# Wafer-Level Cameras - Novel Fabrication and Packaging Technologies

Margarete Zoberbier (1), Sven Hansen (1),
Marc Hennemeyer (1), Dietrich Tönnies (1), Ralph Zoberbier (1),

Markus Brehm (2), Andreas Kraft (2),

Martin Eisner (3) and Reinhard Völkel (3)


(1)
SUSS MicroTec Lithography, Schleissheimerstr. 90,
85748 Garching, Germany
Tel.: +49 89 32007 380, Fax: +49 89 32007 167

Margarete.Zoberbier@suss.com.


(2)
DELO Industrial Adhesives, DELO-Allee 1,
86949 Windach, Germany


(3)
SUSS MicroOptics SA, Jaquet-Droz 7,
CH-2000 Neuchatel, Switzerland

# WAFER LEVEL CAMERAS – NOVEL FABRICATION AND PACKAGING TECHNOLOGIES

Margarete Zoberbier [(*,1)], Sven Hansen[(1)], Marc Hennemeyer[(1)], Dietrich Tönnies[(1)], Ralph Zoberbier[(1)],
Markus Brehm[(2)], Andreas Kraft[(2)], Martin Eisner[(3)] and Reinhard Völkel[(3)]

(1) SUSS MicroTec Lithography, Schleissheimerstr. 90, 85748 Garching, Germany
(*) Margarete.Zoberbier@suss.com. Tel.: +49 89 32007 380, Fax: +49 89 32007 167
(2) DELO Industrial Adhesives, DELO-Allee 1, 86949 Windach, Germany
(3) SUSS MicroOptics SA, Jaquet-Droz 7, CH-2000 Neuchatel, Switzerland

*Abstract*

The increasing demand for more functions and features coming along with cost reduction plays a significant role in today's product design and manufacturing technologies of mobile devices such as PDAs, laptop computer and mobile phones. Besides the main function of the device, imaging is considered as core feature by the user and major mobile phone manufacturers. Therefore the industry puts a lot of effort onto performance improvements and the optimization of the manufacturing method of mobile phone cameras. Wafer Level Camera (WLC) is supposed to be the technology of choice to address these requirements.

In recent years Wafer Level Packaging of CMOS image sensors has become a well established technology in the industry. This technology provides a cost efficient packaging method for shrinking devices sizes coupled with higher I/O density.

In addition to this Wafer-level optics is a novel technology that is designed to meet the demand for smaller form factors of the optical system and cost reduction in the next generation of camera phones. The optical components are fabricated by replicating the optics through a stamp material into a polymer layer, coated on a glass wafer. Another key challenge is the wafer alignment. Replicated lens wafers are aligned and adhesively bonded at the wafer level using a UV curing process in order to achieve excellent alignment results. Finally the bonded Opto Wafers are subsequently diced to form individual camera modules [1].

This paper explores the latest fabrication techniques as used in the Wafer Level Cameras (WLC) where Opto Wafers and CMOS-Wafers are mounted by Wafer Level Packaging (WLP) and describes all the challenges and available solutions. The processing issues encountered in those techniques are discussed with a focus on each WLC process step. A typical Wafer Level Camera layout (Fig. 1) is described, the replication of microlenses (Fig. 2) and the packaging of such microlens wafers (Opto Wafers) via UV curing is depicted as well. Also wafer level packaging of the CMOS wafer using bonding techniques is part of this paper. UV curable materials for microlens replication and for Wafer Level Packaging of Opto Wafers (lens stacking) is presented as well. Optical measurement technology for quality assurance of micro-lenses finally concludes the paper.

