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Monolithic Lens Array fabrication has emerged over the past decade as a constantly growing market, as it eliminates the requirement of using glass substrates and thereby increasing the scalability and material compatibility of optical devices. In this paper, we discuss the capability of SUSS UV-imprint lithography together with an optically tailored, UV-curable epoxy resin from DELO to manufacture double-sided monolithic wafer-level optics, which enables low cost of ownership and high throughput. Monolithic lens arrays are nowadays a key component in next generation flashlights for mobile phones, high pixel count wafer-level cameras, efficient coupling of light from a VCSEL into an optical fibre [1] and integration of LED arrays and many other interesting applications. When talking about micro optical elements produced at highest numbers at low cost, two competing processes can be considered: Injection moulding and polymer on glass (POG) UV replication. While Injection moulding is a standard process for fabrication of miniaturized optics, such optical elements typically cannot withstand high temperatures. The reason is inherent in the process: During injection moulding a plastic solid material is molten, transferred to a mould cavity and solidifies by cooling down. Unfortunately, the same thing happens when the optical element is heated to high temperatures later on (e.g. when using standard reflow soldering with 260° C peak temperature): The lens would just melt and loose its shape. This means that optics can be produced at high numbers and low cost, but the downstream processing requires additional process steps (such like low temperature soldering, or mechanical clamping) increasing both complexity of the process as well as costs. Another disadvantage of injection moulding is limited alignment accuracy of top to bottom mould resulting in limited optical performance.

POG UV replication can address both problems. Dedicated imprint machines like SUSS MicroTec Imprint Lithography Equipment (SMILE) allow for highest alignment accuracy. At the same time, the mechanism for the transition from liquid to solid is completely changed. The liquid-solid transformation is no longer a reversible melting-solidifying process, but a chemical crosslinking mediates the transformation. As this reaction is not reversible, the material would stay solid and in-shape even when heated to high temperatures (provided that appropriate materials are used). The main disadvantage of POG lenses is that they consist of more than one material (polymer and glass). Effects like internal interfaces, CTE mismatch etc. can lead to reliability issues.

Monolithic UV imprint lithography can combine the best of both worlds. As it is monolithic, it avoids all the trouble of material compatibility and at the same time profits from a highly reliable material.

While monolithic lenses offer significant benefits, there are also challenges, which must be solved in order to enable mass production of high quality lenses at low costs.

Main challenges are:

1. **Obtaining arrays with high Residual Layer Thickness (RLT) uniformity over large areas**
2. **Low aberration and distortion of the lens geometry upon thermal stress**
3. **Precise lens-to-lens alignment**

and

4. **Manufacturing of larger sets of interconnected lens arrays**

In this paper we will demonstrate how the combination of SUSS UV-imprint lithography SMILE in combination with a matching UV curing epoxy imprint material from DELO overcomes these challenges and allows to imprint interconnected and double-sided monolithic lens arrays in a single step, while attaining high throughput, desirable quality and low cost of ownership.

SUSS UV-IMPRINT LITHOGRAPHY

The SMILE imprint technology facilitates reaching the targeted epoxy thickness and a very low Total Thickness Variation (TTV) by means of the SUSS Active Wedge Error Compensation (WEC) technique. This method allows for a constant real-time control over the relative positions of the imprint stamps/substrates with a micrometric precision and force detection. A low TTV is not only critical for attaining high RLT uniformity but also for precisely aligning and producing interconnected lens structures. During the process of reaching the final gap, the viscosity of the imprint materials induces resistance against the Z-axis movement. However, the active WEC technique can sustain a force up to 3 kN, thus it plays a crucial role in accurately reaching the targeted Z-position thus spreading the epoxy to the desired thickness. Through its three axis movement it also allows for a controlled releveling of the layers in the machine if forces should induce changes in the parallelism [4].

