Presented at the 41st European Photovoltaic Solar Energy Conference and Exhibition, 23-27 September 2024, Vienna, Austria

HIGHEST THROUGHPUT LASER PROCESSING FOR THIN PLATED CONTACTS

E. Alvarez-Brito[1], R. Haberstroh[1], G. Hoppe[1], K. Du[2], F. Roessler[3], A. A. Brand[1], S. Kluska[1], F. Meyer[1], J. Schneider[1], J. Nekarda[1]
[1] Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany
[2] EdgeWave GmbH, Carlo-Schmid-Straße 19, 52146 Würselen, Germany
[3] Moewe Optical Solutions GmbH, Leipziger Strasse 27, 09648 Mittweida, Germany

The market for solar cells and modules is growing rapidly, but it also poses significant challenges to existing production technologies, including laser processing tools. In this paper, we present our approach for the next generation of laser processing and demonstrate its capabilities for the demanding application of laser contact opening. Our concept is based on on-the-fly processing employing an ultrafast polygon scanner combined with a high repetition rate laser and high-end lens. The on-the-fly process consists of a linear axis transport system synchronized with the scanner, allowing for operation within a quasi 1D scanning field, which enhances the homogeneity of the laser contact openings and the number of elements processed in a time period. The scanning system could achieve a potential throughput of 31,500 M10 (182 mm x 182 mm) wafers on a single lane, with small structures (< 10 µm) at record speeds.
Keywords: ultrafast laser processing, laser contact opening, copper electroplating

1 AIM AND MOTIVATION

The demand for solar cells and modules is increasing quickly, but this growth presents substantial challenges for current manufacturing technologies. The desired wafer format has evolved from M2 to M10 and even M12+, necessitating adapted machine concepts [1]. Another major challenge is the need to reduce the amount of silver used in solar cell production, as it could otherwise exceed global resources [2]. Simultaneously, more efficient yet complex cell architectures, such as IBC or TOPCon, which require large-area laser structuring, must be supported for automated high-throughput production. In summary, all major trends either depend on or significantly benefit from rapid laser processing.

Particularly, laser contact opening (LCO) has been a crucial step for several cell concepts. LCO for electroplating is gaining even more attention, as it enables metallization with copper, providing a cost-effective alternative to silver contacts [3]. Here, the size, homogeneity, and quality of the laser structure significantly influence the contact width, the contact and series resistance, as well as recombination and adhesion properties. The main objective of this work is the development of a novel machine concept that would allow the creation of small structures over a large area at high speed for laser contact opening for metallization with copper electroplating.

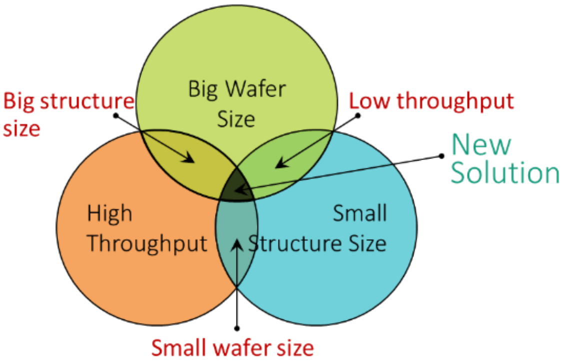

Figure 1: Traditional trade-off between throughput, structure size and wafer size.

Larger wafer format, small structure size and high system throughput are conflicting factors with conventional laser processing technologies. Figure 1 illustrates these requirements. For example, a large beam diameter and small focal length of the focusing optics result in small structures on the workpiece plane. However, a large beam diameter means that the scanner mirrors must be correspondingly large, which in turn can be electromechanically accelerated more slowly than smaller ones, thus reducing throughput [4]. Small structures can be achieved within small field of views as well. By stitching them together, a large workpiece can be addressed with multiple small working fields, but again at the expense of reduced throughput or greatly increased system complexity, multiplexing and cost. With a conventional laser system setup, this leads to ratios that make it appear impossible to apply small structures to large formats at high throughput.

This situation requires a rethinking of laser system technology to find the new approach to reach the goals as shown in Figure 1.

