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High quality diffractive optical elements (DOEs) using SMILE imprint technique

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Abstract: Augmented reality (AR) enhancing the existing natural environment by overlaying a virtual world is an emerging and growing market and attracts huge commercial interest into optical devices which can be implemented into head-mounted AR equipment. Diffractive optical elements (DOEs) are considered as the most promising candidate to meet the market's requirements such as compactness, low-cost, and reliability. Hence, they allow building alternatives to large display headsets for virtual reality (VR) by light-weight glasses. Soft lithography replication offers a pathway to the fabrication of large area DOEs with high aspect ratios, multilevel features, and critical dimensions below the diffractive optical limit down to 50 nm also in the scope of mass manufacturing. In combination with tailored UV-curable photopolymers, the fabrication time can be drastically reduced making it very appealing to industrial applications. Here, we illustrate the key features of high efficiency DOEs and how the SMILE (SUSS MicroTec Imprint Lithography Equipment) technique can be used with advanced imprint photopolymers to obtain high quality binary DOEs meeting the market's requirements providing a very versatile tool to imprint both nano- and microstructures.

Keywords: augmented reality; DOE; imprint; photopolymer; SMILE.

1 Introduction

Diffractive optical elements (DOEs) are a powerful tool to shape and direct light in an efficient way [1]. They can be used in lightweight augmented reality (AR) glasses, where in contrast to virtual reality (VR) headsets, the existing surrounding is superimposed with additional elements. Their structures can vary from simple optical gratings to binary elements or pyramid-like multilevel structures. While gratings are used as diffractive waveguides for the in- and out coupling of laser beams in AR glasses [2], binary or multilevel DOEs create three-dimensional projections for holograms [3] or grids for face-recognition. There are many techniques to fabricate DOEs based on, e.g. greyscale lithography, direct writing using laser or electron beams, and direct machining. However, these methods exhibit great weaknesses such as low surface precision, serial process sequences, high equipment costs, and low volumes limiting their suitability for mass production [3]. Therefore, they are generally used for master originating purpose. In contrast, soft lithography replication enables the mass production of large area DOEs with multilevel features and high aspect ratios. By using UV-curable photopolymers, the replication time can be drastically reduced in comparison to, e.g. hot embossing. Here, we demonstrate the most critical characteristics of highly efficient DOEs and how the SMILE (SUSS MicroTec Imprint Lithography Equipment) technique can be used in combination with advanced imprint photopolymers.

2 DOEs – bridging the gap between nano- and microstructures

The rise of imprint lithography in recent years is based on its capability to resolve both nanometer and micrometer scale patterns and on its low cost and high throughput in comparison to conventional optical lithography. As a result, imprint lithography is the technique of choice to fabricate optical gratings, photonic crystals with critical dimensions and structure heights below 1 µm as well as micro lenses and monolithic lenses (see Figure 1). In this context, DOEs can be located in the nanoimprint regime as their typical structure height is around 1 µm and their lateral feature sizes range between hundreds of nm to a few micrometers.

In order to imprint high quality DOEs, SUSS has developed the SMILE for nanoimprint technology using

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flexible stamps. As illustrated in Figure 2, a UV-curable stamp material with a high Young's modulus (>5 MPa) on a flexible PET foil (Figure 2a) is bent applying a small pressure between the stamp and stamp holder (Figure 2b). A constant movement of the wafer towards the stamp results in an initial contact with the thin photopolymer layer and a radial imprint wave from the center to the edge of the imprint substrate (Figure 2c). As a result, any entrapment of air is avoided and a full-field imprint can be obtained. After an optional force step (Figure 2d), the imprint resist is cured by UV light (Figure 2e) – typical exposure times are between 30 and 60 s – and the imprint substrate is automatically separated from the stamp inside the machine (Figure 2f) enabling high wafer throughputs. As this SMILE imprint technique is based on the same tooling which is used to imprint microstructures (SMILE for microimprint), one SUSS mask aligner equipped with SMILE is capable to imprint both nano- and microstructures covering a huge span of feature sizes from 10 nm to 1000 μm.

