Volume Manufacturing of Head-Up Displays with Step-and-Repeat Displacement Talbot Lithography

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Abstract

With heads-up display devices transitioning from proof of concept to volume production, establishing low-cost and high-throughput patterning of large-area substrates becomes imperative to the future of the industry. Eulitha's proprietary Displacement Talbot Lithography (DTL) is uniquely positioned to manufacture the desired high-resolution periodic nanostructures. This non-contact, optical lithography method allows for the printing of 60 nm half-pitch patterns in industry standard photoresist, facilitating its integration into existing production lines. The newest generation lithography tool, the PhableS, combines DTL technology with step-and-repeat capabilities and fully automated mask and substrate handling for unmatched large-volume production of heads-up displays of 300 mm and beyond.

Author Keywords

Displacement Talbot Lithography, heads-up displays, HUD, periodic nanopatterns, diffraction gratings, step-and-repeat lithography, photonics lithography.

1. Talbot Effect and Displacement Talbot Lithography (DTL)

Many cutting-edge technologies in the areas of optics, photonics, optoelectronics, and heads-up displays (HUDs) rely heavily on high-quality periodic nanopatterns. Here, DTL presents a unique low-cost and high-throughput approach to expose these patterns into standard photoresists. The technology is based on the Talbot effect(1), which is illustrated in Figure 1(a). Highly collimated, coherent, monochromatic light impinging on a grating (i.e., the photomask) creates a real space image of the original grating on the far side of the mask. This image, also called a self-image, is repeated at regular intervals, referred to as a Talbot length z_T.

$$z_\mathrm{T} = \frac{2a^2}{\lambda},$$

where a is the period of the grating and λ is the wavelength of the impinging light. While the Talbot effect can directly be applied to photolithography(2), this comes with severe limitations in depth of focus. In DTL, by contrast, the photoresist-coated substrate is displaced perpendicularly to the diffraction grating (i.e., in parallel to the incident beam), resulting in an integration of the diffracted light field, Figure 1(b).(3) This effectively results in an "infinite" depth of focus, allowing for photolithography on non-flat substrates. In addition to the self-image forming at integer multiples of z_T, there also manifests a laterally shifted image (by $\frac{a}{2}$) at every half-integer multiple of z_T. Hence, integrating over multiple Talbot lengths results in the imprint of a frequency-doubled pattern in the photoresist. After the DTL exposure process, the substrate is developed using standard materials and processes and, finally, the exposed pattern can be transferred to the substrate, for example through etching. In Figure 1(c) this is illustrated by an SEM image depicting a linear line-and-space grating (line width = 60 nm) exposed by DTL and etched into the Si substrate. Note that the DTL method is not limited to 1D linear

