

Advanced Manufacturing Techniques for Wafer-level Freeform Micro-Optics with High Refractive Index

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ABSTRACT

Scaling up from prototype to high volume manufacturing is a challenge for many technologies. In particular for wafer-level manufacturing of advanced freeform micro-optics, there is a gap which needs to be addressed. The combination of two-photon grayscale lithography (2GL), step and repeat nanoimprint lithography (S&R NIL) followed by SmartNIL[®] replication enables to expand design freedom while still being able to scale up from prototype to high volume manufacturing. This entire process flow was used to pattern microstructures with challenging freeform geometries which are required for emerging devices and applications across the photonics market. Additionally, to further increase the flexibility and performance of the devices, it is possible to use advanced high refractive index materials, which, so far, have been limited to applications in sub-micrometer thin layers, for freeform micro-optics and micro lens arrays. The results presented in this work provide an overview of the versatility and recent achievements of NIL in terms of structure sizes and shapes using different imprint resins to obtain even more design flexibility for freeform micro-optics and micro lens arrays.

Keywords: Nanoimprint Lithography, Freeform Structures, Micro-optics, Photonic Devices, Mastering, Two-Photon Grayscale Lithography, Optical Materials, High Refractive Index

1. INTRODUCTION

Advanced manufacturing techniques are increasingly needed to create non-standard freeform microstructures with a broad variety of geometrical designs. These concepts should comply to a wide range of shapes and structures: prisms, spheric and aspheric lenses, micro lens arrays as well as several types of diffractive structures. Crucial to enabling these highly individual, and best performing microstructures in wafer-level production lines using NIL, is a matching combination of mastering techniques, replication process and imprint materials. A highly flexible and economically attractive approach is to start with individual, high-quality patterns created by two-photon grayscale lithography (2GL) which are then transferred, by step and repeat nanoimprint lithography (S&R NIL), to fully populated wafer-scale masters followed by the SmartNIL replication process enabling high volume manufacturing.

As the initial shape, the so-called master, defines the quality of any replication technique, the accuracy of the single-die master is crucial for the whole process. This must be preserved through any replication step which is consequently also the case for S&R and wafer-level NIL. Various methods have been explored for mastering, whereas 2GL has emerged to offer the highest versatility and cost efficiency, to rapidly translate advanced micro-optical designs into real-life applications. The 2GL process is a sequential manufacturing method and the process time is directly linked to the size of the patterned area. This limits the use of the 2GL process directly in large scale manufacturing.

Therefore, it is considered to scale the production by NIL which allows efficient high-volume manufacturing on wafers. To do so, the 2GL manufactured elements are replicated and scaled by the EVG S&R NIL system to achieve a fully populated 200 mm or 300 mm wafer-scale master. This significantly reduces the production time of the large-area master template [1].

The full wafer SmartNIL process, which follows the S&R mastering, consists of two steps. First, a working stamp is fabricated which is then used for the actual imprint on the target wafer. Consequently, from a single wafer-scale S&R master, multiple working stamps can be generated which are again utilized for multiple consecutive imprints. This

approach provides an efficient way to quickly generate a high number of replicas while avoiding the wear-out of the original template.

In addition to the geometry, the choice of material determines the optical performance of the final device. Being able to choose from a wide range of nanoimprint photoresists with different optical and mechanical properties adds another degree of design freedom. So far, materials with a refractive index up to 1.7 were investigated for micro lenses, whereas materials with high refractive index (HRI) greater than 1.7 were almost exclusively used for nanostructures in very thin layers. By combining the optimized mastering and replication techniques with the latest developments in solvent-free nanoparticle-filled polymers, HRI resins are now also applicable for freeform microstructures, which is experimentally demonstrated in this work.

The results show that the combination of NIL, 2GL and dedicated polymers enable a very efficient route to mass-manufacturing of micro-structured optical components with even more complex shapes thus showcasing new design freedoms in terms of dimension, structure, size and material.

2. CONCEPTS & METHODOLOGY

2.1 Two-Photon Grayscale Lithography (2GL)

As mentioned above, the process chain starts with a single die, freeform master printed by Nanoscribe using 2GL. The additive 2GL manufacturing process combines the performance of grayscale lithography and the precision and flexibility of two-photon polymerization (2PP). It is a microfabrication technology and therefore able to provide 2.5D microscale topographies with sub-micrometer resolution. To do so, a power-modulated laser light shapes the height profile of the micro- and nanostructured functional devices.