## Typical Wafer Level Camera Design

Typically a wafer level camera consist of two main pieces, the image sensor and the optics. Figure 1 shows such a schematic cross section of a classical wafer level camera.
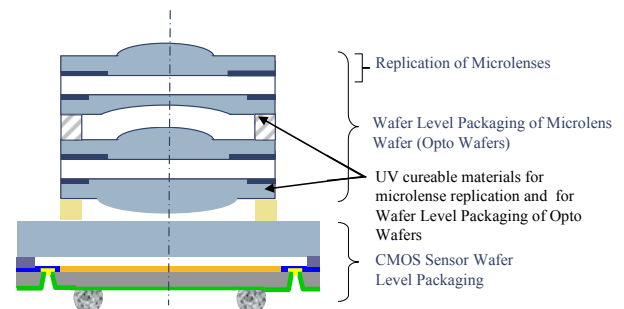


**Figure 1.** *Schematic of Typical Wafer Level Camera Design*



**Figure 2.** *8" Lens Master (left) and replicated 8" Wafer (right) [2]*

## CMOS Sensor Packaging (Glass encapsulation)

In a camera device the CMOS image sensor needs to be covered by a glass layer to protect the active area. This is typically done on Wafer Level using bonding techniques. The challenges in this process are high alignment accuracy and excellent temperature and pressure uniformity to achieve best yield. Void-free bond interfaces are also required. The most popular process is adhesive bonding, chosen because of low bonding temperature (below 200°C). Typically the adhesive is dispensed or rolled on frames located at one of the wafers. The next step is alignment of both wafers. As one of the wafers is transparent (glass) a live alignment is feasible. Due to the sensor dimensions typically the required post bond alignment accuracy is below 10µm. Followed that thermal curing takes place in the bonding chamber, SUSS SB8e. The given pressure uniformity of ±1,5% leads to excellent bonding results. In return the optics is manufactured using other machine types, SUSS MA8 Gen3 Maskaligner equipped with dedicated tooling.

## Fabrication of optical components via UV replication

The replication of optical parts like lenses for WLC is mostly done by molding them from a stamp. Dependent on the method to be used while replicating the lenses, two different stamps are used.

Hard stamps, mainly produced from glass, when the process involves squeezing a dispensed polymer droplet over the wafer area or the structures are embossed into a polymer layer spread over the wafer surface in advance as it is frequently found in hot embossing. Soft stamps, usually produced from silicone rubbers (i.e. PDMS), when the polymer is dispensed into the single lens molds and the lenses are casted by transfer of these polymer droplets onto the supporting wafer (depicted in figure 3). Both methods have their pros and cons.
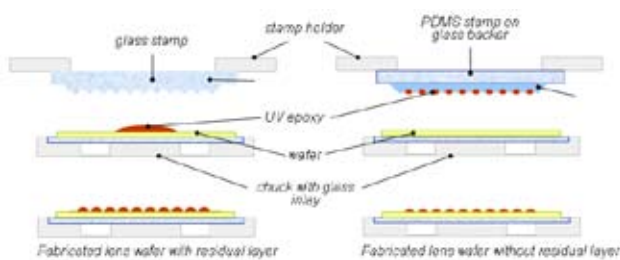


*Figure 3: Comparison between the main imprinting methods. Embossing with residual layer on the left, transfer print without residual layer on the right*

The glass stamp provides a very good control about its total thickness variation (important for the uniformity of the molding result and for the alignment accuracy, as described below) and enables the replication of even the smallest structures due to its high stiffness and resulting contour accuracy. On the other hand the hard stamp requires a base layer as a conformal printing over the whole wafer area is impossible between two hard surfaces. Additionally, imprinting into a predispensed layer requires big forces to displace the material. Machines supporting this imprint method have to be very warping resistant and need actuators that can provide these high forces and allow an active control of wedge errors.

The silicone rubber stamp shows drawbacks as the hard to control total thickness variation, the shrinkage that can appear during stamp production and the worse resolution due to possible deformations in the stamp during imprinting. However, due to its soft surface that adapts to the wafer surface it can produce lenses without the presence of a residual layer. Therefore wafer warpage due to shrinkage of the lens material is strongly reduced. As a side effect also particle contamination is a less serious problem with soft stamps, leading to reduced clean room costs.

As mentioned above, the total thickness variation is not only a problem for the uniformity of the imprint result, but can also cause problems as soon as the replication process includes alignment between the lens layer and the wafer. While a wedge in the stamp can still be compensated by the wedge error correction system of modern mask aligners, substrate warpage or deformations of even higher polynomial grade can not be compensated by the machines. Therefore contact between different points on the wafer area is established at different times and leads to lateral forces between wafer and stamp which are hard to control. These lateral forces are mainly caused by shearing of the stamp material due to the non-uniform load or by viscous forces caused by the non-isotropic flow of glue between the stamp and the wafer.

