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Whitepaper

PFAS-Free Microlens Fabrication with UV Imprint Lithography for Co-packaged Optics Applications

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Contents

Abstract

UV-based imprint lithography is a high-resolution, scalable technique for replicating micro- and nanostructures, particularly suited for optoelectronics such as co-packaged optics (CPO).

This work highlights the integration of advanced equipment from SUSS MicroTec, including automated resist dispensing, wedge error compensation, and interferometric gap control, which collectively enable high-throughput and reproducible imprinting on 300 mm wafers. Uniformity of the base layer beneath microlenses is shown to be critical for optical performance, with total thickness variation (TTV) below 5 µm achieved across multiple wafers.

A key factor in process stability is the choice of stamp material and imprint resist. While traditional soft PDMS stamps exhibit dimensional drift due to swelling, the PFAS-free, UV-curable DELO PHOTOBOND VE 556992 in combination with the permanent imprint resist DELO KATIOBOND OM6611 demonstrates superior long-term process stability, minimal variation in lens dimensions, and consistent separation behavior. These results position this material combination as a strong candidate for sustainable and efficient mass production of microlenses.

Introduction

Microlenses play a pivotal role in a broad spectrum of optical and optoelectronic technologies, such as image sensors, light field cameras, optical communication systems, augmented reality (AR) devices [1], and advanced illumination systems [2]. In emerging co-packaged optics (CPO) and heterogeneous integration architectures, microlenses are increasingly required to enable efficient light coupling and precise alignment at extremely short distances between photonic and electronic components [3,4].

In particular, microlenses positioned near edge couplers or directly adjacent to on-chip light sources improve coupling efficiency, relax alignment tolerances, and mitigate insertion losses in densely integrated optical packages [5–7] (see Fig.1). Their capacity to manipulate light at the microscale enables improvements in light collection efficiency, beam shaping, and resolution. As device architectures become increasingly compact and multifunctional, the need for scalable, high-yield, and environmentally conscious microlens fabrication methods has intensified.

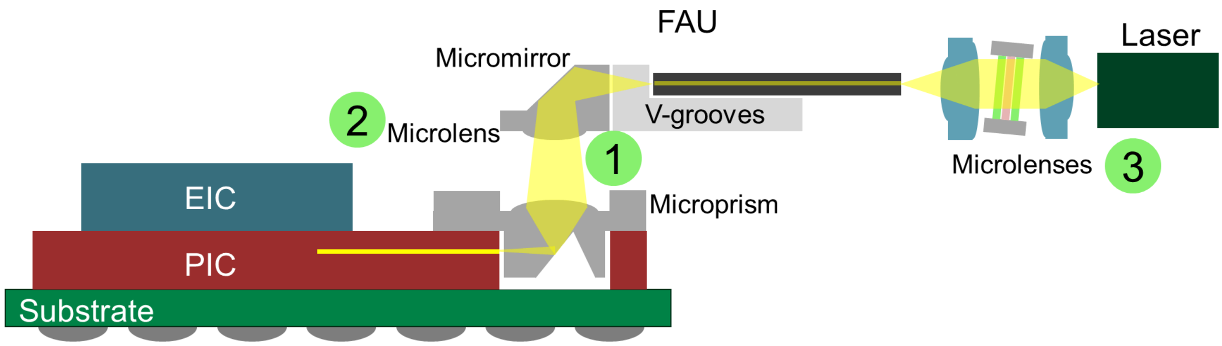

Figure 1: In co-packaged optics (CPO), microlenses can be used (1) near the edge coupler, (2) in the fiber array unit (FAU), and (3) near the light source [5].

Among the various fabrication techniques, imprint lithography has gained prominence due to its high resolution, cost efficiency, and suitability for large-area substrates [8]. Imprint lithography is a patterning technique that transfers nano- and microstructures by pressing a patterned mold into a resist layer. The stamp provides the physical template that shapes the resist, ensuring accurate reproduction of the desired features on the substrate.

