

1. INTRODUCTION

High device efficiency and low costs makes $\text{CuIn}_x\text{Ga}_{(1-x)}\text{Se}_2$ absorber one of the most promising PV technology amongst its thin-film competitors. However, a transition to full-size modules results in increased ohmic losses. To avoid the losses, industrial module production requires CIGS device to be rapidly divided into smaller cells interconnected in series. It is done by three laser scribing steps identified as P1, P2, and P3 [1].

Scaling up the process throughput is one of the major objectives for a successful development of CIGS thin-film technology. Now, modern ultrashort lasers offer high average power at laser pulse repetition rates of 1 MHz. Therefore, the laser scribing speed can be significantly increased exceeding 2 m/s limit.

However, it was reported that high repetition rates can lead to heat accumulation effects [2]. Therefore, elevated temperatures can cause degradation of the absorber material, formation of secondary phases. Ultimately, this would lead to efficiency losses of the solar device [3]. **The aim of the research was to investigate the influence of laser repetition rate on the quality of the P3 scribe in case of the high-speed scribing with high pulse repetition rate (1 MHz) laser.**

2. EXPERIMENTAL SETUP

Table 1. Laser and optics parameters used in the CIGS scribing experiments.

Laser	Atlantic series (Ekspla)	
Pulse duration	13 ps	
Repetition rate	Up to 1MHz	
Wavelength	1064 nm/ 532 nm	
Scanner	ScanLab	Next Scan Technology
Optics	80 mm	190 mm

Samples

- P3:** Complete structure solar cell: (ZnO:Al/i-ZnO/CdS/CIGS/Mo/Glass).



Fig. 2. Schematic cross-section of CIGS solar cell

3. TWO P3 SCRIBE APPROACHES INVESTIGATED

The P3 process is used to electrically isolate the neighboring cells and must avoid laser induced thermal damage to the absorber material.

- P3 „Type 1“:** scribe involves the removal of the front-contact together with the absorber and buffer layers.
- P3 „Type 2“:** only front-contact layer is removed. CIGS layer is considered to be sufficiently resistive to electrically isolate the neighboring cells.

