Laser lift-off: reducing device heights in microelectronics by means of substrate transfer

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There is an inevitable trend towards lighter, slimmer and yet increasingly powerful mobile consumer electronic devices. Reducing size and weight of a terminal device while at the same time adding functionality requires microelectronic devices thin as a euro banknote (0.1 mm). An economical manufacturing of semiconductor structures employing ever larger and thinner substrates is enabled by means of excimer laser-based substrate removal (laser lift-off). The sensitive circuit structures remain unchanged during the highly selective laser lift-off process.

Laser processing has become a key technology in microelectronics frequently fostering innovative developments. Due to the non-contact mode of operation, and the capability of being applied selectively and flexibly, laser-based methods are especially well suited for the fabrication of thin and ultrathin microelectronic devices. Furthermore, introducing the laser into industrial production often eliminates the need for environmentally harmful, wet chemistry processing steps [1].

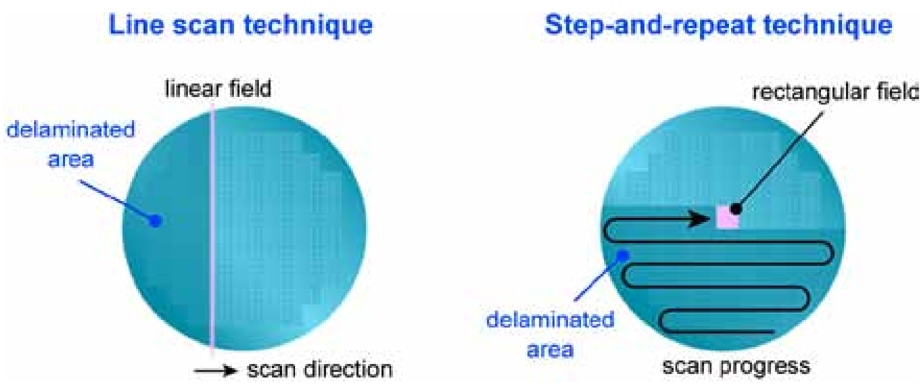

Figure 1: Strategies for fast, large area treatment using an excimer laser

The laser lift-off method

When it comes to gently separating distinct layers as part of a production process, the laser lift-off method is particularly suitable. The concept involves transferring a microelectronic functional layer to a different substrate, which is lower in weight, thinner, and due to its physical properties, improves the performance of the final device, respectively. The separation of layers is mostly achieved via selective laser ablation and evaporation of a strongly absorbing intermediate layer, which is typically a polymer film. The pivotal point is that the adjacent microelectronic functional layer remains unaffected by the energy of the laser radiation. To this end, the laser lift-off method for selective layer separation is based on short wavelength lasers, and excimer lasers in particular. For polymers which are employed in microelectronics at film thicknesses of some 10 to 100 µm, the absorption depth of a UV laser is of the order of only 0.1 µm. Hence, laser lift-off separation of the polymer remains at the short UV wavelength completely unnoticed by the performance-determining functional layer.

Microelectronics production employs increasingly large wafer diameters, extending up to 12 inches. In the digital display market segment, processing is conducted on rectangular glass substrates having an area of up to 5 m^2. For fast and reproducible layer separation on such extended areas, and on an industrial scale, two excimer laser processing strategies can be applied in the case of wafers. Their main difference is the geometry of the homogenized laser field on the substrate. Covering the substrate area for laser lift-off processing occurs either by means of scanning a line beam of an appropriate length or via stitching rectangular laser fields (**figure 1**).

As for the significantly larger glass substrates, which are used only for digital displays, line scan techniques have become established. To this end, homogeneous lines up to 750 mm in length are available and ensure a fast separation of the functional layers on up to 2500 x 2200 mm^2 glass substrate area.

Flexible display production

Flexible displays, whether they will be used in a smartphone, tablet, or e-reader, have one thing in common: the thin film transistor matrix controlling the individual pixels is no longer situated on a rigid glass carrier but instead on a bendable polymer film. It makes no difference which display technology is applied in the final display. Neither must the end product, which contains a flexible display, be bendable. Polymer based display backplanes can control an LCD, an OLED, or an electrophoretic display. For electrophoretic displays the transition from about 1,000 µm thick glass to about 100 µm thin polymer film leads to 50% reduction in weight and to 30% reduction in device height. An additional advantage is the higher resistance of a flexible display against shocks.

The most important process steps in the manufacture of flexible displays are illustrated in **figure 2** using the example of an electrophoretic display as it is regularly used in e-readers.

