Direct write patterning of ITO film by Femtosecond laser ablations

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Abstract
Indium tin oxide (ITO) is a commonly used conducting transparent oxide film (CTO) used in flat panel display applications. Direct write laser ablation is sometimes employed for ITO patterning and it is important that the substrate material and remaining ITO be affected as little as possible by the laser ablation. In this investigation, femtosecond laser ablation of ITO was studied to identify laser processing parameters which cleanly ablated ITO with a minimum of damage to a glass substrate and surrounding ITO. The Ti:Sapphire chirp pulse amplified femtosecond laser used for the experiments had a wavelength of 775nm and produced pulses with a duration of 150fs at a rate of 2 kHz. Ablation was carried out at a sufficiently high panel scanning speed that single ablation spots could be studied. The pulse energy was adjusted to determine feasible spot diameters and depths which could be ablated into the ITO without damaging the glass substrate. Next, ablation of lines without glass damage was also demonstrated. Experiments were also performed with a high repetition rate (100kHz) femtosecond laser.

1. Introduction
Indium oxide doped with tin oxide, usually referred to as indium tin oxide or ITO, is a material that provides high electrical conductivity and transparency in the visible and near IR (Infrared) wavelengths. ITO has been widely used in the fabrication of low current electronic applications such as liquid crystal display (LCD) and other display panels. In thin-film transistor TFT-LCD displays, ITO functions as a transparent electrode, so that voltage control can change polarization angle of the liquid crystal in a display element. Various deposition technologies have been developed for ITO films. Reactive evaporation, thermal evaporation, electron-beam evaporation, activated reactive evaporation and vacuum sputtering evaporation are common technologies in use. Among these processes, vacuum sputtering method is one of the most extensively used techniques for the deposition of ITO films in industries. The optical properties are typically determined by sputtering parameters (oxygen content) in the sputtering gas, target to substrate distance, substrate temperature, post-deposition treatment, film thickness, and target quality including its density and purity [1]. Even though carrier density is lower than the electron density in typical metals, the charge carriers in ITO are highly mobile which means they can travel through the material with relatively longer mean free path. By choosing the right density of tin doping, ITO can be highly effective for display panel applications.

Direct write laser ablation has been studied for patterning of ITO on glass and other substrates, primarily for repair applications. Nd:YAG and Xenon lasers have been used for ablation, but turned out to be ineffective in removing ITO due to its transparency at visible wavelengths[2]. UV lasers such as Excimer lasers can be efficiently used in ITO machining, although the glass substrates can also absorb UV wavelengths. Frequency doubled Nd:YAG lasers are widely used for removing ITO in thin film transistor LCDs. However, this technology is also limited in penetration depth. Xenon laser is another choice of material removal for LCD repair work for aluminum and chrome [2]. The optical and electrical properties are important for both applications and for laser processing of ITO films, and numerous investigations have been done in this area. Screenivas *et al* studied the optical transmission based on different RF deposition environments [3].

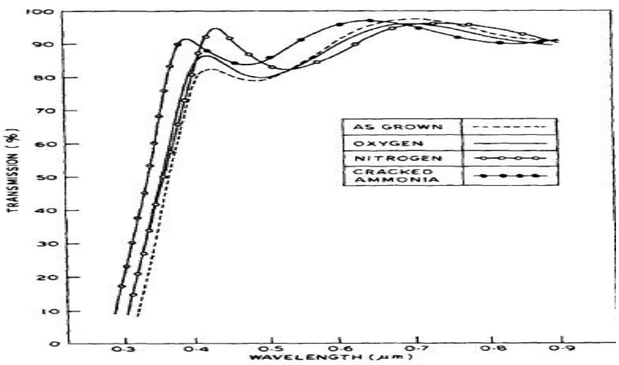

Figure 1 Optical transmission change with different deposition environment [3]

The ultimate goal of laser ablation is to remove unwanted ITO cleanly while retaining the optical and/or other properties of the substrate. Since femtosecond laser radiation has been widely studied for similar applications, it is interesting to investigate its use in ITO ablation. The desirable ablation characteristics of femtosecond pulses arise from the fact that the pulse length - typically on the order of 100 fs for commercially-available lasers - is much shorter than time required for the energy absorbed by free and/or valence electrons to be transferred to the material lattice (usually picoseconds). This, combined with the extremely high power densities in the irradiated area, cause the absorbing material to be ionized and to expand rapidly away from the surface, leaving a relatively small amount of thermal energy in the remaining surface. This non-thermal ablation affect minimizes thermally- induced defects which are difficult to avoid with long pulse lasers. In this paper, we describe the results of ablation of ITO using a femtosecond pulsed laser. The details of the experimental setup are explained and optimum ablation process parameters are determined, based on atomic force microscope (AFM) characterization of the ablation results.

