Ultrafast laser patterning of OLEDs for solid-state lighting

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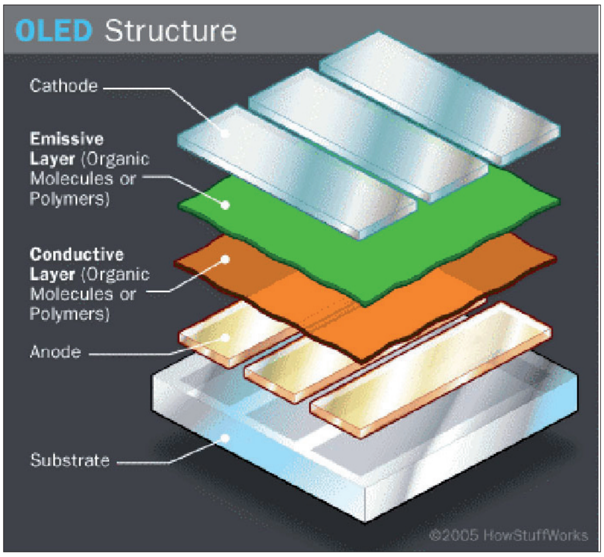
Traditionally, laser micromachining has relied on Q-switched Diode-Pumped Solid State (DPSS), excimer and CO_2 lasers of typically nanosecond (ns) pulse duration or longer. These lasers offer relatively high average power and can achieve high volume removal rates harnessing a combined etching effect from laser and laser-induced plasma processes [1]. As a result, micro-drilling, scribing and fine cutting applications have benefited on an industrial scale [2]. However, the driving mechanism even at short wavelengths is strongly thermal in nature. This arises largely as a result of secondary plasma heating of the target and substrate thermal conduction, and it limits fine control of the ablation process. Undesirable side effects near the irradiated regions such as micro-cracking or edge chipping, burr formation and particle debris that often accompany the micromachining process confirm this claim. As a result, successful laser machining with ns lasers is still viewed by many as a ‘black art’. However, with the ever-increasing miniaturisation of products and processes, this picture is changing rapidly.

Design and technology trends

The trends in most advanced technological applications are towards using material layers as thin as possible (e.g. sub-micron) and offering increased functionality involving complex multi-layered structures. Combinations of thin metals, metal oxides, ceramics or organic layers on glass, metal or polymer substrates are typically encountered, most of the layers being optically and thermally thin. Selective laser patterning of such layers is not a simple task and achieving an industrially robust process becomes very challenging.

In order to comply with stringent engineering and quality control specifications, laser micromachining must be highly reproducible and well confined with tight spatial resolutions near or well below the micron (μm) level. Additionally heat input must be controlled to avoid detrimental effects to the device performance due to collateral damage.

Fortunately, significant technological advances over the last decade in ultrafast* DPSS (and in some cases excimer) laser technology seem to be offering reliable commercial laser solutions for the optical engineer’s toolbox that are especially tailored to best match specific process requirements.



Ultrafast laser micro-machining

In contrast to the nanosecond case, the fluences (incident pulse energy per unit area) typically employed for ultrafast laser micro-machining, are kept close to the ablation threshold to avoid any laser plasma-assisted etching.

The ultrashort pulse duration fundamentally changes the laser-matter interaction. Briefly summarised, the main differences to conventional nanosecond single-pulse laser ablation are [3]:

(a) Very high peak laser intensities (> 10^{14} W/cm^2) can be achieved in the focused beam, powerful enough to ionise and machine any material!

(b) The motion of the emerging ablated matter and its associated complexities for material removal can be ignored. There is no laser plasma interactions involved above the illuminated surface and hence no laser attenuation losses on target

(c) The ablation mechanism for pulses below a few picoseconds (1 ps = 10^{-12} s) in duration decouples for most materials the ablation process from stochastic thermal processes. This has important implications on overall quality and reproducibility; and

(d) The non-linear photon absorption process enables ablation of virtually any material, even materials that have band-gaps above the incident photon energy. It also means that by controlling the laser fluence so that only a smaller portion of a focused beam exceeds the threshold for ablation by non-linear photon absorption, laser damage can be restricted to sub-diffraction levels, paving the way for nano-machining.

In summary, ultrafast-laser micromachining is deterministic, highly reproducible and inherently precise. By utilising the very high laser repetition rates available from modern ultrafast lasers (up to few MHz), throughput is maximised

Fast2light

Oxford Lasers is participating in a recently launched FP7 EU collaborative project (Fast2light) that involves the use of ultrafast thin-film laser patterning in roll-to-roll manufacturing of OLED foils on flexible substrates for intelligent lighting applications.

A typical OLED stack contains many different thin film materials such as conductive oxides, metal, dielectric and organic layers of typical thickness 100-200 nm as shown in the generic sketch above. The thin electrodes as well as the active OLED materials need patterning.

The technical challenge for the Fast2light OLEDs is to selectively pattern one or more layers simultaneously (metal on polymer, metal/polymer on oxide, oxide on ceramic/polymer) while leaving intact all underlying layers on the flexible substrate. This must be accomplished without re-depositing laser generated debris,

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* “Ultrafast” refers here to pulsed lasers emitting pulses of short duration below 1 ns (10^{-11}sec) and typically in the range 10^{-14} to 10^{-11}sec

causing thermal damage to the sensitive light-emitting polymers and without delamination or any other mechanical damage that might compromise the OLED performance while maintaining cost-effective high throughput patterning compatible with roll-to-roll manufacturing technology. Such ultra-fine controlled laser patterning on these materials has not been demonstrated before to our knowledge.