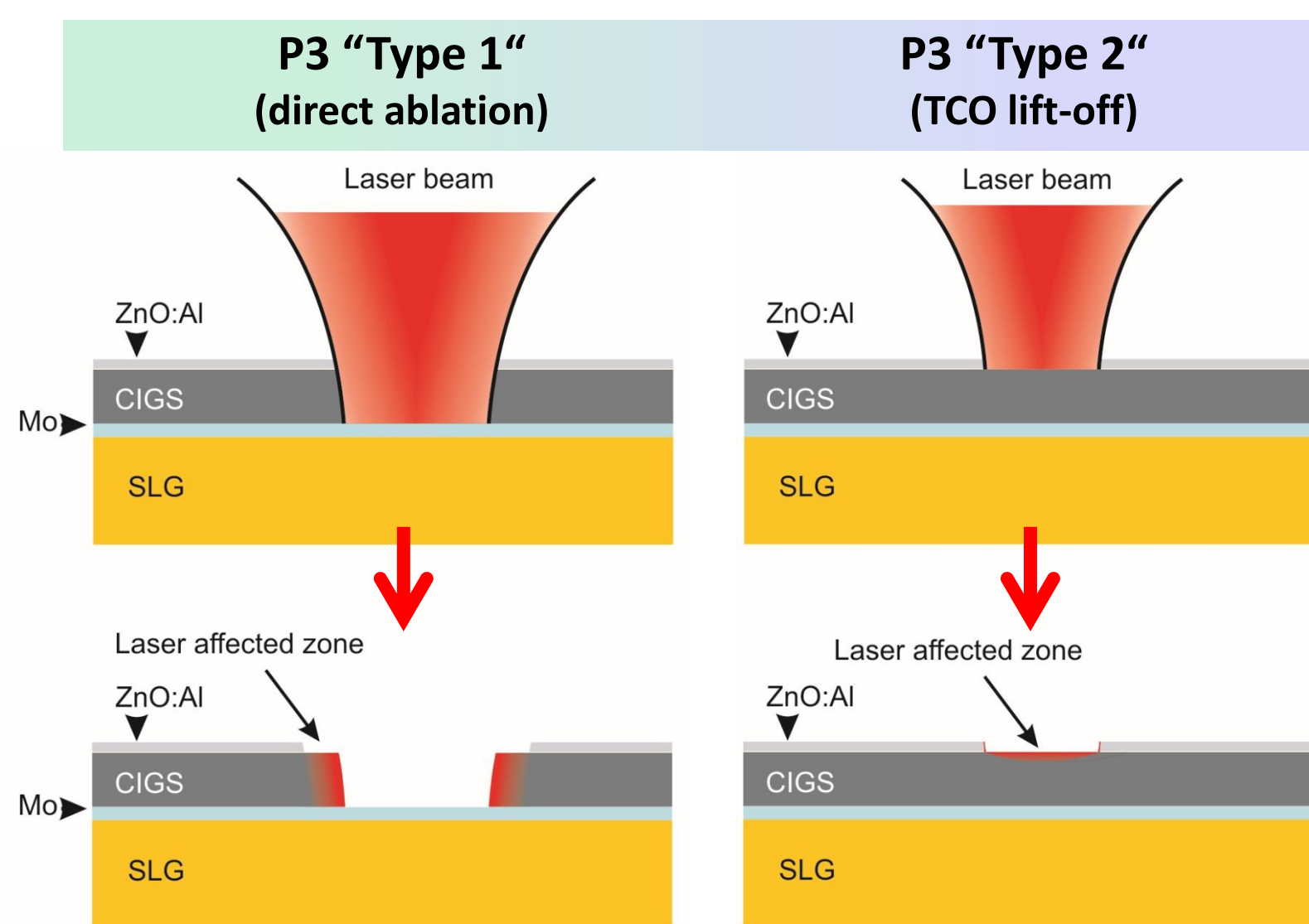
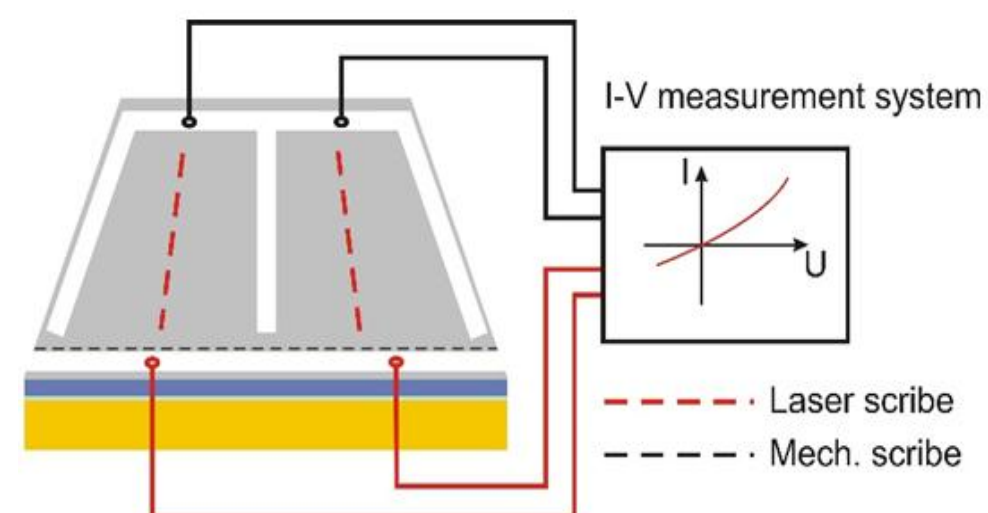


Fig. 3. Schematic cross-section of Type 1 and Type 2 P3 scribes in CIGS thin-film solar cell

4. LINEAR LASER SCRIBING TECHNIQUE (LLST)

LLST technique [4] provides information about the parallel conductivity of laser P3 scribes. Technique includes performing linear laser scribes on the sample and measurement of the cell parallel conductance. Scribe conductivity can be extracted from the scribe length l and cell conductance G_p^{SC} relationship by fitting the results with a simple linear equation (1).



$$G_p^{SC} = \sigma_{SCM} \cdot l \quad (1)$$

Fig. 4. Experimental setup and fitting function for LLST technique for in-process measurement of measurements parallel conductance in fully functional mini-cells.

