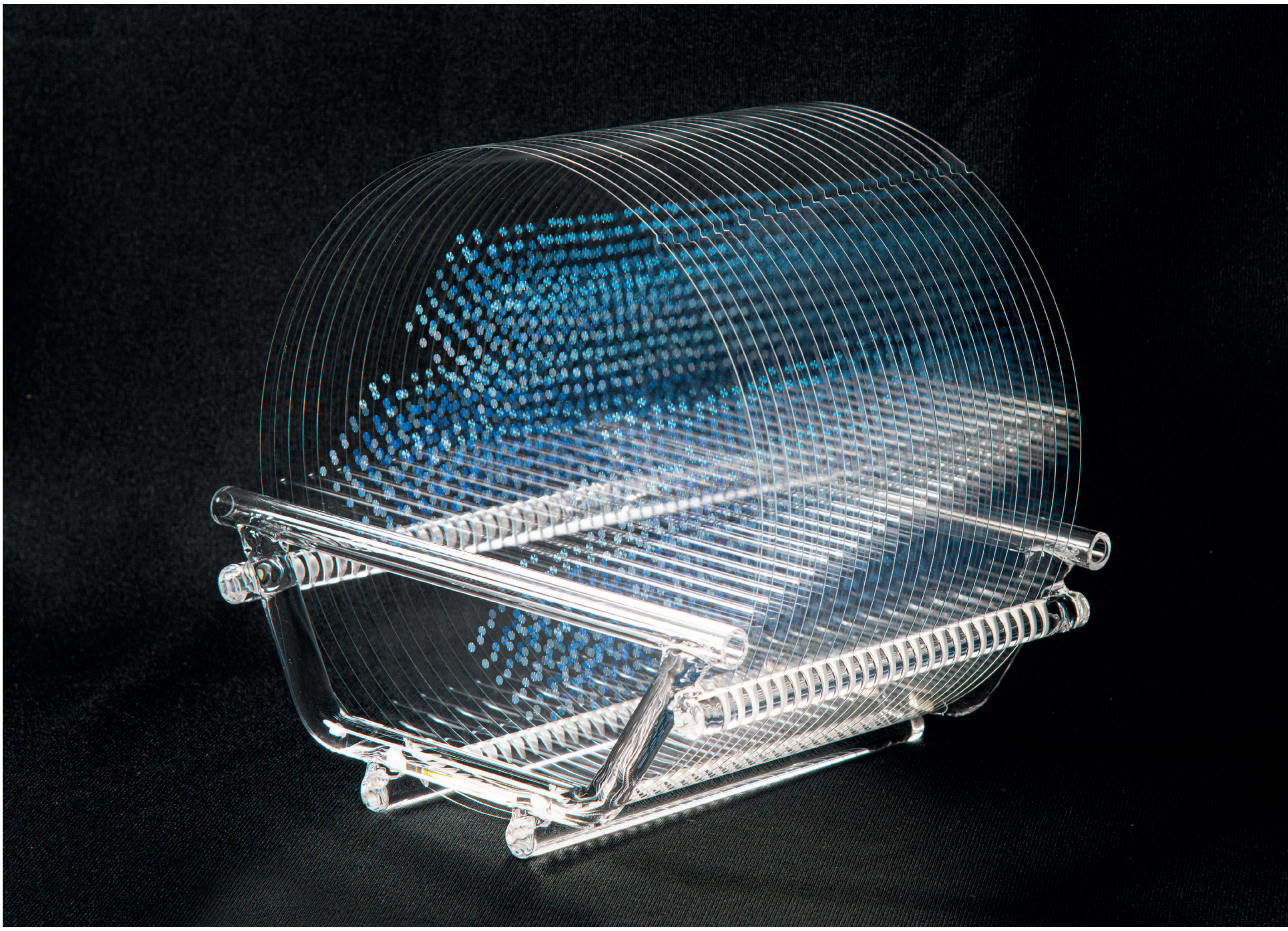
EV GROUP® | Technologies

Manufacturing of Metalenses using Nanoimprint Lithography



Manufacturing of Metalenses using Nanoimprint Lithography

Introduction

Metalenses Markets and Applications

One of the most exciting technologies on the horizon of photonics applications is the use and integration of metalenses and metastructures. As it provides a fundamental change in how to design and implement optical components it can create significant impact basically for any optical device like sensors, emitters, cameras, displays and AR/VR glasses. Metalenses comprise sophisticated nanostructures which enable focusing or dispersing of a light beam similar to a refractive lens. However, they have tremendous advantages as compared to conventional refractive lenses. Outstanding is the fact that they can be very thin and thus are also often referred as flat lenses. This makes them an ideal candidate for the integration into modules as this allows to reduce the size and complexity of lens stacks significantly. On top of this, it is possible to create best performing lenses which are e.g. aberration free, have highest numerical apertures or can focus polarization independently. All these advantages can be created due to flexibility in design and thus, metalenses are seen as next gen. optics. Overall metalenses are considered to replace conventional micro optics and optical elements for many applications but some of the added functions will also be complimentary to conventional micro optical stacks and modules.