Overall, the technology is ideally suited for prototyping and small manufacturing volumes but when it comes to wafer-level NIL and larger manufacturing volumes, a subsequent S&R process is needed. [1]

2.2 S&R Process

Until now, creating a fully populated master out of the single die master, the S&R process was performed on the EVG770 system using the 2GL single die freeform print as a template. The EVG770 system can dispense the photoresist, align the structures, imprint accordingly and demold in a fully automated procedure. This is required to create multiple structures with both high quality and high fidelity to the single die master [2][3]. Repeating this process at different locations on the target wafer, a fully populated wafer, or rather S&R master with multiple dies, is created (see figure 1 below). This S&R wafer-level master is then used for the SmartNIL replication.

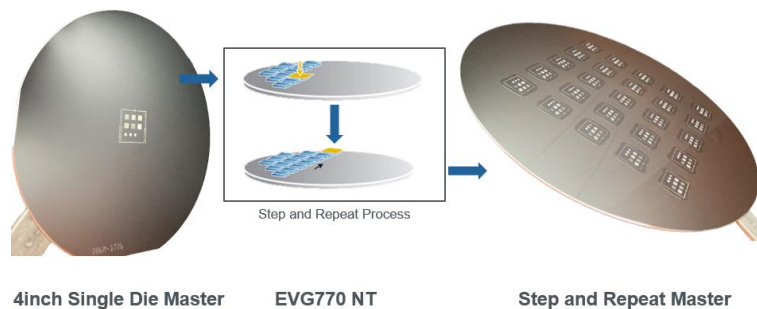


Figure 1: S&R Schematic Process Overview

2.3 SmartNIL® Replication

The S&R wafer is used as a master for the subsequent SmartNIL replication, which was processed on the EVG7300 system. This is a straightforward pattern replication method using the direct contact between a mold (template) and the UV curable resin [4]. As mentioned above, this process consists of two steps, see figure 2 below. First, the S&R master is replicated to fabricate a working stamp (WS). This intermediate step, using a low-cost polymer, improves the overall

economics and process reliability, as it avoids wearing out the original template. To ensure defect free WS fabrication, the initial master is coated with an anti-sticking layer. Next, the WS material is coated directly on the master by a spin coat process (EVG 120) and contacted with a transparent SmartNIL backplane (EVG7300). The WS polymer is cured using an UV LED light source, and finally demolded from the master.

Second, the SmartNIL imprinting process is performed. HRI resin provided by DELO Industrial Adhesives is applied by spin coating on the substrate and can be used directly for imprinting as the material is solvent free. The WS and the substrate with the HRI material are brought in contact, exposed by UV light to cure the resin and demolded from the WS in a fully automated procedure. The reuse of the WS for multiple imprints for the SmartNIL replication is increasing the process efficiency and has been proven already for high volume manufacturing [1][5].

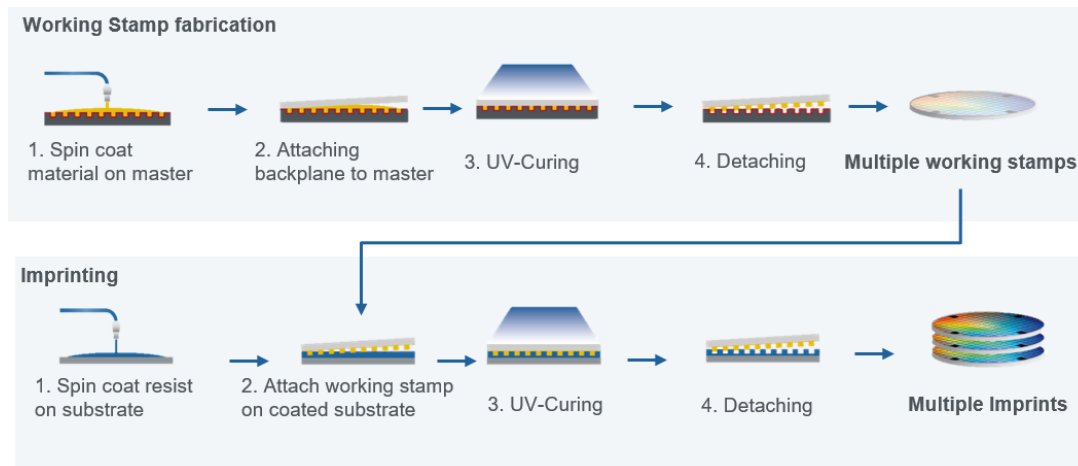


Figure 2: SmartNIL® Process Flow

2.4 High Refractive Index Material

A key ingredient for successful SmartNIL replication of highly individual freeform structures is the optical material used. In this case, a high refractive index resin called DELO PHOTOBOND VE 545188, developed by DELO Industrial Adhesives, was used. This resin is a UV curable and solvent free imprint material with a refractive index of 1.818, depicted in figure 3.