The use of silicone polymer stamps on both sides of the imprint ensures the required high transfer fidelity. The combination of PDMS and a rigid glass back plate provide, both, the large area rigidity and the local flexibility that is needed to imprint monolithic arrays. The PDMS part of the stamp assists the conformal imprinting and thereby minimizes the trapped air. Simultaneously the rigid carrier provides the required in plane rigidity while imprinting to achieve good TTVs. In order to achieve the very good overlay accuracies needed for best optical performance, performing an x-y-alignment after each Z-axis movement step is obligatory until the final gap (and hence the target RLT) is reached. This is due to the forces resulting from the flow of the viscous epoxy between the two stamps with arbitrary geometries. These forces can lead to a resulting shear force that generates a shift in lateral directions. Furthermore, the poor contrast of the fiducials on the PDMS stamp (filled with epoxy) during the imprint process makes it challenging for the pattern recognition and automatic alignment systems. To mitigate this issue Back Side Alignment is applied (BSA, higher depth of focus) which gives the opportunity to capture and train fiducials of the top stamp before the alignment features are concealed by the epoxy and allows for a direct view of the targets on the bottom stamp without interference of structures on the top stamp.

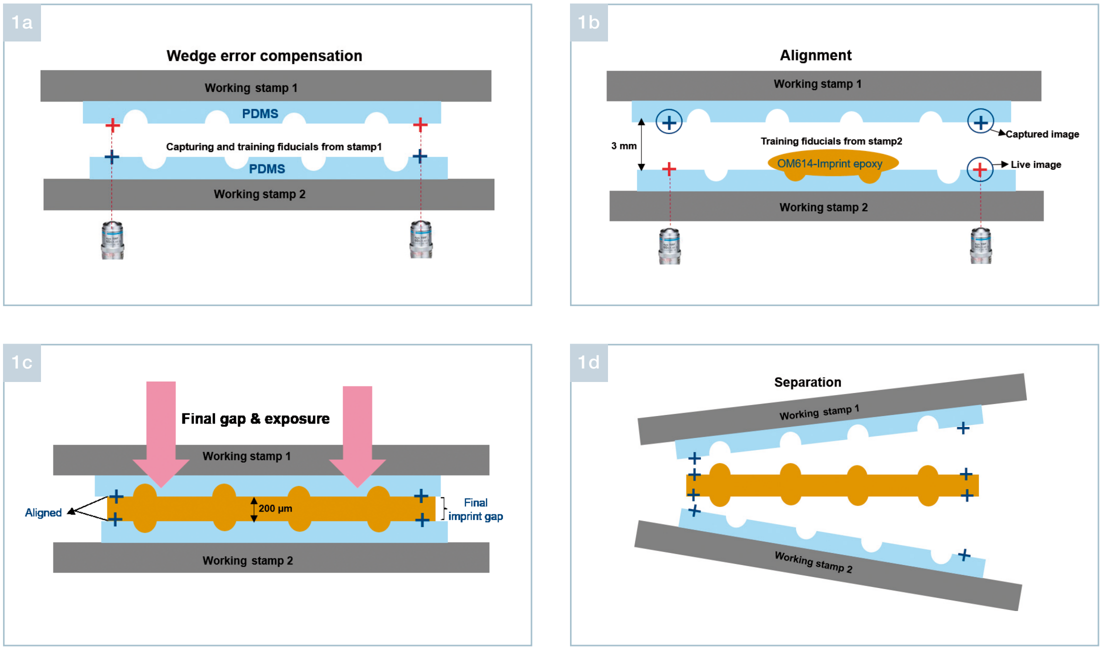

Figure 1 *(a) Performing WEC between the two working stamps and the process of capturing & training fiducials from stamp1 (b) Training fiducials on stamp2 & alignment between the two working stamps with epoxy dispensed on stamp2 (c) Reaching final imprint gap & UV-exposure of the epoxy (d) Separation of the monolithic stack from the working stamps*

General process flow of fabricating monolithic lens arrays is represented in Figure 1a-c.