Key Aspects

- Proven industrial process chain for metalens mastering and subsequent replication
- Process combination allow large scaling factor up to HVM
- High pattern fidelity for different kind of shapes, e.g. triangles, circular structures, diamonds, donut- and rectangular type in arbitrary orientations
- Realized dimensions down to 65 nm
- Aspect ratios of 1:4

Crucial to obtain these highly sophisticated metalenses or metastructures in general is a precise and high-resolution lithography technique. Typical designs consist of pillars which can differ in diameter, pitch and shape. They are manufactured in design specific optical materials. To manufacture best performing designs, highest pattern fidelity physical resolution requirements down to 30 nm are foreseen. Not many lithographic techniques are capable to meet these requirements, but NIL. in combination with high quality e-beam mastering is the only one that enables high volume manufacturing without significantly limiting the metastructure design possibilities.

Consequently, a matching combination of a high-quality mastering technique and a subsequent effective and reliable replication process are needed to unlock the full potential of metastructures and to realize high volume wafer-level fabrication techniques.

This is where NIL technology from EVG combined with the high-quality mastering from Toppan comes into the game. In this work, we show why and how this collaboration and joint effort enables metalenses and overall photonics manufacturing for the future.

Motivation

Right now, we are reaching a point, where conventional lithography technologies are reaching their limits when it comes to future photonic applications like metalenses and, in particular, the creation of the required small and arbitrarily shaped patterns. Here, NIL is a viable alternative for this market due to the high-resolution capability for complex structures. The technology can replicate sophisticated structures very efficiently, on large areas, with less design constraints, and with a very streamlined process flow, for both prototyping and high-volume manufacturing.

Together with Toppan, a leading supplier of photomasks to the semiconductor market, the collaboration aims to establish NIL as an industry standard production process for photonics manufacturing. This joint work offers the required process capabilities to manufacture high-quality metalenses and metastructures and it shows that the necessary infrastructure exists and can be deployed on an industrialised scale to bring mastering and subsequent NIL to HVM quality and volumes.

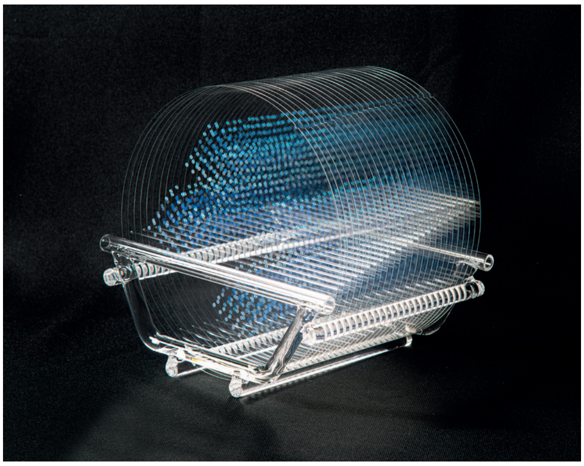


Figure 1: 25 Imprints of Metalens Arrays for HVM

NIL process chain: From single master to HVM

It is key for the high-volume manufacturing of high quality metalenses to have a thorough understanding of all required manufacturing steps and to preserve the quality over the whole process chain. The main necessary manufacturing steps are described below, in the following order:

1. E-Beam mastering on a single die 6-inch square quartz template – Provided by Toppan
2. S&R mastering to full 200 mm or 300 mm wafer-scale – Provided by EVG
3. NIL replication to high volume – Provided by EVG

Mastering

Toppan's POR (Process of Record) for NIL master manufacturing has been developed using basic ingredients of photomask manufacturing. By this it benefits from decades of experiences and superior capabilities using tools and processes originally developed for manufacturing of photomasks for the semiconductor industry. Here a brief overview on the main steps of the manufacturing flow is given (see also figure 2). It begins with the customer transferring the design data for the optical product. The data is converted into a format used by the electron beam pattern generators to expose the pattern onto the blank material.

For the manufacturing of NIL masters for metalenses, a 6-inch square Quartz formfactor is used. But It should be mentioned as well that there are all necessary tools and processes available to offer the same on 200 mm round formfactor. The quartz plate (or blank) is coated with a Chrome (Cr) film which acts as a hardmask.

An electron sensitive resist is coated on the chrome and by electron exposure, the areas which get exposed change their chemical properties such that they can be washed away in the later development step. This chemical change is enhanced by a baking step after the exposure.