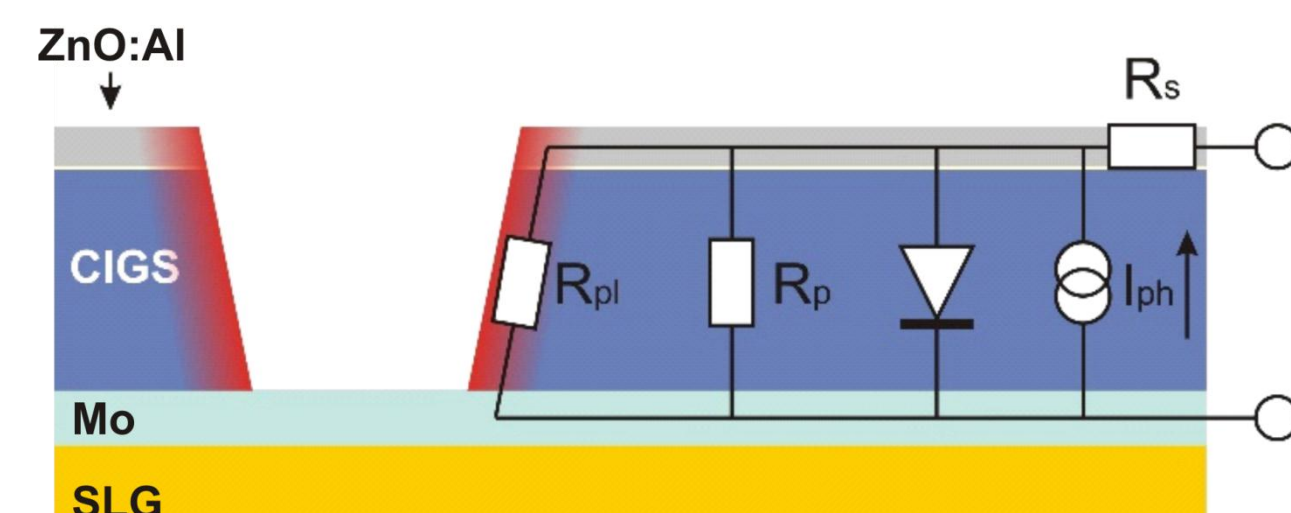


Fig. 5. Schematic cross-section of the P3 scribe region together with equivalent circuit model of a solar cell.

σ_{SCM} – conductivity of P3 scribe

5. RESULTS

Pulse repetition rate and scanning speed varied to maintain constant pulse overlap of 90% :