Results for nanosecond laser patterning

Nanosecond DPSS and excimer lasers have been evaluated with little success so far. In most cases it was found that either terminal damage was induced to the OLED stack or the processing window was poorly defined and at best, extremely narrow for industrial manufacturing. A typical example is shown in figure 1 where the ITO anode has been badly patterned from exposure to a nanosecond UV DPSS (355nm) laser. Most likely as a result of the significant spreading of heat from the laser pulse it was found impossible to maintain a sufficient depth resolution and remove only the 130 nm ITO layer. Reducing the incident laser fluence resulted in uneven machining with severe micro-cracking and damage to the underlying layers.

Results for ultrashort laser patterning

The thermal management of the selective ablation process is of key importance in this application. A very promising laser candidate for OLED patterning uses picosecond laser pulses at very low incident fluences near the single-pulse ablation threshold (few tens of mJ/cm^2) as shown in figure 2. By fast scanning a focused laser beam over the target layer using a galvanometer scanner with an f-theta telecentric lens, the individual laser pulses can be separated to achieve single-pulse ablation at specified locations. In figure 2 the uniformly etched laser craters on indium tin oxide (ITO) can be seen, with a resulting diameter of approximately 4µm, a depth of ~100 nm and, remarkably, no particle debris. By varying the scanning speed, laser pulse frequency and energy density on target appropriately, a continuous track can be scribed on the anode layer that creates electrically isolated pixels.

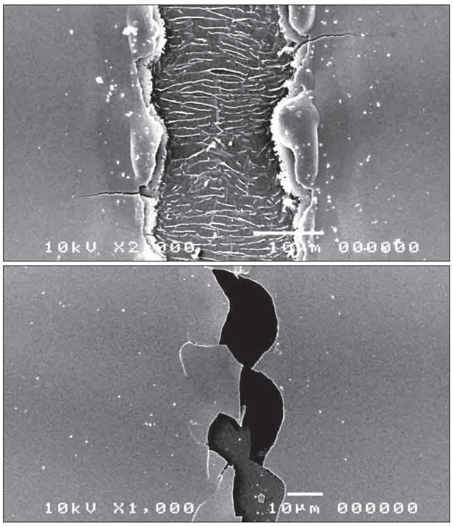

Figure 1. Non-optimised removal of ITO on a flexible substrate with 355 nm ns-pulses showing severe damage

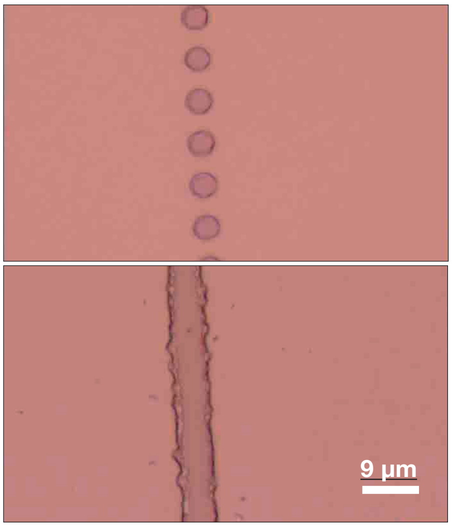

Figure 2. Picosecond laser scribed ITO on a flexible substrate with 532 nm 9 ps pulses. (top) 4 µm holes 100 nm deep; (bottom) 5 times slower scan speed.

Exact processing data cannot be reported at this stage due to confidentiality restrictions but any limitations on the overall process speed is expected to arise from the maximum scanning speed achieved on target rather than the laser itself. In almost all samples examined, the material seemed to have been ablated as intact layers. This observation combined with the lack of debris or evidence for vaporisation strongly implies a photomechanical removal process, commonly referred to in the literature as “cold ablation”. The experimental work continues within the project and conclusive remarks cannot be offered here but it is particularly interesting to note that laser patterning of such fine layers can actually be achieved with infrared, visible and ultraviolet wavelengths either incident directly onto the target thin film or by transmission through the flexible substrate.

It would appear so far that picosecond lasers (femtosecond lasers currently under examination also) are providing a unique enabling solution for this emerging application. The perceived benefits of ultrafast laser ablation applied in this case are associated with the simultaneous application of thermal and stress confinement in the films arising from the appropriate choice of the ultrashort pulse duration [4]. Similar laser scribing technologies using ultrafast lasers are currently applied in thin-film PV solar [5] and other organic electronics applications (flexible displays, electronic paper, etc) which are presently experiencing tremendous year-on-year growth.

The majority of this work was completed using an Oxford Lasers turn-key ultrafast laser station (Picolase 1000) installed at MEC, Cardiff University and operated at 532 and 355nm.

Conclusion

Where conventional nanosecond lasers seem to have failed, ultrafast lasers enable highly reproducible thin-film patterning of OLEDs on flexible substrates. Among the perceived benefits is excellent depth resolution and debris-free machining which could facilitate a new disruptive micro-manufacturing technology.

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