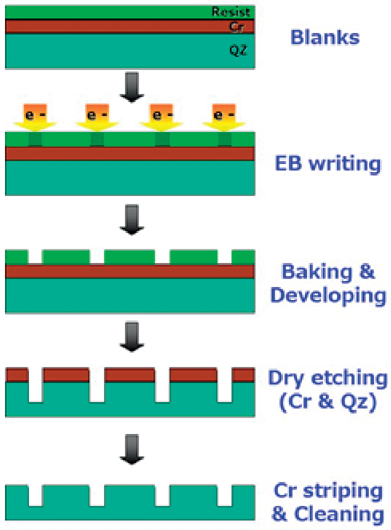


Figure 2: Schematic flow of NILmaster manufacturing

In the areas in which the resist is removed the Chrome is etched away (removed) and thus, the exposed pattern gets transferred into the Cr-hardmask. The patterned hardmask is used to further transfer the pattern into the Quartz. By a selective etch process only the areas with open chrome are etched to the required depth. The selectivity of this etch process ensures that the Chrome is not changed i.e. all patterns are etched into the quartz to a defined depth without any change of the size or shape. Once the quartz is etched to the defined depth the Cr-hardmask is removed. The critical parameters for the master are controlled using SEM metrology for critical dimensions and by AFM for the depth.

The following data were gathered on a metalens demo master that was jointly designed and manufactured by Toppan and EVG. The generic metalens designs were realized to illustrate the capabilities – the results are shown on the next pages

The first results shown are the critical dimension (CD) uniformities of dots of various sizes. One can clearly see the same excellent CD control across the master for all design sizes from large (CD=300 nm) to small (CD=70 nm) pillars.

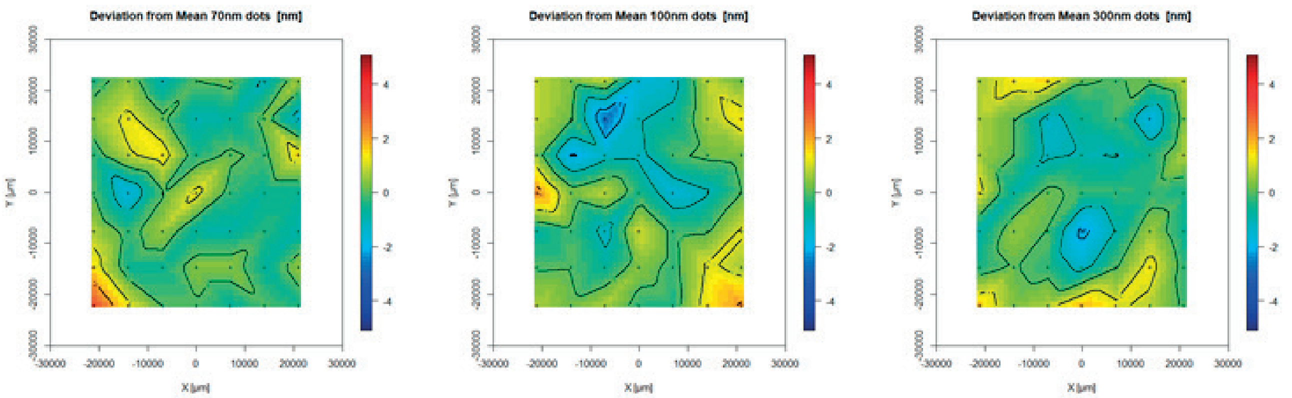


Figure 3: Uniformity of Critical Dimension of pattern across NIL master

The most critical parameter of a master is the quartz etch depth. The metalens demo master was etched down to 200 nm. An optimal uniformity over the entire area of the master was achieved.

The resolution quality of the meta-atoms of various types was assessed using CD-SEM images. These were taken after Quartz etch prior to the hardmask removal, in order to get the best contrast. The hardmask removal will neither change the resolution capability nor the shape of the pattern, i.e. these images are representative for final Quartz pillars. Some examples of these images are shown below.

A design kit providing a list of shapes and minimum sizes of meta atoms which can be manufactured on a master is available.

Additionally, the pattern integrity and defectivity level should be considered to ensure correct functionality of imprint masters. The majority of metalens designs, due to their complexity, cannot be assessed by full pattern inspection as is standard for photomasks. However, the use (or deployment) of the well-established manufacturing environment for photomasks is beneficial. By the excellent cleanliness level and established control schemes for all processes, the NIL master is manufactured with guaranteed low defect level.

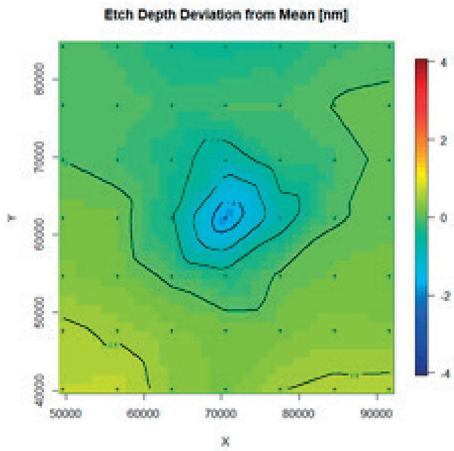


Figure 4: Uniformity of Quartz etch depth across NIL master

To summarize, Toppan's excellent capabilities and experiences of decades of photomask manufacturing serve optimally the needs of NIL master manufacturing, ensuring delivery of 1st class masters to customers.

