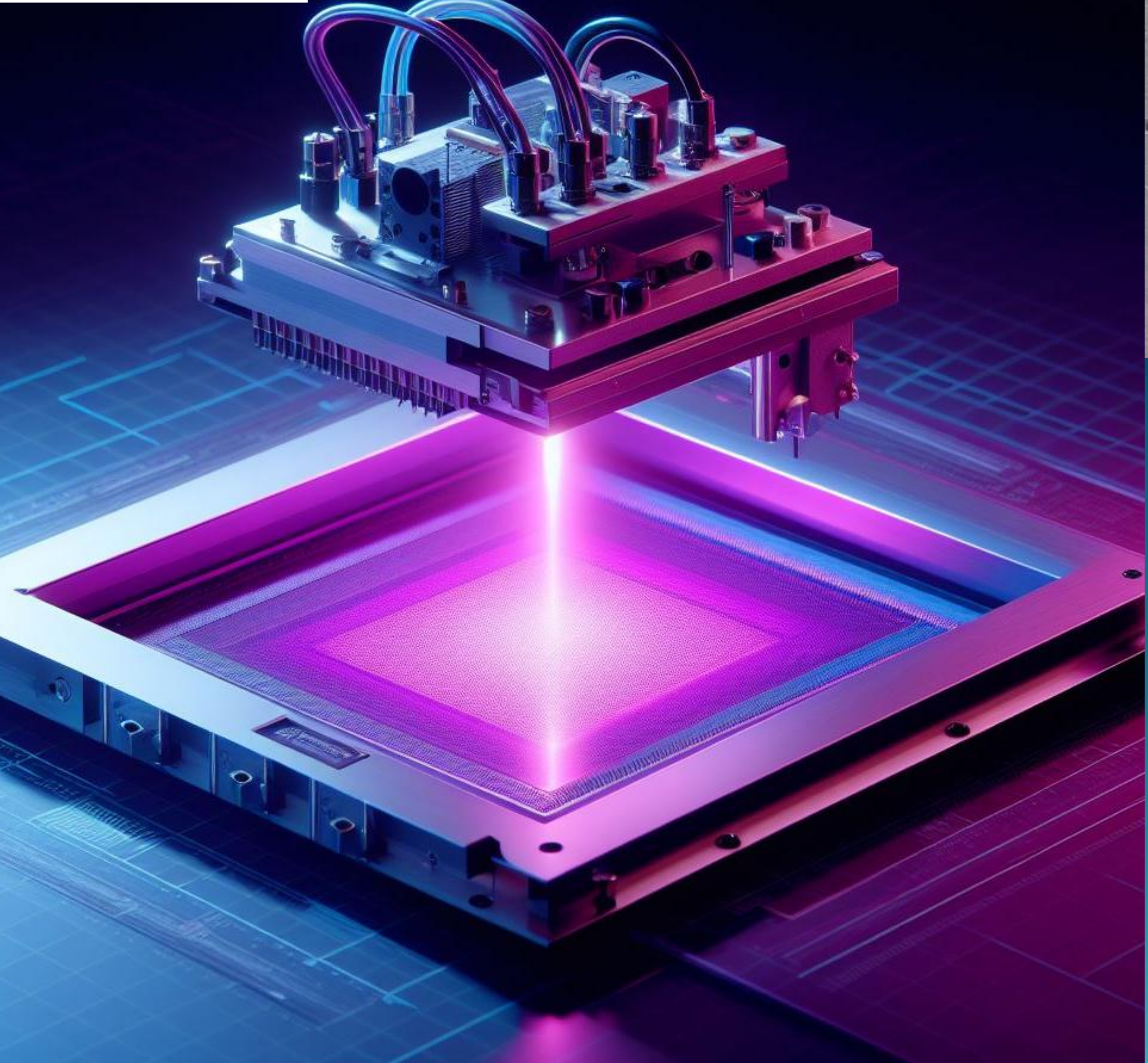
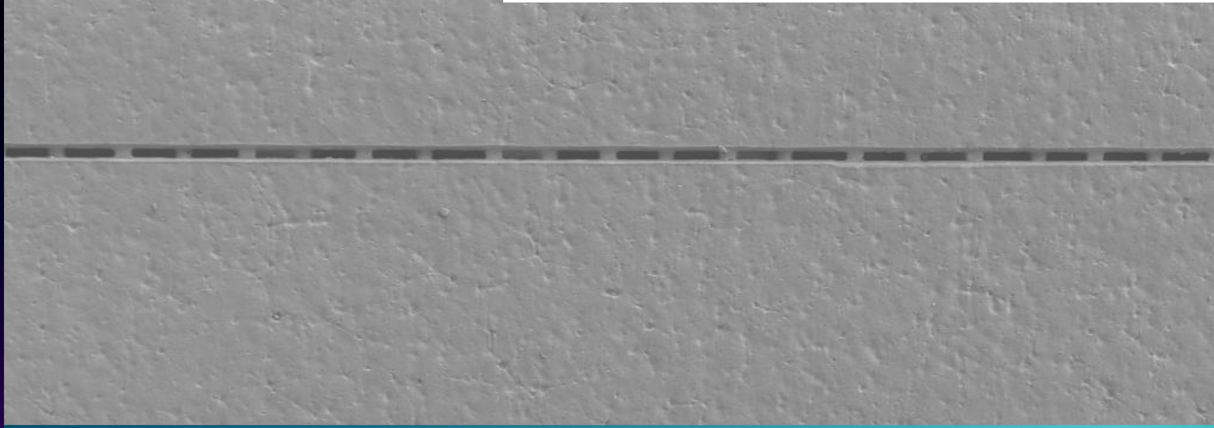


AI generated



Fraunhofer ISE

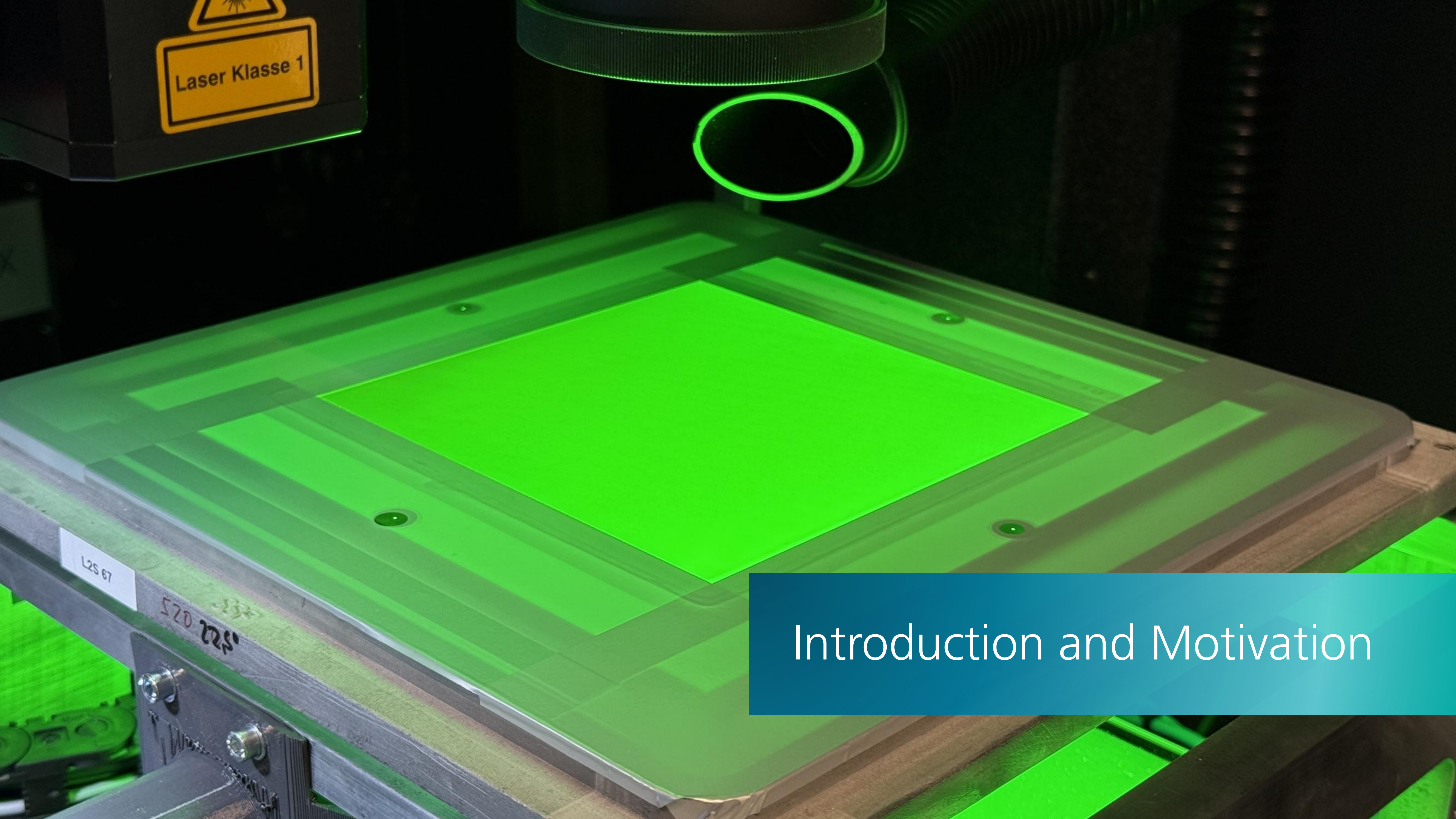
Metallization & Interconnection WORKSHOP

Progress in Fine Line Metallization: Optimization of laser processing during screen production

A. Nair, S. Upadhya, S. Shekar, J. Schneider, A. Lorenz, R. Haberstroh, A. Brand, J. Schube, M. Linse, M. Singler, F. Clement, R. Preu[1]