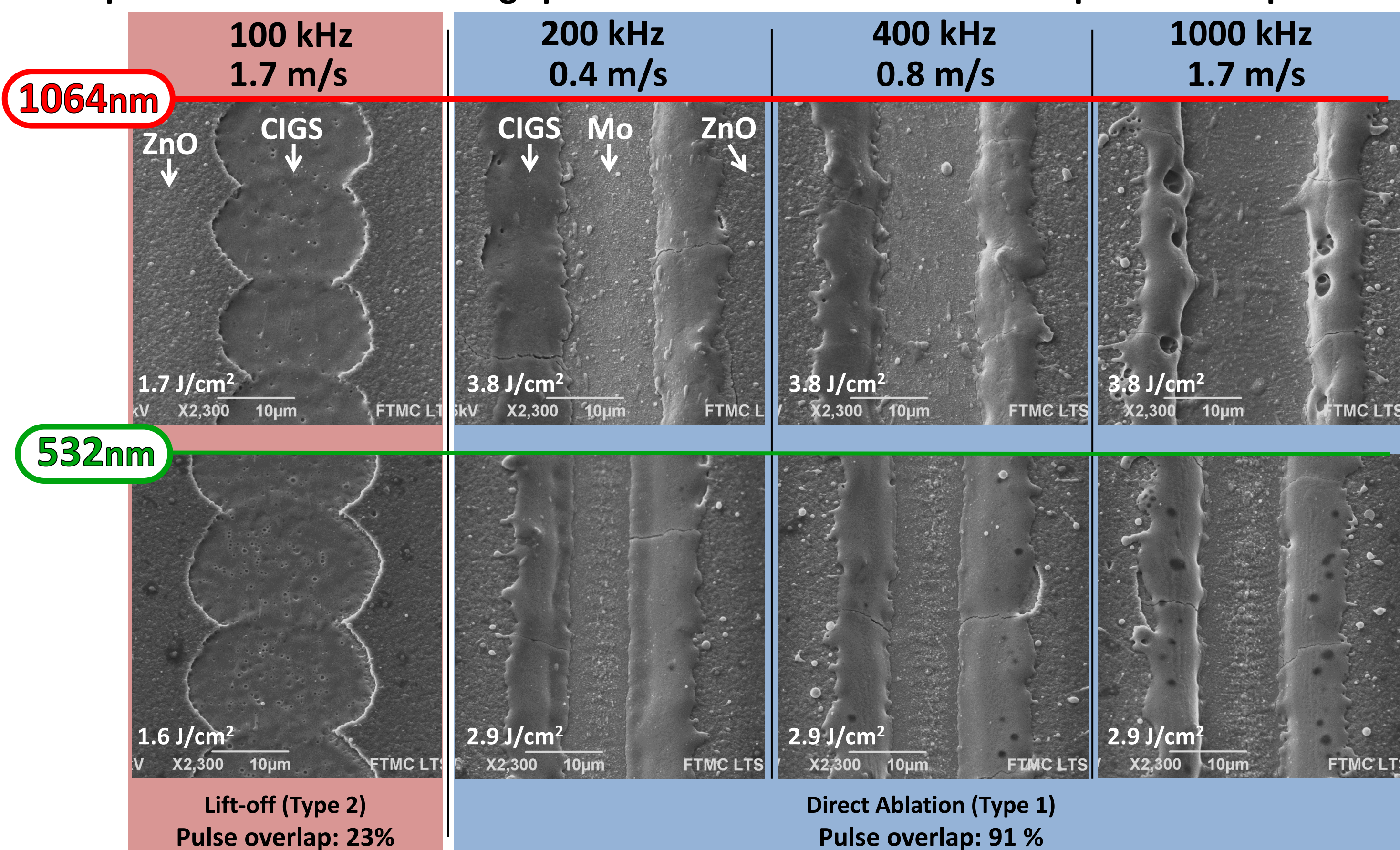


Fig. 6. SEM images of the P3 channels. Scribing was performed at different laser pulse repetition rates keeping the constant pulse overlap of 90 %. The 100 kHz processing represents the P3 Type 2 pattern, while P3 Type 1 processing was performed with 200 - 1000 kHz laser repetition rates.