In the first step, the WEC process levels the two stamps in respect to each other. The alignment targets on the working stamp1 are captured using the BSA microscopes (Fig 1a). Then, the epoxy is dispensed on the centre of the working stamp 2 (Fig 1b). Dispensing epoxy with precise volume and position is extremely important in attaining the desired final RLT while avoiding an overflow of the epoxy. In the next steps the fiducials on stamp 2 are aligned to the grabbed position of the fiducials on stamp 1. The alignment with respect to grabbed positions is needed due to the large gap of up to 3 mm between the two stamps, which makes it impossible to keep the targets of both layers in focus at the same time. The combination of using the grabbed target position from stamp 1 and the live image from stamp 2 allows for reliable pattern recognition and high accuracy alignment, independent of the process gap between the two working stamps. In this paper, the RLT of the monolithic lens array is predefined to be 200 µm. Hence, the realignment and Z-axis movement are performed until the target gap of 200 µm is reached. After reaching the targeted alignment and RLT, the epoxy is exposed for 6 min by using the high intensity i-line band (365 nm) from a broadband SUSS UV-LED unit (Fig 1c) [5]. In the final step, the cured free-standing monolithic lens array is separated from the working stamps, using a SUSS imprint separation tool (Fig 1d).

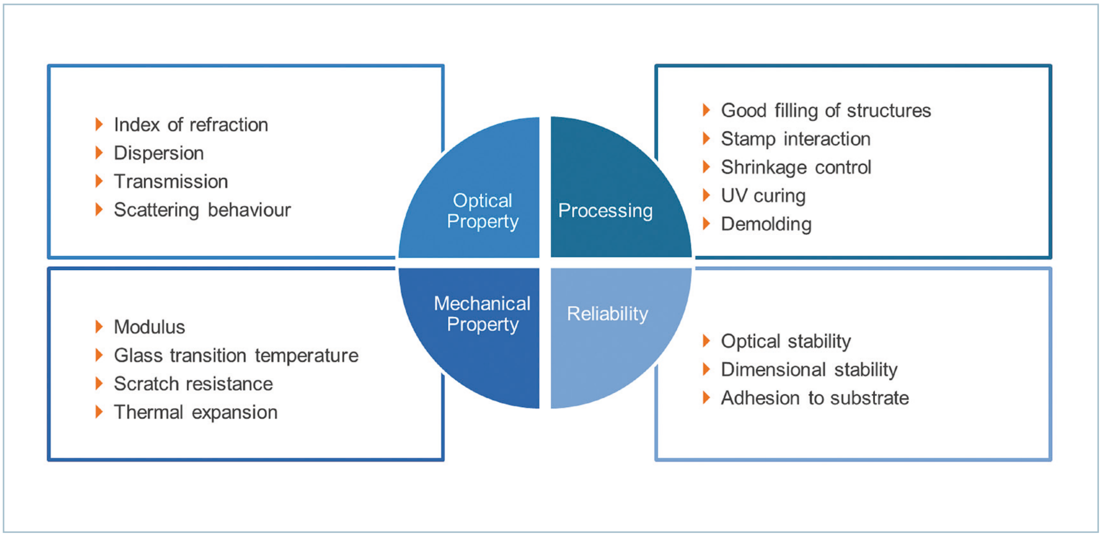

Figure 2 *Many different (and partially competing) properties need to be carefully optimized and balanced*

OPTIMIZED UV CURING EPOXY MATERIALS FOR LENS IMPRINT

When developing or selecting a UV curable imprint material, it is critical to consider and optimize a variety of material properties [6]. These properties can be grouped into four groups as shown in Figure 2.

Rather than trying to optimize a single property (or a group of properties), it is key to balance all these properties. Even the most process-friendly material would need to withstand reliability testing and vice versa. For the work described in this paper, we have chosen to use DELO KATIOBOND OM614, which is a UV curable epoxy material that has been developed for optical imprint application. Besides having a refractive index of ~1.5 (close to standard glass), it shows excellent clarity (low haze) as needed for optical elements.