2 SCIENTIFIC INNOVATION AND APPROACH

2.1 Scanning System and Laser Source

For the application of LCO for copper electroplating metallization, the laser must operate with ultrashort pulses in UV wavelengths to ensure short penetration depths of a few nanometers on the emitter side of the cells. Small structure size below 10 µm on big wafer formats is essential since results from Kluska et al. [3] have already shown an absolute increase in total conversion efficiency of 0.65% abs. of the solar cell when the opening size is reduced from 14 µm to 5.5 µm.

Our development is based on the implementation of a UV polygon mirror scanner (MOEWE Optical Solution GmbH) and its combination and synchronization with a pulse on-demand high repetition rate UV laser system (EdgeWave GmbH), high-end optics, and axis system.

The scanner consists of a multifaceted mirror rotating at high speed, which allows to reach beam deflection speeds up to 1 km/s at a focal length of 560 mm, which is much higher than conventional galvo scanning systems [5]. The polygon scanner is capable of handling large beam diameters due to its free aperture of 30 mm, which allows small focal diameters meeting the challenging structure size requirements of 10 µm or less.

To take advantage of the high scanning speed a laser with high repetition rate must be used. The described setup includes a prototype laser (EdgeWave GmbH) that currently offers sufficient pulse energy for the ablation at the highest on the market available repetition rate of

16.2 MHz at 343 nm UV wavelength with 2.4 ps ultrashort pulses.

2.2 On-the-fly processing

This method achieves focusing with reduced optical distortion by guiding the beam in a narrow area at the center of the scan field (quasi-1D) orthogonal to the transport direction, while the target is moved across the scanning area. In contrast, conventional 2D f-theta lenses exhibit significant distortion in the corners of the scan field. Additionally, the on-the-fly approach increases the number of wafers processed per hour [4].

This technique requires synchronization between the scanning and transport systems. A quadrature encoder signal couples the motion of the conveyor to the scanner, ensuring that scanning is synchronized with transport.

Figure 2a illustrates the schematic of the setup's functionality, showing how the laser beam is directed into the scanner and deflected by the polygon mirror. The output includes an f-theta lens designed to meet the stringent requirements for achieving a small focal spot size for ultrashort UV pulses across the entire field of 210 mm x 210 mm.

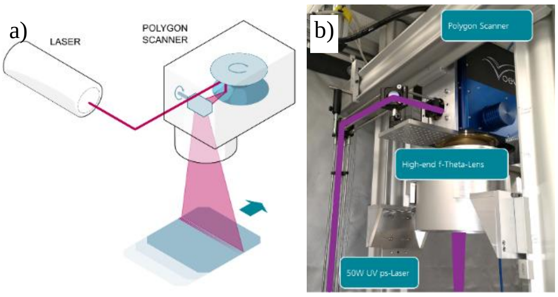

Figure 2: a) Schematic of how the polygonal mirror works b) Photo of the prototype, the laser path to the scanner is shown in purple.

The performance of the proposed on-the-fly process is tested and compared to a laser scanning process where the substrate is static and processed over the full area. In both cases, the same scanning system and laser described previously are used.

Laser ablation is performed at different intensities along the entire surface of the wafer. The ideal opening is made by a Gaussian beam, resulting in a round spot, but due to optical distortions this may not be the case. Size and roundness of the openings made in the passivation layer are evaluated over the entire field. Both processes are performed on a TOPCon silicon wafer of size M10 (182 mm x 182 mm). The resulting structures are observed and imaged by a microscope.

2.3 Metallization with electroplating

In this work, TOPCon precursors (M10 wafer area 330.23 mm², pseudo square) were metallized using electroplating, which allows for the deposition of nickel and primarily copper in the metal stack. At Fraunhofer ISE, an industrial pilot system (InCellPlate; RENA Technologies) is used, with a throughput capacity of up to 5,000 wafers per hour. The metallization process is conducted in an inline system, where one side of the solar cell is metallized during a single pass. This inline system includes four process baths: pretreatment (1.5% hydrofluoric acid), nickel electrolyte, copper electrolyte, and silver electrolyte. For bifacial metallization, the process is repeated for the second side of the solar cell, as shown in Figure 3. [6]

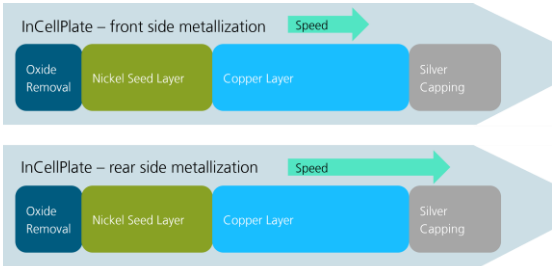

Figure 3: Schematic of the bifacial electroplating metallization sequence made at Fraunhofer ISE.