6. P3 LASER SCRIBE CONDUCTIVITY MEASUREMENTS

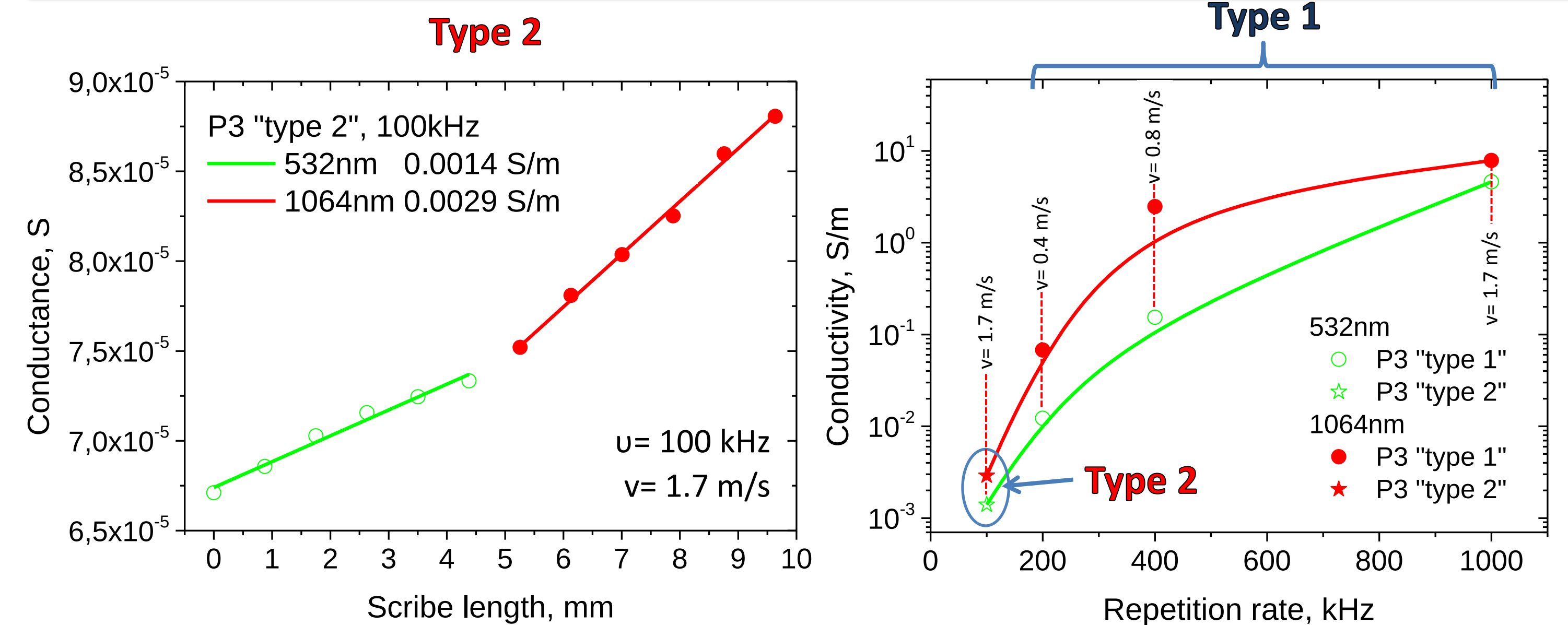


Fig. 7. P3 Type 2 scribe conductivity measurement. Laser repetition rate 100 kHz, scribing speed 1.7 m/s. **Red line:** laser wavelength 1064 nm (1.7 J/cm²). **Green line:** 532 nm (1.6 J/cm²).

Fig. 8. Laser scribe conductivity versus laser repetition rate for 1064 nm and 532 nm wavelengths. P3 Type 1 and Type 2 cases presented.

7. SIMULATION OF CIGS MINI-MODULE EFFICIENCY

To estimate device's efficiency degradation related to P3 scribe conductivity, simple 3-cell solar module simulation was conducted. CIGS mini-cell parameters were adopted from [5]. Simulation was based on a classical Shockley diode equation including the influence of parallel, series, and laser-induced conductivities using Pspice circuit simulator. Isolation between the cells was established via laser scribes depicted as resistors R_{P3} .

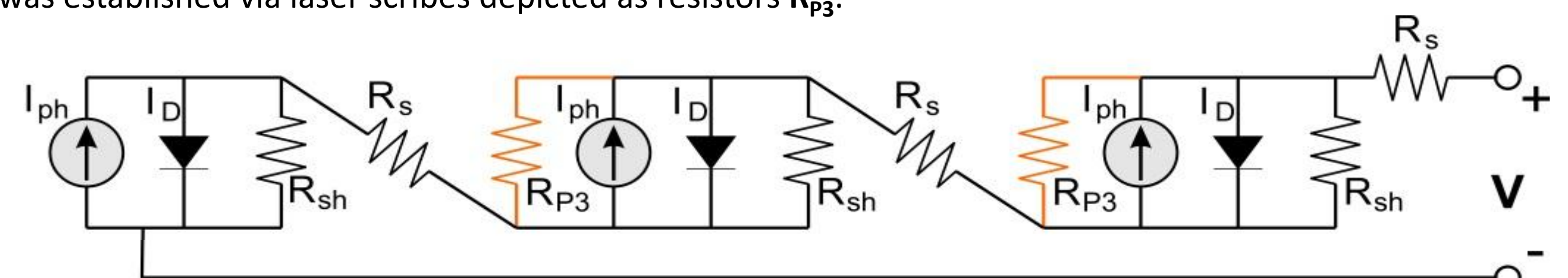


Fig. 9. Equivalent circuit of 3-cell thin-film mini-module interconnected in series.

Diode equation for illuminated solar cell:
 $I = I_{ph} - I_0 \left(e^{q(V+IR_s)/nkT} - 1 \right) - \frac{V + IR_s}{R_p}$
 $R_{P3} = \frac{\rho_{SCM}}{l}$, l – scribe length

Table 2. Electrical parameters for CIGS solar cell presented in the first row. Simulated parameters for a 3-cell mini module are shown in the second row.

	V_{oc} mV	J_{sc} mA/cm²	J_0 A/cm²	n	R_s $\Omega \cdot \text{cm}^2$	R_p $\Omega \cdot \text{cm}^2$	η %
ZSW solar cell [2]	746	36.6	$2.4 \cdot 10^{-11}$	1.38	0.32	1750	21.7
Simulated mini - cell module	2271	36.6	$2.4 \cdot 10^{-11}$	1.38	0.32	1750	21.8

