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Research paper

High rotational symmetry photonic structures fabricated with multiple exposure Displacement Talbot Lithography

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ABSTRACT

Quasi-periodic structures with a high degree of rotational symmetry are desired for photonic applications because of their nearly isotropic optical response, in contrast to the highly directional behavior of periodic lattices. Here we introduce a method based on the superposition of periodic structures obtained by multiple exposure of a photomask with Displacement Talbot Lithography in which the photomask is rotated by a certain angle between exposures. The resulting structure can be considered as a Moiré pattern. High-quality patterns with 10 and 12-fold rotation symmetries and resolutions in the sub-micron to micron range are uniformly and reproducibly printed. The technique is suitable for the mass fabrication of wafer-scale quasi-periodic photonic patterns.

1. Introduction

Periodic patterns are used in many photonic applications for generating, filtering, coupling or otherwise manipulating light. However, the degree of rotational symmetry of purely periodic structures is very limited and very limiting. The maximum rotational symmetry is achieved with a hexagonal array which has a 6-fold symmetry. This means that a high degree of directionality is inevitable in the optical response of such periodic structures. A quasi-periodic structure (QPS) [1], on the other hand, can have much higher rotational symmetry which enables an almost isotropic optical response from the structure which leads to interesting and useful effects. For example, a QPS in certain photonic materials can have less orientation-dependent band gaps due to their higher rotational symmetry [2,3]. A QPS can be used to reduce the azimuthal dependence of emission of light emitting diodes [4] or to capture light more efficiently in photovoltaic devices [5,6]. Furthermore, in plasmonic systems higher rotational symmetry can produce strongly localized states which are not found in randomly or periodically arranged arrays [7].

In order to fabricate QPSs efficiently over large areas on the scale of typical semiconductor wafers (e.g. 100–200 mm diameter) which is needed for most of the mentioned applications, a robust and fast lithography technique is required. QPSs can be fabricated by serial techniques like e-beam or laser-beam direct writing. However due to the absence of translational symmetry a huge amount of data processing is required to generate the code for writing such structures over large areas which makes serial methods by far too time-consuming for mass production. It is more economical to fabricate such structures by parallel patterning techniques like multiple beam interference lithography [8–10], phase-shifting lithography [11], Moiré lithography [12] or even extreme ultraviolet (EUV) interference lithography for high-resolution QPSs [13]. For example, Gorkhali et al. [9] have used the interference of five mutually coherent laser beams to record Penrose QPSs which have 10-fold rotational symmetry. Shir et al. [11] used a phase shifting mask to print 3-dimensional QPSs. In this case the pattern on the mask was a 2-dimensional QPS which was computer generated and written with e-beam lithography. In a different approach, high rotational symmetry patterns were printed by exposing a periodic structure on a photoresist coated substrate multiple times using a phase shifting mask in contact with the substrate [12]. The mask was rotated by a certain angle between the exposures. What is printed with this method is essentially a Moiré pattern formed by the superposition of two or more angularly offset periodic patterns. In this way, Lubin et al. [12] exposed a PDMS photomask with hexagonal structures six times by successively rotating the PDMS mask after each exposure by 10° to achieve a pattern with 36-fold symmetry. However, these parallel lithography techniques also do not lend themselves to volume production due to processing, reproducibility, yield, and scalability issues.

In this paper, we introduce a robust technique for printing QPSs uniformly over large areas with the help of the Displacement Talbot Lithography (DTL). DTL is a non-contact photolithographic technique in which a high-resolution periodic pattern is transferred from a mask to a substrate in a manner similar to proximity printing, except that the separation between the mask and substrate is varied during the exposure by a distance corresponding to the Talbot distance of light-field transmitted

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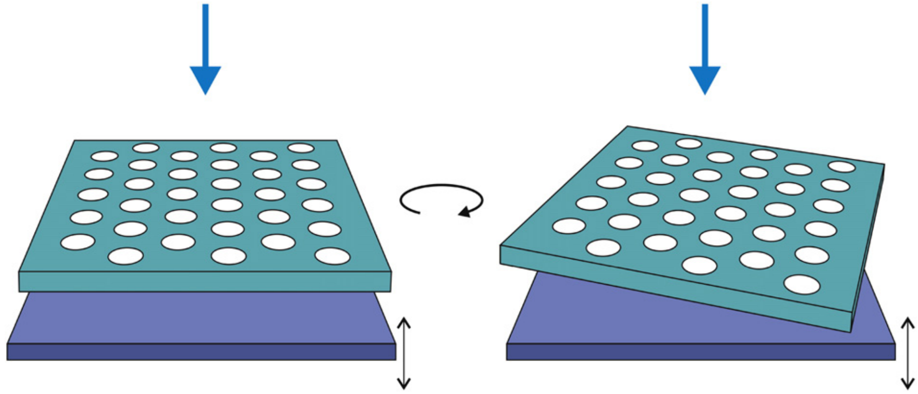

Fig. 1. Schematic illustration of the technique employed. A photoresist coated wafer is first exposed by illuminating a mask with a periodic structure while varying the mask-wafer separation according to Displacement Talbot Lithography. The mask is then rotated and the photoresist film is exposed a second time (or multiple times) to obtain a pattern with higher rotational symmetry.

by the periodic pattern [14]. DTL exposes the photoresist-coated substrate to a time-integrated image that has an effectively unlimited depth of focus as well as high contrast. It therefore enables the fabrication of periodic structures, such as hexagonal or square arrays of holes or linear gratings, over wafer-scale areas with high throughput and sub-micron resolution.

