Lasers in Manufacturing Conference 2021

Roll-to-roll laser processing of flexible devices

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Abstract

In the manufacturing of flexible thin-film devices precision, throughput, and machining quality on ever-smaller structures are playing an important role. The presentation will give a brief overview of different case studies where roll-to-roll laser processing achieve new dimensions in terms of precision, quality and process efficiency.
An example application is the ablation of thin-film layers for medical sensors. In this case, the on-the-fly laser ablation takes place by using an excimer laser and mask projection. The layout of the products is adaptable by various projection masks. The high-repetition rate of the excimer laser allows the production of up to 150 sensors per second.
Innovative laser micro processes paired with sophisticated machining concepts from 3D-Micromac fulfill exactly all requirements for such sensitive and advanced devices.

Keywords: roll-to-roll processing; laser micromachining; flexible thin-fim; solar cells; laser annealing; sensors

1. Introduction

Thin, lightweight and flexible - these features enable applications in numerous areas, such as consumer electronics, medical devices, photovoltaics and lighting. The steady growing demand for flexible devices requires new production processes for mass production.
Besides the production of thin-film devices on rigid substrates, the manufacturing of flexible substrates in a roll-to-roll (R2R) process is increasing. However realizing a micro production technology in a roll-to-roll system means transferring requirements known from process solutions for rigid substrates to a handling approach whose development has been dominated by mass production methods such as printing whilst also transferring processes to the therewith linked requirements such as reduced mechanical and thermal stability of the substrate material.

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In contrast to the stage-based systems where a single sheet is fixed onto a vacuum chuck, R2R tools have to transport the web material either continuously or in a step-and-repeat manner without elongating the material due to high values or sudden changes in web tension.

2. Laser micromachining and roll-to-roll processing: A winning combination

Roll-to-roll processes are a combination of the handling solution with the specific laser process. As the laser processes depend strongly on the actual task and material it is of high importance that the R2R tool provide a seamless integration of the laser sources and their respective beam paths. The following examples show a spectrum of possible applications.

- Excimer laser – Thin film ablation or annealing
- Nanosecond laser – Thin film annealing or cutting of metal substrates
- Ultrashort pulsed laser – thin film patterning or cutting of polymer substrates

Excimer lasers with their specific properties are oftentimes used when a homogenous exposure of an area combined with a short depth of absorption is required.
Nanosecond lasers are often used to ablate thicker layers in a short time because of the available laser power but oftentimes with compromises in the ablation quality due to the thermal load induced based on their pulse duration.

The advantage of ultrashort pulse lasers compared to nanosecond lasers lies in a considerable lower heat input into the material. This guarantees a much higher selectivity for the scribing process, because almost the entire pulse energy is used for the evaporation and ablation of the exposed material. There are no damages of the foil substrate. The bulging of the scribing edges is partly well with only a few ten nanometers. On the whole, the process window for the use of ultrashort pulsed lasers is sufficient to attain a stable ablation process. This is of particular importance with regard to the roll-to-roll laser structuring.

3. R2R processing of flexible thin-film solar cells

An application that is currently seeing a large movement towards lightweight roll-to-roll processing are thin film solar cells. Whilst not achieving comparable efficiencies as bulk silicon solar cells the reduction in weight opens new opportunities and use cases for this new type of photovoltaics. Advanced proprietary laser processes using ultrashort-pulsed lasers enable monolithic interconnection of solar cells to serially connected submodules. The laser process allows the digital customization of cell dimensions and electrical output of submodules. Thus, individual application requirements with consideration of the aesthetics of the cells can be fulfilled.

It is also a great example to show that on the first glance similar products may require completely different solutions for the implementation of laser processes. Depending on the basic design and process flow of solar cells 3D-Micromac has developed two different types of systems for the production of thin film solar cells.
The first type operates in a step & repeat mode. The web is stepped forward then fixed in its position. Cameras detect either the scribes from the previous step or laser scribes implemented earlier in production and align the next set of scribes to those. In the meantime another set of cameras performs a quality control of the previous scribes on width, separation distance and other characteristics. The laser scribes themselves are

carried out by a laser sources projected towards the web surface by a galvanometer scanner moving on a cross-web axis. Complex algorithms optimize the interaction between the scanners and axis to achieve the maximum throughput for any given solar module layout. This approach provides very high positioning accuracy of the scribes below ± 25 µm and a productivity of approximately 250,000 m²/a.