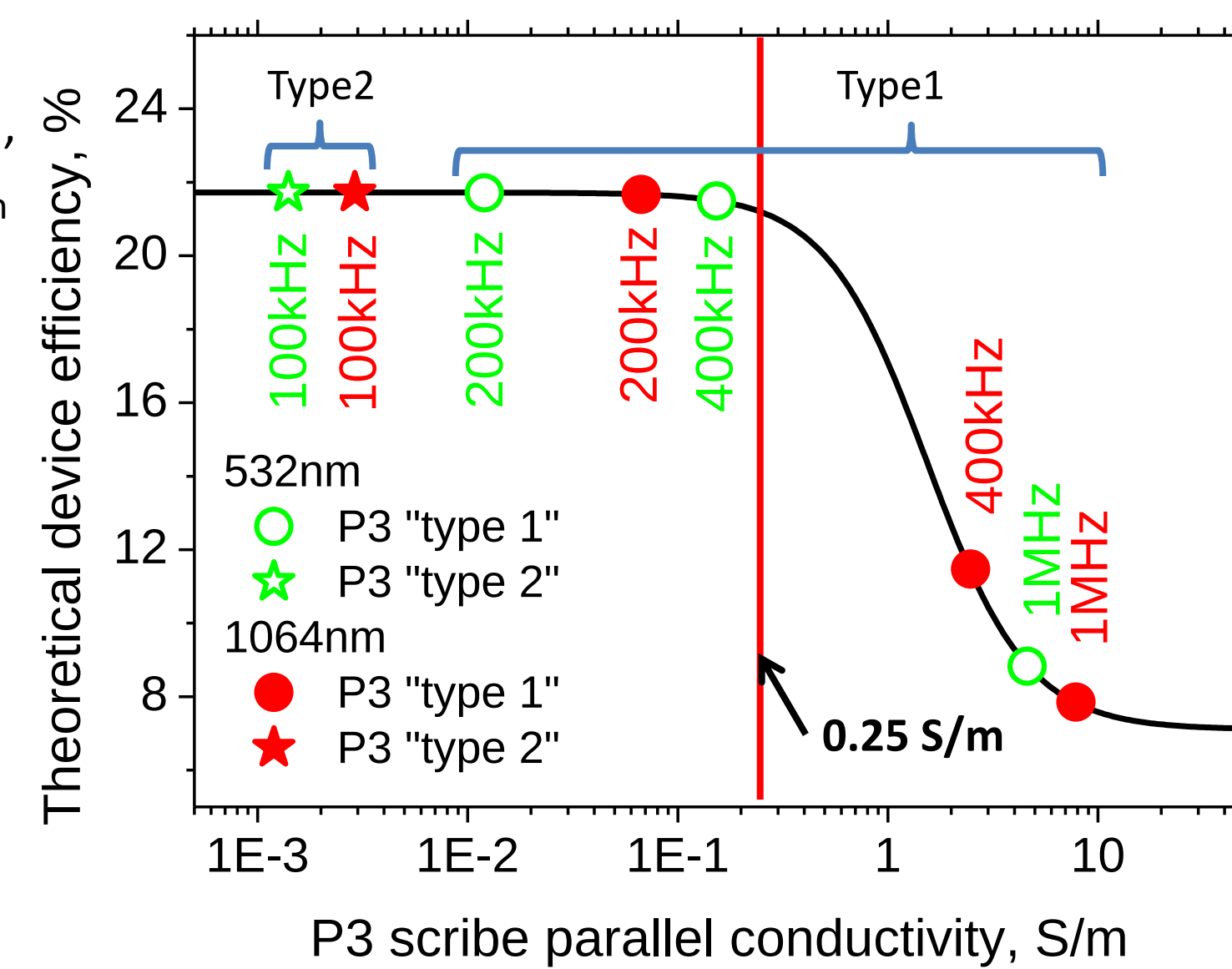


Fig. 10. Simulation of the CIGS 3-cell module efficiency dependence on the P3 scribe resistivity.

