Laser scribing of ITO and organic solar cells

Jens Hänel (haenel@3d-micromac.com), Bernd Keiper, Maurice Clair, Christian Scholz; 3D-Micromac AG; Chemnitz; Germany

Abstract

As advancements thin-film and flexible electronics like printed organic solar cells and organic LEDs bring these devices close to market entry new processing technologies for cost-effective, high quality production have to be developed. Laser technology provides a huge potential to fulfill the demanding tasks that come with the transition from lab to factory. 3D-Micromac looked into the possibilities of ultra-short pulsed lasers for scribing of transparent conductive layers as well as active layers of organic solar cells. This paper presents the results of this research.

Introduction

Thin-film and flexible electronics, especially OPVs and OLEDs, represent a growing market with excellent future prospects. Large progress has been made in the past years regarding efficiencies and manufacturing technologies. 3D-Micromac has put great effort into the laser structuring and scribing of transparent conductive oxide (TCO) materials such as indium tin oxide (ITO). Extensive trials have been conducted using ultra-short pulsed lasers of varying wavelengths in combination with different optical setups to achieve the best scribing results. While glass substrates were used as a starting point for our research, the focus has been shifted to flexible substrates such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) films. The advantage of these flexible materials is the possibility to use high volume printing processes for creating the stack layout which reduce overall production costs. Laser micro structuring is not limited to the transparent conductive layers however. It can also be used to scribe or modify the functional layers of a device. As our research targeted organic solar cells (OPV), we looked into the possibilities of laser micro machining of the light absorbing layer which consisted of a blend of poly(3-hexylthiophene) and phenyl-C61-butyric acid methyl ester (P3HT:PCBM) (see section "OPV layout" for further details).

Experimental setup

As stated before, we mainly used ultra-short pulsed lasers for our research. Extensive trials have been done with picosecond laser sources. The favored system generates pulses of 9 to 12 ps. The wavelength can be 1064 nm, 532 nm or 355 nm with a maximum average power of approx. 50 W (1064 nm, 1 MHz maximum pulse repetition rate). A second laser source generating femtosecond pulses was used to examine the influence of even shorter pulses and the positive effects they might have on the machining process. This laser emits pulses of 1064 nm or 532 nm with pulse durations as low as 254 fs. The maximum average power is approx. 10 W (1064nm, 600 kHz pulse repetition rate). As a comparison a nanosecond laser source operating at 1064 nm and emitting pulses of 120 ns was put to use.

Due to the long period of time during which the trials have been conducted the optical setup was modified several times. Basically a galvanometer scanning system combined with a f-Theta lens was used to process the substrates. Beam expanders have been used occasionally to widen the beam to allow for better focusability. The exception to this standard setup was the trial conducted with the femtosecond laser operating at 532 nm. As it was not possible to acquire a robust enough f-Theta lens in time, a fixed lens in combination with a x-y-stage was used instead.

The first part of our research concentrates on the scribing of ITO layers on glass and PET substrates. While the glass substrates came from a single source, ITO covered PET films from different suppliers have been examined.

As part of a german research project concentrating on flexible organic photovoltaics, active layers of P3HT:PCBM on top of a poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS) and ITO film system have been scribed. The goal was to ablate P3HT:PCBM and PEDOT:PSS without damaging the subjacent ITO (P2 scribe). While the ITO layer was sputtered onto the glass substrate, the PEDOT:PSS and P3HT:PCBM were spin-coated.

Results of ITO scribing

As a starting point we looked into the scribing of ITO layers on glass substrates. Standard nanosecond lasers did not yield acceptable results as the substrate showed cracks which weaken the substrate and have a negative impact on light transmission. Additionally the ITO layer tended to bulge several microns (see figure 1). This has to be avoided at all cost as the bulges may create interconnections between the following layers.