2. Experiments

A schematic diagram of experimental setup is presented in Figure 2. Frequency-doubled pulses from a mode-locked erbium-doped fiber laser are intensified in a Ti:Al2O3 regenerative amplifier laser was used for this experiment. The 1.6 W average output power of the laser and the laser beam profile were optimized at a 2000 Hz pulse repetition rate. The output power was adjusted in two stages. The majority of the attenuation is at the first thin-film polarizing beam splitter, where only a couple percent of the optical power passes through to a ½ waveplate. The beam polarization is adjusted by rotation of this optical element, allowing the additional attenuation at the second polarizing beam splitter to be adjusted. The attenuated laser beam power can be switched on and off by a mechanical shutter and focused on the material after propagating along a beam delivery mirror train. A 25mm achromatic lens and a 10x microscope objective were the focusing optics used in the experiments. To accurately measure processing power before experiments, a power meter inserted after the focusing lens.

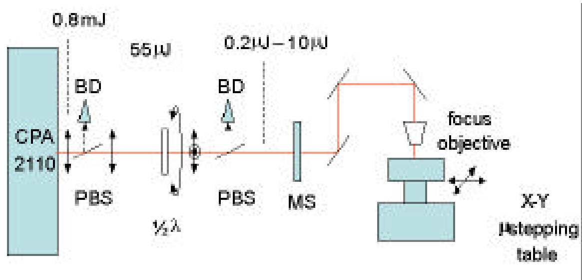

Figure 2 System configuration

The 10x microscope lens had a working distance of approximately 5mm and sufficiently wide aperture to accept the laser beam. The maximum beam power was limited at 20 mW to avoid damaging this optic. The calculated minimum diameter produced by this optic was approximately 2.5 μm, and the resulting laser fluence used for the experiments was between 5 J/cm^2 and 25 J/cm^2. The 25mm focal length achromatic lens was anti-reflection coated to minimize reflection and can accommodate higher energy. The calculated minimum focus diameter for this lens was approximately 7.5 μm.

Processing was done by scanning the focus spot over the material surface at speeds ranging from 1.5 to 20 mm s^{-1} and laser powers ranging from 0.1mW to 6mW. At the 2 kHz pulse repetition frequency, these powers correspond to pulses energies of 50nJ to 3000nJ. At the higher speeds, the ablation spots were not over-lapped and the single-spot ablation performance could be assessed. The ablation dimension measurements were done in an Atomic Force Microscope (AFM) stage.

3. Results and Discussion

3.1 Ablation diameter and depth

Figure 3 shows the single spot ablation diameter produced by the 10x microscope objective lens as laser fluence increased. The maximum diameter was found to be 2.5µm and a minimum diameter of 800nm was achievable.

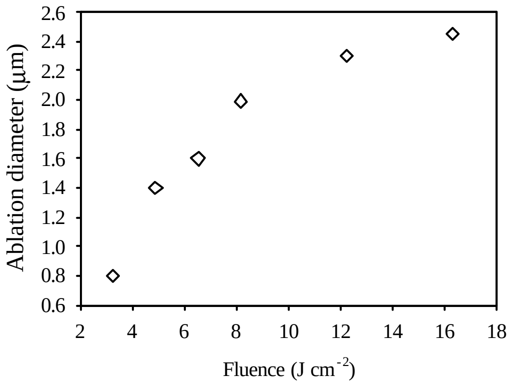

Figure 3 Ablation diameter with 10x objective lens

Figure 4 shows the experimental results with 25.4mm achromatic lens.