As environmental regulations increasingly target the elimination of per- and polyfluoroalkyl substances (PFAS) due to its health risks [9], there is a growing need for PFAS-free stamp materials that also meet the mechanical and optical demands of microlens fabrication.Additionally, UV-curable materials are preferred for their rapid processing, low thermal budget, and high pattern fidelity, which are essential for high-throughput manufacturing.

Another key challenge in microlens production is maintaining uniformity across the wafer, particularly in controlling total thickness variation (TTV) of the base layer [10]. Consistent thickness is essential for achieving uniform lens profiles and optimal optical performance. This paper details the imprint process flow, material selection, and equipment configuration used to fabricate microlenses on 300 mm wafers. The process employs the SUSS MA12 mask aligner, equipped with an interferometer unit for wedge compensation and an automated dispensing system to ensure uniform material distribution.

For the stamp material, we utilize the UV-curable, PFAS-free DELO PHOTOBOND VE 556992, which aligns with current environmental regulations aimed at eliminating per- and polyfluoroalkyl substances (PFAS). This material offers excellent mechanical and optical properties while minimizing ecological and health hazards. The demonstrated approach provides a sustainable and scalable solution for microlens fabrication, suitable for integration into next-generation optical systems.

UV-based imprint lithography and stamp fabrication with SUSS tools

Imprint lithography is a replication technique in which micro- and nanostructures are transferred from a mold or stamp into a liquid resist by mechanical contact. When UV-curable resists are used, the pattern is cured by ultraviolet exposure, enabling fast and precise structuring with high resolution and reproducibility. This method is well-suited for creating microstructures across a wide range of substrates and applications, offering advantages in scalability, material efficiency, and process simplicity. SUSS provides equipment for both stamp fabrication and imprinting, specifically designed for UV-based processes. These systems offer controlled imprint force, accurate alignment, and integrated UV exposure (see Fig. 2). The stamp fabrication tools (SFTs), NIL-SFT8 and NIL-SFT12, are designed to produce stamps for W-200 (wafers with a diameter of 200 mm) and W-300 (300 mm wafers) imprints, respectively. Master molds up to 9” and 13” can be used in these systems. Traditionally, stamp production relied on thermal curing, which could require several hours. However, new stamp materials have been developed that cure under UV light, reducing manufacturing time to just a few minutes. With a high UV-light uniformity of ±2.5 % at a wavelength of 365 nm, the system ensures homogeneously cured stamps and, consequently, high structure fidelity. The tool also offers great flexibility due to its compatibility with a wide variety of UV-curable stamp materials, supporting applications from R&D to high-volume manufacturing (HVM). The MABA6, MABA8 Gen4, and MA12 Gen3 imprint tools are used to replicate nano- and microstructures. The MABA6 and MABA8 Gen4 are equipped with collimated light sources suitable for conventional optical lithography on 150 mm and 200 mm wafers, respectively. In contrast, the MA12 Gen3 features a DELO flood exposure unit consisting of four DELOLUX 20 lamps that deliver high UV intensities up to 200 mW/cm^2 with exceptional homogeneity for 300 mm wafers.

Figure 2: SUSS machines to fabricate stamps (NIL-SFT8 and NIL-SFT12) and imprint nano- and microstructures (MA/BA6/8 Gen4 and MA12 Gen3)

All these machines incorporate an active wedge error compensation (WEC) unit, consisting of gap sensors and piezoelectric elements, which enables precise control of base layer uniformity throughout the imprint process. Additionally, the MA12 Gen3 is equipped with interferometer units that measure the gap between the stamp and substrate in the active imprint area. This allows for real-time compensation of any wedge errors until the imprint resist is fully polymerized. One tool that significantly improves throughput, yield, and reproducibility is the automated dispense unit integrated into the MA12 Gen3 system (see Fig. 3a). After wedge error compensation (WEC), the machine automatically dispenses a predefined amount of imprint resist onto designated areas of the substrate—eliminating the need for manual intervention. This ensures that the target gap, and consequently the base layer thickness, is achieved without resist overflow.