Due to these forces shifts between stamp and wafer can occur during the imprint process. To compensate for the shifts, processes with multiple approaching and realigning steps are necessary. Especially during the last steps of such an imprinting process the contrast of the fiducials, which are typically produced in polymer during the imprinting process themselves, can be very week. Here only the combination of well chosen microscopic techniques and made to purpose fiducial design can provide images offering sufficient reliability for automated alignment. Fiducial geometry should take care about reducing deformations of the polymer pattern as well as about the needs of the pattern recognition systems.

To achieve highest reliability, the pattern recognition systems need expanded strucutres. Those expanded polymer fiducials may be created by dispensing opaque polymers onto the fiducial region or by creating rough surfaces which cause increased scattering, but further development is needed at this point (figure 4).
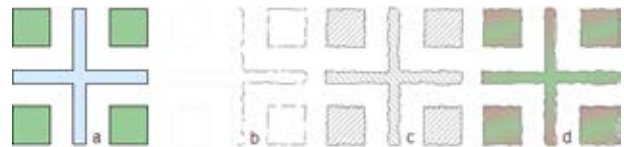


*Figure 4: schematic drawing of polymeric alignment marks and their microscope images. a) mark as designed, b) left half: very weak contrast as obtained with standard reflected light illumination, right half: stronger contrast with transmitted light. Still the pattern is not ideally suited for pattern recognition due to its narrow contrasted structures. c) internal surface patterning of the target to enhance contrast and create expanded structures d) contrast as obtained with DIC microscopy or similar method resulting in better contrasts and expanded structures*

Also transmitted light microscopy can help to increase structure contrast. Besides that, the use of microscopy optics with small numerical apertures and advanced illumination techniques as dark field or DIC (Differential Interference Contrast) may be useful and are therefore options in SUSS machines.

## Wafer Level Packaging of Opto-Wafers

Certainly camera systems consist of several optical elements that need to be assembled quite accurately to provide the best possible optical performance. Until today camera systems have been manufactured by manually assembling lenses into a barrel. This procedure is very costly, time consuming and doesn't seem to be a reasonable approach for the manufacturing of multi level, miniaturized lens stacks that are supposed to be use in modern camera systems for mobile phones.

Wafer level bonding technologies seem to solve this issue. The industry started to use wafer bonding equipment platforms to bond lens wafers with spacer wafers or a

second lens wafer with thermal curable adhesives. For this technology state of the art bond aligning and bonding tools can be use. The wafers with applied adhesive on one of the wafers get aligned, get clamped in a transport fixture and get finally bonded in a substrate bonder. However, this process has limits in terms of the achievable alignment accuracy. The reason is that thermal stress in the bond process and the required handlings from the bond align to the bond tool impacts the alignment accuracy and limits process reliability.

As lens wafers are transparent for UV light the usage of UV curable adhesives seems to be the solution of choice for a cost effective and highly accurate wafer level assembly with "in-situ" alignment on a mask aligner type of equipment. Leading edge mask aligner technologies allow alignment accuracies well below 0.5µm and offer high intensity UV illumination for effective UV curing processes. The sequence of a UV bond is very similar to common mask aligner photolithography. Two substrates have to be aligned in an accurately controlled alignment gap and UV exposure finalizes the process step. However, for UV bonding the Mask Aligner requires a specific substrate holder that includes a UV transparent chucking plate to hold the top lens wafer. This is shown in figure 5. The lower lens wafer is handled onto an exposure chuck which is typically designed for wafer edge handling or for the usage of "buffer wafer". Buffer wafers are typical spacer wafers (glass wafers with holes at the position and with the size of the lenses) that are needed and used to ensure a well defined and controlled distance between lens wafers. Both are dedicated to safely handle the wafers with replicated convex lenses.
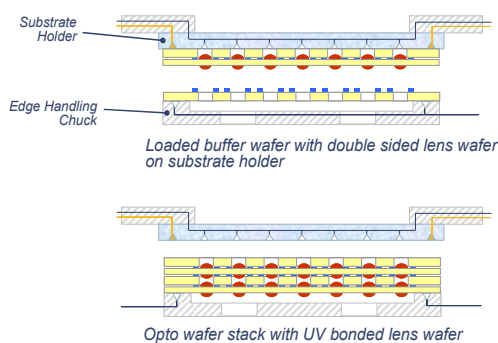