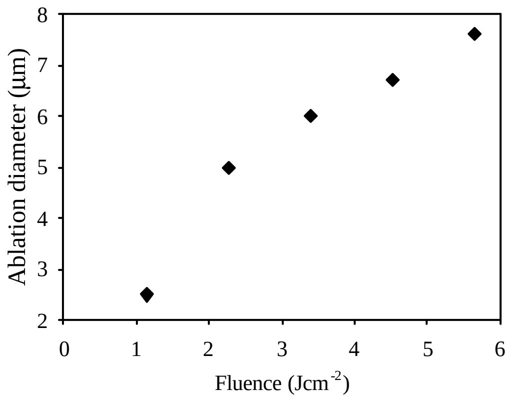

Figure 4 Ablation diameter with 25.4 mm achromatic lens

The ablation diameter ranges between 2.5 µm and 8µm, and input laser fluence was varied between 1 J cm^{-2} and 6 J/cm^2. Figure 5 shows the ablation depth with respect to laser fluence with the 25mm achromatic focus lens. The threshold fluence for detectable single-pulse ablation was approximately 0.9 J/cm^2 and the minimum laser fluence which was required to completely ablate the 150 nm layer of ITO was 2.3 J/cm^2. As shown in the figure, the ablation depth did not vary much in the fluence range between 2.3 J/cm^2 and 4.5 J/cm^2. However, when the laser fluence exceeded 5 J/cm^2, the ablation depth began to increase again. Based on these results, one could conclude that the minimum energy required to completely ablate the 150 nm ITO layer was 2.3 J/cm and maximum energy that ablated the ITO with minimum ablation of the glass substrate was 4.5 J/cm^2

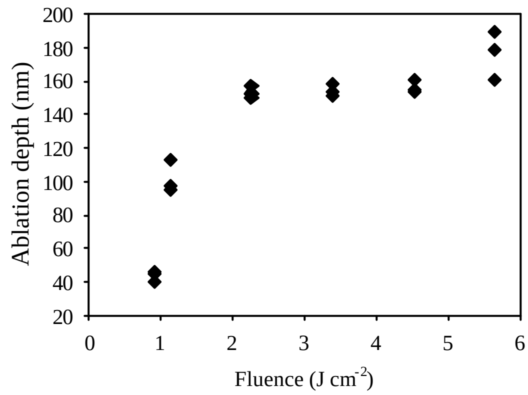

Figure 5 Ablation depth (25.4mm achromatic lens)

Figure 6, shows a typical profile of the ITO surface after laser ablation as a scanning speed the produced approximately 25% spot overlap. The ablated surface was reasonably smooth and no specific defects are found at overlapped area. Ridges of recast material were located along the edges of the ablated line and surface profile of this recast was not as uniform as the line depth or the un-ablated surface. The average recast material height was measured between 20 nm and 100 nm relative to the un-ablated ITO surface. Some additional amounts of re-deposited material were also noted further from the edge of the ablated line.

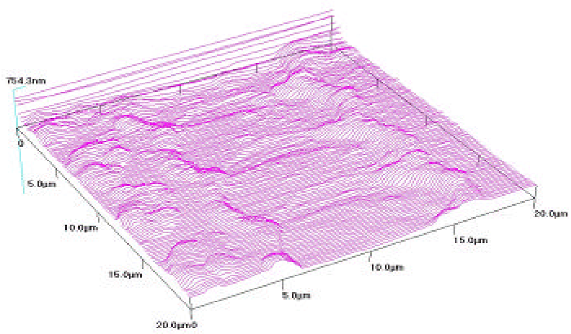

Figure 6 Surface profile of laser ablation (25.4mm achromatic lens - 5.7J/cm^2 Traveling speed: 20mm/s)

Similar experiments were done with the 10x microscope objective focusing lens, and results are shown in Figure 7. In this experiment, it was found that the feasible ablation range was between 6.5 J/cm^2 and 16.3 J/cm^2. Unlike the case with the 25.4 mm lens, no minimum fluence for ablation was found.

Also, the feasible fluence range for full ablation of the ITO layer was found to be higher than that for the 25.4 mm focal achromatic lens. This fact indicates that some energy may be lost through to the substrate. The energy deposited on the substrate is attenuated after ablating the ITO on the top. The remaining energy is not enough to ablate the substrate.

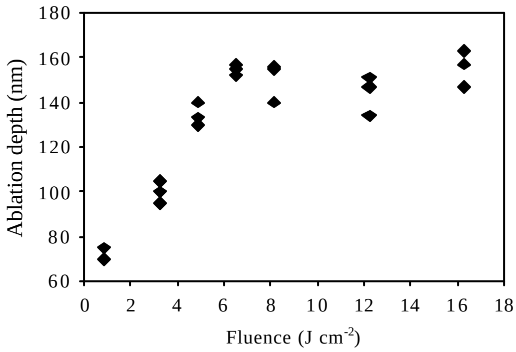

Figure 7 Ablation depth (10x objective lens)

The surface profile of the ablated spots was also measured by AFM scanning. The 3D profile and a cross section of an ablation hole are presented in Figure 8. The hole shape generally has straighter sides than holes made with the achromatic lens, but the recast ridge height was also generally higher than results with the achromatic lens.