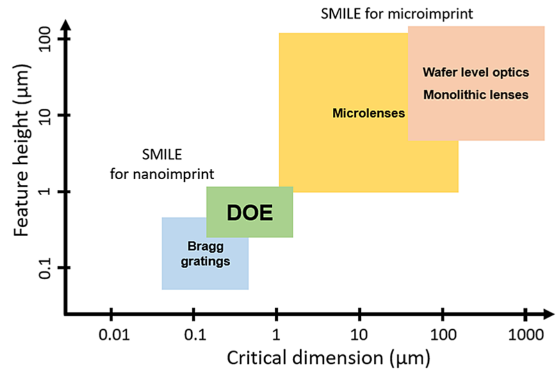

Figure 1: Typical imprint applications classified according to their feature height and critical dimension. Both nano- and microstructures can be imprinted using the SMILE imprint technology.

3 DOEs – from a laser beam to a projected three-dimensional image

The basic working principle of DOEs is illustrated in Figure 3. In refractive optical elements, an incident light beam undergoes a change in its direction when entering another medium with a different refractive index. Leaving a prism with an apex angle β and the refractive index n_1 (Figure 3a), the original path of a laser beam with the wavelength λ is deflected by γ when reaching the second medium with the refractive index n_2. The degree of the refraction depends on the incident angle of the laser beam α_1 and the refractive indices [4]:

$$n_1 \sin \alpha_1 = n_2 \sin \alpha_2. \tag{1}$$

Similar to the design of Fresnel lenses as a further development of conventional lenses, the amount of the material needed for the fabrication of these structures can be reduced by using a blazed diffractive structure (Figure 3b). The deflection of the light beam is now determined by the structure height of the blaze and its period d. In order to facilitate the production of these elements, the design can be further simplified using a binary structure (Figure 3c). As a result, the incident beam is now diffracted at the optical grating leading to an interference pattern behind the DOE. The maxima of the interference pattern can be calculated using the following formula:

$$d(\sin \theta_i + \sin \theta_m) = m\gamma, \tag{2}$$

where θ_i is the angle of the incident light beam, θ_m is the angle under which the mth maximum can be observed and m is an integer which can be attributed to the mth order. Considering the maxima of the first order, which has the highest intensity among the diffracted light beams (e.g., ~40.5% of the incident light intensity when using the simplest form of a binary element [5]), one grating constant results in one "pixel" of the projected image. By combining many different grating constants, an incident light beam can be converted into an array of pixels behind the optical element yielding a diffracted pattern (see Figure 3d). As an application, the projection can be used as structured light for face recognition cameras using near infrared light in mobile phones allowing an effective identification from different angles (see Figure 3e).

In order to ensure a high efficiency of DOEs manufactured by imprint technique, the replicated structures in the photopolymer layer have to fulfill many requirements. The most crucial feature is the profile fidelity as it directly affects the optical functionality and projection quality. In general, DOEs are designed for one specific wavelength in terms of a certain structure height. Even small deviations within the structure height of a single DOE result in a significant drop of the intensity in the diffracted pattern. Therefore, the uniformity of the structure height (defined as the absolute height variation divided by designed structure height) should be better than 1% in order to obtain sharp diffracted patterns. Furthermore, vertical sidewall angles especially in binary DOEs are important to obtain a high quality projection. Any unintentional transition region between the plateaus and the trenches would

