

Lasers in Manufacturing Conference 2013

Large-area laser-lift-off processing in microelectronics

R. Delmdahl*, R. Pätzelt, J. Brune

Coherent GmbH, Hans-Böckler-Str. 12, 37079 Göttingen, Germany

Abstract

Laser lift-off is an enabling technology for microelectronics growth markets such as light emitting diodes, densely packaged semiconductor devices, and flexible displays. For example, thin film transistor structures fabricated on top of polymer layers spun on glass carriers must be delaminated from rigid substrates to create lightweight and rugged flexible displays on polymers. Low-thermal-budget processes are generically required to protect adjacent functional films. Excimer lasers provide short UV 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.

© 2013 The Authors. Published by Elsevier B.V.

Selection and/or peer-review under responsibility of the German Scientific Laser Society (WLT e.V.)

Keywords: Excimer laser; laser lift-off; HB-LED; flat panel display; thin wafer debonding

1. Introduction

UV laser lift-off delamination opens the path to both novel three-dimensional wafer-based electronic device structures and polymer-based active matrix display panels such as AMOLED for smartphones, reader, tablets and potentially large size TV.

The proper choice of wavelength, optical system and fluence enables layer-selective laser lift-off (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 is continuously downscaled. Such trends motivate the ongoing development of suitable excimer laser sources and optical beam delivery systems for the most appropriate 248nm and 308nm wavelengths, respectively.

* Corresponding author. Tel.: +49-551-6938-397 ; fax: +49-6869-1 .

E-mail address: ralph.delmdahl@coherent.com .

Next to elucidating the necessary ingredients for a defect-free delamination of micron thin layers covering large size wafers and even entire display substrate panels, it is imperative to familiarize machine builders with the achievable throughput metrics in excimer laser lift-off processing.

2. Laser-Lift-Off Processing

Laser processing is a key technology in driving new developments in microelectronics. Owing to the fact that laser radiation is locally and flexibly applicable as well as a non-contact type of interaction, laser processes are particularly suited for manufacturing thin microelectronic components. For a recent overview on excimer lasers in microelectronics see Delmdahl, 2010. Furthermore, lasers in industrial production often eliminate the use of hazardous, wet-chemical substances for etching or post-processing. The Laser-lift-off process step comes into play as soon as the manufacturing strategy demands for a gentle separation of thin layer systems. Mostly, the reason is to achieve a transfer of a microelectronic functional layer onto a new substrate which is of less weight and thinner, respectively, and owing to its physical properties improves the performance of the final module. Laser-lift-off separation of the two layers mostly occurs by means of selective laser ablation and evaporation of a strongly absorbing interfacial area. Frequently, this is an isolating polymer layer. It is of utmost importance, that the adjacent microelectronic functional layer is not deteriorated by the laser energy. Therefore, the laser-lift-off method for selective thin layer separation has become the realm of short-wavelength lasers and of the excimer laser at wavelengths of 248 nm and 308 nm, in particular.

The absorption depth of excimer laser radiation in commercial polymers for microelectronics is just a few hundred nanometers with typical polymer layer thicknesses extending from some ten to some hundred micrometers. As a consequence, laser-lift-off separation with short-wavelengths occurs entirely unnoticed by the adjacent performance determining functional layer. The absorbing interface is not necessarily a polymer as is illustrated in section 4. In any case, however, the layers which are found in today's microelectronic components are generally very thin with thicknesses in the micrometer range and the wavelength and the absorption depth, respectively, should therefore be as short as possible. Excimer lasers are thus the laser technology of choice ensuring a highly selective, functional layer preserving laser-lift-off delamination.