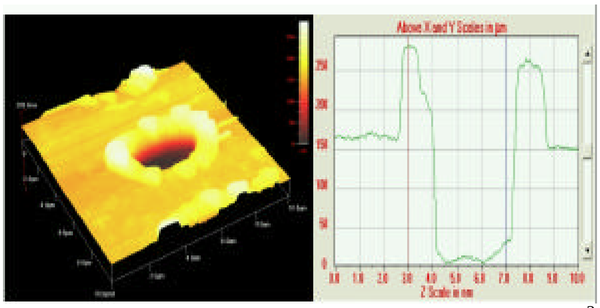

Figure 8 Surface profile (10x objective lens-8.1 J/cm^2)

3.2 Ablation threshold for manufacturing

The ablation characteristics of the soda-lime glass substrate are also of interest for this research. For this experiment, the 10x objective focusing lens was used to focus the laser beam onto the uncoated substrate. As shown in Figure 9, ablation was detectable at fluence above approximately 4.9J/cm^2. As laser fluence increased above this level, the ablation depth also increased although the rate of increased was slower and the depth increase was nearly saturated at a fluence of 16.3 J/cm^2.

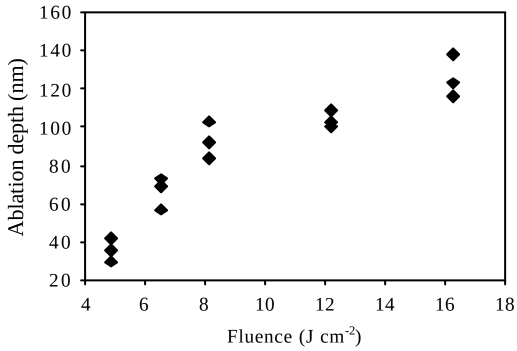

Figure 9 Glass ablation threshold

Based on experimental data, one might initially conclude that a feasible range of process operating fluence where ITO is ablated but the substrate is not damaged is minimal. Figure 10 compares the ablation depths for ITO and uncoated glass using the 10x microscope objective lens. Note that at according to this data, at fluence below about 5 J/cm^2, the glass is not damaged and we can likely perform multiple pulse ablation of ITO without substrate damage. However, this "worst-case" assessment of the data neglects the fact that, in the actual ablation process carried out at low fluence, the bulk of the laser energy is absorbed and subsequently removed along with the ITO material. Therefore, the glass is not substantially ablated until fluence greater than 25 J cm^{-2} is applied. Based on the minimum fluence that produces detectable ablation in glass, it might be concluded that, at 25 J/cm^2 applied fluence, approximately 5 J cm^{-2} is incident on the glass surface and that the energy contained in the ablated ITO is at most 20 J cm^{-2} or about 1 μJ of energy within the ablated volume of ITO. Thermal properties of ITO films are difficult to locate in the literature, but it seems evident that this energy content would correspond to a very high temperature.

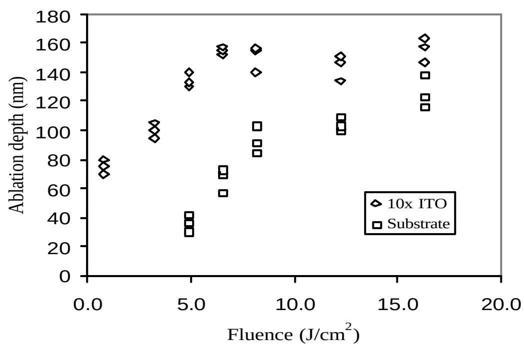

Figure 10 Manufacturing threshold

One can conclude from the single pulse results that there lines can be ablated in ITO by a multiple-pulse process or a single-pulse process. For example, at laser fluence of 1.3 J/cm^2, the ablation depth is 70nm. One can estimate that 2~3 laser pulses will completely remove the ITO without damaging the substrate. For ablating lines, three-pulse ablation implies that at least 67% of overlap would be required to ensure that three pulses are incident on the ITO at all locations. Figure 11 shows an example of multipulse ablation at low energy fluence. At fluence above 10 J/cm^2, a single pulse will ensure that ablation depth is 150 nm. With single pulses, we can maximize the travel speed. However, there is a risk that the surface of the substrate may be damaged.