As a first step, a common rectangular glass substrate serving as a temporary carrier is coated with a 100 µm thin polymer film, which is subsequently cured. On the cured polymer layer, the backplane of silicon circuits, i.e. the matrix of thin film transis-

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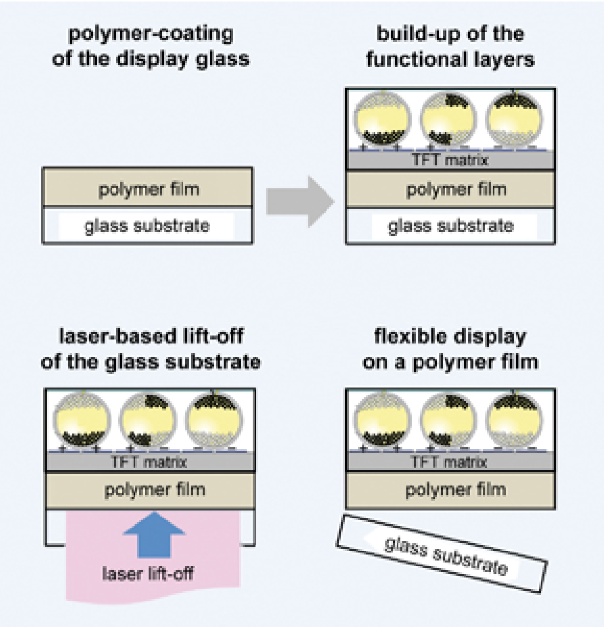

Figure 2: Process schematics of flexible display manufacturing using laser lift-off

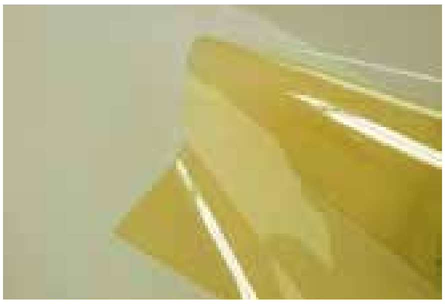

Figure 3: Polyimide coated display glass after laser lift-off separation

tors (TFTs) is built sandwiched by additional layers of electrodes and microcapsules the so-called frontplane.

The formation of a truly flexible display occurs only within the last process step. Here, the line beam of an excimer laser having a wavelength of 308 nm is focused through the carrier glass onto the polymer film and evaporates a thin fraction of the polymer layer most adjacent to the glass. This happens within a single laser pulse and at an energy density of about 200 J/cm^2. Hence, using a generation 4 glass carrier of size 730 x 920 mm^2 a couple of thousand laser pulses is sufficient for gently, releasing over 55 flexible, polymer based, 5 inch displays. The photograph shown in **figure 3** demonstrates the material-friendly nature of the process. The 100 µm thin polymer film is easily delaminated in one piece from its glass carrier following excimer laser lift-off at 308 nm.

The smooth transition from rigid glass based displays to flexible polymer based displays is the main benefit for display manufacturers in using temporary glass carriers and laser lift-off release because there is no need for investing in new production equipment.

Laser debonding of thin wafers

The increasing functional density and the on-going miniaturization in consumer electronics drive the transition from planar-integrated chip architectures towards vertically stacked chip structures. Increasing the package density by involving the third dimension (3D integration) enables shorter signal path lengths and thus higher data processing rates while simultaneously reducing energy consumption. Moreover, a variety of different components such as processors, sensors, memory and radio interfaces can be integrated on a single chip.

In order to effectively increase the package density, the reduction along the lateral dimensions must not be gained at the expense of the vertical device dimensions as exemplified in **figure 4**. From a manufacturer's perspective, this means that individual chips, and hence, silicon wafers must be thinned from a standard thickness of some 800 µm to a thickness of down to 10 µm depending on the application. Reducing the wafer thickness is usually achieved mechanically and via diverse etching methods, respectively.

According to the latest market survey, by the year 2017 three quarters of all processed silicon wafers will be thinned wafers with a thickness of less than 100 µm [2].

In order to ensure secure and stable handling along the process steps, the wafer, prior to thinning and with its already patterned frontside, will be temporarily bonded with a polymer bond to a glass carrier (**figure 5**). Afterwards, the silicon wafer is thinned by means of lapping and polishing. The thinned wafer will then undergo backside processing, which provides the desired functional structures on the wafer

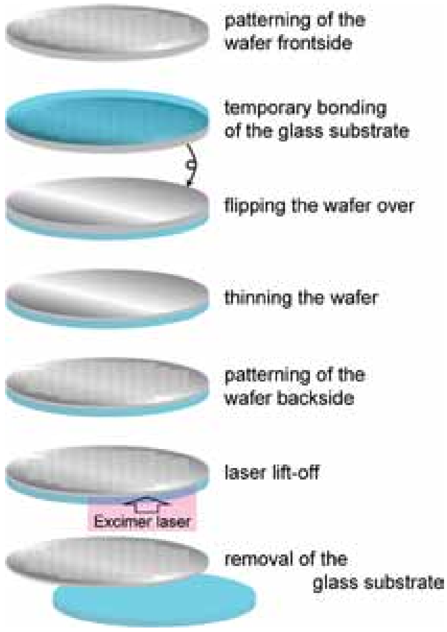

Figure 5: Handling of thin silicon wafers using laser lift-off debonding of the temporary glass wafer

backside. In this way, diverse contact layers and holes for through contacting (vias) can be formed in order to electrically connect front and backside of the chips.

