Published in the SUSS report 2019

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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 [1] as they replace large display headsets for virtual reality (VR) by light-weight glasses. Their structures can vary from simple optical gratings to binary elements or pyramid-like multilevel structures. While gratings are used as diffractive wave guides for the in- and outcoupling 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 process variability and surface precision, high equipment costs, and low volumes limiting their suitability for mass production [3]. In contrast, 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. In combination with UV-curable materials, the fabrication time can be drastically reduced in comparison to, e.g. hot embossing replication methods, making it very appealing to industrial applications [3]. Here, we illustrate how the SMILE (SUSS MicroTec Imprint Lithography Equipment) technique can be used to obtain high quality binary DOEs meeting the market's requirements providing a very versatile tool to imprint both nano- and microstructures.

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.

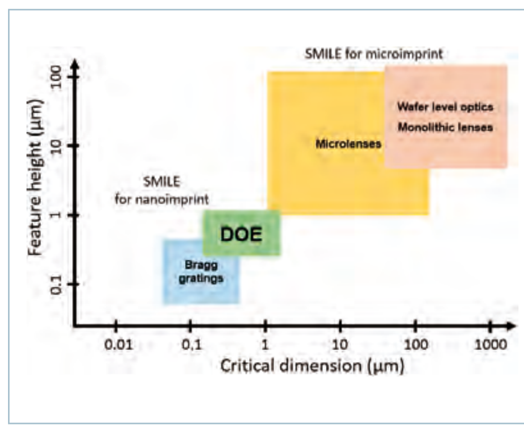

Figure 1 Typical imprint applications classified according to their feature height and critical dimension. Both nano- and microstructures can be imprinted using the SMILE imprint technology