The auto-dispense unit also enables the creation of specific resist patterns tailored to specialized lens die layouts.
Following the resist dispense (Fig. 3b(1)), the wafer is moved upward to bring the resist into contact with the stamp (Fig. 3b(2)). The gap between the stamp and wafer is then gradually reduced until the resist spreads to the wafer edge or the target gap is reached (Fig. 3b(3)). During this process, the z-axis can apply forces up to 9000 N, allowing the use of highly viscous materials. Subsequently, the imprint resist is cured using UV light emitted by a DELO flood exposure unit (Fig. 3b(4)) which homogeneously irradiates the full wafer area with intensities up to 200 mW/cm^2 at 365 nm. In the final step, the imprinted substrate is separated from the stamp (Fig. 3b(5)), which can then be reused for the next imprint cycle.

DELO PHOTOBONDVE 556992 – DELO's PFAS-free UV-curable stamp material

DELO, a German company renowned for its high-performance adhesives and resists, has been actively engaged in advancing imprint lithography technologies. DELO's expertise in precision bonding and UV-curable materials positions the company as a key player in the development of next-generation lithographic processes. In the context of environmental sustainability and regulatory pressure, the elimination of per- and polyfluoroalkyl substances (PFAS) from stamp materials has become imperative. PFAS compounds, often used for their non-stick and chemical-resistant properties, pose significant ecological and health risks due to their persistence and bioaccumulation. Consequently, the industry is shifting toward PFAS-free alternatives to ensure compliance with emerging environmental standards.

Moreover, to enhance throughput and reduce cycle times in nanoimprint lithography, there is a growing demand for UV-curable stamp materials. Unlike thermally cured systems, UV-curable formulations enable rapid polymerization under light exposure, significantly shortening the stamp fabrication process from days to minutes and improving overall efficiency. In response to these dual challenges—environmental responsibility and process optimization — DELO has introduced DELO PHOTOBOND VE 556992 as a promising candidate. This material is PFAS-free and UV-curable, offering a sustainable and high-performance solution for imprint lithography applications.

The perfect material combination for high fidelity microstructure replication

Creating precise optical structures through lens imprint technology requires a carefully engineered material system that can accurately transfer microscopic patterns while maintaining exceptional optical clarity and dimensional stability. The combination of DELO KATIOBOND OM6611 as the imprint material and DELO PHOTOBOND VE 556992 as the stamp material represents an optimized solution that addresses the complex challenges of modern optical manufacturing.

DELO KATIOBOND OM6611 is a specially formulated epoxy resin with low, predictable shrinkage behavior of only 2.4 vol.% that ensures replicated optical features maintain their precise dimensions. This material demonstrates remarkable thermal stability, meaning it retains its structural integrity and optical properties even when subjected to high-temperature processing steps like reflow soldering with peak temperatures up to 260 °C, commonly used in electronics manufacturing.

