

Laser ablation of ITO thin films on glass for flat panel display manufacture

Matt Henry, Paul M Harrison, Jozef Wendland

Powerlase Ltd, Imperial House, Link 10, Napier Way, Crawley, Sussex. RH10 9RA.
United Kingdom

matt.henry@powerlase.com

Abstract. Active thin films are ubiquitous in the manufacture of all forms of Flat Panel Display (FPD). One of the most widely employed thin films is Indium Tin Oxide (ITO) a transparent electrically conductive material. This thin film is traditionally patterned using wet-etch lithography to create transparent circuitry on glass. Lithographic manufacturing techniques are extremely costly, requiring multiple processing stations. An emerging industrial alternative is the use of high average power Q-switched diode pumped solid-state lasers at IR wavelengths; imaged on to the substrate using mask techniques to directly pattern the thin film. Driven primarily by innovative manufacturers of Plasma Display Panels (PDPs), this technique is also being adopted by competing FPD technologies such as Liquid Crystal Displays (LCDs). The authors describe the optical and processing techniques employed in successful laser direct write of ITO on glass. The effects of fluence and irradiance upon the process are explored and quantified in terms of material removal using advanced analytical techniques such as Atomic Force Microscopy. Issues such as glass damage threshold, homogenisation techniques and optical design are discussed with reference to practical manufacturing. The authors demonstrate successful ITO ablation of pixels $>1\text{mm}^2$ to create area patterning of a glass substrate at high speed.

1. Introduction

The industrial use of transparent conductive thin films is essential in the manufacture of both Flat Panel Displays (FPDs) and Solar Cells – two market sectors in rapid growth. These thin films allow the creation of circuitry that is largely transparent in the visible spectrum.

Typically in the order of hundreds of nanometres thick these thin films allow the creation of complex monolithic electronic structures on substrates like glass. It is possible to create thin films of metallics, semiconductors and even organic materials. Amongst the most widely employed thin films in FPDs belong to the family described as Transparent Conducting Oxides (TCOs). Such TCOs are generally deposited on glass, and are required to be sufficiently conductive to act as active electrode structures when patterned, whilst remaining transparent in the visible spectrum. By far the most common industrially employed TCO is Indium Tin Oxide (ITO), which is more correctly described as Tin-doped Indium Oxide. An n-type semiconductor, it offers an optimum performance in terms of conductivity and transparency that is industrially proven [1].

In order to utilise properties of thin films such as ITO it is usually necessary to pattern them to create functional structures. The conventional industrial method for doing this is to use wet-etch lithographic techniques analogous to those used in the semi-conductor industry. Such techniques

require multiple process stages, large expensive machinery, employ toxic chemicals and are extremely costly.

One alternative is 'laser direct write' or Rapid Laser Patterning (RPL), in which a high intensity laser pulse is used to remove a section of the ITO layer directly from the substrate without damage. By scanning the laser beam across the substrate it becomes possible to rapidly pattern large areas of active thin-film. This RLP strategy is particularly well suited to the manufacture of PDPs, as described in the comparison with lithography above. This is due to the design requirement to have an ITO patterned glass front plate. See figure 1 below.

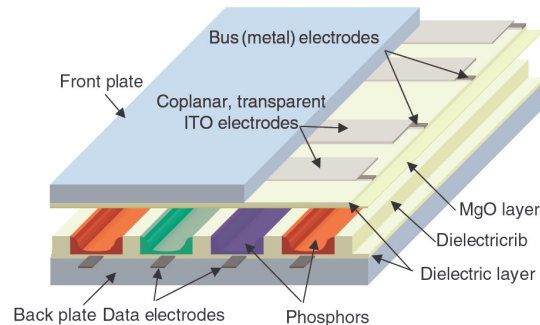


Figure 1: PDP architecture schematic [2]

Required positional accuracy is of the order of $5\mu\text{m}$ – within the capabilities of modern laser scanners. Feature size is of the order of $1 \times 1 \text{ mm}$ with a resolution of $10\mu\text{m}$ – all ideally suited to RLP. Given the large areas of PDPs, 42" and above, a high speed manufacturing technique is needed [3]. Due to the commercial drive for alternatives to lithography, RLP has been investigated for virtually all commercially available short pulse lasers (nanosecond or below) for processing ITO - ranging in wavelength from the Infrared (IR) to the Deep Ultraviolet (DUV).