[1]Also affiliated with University of Freiburg

October 21st 2025, Berlin
13th Metallization and Interconnection Workshop

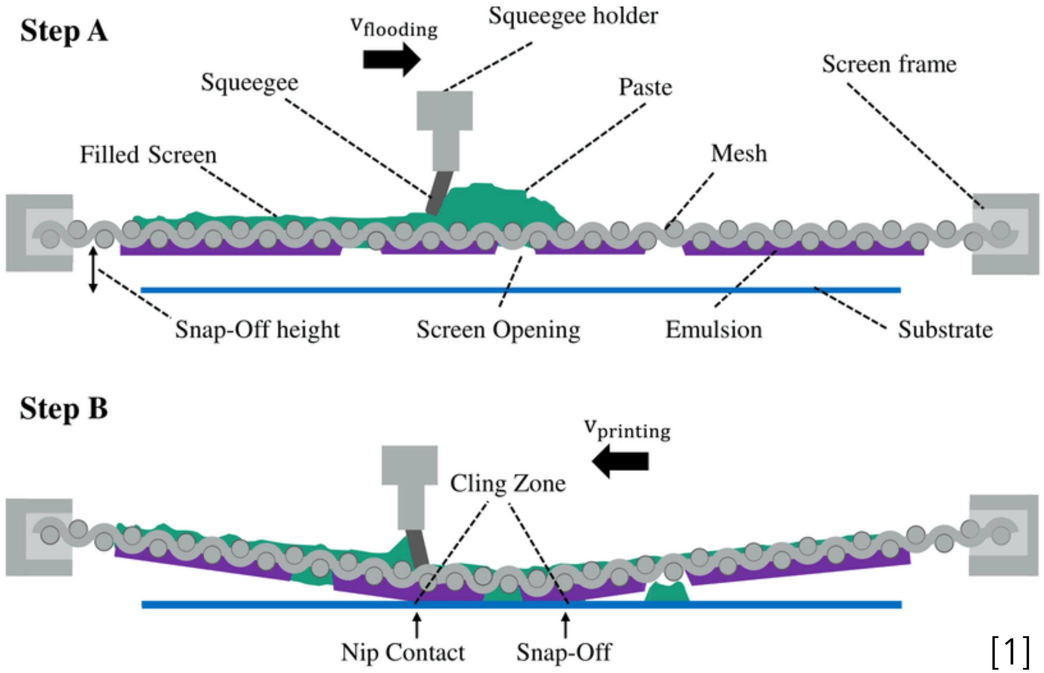


Introduction and Motivation

Motivation

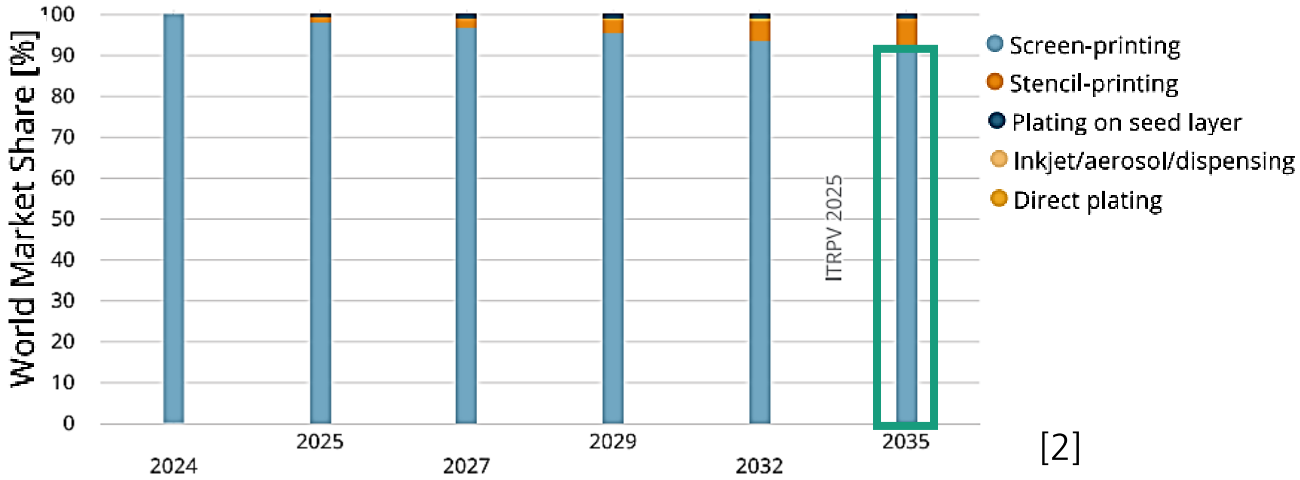
Fine-line Screen Printing

- Reliable
- Robust
- Cost - effective



[1]

- Expected to remain leading method of metallization over the next decade



[2]

[1] S. Tepner, A. Lorenz, Progr. Photovolt Res Appl 31 (6), S. 557–590. DOI: 10.1002/pip.3674.

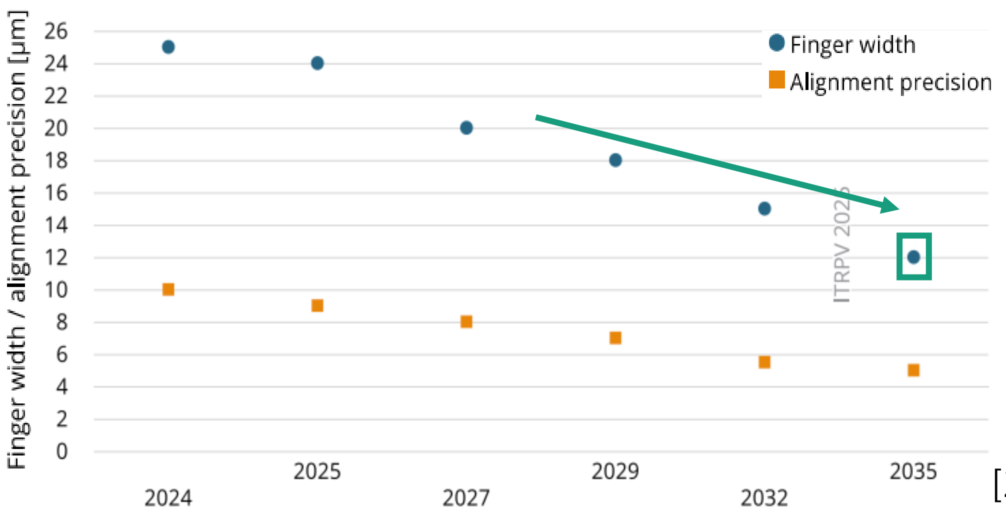
[2] ITRPV, 2025

Fraunhofer ISE

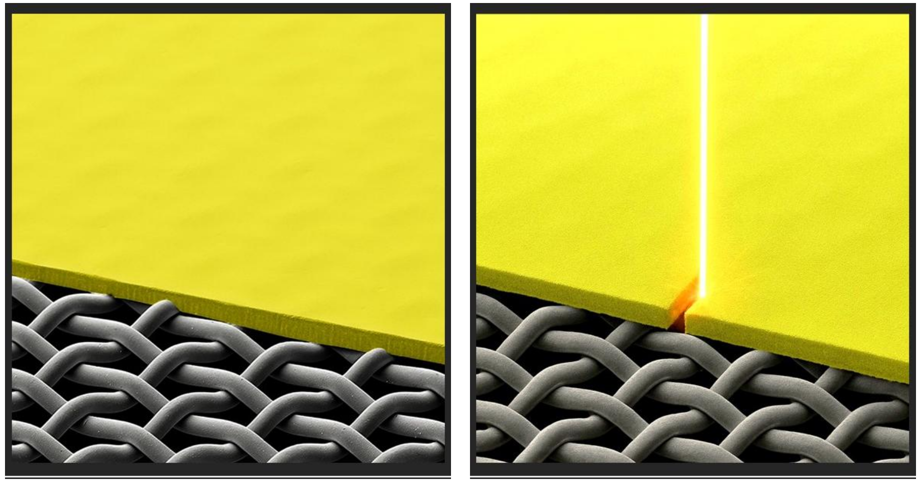
Motivation

Screen structuring with laser technology

- To achieve terawatt level PV production sustainably, silver consumption must be reduced[1]
- Finger width of front side metalliztion expected to reach 12 µm in 2035
- This goal can be realized by optimizing the screen structuring process through:
  - **Laser structuring**
- Technology introduced in 2018[4]
- Aim: To further optimize this process and obtain finer openings



[2]



[3]

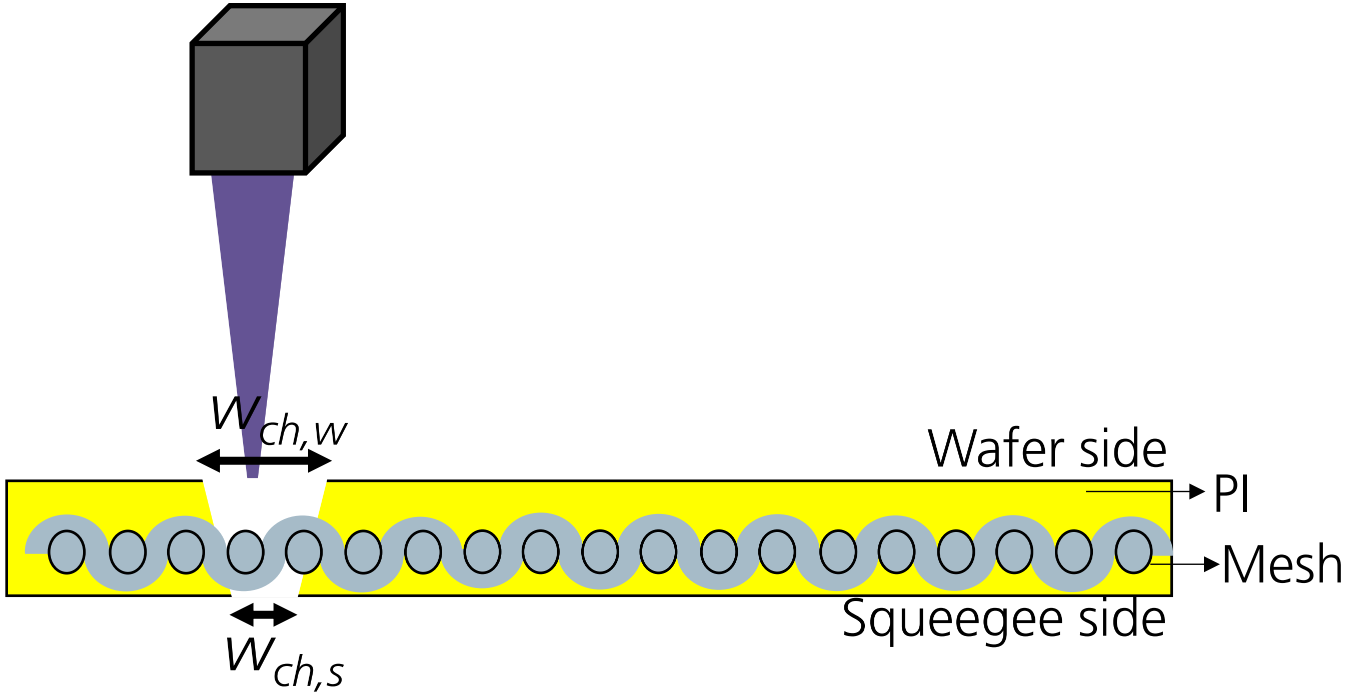
[1] M. Kim, Y. Zhang, P. Verlinden, B. Hallam, Towards sustainable silicon PV manufacturing at the terawatt level, in: SiliconPV 2021, the 11th International Conference on Crystalline Silicon Photovoltaics, Hamelin, Germany/Online, 2022 90001
[2] ITRPV, 2025
[3]AI generated image
[4] Brave C&H supply Co [Online], https://en.bch.com.tw/ , Accessed 14.10.25.

