I. INTRODUCTION

Periodic arrays of submicron and nanometer sized structures have unique properties that make them very useful for specific applications, such as single particle sensing using stimulated surface Raman scattering, plasmonic optics, plasmonic lithography, and meta-materials.1–6 In order to optimize the performance of devices based on nanostructures, it is desirable to obtain large area and high homogeneity of the periodic structures. Different printing methods have been developed toward this goal including interferometric lithography, nanoimprint, and a variety of soft lithographies based on self-assembled block copolymers. In the case of self-assembly, the arrangement of nanostructures is often random or at best organized in reduced areas only when self-ordering strategies have been applied.7–11

In this paper, we present a defect tolerant extreme ultraviolet (EUV) lithographic technique based on coherent Talbot imaging. A diffractive semi-transparent periodic object—referred further in the text as the mask—is illuminated by a coherent table top EUV laser beam, creating self-images which are recorded in a photoresist. Despite the existence of defects in the periodic mask, the prints rendered by this method reproduce the main features of the mask without the presence of these defects. The lack of defects in the print was verified by two independent techniques: atomic force microscopy (AFM) and scanning electron microscopy (SEM). Self-correcting printing is a consequence of the self-imaging effect due to the mask periodicity and the use of coherent illumination.

The working principle of the defect tolerant EUV lithography method relies on the effect of self-imaging discovered by Talbot in the 19th century.12 As noticed by Talbot, periodic structures create self-images when illuminated with coherent light. The self-images are produced by the replication of the electric field in loci situated at a certain distance from the mask and its integral multiples called Talbot planes. The distance between consecutive Talbot planes is determined by the periodicity of the mask and the wavelength of illumination, and it is referred to as the Talbot distance. This coherent imaging effect was used by Zanke et al. for patterning photonic crystals in, what was defined as, coherent diffraction lithography.13

A generalization of this effect was reported by Isoyan et al.14 Instead of a simple diffraction grating, like in the original experiment described by Talbot in 1836, the mask was an array composed of an arbitrary motif, tiled periodically. Self-images of this periodically tiled arbitrary structure were recorded in resist, obtaining faithful replicas of the original mask. Moreover, as demonstrated in Ref. 15, the technique has the potential of producing demagnified self-images by illuminating the mask with a convergent laser beam. This is a noncontact, size-scalable, parallel, and high-fidelity printing technique.

Dammann et al.16 noticed that when a faulty periodic mask is used, it will produce self-images without an apparent defect. In the case presented by Dammann, the defect had the form of a thin scratch made on a periodic mask. As such, the defect size was small compared to the size of only a few features in the mask.

In this work, we are exploring the extent of defect tolerance inherent to Talbot imaging by planting defects in the periodic masks which are in area comparable to and much larger than a single cell. We provide a theoretical description of the self-imaging of a periodic mask with a defect using the Fresnel–Kirchhoff diffraction formalism. Furthermore, we present numerical simulations of self-images of a mask with a defect illuminated by coherent light and experimental evidence using a specially designed mask and a table-top EUV laser. The experimental results are in very good agreement with the analytical and numerical predictions.

II. THEORY

One convenient way to describe the Talbot effect is in the spatial frequency domain. The derivation presented here follows closely that of Lohmann et al.17 For brevity, the
analysis is done for only one dimension; however, it can easily be extended to a plane.

Let us introduce a periodic structure with a transmission function given by $U_T(x)$. This is a general prescription for a mask composed of arbitrarily shaped motifs arranged periodically

$$U_T(x) = U_T(x+p) = \sum_{m} A_m \exp\left(i 2\pi m \frac{x}{p}\right), \quad (1)$$

where $A_m$ is the $m$th order Fourier series coefficient, $p$ is the period of the mask, and $x$ is the spatial coordinate in the direction transverse to the direction of propagation. The corresponding spatial frequency spectrum can be calculated using the Fourier transform and is given by

$$\int U_T(x) \exp(-i 2\pi \nu x) dx = \hat{U}_T(\nu) = \sum_{m} A_m \delta(\nu - m\nu_0), \quad (2)$$

where the frequency $\nu_0$ is the inverse of the period of the mask

$$\nu_0 = \frac{1}{p}. \quad (3)$$

Immediately behind the mask, the field can be described by

$$U(x,0) = U + \sum_{m \neq 0} A_m \exp(i 2\pi mx\nu_0) = A_0 + u(x,0). \quad (4)$$