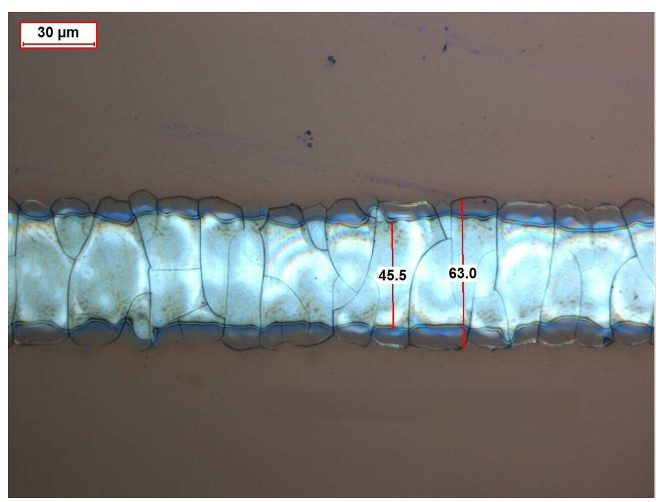

Figure 1. *Scribed ITO on glass substrate using a nanosecond laser (1064 nm)*

However excellent results were achieved using pico- and femtosecond lasers. The glass substrate remained completely undamaged and bulging of the ITO layer at the edge of the trench could be avoided (see figure 2). The wavelength 1064 nm proved to be the best choice though 532 nm and 355 nm can also be employed yielding comparable results. While the step from nano- to picosecond pulses has a great impact on the scribing quality, the transition from pico- to femtosecond pulses does not result in better scribing quality. There are no advantages that would compensate for the significantly higher cost of ownership for a femtosecond laser source.

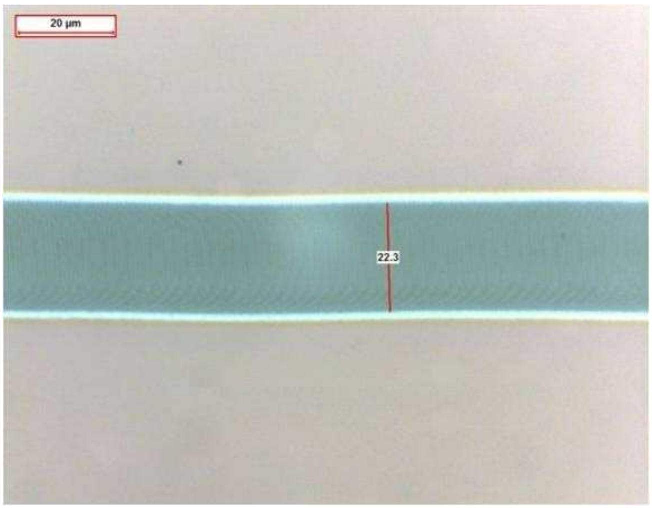

Figure 2. *Scribed ITO on glass substrate using a picosecond laser (1064 nm)*

As part of the research project some the substrates, structured with the picosecond laser source, were used to produce working organic solar cells. Photon conversion efficiencies of up to 2% were achieved this way.

Having demonstrated the possibility of laser scribing of ITO layers on glass substrates the next logical step was to advance to flexible substrates. PET film is currently the most common substrate due to the relatively low price though PEN film is used occasionally. Using the nanosecond laser the PET film was heavily damaged making it completely unfeasible for further processing (see figure 3).

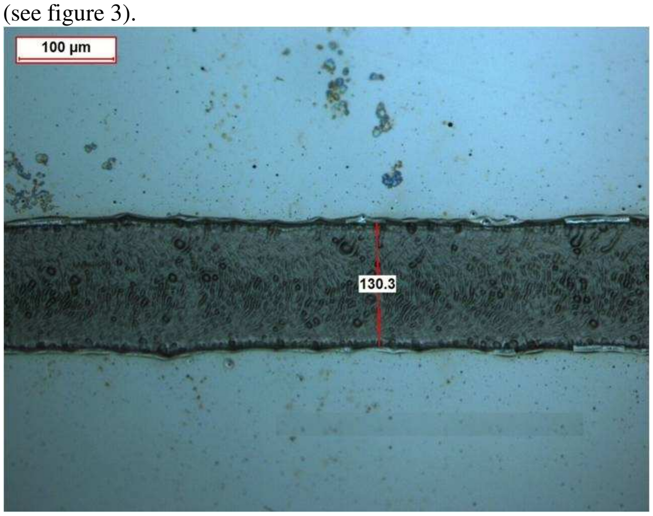

Figure 3. *Scribed ITO on PET film substrate using a nanosecond laser (1064 nm)*

Significantly better samples could be produced using the picosecond laser (see figure 4). Especially at 1064 nm very low bulging of ITO at the edge of the trenches could be observed. These bulges were as low as 20 nm which is acceptable in regard to further processing such as coating. Damages to the PET film substrate could not be completely avoided. Working organic solar cells could be produced using these substrates which achieved photon conversion efficiencies of up to 0.5%.

