Fabricating the Flexible Future

How UV laser systems enable the transition from rigid to flexible in microelectronics manufacturing

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By leveraging the unparalleled pulsed UV-power of excimer lasers, gossamer-thin functional foils attached to rigid wafer- or panel-type carriers can be detached with high yield and fast rate, increasing productivity and lowering the costs of manufacturing a new generation of thin and flexible components and devices.

Laser processing has always been a key technology in achieving breakthrough developments in microelectronics devices. As the structural dimensions of microelectronics components continuously shrink, there is a trend towards employing short wavelength UV-lasers delivering highest machining resolution, both along lateral and vertical direction. The combination of modern excimer lasers, being the most capable in the UV laser landscape, with large-field projection optics bridges the long-standing gap between "fast processing" and "precise processing" due to an unprecedented effective illumination footprint, some 10,000 times larger than the achievable resolution.

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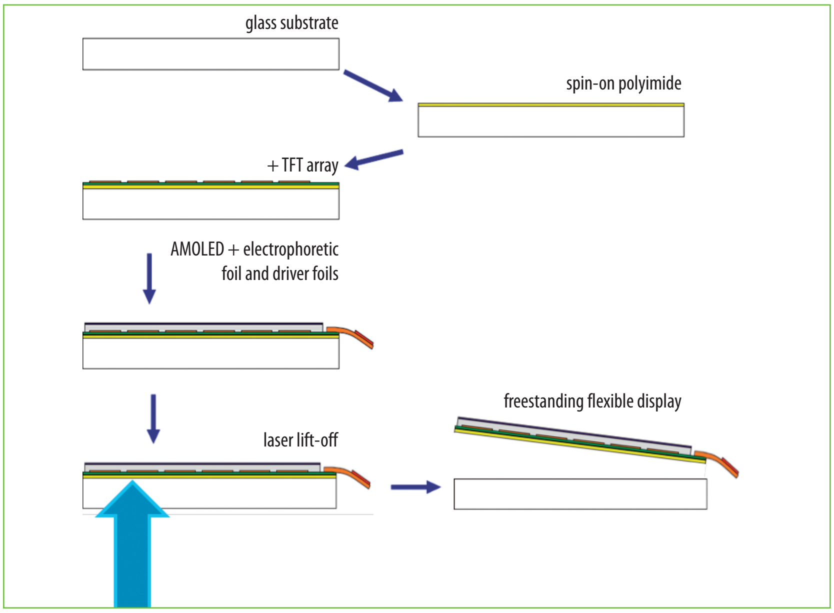

Fig. 1 Schematics of flexible display fabrication steps using rigid carriers and excimer laser lift-off release.

The rigid carrier approach to flexible microelectronics manufacturing

Flexible displays as used in smartwatches, wearables or curved smartphones have enormous commercial potential, but their manufacturing poses significant technical challenges. In particular, the thin plastics substrates used for flexible displays are too delicate to handle with conventional tooling and will typically lose their limited rigidity at the high temperatures experienced in several production steps. One experiences a similar challenge when processing thin wafers which will be thinned down to such extent where they become flexible in order to support space saving vertically stacked logic and memory chip architectures packed inside our highly functional mobile devices. The common approach to volume production of flexible display panels or ultrathin semiconductor wafers: Fabricating the circuitry on a polymer-coated, rigid glass carrier and detaching the finished devices in the final process step. Technically, the UV excimer laser line beam is shown through the carrier glass substrate on the polymer layer. Due to the short wavelength, only the polymer in the direct vicinity of the glass substrate evaporates. The layer separation using the 308 nm excimer laser occurs within a single laser pulse of circa 25 ns full width at half maximum (FWHM) pulse duration, using about 200 J/cm^2 energy density. The short wavelength, moreover, eliminates the need for absorption enhancement by means of additional sacrificial layers.

The true value of UV performance and reliability

A number of rigid carrier separation techniques turn out to be unsuitable for mass production purposes. For example, mechanical lift-off or chemical etch processing are rather time-consuming and unspecific methods and hence prone to production yield losses. The latter method, moreover, suffers from environmentally hazardous substances issues. Separation by laser lift-off is the better alternative under the premise that a sufficiently short wavelength (> 350 nm) is applied, in order to restrict the absorption of the laser energy to the polymer-glass interface region. As excimer lasers uniquely provide the shortest wavelengths (typically, 308 nm but also 248 nm wavelengths are employed in laser lift-off manufacturing) in combination with highest energy and power output, they both ensure high yield separation of the delicate microelectronics and unsurpassed throughput for the high volume microelectronics markets.

In fact, one cannot overestimate the importance of the high production yield supported by using short wavelengths excimer laser systems in combination with high-quality line beam optics:

- Laser lift-off carrier separation takes place on a valuable part
- Laser lift-off processing is among the last of a multitude of costly processes
- Many high-value parts and the resulting microelectronics devices are at stake during the lift-off process
- A yield loss of just 1 % during display laser lift-off sums up to many millions of dollars profit loss a year.