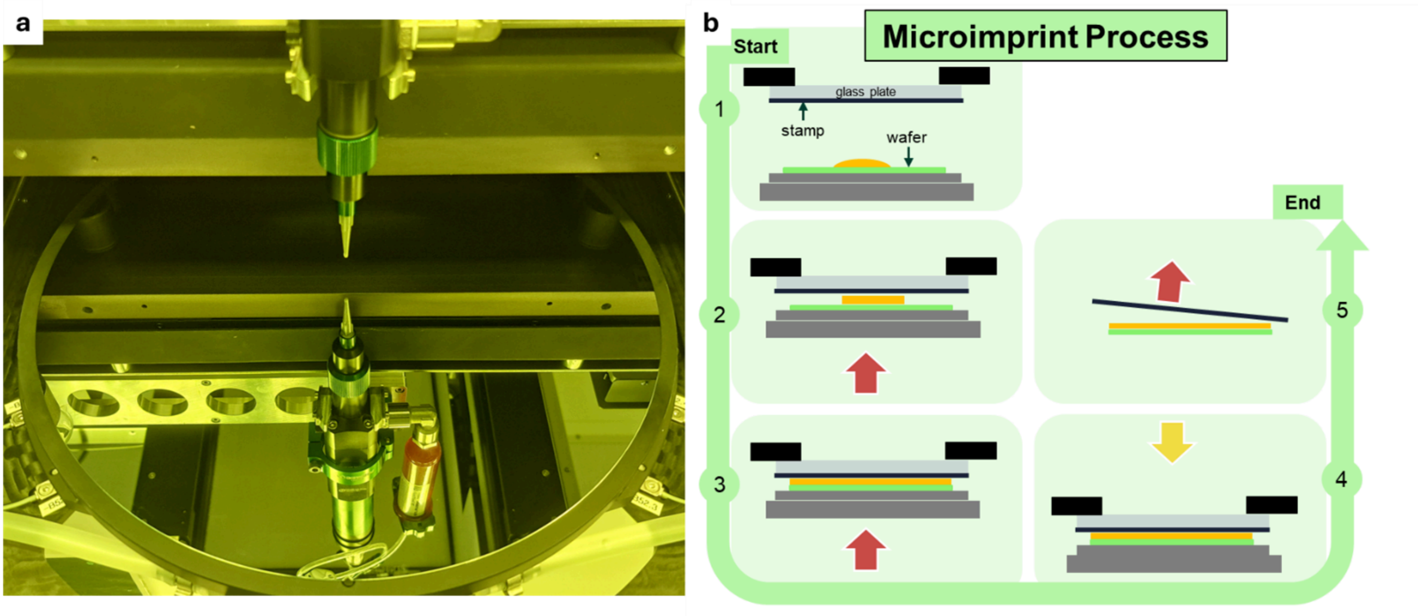

Figure 3: Optical image of the automated dispenser in the MA12 Gen3 (left). (Right) Schematic illustrating the "SMILE for microimprint": after dispensing a puddle on the wafer (1), the wafer is moved upwards until the puddle touches the stamp (2). Force is used to spread the resist until the edge of the wafer (3) before it gets exposed by UV light (4). In the end, the wafer with the imprinted microstructures is separated from the stamp (5).

Its resistance to yellowing under UV exposure and moisture absorption prevents degradation that could compromise optical performance over time ensures that the polymer remains completely transparent and colorless throughout its service life, even in most demanding applications like Co-Packaged Optics or Automotive Lighting. DELO PHOTOBOND VE 556992 serves as the complementary stamp material, engineered as a flexible polymer with carefully controlled flow properties at 500 mPa·s viscosity that allows it to conform perfectly to surface details during the imprinting process. Upon UV exposure at 365 nm, this material cures rapidly within 25 seconds at 200 mW/cm^2, forming a soft elastomer with the ideal balance of flexibility needed for clean mold release while maintaining enough structural integrity to preserve fine pattern details through multiple manufacturing cycles.

Targeted chemical formulation and iterative optimization of both stamp material and imprint resist has resulted in an optimized material pairing with minimum chemical interference and easy detachment performance over multiple imprints, perfectly suited for high quality microstructure replication in large volume manufacturing. This is proven by the results shown in the following sections.