The metallization process comprises a nickel seed layer (1 µm height), a highly conductive copper layer (8 µm height), and a very thin silver layer (<0.5 µm) to prevent oxidation of the copper layer and to ensure good solderability. In total, the finger height is 10 µm and the finger width is 25 µm. The reference samples were metallized by printing silver-aluminum and silver pastes on the front and rear sides, respectively.

3 RESULTS

3.1 LCO in static process

Although the f-theta lens was specifically designed to scan large areas, up to 210 mm x 210 mm M12 wafers, a clear distortion of the structure shape can be observed at the corners of the wafer, as shown in Figure 3, while the center of the wafer has rounder spots.

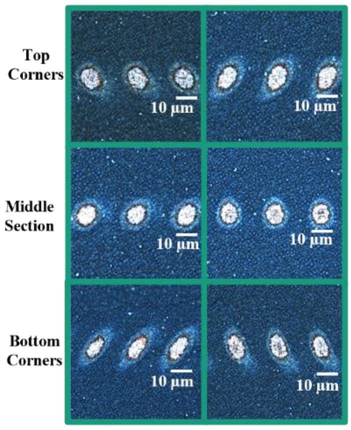

Figure 3: LCO images taken for static process in different locations over the wafer.

These spots at the extremes of the wafer are evaluated and compared to those in the middle section to verify their quality. The metric used for comparison is ellipticity, or flattening, which measures the compression of a circle to form an ellipse, as shown in Figure 4.

The results of these measurements reflect the distortion obtained far from the center of the scan field. In addition to the increase in ellipticity, the consistency of this value is decremental. The roundness and homogeneity obtained in the center are desirable results and support the argument for reducing the scan field as much as possible and lasering in the center of the field in on-the-fly mode.

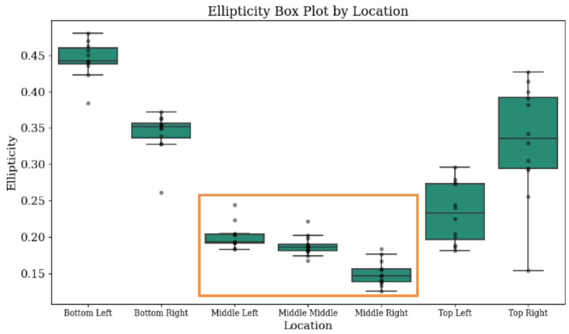

Figure 4: Evaluation of openings ellipticity over the wafer. The orange box highlights the desirable results.

3.2 LCO in on-the-fly process

To test the proposed technique, a linear axis is used. Thanks to the encoder signal, the scanner can follow the movement of the wafer and perform the desired process. By implementing this technique, the scanning field in the transport axis was reduced to 2 mm. Figure 5 shows the results for two different LCO processes in the center and corners of the wafer.

From Figure 5a it can be noted that the distortion observed in Figure 4 is not present. Both the ellipticity and the opening size are reduced and the homogeneity in the transport axis is improved.

Figure 5b shows that it is possible to create thin, continuous openings in the substrate with a width of approximately 10 µm, which is the target value for subsequent metallization steps.

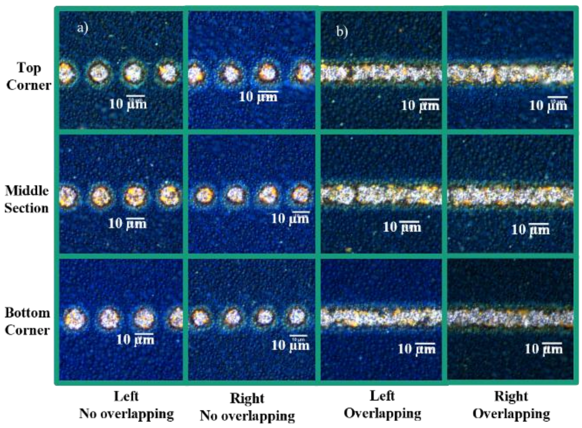

Figure 5: Collage of images taken at different positions on the wafer for two different processes a) LCO without overlap at a scan speed of 250 m/s, resulting in dots b) LCO with overlap at a scan speed of 125 m/s, resulting in continuous lines.

