Journal of Information Display, 2014
Vol. 15, No. 1, 1–4, http://dx.doi.org/10.1080/15980316.2014.881428

Laser lift-off systems for flexible-display production

Ralph Delmdahl*, Malene Fricke and Burkhard Fechner

Coherent LaserSystems GmbH & Co. KG, Hans-Böckler-Str. 12, D-37079 Göttingen, Germany

(*Received 25 September 2013; accepted 29 December 2013*)

Laser lift-off (LLO) delamination opens the path to polymer-based display backplanes for use in electrophoretic e-readers, AMOLED (Active-Matrix Organic Light Emitting Diode) smartphones, tablets, and OLED-TV. The proper choice of wavelength, optical system, and fluence enables the layer-selective LLO processing of functional thin films not achievable with other radiative or non-radiative heat sources. This becomes increasingly attractive as the feature size and film thickness in microelectronics applications are continuously being downscaled. Excimer lasers provide the 308 nm wavelength and short pulse duration required for highly localized energy coupling. The high output power of excimer lasers enables a large processing footprint and the high-throughput rates needed in mass manufacturing. Thin-film transistor structures fabricated on top of polymer layers spun on glass panels must be delaminated to create thin, lightweight, and rugged flexible-display backplanes. Low-thermal-budget lift-off processing with UV lasers protects the adjacent functional layers. When it comes to large Gen 4.5–Gen 8 substrate panels, which have to be released from polymer thin films, it is most effective to use line beam scanning for LLO within one to three consecutive scans.

Keywords: excimer laser; laser lift-off; flexible displays; ultraviolet; polymer backplane

1. Introduction

The flat-panel display industry is evolving with enormous speed. Displays are being used for many different applications, such as mobile computing, touch panels, or other portable devices, and can be produced using LCD (Liquid Crystal Display) or OLED (Organic Light Emitting Diode) as the frontplane technology. The newest and probably most notable market trend is flexible displays. Flexible displays, whether employed in smartphones, tablets, or e-readers, always share a common feature: the backplane of circuit layers used to individually drive each pixel is no longer situated on a rigid glass carrier but on a flexible polymer foil [1]. That is, in fact, independent of the display frontplane technology, which will be used in the final display; nor must the final device containing the polymer backplane necessarily be bendable. To manufacture flexible displays, it is necessary to substitute the conventional glass substrate with a flexible polymer foil. For production, the polymer-based display has to be detached from the rigid temporal glass carriers, which are necessary for majority of the processing steps along the manufacturing chain. The final glass carrier separation is best done via laser lift-off (LLO), using excimer laser photons with an ultra-short wavelength (308 nm), which is the superior technology for ensuring both high throughput and superior display quality [2]. This paper describes a cost-effective excimer-laser-based optical system approach for UV LLO for flexible-display production.

2. LLO processing aspects

The essential process steps used for the fabrication of flexible displays are schematically illustrated in Figure 1, forming part of this example of an electrophoretic display as it is commonly applied in lightweight e-readers. As the first step, a temporary glass carrier substrate is spin-coated with a 100 µm-thin polymer film, which is cured thereafter. On top of the polymer layer will be built the circuit backplane (i.e. the matrix of thin-film transistors), followed by the display frontplane, which contains the layers for electrodes and microcapsules. Finally, the transition from rigid to flexible display is realized through LLO processing.

Technically, the excimer laser line beam of a 308 nm wavelength is shown through the carrier glass substrate on the polymer. Only the polymer in the direct vicinity of the glass substrate is evaporated, as illustrated in Figure 2. LLO separation using the 308 nm excimer laser occurs within a single laser pulse of ca. 25 ns Full Width at Half Maximum (FWHM) pulse duration, using an about 200 J/cm^2 energy density. The short wavelength advantages, in particular, are the about-two-orders-of-magnitude-higher absorbance of the 308 nm wavelength compared with a 532 nm wavelength [3]. The short wavelength thus also eliminates the need for absorption enhancement by means of additional sacrificial layers [4].