Microelectronics production uses wafers of increasing diameter up to 300 mm. Digital display applications in turn already employ rectangular glass substrates extending up to 5 m² in size. In order to achieve fast and reproducible laser-lift-off separation over such large areas on an industrial scale, two industry-proven optical processing strategies based on excimer lasers are fundamentally applicable. They differ as to the geometry of the homogeneous laser field on the substrate. As shown in fig.1, laser-lift-off processing occurs either via scanning the substrate using a only a few 100 μm wide line beam of appropriate length (line-scan-method) or via stitching rectangular fields (step-and-repeat method).

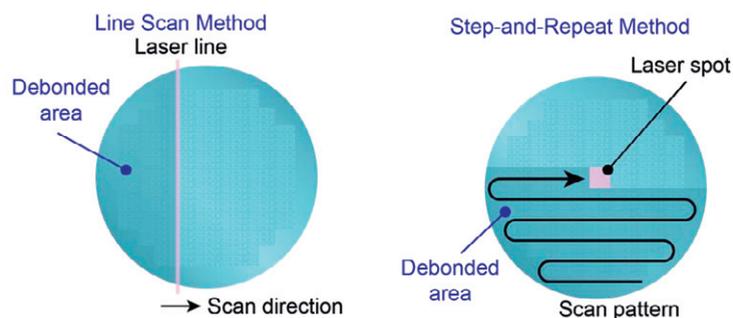


Fig. 1. Fundamental strategies for fast large area processing using the excimer laser

Both processing strategies are suitable for wafer based laser-lift-off, whereas in the case of the much larger display substrates exclusively the line-scan-method has been adopted. 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 generation-8-size substrates (2,500 x 2,200 mm²). The extraordinary full length homogeneity of a line beam field of 1.24 percent given for the two sigma confidence interval is depicted in fig.2.

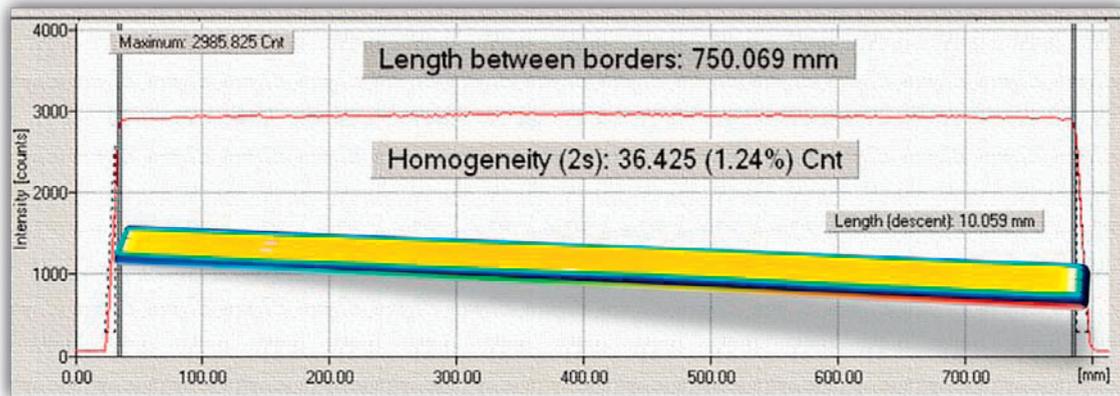


Fig. 2. Long axis cross section of the energy distribution of a 750 mm long line beam field

3. Flexible Display Manufacturing by Laser-Lift-Off

Flexible displays, whether they will be employed in smartphones, tablets or e-readers, have always share a common feature: The backplane of circuit layers used to individually drive each pixel are no longer situated anymore on a rigid glass carrier but instead on a flexible polymer foil. This is, in fact, independent of the display technology which will be used in the final display nor must the final device containing it be bendable. Polymer-Backplanes can drive an LCD, an OLED or an electrophoretic display. In the latter display type, the transition from the ca. 1 mm thick glass carrier to the just about 100 μm thin polymer foil leads to a 50 percent reduction in weight and a 30 percent reduction in design height. Another general advantage is the ruggedness of the flexible display against mechanical impact.