S&R Mastering

For increasing production volumes of metalenses, time and cost-efficient scaling is key. As the manufacturing time of high-quality single die masters is directly linked to the size of the patterned area, meaning the costs scale with the patterned area, it is considered to scale the single die master from Toppan by step and repeat (S&R) which allows high volume manufacturing on wafers very efficiently.

To do so, the 6-inch square Quartz master is replicated multiple times on a 200 mm or 300 mm wafer by the EVG®770 step and repeat (S&R) NIL system to create a full area wafer scale master. The system can dispense resist, align the structures, imprint and demold in a fully automated procedure. This is required to create multiple elements with a high quality and fidelity as close as possible to the original master. This significantly reduces the production time to achieve full wafer-scale master (S&R master) which are then used for the following NIL replication – see figure 5.

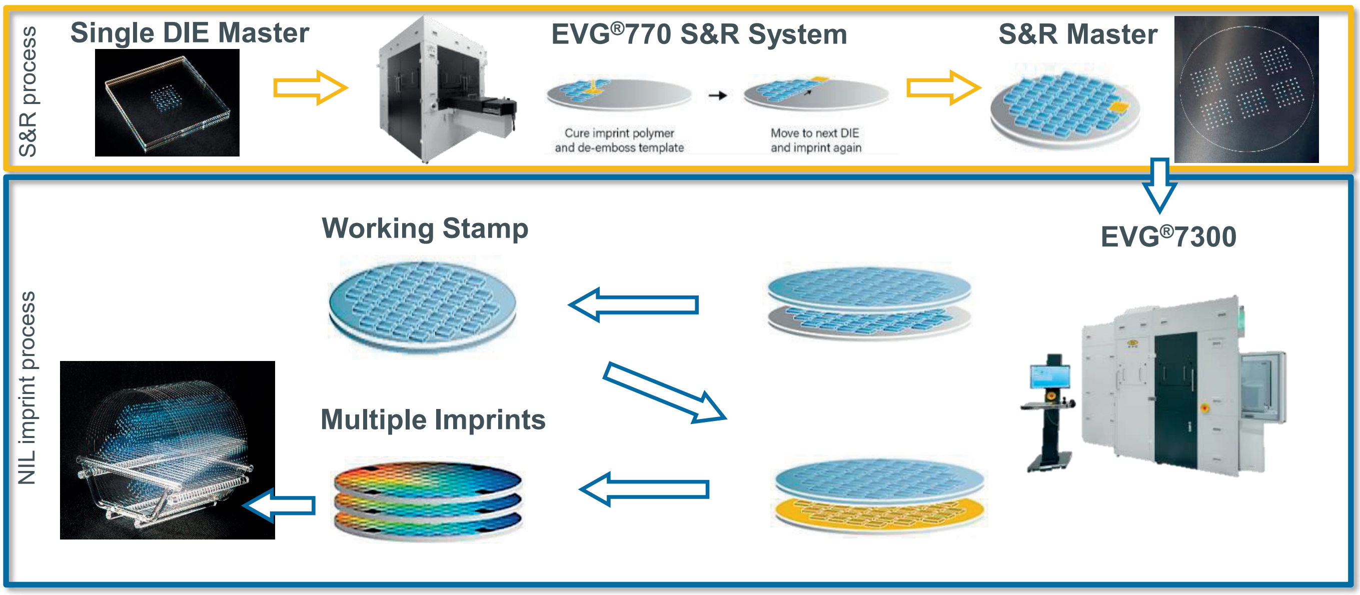


Figure 5: Schematic of S&R and NIL replication process flow

NIL Replication

For the subsequent wafer-level NIL replication process itself, the SmartNIL® technology is used. The process flow consists of two steps: First manufacturing multiple low-cost polymer working stamps (WS) out of the previous manufactured S&R master and utilizing them for the second step, the actual imprints. This intermediate approach avoids wearing out the original template and improves the overall production economics because the achievable number of imprints is increased tremendously. Defective working stamps can be replaced quickly and at low cost, which can be particularly advantageous during high-volume production runs.

The NIL process in detail is depicted in the figure 6 below: To ensure defect free WS fabrication, the S&R master is coated with an anti-sticking layer applied by spin coating. Next, the WS material is dispensed directly on the master, also by a spin coating process. Afterwards, the transparent SmartNIL backplane is attached on the coated master. The WS polymer is then cured using an UV LED, and finally demolded from the master. Second, the actual SmartNIL imprinting process is performed. To do so, a dedicated material is applied by e.g. spin coating on the substrate using the same process used for the WS fabrication. The WS and the substrate with the dispensed material are brought in contact. Similar to the WS fabrication, this step is followed by UV curing and demolding, so that multiple imprints are made with the final structures (metalenses). 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.