Excimer lasers offer nanosecond pulses at UV wavelengths and are widely used for precision micro-fabrication. It is reported that ITO and other TCOs can be successfully removed from glass using KrF excimer lasers at 248nm wavelength. However this requires precise process control to selectively remove the TCO, as the Excimer pulse can etch and damage the glass beneath [4, 5, 6, 7]. Furthermore, Excimer lasers are not favoured in industry due to high cost of ownership and safety issues stemming from the use of corrosive halogen gases.

Ultrafast lasers operating in the picosecond and femtosecond regime have also been investigated for a variety of thin films on glass. High quality thin film removal has been demonstrated without glass damage for both solar cell and FPD applications [8, 9]. A particularly interesting application is for ablating ITO from glass with feature sizes of the order of $15\mu\text{m}$ for the manufacture of OLEDs. Researchers report a promising comparison between test OLEDs manufactured using a femtosecond laser to pattern ITO and those employing purely lithographic means [10]. However in all cases ultrafast lasers have relatively low pulse energies – in the order of 1mJ. Thus to achieve thin film removal they are focused to fine spot sizes in the order of $10\mu\text{m}$ to achieve sufficient energy density (Fluence). This makes them unsuitable for creating large area TCO structures at the commercial rates required for large area FPD manufacture, although smaller scale FPD applications such as OLED may be viable.

Q-switched diode pumped solid state lasers (DPSSL) are amongst the most widely employed in high volume production industry; being compact, low maintenance and robust. They offer nanosecond pulse durations, wavelengths in the near-IR and the option for output in the visible and UV through non-linear frequency conversion. Takai and Yavas et al report in a series of papers upon ITO ablation from glass using a low M^2 Nd:YLF laser with a 6ns pulse duration. Using simple Gaussian optics, the beam is focussed to a small spot per pulse and the spots are overlapped to create bulk patterning. The performance of the fundamental IR wavelength and all three harmonics (1047, 523.5, 349 and 262nm,

respectively) are compared [11, 12, 13, 14]. It is found that the near UV (349nm) and visible (532.5nm) wavelengths are least effective due to the high transparency of both ITO and glass in this region. Optimal quality is found at DUV, 262nm, where it is demonstrated that absorption in the ITO layer and also at the glass-ITO interface results in uniform heating and consistent evaporation of the thin film. However at 1047nm it is found that the ITO absorbs more strongly than the glass substrate – and although ablation quality is not quite as uniform as in the DUV it is sufficient to achieve consistent electrical isolation. But the much higher pulse energies available at the fundamental wavelength mean that very high-speed patterning is possible with kHz repetition rates at an acceptable quality for manufacture.

In recent years the FPD industry has fixed on an optimal solution for laser direct write of ITO on glass. This technique has moved from the lab to pilot lines and in the last two years has been introduced into volume production for the manufacture of PDPs. The solution has been enabled by the advent of industrial high average power Q-switched diode pumped solid-state lasers (DPSSL). Such lasers offer average power levels >800W, at kilohertz repetition rates, with nanosecond pulse durations and pulse energies of >100mJ. Such high pulse energies allow the use of beam delivery techniques more commonly associated with Excimer lasers. The beam is homogenized, imaged onto a mask and reimaged on to the substrate. The high pulse energies allow sufficient energy density to ablate large pixels (>1mm²) with a single pulse. Kilohertz repetition rates mean that thousands of pixels can be ablated per second – and by ‘stitching’ the pixels together large areas of active ITO electrode structure can be created very rapidly. To further improve throughput industrial systems often employ multiple lasers upon a single processing station, up to 8 being reported [3, 15, 16].

2. Commercial comparison: Lithography vs. RLP

It has been demonstrated for the contemporary manufacture of Plasma Display Panels (PDPs) that a single lithographic manufacturing stage will require a minimum of six processing stations, each capable of handling a Gen. 7 mother glass panel 2160 x 2460mm in size. Each processing station will cost several million dollars – with the most expensive, the wafer stepper, costing around \$12M alone. Mask sets are in the order of \$1M each, and wet-etch lithography requires the use of toxic, acidic chemicals incurring significant environmental disposal costs.