The absorption depth of 308 nm excimer laser radiation in commercial polymers for microelectronics is just

*Corresponding author. Email: ralph.delmdahl@coherent.com

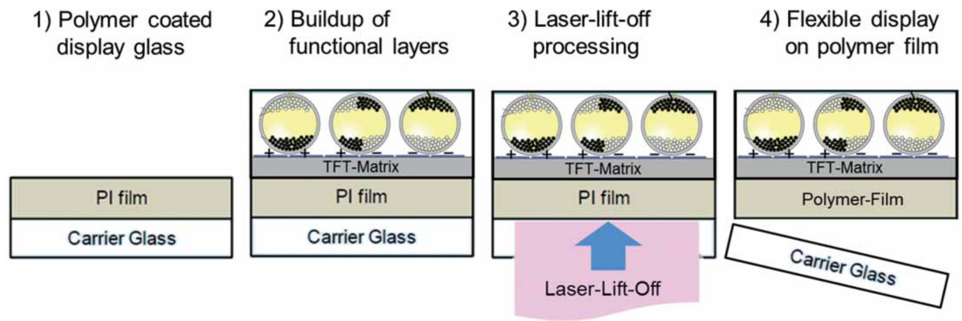

Figure 1. Fabrication scheme of flexible displays by means of excimer LLO.

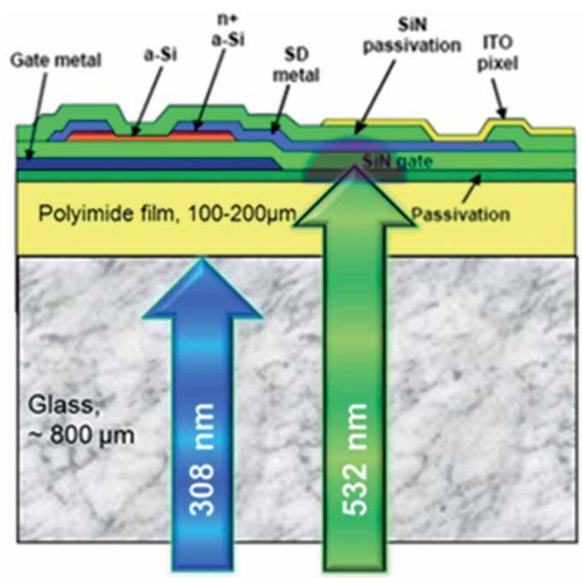

Figure 2. Schematics of the LLO characteristics using short and long wavelengths.

about 100 nm, with the typical polymer layer thicknesses extending from some ten to some hundred micrometers [5]. As a consequence, LLO separation with short wavelengths occurs in a highly selective manner entirely unnoticed by the adjacent performance-determining functional layers. The current digital display applications employ rectangular glass substrates extending up to about $5\,m^2$ in size. To achieve fast and reproducible LLO separation over such large areas on an industrial scale, line beam scanning based on excimer laser optical systems has become the industry-proven processing strategy of choice. Nowadays, large line lengths of up to 750 mm have made it to the display production floor, enabling the rapid separation of functional layers even in the case of large Gen 8 substrates ($2500 \times 2200\,mm^2$). The extraordinary full-length homogeneity (1.24%) of a line beam field given for the two-sigma confidence interval is shown in Figure 3.

3. Lift-off system characteristics

Line beam scalable laser optical solutions for flexible-display LLO manufacturing are required to match the carrier glass generations used in diverse production lines of display manufacturers. Line beam lengths extending from 250 to 750 mm are commercially available for substrate sizes from Gen 4 to Gen 8. The most important LLO system parameters obtained with the recently introduced UV blade system platform, which will be characterized shortly, are summarized in Table 1.