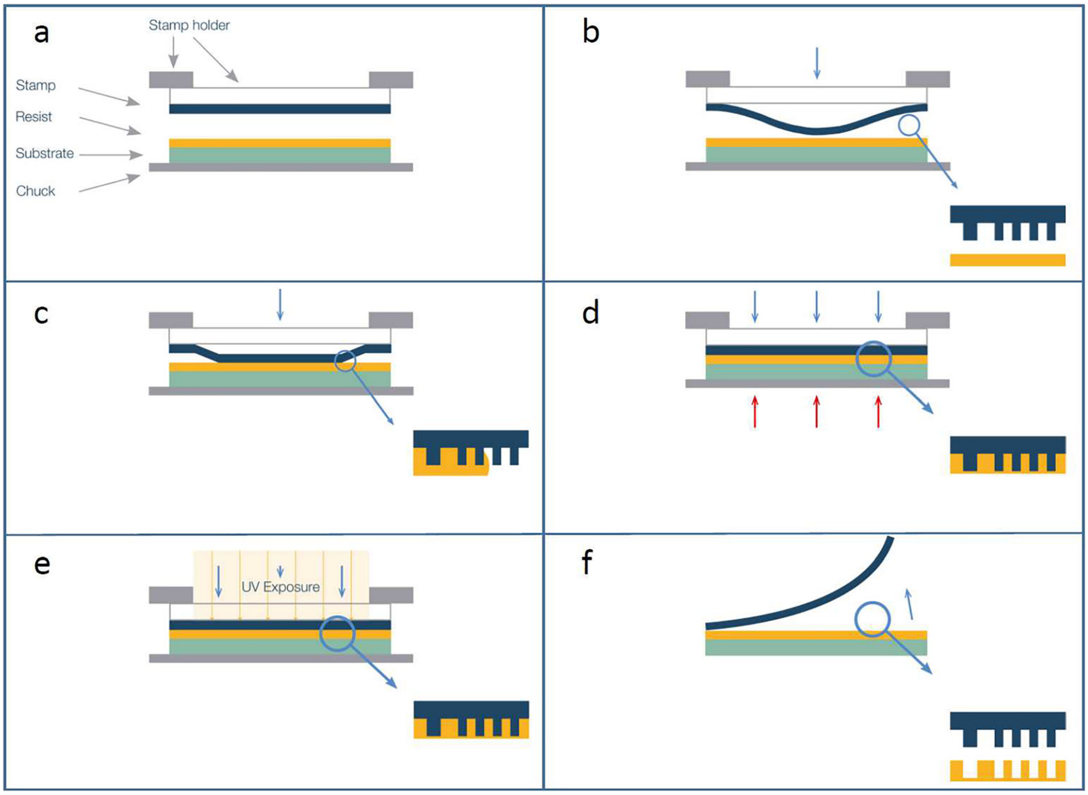

Figure 2: Schematic illustrating the “SMILE for nanoimprint” process. After the alignment of the stamp to the imprint substrate (a), a small pressure is applied to bend the flexible stamp (b) resulting in an imprint wave from the center to the edge of the wafer (c). After an optional force step (d), the imprint resist is cured (e) and the imprint substrate is separated from the stamp inside the machine (f).

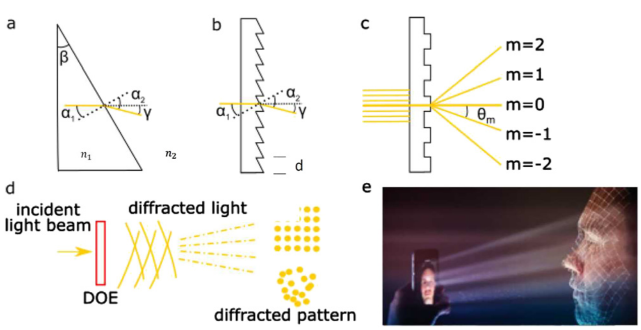

Figure 3: Deflection of a light beam in a (a) refractive, (b) blazed diffractive, and (c) binary diffractive optical element. (d) Schematic showing the transformation of an incident light beam into a diffracted pattern. (e) Application of a DOE in face ID cameras.

lead to misdirected light beams weakening the intensity of the projection behind the DOE. Therefore, a sidewall angle very close to the original design is needed to obtain a high performance of the DOE.

Similar to the vertical accuracy, the lateral precision is crucial to get a high quality projection by a DOE. If the lateral dimensions in the *xy*-plane of the DOE imprint vary from the original design, the variation in the grating period *d* would result in alterations of the projected image weakening its intensity. Therefore, any changes, resulting e.g. from material shrinkage during photopolymerization, process-based stamp expansions, etc., have to be considered in the master design.