By comparison a Rapid Laser Patterning (RLP) manufacturing solution for PDP will require only two processing stations to accomplish the same task: one for RLP and the second to rinse the glass substrate. An industrial RLP station itself is estimated to cost less than \$6M - a significant capital cost saving. Other benefits are: a large footprint reduction - effectively reducing the number of processing stations by two thirds - plus RLP industrial masks cost only a few thousand dollars at most. Furthermore RLP is a dry process and the secondary rinse stage typically employs distilled water – so the use of toxic chemicals and resulting disposal costs are avoided. It is also reported that significantly improved yields are achieved over lithography due to difficulties in achieving uniformity of wet etching over such large glass panels [2, 3, 15, 16].

3. Experimental

All substrates are 100nm thick ITO coated on PDP grade glass 2.8mm thick. The laser used is a 400W Starlase AO4 Q-switched DPSSL at the Nd:YAG fundamental wavelength of 1064nm. At 6kHz repetition rate, output pulse energy is 53mJ with pulse duration of 35ns. The Starlase range of lasers is manufactured exclusively by Powerlase Ltd, UK. The laser is attenuated externally using a proprietary Powerlase unit. The beam is collimated using a Galilean telescope and homogenized by an integrated orthogonal lens array manufactured by LIMO GmbH. The beam is imaged on to a test mask; this mask plane is relayed to the substrate and demagnified using a Rodenstock f-theta 163mm focal length lens. A HurryScan 25 galvanometric scanner manufactured by Scanlab GmbH is used to scan the beam across the sample. An image plane of 1mm² is achieved at the workpiece. ITO ablation is assessed using a Nikon LM1500 optical microscope with a PC interface via a 12 Mega pixel camera into Lucia G software. This software allows microscopic measurements to be made against a Nikon calibrated

standard. Further assessment of the ITO ablation is done using an Atomic Force Microscope (AFM). Power measurements are made at the workpiece using a Molecron power meter.

4. Results and Discussion

For single pulse ITO ablation of a large pixel size, optimum laser performance for a Starlase AO4 is at 6 kHz repetition rate. This is the highest rep. rate at which maximum pulse energy of 53mJ at 35ns pulse duration is achieved. Therefore this represents optimal performance for large pixel size, and all experiments are carried out at this setting. Nominal pixel dimensions are 1x1mm, and the empirical mask used creates an electrode structure on the ITO that is illustrative of that in production PDPs. The pixels are 'stitched' together to create large area active electrode structures. A range of trials is conducted from 1.2-3.4J/cm² in 0.2 J/cm² increments in order to determine ablation threshold.