In terms of process capability, we want to focus on two properties: Compatibility with the stamp and shrinkage. During the imprint process, the liquid imprint material is brought into contact with the stamp (PDMS in the work described in this paper). While still in liquid phase, the imprint material might migrate into the stamp material (Figure 3), giving rise to a change of the stamp geometry by swelling. This might affect the shape of the replicated lens and result in poor optical quality. When cured, it is important that the adhesion of the replicated optics to the stamp material is as low as possible. High adhesion would not only make the demoulding

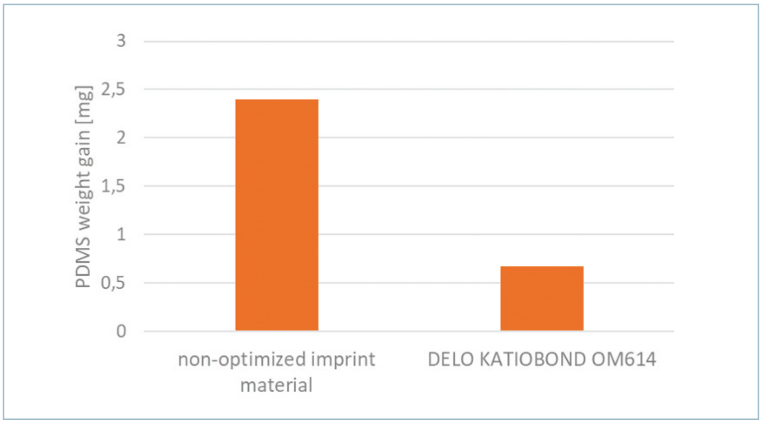

Figure 3 *Typical acrylic or epoxy materials show high migration into PDMS. The formulation of DELO KATIOBOND OM614 has been carefully optimized to reduce such migration. The graph shows weight gain of PDMS after 20 minutes of contact to imprint material*

difficult, but would also lead to higher wear resulting in reduced stamp lifetime which would increase overall process costs. In the case of DELO KATIOBOND OM614 the formulation has been optimized such to reduce both effects.

Shrinkage is key in any imprint process, as the level of shrinkage directly relates to the level of deviation of the replicated lens from the master. In the case of monolithic imprint, shrinkage becomes even more important: Compared to “standard” POG imprint, the overall thickness of the imprint material is much thicker, so shrinkage is more evident. Fortunately, shrinkage can (at least to some extent) be compensated by considering the shrinkage already in the design phase. Therefore, a reproducible and uniform shrinkage is probably more important than the level of shrinkage itself. In order to reduce shrinkage induced variations (like TTV or lens height deviation as discussed in the following paragraph), it is necessary to consider both the process (i.e. machine) part as well as the material part. The machine needs to eliminate as much as possible all variations from the process (e.g. excellent wedge compensation, homogeneous intensity distribution, etc.). The material however needs to provide as much robustness and predictability as possible. “Robustness” in this sense refers to an insensitivity to inevitable variations (e.g. intensity variation from top to bottom of the imprinted structure, see Figure 4) while “predictability” refers for example to a negligible batch-to-batch variation of the level of shrinkage.

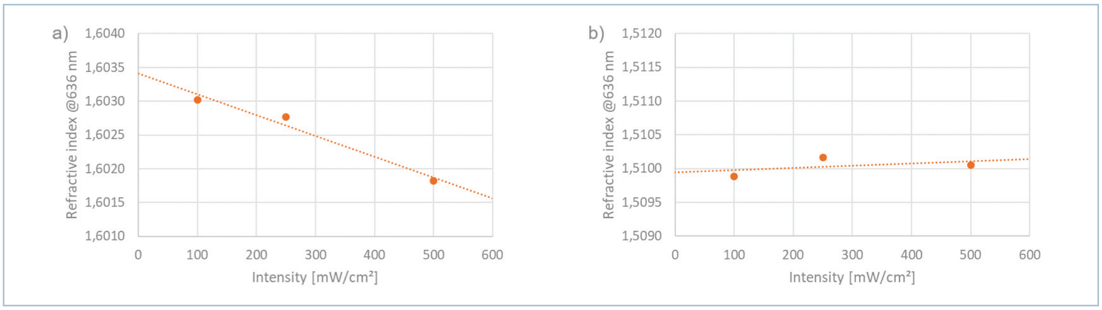

Figure 4 *Refractive index vs. intensity of UV exposure. For a standard UV cure material (a) a clear tendency of lower refractive index with higher UV intensity is visible. DELO KATIOBOND OM614 (b) shows much reduced sensitivity to intensity variation*