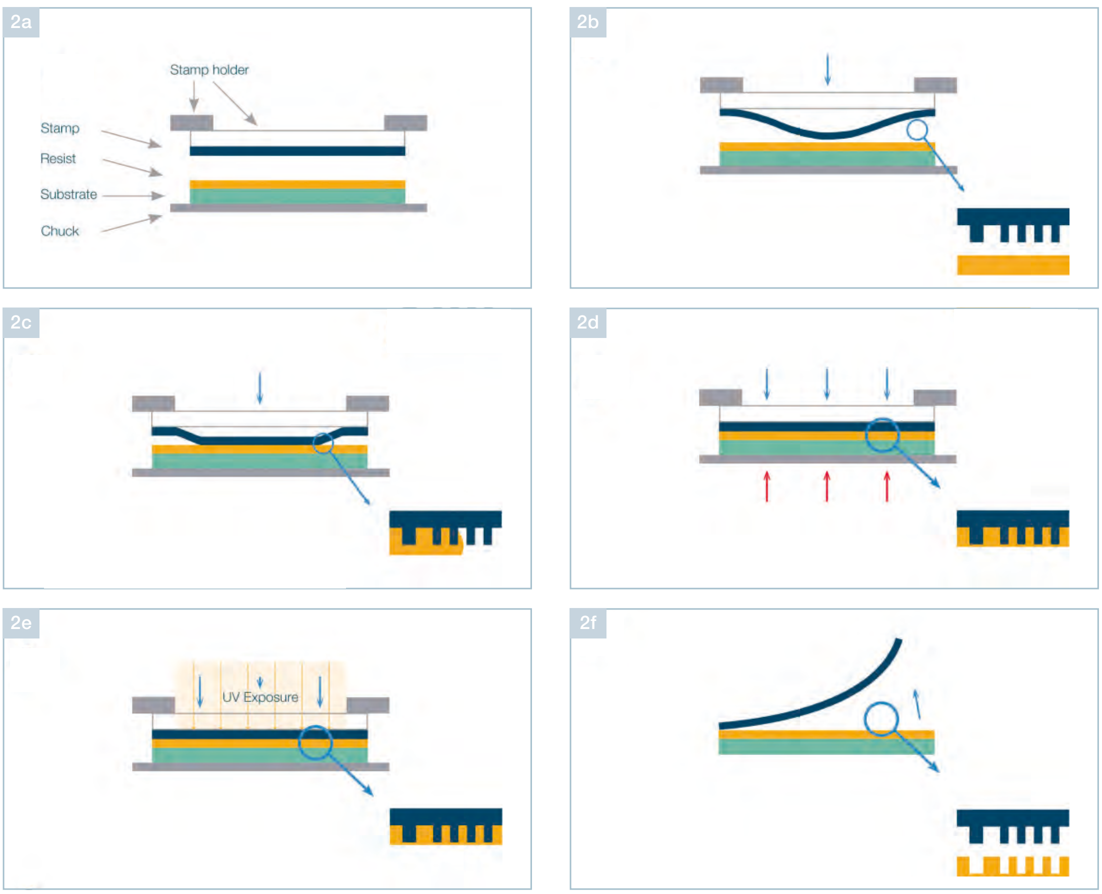

Figure 2 Schematic illustrating the "SMILE for nanoimprint" process. After the alignment of the stamp to the imprint substrate (a), a small pressure is used to bend the flexible stamp (b) resulting in an imprint wave from the center to the edge of the wafer (c). After an optional force step (d), the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

In order to imprint high quality DOEs, SUSS MicroTec has developed the SMILE for nano-imprint technology using flexible stamps (see Storace, SUSS Report 2015). As illustrated in Figure 2, a UV-curable stamp material on a flexible PET foil (Figure 2a) is bent using a small pressure between the stamp and stamp holder (Figure 2b) resulting in a radial imprint wave from the center to the edge of the imprint substrate (Figure 2c). As a result, any enclosure 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 seconds – 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 can imprint both nano- and microstructures covering a huge span of feature sizes.

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 wave length 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:

$$n_1 \sin\alpha_1 = n_2 \sin\alpha_2 . \qquad \text{(Eq. 1)}$$

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:

$$d\,(\sin\theta_i + \sin\theta_m) = m\gamma, \qquad \text{(Eq. 2)}$$

where θ_i is the angle of the incident light beam, θ_m is the angle under which the m-th maximum can be observed and m is an integer which can be attributed to the m-th 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 [4]), 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 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, the imprinted structures have to fulfill many requirements. The most crucial feature is the profile fidelity. In general, DOEs are designed for

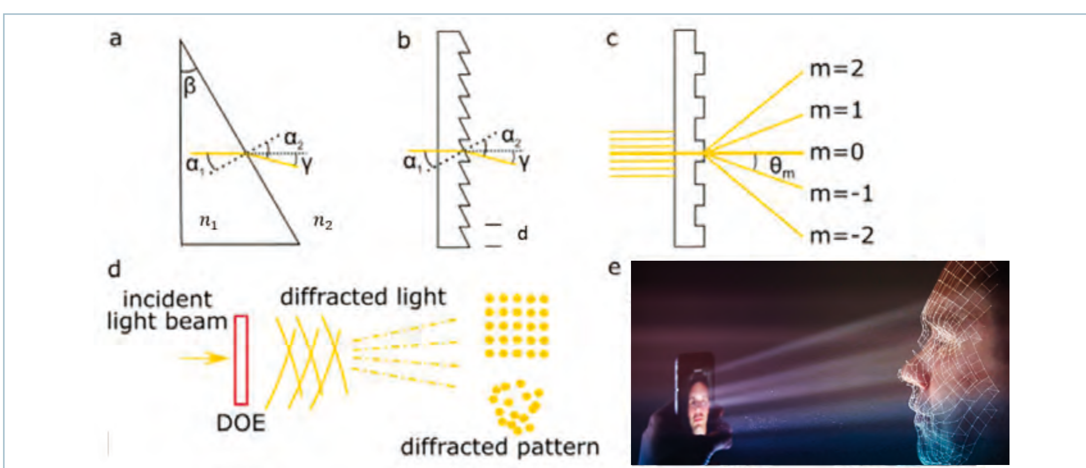

Figure 3 *Deflection of a light beam in a (a) refractive, (b) blazed diffractive, and (c) binary diffractive optical element. (d) Schematic showing the transformation of an incident light beam into a diffracted pattern. (e) Application of a DOE in face ID cameras*

one specific wave length 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 should be better than 1 % in order to obtain sharp diffracted patterns. Furthermore, vertical side wall angles especially in binary DOEs are important to obtain a high quality projection. Any transition region between the plateaus and the trenches would lead to misdirected light beams weakening the intensity of the projection behind the DOE. Therefore, a side wall angle larger than 85° 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 critical dimension (CD) in the xy-plane of the DOE imprint varies 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, e.g. resulting from material shrinkage, process-based stamp expansions, etc., have to be considered in the master design.

