Optical properties of a polymer film substrate after laser ablation of transparent conductors

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Abstract. In the article some aspects of laser processing of conductive and transparent film of ITO (indium tin oxide) layer on PET (polyethylene terephthalate) substrate are discussed. The optical properties of polymeric substrates after laser ablation of an ITO layer was the main subject of these studies. Determination of conditions of the laser treatment without damage of polymer substrate was the purpose of presented investigation. The influence of a scanning speed, duration and energy of laser pulses on the results of interaction of nanosecond fiber laser on ITO film have been presented. Optical properties of PET substrate after laser ablation of ITO layer have been estimated by measurements of a spectral transmission coefficient and microscopic examinations. The process parameters window for completely ablation of ITO layer without damage of the polymer substrate was established.

1. Introduction
Due to its high optical transparency, flexibility and good electrical conductivity ITO (indium tin oxide) is widely used as a transparent electrode in plastic-based flat-panel displays [1]. Transparent conductors are also applied for optoelectronic devices, such as organic light-emitting diodes (OLEDs), photovoltaic structures and touch screens [2]. It was shown that structures patterned in transparent conductive film can be seen suitable for passive elements and sensors in cryogenic systems [3,4]. Invisible joule heaters are the special applications of transparent conductors [5]. Some technologies well known from microelectronics, such as photolithography and subsequent wet etching or plasma dry etching, are used in the fabrication of components and circuits in the ITO layer [6-8]. Over last 20 years laser technologies for patterning of elements in ITO layers are developing rapidly. Laser Direct Writing (LDW) methods in nanometer thick films of ITO are used in the manufacture of flexible electronic circuits and sensors on the sub-millimeter scale [9]. Laser direct writing was applied among other to electrode patterning for flat panel displays [10], electrode isolation in ITO layer in touch panels of mobile phones [11], for source and drain electrodes patterned in ITO in pentacene thin film transistor (TFT) [12], fabricating a miniature transparent gas flow meter [13]. It is well known that laser processing of layers of nanometer thickness can be performed using laser beams of short wavelength and short pulse duration. Patterning of ITO thin films was performed using laser beam pulses of ultraviolet to infrared wavelength of picosecond, femtosecond or nanosecond duration [14-
Thin ITO layers and transparent substrate (PET) have similar ablation threshold fluence, therefore laser processing should be very carefully performed to polymer substrate damages be avoided.

The main goal of our former research was to study the possibility of producing structures of possible smallest dimensions while maintaining acceptable quality [3-5,9]. We have shown that the LDW method by nanosecond laser ablation ensures good conditions for prototyping structures with very high pattern fidelity [3-5,9]. In a present research, we focused on the optical properties of the substrate caused by the ablation of the ITO conductive layer, as the polymer (PET) layer should remain transparent and not damaged by laser processing.

2. Experiments

Research was carried out using transparent conductive ITO layer on polyethylene terephthalate (PET) foil. Laser micro-treatment was performed by single mode Red Energy G 20 SM (SPI) fiber laser that generate beam of 1060 nm wavelength. Laser beam was focused to spot of diameter of 26 µm by a F-theta objective (GEOMATEC, focal length 160 mm). Ablation of the area of the desired shape and size was obtained by scanning the laser beam along lines shifted by 10 m using a Xtreme beam scanner, (NutfieldTechn. Inc.). Ablation process was controlled by software Waverunner (Nexlase).

The experiments were performed using varied duration of laser pulses in the range of 15–35 ns and repetition frequency from 290–80 kHz. The evaluation of the preliminary research results showed that the best ablation effects were obtained with the use of pulses with the shortest duration of 15 ns. During next experiments repetition frequency, scanning speed and average power of laser beam were varied. The main goal of research was to remove the ITO layer without damaging the substrate and without worsening the transmittance.

Optical properties of PET substrate after laser ablation of ITO layer have been estimated by measurements of a spectral transmission coefficient and by microscopic examinations. The transmission coefficient was defined as the average value measured in 5 points on each sample. Microscopic observations were performed using an optical microscope. The following apparatus was used to measure the optical transmittance of the PET substrate after ablation of the ITO layer:

- HR4000 spectrometer that allows to record radiation in the range of 200 - 1100 nm,
- two optical fibers cables with a core diameter of 400 µm,
- holder with collimating lenses, enabling the attachment of optical fibers and holding the sample
- a source of optical radiation, consisting of a deuterium lamp and a halogen lamp, emitting radiation in the range of ~ 250 - 1000 nm.

