Laser machining of thin films on top of flexible substrate carriers

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Abstract

Devices based on flexible thin film structures enjoy an increasing industrial focus especially in printed electronics and photovoltaic applications. The common results of the laser-structured layers demonstrate the important differences between laser types and laser parameters. Best results regarding smallest material layer damages will be obtained by ultra short laser pulses. Many of the emerging applications of ultra short laser pulses in material processing require high up to medium intensities depending on performance and quality. For example, micro machining of various material layers of flexible solar cells uses predominantly picosecond or femtosecond pulses to ablate material from surfaces without inducing changes to the underlying material. In general energies in the range of some ~10 µJ are needed in order to exceed typical ablation thresholds on a working spot size of 50 µm, allowing good process control and achieve high throughput.

But also laser machining with nanosecond laser pulses suits a lot of applications in printed electronics. Especially the removal of thicker layers requires other machining processes like structuring with nanosecond lasers to be competitive for a mass market solution.

The common used Roll-to-Roll systems offer the potential to meet the resulting demands of the industry by providing the optimized performance and cost-efficiency. Completed by an in line and on-the-fly laser processing the flexible thin film machining becomes even more efficient, including the digital automatic process from designing the structuring layout to the resulting laser treatment.

Introduction

The potential of an on-the-fly laser processing is shown at selected examples. The investigations of laser processing were done at thin films on top of flexible substrate carriers for electronic devices and at flexible solar cells. Ultra-short pulsed lasers are proven ideal for processing of heat sensitive thin films in a Roll-to-Roll application because of their short interaction with solid state bodies (nearly non-thermal ablation by energy-coupling into the electronic and not into the phononic system). Furthermore an interaction with the ablation plasma is nearly absent because of the lack of coincidence. All these facts lead to a minimum of stress at the borders of laser processing and generate a minimal heat affected zone. Therefore it is possible to perform steep edges at different kinds of materials with a maximum of precision. The utilization of ultra-short pulsed lasers allows also the processing of stacked thin film layers while delamination of single layers is reduced.

Structuring of flexible circuit tones

To make flexible electronics available for the mass market they have to be made in low-priced processes. Printed circuits on polymer base are by far cheaper than those made by chemical or physical precipitation processes electrical circuits. Hence it lends itself to superimpose these functional layers with conventional mass printing methods of a Roll-to-Roll process on the carrier material. Unfortunately there are technological process steps which are not or only with big effort covered by the common printing technologies. Those are for example the interconnection for producing double sided polymer circuit cards respectively film systems or the later directed override of the printed circuits by ablation of material without influencing the substrate. With the integration of a direct writing laser process the process steps which are not covered by conventional methods can be realised.

PEDOT

One example for printable conductive layer material on polymer base is PEDOT. This material has, by wavelengths between 330 and 1100 nm, a very low absorption which is insignificant higher than the common used PET carrier foil. This impedes a layer machining without influencing the substrate.

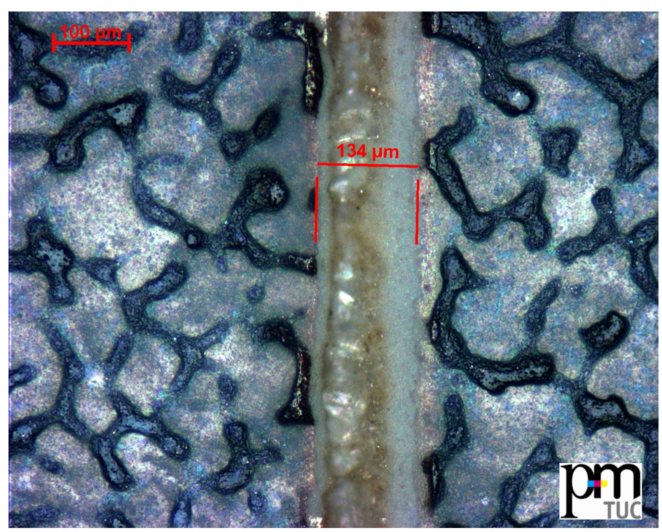

***Figure 1**. Structuring of PEDOT on paper (λ=355 nm, pulse duration 50 ns)*

Machining tests with different laser wavelengths (266…1064 nm) and pulse durations (12 ps…100 ns) on 2 µm thick polymer-layered PET substrates have been carried out. Firstly different lasers with 1064 nm wavelength and different pulse durations between 12 ps and 100 ns have been used. Because of the low absorption of the layers a damage of the substrate could be noticed, while no ablation of layers could be achieved. Based on these experiences tests with 355 nm wavelength have been done on the carrier substrates paper (Figure 1) and foil (Figure 2). Though the layer could completely be removed with pulse durations of 50 ns, the PET foil was damaged, too (blistering).