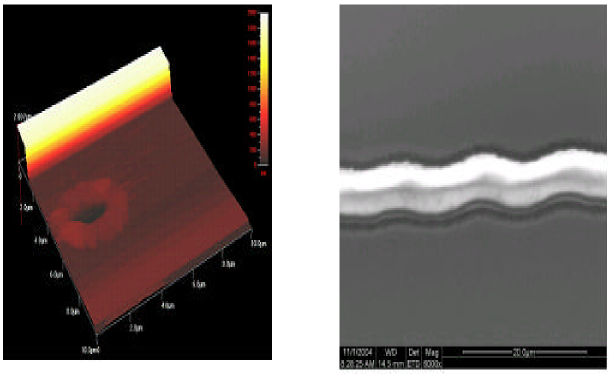

Figure 11 Multipulse ablation at low energy fluence (6.4 J/cm^2 with 1.55mm/s) stationary (left) and travel (right)

It is well known that ablation shapes differ depending on optical and mechanical properties of material. The shape of the single pulse ablation holes in both ITO and glass were studied. Figure 12 shows the different shapes for the two materials. ITO is basically a semiconducting material that has some number of free electrons to initiate an ionization avalanche. Once the central region of the resulting plasma reaches a critical electron density, it will reflect additional laser energy. This will tend to cause the ITO ablation crater to appear as a flat-bottomed cylinder. In glass substrate ablation, the spatial variation of the laser intensity can create a spatially varying refractive index in substrate. Since the beam intensity distribution is close to a Gaussian profile, the index of refraction is also larger towards to the center of the beam. As a result, the glass has a lens-like effect that tends to produce self-focusing of the laser beam. This self-focusing effect may have some relationship to the curved, almost Gaussian profile measured in the glass single ablation craters.

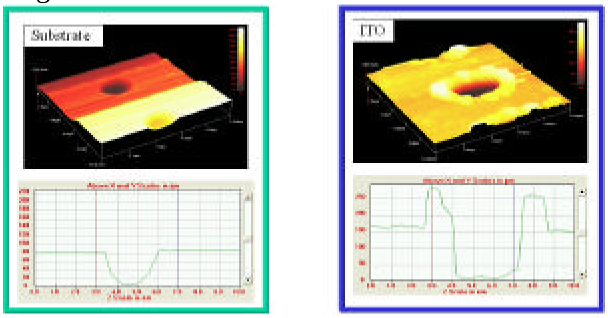

Figure 12 Ablation shape (Fluence:12.7 J/cm^2)

3.3 High repetition rate laser

High repetition rate chirp-pulse amplified femtosecond lasers are available on the market and experiments were performed with one such laser (IMRA FCPA *mJewel*). Figure 13 shows examples of lines ablated by the single spot ablation (the width of the 90 nJ line is approximately 3.5 μm) [4]. The results showed a clean ablation without damaging the substrate at fluences similar to those obtained with the lower pulse repetition rate laser used for the first experiments. The results also confirm the possibility for high productivity ITO ablation with femtosecond lasers. Since lasers such as the one used for these experiments can produce 100 nJ pulses at pulse repetition rates as high as 5 MHz, it may be possible to produce similar ablation results at scanning speeds of 5m/s.

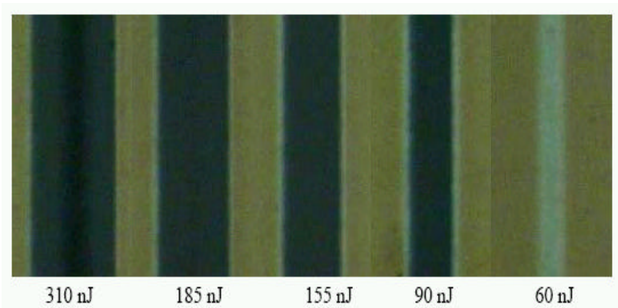

Figure 13 Beam diameter: 3.6μm, 100kHz, Scan speed 25mm/s)

4. Conclusions and future work

In this paper, we studied the laser fluence range of ITO ablation with femtosecond laser. The experimental results showed that femtosecond laser ablation was effective for patterning ITO film at relatively low pulse energies. Ablated holes varied between 0.8μm and 8μm. The energy fluence range for ITO ablation was observed to be wide and no damage was found on the substrate. By studying the ablation threshold of substrate, we could develop regions for both a single pulse ablation and multipulse ablation windows for the creation of lines in ITO film. Two different focusing optics (25.4 mm achromatic lens and 10x microscope objective lens) were used and they can be selectively used depending on ablation area. The minimum ablation diameter was observed to be 800nm and the minimum ablation depth was also found to be 70nm. The ablation quality was smooth enough and acceptable for production purpose.

5. Acknowledgement

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6. References

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