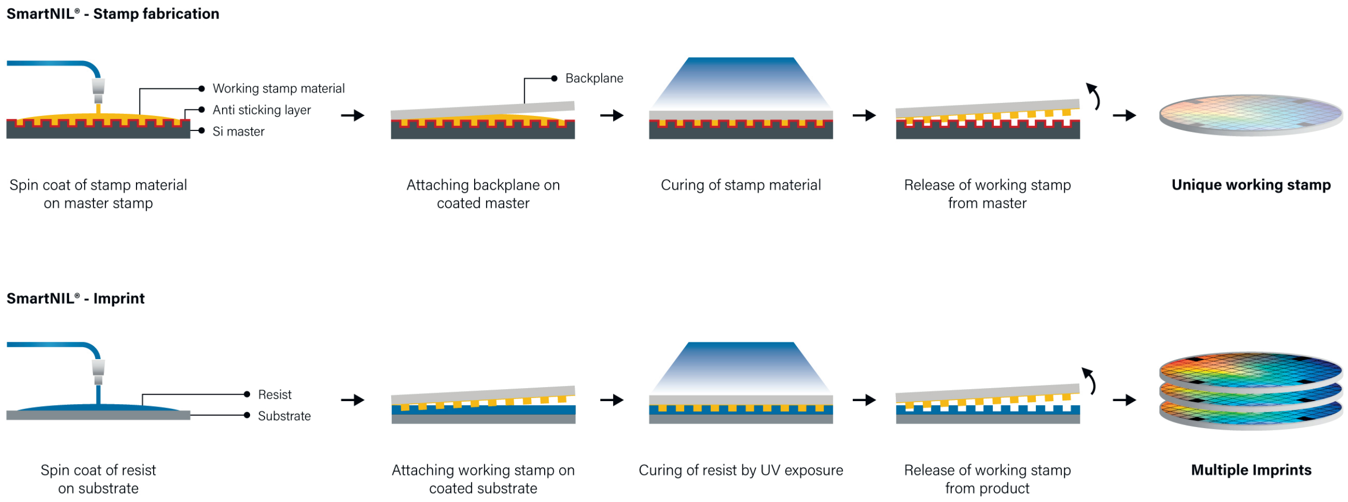


Figure 6: SmartNIL® replication process flow in details

Even though the full SmartNIL imprint process described above is split into two parts - manufacturing the working stamp and subsequently imprinting the wafer - the entire process can be implemented on the same equipment. This work is performed on the EVG®7300 SmartNIL system using 200 mm or 300 mm wafers.

Currently, this metalens manufacturing process is typically followed by an etch process to achieve best optical quality. This process is also referred to as "sacrificial imprint", because the NIL imprint is used as etch mask (pattern transfer). Most common material is amorphous silicon (for infrared applications) and TiO2 for visible light due to their beneficial material properties. However, all semiconductor and dielectric materials are within scope of metalens and metasurface applications.

Whereas in R&D, permanent (or direct) imprint is gaining momentum, mostly in combination with high refractive index resists, because this process has the advantage, that one can enable complex structures without additional costs because no etching process is required.

Process Results

Not only is the cost efficiency and HVM manufacturability of the process described above crucial, but it also preserves the pattern fidelity and quality of the metalens structures throughout the whole process. Thus, the replicated structures are evaluated in more detail in terms of height and dimensions, overall stability and repeatability.

Pattern fidelity from master to final print

To demonstrate the stability of the patterns within the whole process, the critical dimension (CD) / height of the original quartz master is compared to the height of the structures on the fully populated S&R master and on the final imprints. This is investigated for different realized patterns, to see the impact of the different shapes. Within the S&R process step, die 1 and die 6 are measured as representative examples.

Process chain	Round pillar height (AFM) average	Donut shape pillar height (AFM) average
Toppan Master Template	196 nm	194 nm
S&R fully populated wafer - Die 1	190 nm	189 nm
S&R fully populated wafer - Die 6	192 nm	188 nm
Final imprint	184 nm	180 nm

The numbers show that the overall die variation is less than 5 % (within metrology error). The height loss from the initial master to the final imprint is explained by material shrinkage. This factor is already considered when creating the master design, ending up with highly reproducible dies and replications on wafer-level. Additionally, no missing structures (e.g. pillars) are observable - showcasing overall an excellent pattern fidelity.

Repeatability - Imprint series

Next to the pattern fidelity from the original master to the final imprint, special focus is given to the repeatability over the final imprint (series) itself. To demonstrate this, 25 NIL replications using the EVG UV-A resin were executed. To prove the imprint-to-imprint quality, the height of the patterns of all 25 wafers has been measured and plotted in Figure 7.

