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Research paper

# Sub-wavelength printing in the deep ultra-violet region using Displacement Talbot Lithography

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ABSTRACT

Printing of sub-100 nm half-pitch periodic structures is demonstrated using Displacement Talbot Lithography (DTL) and a deep ultra-violet light source. DTL is a recently developed mask-based photolithography for forming high-resolution periodic structures over large areas using a relatively simple and low-cost system. A phase shift mask consisting of a 40 × 40 $mm^2$ transmission grating with a half-pitch of 150 nm is fabricated by electron-beam lithography followed by reactive ion etching. The geometry of the phase grating is optimized by numerical simulation. Using this mask, dense line/space patterns and two-dimensional arrays of pillars, both with a half-pitch of 75 nm, are printed onto silicon wafers. This new technique is suitable for uniform and high-throughput patterning of large-areas for such applications as moths-eye anti-reflective nanostructures, distributed feedback lasers, zeroth-order gratings, wire-grid polarizers and engineered substrates for LEDs.


## 1. Introduction

Over the last five decades, the semiconductor industry has been steadily scaling down feature sizes to produce faster, more efficient and more compact integrated circuits (IC) at lower cost, in accordance with the prediction of Moore's law [1–3]. Optical lithography has been the dominant patterning method in the microelectronics industry because it enables high resolution and high throughput [3]. State-of-the-art immersion photolithography using a 193 nm excimer laser source and expensive projection optics enables the printing of features down to 14 nm and even smaller nodes by double or quadruple patterning [3]. There are, however, other applications in industry and research institutes that require a simpler, lower-cost yet reliable patterning tool for fabricating high-resolution periodic patterns. Examples are linear gratings for the ultra-violet (UV) wire-grid polarizers [4,5], and square or hexagonal arrays of pillars or holes for plasmonic [6] or photonic crystal structures.[7] The requirements of these applications, in particular for feature sizes in the sub-100 nm regime, remain a challenge for conventional lithographic techniques. The development of a suitable alternative patterning technology therefore continues to be an important field in modern nanotechnology that will have substantial impact on both industrial manufacturing and academic research [5].

Displacement Talbot Lithography (DTL) is a new mask-based photolithography technique for patterning high-resolution periodic patterns that uses a relatively simple and low-cost system [8]. DTL is a non-contact technique in which a periodic pattern is transferred from a mask to a substrate in a manner similar to proximity printing except that the gap between the mask and the substrate is varied during the exposure by a distance corresponding to the Talbot [9] length of the light-field transmitted by the mask. The mean, or time-integrated, intensity distribution that illuminates the substrate has an effectively unlimited depth of focus, and so enables periodic patterns to be printed uniformly over large areas and non-planar surfaces. All the light diffracted by the mask contributes to the aerial image, and therefore the numerical aperture (NA) of the imaging system is equal to one [8], being obtained without any expensive projection optics. In the case of one-dimensional line–space patterns, the period of the pattern printed using the DTL technique is half of that in the mask, and so the ultimate imaging resolution obtainable without liquid immersion is equal to one quarter of the illumination wavelength. As for conventional projection lithography, the resolution ($R$) scales linearly with the illumination wavelength ($\lambda$). The first demonstration of the DTL technique was performed using light in the near-UV which limited the resolution of the printed patterns to about 100 nm [8]. Here, we report the results using instead light in the deep-UV (DUV) region to print higher-resolution structures, in particular, dense line/space patterns and square arrays of pillars with a half-pitch of 75 nm over an area of 40 × 40 $mm^2$ on a four-inch silicon wafer. The potential of deep-UV displacement

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Talbot lithography for high-throughput and low-cost sub-100 nm patterning over large areas is demonstrated.

## 2. Simulations and experiments

A well-designed photomask is important for a successful DTL exposure of high-resolution patterns. As for standard proximity photolithography, a phase mask can be used for improving the imaging contrast in a DTL exposure. For a periodic pattern a high-contrast aerial image can be realized by reducing the intensity of the 0th diffracted order. A deep intensity minimum is obtained when the depth of the features in the periodic pattern on the mask introduces a 180° phase shift into the transmitted light relative to the light transmitted outside of the features [10–11]. In general, minimization of the 0th diffracted order and maximization of the 1th diffracted order can be achieved by tuning the duty cycle and the feature depth of the phase gratings for the grating pitch concerned [12]. In this report we designed the DUV phase mask with the help of computational electromagnetic simulation programs based on rigorous coupled-wave analysis (RCWA) [13]. Fig. 1a shows a schematic of the mask grating with parameters pitch *p*, height *h* and linewidth *d* on a quartz substrate that was considered for the DUV DTL exposures. Silicon nitride ($Si_3N_4$) was chosen for the phase-shifting material because its high refractive index enables the formation of relatively strong 1st diffraction orders for periods approaching the wavelength. In the simulations, the grating was assumed to be illuminated with collimated light at 266 nm wavelength and polarized parallel to the grating lines. The pitch of the line grating was selected to be 300 nm so that the period of the printed pattern, which is half of that in the mask using the DTL technique, is 150 nm and in the working range for UV wire-grid polarizers [14]. The dependencies of the 0th- and 1st-order intensities on the other two parameters, namely the grating height *h* (phase shift thickness) and linewidth *d*, were calculated using the simulation program. Maps of the results illustrating the dependencies of the 0th and 1st intensities are shown in the Fig. 1b and c. Please note that the Y-axis in both maps is the duty cycle, defined as the ratio of grating linewidth to pitch ($d/p$). Inspection of the two maps reveals that minimization of the 0th order minima and maximization of 1st order can be achieved simultaneously with the same grating parameters. In particular, with a grating duty cycle of 0.3–0.5 and a grating depth of 120 ± 20 nm, the intensities of the 0th and 1st diffracted orders are respectively ~5% and 40% of that of the incident light. In photolithography, the contrast of the aerial image determines the pattern quality on the resist [15]. The image contrast of the time-integrated intensity distribution printed using DTL can be calculated from the formula $2I_1/(2I_1 + I_0)$, where $I_0$ and $I_1$ refer to intensities of the 0th and 1st diffraction orders. Applying this formula to the two intensity maps of Fig. 1b and c, we can derive the image contrast map shown in Fig. 1d. Similarly, the highest image contrast is obtained with a duty cycle of 0.3–0.5 and a grating depth of 120 ± 20 nm. Note that the relatively large insensitivity of the maximum contrast to the parameter values facilitates the phase mask fabrication due to reduced precision requirements on linewidth and height.