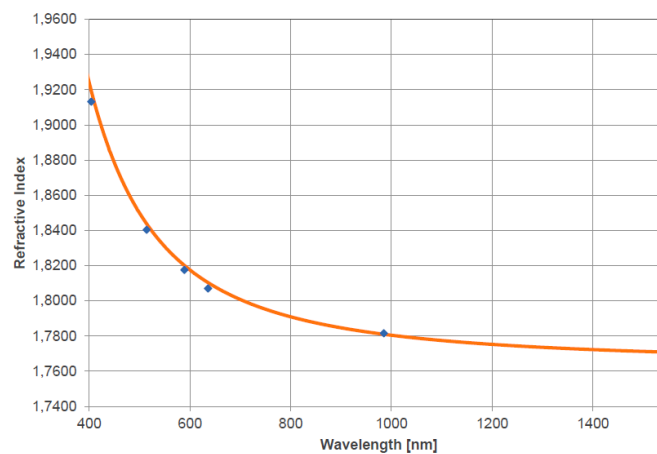


Figure 3: DELO PHOTOBOND VE 545188, Wavelength [nm] versus Refractive Index

Despite the high degree of inorganic fillers, which is required to increase the refractive index to 1.8 and beyond, the resins show sufficient performance in the imprint process. Reliable filling of the mold structures, a high pattern fidelity and easy demolding from the stamp are proven key features to achieve a high-performance wafer-level NIL process.

3. RESULTS

After the processes were performed as described above, the resulting imprints were investigated in terms of replication quality. In particular, stable pattern fidelity and low surface roughness, are crucial for high-quality optical devices. This has been investigated in greater detail.

3.1 Pattern Height Variation: Pattern Fidelity

To ensure a stable performance of the freeform photonic devices, while still manufacturing in a cost-efficient method, it is essential to provide a reliable imprint quality. Within the entire process, it is therefore important that the height and dimension of the patterns are preserved.

To demonstrate this, the S&R master with micro lens array (MLA) structure was used. The dimensions of the inspected lenses are approximately 26 μm tall and 50 μm in diameter. Interferometry measurements results demonstrate a stable height of the structures over twenty-five replications with a variation of about 2%, shown in figure 4.

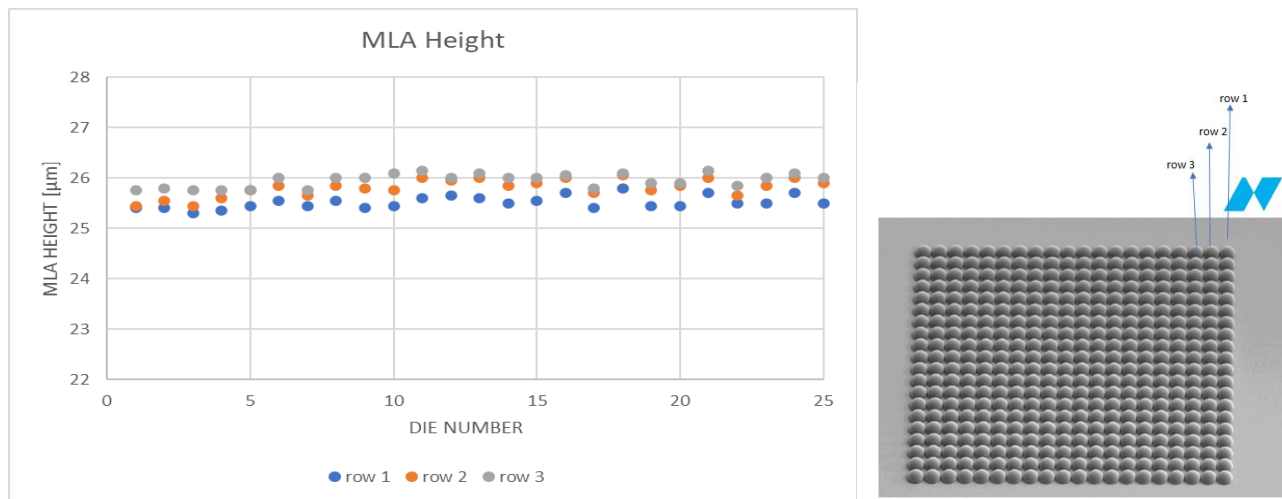


Figure 4: Preserving a stable pattern height for a micro lens array (MLA) structure over 25 imprints

Additionally, the overall pattern height variation along the entire process was determined. To do so, the heights of the 2GL master, the S&R master and the final HRI imprints were measured. The values are shown in the table 1 below.