**Figure 5:** *UV bonding incl. in-situ alignment on the SUSS MA8 Gen3 with the usage of buffer wafers*

Besides the alignment and bond equipment, the dispense technology and process play a significant role in the manufacturing of WLC. The dispense volume and pattern of the adhesive need to be controlled to achieve a void free and reliable bond interface. Too much material results in contaminated optical elements while too less material results in leakages of the module itself. The adhesive itself needs to be chosen carefully to fit to the general requirements to be a fast curing, highly reliable, dispensable and last but not least reflow compatible material. In addition material suppliers like DELO offer material with integrated filler particles to achieve a uniform and automatic residual thickness control by the material itself.

With the use of opto wafers with lenses that are embedded in the polymer, roller dispense processes can be

adopted. This offers a much easier dispense process but limits the design of the lens wafer.

High accuracy alignment of opto wafers can be achieved on manual and automatic mask aligners from SUSS MicroTec. As described above, sophisticated toolsets are used to safely handle the lens wafers and to ensure an excellent leveling of both wafers during the gap setting and alignment step. One of the key challenges at the alignment process is the very large distance between alignment fiducials. Depending on the number of wafers to stack, the distance between the alignment targets can get up to several mm. The optical alignment system incl. the microscope and focus settings need to be highly accurate in design and setup. In addition, leading edge technologies like SUSS "Assisted Alignment", which provides live overlay measurements and direct operator feedback, are required to achieve alignment accuracies <0.5µm. Today, WLC lens stacks with sub-micron post bond accuracy are within reach when adopting UV bonding.
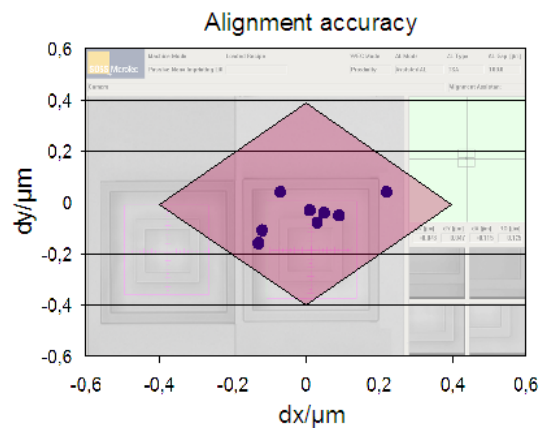


**Figure 6:** *Alignment results obtained during UV-stacking on a SUSS MA8 Gen3. The points represent results measured with the cognex system in the machine. Vernier measurements resulted in alignment accuracy better than the 0.4 µm resolution of the Vernier (red area)*

### Fast UV-curable materials for Wafer Level Camera Manufacturing

UV curing adhesives are currently widely used for mass production in the electronics and optics assembly industries. Depending on the chemical basis – acrylic or epoxy- these materials differ in some of the basic parameters.

Acrylic adhesives are known to be very fast curing, but are limited at high temperature processes and have high polymerization shrinkage. On the other hand, epoxy based system are known for good thermal stability and low shrinkage. Therefore they are used in high reliability applications, like automotive and optical assembly.

The challenge for Wafer Level Optics (WLO) manufacturing is to develop materials with fast curing mechanism, high optical transmission and high thermal stability (reflowable optics).