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 are needed which, however, imprint resists might not be able to provide. As a solution, the imprint pattern can be transferred into the underlying substrate with a higher refractive index. Using this approach, the imprint does not serve as the actual DOE but as a barrier for reactive gases (see Förthner et al, SUSS Report 2017). Thin residual layer (RL) thicknesses and a high control on 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 [5]. As a result, the etched imprint substrate with a high refractive index can serve as DOE.

MEETING THE MARKET'S REQUIREMENTS

The SMILE imprint technique 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 side walls are needed. Any deviation from this angle would lead to misdirected light beams weakening the intensity of the projection behind the DOE. Figure 4a shows a SEM side view image of a typical DOE structure imprinted using SMILE imprint technology. It reveals a complete filling of the DOE structure and a very low height variation. This is also confirmed by the atomic force microscopy (AFM) map in Figure 4b allowing a quantitative analysis of the imprint. In the depicted area of 10 x 10 µm², the total height variation is smaller than 10 nm yielding a structure height uniformity of better than 1 %. Furthermore, a side wall angle close to 90° can be observed

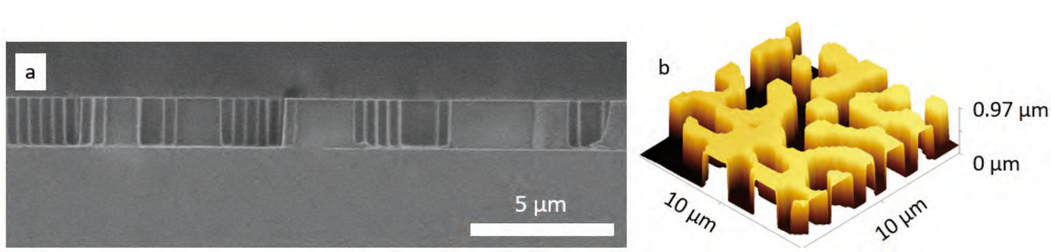

Figure 4 *(a) SEM image (side view) and AFM map (tilted view) of a DOE imprinted using the SMILE technology confirming a very good profile fidelity*

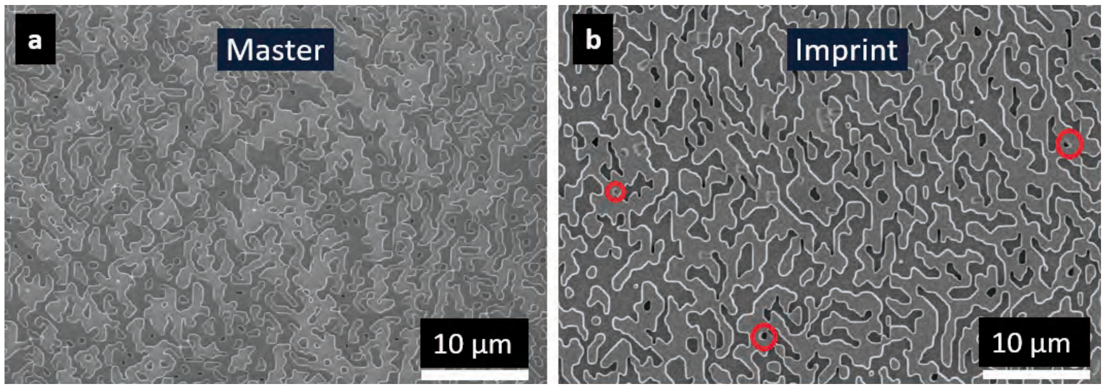

Figure 5 *SEM images comparing the DOE structure of the master wafer (a) to the imprint (b). The red circles in (b) indicate high aspect ratio features*

both in the AFM and the SEM image indicating a very high profile fidelity. The excellent lateral accuracy of the SMILE imprint technique is illustrated in Figure 5. Comparing the imprinted structures (Figure 5b) to the master wafer (Figure 5a) and taking the material shrinkage into account yield a full process-independent agreement in the lateral dimensions. Even high aspect ratio features (see red circles in Figure 5b) 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 material 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 illumination helps obtain high uniformity level. As indicated in Figure 4, typically achieved uniformity levels are better than 5 %.
Another important requirement for the imprint of DOEs is the alignment accuracy. Especially if multiple fabrication 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 (see Hennemeyer et al., SUSS Report 2015), furthermore, allow an operator-independent and fast alignment with a high wafer throughput.

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 augmented reality devices enhancing the existing surrounding environment by adding virtual elements and, therefore, attract huge commercial interest. Using the SMILE imprint technology, 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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