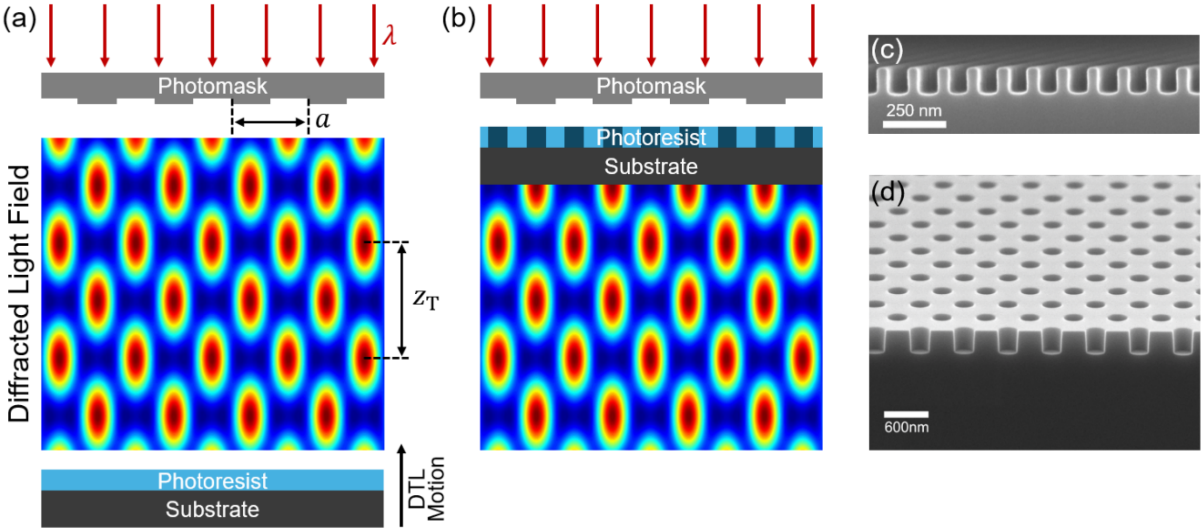

Figure 1: (a) The periodic photomask (period = $\boldsymbol{a}$) is illuminated by coherent light of wavelength $\boldsymbol{\lambda}$**.** This leads to the emergence of a diffracted light field on the far side of the mask. This light field forms self-images of the mask which repeat with a period of $\boldsymbol{z_\mathrm{T}}$ (Talbot length) in the direction parallel to the incident light. At half-integer multiples of $\boldsymbol{z_\mathrm{T}}$, self-images laterally shifted by $\frac{a}{2}$ are forming. The photoresist-coated substrate is vertically moved through the diffracted light field by several Talbot lengths. (b) The substrate displacement leads to the integration of the Talbot pattern and a frequency-doubled version of the mask pattern is imprinted into the photoresist. Subsequently, the photoresist is developed, and the exposed pattern can be transferred (e.g. through etching) into the substrate. This is exemplified by cross-sectional SEM images for a linear line-and-space grating in (c) and a square array of holes in (d).

patterns. It can be applied to various periodic structures, as for example a two-dimensional square lattice of holes, as depicted in Figure 1(d).

2. Advantages of DTL

The DTL technology brings a number of inherent advantages for the manufacturing of periodic nanostructures:

- Vertically displacing the substrate during the exposure and, hence, integrating the diffracted light field removes the depth of focus limitation and allows for exposures on bowed, warped, and curved substrates. This is especially interesting for HUD applications, where the large substrate may display limited flatness. This challenge can be overcome by DTL.
- DTL is a contact-fee printing technique. This, especially in contrast to nano imprint lithography, drastically reduces the danger of particle contamination and improves line edge roughness. Simultaneously, it considerably enhances the lifetime of the photomask.
- The compatibility with industry-standard photoresists, development chemicals, and photomasks makes it easy to integrate DTL into existing production lines.
- DTL allows for high-resolution exposures with minimum feature sizes down to 60 nm.
- The absence of complex projection optics makes DTL a far lower cost method compared to traditional projection lithography.
- The frequency doubling during the exposure allows for the use of lower resolution (i.e., cheaper) photomasks.
- No reduction of the exposure field takes place. Hence, patterns up to 140×140 mm^2 can be printed in a single exposure. This is crucial for the exposure of large-area diffractive elements in HUD applications, see Figure 2.

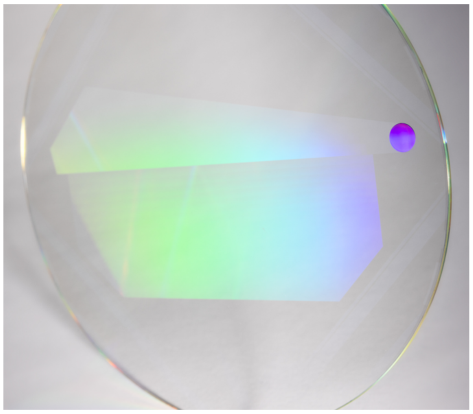

Figure 2: Heads-up display on 200 mm transparent substrate, exposed using DTL and subsequently etched. All three gratings (in-coupling, expansion, out-coupling) were exposed in a single, seamless shot.

For fast and seamless integration of new device architectures, lithography simulations have become an indispensable tool. Accurate simulation results enable an efficient photomask design and result in the highest possible pattern quality. To streamline this process, a dedicated suite for DTL exposures was developed for the industry-leading Synopsys S-Litho software package.(4) DTL capabilities can also be extended to patterns more complex than line-and-space, holes, or pillars. This is enabled through Eulitha's in-house-developed Inverse Lithography Mask Design.(5) This computational technique uses machine learning to generate potential mask designs from a user-supplied target wafer pattern, bringing DTL to an even wider range of possible industry sectors.