Motivation

Screen structuring with laser technology: Advantages

Advantages:

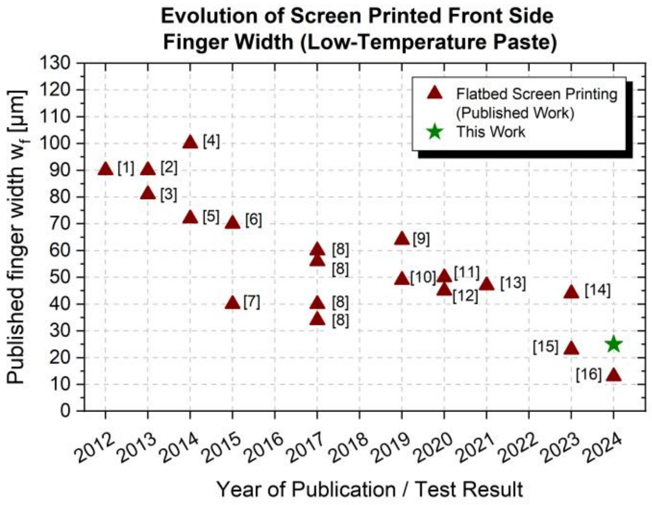
- Flexibility to laser any barrier layer material
- Tapering effect can be tuned
- Faster than "traditional" photolithography
- Precision: Could be used to create openings between wires in case of knotless screens
- Potentially finer openings *(i.e. for contact fingers)*

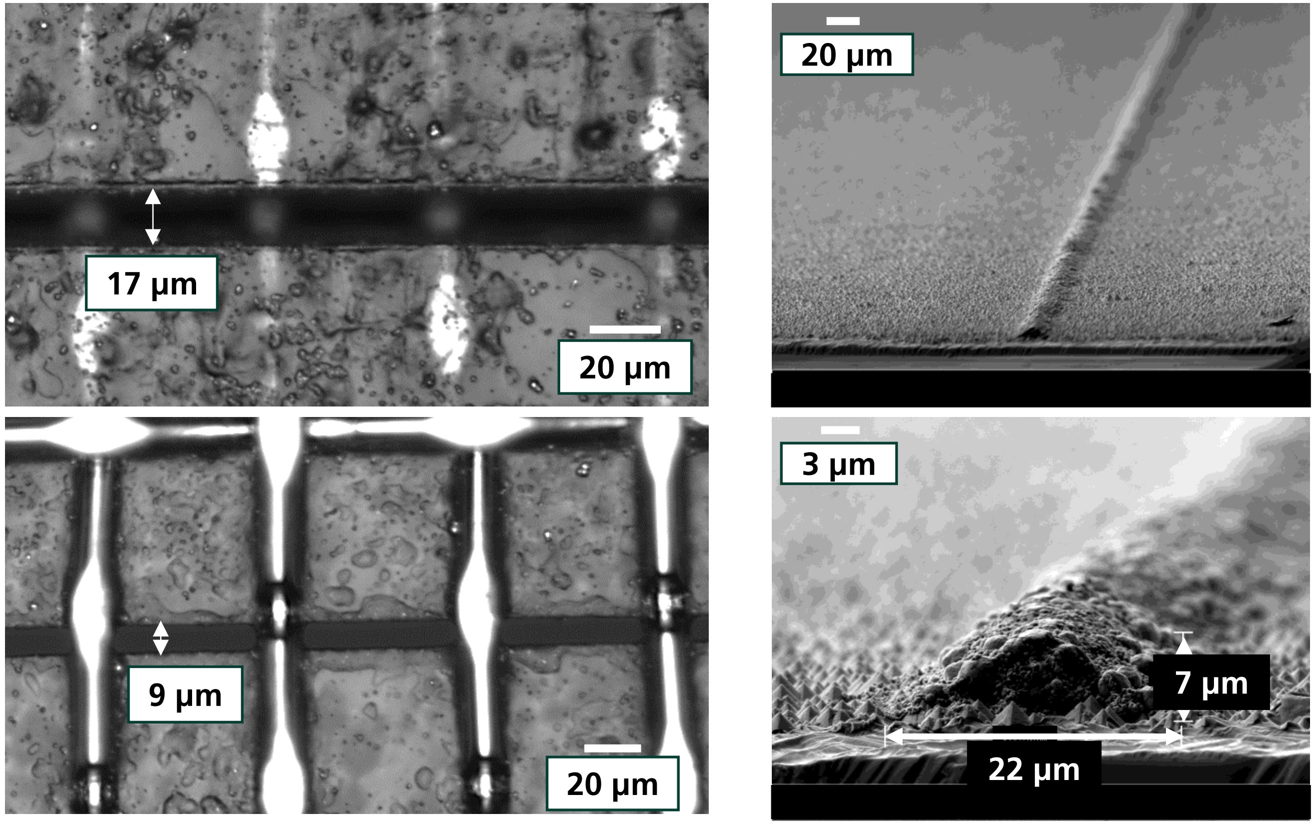


Motivation

Laser structuring of screens, published results

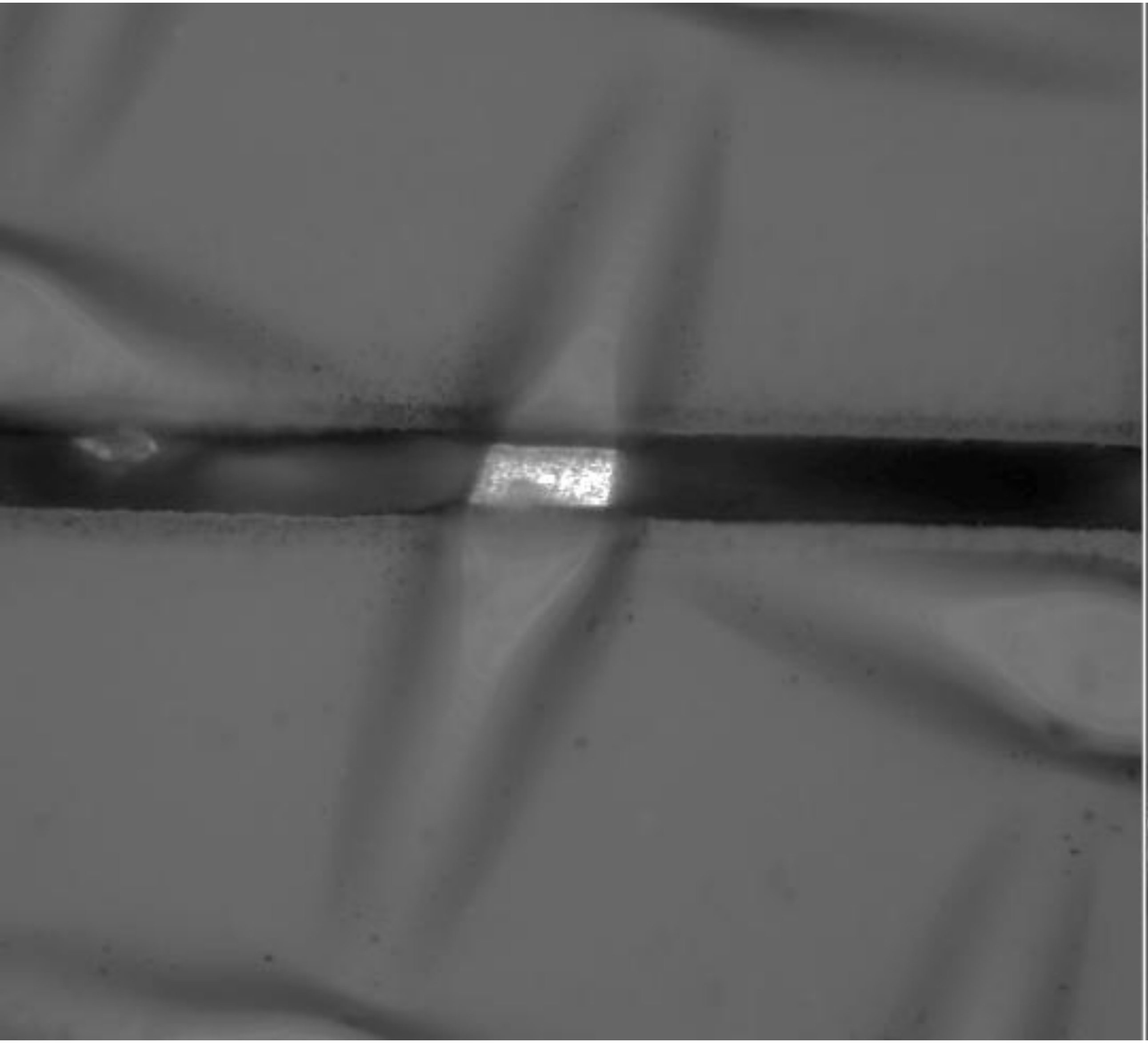
- Successful laser structuring of full layout in **10 minutes** on 520/11/0° screen and hybrid barrier layer
- Channel opening was tapered
- Average finger width of 23 µm measured on M2 HJT wafers

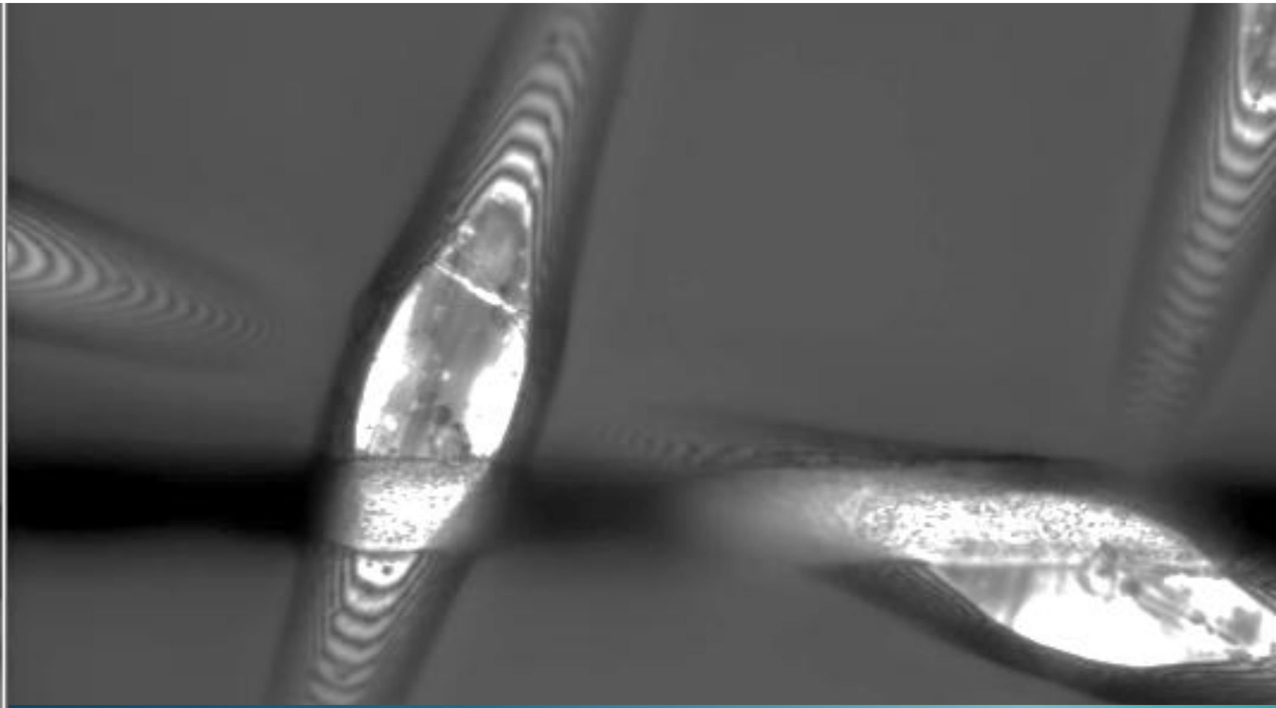




[1] A. Nair, SOLMAT, DOI: 10.1016/j.solmat.2025.113732 (2025)