For convenience, the 0th-order term denoted by $U$ is dealt with separately. Consequently, the spatial frequency spectrum takes the form

$$\hat{U}(\nu,0) = A_0 \delta(\nu) + \sum_{m \neq 0} A_m \delta(\nu - m\nu_0)$$

$$= A_0 \delta(\nu) + u(\nu, z = 0). \quad (5)$$

The space propagation of the spatial frequency spectrum is equivalent to a multiplication by a quadratic phase term, which in the paraxial approximation takes the following form:

$$\exp(-i\pi \lambda z \nu^2) = \exp(-i\pi \lambda z m^2 \nu_0^2), \quad (6)$$

where $z$ denotes the direction of the propagation of light. Substituting Eq. (6) into Eq. (5) yields

$$\hat{U}(\nu, z) = A_0 \delta(\nu) + \sum_{m \neq 0} A_m \exp(-i\pi \lambda z m^2 \nu_0^2) \delta(\nu - m\nu_0)$$

$$= A_0 \delta(\nu) + u(\nu, z). \quad (7)$$

A simple substitution in Eq. (8) defines the Talbot distance $z_T$

$$-i\pi \lambda z m^2 \nu_0^2 = -2i \pi m^2 \frac{z}{z_T}, \quad z_T = \frac{2}{\lambda \nu_0^2} = \frac{2p^2}{\lambda}. \quad (8)$$

Equation (7) can then be rewritten in the following form:

$$\hat{U}(\nu, z) = A_0 \delta(\nu) + \sum_{m \neq 0} A_m \exp\left(-i 2\pi m^2 \frac{z}{z_T}\right) \delta(\nu - m\nu_0). \quad (9)$$

Equation (9) is subsequently transformed back to spatial domain to obtain

$$U(x, z) = A_0 + \sum_{m \neq 0} A_m \exp\left[-2i\pi \left(m\nu_0 x - m^2 \frac{z}{z_T}\right)\right]$$

$$= U(x, z + Nz_T). \quad (10)$$

From Eq. (10), it can be seen that the field distribution has a periodic character also along the $z$ direction. The periodicity in the direction of propagation described by Eq. (10) can be visualized using a computer simulation. Let us consider a plane wave impinging on a periodic mask. Using the Fresnel–Kirchhoff formalism, it is possible to calculate the diffracted electric field across the transverse coordinate $x$ and along the propagation coordinate $z$. This 2D graph is usually referred to as a “Talbot carpet.” A Talbot carpet produced by a rectangular grating with binary transmission is presented in Fig. 1. The binary grating is represented in the left-hand side of the figure with a series of black rectangles indicating the opaque regions of the mask. A coherent plane wave impinges on the mask from the left and propagates in the $+z$ direction. The electric field intensity is represented by a pseudo-color 2D map. It can be seen that the original electric field distribution at $z = 0$ is reproduced at the Talbot distance $z_T$. For clarity, the mask profile is repeated in the figure in dashed lines at the Talbot distance. The same effect holds true for any arbitrary structure tiled periodically. This is known as generalized Talbot imaging (GTI) and was described in Ref. 13. Figure 2 illustrates an example of GTI. The replica of the electric field at the plane of the mask is also observed at the Talbot distance.
In the case of a diffracting periodic mask with a defect, a similar analysis can be carried out. Introducing \( D(x) \) as the contribution from a defect, the total field amplitude is given by

\[
U_{TOT}(x) = D(x) + \sum_m A_m \exp\left( i 2\pi m \frac{x}{p} \right). \tag{11}
\]

Using the same Fourier formalism described before, immediately after the mask the field is equal to

\[
\hat{U}_{TOT}(\nu, z = 0) = d(\nu, z = 0) + A_0 \delta(\nu) + \sum_{m \neq 0} A_m \delta(\nu - mv_0)
\]

\[
= d(\nu, z = 0) + A_0 \delta(\nu) + u(\nu, z = 0), \tag{12}
\]

where \( d(\nu, z = 0) \) is the spatial frequency spectrum of the defect. By analogy to Eqs. (7)–(9), the resulting intensity distribution in the spatial frequency domain can be rewritten to the following form:

\[
\hat{U}_{TOT}(\nu, z) = d(\nu, 0) + A_0 \delta(\nu) + \sum_{m \neq 0} A_m \exp\left(-2i\pi m^2 \frac{z}{z_T}\right) \delta(\nu - mv_0). \tag{13}
\]

Thus transforming it to the spatial domain, we obtain

\[
U_{TOT}(x, z) = D(x, z) + \sum_m A_m \exp\left[-2i\pi\left( \frac{mv_0 z - m^2 z}{z_T} \right) \right]
\]

\[
= D(x, z) + U(x, z + Nz_T). \tag{14}
\]

In Eq. (14), the first and second terms can be identified as contributions from the defect and the intact part of the mask, respectively. Equation (14) addresses the question of defect tolerance. A localized defect in the mask does not have periodic character along the axis of propagation. If there is a local defect in the mask, the diffracted field emanating from it will be of relatively small contribution to the total intensity distribution at the Talbot plane. Thus, the defect will not be apparent at the reconstruction plane.