The second type operates in a continuous winding mode with process web speeds of up to 3 m/min. This tool has been designed for maximized throughput. It also uses multiple camera systems for alignment and quality control which, due to the continuous transport are located upfront and after the actual laser process. A cross axis to address the whole web width is not compatible with this approach, therefore multiple laser sources, beam paths and scanner systems were installed to cover the complete width. As this results in a rather complex setup the actual position accuracy is reduced to ± 75 µm. On the plus side this system enables production capacities exceeding 1,500,000 m²/a. Depending on the underlying deposition technology this solution was realized in atmosphere and vacuum.

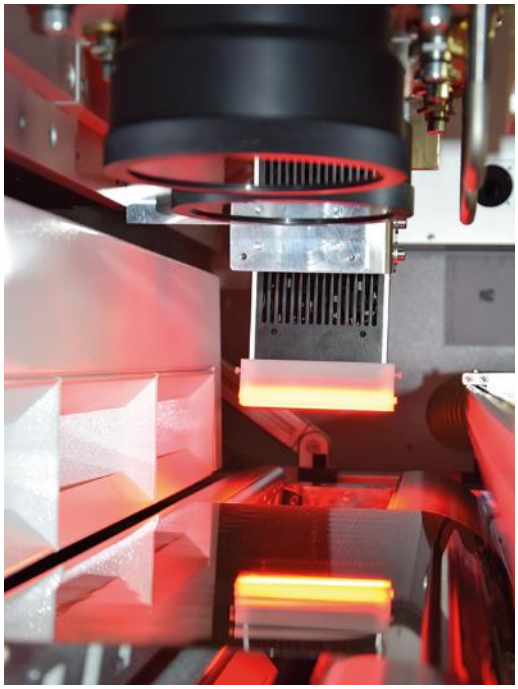

Fig. 1. Laser machining of flexible solar cells in a roll-to-roll (R2R) process for monolithic interconnection to serially connected submodules in P1, P2 and P3 process steps.

4. R2D laser annealing

An increasingly requested technology is the local or depth selective annealing of thin layers. Whereas typical request applications such as the laser based pinning of magnetic fields, the ohmic contact formation or dopant activation are typically conducted on wafer based substrates a first transfer to a flexible metal substrate has also been achieved.

The initial process was qualified on a sheet based process flow and needed to be improved in its overall

throughput. In order to realize the required throughput, two high power nanosecond laser sources were integrated. Their individual beam was shaped into a 75 mm long and less than 10 µm wide lines, while the overall homogeneity was kept above the a 90 % threshold, typically required for good annealing results. However this resulted in a very low depth-of-field potentially reducing the process stability. To compensate this a precise height measurement of the substrate in combination with a continuous adjustment of the focal plane during the movement of the laser lines over the substrate was implemented.
As reliability and yield of the system were of highest importance for the customer, the laser parameters and also the beam parameters had to be monitored constantly. A camera-based beam analyser was integrated to record beam parameters such as line width, energy distribution and edge steepness. Not only did the camera provide reliable data on the current condition of the beam but also long-time statistical data that was used to monitor the status of the beam-shaping optics.

The roll-to-roll web handling system formed the second piece of the upscaling efforts. As the laser lines were moved over the web substrate perpendicular to the web's transport direction, the web had to be transported in very precise steps so that subsequent line scans would form a fully annealed surface without gaps. Another important requirement was that web must not be touched on the silicon coated top-side at any time. To achieve highest precision and a positioning accuracy of <10 µm, a large driven vacuum drum was used for web transport.

5. Laser ablation for production of sensors

A further application for roll-to-roll processing is the laser ablation of thin-film layers for sensor manufacturing. Despite being limited to very narrow web widths below 50 mm an annual throughput of more than 500,000 m²/a can be achieved simply by very high web speeds up to 50 m/min.

The effect that is utilized to process this fast is the ablation of thin layers below 100 nm with one single laser pulse from an excimer source on comparably large area of approx. 45 mm x 15 mm. A positive side effect is that because of the ablation mechanisms at work the metal is selectively ablated from a polymer substrate without damaging it. The combination of an excimer laser source with a mask projection system resolves features down to 5 µm despite the large area exposed. The productivity of this ablation process scales with the available repletion rates of the laser sources which today can achieve up to 150 Hz meaning that 150 sensors per second can be produced. The high speed not only being a highly cost efficient process but also the risk that in case of a failure a lot waste is produced in a short time. A camera system for quality control based on pattern comparison was installed providing a 100 % quality control of the produced sensors – also resolving features in the range of 5 µm.