Fraunhofer ISE





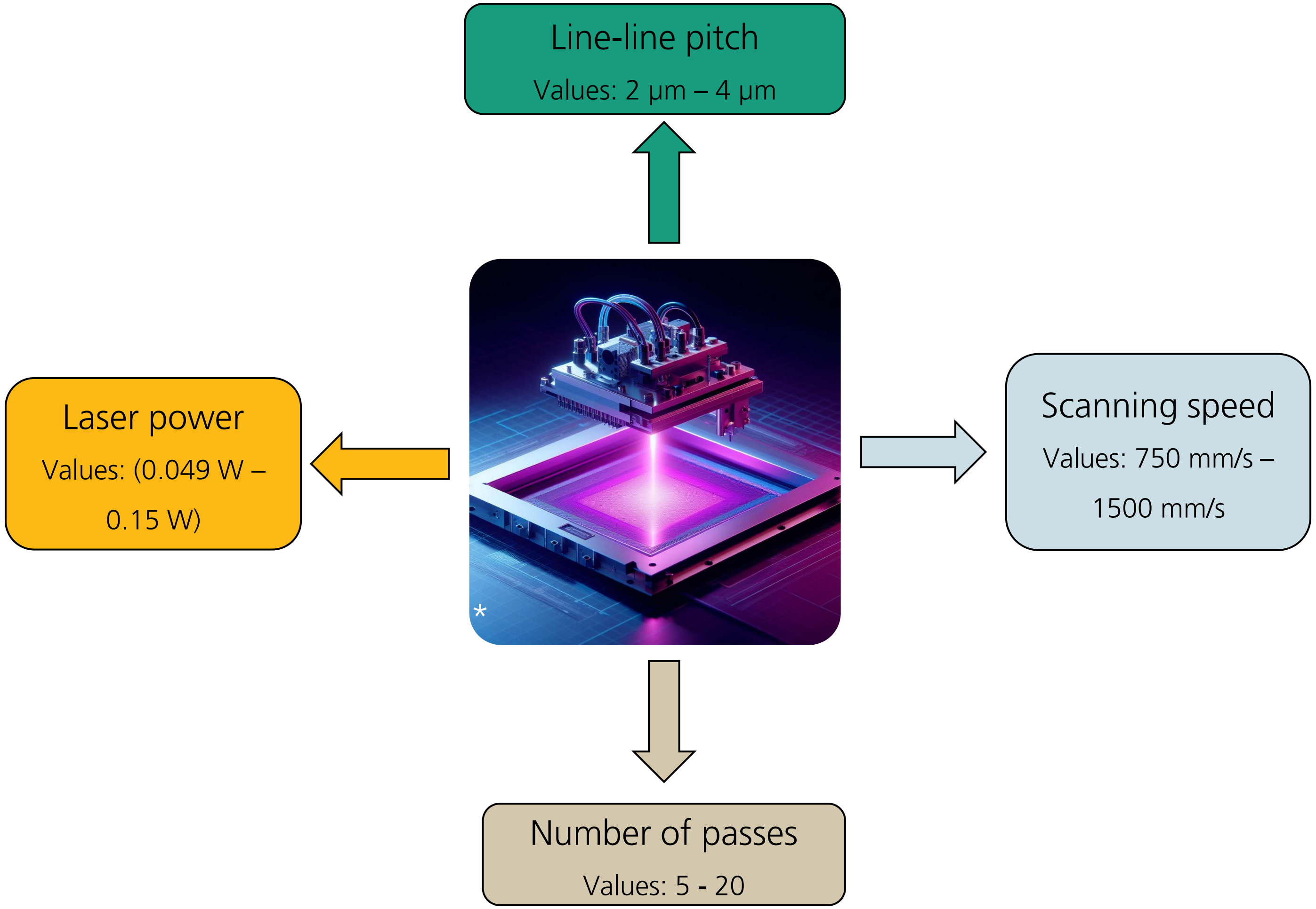
Optimization of laser parameters using statistical analysis

Fraunhofer ISE

Optimization of laser parameters using statistical analysis

Parameters varied

- Laser structuring process is highly dependent on several critical input laser parameters
- These parameters are crucial to determine the desired screen opening width and taper
- Following laser input parameters were varied:



*AI generated image

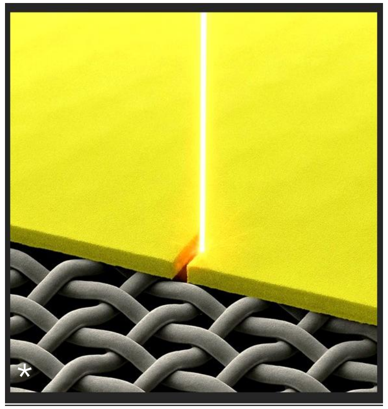
Optimization of laser parameters using statistical analysis

Parameters varied

- Output parameters measured were:

Wafer side opening

Damage on mesh



Squeegee side opening

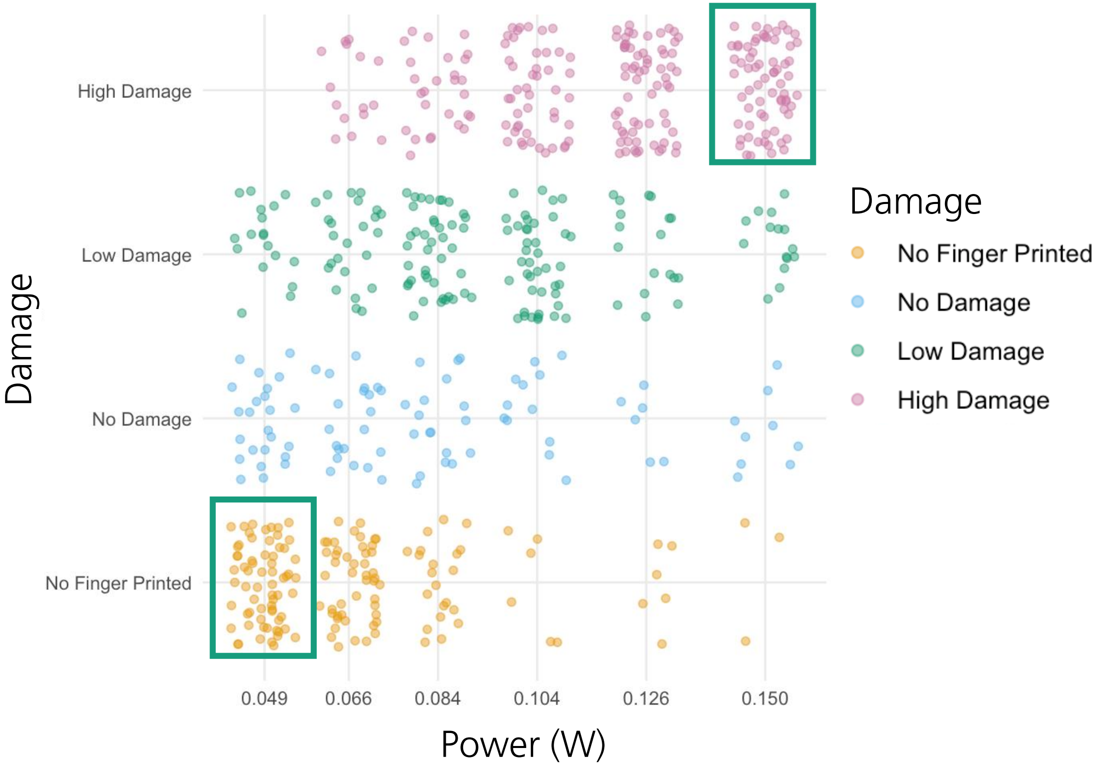
Print results of the varying openings

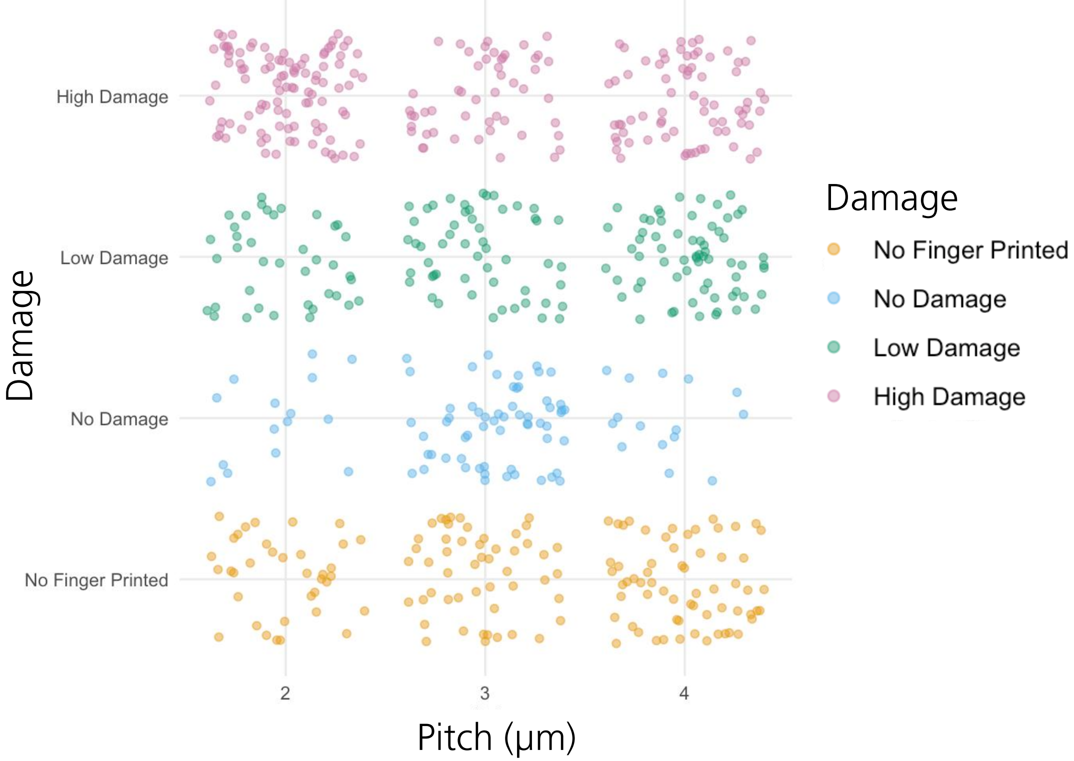
*AI generated image

Optimization of laser parameters using statistical analysis

Results

- Power had the highest impact on the screen structuring process



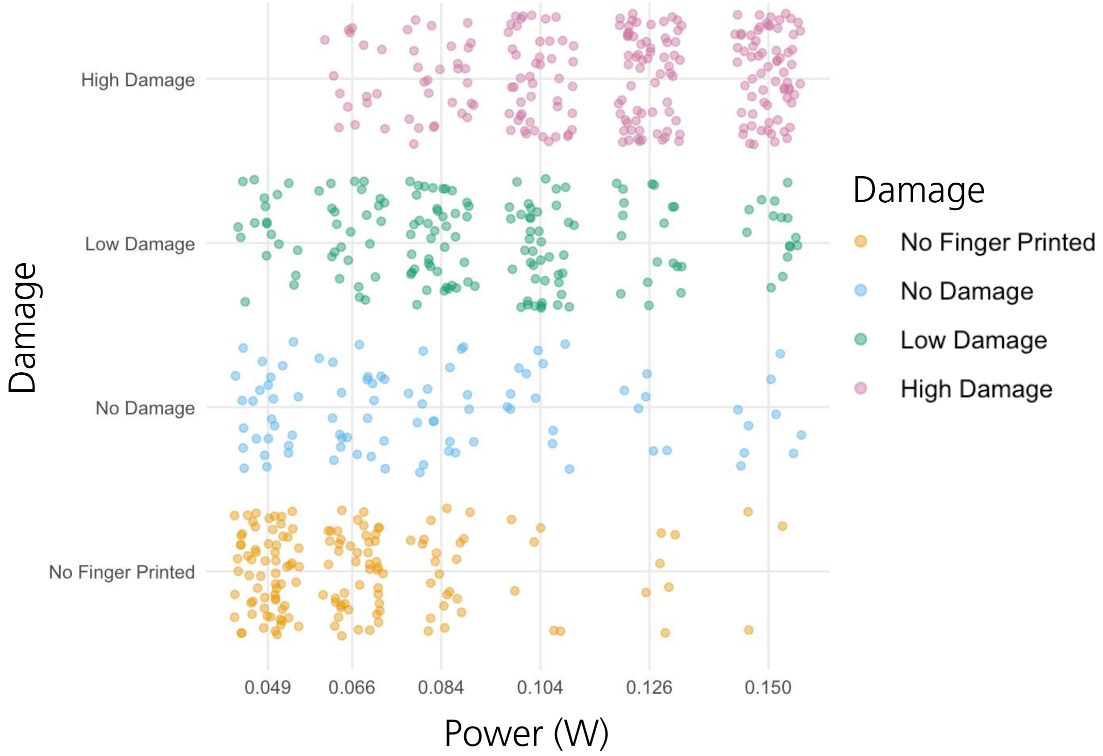


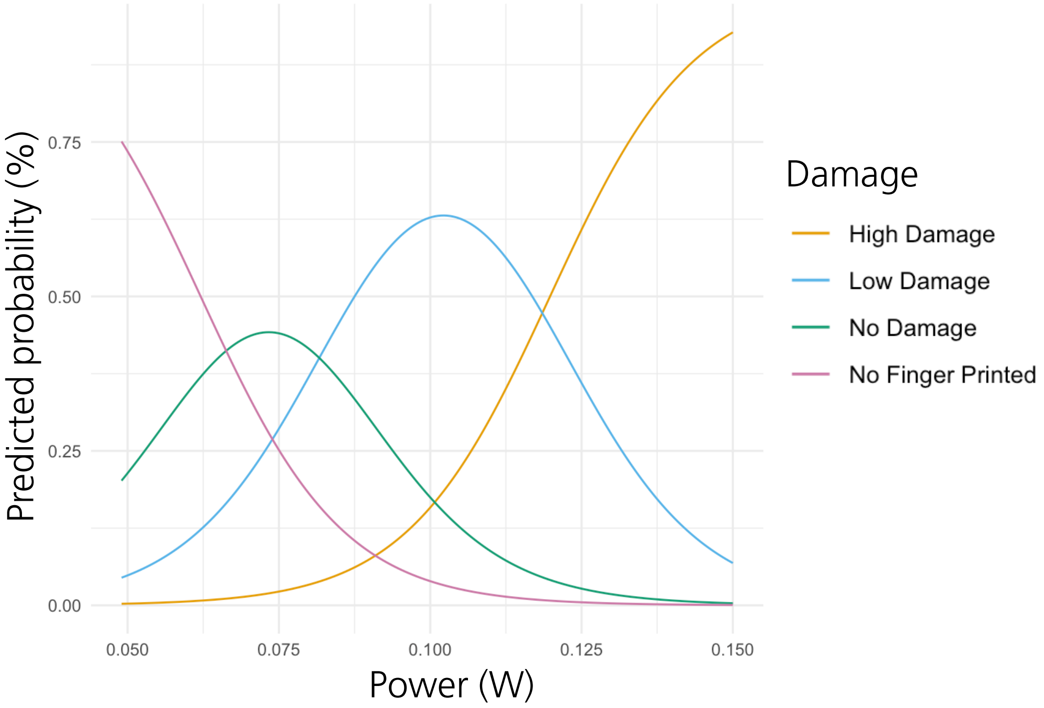
[1] A. Nair (to be published)

Optimization of laser parameters using statistical analysis

Results

- Power had the highest impact on the screen structuring process
- Predicted probability: Find parameter combinations that cause least damage to screen and successful print is expected



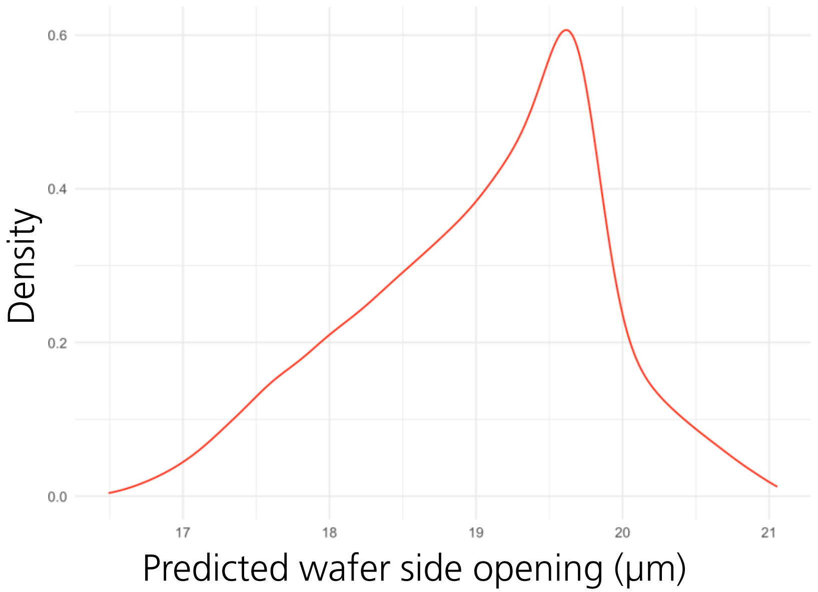


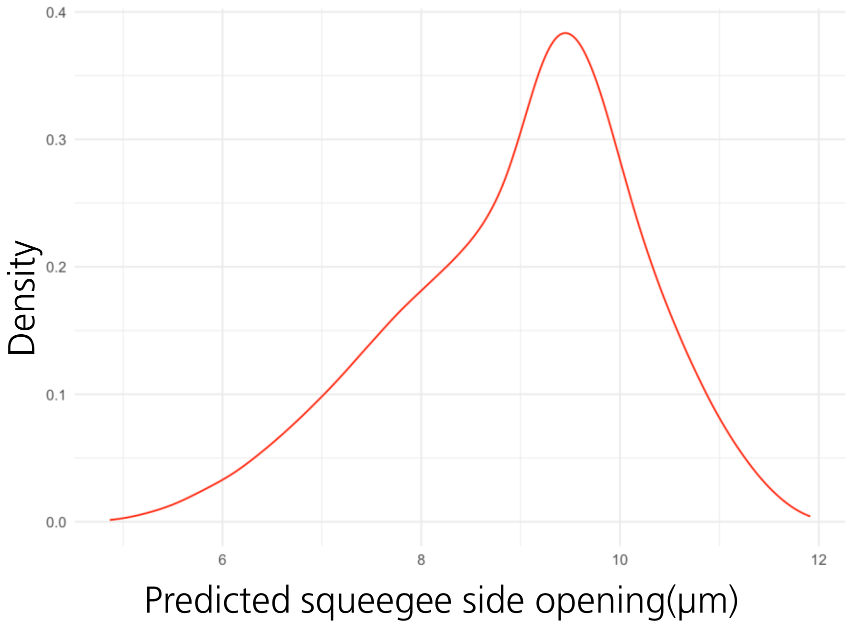
[1] A. Nair (to be published)

Optimization of laser parameters using statistical analysis

Results

- Predicted probability of the input laser parameters yields predicted wafer and squeegee side measurements that cause less damage to the mesh



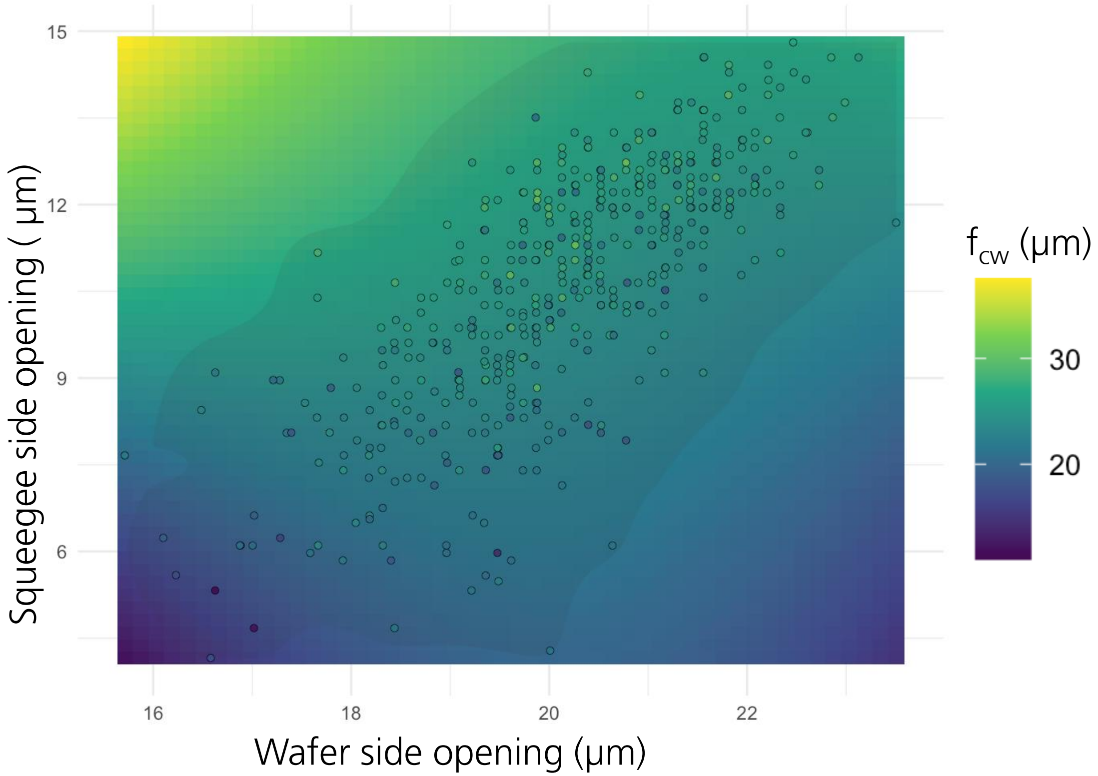


[1] A. Nair (to be published)

Optimization of laser parameters using statistical analysis

Results

- Predicted probability of the wafer and squeegee side values yields predicted finger core width (f_{cw}) measurements