8. POLYGON SCANNER FOR ULTRA-HIGH SPEED SCRIBING

P3 scribing speed of 50 m/s was reached

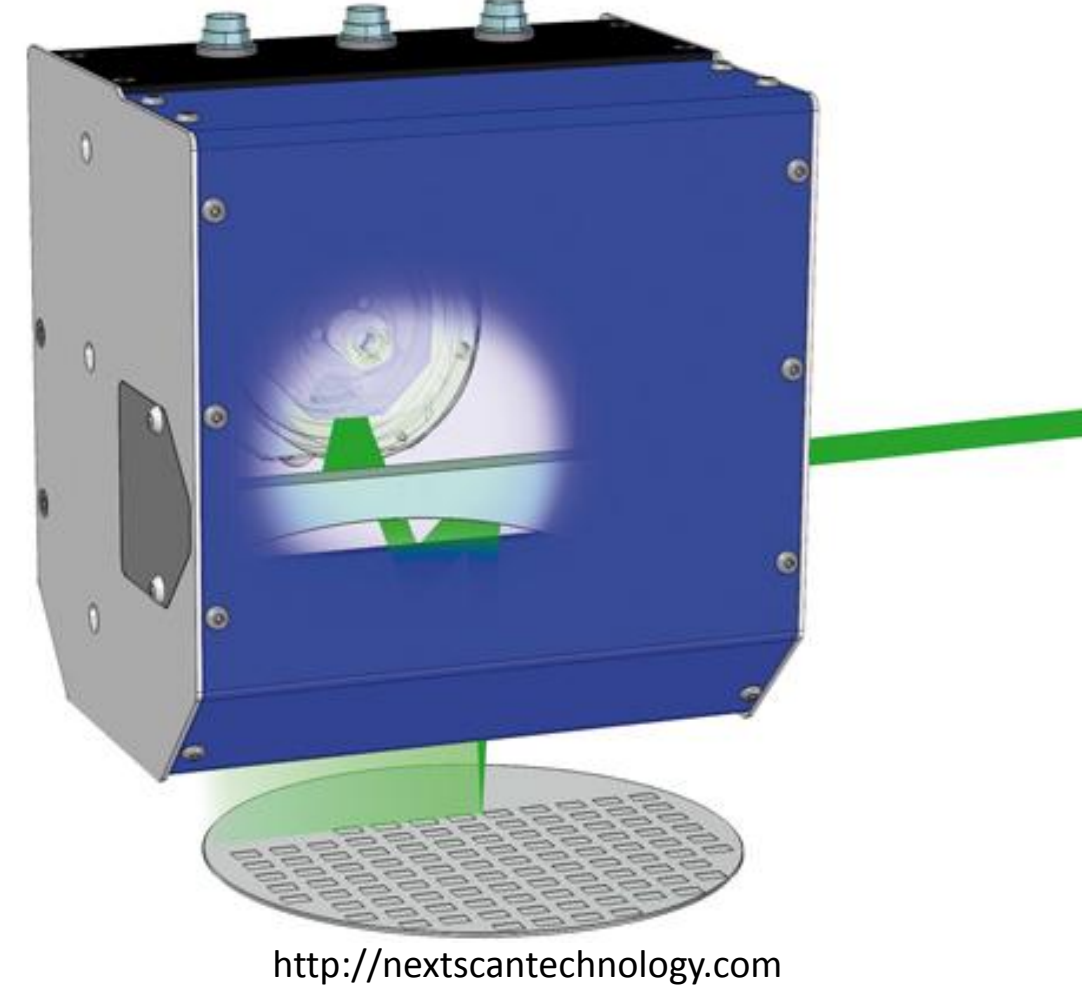
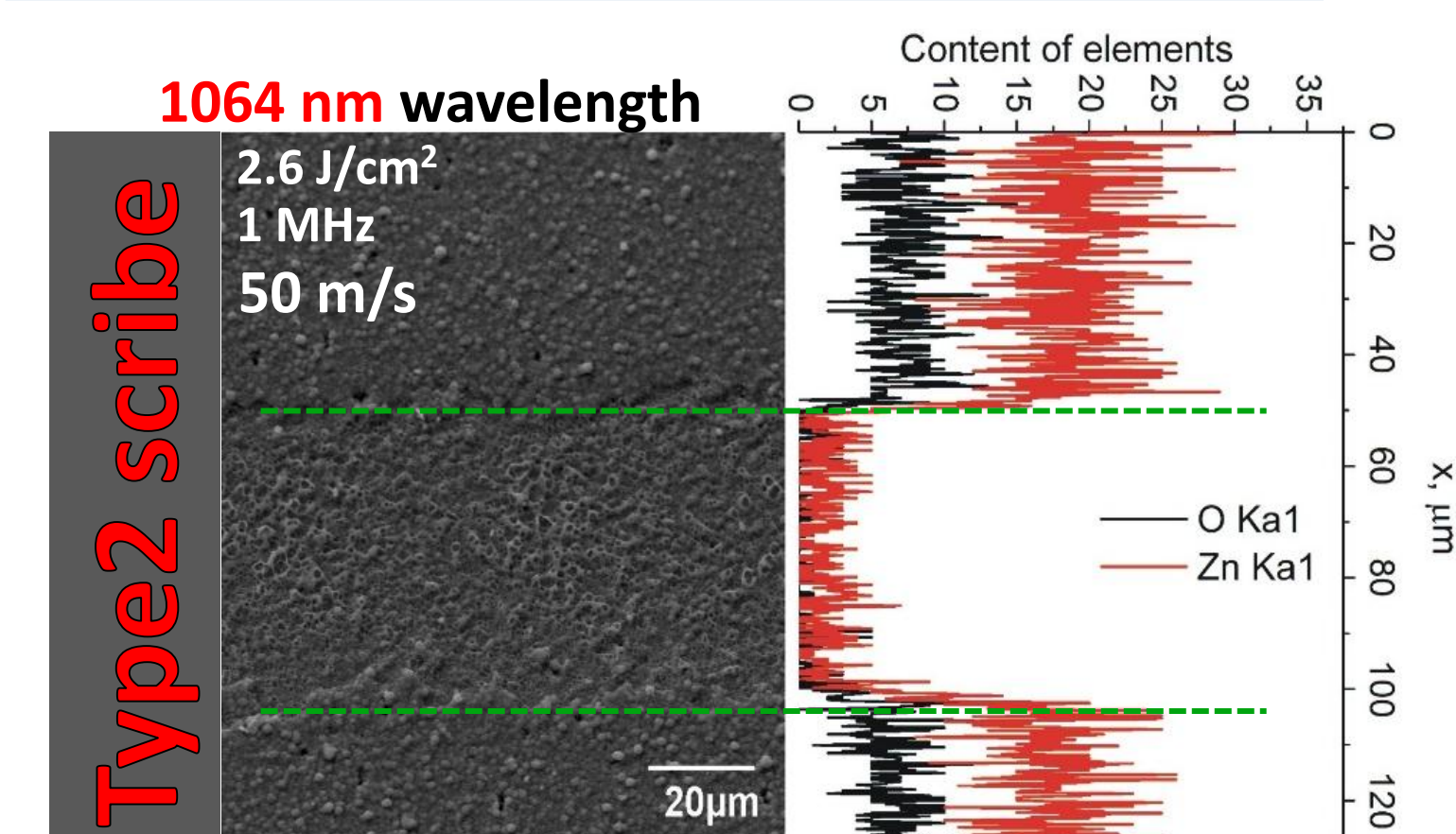