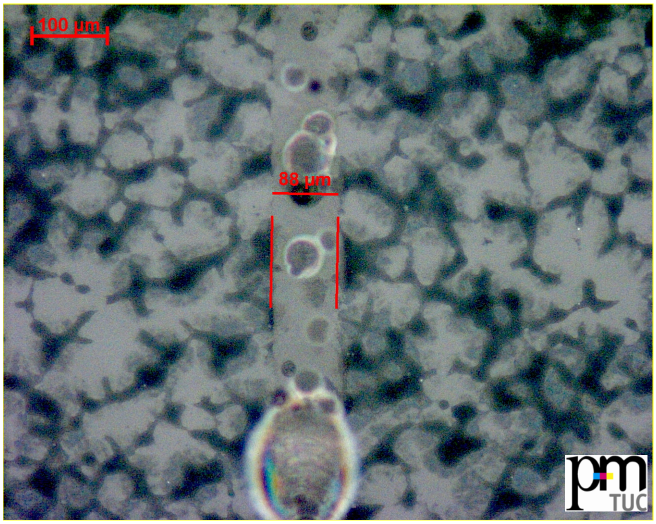

***Figure 2**. Structuring of PEDOT on foil (λ=355 nm, pulse duration 50 ns)*

The operation with ultra short-pulsed lasers (12 ps) achieves ablations of the top layer without blistering inside the foil. By using a laser fluence which allows an isolation of the polymer layer, a small amount (less than 10 µm) of substrate material has been removed. This rill is uncritical in various applications; e.g. when isolations between two conductive areas should be achieved. The cutting speed depends on the cutting geometry. Therewith a cutting speed of 5 m/s is possible by using a repetition rate of 640 kHz and generating a cutting width of 28 µm. Another raise of the cutting speed can be achieved by using lasers with higher repetition rate.

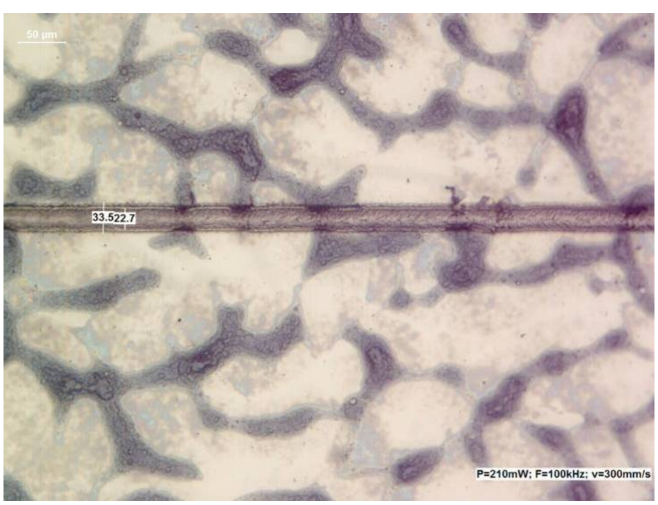

***Figure 3**. Structuring of PEDOT (λ = 266 nm, pulse duration 12 ps)*

Because of the extreme short interaction time per pulse with the material system, there is almost no heat input into the sample. Moreover there is a multiphoton absorption when there is enough photon density. Thereby the according transparent material layer on the surface can be ablated without damaging the substrate when ultra short-pulsed lasers are used. With the same optical setup and usage of ultra short-pulsed lasers considerably smaller cutting width of about 10 µm can be achieved, compared to 100 µm by lasers with pulse durations in the nanosecond area.

The depth of the rills in the substrate material could be reduced by downsizing the wavelength to 266 nm and pulse duration of 12 ps to ca. 2 µm (Figure 3). This results of the fact that the absorption of the PEDOT below 330 nm wavelength rises significantly. The disadvantage by using this wavelength is the lower available power in the, apart from that, same laser system as well as a higher effort for the optical system in that way that it is necessary to decide for every single application which wavelength suits the requirements best.

Aluminum

Beside the thin film structuring of polymer based material further investigations were done at metal layers on flexible substrates. The common antenna material for smart labels that operate in the ultra-high-frequency range is aluminum [1]. Therefore the structuring of a 10 micrometer layer of aluminum on a PET-substrate in a Roll-to-Roll process was investigated. The goal of cutting the aluminum layer without influencing the substrate was achieved by using a nanosecond-laser.