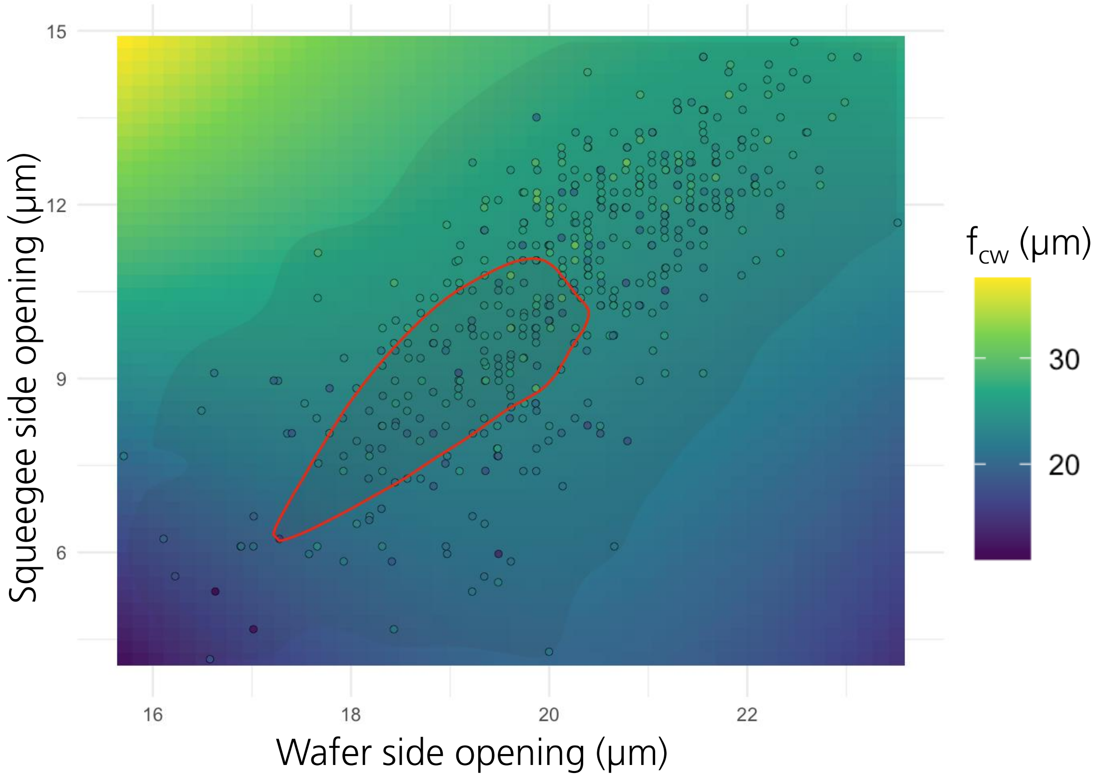


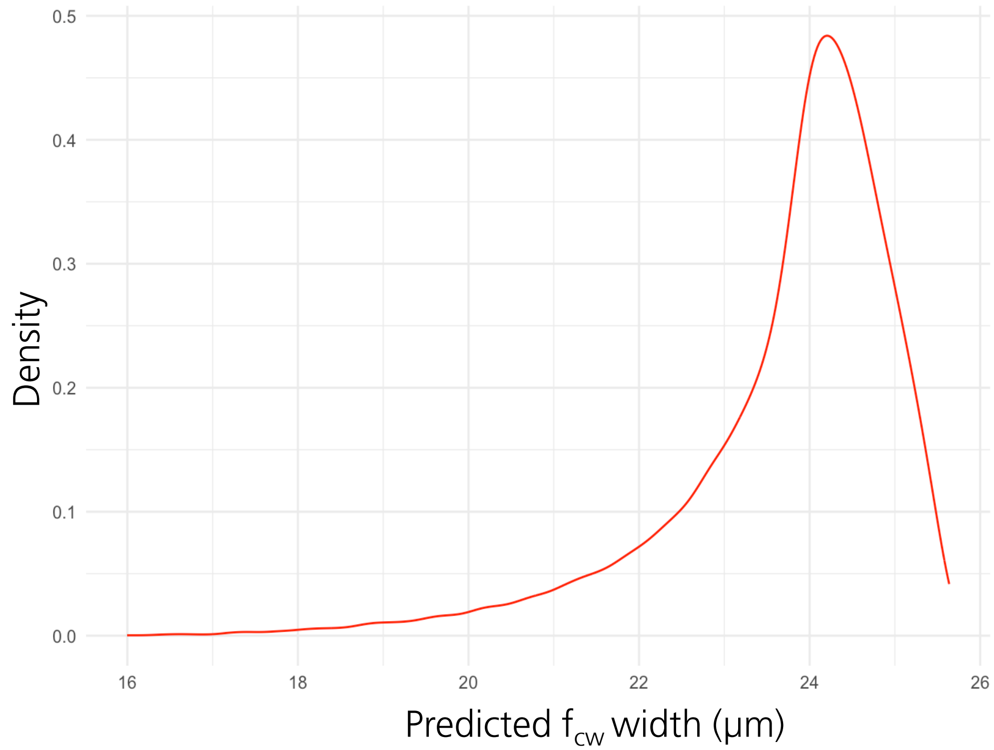
[1] A. Nair (to be published)

Optimization of laser parameters using statistical analysis

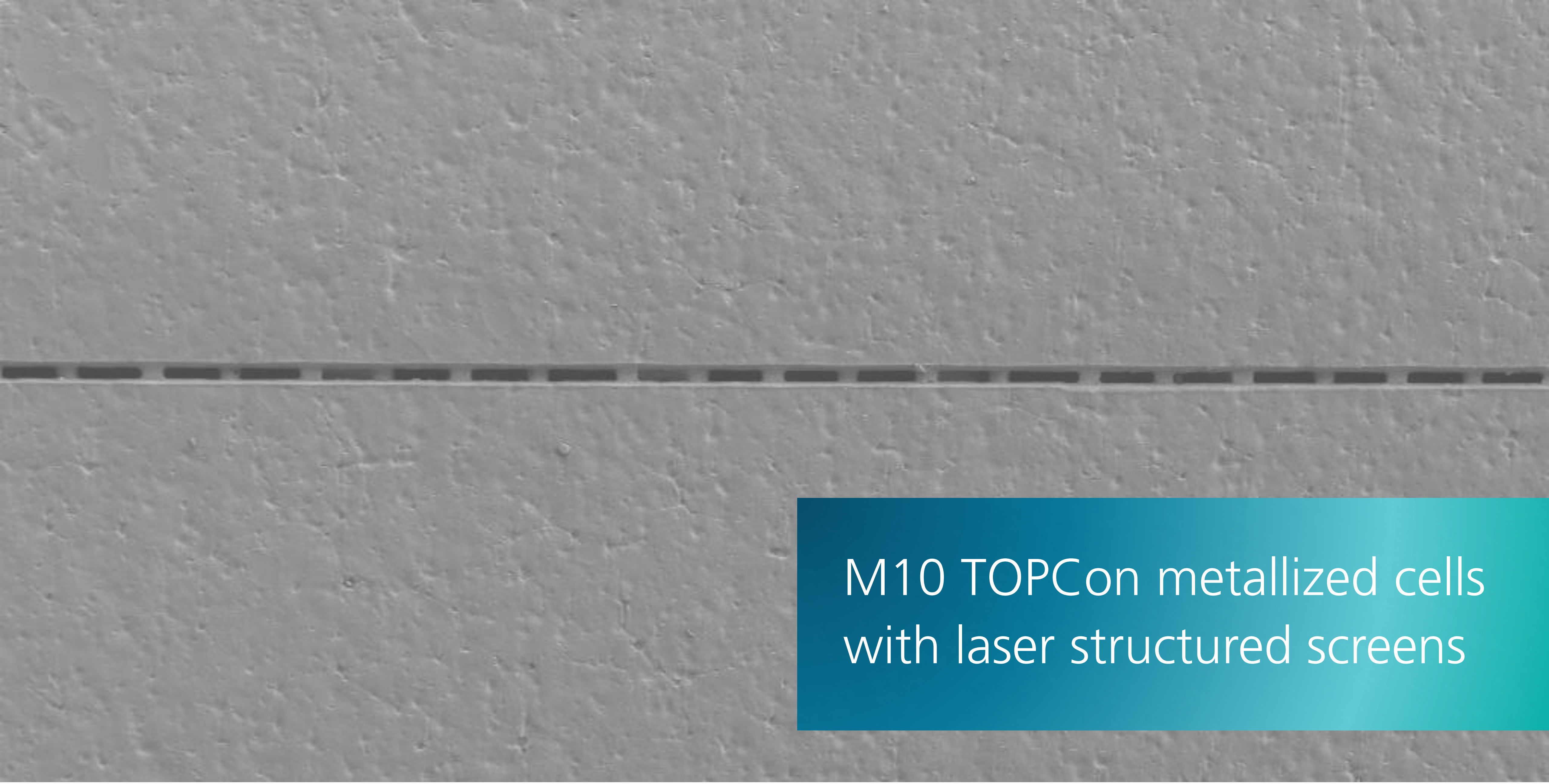
Results

- Predicted probability of the wafer and squeegee side values yields predicted finger core width (f_{cw}) measurements





[1] A. Nair (to be published)



M10 TOPCon metallized cells with laser structured screens

M10 TOPCon metallized cells with laser structured screens

Aim and experimental setup

Aim:

- Compare in-house lasered screens with an industry standard screen

Experimental setup:

- Screen/paste variation:
  - Fraunhofer ISE TOPCon precursors (M10)
  - Constant screen opening width of 20 µm
  - High-performance partially diluted Ag paste (B)

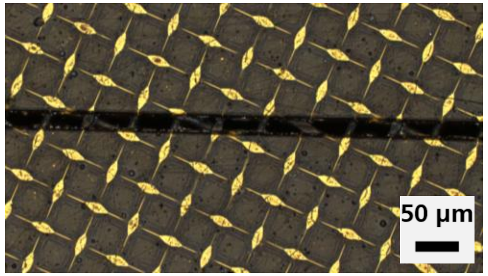
	Screen 1 (ISE lasered)	Screen 2 (ISE lasered)	Screen 3 (ref)
Mesh configuration	520/11/22.5°	520/11/22.5°	520/9/0°
Nom. Finger width w_n [µm]	20	20	20
Paste	B	B	B
Time to laser structure full layout	40 mins	40 mins	N/a

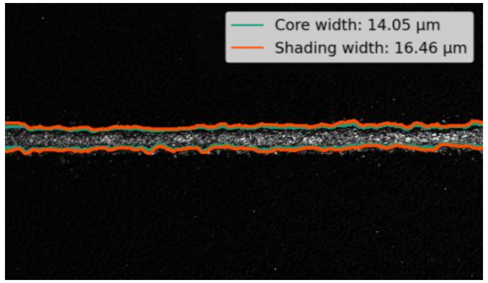
Experimental setup – Overview of screen variations for the conducted TOPCon fine line test batch.

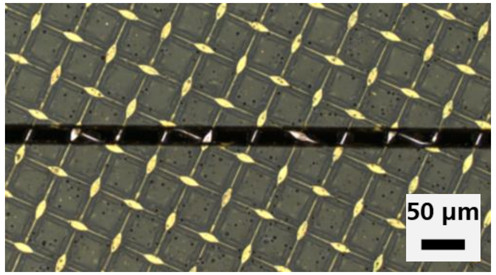
M10 TOPCon metallized cells with laser structured screens

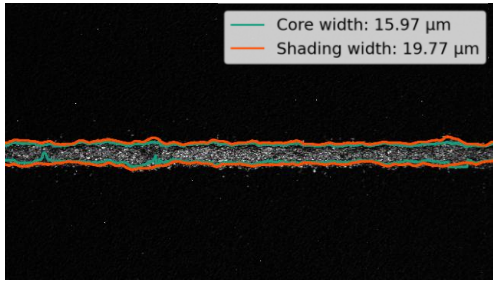
Screen printing results

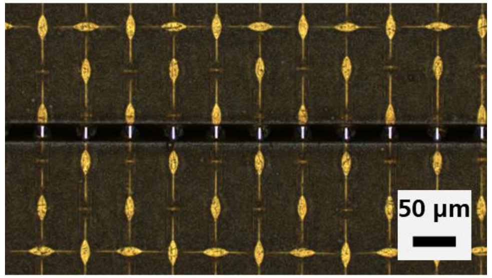
Screen 1 | 520/11/22.5°	Screen 2 | 520/11/22.5°	Screen 3 | 520/09/0°
ISE Lasered		Reference