3.3 Laser throughput calculation

For this case study, two types of structures required for electroplating are realized. The first one is an LCO pattern of continuous lines along the wafer with a 1 mm spacing between each opening. The second pattern are bus bars that are placed every 14 mm each one consisting of 3 lines. Figure 6 shows a close-up image of these structures.

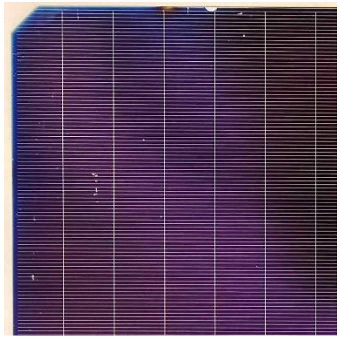

Figure 6: Close-up image of the resulting pattern. bus bars can be seen as vertical ticker lines, meanwhile the connectors are horizontal thinner lines.

To predict the production capacity and time requirements of the process, calculation tools have been developed to account for dynamic factors. The most relevant variables to consider include the laser repetition rate, which limits the scanning speed to ensure overlapping openings. This, in turn, dictates the line frequency of the polygon scanner and the optimal speed of the axis system [4]. The potential throughput is determined by calculating and extrapolating the time required to scan a given pattern. Wafer handling and positioning are not included in these calculations.

The results of the throughput calculations are shown in Table I, which compares a galvanometer-based scanning system and our approach with the polygon scanning system.

Table I: Throughput results for a system with a polygon scanner and another with galvanometer scanner.

LCO structure	Scanner type	time [s]	Throughput [wph]
Lines	Galvanometer	4.637	776
Lines + Bus bars	Galvanometer	5.579	645
Lines	Polygonal	1.241	2900
Lines + Bus bars	Polygonal	2.482	1450

The results presented in Table I show that the setup implemented by the polygon scanner has a processing capacity 2x to 4x times higher than that of the galvanometer scanner. However, it should be noted that these values are limited by the structure to be created on the substrate.

When calculating the throughput for the on-the-fly case with the polygon scanner, the laser frequency proved to be the main limitation. Although the polygon scanner can achieve processing speeds in excess of 1 km/s, 125 m/s was chosen. Otherwise, the spot-to-spot distance, or pulse pitch, would have been too big, avoiding formation of a continuous line. In this study, the maximum laser frequency at which ablation is possible was 16.2 MHz with a pulse pitch of 7.72 µm, ensuring sufficient overlap and line homogeneity. Overall, the constraint is shifted from the scanning system to the laser unit.

3.4 Electroplating and cell results

In this study, it was demonstrated for the first time that LCO produced by the high-throughput system is applicable for the metallization of large M10 (330.23 cm²) TOPCon wafers through electroplating. In Figure 7 the resulting contacts are shown for the different regions of interest over the wafer. Comparable wafers were produced using silver screen printing. The IV data were collected using an industrial measurement setup (LOANA, pv-tools) according to the categorization established by Rauer et al. [7], following the brn | grn, hrc classification. Table II presents the characteristic IV data for the best lasered, electroplated, and screen-printed solar cells. These results demonstrate that comparable efficiency can be achieved with the plated cell as with the standard screen printing process.

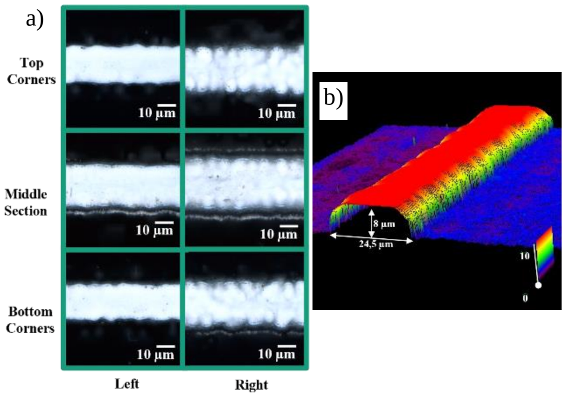

Figure 7: Result of the electroplating metallization process a) Collage of images taken at different positions on the wafer b) 3D magnification of a single contact line.