The market for flexible displays will increase sixfold to more than three billion dollars within the next five years according to sales revenue forecast by market researchers from MarketsandMarkets. Flexible displays based on polymer foil are among others produced by Samsung under the trademark name YOUM and by E-Ink in collaboration with LG. This innovative and promising display type is supposed to revolutionize next generations of smartphones, tablets und e-readers.

The essential process steps used for the fabrication of flexible displays are schematically illustrated in fig.3 in this example forming part of an electrophoretic display as it is commonly applied in 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 (TFTs) followed by the display frontplane which contains the layers for electrodes and microcapsules. Finally the transition from rigid to flexible display is realized by laser-lift-off processing. Technically, the excimer laser line-beam of a wavelength of 308 nm is shown through the carrier glass substrate on the polymer. Only the polymer in direct vicinity of the glass substrate, i.e. to a depth of ca. 200 nm is evaporated; each area by a single pulse of ca. 25 ns using an energy density of ca. 275 J/cm².

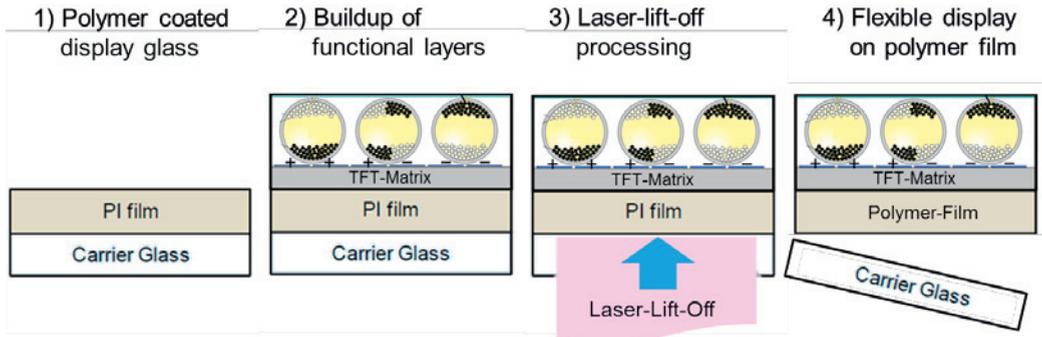


Fig. 3. Fabrication scheme of flexible displays by means of laser-lift-off

By appropriately moving the substrate under the pulsing laser line beam field it is possible to cover an entire generation 4 display panel (730 mm x 920 mm), from which about 55 displays with 6 inch diagonale are obtained. Fig.4 depicts a glass carrier which has been coated with a 100 μm polyimide film. After laser-lift-off at a wavelength of 308 nm applying the line-scan-method the polyimide film was easily delaminated without the need for any post-processing.

A huge advantage of starting from temporary glass substrates in combination with laser-lift-off 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 for major investments in completely new production equipment.



Fig. 4. Polyimide coated display glass substrate delaminated via laser-lift-off

4. Laser-Lift-Off Debonding of Thin Wafers

Owing to increasing functional density and ongoing miniaturization in consumer electronics a steady change from planar integrated chip architectures to vertically stacked chips is visible. The increase in packing density along the third dimension, hence the technical expression 3D integration, permits at the same time shorter signal pathways and a higher data transfer rate at reduced energy consumption. Moreover, this approach enables the integration of various functional chips such as processors, sensors, memories and radio communication interfaces in a single chip. In order to increase the packing density effectively, the gain in lateral dimensions must however not be achieved at the expense of design height as indicated in fig.5.