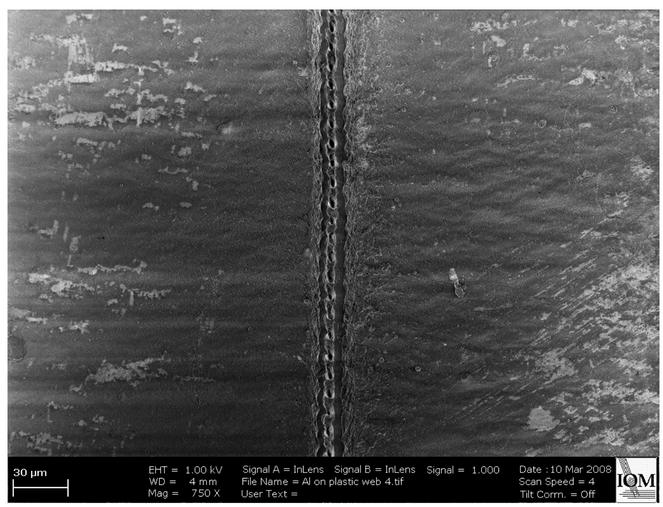

***Figure 4**. SEM-Picture of structured Al (λ = 355 nm; P = 12.8 W)*

The conductive area has been cut using = 355 nm within P = 12.8 W, at a cutting speed of 1 m/s (Figure 4). A further parameter optimization led to the result shown in Figure 5. The aluminum is completely removed out of the groove and a minimal ablation of PET-substrate at the bottom can be seen. That proofs a secure electrical isolation combining a minimal ablation of the substrate. The bulging on the cut edges refers to beam irregularities but the height of only a few micrometers is not high enough to create an electrical contact via the laser cut groove. According to the absorption of PET and Aluminum both materials are close together. Therefore a selective ablation is limited and substrate removal can be seen at the border of the conductive aluminum layer. According to the substrate layer thickness of 80 µm this fact is insignificantly but it can be further minimized by a more precise localization of the laser cut using an adequate image processing system.

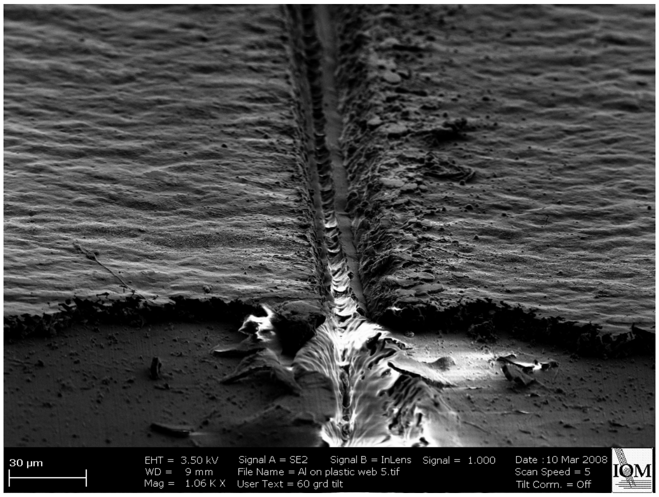

***Figure 5**. SEM-Picture of structured Al (λ = 355 nm; P = 12.8 W)*

Structuring of flexible CIS-solar cells

Based on the productivity of roll-to-roll processes it is also possible to use this method to produce flexible solar cells. Laser machining to establish CIS-solar cells is adequate, as a selective, less damaging ablation of photovoltaic film systems on CIS-base with ultra short-pulsed lasers is feasible (Figure 6). This has already been proved by 3D-Micromac in recent projects.

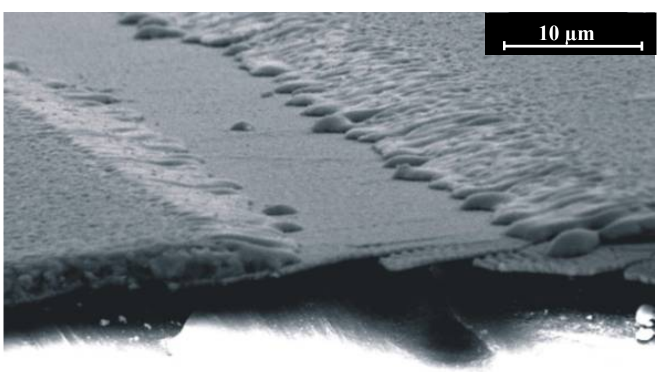

***Figure 6**. SEM-Picture of a structured CIS-solar cell*

Additionally an industrial process technology of picosecond laser micromachining up to 1.5 µm thick CIS-absorber layers on polyimide base has been developed. First above energies of about 1µJ a transaction of the CIS-layers can be noticed. The result is pictured in Figure 7 (process optimised) and in Figure 8 (efficiency optimised).