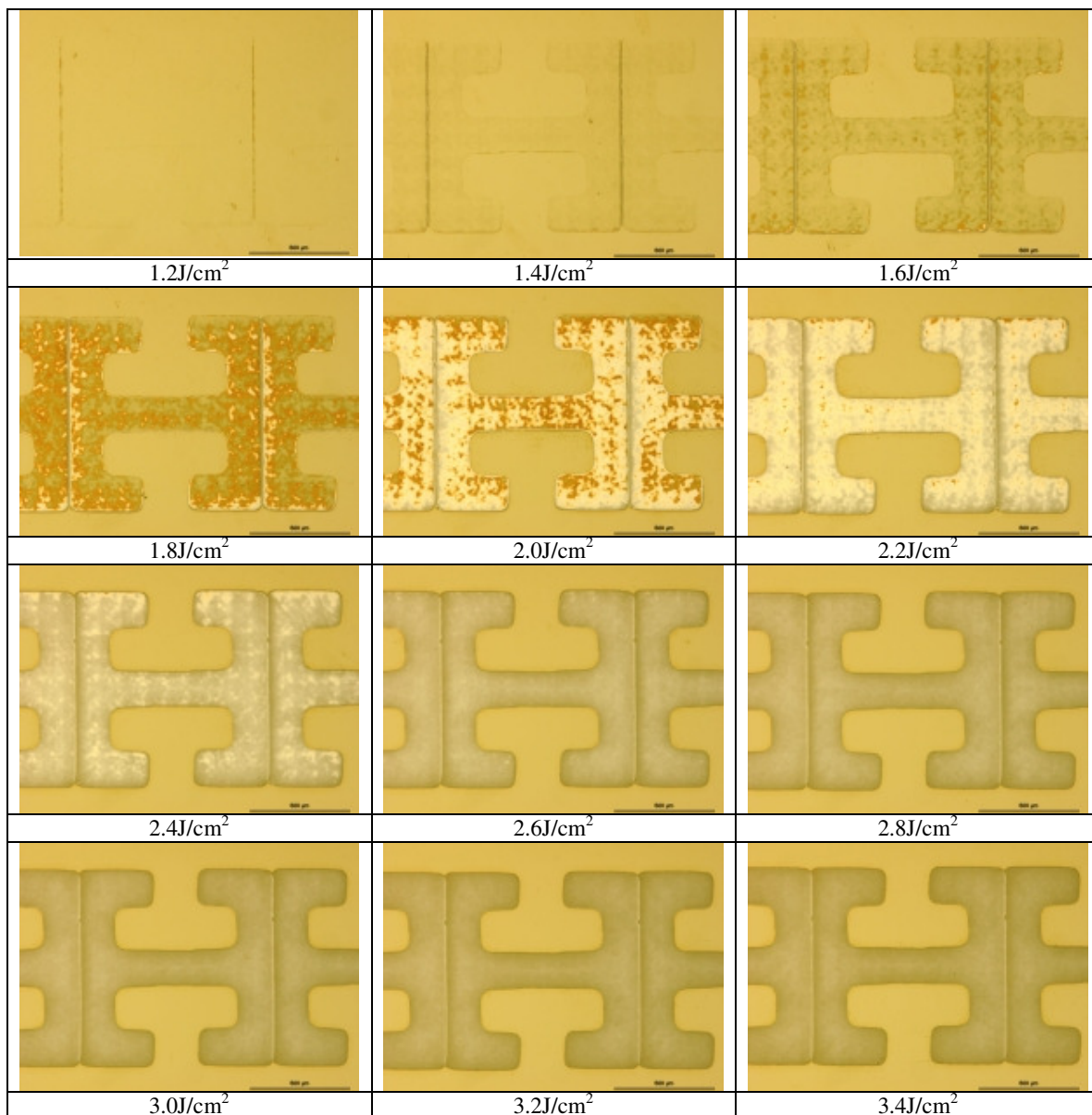


Figure 2: Increasing fluence vs. ITO ablation

Figure 2 shows images of the resulting ITO ablation at increasing fluence. A clear trend emerges from the images: at low fluence the ITO is barely affected, from $1.6\text{J}/\text{cm}^2$ onwards structure appears that corresponds with the ripples on the top of the homogenised structure and more ITO is removed with increasing fluence. As the energy density reaches $2.6\text{J}/\text{cm}^2$ the ITO removal becomes very uniform and from $2.8\text{J}/\text{cm}^2$ to maximum fluence there is no discernable change in the ablated ITO region. This suggests that above a certain threshold all the ITO is removed and that the process effectively saturates. Using this visual assessment it is clear that the ITO ablation threshold in this case is $2.8\text{J}/\text{cm}^2$. It is also encouraging that the ITO removal is consistent from this point on because it means that the process is reasonably tolerant of energy variation and is therefore well suited for practical industrial use.

The results shown in figure 2 are simply a change in visual contrast between the processed and unprocessed regions. The analysis above is therefore only an interpretation of these images, so to ensure that the ITO thin film really is being removed it is necessary to corroborate these results using another analytical method – in this case Atomic Force Microscopy. AFM employs a fine silicon carbide needle mounted upon a piezo-electric actuator. The needle is rapidly scanned across a $100\times 100\mu\text{m}$ square area and a 15nA nominal current maintained by height control between tip and substrate. By use of a laser interferometer measuring the position of the tip, surfaces can be mapped with nanoscale resolution.

