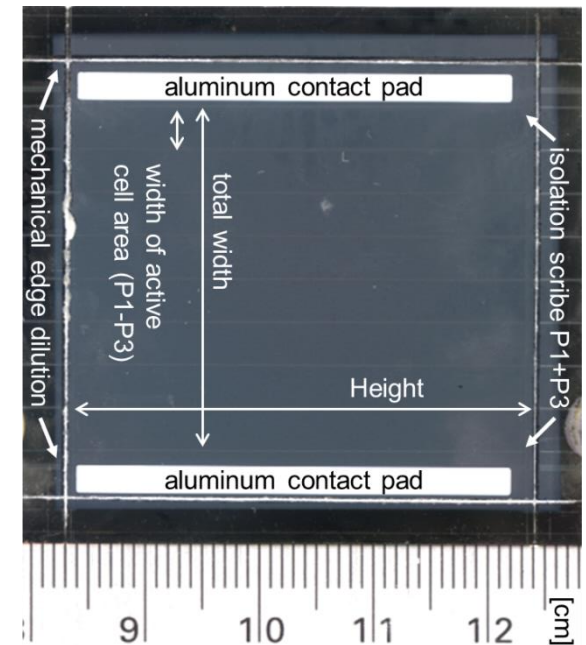
$\Delta z = 1\text{ mm}$ per line

Functional mini-modules

- ▶ Scribing pattern used for mini modules
- ▶ Cell height approx. 4 mm
cell area approx. 1.68 cm²



finished 8-cell mini-module



- ▶ Functional modules produced on 50 x 50 mm² float glass substrate.
- ▶ Aluminum pads added for secure contacting.

Electrical performance of the module

▶ Test conditions

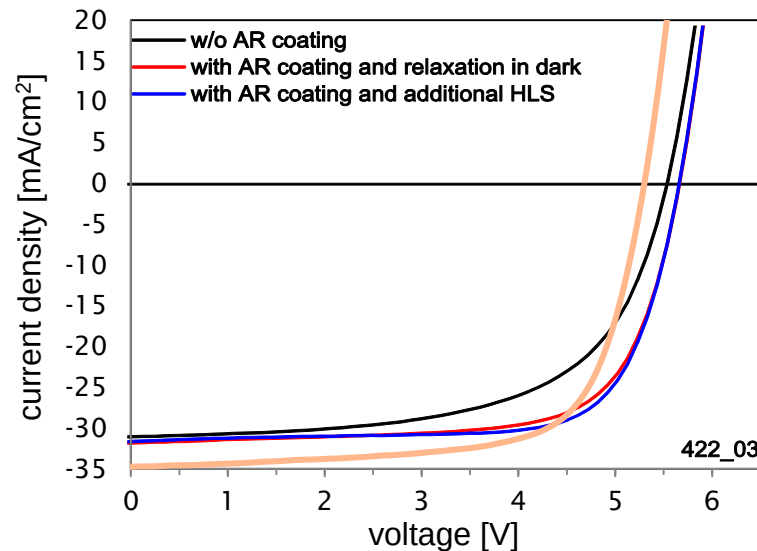
illuminated current voltage (JV) characteristics measured at Empa lab according to international standard **IEC 60904-1**, AM1.5G irradiation spectrum and 1000 Wm^{-2} irradiation intensity; constant temperature 25° C .

▶ module characteristics (as deposited):

V_{OC}/cell [mV]	663
J_{SC} [mA/cm ²]	30.1
FF [%]	70.0
η [%]	14.0

▶ compare to reference champion module:

	Initial	relax	HLS
V_{OC}/cell [mV]	688	703	707
J_{SC} [mA/cm ²]	31.3	32.0	31.7
FF [%]	61.2	70.5	74.5
η [%]	13.2	15.9	16.7



Data from our publication:

Nishiwaki et al., A monolithically integrated high-efficiency Cu (In, Ga) Se₂ mini-module structured solely by laser. Progress in Photovoltaics: Research and Applications, 23(12), 1908-1915, 2015

Conclusion

- ▶ We have demonstrated a successful scaling of the classical P2 scribing process by simple refractive beam shaping.
- ▶ P2 scribing velocity is limited by available average power (onefive Genki) and pulse energy (EKSPLA Atlantic).
- ▶ A full set of scribing processes for an industrial scenario with 1-2 m/s scribing velocity (P1, P2, P3) is available.
- ▶ Processes have been validated in a 8-cell functional module with 14% efficiency (as deposited).

Outlook

- ▶ Direct electrical characterization of the P2 (contact resistance) is in progress.
- ▶ A direct comparison of different high-throughput P2 scribing processes will follow in a further publication.

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EKSPLA for providing the Atlantic 60W laser for tests
Josef Zürcher for SEM image acquisition
Manuel Ryser for helpful discussions

supported by



Thank you for your attention!

contact: andreas.burn@bfh.ch

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