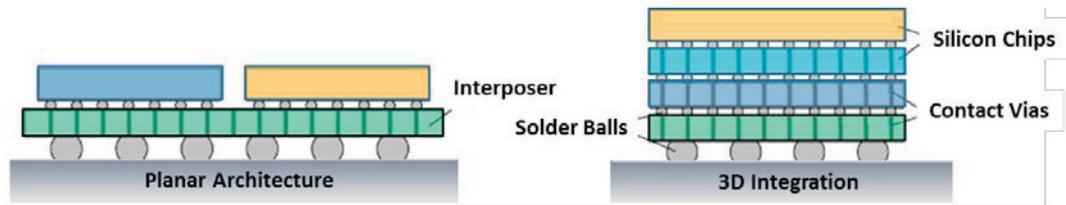


Fig. 5. Illustration of the transition from planar to vertical chip integration

From a manufacturer's standpoint this requires that the functional chips and hence the entire silicon wafers need to be thinned from standard thicknesses of about 800 μm to between 200 μm and 10 μm depending on their application. According to the latest market research by Yole, by the year 2017 a fraction of three quarters of all processed silicon wafers will be thinned wafers with a thickness below 100 μm .

The essential thin wafer handling process steps are schematically depicted in fig.6. In order to ensure a safe and stable handling of the thinned wafer over the course of many manufacturing steps, the wafer will prior to thinning be bonded with its already structured frontside to a carrier wafer made of glass. As temporary adhesive bonding material polymers are frequently used. See, for example, Zussman et al., 2010. Subsequently, the silicon wafer will be thinned and undergoes the various processes involved in backside structuring. Depending on the process step temperatures as high as 400 $^{\circ}\text{C}$ will be achieved rendering temperature stable polymers such as polyimide the adhesive material of choice.

At last, the glass carrier will be separated via laser-lift-off from the finished thin wafer. To this end, the excimer laser beam at a wavelength of 308 nm and an energy density of 275 J/cm^2 is shown through the glass carrier wafer. Again, only the polymer in direct vicinity of the glass substrate, i.e. to a depth of ca. 200 nm is evaporated and the functional layers will not experience any physical alteration.

To achieve full-area laser-lift-off in the case of a 300 mm wafer about 1,000 laser pulses are sufficient. Thin wafer technology in conjunction with laser-lift-off debonding enables the assembly of highly-integrated multi-layer 3D chips, e.g. for use in advanced smartphones, with a total design height of less than one millimeter.

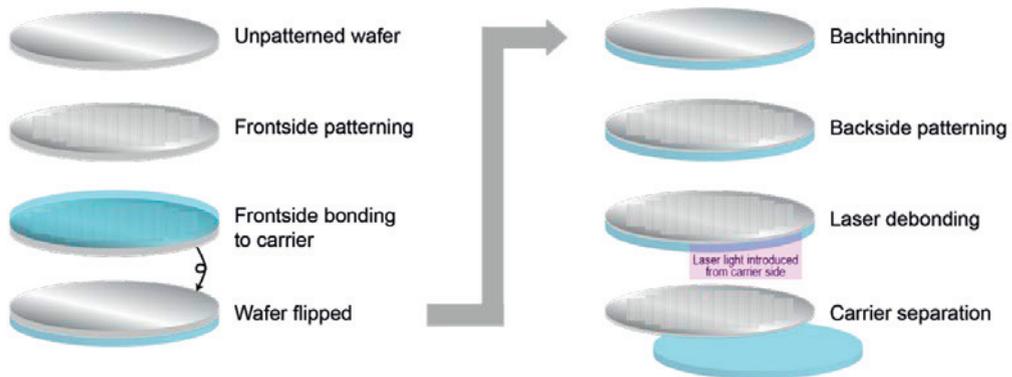


Fig. 6. Handling of thin silicon wafers via laser-lift-off debonded glass wafers

5. Laser-Lift-Off in the Production of Vertical High-Brightness Light-Emitting Diodes

Compact and energy saving light emitting diodes (LEDs) are present in today's smartphone displays, TV screens and automobiles. Almost 100 percent of mobile displays use LED backlighting. The current market growth of LEDs, largely triggered by governmental energy-saving policies introduced in most of the developed countries comprising the abolition of the incandescent light bulb is seen in general lighting. Starting in 2015, high-brightness-LEDs will reach a higher market share than energy saving lamps according to various market research firms. By the year 2016, the demand for high-brightness-LEDs for general lighting applications is supposed to rise from an actual amount of 3 billion US dollars up to almost 6 billion US dollars.