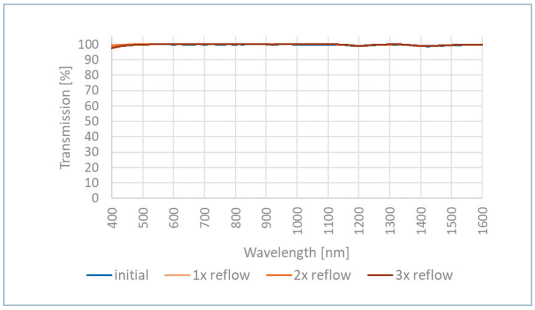

Figure 5 *Transmission spectrum of a 100 µm thick layer of optical imprint material on glass. While typical polymer material would show severe yellowing after exposure to reflow soldering (260° C peak temperature), big efforts were taken to formulate a material that shows very minor yellowing only*

One of the biggest advantages of UV replicated monolithic lenses over standard injection moulded lenses (e.g. from PC) is the ability to withstand a standard reflow soldering process with peak temperatures of 260° C. Such high temperatures are however, a challenge for all organic materials especially concerning yellowing and form stability. While requirements on yellowing might be more relaxed for imprint applications which require thin layers only, monolithic lenses put highest requirements as even low yellowing might introduce visible effects due to the rather high layer thickness. Figure 5 shows the transmission spectrum of DELO KATIOBOND OM614 before and after reflow soldering process.

Monolithic lenses require a hard but not brittle material. Hardness is important to maintain good form stability and scratch resistance. If however the material was too brittle, effects like chipping might happen during dicing process or handling. DELO KATIOBOND OM614's Young's modulus of 3 GPa (at room temperature) is a near-to-perfect balance of these requirements.

RESULTS AND DISCUSSIONS

As discussed in the above sections, manufacturing of fully functional and reliable monolithic lens arrays requires a very good control of RLT uniformity, high transfer fidelity and ultra-high precision of lens-to-lens alignment. The combination of all these factors define how well the outgoing beam deviation and coupling losses are controlled in an ultimate micro-optics stack. All required measurements to qualify the monolithic lens arrays are done using a laser confocal microscope at eight different locations over the 8-inch area. The investigation of RLT uniformity is carried out on five monolithic wafers that are treated under same process conditions. The desired monolithic thickness is 200 µm. The within-wafer and wafer-to-wafer RLT variations are plotted in Figure 6a. The imprints achieve a total thickness variation of < 20 µm and the RLT uniformity of < 10 %, within-wafer and are therefore within typical customer specification limits of TTV < 25 µm. The average RLT varied < 8 µm from wafer-to-wafer. The transfer fidelity of the imprint process is determined by evaluating the lens height and diameter. The lens diameter measurements showed a deviation of ± 2 µm from the 485 µm lens diameter on the master. An overall diameter uniformity of the imprinted lenses of < 1 % is reached, as shown in Figure 6b. The lens height deviation of ± 3 µm from the master's value of 90 µm, with a uniformity of < 3 %, is achieved, as shown in Figure 6c.