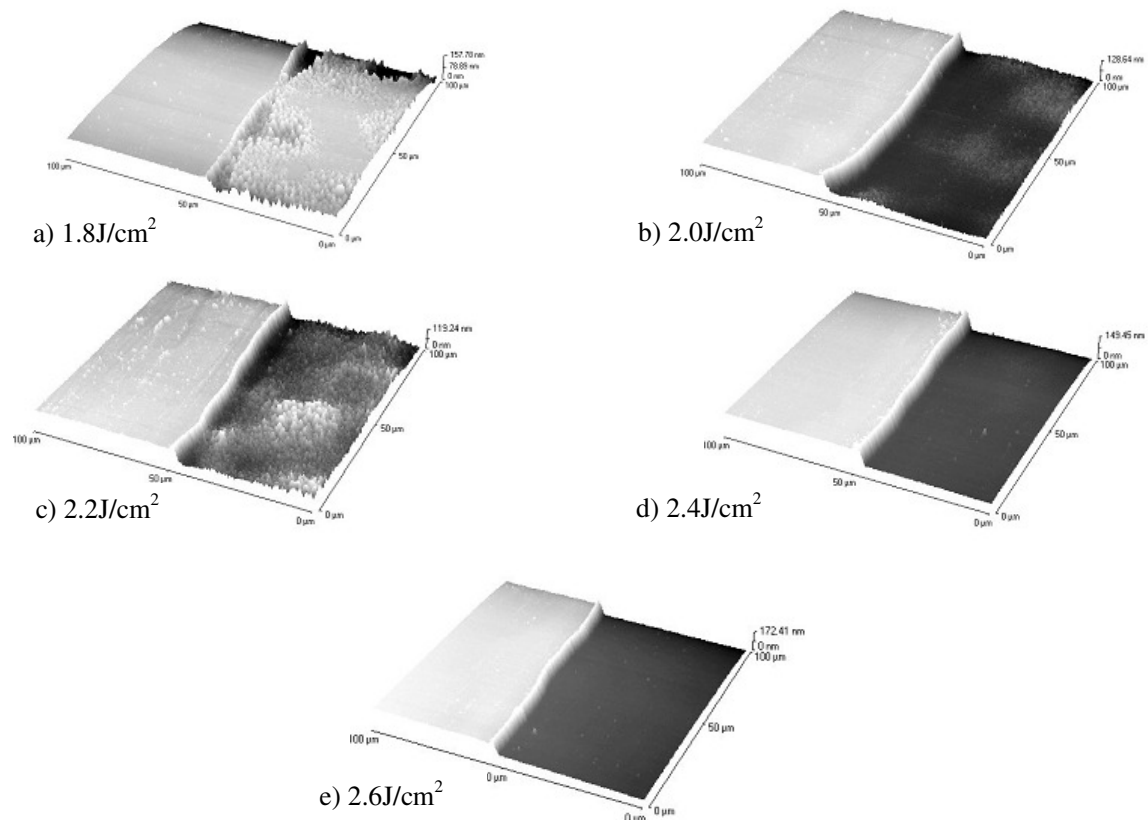


Figure 3: 3D AFM scans across an unprocessed ITO boundary at increasing fluence

Figure 3 is highly informative and gives detailed insight into the ITO removal. At $1.8\text{J}/\text{cm}^2$ the bulk of the ITO remains, but the surface is damaged. As fluence increases the ITO residue diminishes until

it appears completely removed by $2.4\text{J}/\text{cm}^2$. Figure 3 also serves to illustrate the precision of this process; the edge between the virgin ITO and remaining glass substrate clearly defined with the ITO a consistent 100nm above the glass; and a $1\mu\text{m}$ edge interface in sharp relief. The ablated area is also as flat as the virgin ITO, a further indicator of a selective, precise process.

Combined all this corroboratory data strongly supports the opinion that ITO is completely removed by the laser direct write process. The AFM threshold for ablation is $2.4\text{J}/\text{cm}^2$, but given the desire to be conservative for a robust industrial process, we suggest $2.8\text{J}/\text{cm}^2$ as determined by optical microscopy as the optimal value for this example industrial substrate.

5. Commercial Application

Table 1: Comparison of Laser vs. Patterning Potential

Laser	Av. Power (W)	Max. Pixel Area (mm^2)	Max Pixel Size (mm)	1mm^2 Pixels/Min	Pixels/Min x8 Lasers (Million)	Area Coverage/Min x8 Lasers (m^2/min)
AO4	400	> 1.0	> 1.0 x 1.0	360,000	2.88	2.88
AO6	600	> 1.5	> 1.2 x 1.2	660,000	5.28	5.28
AO8	800	> 2.0	> 1.4 x 1.4	900,000	7.2	7.2

Identifying the optimum process fluence as $2.8\text{J}/\text{cm}^2$ allows for comparison with available commercial lasers, see table 1. It is possible to extrapolate to the rate of area patterning for a SOTA eight laser RLP system – in this case 7.2 square metres of ITO coated glass per minute.