Depending on the individual processing step process, temperatures of up to 400°C can be reached and thermally stable polyimides as bond material connecting carrier and substrate wafers are well-suitable [3].

In a final step, the glass carrier is released from the finished thin wafer via laser lift-off. To this end, the excimer laser is shown through the glass wafer and selectively evaporates the most adjacent fraction of polymer film. Complete debonding of a 12 inch thin wafer requires about a thousand laser pulses. Using thin wafer technologies dense, multi-layered 3D chip packages can be fabricated with a total device height of one millimetre or below.

Fabrication of high-brightness light emitting diodes

In smartphone displays, flat screen televisions, and cars, energy and space saving light emitting diodes (LED) have proven successful already. The growth prospects for

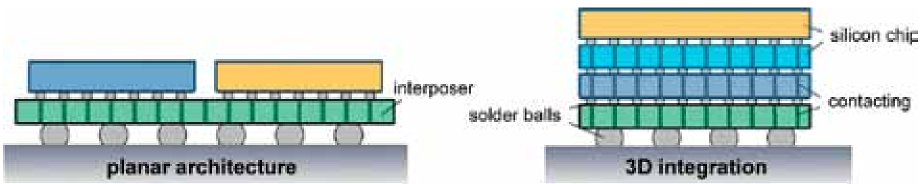

Figure 4: Illustration of the transition from planar to vertical chip integration

Figure 6: Generating vertical GaN-LEDs by laser lift-off removal of the sapphire wafer

the LED market point toward general lighting. According to the forecasts, 2015 will be a landmark year where high-brightness LEDs will command a market share larger than that of the energy-saving light bulbs. By the year 2016 the demand for high-brightness LEDs for solid state lighting is forecast to rise from currently three billion to almost six billion US Dollars.

In order to illuminate streets, public areas and interiors, high-brightness LEDs must provide high white-light luminous efficacies of 150 to 250 lm/W. This is achieved on the basis of blue emitting LEDs containing gallium nitride (GaN) crystal layers, which are grown with high quality on sapphire wafers. By combination with appropriate phosphor material, which upon excitation emits in the yellow spectral range, a blue emitting GaN-LED turns into a white-light LED. Although sapphire is the preferred growth substrate for the GaN layers, it limits the achievable luminous efficacy of the final LED chip on account of its very low electrical as well as thermal conductivity. The production of the latest generation of high-brightness LEDs thus includes a sapphire wafer removal by means of laser lift-off after the GaN layer has been grown and has been bonded to a metal-type wafer as illustrated in **figure 6**. With suitable process management the separated sapphire wafers are reusable as GaN growth wafers.

Separating the sapphire wafer from the GaN is done by means of the 248 nm excimer laser, which selectively irradiates the GaN through the sapphire wafer. At such short UV wavelength sapphire is virtually transmissive while GaN is strongly absorbed. The penetration depth of the 248 nm photons is limited to the GaN buffer layer closest to the adjacent sapphire and at the typically used laser energy density of 750 mJ/cm^2 amounts to about 0.1 µm. To this depth the applied laser energy converts the gallium nitride into metallic gallium, which becomes liquid at about 30°C. The sapphire wafer is thus easily removed from the adjacent layer of metallic gallium which was formed during the laser lift-off process. The about 2 µm lower lying, light emitting multi-quantum-well (MQW) layer remains unaltered during and after laser lift-off step.

The laser lift-off separation of sapphire can either be achieved by using a line beam or by using a square field for processing. The microscope image in **figure 7** shows the gallium surface after laser lift-off processing using a line field (A) and a square field (B). The grooves in the overlap area are well-discernible and are approximately 100 nm deep [4]. As the delamination is achieved within a single laser pulse per area, processing a 6 inch sapphire wafer requires only a few thousand laser pulses using an appropriate processing field.

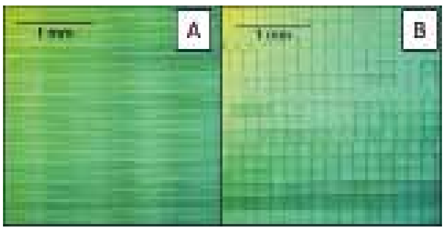

Figure 7: Gallium surface after laser lift-off via line field (A) and via square field (B)

The transfer of the GaN from sapphire to metal substrate, possible by the laser lift-off method, ensures an optimal heat dissipation of the high-brightness LED during operation and due to frontside and backside contacting provides a vertical and thus unrestrained current flow. Hence, the name vertical high-brightness LED. Such a vertical design of an LED enables the operation at significantly higher drive currents and chip sizes up to 1.5 x 1.5 mm^2 can be realized. With substrate transfer vertical LED chips as thin as 150 µm are achieved.

Conclusion

Laser lift-off has firmly established itself as a key technology for gentle substrate separation in the manufacturing of sensitive microelectronic devices with low overall height. Excimer lasers provide the necessary pulse energies in the ultraviolet wavelength regime. Large processing areas with the appropriate geometry can be generated for fast debonding of carrier wafers of all diameters as well as for debonding of large display glass substrates up to generation 8.

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