3. Step-and-Repeat DTL on the PhableS Lithography Tool for HUD Manufacturing

To keep up with the imminent upscaling of HUD production, adapting to the industry's demand to process large-area substrates is crucial. An industry-standard 6-inch photomask enables a maximum exposure field of 140×140 mm^2. While this is enough to expose an entire 6-inch substrate and most of an 8-inch substrate, it only covers ~28 % of a 12-inch substrate. See Figure 3(a) for a comparison. To overcome this issue, Eulitha combines its established DTL technology with a step-and-repeat approach in its newest lithography tool, the PhableS, Figure 3(b).

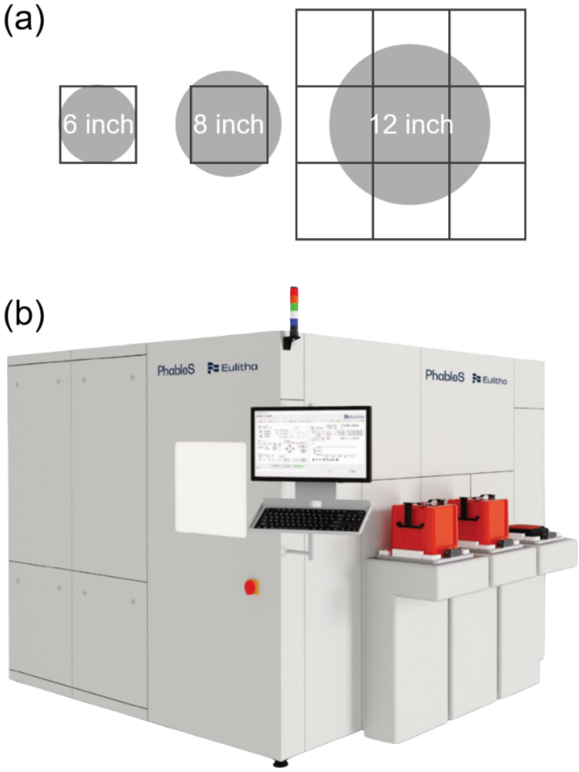

Figure 3: (a) Overlay of the 140×140 mm^2 exposure field of an industry-standard 6-inch photomask on 6-, 8-, and 12-inch substrates. In the PhableS, the 12-inch substrate can be exposed over its entire surface using the tool's step-and-repeat functionality. (b) The PhableS step-and-repeat lithography tool allows for the fully automated processing of up to 12-inch wafers.

The PhableS is a fully automated lithography tool designed for large-volume production in an industrial environment. It features robotic mask and wafer handling, allowing for fully automated cassette-to-cassette production. The integrated beam shaper allows for industry-standard exposure control. In addition, the particle-controlled mini-environment ensures highest quality and cleanliness in a production setting. The key characteristics of the PhableS are summarized in Table 1.

Table 1: Key characteristics of the PhableS step-and-

repeat lithography tool.

Property	Value
Exposure mode	DTL, non-contact
Substrate size	up to 12 inch (300 mm)
Resolution (linear grating)	< 60 nm half-pitch
Pitch accuracy	2 pm
Photomask	standard 6-inch (6025)
Mask handling	fully automated
Wafer handling	fully automated
Max. throughput	up to 40 wafers per hour
Alignment accuracy	< 1 µm
Tool footprint	2.5×2.7 m^2

4. Conclusions

Mass production of HUDs requires a high-throughput, low-cost technique for the patterning of high-resolution periodic nanopatterns over large substrates. Eulitha offers all of this in its newest PhableS lithography tool combining its industry-proven, non-contact Displacement Talbot Lithography with step-and-repeat functionality. The fully automated system can process large (300 mm and beyond) substrates with minimum feature sizes down to 60 nm, leading the way to mass manufacturing of HUDs.

5. References

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