An alternative processing route employs pattern transfer by dry etching techniques. According to Eq. (1), the degree of the refraction of light beams depends on the angle of the incident light beam and on the refractive indices. In some cases, to get the desired projection pattern, high refractive indices (>1.7) are needed which, however, generic imprint resists might not be able to provide. As a solution, the pattern is imprinted into a nanoimprint resist, of e.g. the mr-NIL210 series (*micro resist technology* GmbH) before it is subsequently transferred into the underlying high refractive index glass substrate. Using this approach of standard nanoimprint lithography, the imprinted polymer layer does not serve as the actual DOE but as a polymeric mask layer for reactive gases (see Förthner et al., SUSS Report 2017). Thin residual layer (RL) thicknesses and a high control over its uniformity in combination with a good etching selectivity between the imprint resist and the imprint substrate are paramount to obtain a good pattern transfer into the substrate [6]. As a result, the surface patterned glass substrate with a high refractive index can serve as DOE.

4 Meeting the market's requirements

The SMILE imprint technique and the use of tailored NIL photopolymers ensures the fabrication of high quality DOEs with a high efficiency. As discussed above, a high profile fidelity in terms of a uniform structure height and vertical sidewalls are needed. This applies for both alternative processing routes, i.e. imprint in nanoimprint resist prior to a pattern transfer (i.e. photopolymer is consumed during post-processing) and imprint in functional optical grade photopolymer (i.e. imprinted pattern is not consumed, but remains for permanent application). Any deviation from the designed sidewall angle would lead to misdirected light beams weakening the intensity of the projection behind the DOE. In the following, two examples demonstrate that this market requirement can be achieved. Figure 4a shows a SEM side view image of a typical DOE structure imprinted into a nanoimprint resist of the mr-NIL210 series (*micro resist technology* GmbH) using our SMILE imprint technology. The mr-NIL210 series is a tailor-made resist formulation for subsequent pattern transfer after the nanoimprint step. The unique key features of the products are outstanding film forming and imprinting performance beside excellent pattern fidelity and – most importantly – plasma etch stability for substrate materials such as Si, SiO_2, Al, or sapphire. The SEM image in Figure 4a reveals a complete filling of the DOE structure and a very low height variation. This is confirmed by the second example (Figure 4b), where the pattern was replicated into the UV-curable hybrid polymer OrmoComp® (*micro resist technology* GmbH) [7], as can be seen in the atomic force microscopy (AFM) map allowing a quantitative analysis of the imprint. In the depicted area of $10 \times 10\ \mu m^2$, the total height variation is smaller than 10 nm yielding a structure height uniformity of better than 1%. Furthermore, a sidewall angle close to 90° can be observed in both the AFM and the SEM image indicating a very high profile fidelity. It is important to mention for this example, that hybrid polymers, such as OrmoComp®, exhibit both inorganic and organic units, thus combining superior properties in one material class. On the one hand, the organic units bear polymerizable moieties and various functional groups which enable photon-induced radical polymerization. On the other hand, the inorganic backbone provides outstanding optical transparency, high temperature, and climate stability as well as excellent mechanical stability. Therefore, hybrid polymers are excellent candidates to allow replication of permanent DOE patterns.

The excellent lateral accuracy of the SMILE imprint technique is illustrated in Figure 5. A comparison between the patterns of the original master wafer (Figure 5a) and those of the imprinted structures into OrmoComp® (Figure 5b) reveals a full process-independent agreement in the lateral dimensions taking the low and reproducible material shrinkage into account. Even high aspect ratio features of up to five (see red circles) can be imprinted. As a result, high efficiency levels and, in turn, a high performance of the DOEs can be expected.