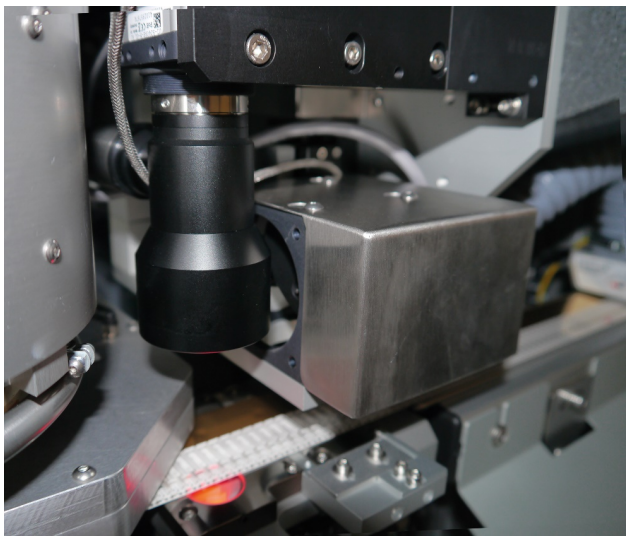

Fig. 2. A R2R machining area for the processing of flexible sensors using an excimer laser.

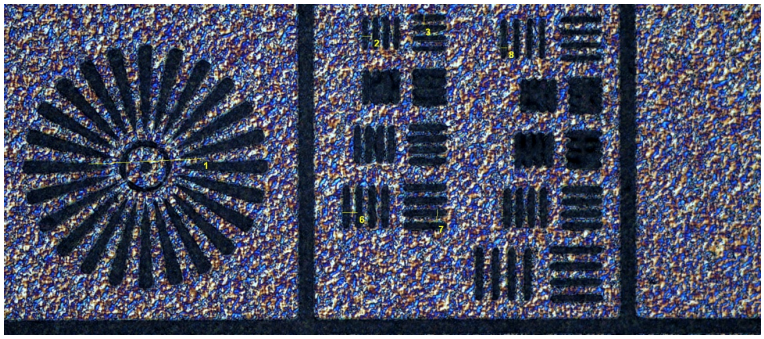

Fig. 3. A reference pattern for sensor manufacturing processed by excimer laser in a R2R process.

6. Requirements for laser-based R2R production equipment

The main aspect in the design of 3D-Micromac's new R2R platforms was the high-precision transport of the flexible web material so that the laser process could achieve the required accuracy. For narrow web widths up to 520 mm a solution was developed by use of a large diameter, direct-driven, precision manufactured main roller. At a diameter for 300 mm this roller featured perfectly machined surface with run-out below 10 µm. To achieve accurate acceleration, deceleration and positioning of the main roller, a highly integrated torque motor was chosen to act as the main drive in the tool. To minimize jerking of the web during acceleration and also to allow for low web tensions between 15 and 90 N at a web width of 520 mm, friction-reduced dancer rollers were installed. With all these features combined and a control scheme to take full advantage of the component's capabilities, a web transport accuracy of < 2 µm at a web speed of 6 m/min

could be achieved. That means the web is never more than 2 µm off its supposed position at any time, thereby providing an excellent basis for high-precision Laser processes.

For larger webs up to 1,500 mm two further platforms were developed mainly focusing on the challenges introduced by the increased web width, namely the weight of the coils and the waviness of the material. To reduce the impact of the waviness of the material several approaches have been tested and are available depending on the overall requirements of the laser process. Typical solutions are spreading rollers combined with either air bearings or vacuum units to introduce a cross tension into the web to flatten it down. A precise web tension control is also applied, typically with at least 2 tension zones that are controlled individually in the range between 30 N or 1000 N – depending on the substrate and its properties.

7. Conclusion

Roll-to-roll laser machining guarantees high throughput and large machining areas for the production of flexible devices. In order to achieve a cost reduction for the production of flexible devices, the machine technology needs to be reliable, sophisticated and scalable. The German based laser specialist 3D-Micromac AG develops and manufactures its microFLEX machines for roll-to-roll laser scribing since more than ten years. The integration of different laser sources and wavelengths, various optical setups allow the processing of thin-film devices on various substrates, such as metal foils, polymer and paper, with substrate width of up to 1,500 mm. Furthermore, 3D-Micromac offers the development and optimization of roll-to-roll laser processes and machines from the first idea to maturity for serial production in a close co-operation with the customer. All stages of the process and technology development, from preliminary tests to feasibility and the development of (functional) prototypes to contract manufacturing of the final devices are undertaken in 3D-Micromacs application lab.

Fig. 4. Example of the microFLEX platform for roll-to-roll laser processing.