The following results show the current status of the material development within DELO:

### a.    Fast curing with good adhesion

Due to the reflow requirements in the WLC module and the high throughput needed for low cost wafer level manufacturing, DELO has developed new fast UV-curing epoxy-based adhesives. Referring to figure 7 initial strength of Glass/ Glass samples is reached very fast, at 10 sec after exposure.
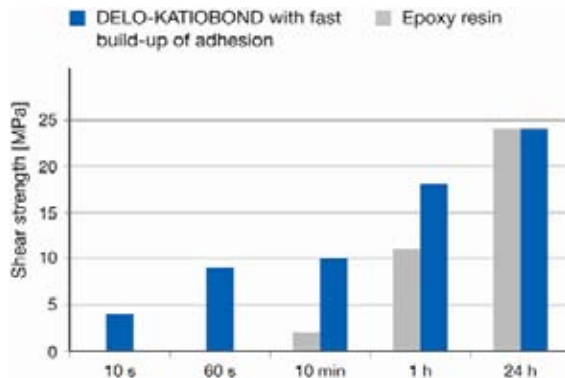


***Figure 7***. *Time of reaching initial Shear Strength after UV exposure, compared to standard UV curing epoxy*

### b.    Adhesion to Stamp Material

For imprint materials, it is very important to have excellent adhesion to glass (wafer), whereby the adhesion to the stamp material should be as low as possible. In our tests, all printed optics wafers could be easily removed from the used stamp material (2 component - silicone).

### c.    Low Outgasing and Low Shrinkage

Another important parameter in optics applications is the outgasing of the adhesive at high temperatures. Looking at process temperatures up to 260°C, one can see, that the weight loss of the DELO KATIOBOND AD VE 18499 is < 2% @ 260°C (Fig. 8).
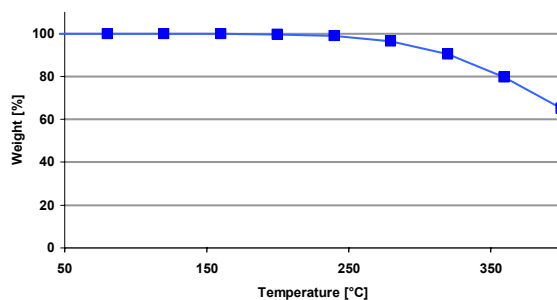


***Figure 8***. *TGA Curve of DELO KATIOBOND AD VE 18499*

The shrinkage was measured at 3 positions on a wafer during the imprint process. Thickness shrinkage was < 1.5%  (Table 1).

| [μm] | Before UV Cure | After UV Cure | Shrinkage |
|---|---|---|---|
| Left | 250 | 246,5 | 1,4% |
| Right | 250 | 246,8 | 1,3% |
| Top | 250 | 246,6 | 1,4% |

***Table 1***. *Thickness change at Curing of DELO KATIOBOND AD VE 18499*

### d.    Reliability Testing

### -    Optical stability

Transmission Measurements were done on 100μm thick foils of cured adhesive with no protection. The foils were analyzed after:
a.    168h Xenon Solar Light exposure
b.    2min @ 270°C (Reflow Simulation)
c.    168 h 85°C/ 85% r.H.
d.    168h 125°

As can be seen on Figure 9, an optical transmission of larger than 80% over the visible range (400nm – 750nm) was achieved for all the conditions tested.
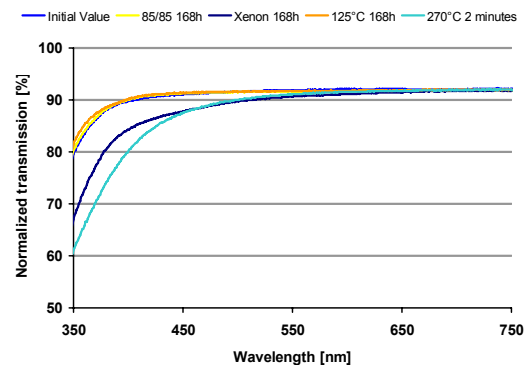


***Figure 9***. *Transmission of 100μm thick foils of DELO KATIOBOND AD VE 18499*

### -    Thermal stability

In order to simulate the mechanical stress in a wafer level optics module, 2 different samples (A, B) were tested:

**A:**    20mm x 20mm x 5mm glass plates with a 500μm adhesive layer

**B :**    4mm x 4mm x 4mm glass cubes with a 100μm adhesive layer

Stress on both samples was introduced by a grinding process to simulate the sawing process and to generate possible micro cracks at the edges of the sample.