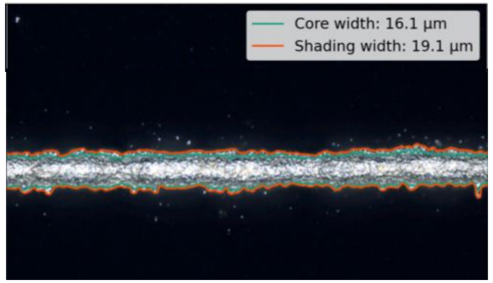












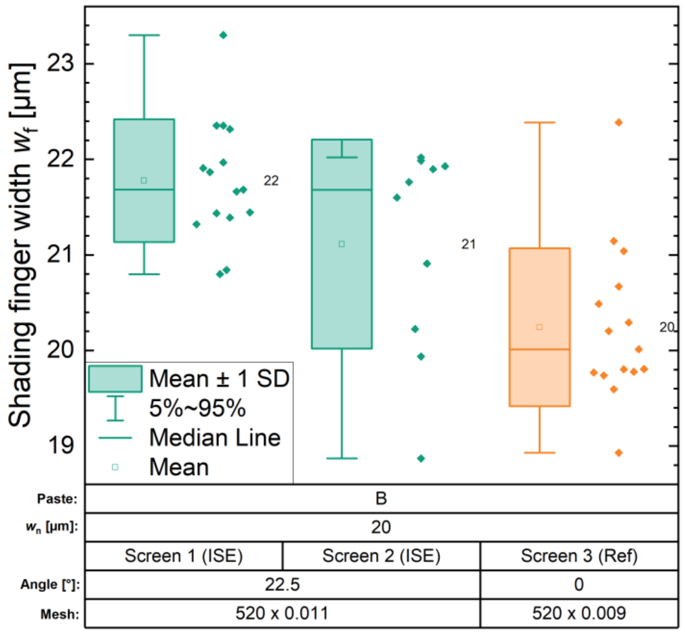
M10 TOPCon metallized cells with laser structured screens

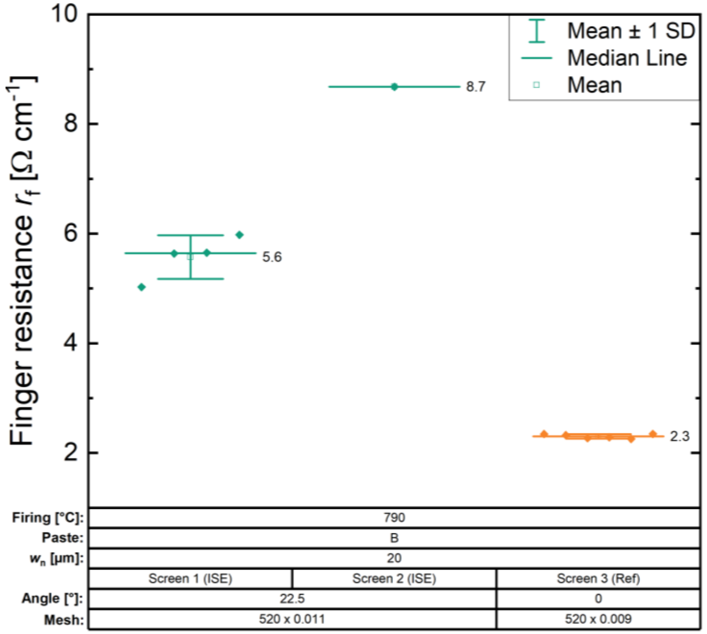
Screen printing results

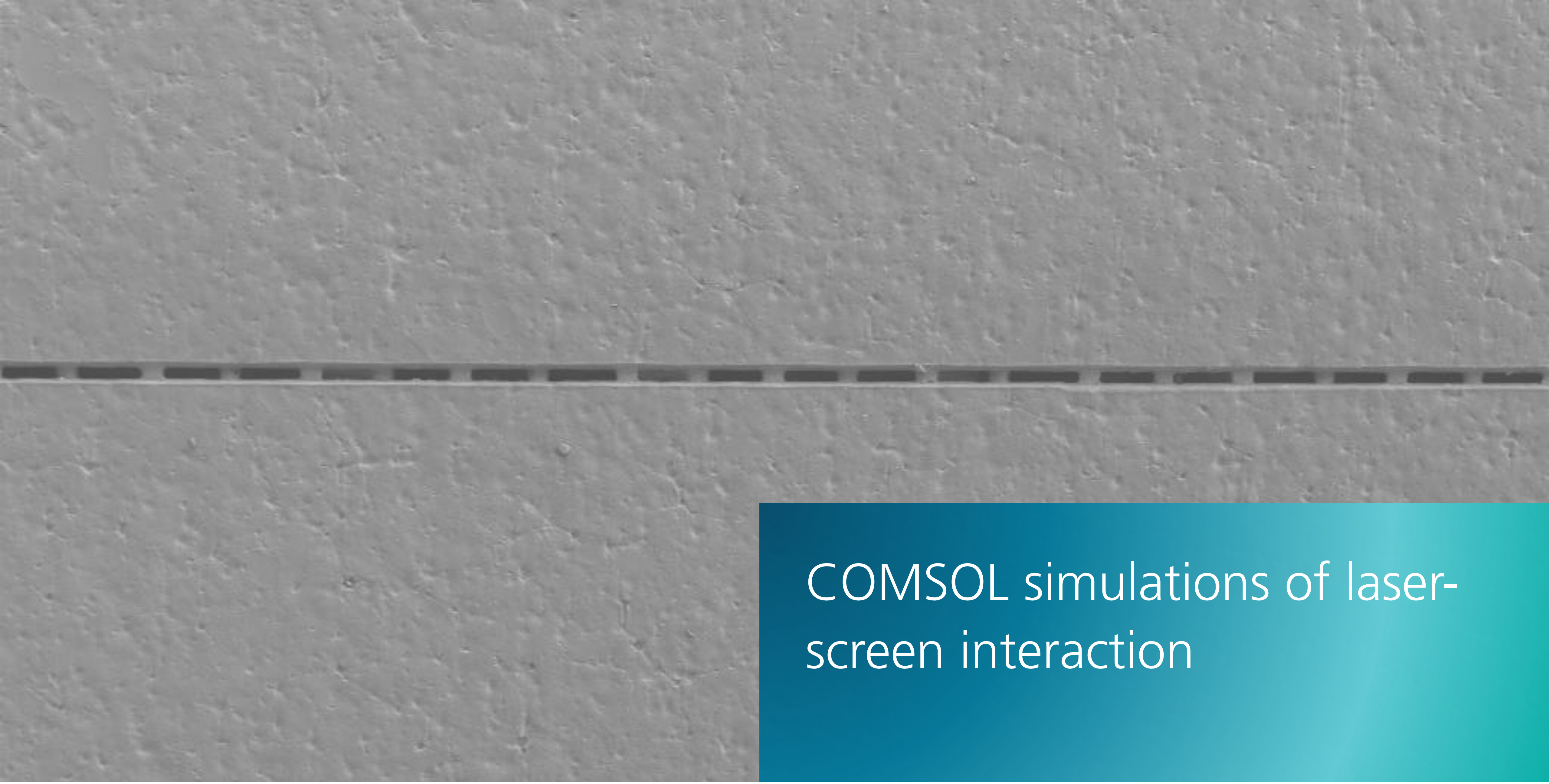
- Shading width of printed fingers comparable with industry reference Screen 3
- However, higher finger resistance compared to industry standard due to the use of angles screens

Future Outlook:

- Currently working on realizing laser openings in knotless screens







COMSOL simulations of laser-screen interaction

COMSOL simulations of laser-screen interaction

Introduction and Motivation

Processes Involved during material interaction with a laser:

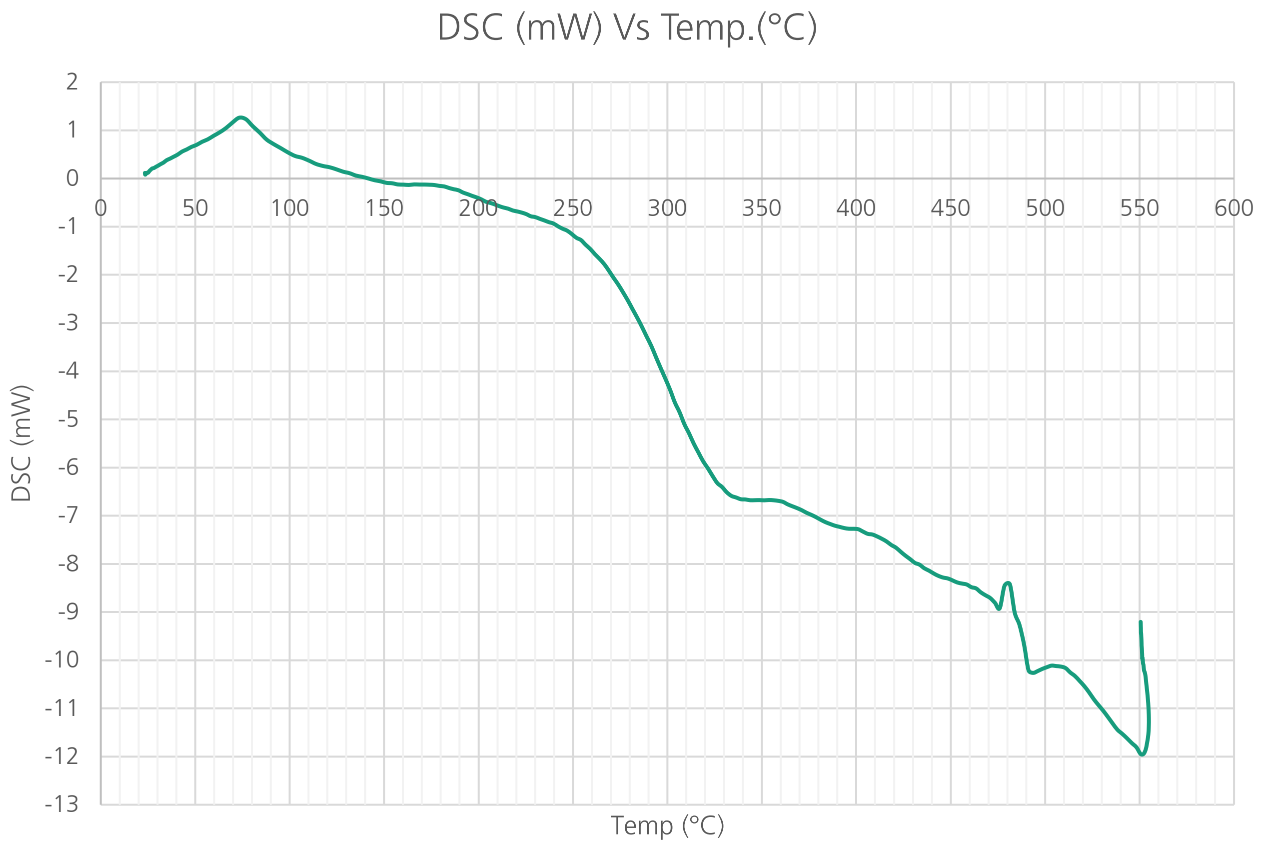
Energy absorption and heat transfer → **Material decomposition and vaporization** → **Interface effects and surface recession**

- Aim
  - To simulate a large parameter space and corroborate with the experimental findings
  - Advantage: Reducing parameter variation experiments and reducing screens used

[1] A. Nair (to be published)