Large-footprint UV laser lift-off processing

Display manufacturers employ rectangular glass carrier panels from one to about five square meters in size. The essential lift-off process steps used for the fabrication of flexible displays are shown in Fig. 1. In the first step, a temporary glass carrier substrate is spin-coated with a thin polymer film which is cured thereafter. On top of the polymer layer, the circuit backplane (i.e. the matrix of thin-film transistors) is built, followed by the display frontplane which contains the functional light-generating layers. Finally, the transition from rigid to flexible display is realized through laser lift-off processing.

In order to achieve laser lift-off separation of large panels on an industrial scale, line beam scanning based on excimer laser optical systems has become the industry proven processing strategy of choice. Starting with lift-off systems providing 250 mm long line beams, nowadays excimer laser systems with extended line lengths of up to 750 mm have made it to the flexible display production floor (Fig. 2). At a line width of ~ 0.4 mm, the respective processing footprint, i.e. the substrate area covered within each laser pulse ranges from 1 cm^2 for a 250 mm line beam length to 3 cm^2 for a 750 mm line beam length. As a single shot per area is sufficient and the overlap between the applied pulsed is of the order of a few percent of the line beam width, the panel throughput directly scales with the laser repetition rate. Depending on the panel size and the applied line beam length, large-footprint excimer laser lift-off processing rates comparable to about 10,000 flexible smartphone displays per hour are achievable.

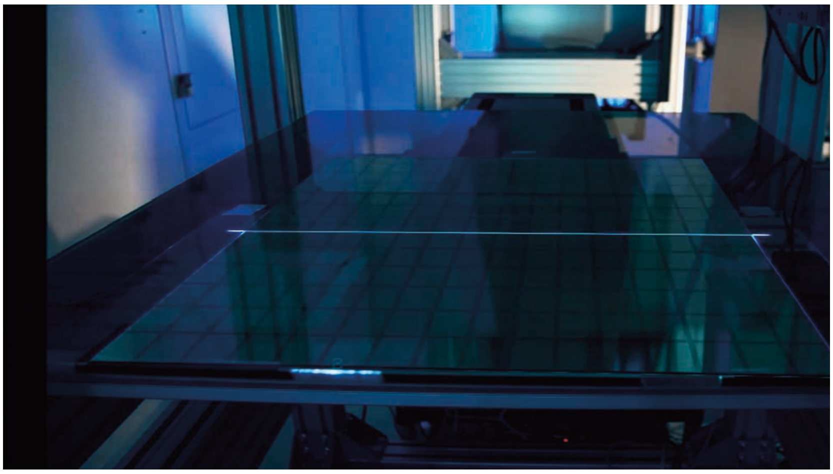

Fig. 2 Carrier panel moving below an excimer laser line beam during laser lift-off separation of flexible displays.

The merits of an all flat-top beam profile

The high UV pulse energy of the excimer laser reaching up to one Joule in the energy stabilized operation mode, supports shaping large beams with a flat-top energy density distribution as demanded by the individual process window for reliable single-pulse laser lift-off. Using insufficient energy density results in incomplete lift-off release whereas too high of an energy density leads to high heat-load and potential warpage or carbonization of the thin film. These are typical problems observed with solid-state based UV laser systems where at least one beam axis has a Gaussian cross-section with only 25 % lift-off effectivity. The entirely flat-top beam characteristics of excimer laser lift-off systems (Fig. 3), also along the short axis of line beam systems, provide an 80 % effective beam area and support fast rate laser lift-off at uniform energy density applied across the entire carrier with smallest beam overlap and hence a minimum number of UV pulses per carrier.

Pulse-on-demand – saving laser pulses in practice

Laser pulses and those in the UV spectral region in particular come at a cost. These costs are associated with the pulse-limited wear and tear of certain laser consumables such as optical components. At Coherent, excimer laser lift-off systems such as the UVblade family are designed for operation in the pulse

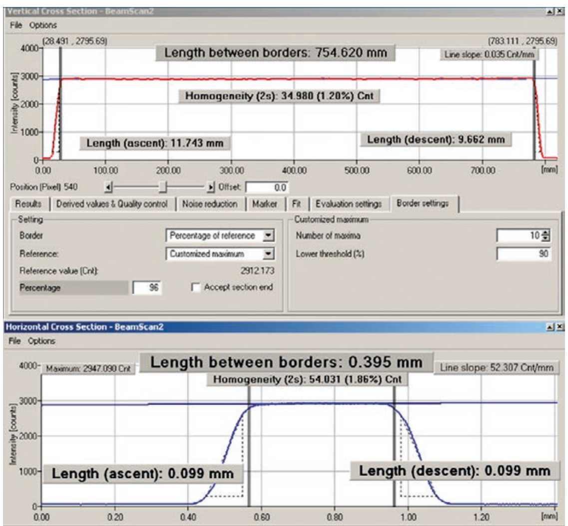

Fig. 3 Cross sections along the horizontal axis and the vertical axis of a 750 mm long excimer laser line beam.