6. Conclusions

The commercial potential is demonstrated of RLP versus wet-etch lithography for the patterning of ITO on glass for the manufacture of PDPs. Empirical studies show that very high quality ITO removal can be achieved and that an optimum industrial fluence of $2.8\text{J}/\text{cm}^2$ is identified for 100nm thin film using advanced analytical techniques. Furthermore it is shown that a commercial Rapid Laser Patterning system could potentially process $> 7\text{m}^2$ of ITO coated glass per minute.

7. References

- [1] Minami, T. (2005) Transparent conducting oxide semiconductors for transparent electrodes, *Journal of Semiconductor Science and Technology*, 20 S35-S44
- [2] Beouf, J. P., (2003) Plasma display panels: physics, recent developments and key issues, *Journal of Physics D: Applied Physics*, 36, R53-R79
- [3] Venkat, S., Dunskey, C., (2006) Laser Patterning of ITO in Flat Panel Display Manufacturing, *Photon Processing in Microelectronics and Photonics V Photonics West*, San Jose, Proceedings of SPIE Vol. 6106, 610602
- [4] Molpeceres, C., et al (2005) Microprocessing of ITO and a-Si thin films using ns laser sources, *Journal of Micromechanics and Microengineering*, 15, 1271-1278
- [5] Lunney, J. G., O'Neill, R. R., Schulmeister, K., (1991) Excimer laser etching of transparent conducting oxides, *Journal of Applied Physics Letters*, Vol. 59, No. 6 pp.647-649
- [6] Szörényi, T., Laude, L. D., Bertóti, I., Kántor, Z., Geretovsky, Z., (1995) Excimer laser processing of indium-tin oxide films: An optical investigation, *Journal of Applied Physics*, Vol. 78, No. 10 pp.6211-6219
- [7] Rumsby, P., Harvey, E., Thomas, D., Rizvi, N., (2005) Excimer laser patterning of thick and thin films for high density packaging, *Proceedings of SPIE Vol. 3184*
- [8] Hermann, J., et al (2005) Selective ablation of thin films with short and ultrashort laser pulses, *Journal of Applied Surface Science*
- [9] Choi, H-W., Farson, D., Kim, K-R., Hong, S-K., (2005) Direct write patterning of ITO film by femtosecond laser ablation, in *Proceeding of the Laser Microfabrication Conference, ICALEO 2005*, Miami, pp.20-27
- [10] Park, M., et al (2006) Ultrafast laser ablation of indium tin oxide thin films for organic light-emitting diode application, *Journal of Optics and Lasers in Engineering* 44 pp.138-146
- [11] Yavas, O., Takai, M., (1998) High-speed maskless laser patterning of indium tin oxide thin films, *Journal of Applied Physics Letters*, Vol. 73, No. 18 pp.2558-2560
- [12] Takai, M., Bollmann, D., Habberger, K., (1994) Maskless patterning of indium tin oxide layer for flat panel displays by diode-pumped Nd:YLF laser irradiation, *Journal of Applied Physics Letters*, Vol. 64, No. 19 pp.2560-2562
- [13] Yavas, O., Ochiai, C., Takai, M., (1999) Substrate-assisted laser patterning of indium tin oxide thin films, *Journal of Applied Physics A*, 69, [Supplemental], S875-878
- [14] Yavas, O., Takai, M., (1999) Effect of substrate absorption on the efficiency of laser patterning of indium tin oxide, *Journal of Applied Physics*, Vol. 85, No. 8 pp.4207-4212
- [15] Henry, M., Harrison, P.M., Wendland, J., (2006) Laser direct write of active thin-films on glass for industrial flat panel display manufacture, *Proceedings of the 4th International Congress on Laser Advanced Materials Processing*, Kyoto, Japan
- [16] Rumsby, P. T., (2002) Advanced laser tools for display device production on super large substrates, *IMID '02 Digest*