UV blade line beam scanning systems for LLO processing consist of the UV excimer laser source, which nowadays extends to output power levels beyond kilowatts [6], and a line beam optical system design, as shown in Figure 4. The optical train transforms the laser beam into an extremely

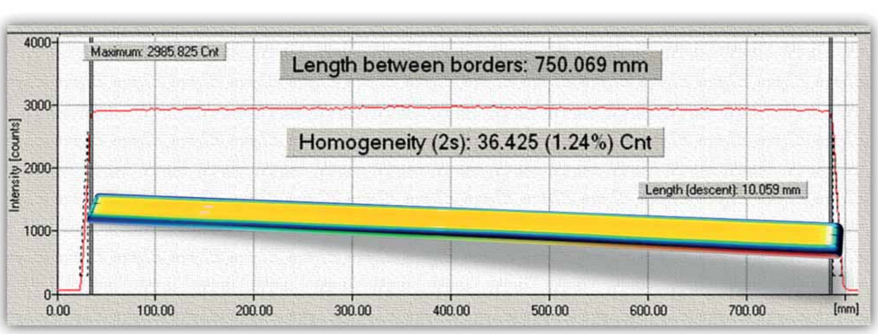

Figure 3. Long-axis cross-section of the energy distribution of a 750 mm-long line beam.

Table 1. LLO system line-up and specifications overview.

	UV blade 250	UV blade 380	UV blade 465	UV blade 750
Wavelength (nm)	308	308	308	308
Pulse energy (mJ)	580	580	900	950
Repetition rate (Hz)	200	200	300	300
Energy density (mJ/cm^2)	270	235	235	235
Line length (mm)	250	380	465	750
Beam width2 (μm)	400	300	400	250
Homogeneity long axis	$\leq$1.8%, 2 σ	$\leq$1.8%, 2 σ	$\leq$1.8%, 2 σ	$\leq$1.8%, 2 σ

homogeneous line field of the appropriate energy density, which is applied to the substrate.

The optics system is schematically shown in Figure 5 and is designed to generate a homogeneous line beam length in the range of 250–750 mm to match the substrate size to be processed in the experiments. The line beam width is 0.25–0.4 mm, depending on the line length. Such a high aspect ratio of the line beam field is generated by independently shaping the two axes of the homogenized excimer laser beam. The long-axis dimension is defined solely in the homogenizer, which therefore includes a cylindrical condenser lens in the beam path.

The short axis can be focused onto a slit mask. The slit can clip the short axis of the beam profile, ensuring steep fall-off at the edges of the line beam. The slit plane is then imaged by a cylindrical doublet lens that reduces the short axis to its final width. With this approach, a line beam with a long-axis homogeneity of below 2% of the two-sigma confidence interval is achieved along the entire line length. Optionally, the LLO systems feature a CCD (Charge Coupled Device) beam profiler camera for measuring the line beam profile at the substrate plane.

By appropriately moving the substrate under the pulsing excimer laser line beam field in one or two scans, it is possible to cover an entire Gen 4.5 substrate panel

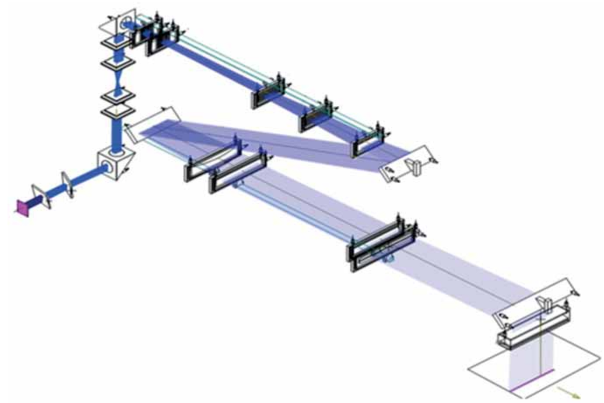

Figure 5. Sketch of the optical line beam delivery system.

Table 2. Processing metrics for the Gen 4.5 substrate LLO in one scan and two scans.

Laser parameters and panel throughput		
Substrate size	Gen 4.5	Gen 4.5
Number of scans	1	2
Line length	380 mm	750 mm
Pulses/panel	4600 pulses	2300 pulses
Repetition rate	200 Hz	300 Hz
Throughput	~50 panels/h	~70 panels/h

(730 × 920 mm), from which, for example, about 55 displays with a 6-in. diagonal are obtained within only a few thousand laser pulses. Table 2 shows the LLO system parameters and the calculated throughput parameters for the two- and single-scan approaches using 380 and 750 nm line beam lengths, respectively.