Table II: Comparison of silver screen printed (SP) and electroplated copper (plated) contacts in respective to the IV results.

	Eta [%]	Jsc [mA/cm²]	Voc [mV]	FF [%]
SP cell	22,7	40,2	707,2	80
Plated cell	22,8	40,2	697,7	84

4 CONCLUSIONS AND OUTLOOK

The presented on-the-fly laser micromachining concept enables application of laser contact openings with following achievements:

- The opening size is below 10 µm, exhibiting minimal ellipticity.
- Optical distortions are minimized in the central region of the scanner field.
- The LCO of continuous lines obtained meets the requisite standards for electroplating for M10 wafers.
- The resulting throughput is higher by a factor between 2x and 4x than that of other systems, depending on the scanned structure. However, the throughput is limited by the pattern and repetition rate of the laser, and thus, the theoretical maximum throughput is 31,500 wph, which is 40 times higher than that of the reference system.
- The new laser-contact opening method for metallizing M10 TOPCon wafers via electroplating achieves comparable efficiency to standard silver screen-printing with an equivalent grid layout.

This work has demonstrated that high throughput in a large wafer format (M10+) is achievable while maintaining a small opening size uniformly across the entire area. This approach overcomes the classical trade-off between speed, area, and structural quality, which was the primary motivation for developing the on-the-fly method and this setup.

To fully leverage the 1 km/s speed while maintaining the necessary pulse-to-pulse spacing for generating a continuous line, a laser operating at approximately 130 MHz would be needed. Even though this type of laser is unavailable yet; if it were accessible [8], the potential throughput could reach an impressive 31,500 wafers per hour. The upcoming work should include further benchmarking of this prototype with the state-of-the-art systems on M12 wafers and with different patterns.

6 REFERENCES

[1] M. Fischer, M. Woodhouse, P. Baliozian e J. Trube, International Technology Roadmap for Photovoltaic (ITRPV), Frankfurt am Main, Germany: VDMA e. V., 2023.

[2] Y. Zhang, M. Kim, L. Wang, P. Verlinden e B. Hallam, «Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption,» *Energy Environ. Sci.,* vol. 14, n. 11, pp. 5587-5610, 2021.

[3] S. Kluska, R. Haberstoh, B. Grübel, G. Cimiotti, C. Schmiga, A. A. Brand, A. Nägele, B. Steinhauser, M. Kamp, M. Passig, M. Sieber, D. Brunner e S. Fox, «Enabling savings in silver consumption and poly-Si thickness by integration of plated Ni/Cu/Ag contacts for bifacial TOPCon solar cells,» *Solar Energy Materials and Solar Cells,* 2022.

[4] G. Hoppe, E. Alvarez-Brito, G. Emanuel, J. Nekarda, M. Diehl, R. Preu e F. Meyer, «Overcoming Throughput Limitations of Laser Systems in Solar Cell Manufacturing via On-The-Fly Processing Using Polygon Scanners,» *Energy Tech (Energy Technology),* 2023.

[5] S. Klötzer e A. Streek, «Polygonscantechnik für Lasermikrobearbeitung,» in *Lasertagung Mittweida,* 2015.

[6] S. Kluska, B. Grübel, G. Cimiotti, C. Schmiga, H. Berg, A. Beinert, I. Kubitza, P. Müller e T. Voss, «Plated TOPCon solar cells & modules with reliable fracture stress and soldered module interconnection,» *EPJ Photovolt. (EPJ Photovoltaics),* vol. 12, p. 10, 2021.

[7] M. Rauer, A. Krieg, A. Fell, S. Pingel, N. Wöhrle, J. M. Greulich, S. Rein, M. C. Schubert e J. Hohl-Ebinger, «Assessing current-voltage measurements of busbarless solar cells,» *Solar Energy Materials and Solar Cells,* vol. 248, 2022.

[8] «UKP Workshop,» [Online]. Available: https://www.ultrakurzpulslaser.de/de/ukp-workshop/rueckblick/6--ukp-workshop.html.

This work has been supported by the German Federal Ministry of Economic Affairs and Climate Action under the project name Miracle (No.:03EE11487A).