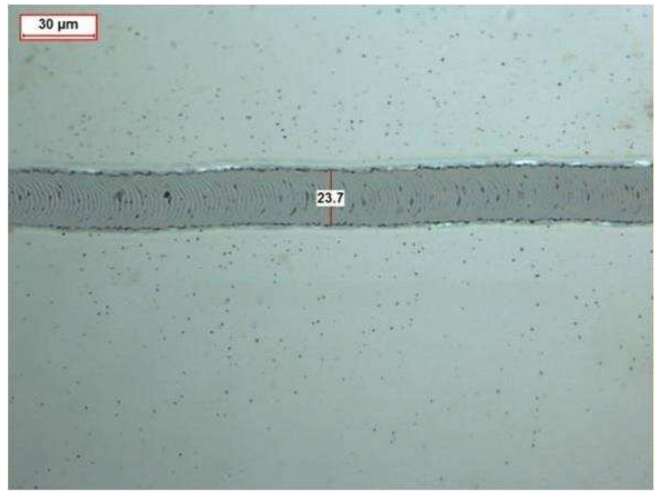

Figure 4. *Scribed ITO on PET film substrate using a picosecond laser (1064 nm)*

Comparable results could be achieved using 532 nm but there are no real advantages except for better focusability compared to 1064 nm. As PET shows high absorption in UV spectrum 355 nm proved to be the least favorable choice. Acceptable samples could be produced but the processing window was significantly narrower compared to 1064 nm and 532 nm making it more challenging to establish a safe machining process. Again focusability might be the only reason to use 355 nm for ITO scribing.

For future industrial applications it might be useful to be able to scribe the ITO layer from the backside through the PET film. Using 1064 nm it is possible to ablate the ITO without damaging the PET film more than with normal front side machining. However substrates of some suppliers showed significantly higher damage than others. This might be due to the exact material composition but needs further investigation.

In contrast to the results on glass the femtosecond laser operating at 1064 nm yielded a real improvement when machining ITO on PET film (see figure 5). The damage to the substrate could be further reduced and also the bulges could be reduced. As with the picosecond laser operating the femtosecond laser at 532 nm did not improve the results.

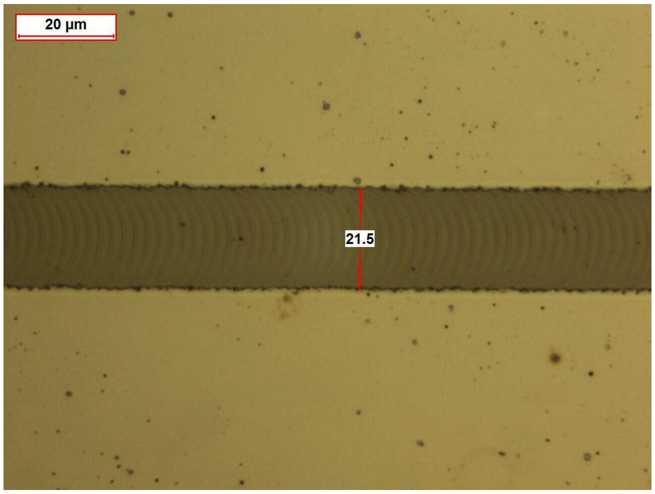

Figure 5. Scribed ITO on PET film substrate using a femtosecond laser (1064 nm)

Having produced several samples of structured ITO substrates which in turn could be used to produce working organic solar cells the next step was to look into the machining possibilities for the active layer of the solar cells. Scribing the active layer without damaging the subjacent conductive layer corresponds to the scribe commonly known as P2 for standard inorganic solar cells. For our solar cells the active layer is P3HT:PCBM though we also tried to ablate the subjacent PEDOT:PSS layer in order to decrease the electric resistivity between the ITO and the top electrode.

Ablating the P3HT:PCBM with the nanosecond laser resulted in heavy damage to the active layer which seemed to melt and burn. However the PEDOT:PSS could not be removed without removing the ITO in the process.

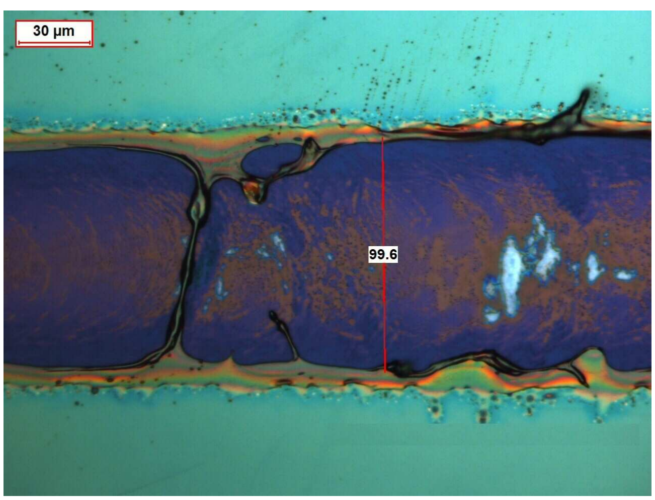

Figure 6. Scribed P3HT:PCBM and PEDOT:PSS on glass substrate using a nanosecond laser (1064 nm)