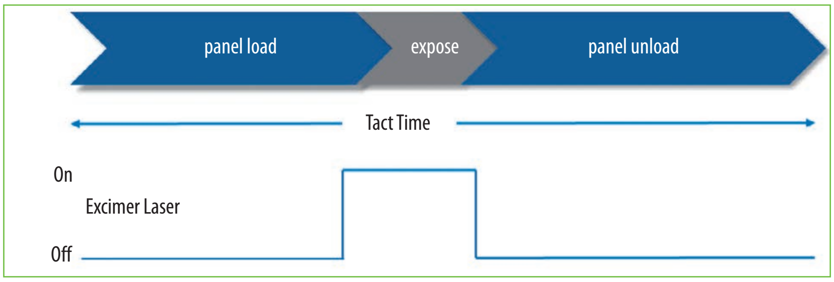

Fig. 4 Minimization of total laser pulse number via excimer laser pulse-on-demand mode versus continuous mode in laser lift-off processing.

saving pulse-on-demand mode. In practice, during laser lift-off processing in a flexible display fab, the UV laser system only fires less than 40 % of the machine's tact time. With the pulse-on-demand mode, selectable for the excimer laser the laser lift-off system only fires during panel exposure and not during the times required for stepping or panel loading and unloading and other idle times (Fig. 4). Pulse-on-demand thus greatly reduces the number of laser pulses per panel and consequently the cost of operation per panel. The manufacturer can thus directly relate the laser operation costs to the generated value. By virtue of the minimized pulse accumulation of pulse-on-demand excimer laser systems are typically operated over periods in excess of five years under industrial production conditions without significant maintenance and with an overall equipment uptime of more than 95 %.

Depth-of-field – compensating height deviations over large areas

One of the most important factors in achieving high yield when large display carrier panels is the depth-of-field of the laser lift-off system. Due to the high pulse energy available from state-of-the-art excimer lasers, a line beam imaging system is designed with low numerical aperture resulting in a very high depth-of-field of the order of ± 150 µm (Fig. 5). Changing the substrate plane in vertical direction relative to the line beam focal plane results in a line width change of about 2 % when measured at 50 %, 90 % and 96 % line width levels. Substrate height variations during panel scanning are thus largely unnoticed. On the contrary, frequency-tripled solid-state lasers need higher focusing as they deliver low pulse energy at UV wavelengths. As a consequence, solid state systems have depth-of-field of only some 20 µm. This severely reduces the process window margin in the case of larger carriers and suboptimal stage accuracy

Summary

In conclusion, laser lift-off in conjunction with the enabling UV power of modern excimer lasers has become a key technology for high yield thin layer release in the manufacturing of the next generation of lightweight and flexible microelectronic devices. In excimer laser-based lift-off systems, both, large depth-of-field, all flat-top beam characteristics, and the superior pulse stability of a native pulsed UV laser technology unite to the perfect carrier separation tool. Excimer lasers uniquely provide the necessary pulse energies and optical performance characteristics to support square centimeter scale processing areas with optimum beam geometry for fast debonding of carrier wafers up to 300 mm diameter as well as for detaching large display glass substrates.

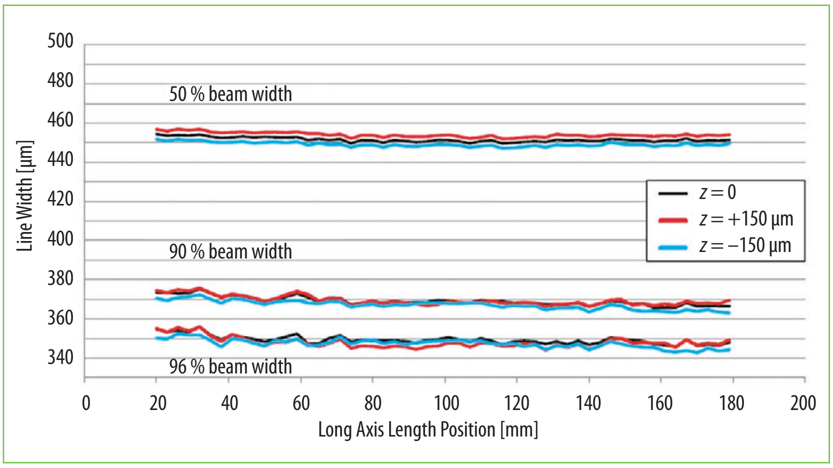

Fig. 5 Short axis line width measured as a function of shifting the vertical substrate position.

Author

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