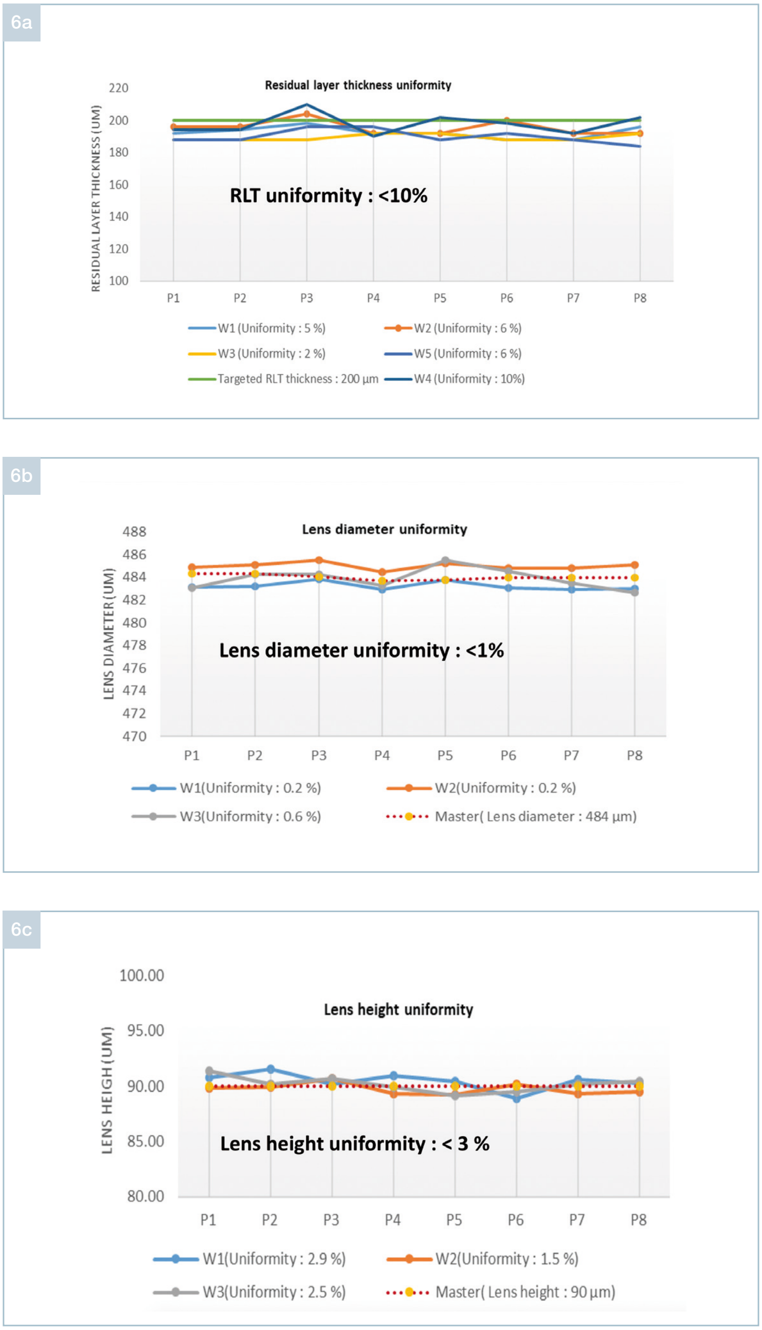

Figure 6a-c *(a) The graph indicates the variation in final thickness for four different wafers and show overall & each wafer RLT uniformity (b) the graph displays the variation in lens diameter and uniformity for three different wafers (c) the graph shows the variation in lens height and uniformity for three different wafers (d) picture of a double sided monolithic lens array*

Measurements of a set of three wafers resulted in a front to back alignment accuracy of < 1.3 µm for double-sided monolithic lens arrays, based on the equation

$$\mathrm{Max}\,[\,(X_L + X_R)\,/\,2,\ (Y_L + Y_R)\,/\,2\,)\,]$$

In addition, the employed DELO epoxy showed minimal adhesion problems with the PDMS material. In our tests, we could successfully separate all imprinted monolithic lens arrays from the working stamps. Moreover, no micro cracks or discolorations from the epoxy were observed.

Picture of a freestanding, full wafer-level monolithic lens array sheet fabricated using SUSS Imprint Lithography Equipment and DELO epoxy resin is shown in Figure 6d.