For the illumination of streets, public places and buildings high-brightness LEDs must deliver highest white-light output performance in the range of 150-250 lm/W.

This performance target is achieved based on blue LEDs made from crystalline gallium nitride (GaN) layers, which are generally grown with highest quality on sapphire wafers. By combining the blue GaN-LED light with phosphor material, emitting yellow light, a white light emitting high-brightness LED is obtained from the blue emitting GaN-LED.

Although sapphire is the growth substrate of choice for epitaxial GaN layers, it limits the performance of the final LED device. This is due to the fact, that in comparison with metals it has a poor electrical and thermal conductivity. During the production of high-brightness LEDs of the latest generation, the GaN-epiwafer will therefore be contacted and bonded to a better suited metal wafer (see fig.7). After that the sapphire wafer will be gently removed from the thin GaN epilayer system by means of laser-lift-off. Employing the appropriate laser parameters, the sapphire wafer can be re-used multiple times generating significant cost-saving potential.

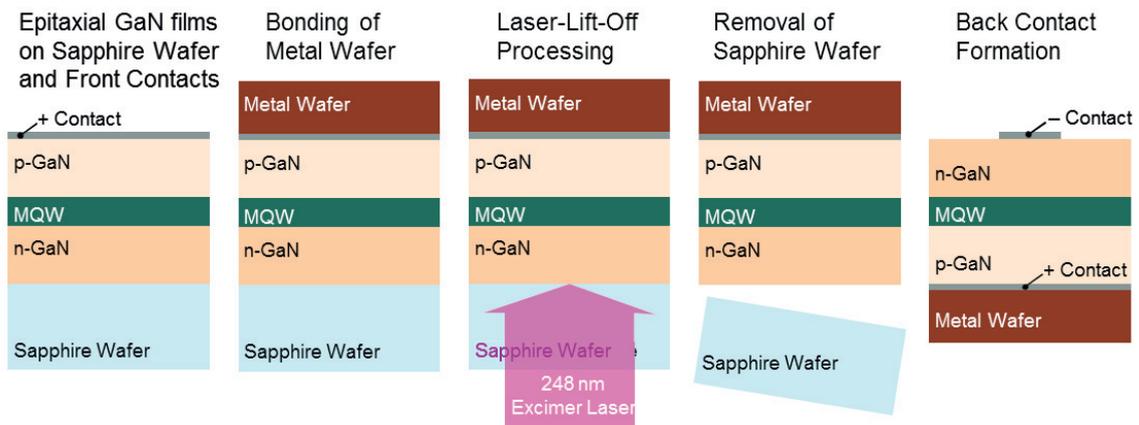


Fig. 7. Fabrication of vertical GaN-LEDs via laser-lift-off sapphire removal

The separation of the sapphire wafer from the GaN layer is best achieved with the 248 nm wavelength illuminating the GaN through the sapphire wafer. At such short wavelength regime sapphire shows virtually zero absorption, whereas the functional GaN layer absorbs very strongly. Therefore, the absorption depth of 248 nm photons is only about 0.1 μm at a typically applied laser energy density of 750 mJ/cm^2 . Only the interfacial section of the overall 5 μm thick GaN layer system is thus affected by the laser energy. In this case, the laser energy does not lead to ablation of material but to selective thermal decomposition of the GaN into

metallic gallium and nitrogen gas. As the uppermost metallic gallium layer melts at 30 °C, the sapphire wafer is easily removable at slightly elevated temperature. The light emitting multi quantum well (MQW) region is still two microns away from the decomposition zone and hence maintains its structural integrity.