A huge advantage of starting from temporary glass substrates in combination with LLO processing lies in the fact that the display manufacturer can extend his portfolio from rigid-glass-based to flexible-polymer-based display backplanes, without the need to make major investments in entirely new production equipment [7].

Figure 6 depicts a Gen 4.5 glass carrier sample that had been coated with a 100 μm polyimide (PI) film. After LLO at a 308 nm wavelength applying the line scan method, the

Figure 4. System layout of a UV blade LLO system.

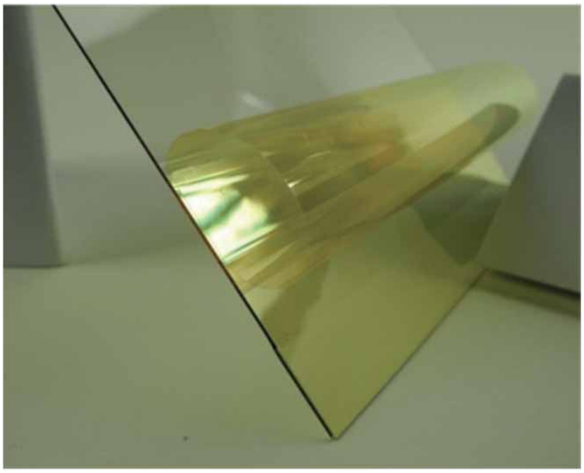

Figure 6. PI-coated glass substrate delaminated via LLO at 308 nm.

PI film was easily and cleanly delaminated without the need for any post-processing.

The lift-off performance and process quality depended first and foremost on the employed energy density. For line beam fluences below 220 mJ/cm^2, lift-off delamination was not possible. Close to this threshold value, lift-off delamination was incomplete and uncontrollable. For the proposed PI glass system, optimum lift-off conditions slightly above the ablation threshold were achieved at a fluence value of 235 mJ/cm^2. Increasing the fluence to a value beyond 250 mJ/cm^2 still resulted in good lift-off delamination but at the expense of significant carbonization and debris formation due to the excess laser energy. Although a rather tight lift-off process window (235 ± 15 mJ) was observed, this was easily met by the energy density distribution of the homogenized line beam field ($< 1.8\%$, 2σ).

Although PI as used in this work can withstand high processing temperatures up to 350°C, various other polymer films are of interest for flexible-display applications. For example, polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) show low water absorption, high chemical and mechanical resistance, and good dimensional stability [8]. The polarization-changing birefringence of the semi-crystalline PET and PEN backplanes is of no concern in the case of OLED and electrophoretic displays. Another advantage of PET and PEN is their high visible-light transmission, which is particularly relevant for bottom-emissive OLED displays. Here, PI with its yellow color has limitations and is thus better suited for top-emissive backplanes. Further advances in flexible-display fabrication will largely be driven by progress in polymer formulations and by the adequate selection of the polymer, which will finally be transferred from the glass panel.

4. Conclusion

UV LLO delamination opens the path to polymer-based active-matrix display panels such as smartphones, e-readers, tablets, and potentially large OLED-TVs. The proper choice of wavelength, optical system, and fluence enables the layer-selective LLO processing of functional thin films not achievable with other radiative or non-radiative heat sources. This becomes increasingly attractive as the feature size and film thickness in microelectronics applications are continuously downscaled. Such trends motivate the ongoing development of suitable excimer laser sources and optical beam delivery systems for the most appropriate 308 nm wavelength. Excimer lasers deliver the high pulse energies required to support the large processing footprint of excimer-laser-based optical systems, which are already scalable up to Gen 8, with industrial processing speed.

Acknowledgement

The authors gratefully acknowledge their valuable discussions with J. Brune and R. Senczuk from Coherent LaserSystems GmbH & Co. KG on LLO parameter testing on various substrates.

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