Low base layer variation – the key to high yield

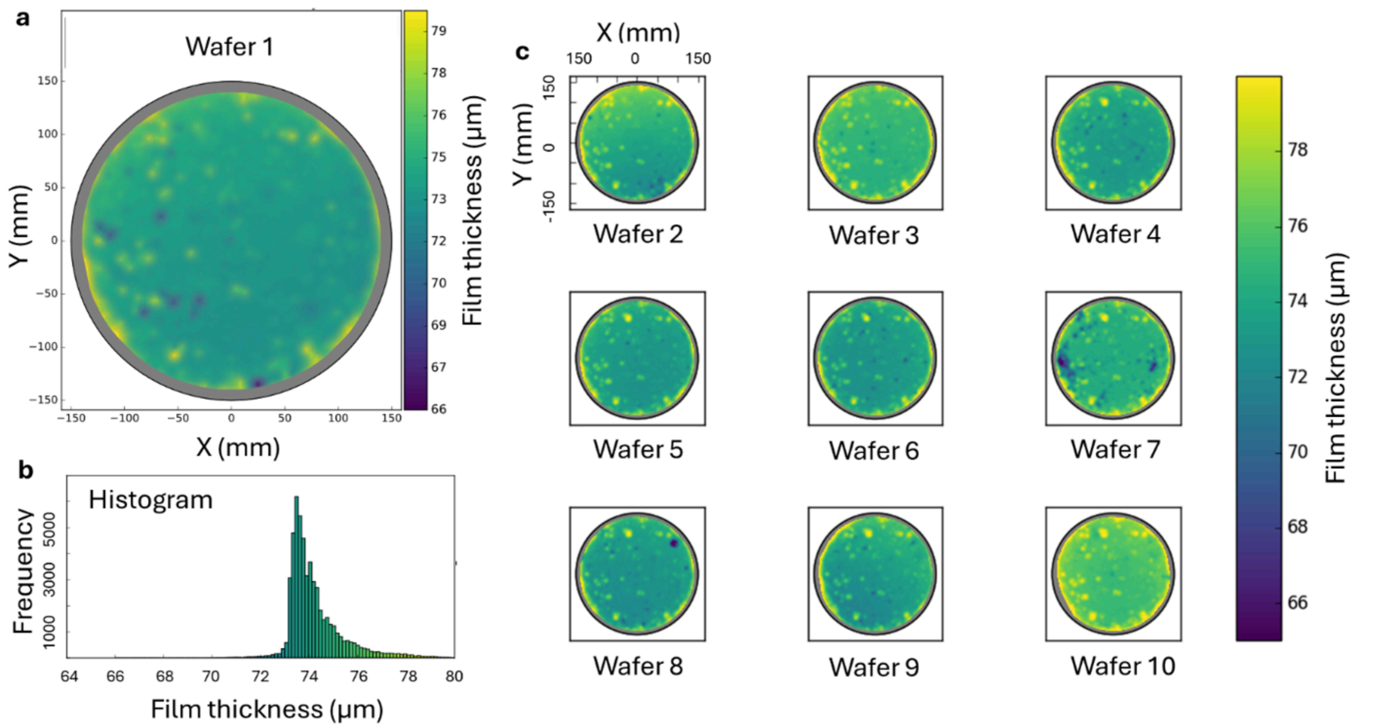

Figure 4: Total thickness variation (TTV) of the base layer on 10 imprinted W-300 lens wafers: (a) Contour plot of wafer 1 with (b) corresponding histogram. (c) Contour plots of wafers 2 to 10. For each wafer, more than 70,000 spots have been measured.

Every imprinted microlens is designed for a specific base layer—the continuous resist layer beneath the lens structure. The optical efficiency of microlenses strongly depends on deviations from this designed base layer thickness. Therefore, achieving high uniformity across the base layer is critical to ensure high yield on 300 mm wafers.

Thanks to the built-in interferometer unit in the MA12 Gen3 and the use of high-quality flat tooling, the total thickness variation (TTV) of the imprinted layer can be as low as 5 μm on 300 mm wafers. Fig. 4 shows the base layer thickness measured at more than 70,000 locations across ten wafers imprinted with microlenses. The contour plot (Fig. 4a) and the corresponding histogram (Fig. 4b) of the first wafer demonstrate excellent uniformity across the entire wafer.