Based on the results of the computational simulations, a DUV DTL phase mask was fabricated on a fused silica mask blank coated with

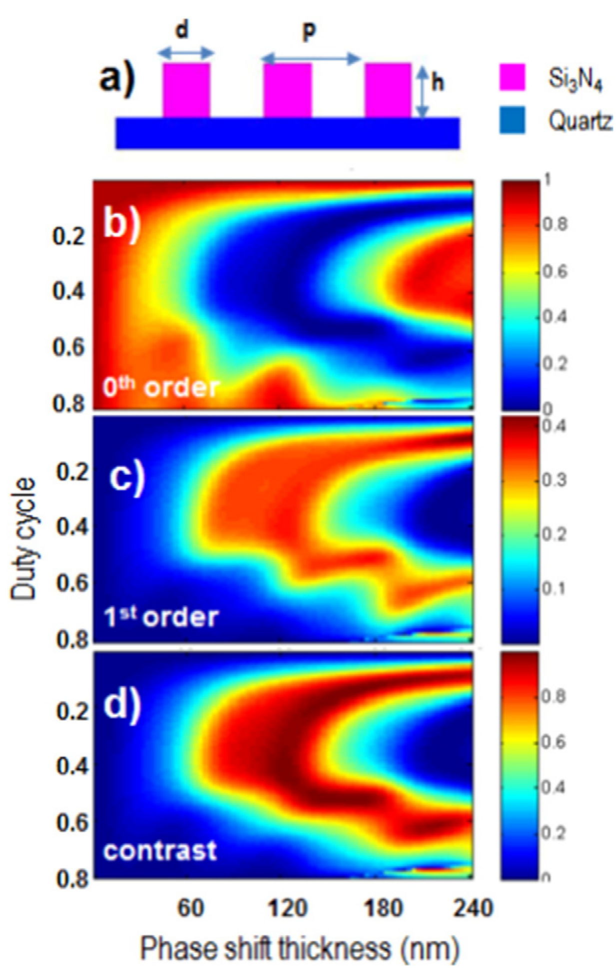


**Fig. 1.** a) Schematic showing mask design parameters employed for the electromagnetic simulation of the light diffracted by the silicon nitride gratings. b) and c) Normalized intensity maps showing the dependencies of respectively the 0th and 1st orders diffracted on the duty cycle ($d/p$) and depth ($h$) for a grating with pitch 300 nm. d) Aerial image contrast map derived from the intensity maps of 0th and 1st orders for optimizing the grating parameters.

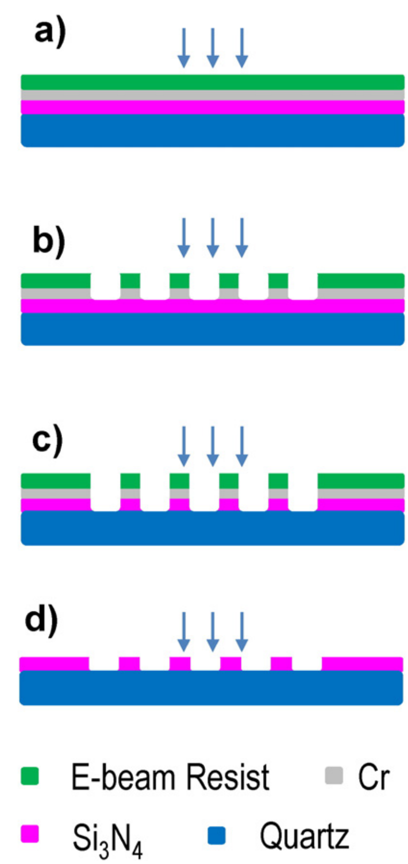


**Fig. 2.** Process flow for the fabrication of the DUV DTL phase mask. a) E-beam exposure of the resist coated quartz mask blank with silicon nitride ($Si_3N_4$) and Cr layers. b) RIE etching of the Cr layer, c) pattern transfer to the $Si_3N_4$ layer and d) strip-off of the additional layers.