- **Samples A  were tested  after 500h 85°C/ 85% r.H.**

The optimized DELO adhesive did not show any delamination, in contrast to some of the standard adhesives.

- **Samples B were run through the following conditions:**

**- Temperature shock test: -40°C → 85°C**

The left picture in figure 10 shows delamination of the standard adhesive at the edge of the sample. The right picture in figure 10 shows optimized adhesive, where no delamination occurs.
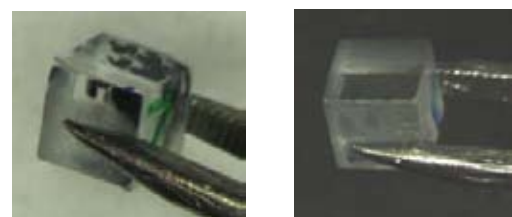


***Figure 10***. *Images after 300 temperature shock cycles*

**- Reflow Condition**

A typical reflow profile was simulated in a temperature controlled chamber. None of the samples did show delamination.

**Characterization of Micro Lenses (Master, Silicon Stamp and Replicated Lens)**

For the measurement of surface deviations the Twyman-Green Interferometer is best suited (Prof. J. Schwider, University Erlangen). The light of a partially coherent source is used to illuminate the interferometer. The deviation of the reflected beam in the test arm (condenser objective / spherical surface) from a plane wave provides the information on the deviations from the sphericity of the micro surface.
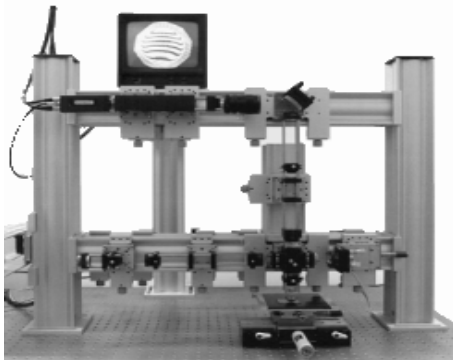


**Figure 1:** *Twyman-Green Interferometer for measuring surface deviations and radius of curvature.*

Besides of the measurement of surface deviations the radius of curvature of a micro sphere can be determined with the help of this interferometer (= difference between basic position and cat's eye position).

The just described interferometer was used to compare the shape of master, stamp and replicated micro lenses.

For the fabrication of the stamp and the replicated lenses the new Mask Aligner MA/BA8 Gen3 from SUSS MicroTec was used. The replicated lenses were fabricated in UV curing adhesives from DELO.

The following table shows measurement values (radius of curvature, deviation from ideal sphere) over 5 points of a 4 inch wafer (centre, right, bottom, left and top) and gives an idea about the very good uniformity which was achieved.

| | Centre | Right | Bottom | Left | Top |
|---|---|---|---|---|---|
| Master | 2221um (0.04λ) | 2216um (0.03λ) | 2224um (0.04λ) | 2246um (0.04λ) | 2239um (0.04λ) |
| Stamp | 2208um (0.04λ) | 2205um (0.03λ) | 2207um (0.04λ) | 2230um (0.04λ) | 2235um (0.04λ) |
| Replica-tion | 2206um (0.04λ) | 2202um (0.03λ) | 2203um (0.04λ) | 2226um (0.03λ) | 2227um (0.03λ) |

**Table2:** *Radius of curvature and surface deviation from ideal sphere (λ = 633nm) for 5 points measured for master, stamp and replicated wafer.*

**Conclusion**

In this paper novel fabrication and packaging technologies were introduced. Some required equipment characteristics were introduced, which are beneficial for processes in creating wafer level cameras, like the in-situ alignment and UV-bonding in one tool.

UV curable materials for microlens replication and for Wafer Level Packaging of Opto Wafers were presented with their attainable parameters. The developed new materials are showing very good optical and mechanical reliability, as well as excellent reflow behavior. Therefore they were selected for further testing for the imprint processes.

Finally characterization of micro lenses was discussed and measurement values of master, stamp and replicated wafer were shown.

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