Full-wafer laser-lift-off separation of sapphire is possible both via the line-beam method and via the step-and-repeat method using quadratic laser fields. Light microscopic images depicted in fig.8, show the gallium surface pattern after laser-lift-off processing using a line beam (A) and a quadratic laser field (B). As has been shown by Delmdahl et al., 2012, the pattern is due to shallow trenches of a depth of below 100 nm generated in the overlap area of two adjacent laser pulses. As the decomposition of the interfacial GaN requires just one pulse per area, a 150 mm diameter sapphire wafer is entirely rastered by only a few thousand laser pulses.

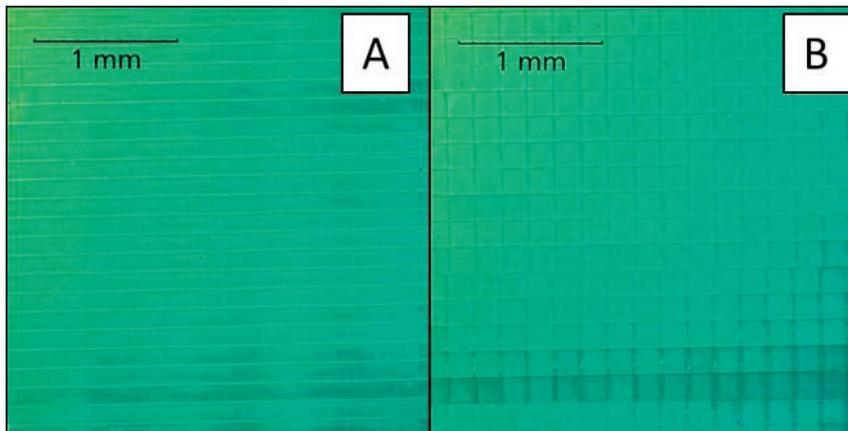


Fig. 8. Gallium surface after laser-lift-off using line scan (A) and square field stitching (B)

The laser-lift-off mediated transfer of the GaN epilayer from the temporary sapphire growth substrate to the final metal wafer eliminates the trade-off between optimum growth and optimum heat dissipation of the LED. Moreover, the metal substrate design can be contacted on the frontside and on the backside, which leads to a less limited current flow spreading out perpendicularly to the MQW layer. Hence the name vertical high-brightness LEDs. Vertical high-brightness LEDs can be operated at much higher currents and also be scaled to large chip sizes of up to 1.5 mm x 1.5 mm resulting in significantly increased light output per LED chip. At the same time, the overall LED chip thickness can be reduced to below 150 μm .

6. Conclusion

Laser-lift-off is a well-established and enabling technology for material-friendly substrate separation in the industrial production of microelectronic components requiring high performance at shallow design heights. Excimer lasers deliver the necessary pulse energies in the short wavelength regime, which are mandatory for highly selective, large area laser processing. The large processing footprint of excimer laser based optical systems enables wafers of all diameters and display glass substrates up to generation 8 size to be entirely rastered at industrial process speed.

Acknowledgements

The authors gratefully acknowledge Rolf Senczuk from Coherent GmbH for valuable application testing and helpful discussions.

References

- Delmdahl, R., 2010. The Excimer laser: Precision Engineering, *Nature Photonics* 4, p. 286.
- Zussman, M., Milasincic, C., Rardin, A., Kirk, S., Itabashi, T., 2010. Using Permanent and Temporary Polyimide Adhesives in 3D-TSV Processing to Avoid Thin Wafer Handling, *J Microelectronics and Electronic Packaging* 7, p. 214.
- Delmdahl, R., Pätzel, R., Brune, J., Senczuk, R., Göbner, C., Moser, R., Kunzer, M., Schwarz, U., 2012. Line Beam Processing for Laser Lift-Off of GaN from Sapphire, *Phys Status Solidi A* 209, p. 2653.