The film thickness distribution is centered around 74.0 μm, with a variation of less than 2.5 μm. Minor peaks and valleys in the base layer thickness are attributed to particle defects occurring during stamp fabrication or the imprint process. A similar thickness distribution is observed on wafers 2 through 10 (see Fig. 4c). All contour plots from the imprint series confirm a TTV of less than 5 μm across 300 mm wafers, demonstrating the high repeatability of the SMILE microimprint process.

Since the microimprint process closely resembles the UV-stacking process, this level of uniformity can be transferred to UV stacks—such as those consisting of two glass wafers bonded with UV adhesives.

Long-term stability of UV-curable stamp materials for microlens imprinting

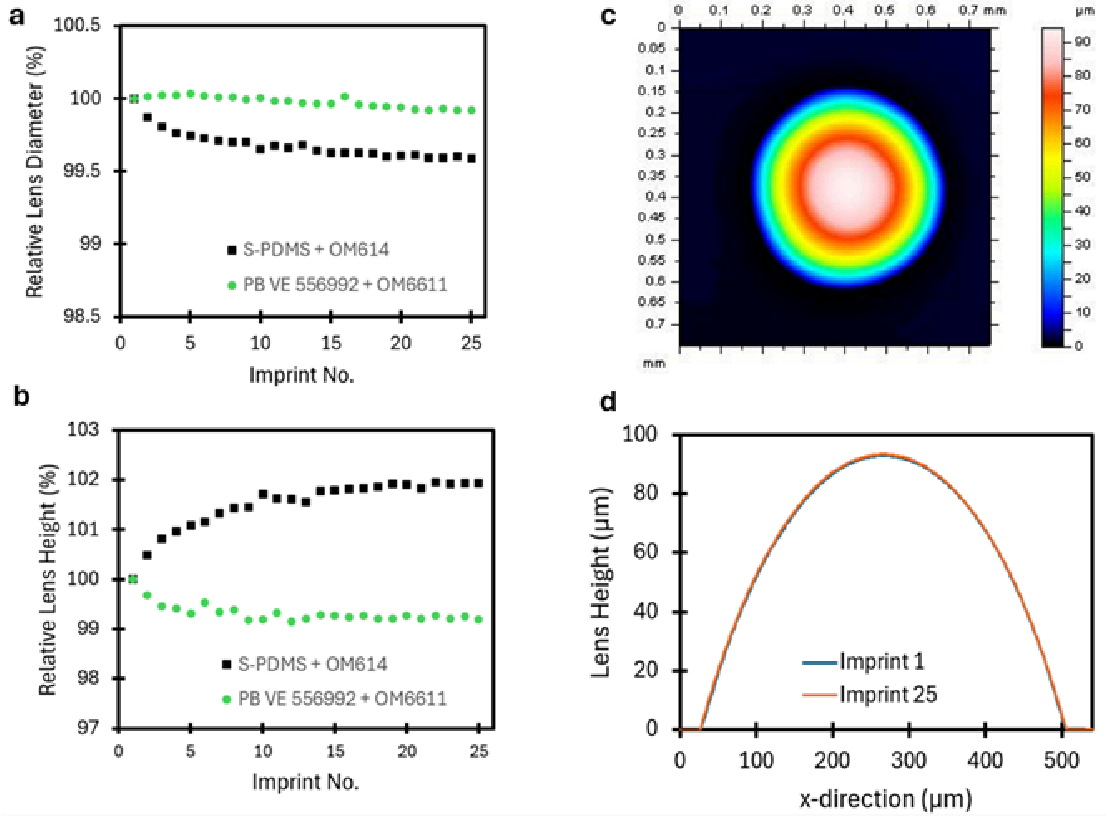

Figure 5: Evolution of (a) the relative lens diameter and (b) the relative lens height for 25 imprints for S-PDMS and DELO KATIOBOND OM614 (black boxes) and DELO PHOTOBOND VE 556992 and DELO KATIOBOND OM6611 (green circles), (c) profilometer measurement of an imprinted lens on the first imprint, (d) lens profile across the lens center of the first (blue line) and 25th imprint (orange line) using DELO PHOTOBOND VE 556992 and DELO KATIOBOND OM6611.