Table 1: Height variation along the whole process

Process chain	AFM: height value
Height of 2GL master	27.0 μm
Height of S&R master	26.0 μm
Height of HRI imprint	25.8 μm

The height loss from the initial 2GL master to the final HRI imprint of about 4% is explained by material shrinkage. This factor is already considered when creating the master design, ending up with highly reproducible NIL replications.

3.2 Surface Roughness

Special focus with such freeform imprints is given to the surface roughness. In general, the surface roughness should be in the same range for the 2GL master, the S&R master and the final imprints.

Figure 5 shows the AFM average roughness (Ra) of imprints using the initial S&R prism master with a standard refractive index material compared to the high refractive index DELO resin ($n = 1.818$) imprint. The Ra values are less than four nanometers for all measured S&R prism master imprints and are slightly higher for the HRI imprints. This result is expected as such resins typically contain nanoparticle fillers which contribute to the surface roughness. Nevertheless, Ra in this range is a particularly good value for an initially used 2GL master.

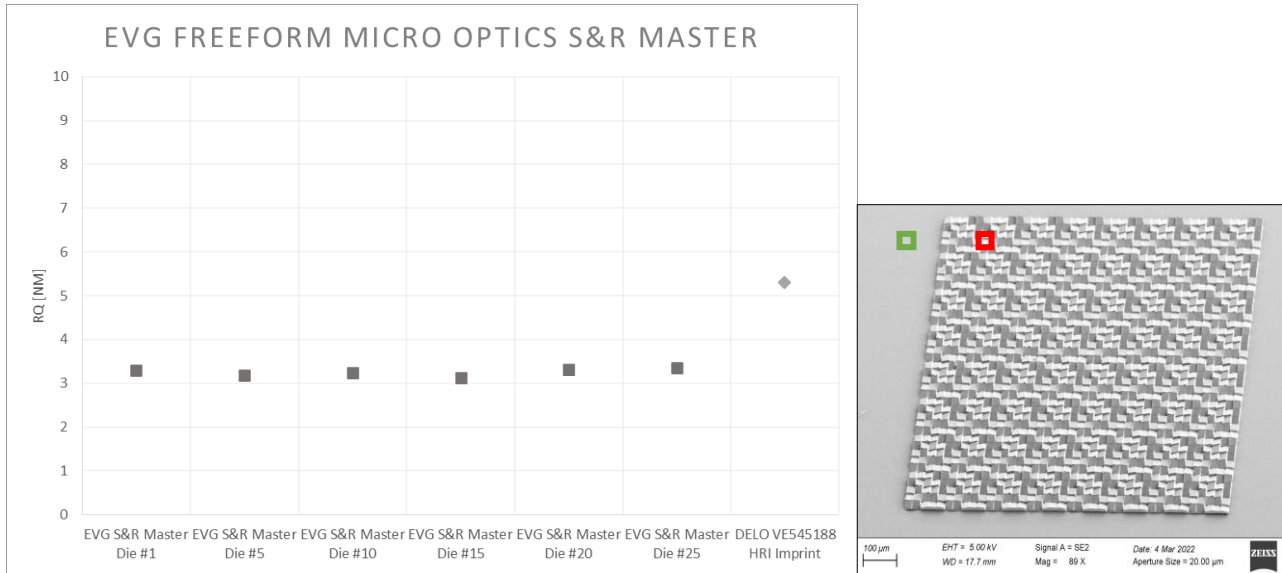


Figure 5: Right: comparison of surface roughness data measured by AFM for the S&R prism master and the high refractive index imprint. Left: depicting the selected area on the prism structure for Ra measurement

To underline this finding, additional AFM Ra measurements outside the prism structure were taken, see below in table 2. These results demonstrate again that the increased roughness for the final imprinted wafer is caused by the HRI material and not due to the imprint process itself.