6d

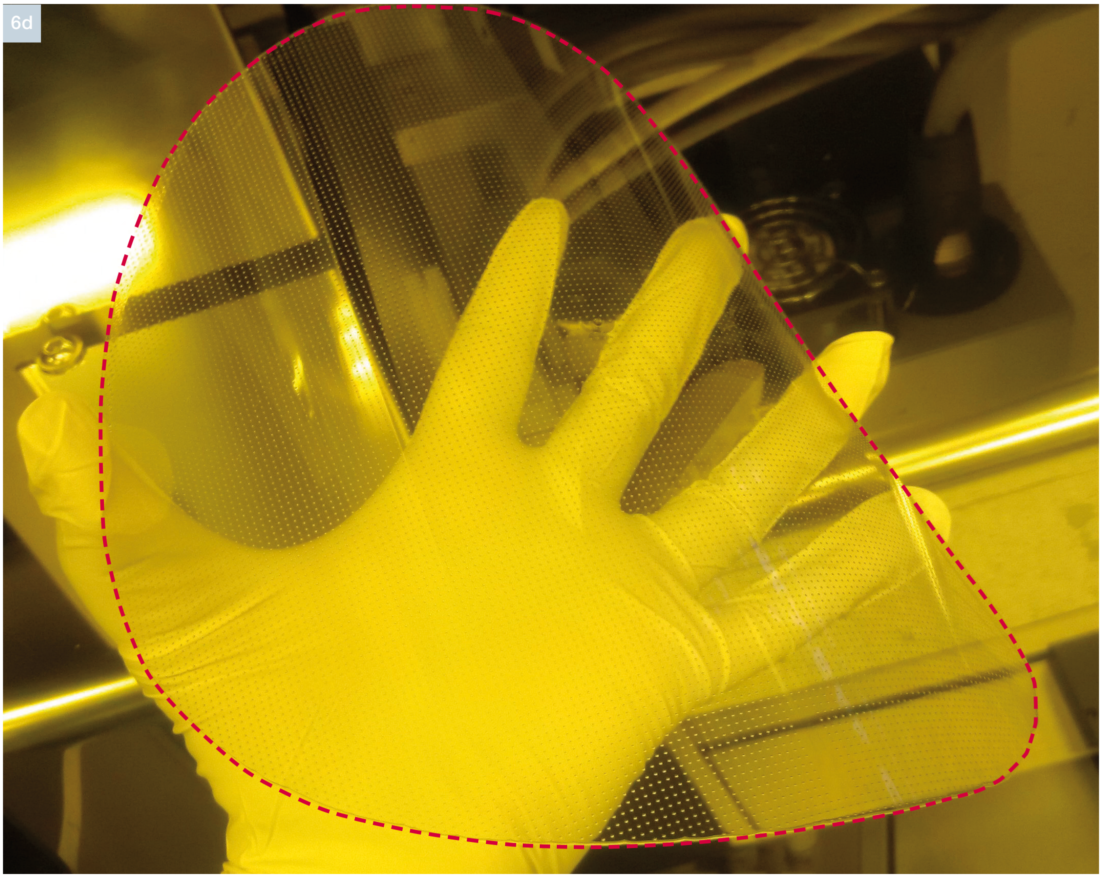

Figure 6d *Picture of a double sided monolithic lens array*

SUMMARY

The feasibility of fabricating a 200 mm double-sided monolithic lens array (200 µm thick) with single step imprinting technique is demonstrated. In addition, the parameters that verify the dimensional stability and imprint uniformity of the lens layout were also discussed and presented. These parameters play a crucial role in defining the process stability and reliability. An RLT uniformity of < 10 % has been achieved, alignment precision < 1.3 µm and variation in lens geometry better than 3 % were presented and discussed. Hence, by using SUSS imprint technology, fabrication of full wafer double sided monolithic lens array is achievable in a single step and thereby enabling low cost of ownership and high throughput. In combination with imprint process flow, the epoxy resin OM614 from DELO provided a very good mechanical and thermal stability. The samples also showed minimal shrinkage while UV-curing and thereby providing high dimensional stability. The epoxy also provided an excellent compatibility with the working stamp materials and thereby enabling a defect free demoulding of the cured monolithic lens array after the imprint process. Concluding, in this paper, we demonstrated the capability of SUSS UV-imprint lithography and an optically tailored, UV-curable epoxy resin from DELO to manufacture free-standing, double-sided monolithic wafer-level-optics, which enables low cost of ownership and high throughput.

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Dr. Vijay Ramya Kolli received her PhD in microelectronics engineering from University of Kassel. She joined SUSS MicroTec in 2015 as an applications engineer for Imprint technologies, where she has been responsible for demonstration and development of customer relevant Micro & Nano imprint processes. Since 2018 she is a Lead Technologist, leading imprint projects, providing technical sales support & customer analysis to deliver innovative solutions for technical challenges.