To make a UV-curable stamp material suitable for the mass production of microlenses, long-term stability is of utmost importance. Critical parameters such as lens diameter, lens height, and overall process stability must exhibit minimal variation across repeated imprints. Additionally, reliable and easy separation of the imprinted substrate from the stamp is essential for consistent performance over time.

A well-known material that has been widely used in imprint lithography is thermally curable soft PDMS [11]. Fig. 5 illustrates the evolution of lens diameter and height over 25 imprint cycles using soft PDMS with DELO KATIOBOND OM614 (black squares) and DELO PHOTOBOND VE 556992 with DELO KATIOBOND OM6611 (green circles). For soft PDMS, significant changes are observed, particularly during the initial imprints: the lens diameter decreases by approximately 0.3 %, while the lens height increases by more than 1.0 % after five imprints. After 10 imprints, the lens diameter decreased by 0.3 % and the lens height increased by almost 2.0 % relative to the first imprint. This behavior is attributed to the swelling of the stamp material. Upon contact with the imprint resist, the porous structure of soft PDMS absorbs components of the resin, leading to a slight increase in volume and, consequently, changes in lens dimensions.

As the stamp becomes saturated, this effect diminishes. In contrast, DELO PHOTOBOND VE 556992 exhibits much greater dimensional stability. The lens diameter and height show smaller changes of 0.2 % and 0.7 %, respectively, and remain very constant after the fifth imprint. Furthermore, the separation force required to release the imprinted wafer is very similar throughout the imprint series. Fig. 5c shows a profilometer measurement of a typical lens imprinted using DELO PHOTOBOND VE 556992 with DELO KATIOBOND OM6611 revealing the excellent quality of the imprinted microlenses. In this case, the lens diameter is 480 µm and the lens height is 95.0 µm. The lens is completely filled and does not show any sag which is confirmed by the profiles in Fig. 5d across the center of imprinted lens. Furthermore, no difference in the lens dimensions can be observed between the first and the 25th imprint.

Overall, the excellent imprint stability combined with straightforward handling makes DELO PHOTOBOND VE556992 a highly promising candidate for the mass production of microlenses.

Conclusion

UV-based imprint lithography has emerged as a powerful technique for replicating micro- and nanostructures with high precision, scalability, and efficiency. The integration of advanced tooling, such as SUSS MicroTec's MA12 Gen3 and NIL-SFT systems, enables rapid stamp fabrication and high-throughput imprinting, supported by features like automated resist dispensing, active wedge error compensation, and high-intensity UV exposure.

Uniformity of the base layer beneath microlenses is critical for optical performance and yield. The MA12 Gen3, equipped with interferometric gap measurement and precision control, achieves total thickness variations (TTV) below 5 µm across 300 mm wafers, ensuring excellent repeatability and enabling transfer of this uniformity to related processes such as UV stacking.

A key challenge in scaling imprint lithography for mass production is the long-term stability of stamp materials. Traditional soft PDMS stamps exhibit dimensional drift due to swelling, impacting lens fidelity over repeated use. In contrast, DELO PHOTOBOND VE 556992, a PFAS-free, UV-curable stamp material, demonstrates superior imprint stability, minimal dimensional variation, and consistent separation force. Additionally, the fact that DELO PHOTOBOND VE 556992 can be cured by UV light within seconds, dramatically speeds up the process of stamp fabrication from >12 h in the case of room temperature curing PDMS to few minutes. Compared to heat curing (or heat-accelerated) stamp materials, UV curing avoids thermal runout and therefore allows best alignment. These properties make it a highly promising candidate for sustainable, high-volume microlens manufacturing.

Together, the combination of optimized equipment such as the MA12 Gen3 and advanced materials like DELO PHOTOBOND VE 556992 paves the way for reliable, scalable, and environmentally responsible imprint lithography solutions.

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