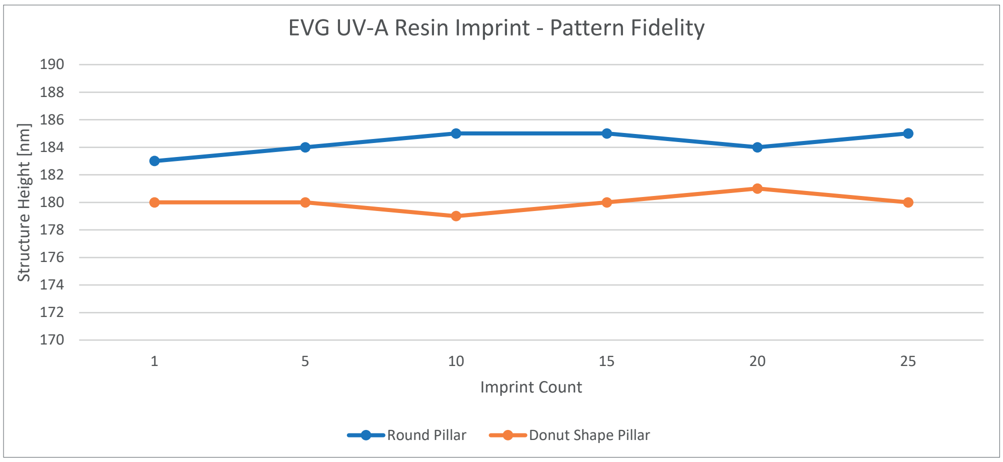
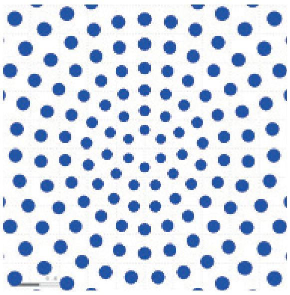
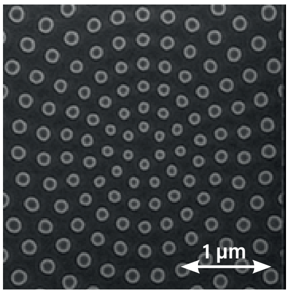
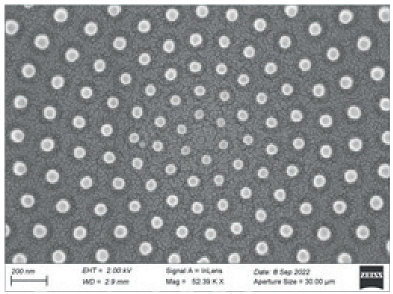
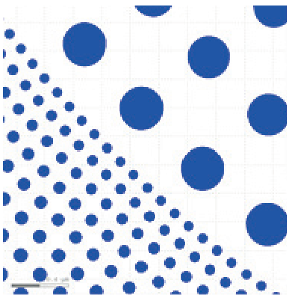
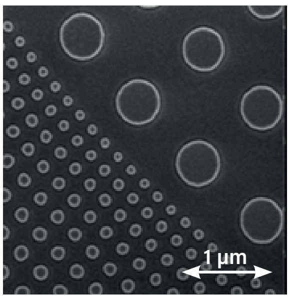
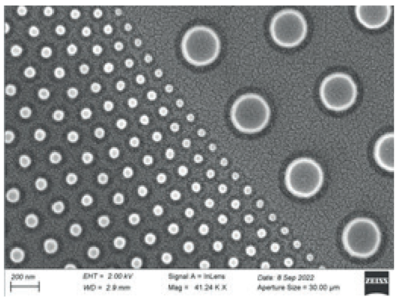
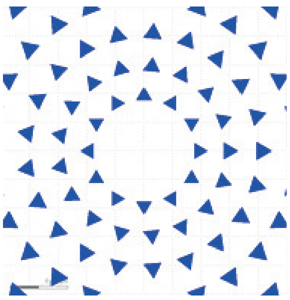
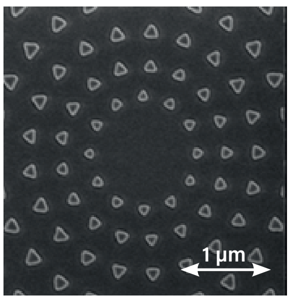
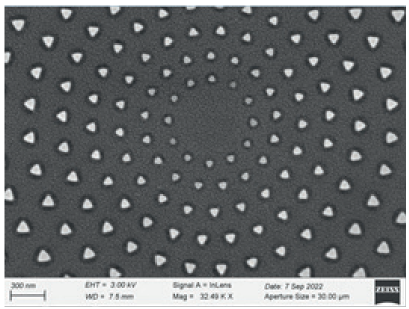