For generating QPSs the DTL technique is adapted by superposing two or more periodic patterns with a rotation of the mask between the exposures. By changing the rotation angle, and/or using, for example, a different pitch or shape of mask feature, a large number of different types of QPSs can be created.

2. Experimental method and results

For the DTL exposures a PhableR100 tool from Eulitha AG was used. It enables periodic structures with feature resolution down to about 100 nm to be printed with good pattern uniformity into standard i–line photoresist on substrates with diameter up to 100 mm in exposure times less than a minute. Both phase-shifting and amplitude-type (Cr) masks may be used for the DTL exposures. Phase-shifting masks have the advantages of enabling higher image contrast and shorter exposure time.

The application of DTL to QPS is first demonstrated using a phase shift mask defining a two-dimensional hexagonal array of circular holes of about 500 nm with a nearest-neighbor distance of 1 μm. A single DTL exposure of the mask pattern would print the same hexagonal pattern in the photoresist, as shown by the scanning electron microscope (SEM) image of the printed structure in Fig. 2a. For obtaining a QPS from this mask, a double exposure scheme was instead employed in which the mask pattern was rotated by 30° between the two exposures with the same exposure dose being used for both exposures. The exposure sequence is illustrated in Fig. 1. The 30° rotation of the mask pattern was practically obtained by rotating the mask by 90° on the mask chuck between the exposures. Examples of the resulting two-dimensional QPSs in photoresist are shown in Fig. 2b and c. The pattern in 2c was obtained in the same way as 2b but using twice the exposure dose for the two exposures. By adjusting the exposure dose the size and the shape of the structures can be tuned as desired. The inset in 2b shows the Fourier transform of the printed pattern. The first order peaks clearly show the achievement of 12-fold symmetry and hence doubling of the 6-fold symmetry of the hexagonal pattern obtained from a single exposure. With DTL it is moreover possible to fabricate such patterns uniformly over large areas as illustrated in the photograph of Fig. 2d which shows the result after transferring the resist pattern into Si by dry-etching in an ICP-RIE tool. In this case the pattern area was 50 mm × 50 mm, only limited by the size of the patterned area on the mask.

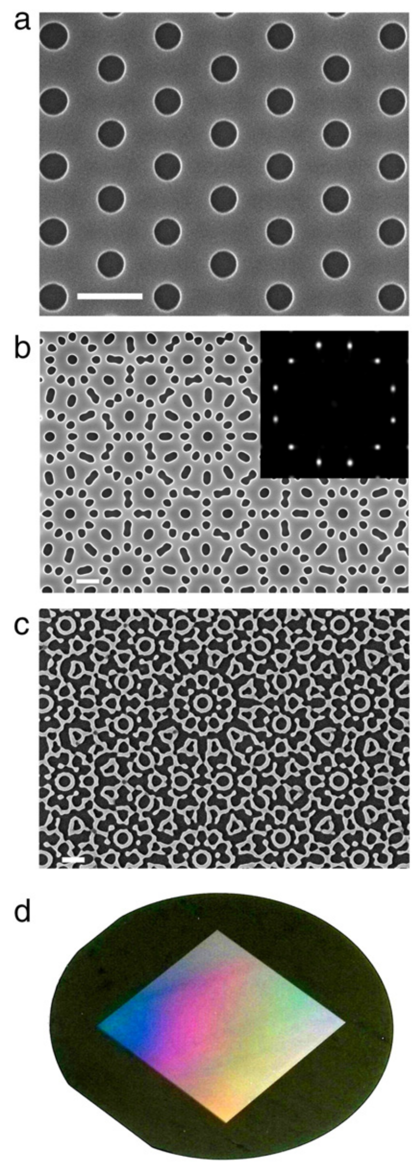

Fig. 2. (a) SEM image of an array of holes on a 1-μm-period hexagonal lattice printed in photoresist by a single exposure. (b) Result of double exposure in which the mask was rotated by 30° between the exposures. The inset shows the Fourier transform of the image where the 12-fold symmetry of the obtained structure is evident. (c) Structure obtained in the same way as (b) but using twice the exposure dose. All scale bars are 1 μm long. (d) Photograph of a 100 mm-wafer patterned with the 12-fold symmetric structure shown in (b). The patterned area is 50 mm × 50 mm.