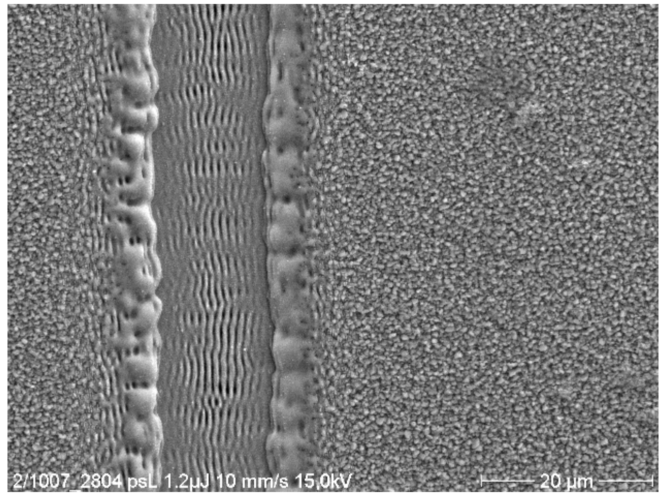

***Figure 7**. SEM-Picture of structured CIS (E = 1.2 µJ, v = 10 mm/s)*

The edges of the rills show variances in the micro structure which point that the absorber layer in this ca. 5 µm wide area was marginally melted and solidified afterwards.

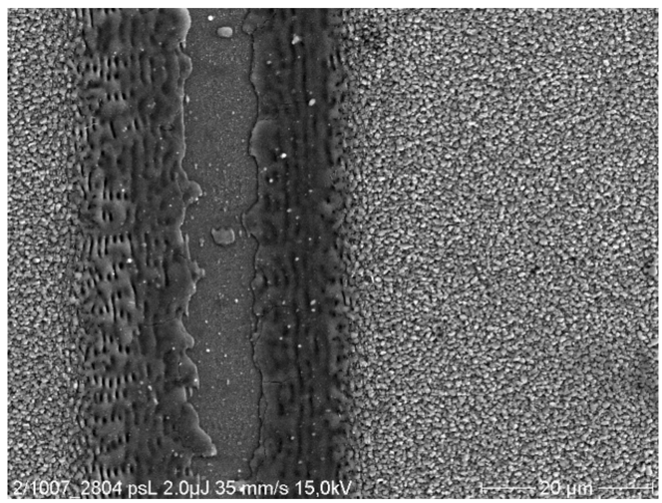

***Figure 8**. SEM-Picture of structured CIS (E = 2 µJ, v = 35 mm/s)*

Based on detailed researches using transmission electron microscopy of cross-section compounds (incl. energy dispersive X-ray) and Raman micro-spectroscopy the ablation selectivity could have been proved. Moreover the damage free machining, especially the cease of creating a function-damaging Cu_xSe phase, could have been documented.

Roll-to-roll standard machining tool

A standard machining tool for the roll-to-roll process is depicted in Figure 9. In this machine rolls up to 600 mm roll width and 100 kg roll weight can be handled. For damage-free winding and a continuously laser processing the substrate thickness should not be thinner than 50 µm (PET) or 100 µm (Paper).

***Figure 9**. Roll-to-roll standard laser machining tool for flexible substrates*

The on-the-fly work flow requires a combination of image processing of the moving substrate and the laser processing itself. Therefore the image grabbing is realized by a modified camera. By using this camera an automatic recognition of industrial used adjustment marks is realized. According to the knowledge of the web position a targeted laser processing is possible.

The illumination for image processing is realized by two separate light sources. Diffusers and other optical elements assure an optimal illumination level for opaque and transparent materials. The laser adjustment on the moving web is achieved by a permanent correction of the vector output of the laser scanner. The absence of an on-the-fly correction would generate distortions in the laser processed geometry. Therefore the vector output is controlled according to the web velocity.

The interaction of all these components enables a targeted on-the-fly laser processing of thin films on top of flexible carriers.

Conclusion

The laser machining on top of flexible substrates offers a high potential to printed electronics, photovoltaics, OLED- and smart card production and the machining tool can also be combined with inkjet technology and laminating processes. With the demonstrated technique a subsequent laser treatment can be combined with an on-the-fly machining in a roll-to-roll process. This method increases the throughput at a high quality level and the integration of different laser sources offers various machining opportunities. The best processing results for the structuring of PEDOT could have been achieved by using an ultra-short pulsed laser ($\lambda = 266$ nm, 12 ps). With this setup the substrate rills were minimized down to 2 µm. The picoseconds laser has also proven to be an appropriate method for the machining of CIS-solar cells. Especially the avoiding of a Cu_xSe phase has been shown and proven by detailed researches. For structuring the aluminum layer the nanosecond laser ($\lambda = 355$ nm, 50 ns) fits the application best. The rills were minimized but they are still deep beside the aluminum layer because of the similar absorption coefficients of PET and aluminum.

Acknowledgements

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Author Biography

Dipl.-Ing. Jens Hänel was born in 1966 and received his diploma in technical cybernetics / measurement and control at the University of Technology Leipzig, Germany in 1993. Since 1999 he is working in the field of research and development in laser micro machining. In 2002 he was appointed to the Chief Technology Officer in 3D-Micromac AG´s board of directors with main focus on R&D and quality management in the company.