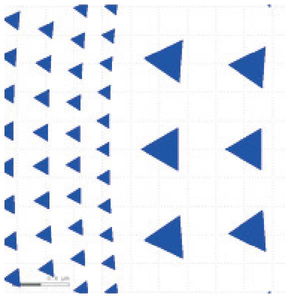
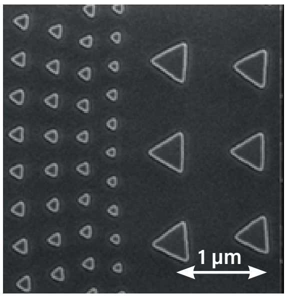
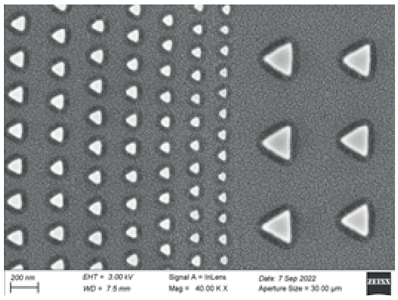
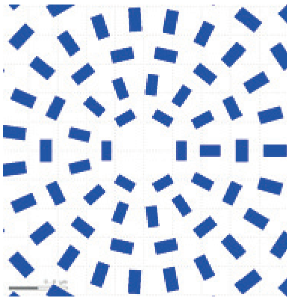
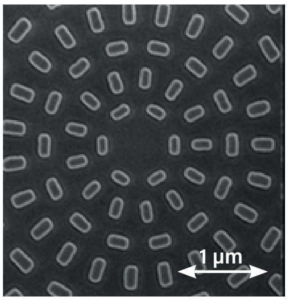
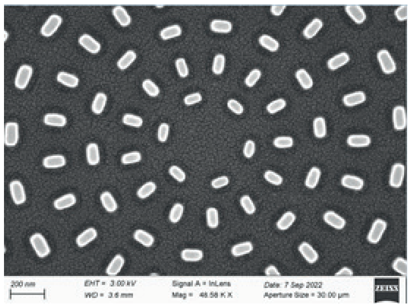
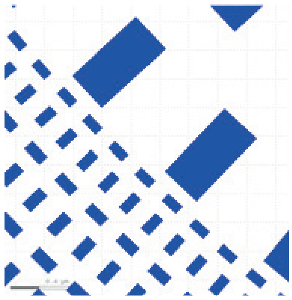
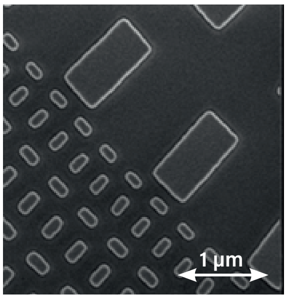
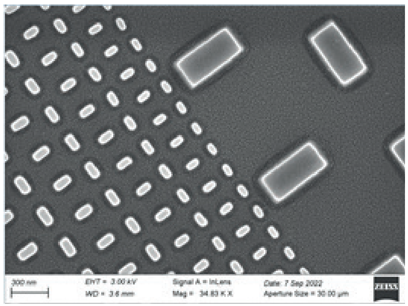
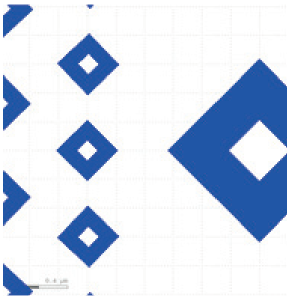
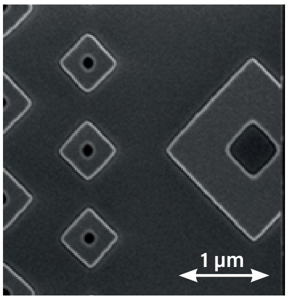
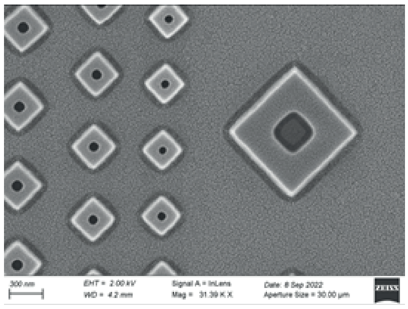
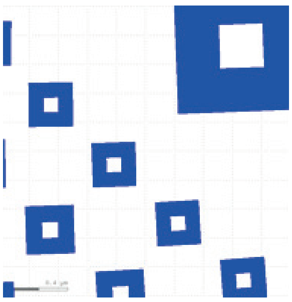
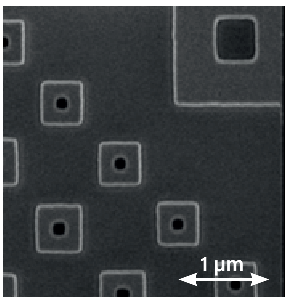
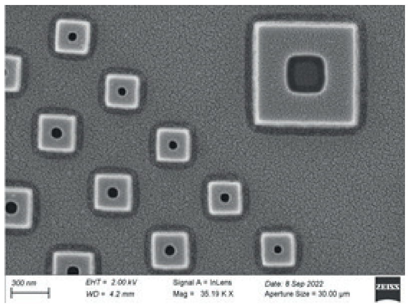
Figure 7: Structure height over 25 imprints (imprint series)

Despite a minor variation of a few nanometers, no systematic degradation of structure height is observed – underlining again the excellent repeatability, stability and quality along the whole process chain.

Images from design through S&R master to multiple imprint wafers

To demonstrate the results, SEM images are taken: from initial design, from the master and from the imprint.

Design	Master	Imprint
		
		
		

Design	Master	Imprint
		
		
		
		
		

How to access these capabilities

The figure 8 below shows, how to access these capabilities and how Toppan and EVG give the opportunity to implement new innovations and how to ramp up new ideas using the described technologies – resulting in customer tailored solutions.