The picosecond laser operating at 1064 nm produces slightly better results but still the active layer was heavily damaged. This means that the pulse duration does not have such a significant impact on machining of the active layer as it has on machining of the ITO. The bulges of the active layer effectively prevent any further processing. Additionally the PEDOT:PSS could not be ablated without damaging or ablating the ITO.

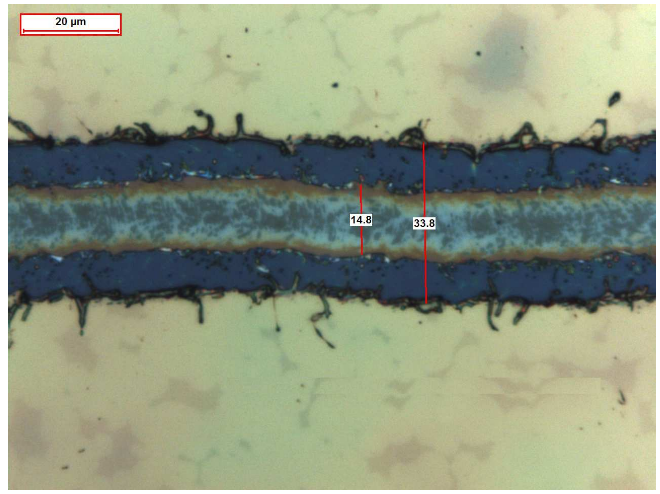

Figure 6. Scribed P3HT:PCBM and PEDOT:PSS on glass substrate using a picosecond laser (1064 nm)

As P3HT:PCBM shows high absorption in the visible spectrum, 532 nm was expected to be a better choice. Trials confirmed this expectation as figure 7 clearly demonstrates. Though the active layer shows slight changes on the edges of the trench, there is no burning of the P3HT:PCBM. Still the PEDOT:PSS cannot be removed without removing the ITO.

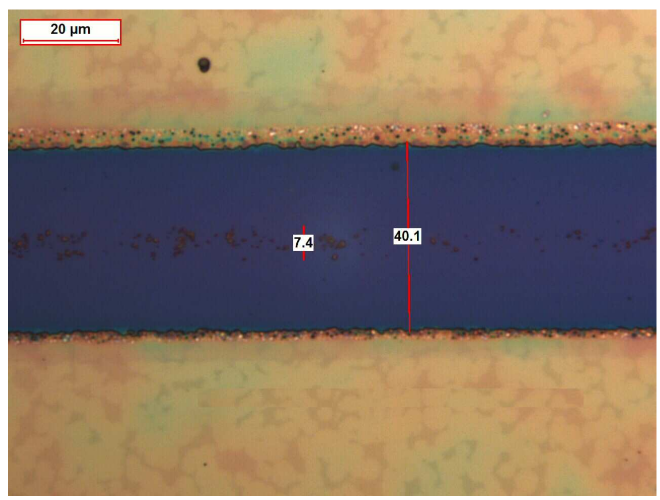

Figure 7. Scribed P3HT:PCBM and PEDOT:PSS on glass substrate using a picosecond laser (532 nm)

The last trials with the picosecond laser involved 355 nm. Using this wavelength results slightly better compared to 532 nm could be achieved (see figure 8). There are no visible changes in the active layer. However UV radiation damages the active layer so it is thinkable that 355 nm also leads to degradation of the areas surrounding the scribe but this has still to be confirmed. Removing the PEDOT:PSS is still not satisfying.

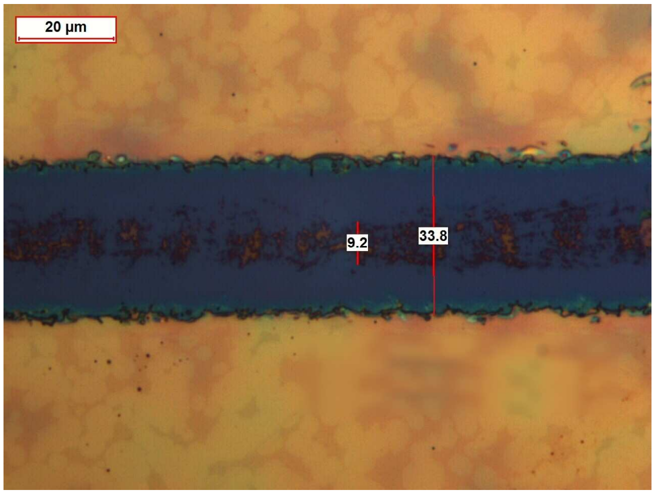

Figure 8. *Scribed P3HT:PCBM and PEDOT:PSS on glass substrate using a picosecond laser (355 nm)*