Fig. 11. NST polygon scanner with scanning width of 170 mm and maximum scribing speed of 100 m/s [6] (left). SEM image and EDS analysis of the top-contact lift-off process (right).



- Fine scribe quality shown by SEM,
- EDS confirmed complete removal of ZnO layer,
- CIGS scribing speed reach **50 m/s**
- At laser repetition rate of **1 MHz**.

9. SUMMARY

- Up-scaling the P3 process is a challenging task. In case of high pulse repetition rate scribing heat accumulation effects becomes highly dominant.
- Type 1 process showed high scribe conductivity dependence on the laser repetition rate. Highest conductivity reached 7.9 S/m at 1 MHz rep. rate. According to simulations, 3-cell mini module suffered from severe efficiency losses.
- The P3 lift-off (Type 2 process) ablation showed most promising results. Extracted scribe conductivity was less than 0.003 S/m for 532 and 1064 nm radiation wavelengths. Simulations revealed no efficiency losses of CIGS mini-module device.
- Type 2: Scribing speed of 50 m/s was shown by exploiting polygon scanner combined with 1 MHz laser.

10. ACKNOWLEDGEMENTS

The research leading to these results was partially funded by the European Union FP7 Program under grant agreement No 609355.

appolo

REFERENCES

- P. Gečys, E. Markauskas, A. Žemaitis, et al., Variation of P2 series interconnects electrical conductivity in the CIGS solar cells by picosecond laser-induced modification, Solar Energy, 132: 493-502 (2016).
- F. Bauer, A. Michalowski, et al., Heat accumulation in ultra-short pulsed scanning laser ablation of metals, Optics Express, 23: 1035-1043 (2015).
- J. Hermann, M. Benfarah, et al., Comparative investigation of solar cell thin film processing using nanosecond and femtosecond lasers, Journal of Physics D: Applied Physics, 39: 453-460 (2006).
- E. Markauskas, P. Gečys, et al., Validation of monolithic interconnection conductivity in laser scribed CIGS thin-film solar cells, Solar Energy, 120: 35-43 (2015).
- P. Jackson, D. Hariskos, R. Wuerz, et al., Properties of $\text{Cu}(\text{In,Ga})\text{Se}_2$ solar cells with new record efficiencies up to 21.7%, Physica Status Solidi (RRL) – Rapid Research Letters, 9(1): 28-31 (2015).