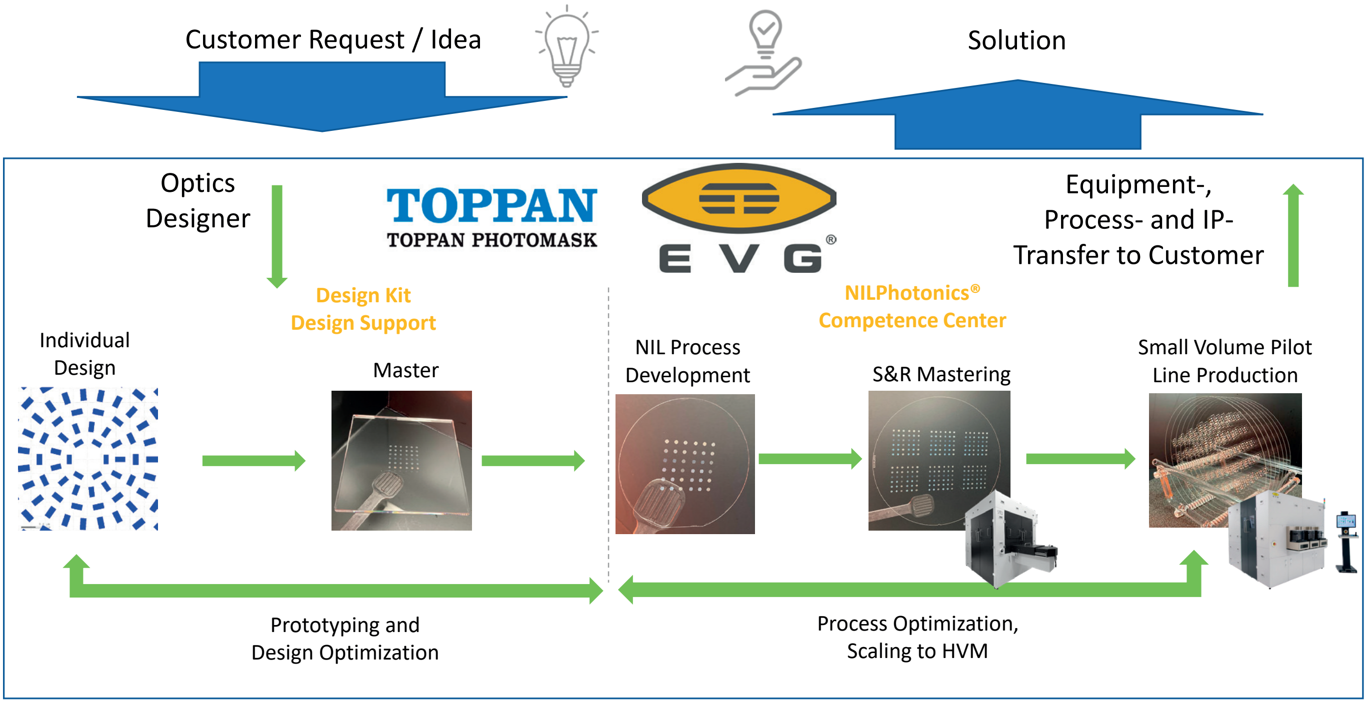


Figure 8: Schematic of "How to access these capabilities?"

The innovator has access to the Process Design Kit (PDK) from Toppan to design a new product. The design is then transferred to Toppan, using an established data path. An automated data handling process is then deployed to the lithography system to generate the production grade master. The master is manufactured using semiconductor standards to ensure optimally controlled repeatable process. These processes are well controlled, proven to be stable, suitable, and with low defect level, complying to semiconductor industry standards.

The master will then be used at the EVG NILPhotonics® Competence Center to commence the process optimization of the product for high volume manufacturing (HVM). The NILPhotonics Competence Center is a 1.300 m^2 cleanroom area at EVG headquarter where EVG helps customers to ramp up their ideas by providing NIL process development, S&R mastering service, as well process optimization and prototyping up to and including 'pilot line' production phase. After that, the process and dedicated NIL equipment are transferred to the customers. This ensures the highest level of IP protection for every aspect of development. The competence center covers everything that is needed for NIL: equipment, dedicated metrology, materials and access to technical expertise incorporating the complete NIL supply chain, including Toppan masters. This open access innovation incubator helps customers to shorten development cycles and time to market for innovative photonic devices and applications.

Summary and Conclusion

Together Toppan and EVG have shown that it is possible to set up a high-volume manufacturing line using precision masters and subsequent nanoimprint lithography for S&R mastering, as well as for wafer-level production. All process steps from a single die master to the final imprints are well controlled and provide high pattern fidelity. This enables to scale the manufacturing of complex devices such as metalenses to mass manufacturing.

This collaboration and the associated synergy of both technologies intend to further fuel the adoption of NIL as a mainstream HVM technology for the photonics industry, especially to showcase the readiness of equipment and processes to serve the demands to manufacture sophisticated metalenses and other complex optical structures.