The radiation emitted by the deuterium and halogen lamps was directed via the optical fiber onto the flat surface of the sample. The end of the second optical fiber led the $D(\lambda)$ radiation to the spectrometer cooperating with a PC. The radiation, measured with the test sample taken out, has been the reference level $R(\lambda)$. The background level $D(\lambda)$ was also measured.

The transmittance was calculated using the equation (*) [18]:

$$ T(\lambda) = \frac{S(\lambda) - D(\lambda)}{R(\lambda) - D(\lambda)} \quad (*) $$

where:

- $R(\lambda)$ – reference radiation, emitted by a deuterium and halogen lamp,
- $S(\lambda)$ – radiation transmitted through the test sample,
- $D(\lambda)$ – signal recorded by the spectrometer in the absence of radiation emission by the deuterium and halogen lamp.

3. Optical properties of substrates after laser ablation

Plots of transmittance $T(\lambda)$ and microscopic pictures for selected laser ablation parameters are shown in figure 1, figure 2 and figure 3.
Figure 1. Influence of laser beam power on optical transmittance of the substrate, $f_{\text{rep}}=290$ kHz; $v_{\text{scan}}=4000$ mm/s: a – 6 W; b – 5 W; c – 3 W

Figure 2. Influence of laser beam power on optical transmittance of the substrate, $f_{\text{rep}}=80$ kHz; $v_{\text{scan}}=1500$ mm/s: a – 4 W; b – 3 W; c – 2.5 W
Figure 3. Microscopic pictures of PET substrate surface after ITO layer ablation in high magnification

Figure 4. Influence of extreme power of laser beam on substrate optical transmittance, $f_{\text{rep}}=290$ kHz; $v_{\text{scan}}=4000$ mm/s: a – 8 W; b – 10 W; c – 12 W; 1 - optimal process conditions - 4 W

4. Discussion and conclusions
The microscopic images shown in figure 1 and figure 2 confirm that at a certain value of the average power of the laser beam, complete removal of the ITO layer takes place (figure 1a, figure 2a). The lower value of the laser beam power does not allow to achieve complete removal of the ITO layer (figure 1b, figure 2b). The effects of further reducing the power of the laser beam are shown in figure 1c and figure 2c. There are clear traces of ablation paths smaller than the diameter of the laser spot. The comparison of figure 1b and figure 2b shows that a more effective ablation occurs with a high pulse repetition frequency.

Plots of transmittance $T(\lambda)$ (figure 1 and figure 2) are consistent with the above observations. The total ablation of the ITO layer over the entire spectral range increases the transparency of the polymer
substrate in relation to the ITO layer, while the $T(\lambda)$ curve is typical for PET. Incomplete ablation lowers the transmittance value, and the nature of the $T(\lambda)$ relationship indicates the optical properties similar to the ITO layer (figure 1c, figure 2c). However, in this case the transmittance value is lower than for the ITO layer. The justification for this fact is shown by microscopic examinations. carried out at high magnification and examining the surface profile of the substrate (figure 3). As a result of the overlapping of successive pulses and adjacent scan lines in the polymer substrate, which undergoes slight ablation, grooves with a small depth of several dozen nanometers have been formed. These pits may cause local scattering or interference of the incident radiation and lower transmittance value.

Interesting results were obtained with ablation with a beam with a power greater than optimal (figure 4). The ITO layer has been completely removed, however, damage and gas bubbles appear inside the polymer substrate, indicating local degradation of the polymer. The damage density increases with increasing the power of the laser beam, which contributes to the reduction of optical transmission over the entire spectrum.

Studies have shown that using of nanosecond pulses of fiber laser (1062 nm) is possible to completely ablate the ITO layer on the PET substrate. The window process parameters is consisted of a small range of the average beam power, between incomplete removal of the ITO layer and the formation of internal damage in the polymer substrate. Under the optimal conditions of the process, the polymeric substrate maintains excellent optical transparency.

5. References

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