The results of femtosecond laser operating at 1064 nm are comparable to those of the picosecond laser as figure 9 shows. Again the P3HT:PCBM shows signs of burning and the PEDOT:PSS is either ablated together with the ITO or not at all.

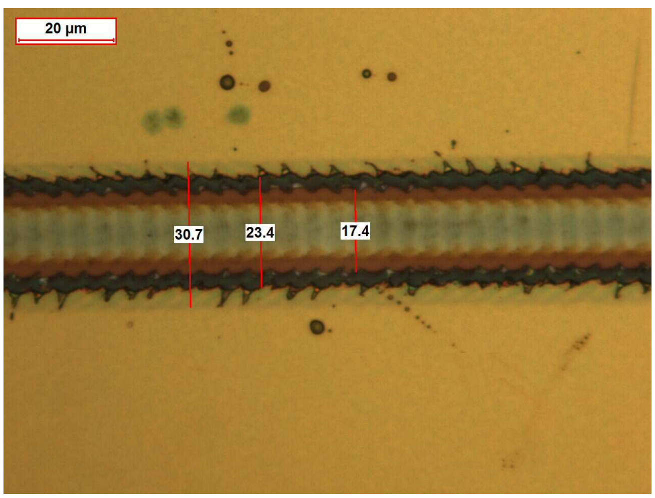

Figure 9. *Scribed P3HT:PCBM and PEDOT:PSS on glass substrate using a femtosecond laser (1064 nm)*

The best results so far concerning the ablation of the PEDOT:PSS layer could be achieved with the femtosecond laser operating at 532 nm. The process parameters are critical but manageable. As stated in the experimental setup section an x-y-stage had to be used. Further trials will be conducted to confirm that this had no fundamental influence on the scribing process.

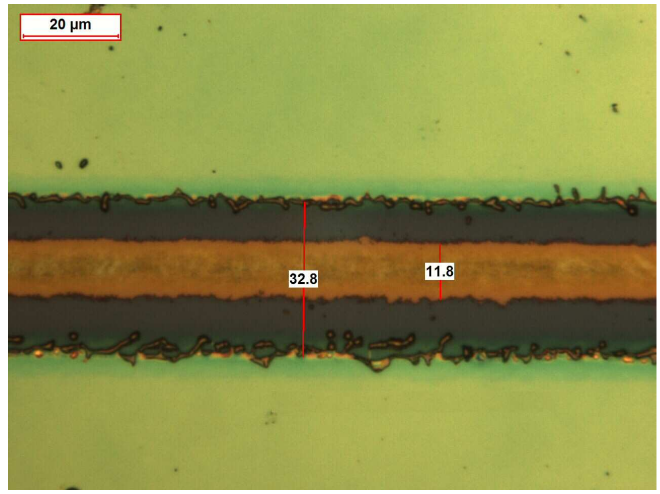

Figure 10. *Scribed P3HT:PCBM and PEDOT:PSS on glass substrate using a femtosecond laser (532 nm)*

Conclusion

It has been demonstrated that ultra-short pulsed lasers such as pico- and femtosecond lasers are well suited to the tasks of scribing of TCO and active layers. While nanosecond lasers significantly damage the substrates and the functional layers, ultra-short pulsed lasers can produce high quality samples. Scribing of ITO on glass substrates is generally uncritical and can be easily done using a picosecond laser with the common wavelength of 1064 nm. When it comes to flexible substrates such as PET, the picosecond laser with 1064 nm is a good choice again. While the femtosecond laser yields even better results it also comes with an increased cost of ownership which has to be taken into account.

For scribing of the active P3HT:PCBM of organic solar cells the wavelengths of 532 nm and 355 nm of the picosecond laser proved to be a good choice. However no satisfying solution for ablation of the PEDOT:PSS layer using the picosecond laser has been found so far. Only the femtosecond laser operating at 532 nm proved to be able to fulfill that task. However it remains to be seen if the PEDOT:PSS layer has a significant negative impact on the performance of the solar cell in case it is not or only partially removed.

Acknowledgements

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