Table 2: Roughness comparison outside the structure

	AFM: Ra value
S&R master (outside the prism array structure)	Die#1 Ra = 2.25 nm Die#25 Ra = 2.46 nm
HRI imprint (outside the prism array structure)	Ra = 4.61 nm

3.3 SEM Pictures

Figure 6 shows different SEM micrographs of the final HRI imprints and illustrates the flexibility in pattern shape for various applications such as oval freeform micro lens and prism arrays for photonic applications, as well as hybrid lens and tetrahedron pile arrays. These structure heights range from lowest 10 µm to 250 µm and diameters from 50 µm to 700 µm.

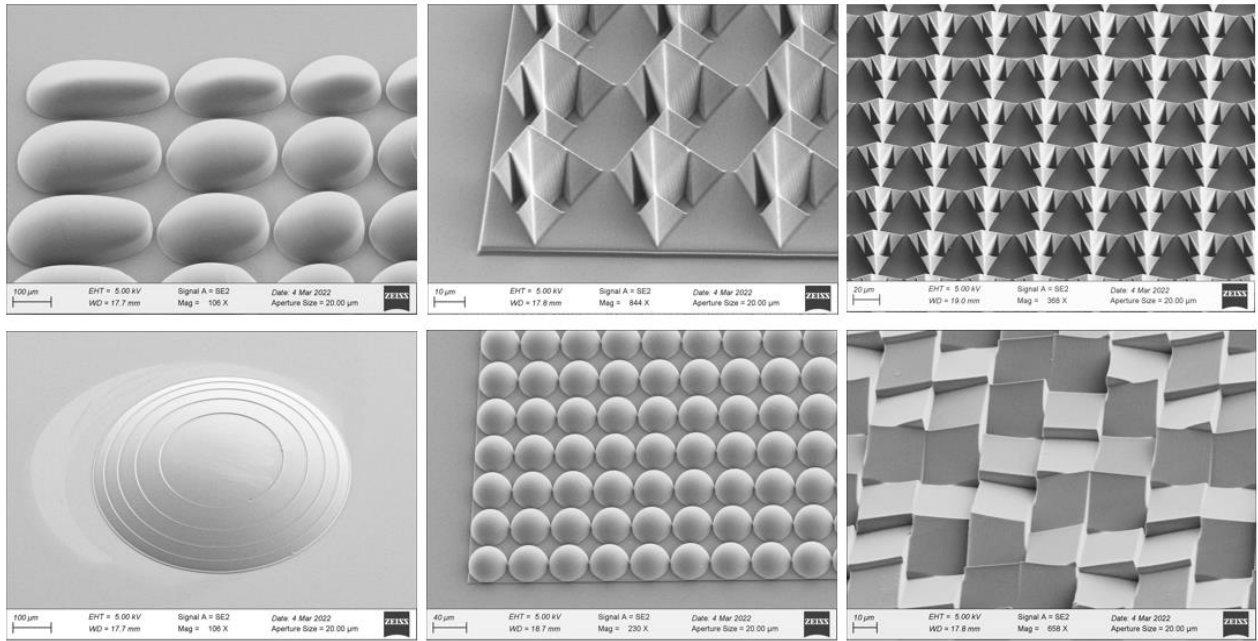


Figure 6: SEM images (from top left to bottom right) showing freeform lenses, tetrahedron pile arrays, hybrid lens, arrayed micro lenses and prism arrays

The results provide an overview of the versatility and flexibility of NIL. Even complex shapes and freeform microstructures can be replicated thus showcasing a new design freedom in terms of dimension, structure, size and material.

4. SUMMARY

By combining the performance and flexibility of 2GL with S&R process and SmartNIL as a precision replication technology, rapid prototyping becomes possible and high-precision freeform structures can be transferred to mass production on wafer sizes up to 300 mm. By using a high refractive index material for the optical structures, the design flexibility, and therefore the use cases and applications, can be further increased.

All process steps are well controlled and provide a preserve quality of the surface roughness in a low range of four nanometers for 2GL and S&R, and roughly five nanometers for HRI imprints ($RI = 1.818$). Additionally, a stable pattern height over twenty-five S&R imprints with roughly 2% height variation could be demonstrated.

As shown in this work, the quality from the master mold to the final imprint could be maintained. Therefore, the processes and equipment, as well dedicated solvent free high refractive index materials, are ready to serve the demands of next generation optical devices.

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