COMSOL simulations of laser-screen interaction

Methodology: Differential Scanning Calorimetry (DSC) measurements



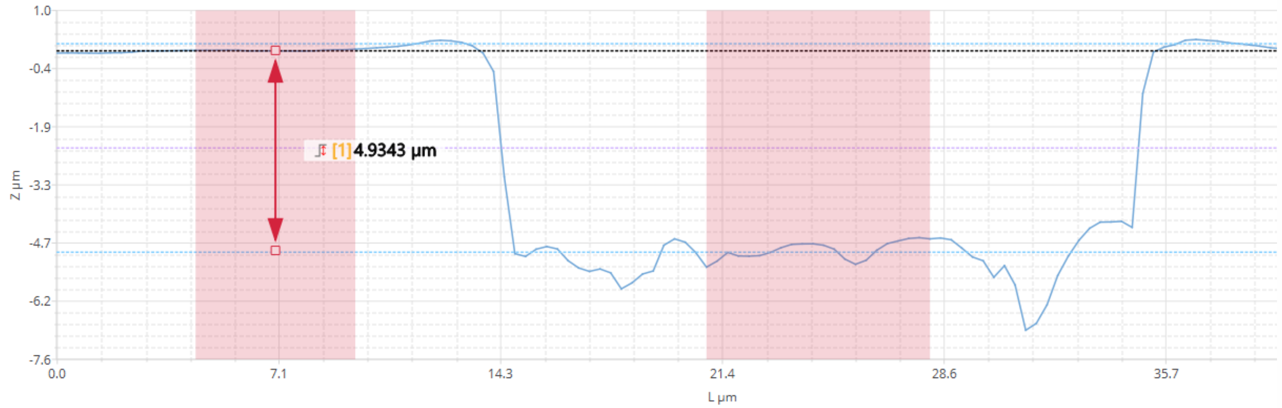
- **Ablation Temperature: 185 ˚C**
- **Latent Heat: 685.75 J/g**
- **Laser parameters used for simulation**
  - Laser power: 0.17 Watt
  - Pulse duration: 15 Picoseconds
  - Wavelength: 355 nm
  - Focal spot size radius: 4 µm
  - Scanning speed: 3 m/s

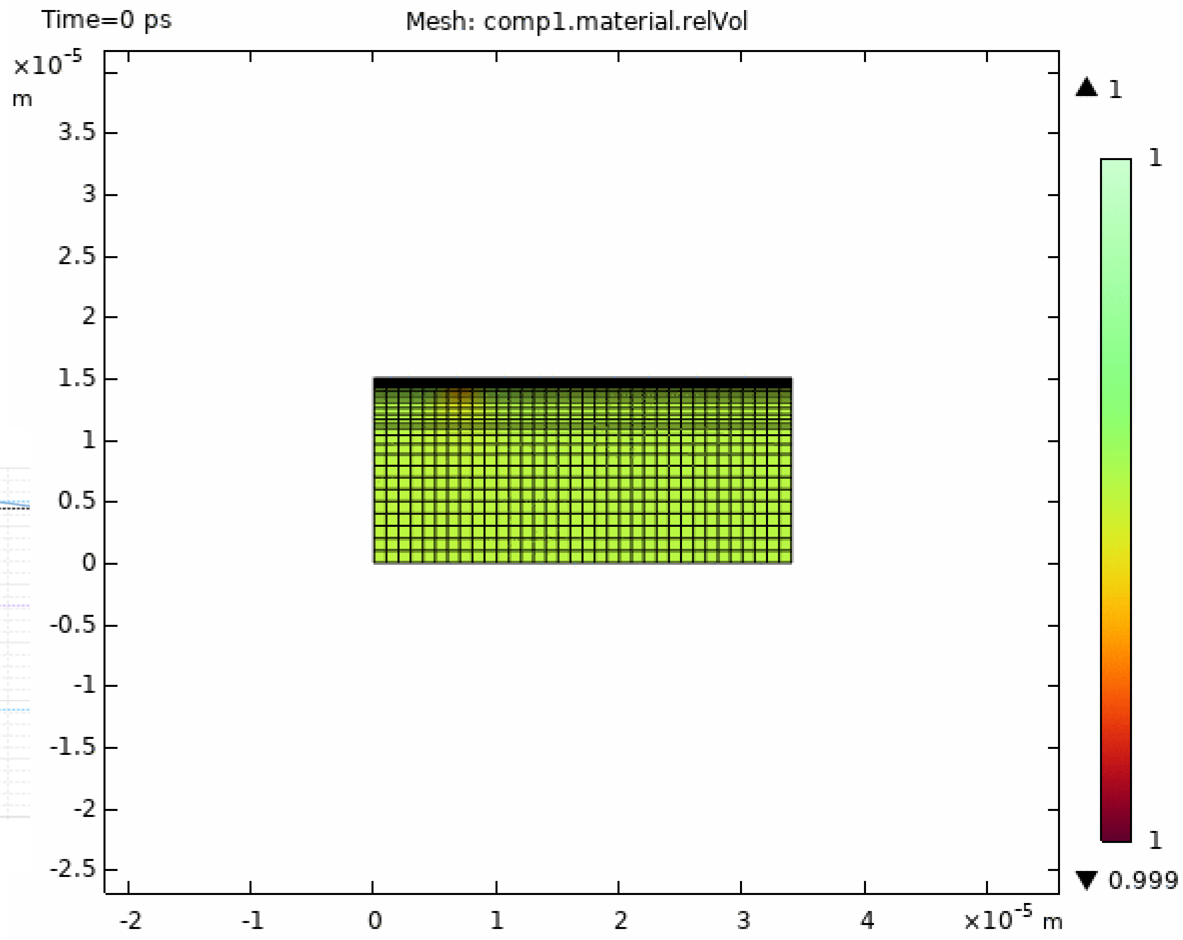
[1] A. Nair (to be published)

COMSOL simulations of laser-screen interaction

Results: 2D simulation

- Successful simulation of ablation mechanism on a polyimide layer
- At pass = 1, material of 5 µm removed according to simulation
- Comparable with real life results obtained from 3D microscopy (below)





[1] A. Nair (to be published)

Fraunhofer ISE

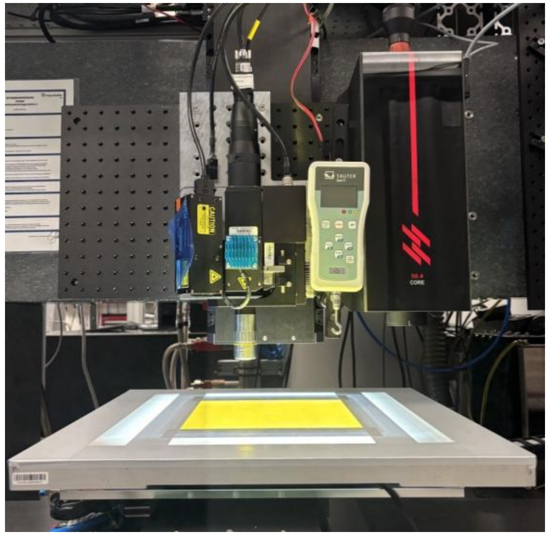
Summary and Future Outlook

Results:

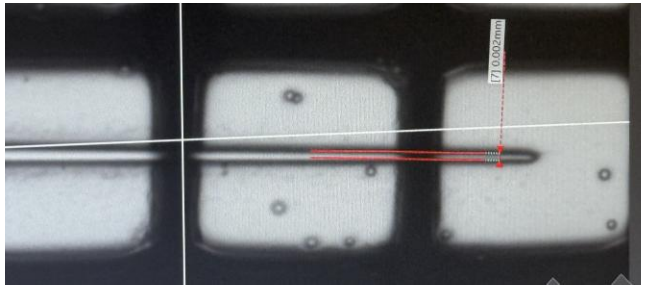
- Successful structuring of fine line openings = 20 µm on screens
- Finger widths of 21 µm printed on M10 TOPCon cells
- 2D COMSOL simulation of ablation by pulsed laser of screen similar to experimental results

Next Steps:

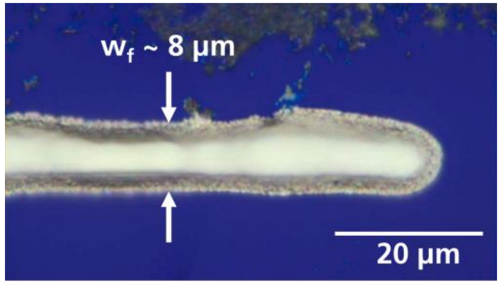
- Using the automated microscope to detect damages on wires
- Conducting print test on wafers with knotless screens with a screen opening of 1 µm with optimized pastes
- Conducting 3D COMSOL simulation of laser-screen interaction to gauge the taper observed in experiments



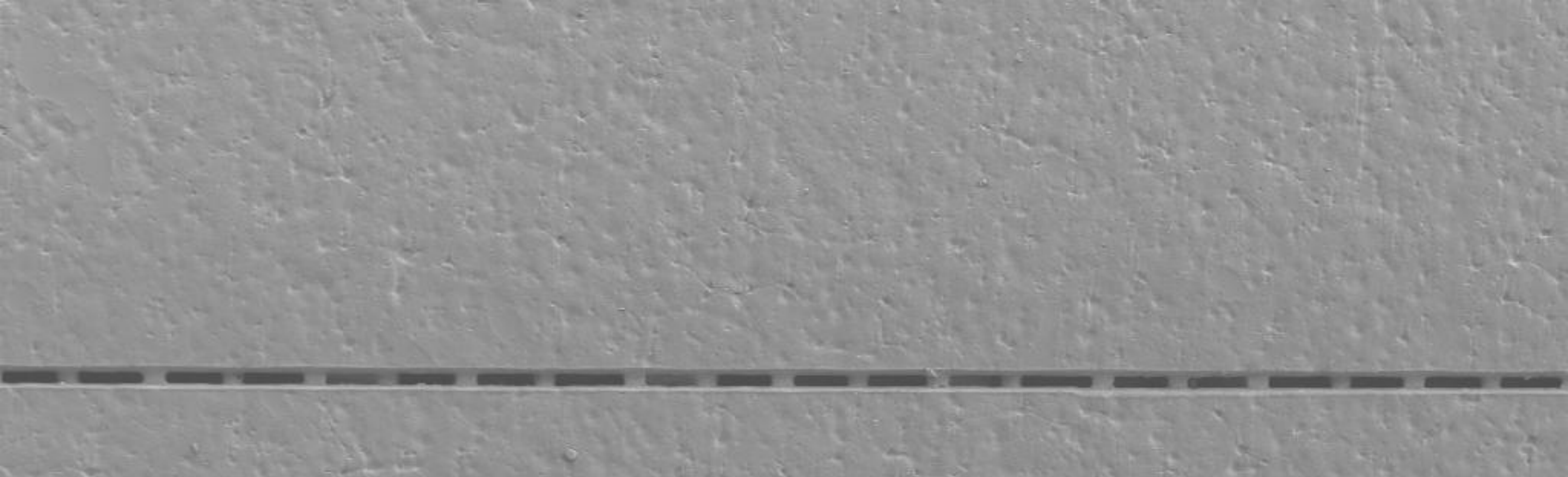
Setup of automated microscope at Fraunhofer ISE for faster and accurate screen characterization



Ultra narrow tapered channel in between two wires (500-05 mesh)



Screen-Printed ultra fine contact with w_f ~ 8 µm



Thank you for your attention!

Aathira Krishnadas Nair
Aathira.krishnadas.nair@ise.fraunhofer.de

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

This work has been funded by the Federal Ministry for Economic Affairs and Climate Action within the project "Laser2Screen" (No.: 03EE1100E).