As discussed above, if a pattern transfer into a high refractive index glass substrate is necessary, a high control of the RL thickness and its uniformity are crucial to obtain good etching results. The SEM image of a DOE imprint using the SMILE imprint technology in Figure 4a exhibits a RL thickness well below 25 nm. Using additional pressure on the imprint before UV-exposure helps obtain high uniformity levels. As indicated in Figure 4, typical achieved uniformity levels are better than 5%.

Another important requirement for the imprint of DOEs is the alignment accuracy. Especially if multiple fabrication

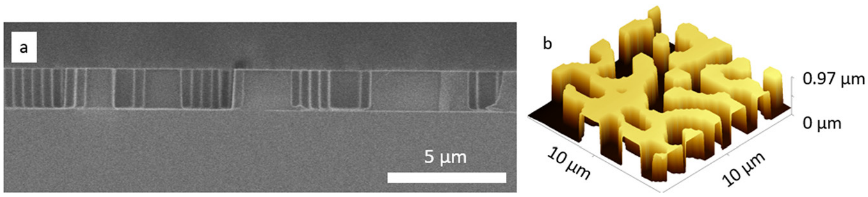

Figure 4: Illustration of achievable pattern profile fidelity by a (a) SEM image (side view) of an imprinted DOE into a NIL resist layer of the mr-NIL210 series and (b) AFM map (tilted view) of a similar pattern replicated into the UV-curable hybrid polymer OrmoComp® using the SMILE technology.

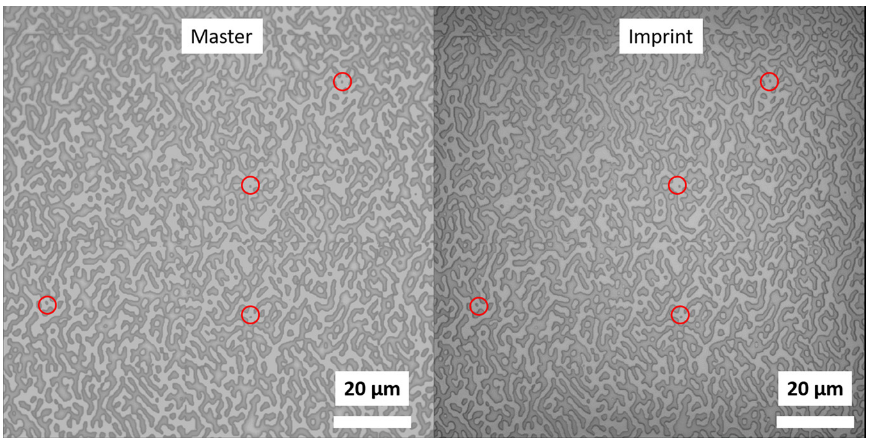

Figure 5: SEM images comparing the DOE structure of the master wafer (left) to the imprint (right). The red circles indicate high aspect ratio features. Structure height 1 µm (see Figure 4b).

steps are required, e.g. the imprint of DOE structures on top of a micro lens instead of a flat glass substrate, a high alignment precision is needed to ensure the proper diffraction of light beams. To this end, the excellent alignment capabilities of SUSS mask aligners can be used to precisely locate the stamp position with respect to the imprint substrate. The auto-alignment option with automated pattern recognition software, furthermore, allows an operator-independent and fast alignment with a high wafer throughput.

5 Conclusion

In summary, diffractive optical elements (DOEs) are a powerful tool to manipulate the way of light creating high quality projections. They are the basic components for facial recognition technology by structured light and in future for augmented reality devices enhancing the existing surrounding environment by adding virtual elements and, therefore, attract huge commercial interest. We demonstrated that using the SMILE imprint technology with advanced replication materials such as mr-NIL210 series and OrmoComp®, defect-free DOE imprints with a high profile fidelity and lateral accuracy can be obtained. The possibility to employ additional pressure before the cross-linking of the UV-curable imprint resist ensures a high residual layer control enabling to transfer the DOE pattern into the underlying imprint substrates. Furthermore, the most modern alignment processes of the SUSS mask aligners provide a very high alignment accuracy which is of high importance for multilevel DOE processing.

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