To corroborate this analytical solution, numerical simulations were carried out. A periodic mask was created by tiling \( 10^5 \) cells in a square lattice. The cell was chosen to be a completely arbitrary motif; in our case, it was the profile of a “Space Invader,” a character from a classic video game. The defect embedded in the periodic mask was another (alien) species of Space Invader that replaces the native one. The mask with these characteristics was used to calculate the image formed at the first Talbot plane. Figure 3 shows the output of the simulation. In the left-hand side is a picture of the central part of the mask where the middle cell was replaced by a defect (a different alien profile). The image in the right-hand side of Fig. 3 corresponds to the calculated light intensity at the first Talbot plane. The defect (or different alien) is not present in the reconstruction. This calculation shows that the reconstruction of a mask with a defect reproduces only the pattern of the original mask. This characteristic of the Talbot imaging is of significance when GTI is applied to optical lithography, because the mask replicating process is error tolerant.

III. EXPERIMENTAL SETUP AND MASK DESIGN

In order to verify the concept of defect tolerance in GTI, we designed an appropriate experiment utilizing a compact EUV laser. Inline geometry was used to illuminate a specially designed mask. The schematic of the experimental setup is shown in Fig. 4. The main components of the setup are the light source (EUV laser), the diffractive mask, and the recording medium.

The light source used in this experiment is a compact, capillary discharge laser. It is well-suited for this experiment in that it provides both temporally and spatially coherent light with an average energy per pulse of 0.1 mJ. This tabletop pulsed laser, designed at Colorado State University, emits at \( \lambda = 46.9 \) nm, which corresponds to the \( 3s^1P_1-3p^1S_0 \) transition in the \( \text{Ar}^{+8} \) ion. An argon gas is ionized by a fast current discharge with a \( 24 \) kA peak value and \( 55 \) ns rise time. The spectral bandwidth of the laser pulses is approximately \( \Delta \lambda / \lambda = 3.5 \times 10^{-5} \), yielding a coherence length on the order of \( \sim 700 \) \( \mu \)m.  The spatial coherence radius is...
approximately 550 μm at the distance where the exposure take place.\textsuperscript{19,20}

The mask was designed as a periodically tiled set of arbitrarily shaped cells, arranged in a square lattice. The primitive cell size is $5 \times 5 \text{μm}^2$ resulting in a Talbot distance of 1 mm at the wavelength of illumination of 46.9 nm. The entire mask is composed of a 100 × 100 array of cells. The defects were planted by substituting the native motif with a completely different one. To investigate the extent of defect tolerance, two different arrangements of defects were applied. In the first case, a single impostor cell was planted in the middle of the mask, yielding the ratio of the defect area to the entire mask area of 0.01%. In the second case, an entire row of native cells was replaced by a row of the impostor motif, yielding a defect to mask area ratio of 1%. An electron microscope scan of the mask with a row of defects is shown in Fig. 5 (left figure). A more detailed description of the mask fabrication can be found in Ref. 13.

A piece of silicon wafer coated with ~100 nm thick layer of poly-methyl-mathacrylate (PMMA) resist was used to record the self-image of the mask. The distance between the mask and the sample was measured with a displacement sensor and controlled with an actuator. The exposure time was 5 min with the laser repetition rate at 1 Hz. This exposure time can be reduced by increasing the repetition rate of the laser.\textsuperscript{21} The sample was placed at the first Talbot plane. The postexposure puddle developing procedure was applied to the resist. The developing mixture was a 25% solution of methyl-isobutyl ketone in isopropyl alcohol. Subsequently, the sample was rinsed with pure isopropyl alcohol and blown dry with ultrahigh purity nitrogen. Samples developed in such a way were then imaged with an SEM.

IV. RESULTS AND DISCUSSION

Figure 5 shows the results corresponding to the most severe defect density (1%). In the left hand side, the SEM micrograph of the mask shows the complete row of defects represented by the different alien motif. The defect is fully eliminated from the reconstructed image, as can be seen in the micrograph to the right. The arrow indicates the row in the image that corresponds to the row of defects in the mask. No evidence of the defect is apparent in the final print. The inset in the figure is a higher magnification image of the print.

The effect of defect tolerance is a result of both lateral and longitudinal periodicity of the light diffracted by the mask. The intensity of the light diffracted by the defect decays with the propagation distance and is proportional to the defect size. The light diffracted by the periodic mask (much larger in area than the defect) creates a self-image by constructive interference at the Talbot distance and thus overwhelms the contribution of the field diffracted by the defect. While the result presented here with a 1% defective mask produced satisfactory results, the relation between the defect density and the quality of the print needs a more detailed analysis. The resolution achieved in the printing will be influenced by the response of the photoresist, the coherence of the illumination, the spatial spectral composition of the unit cell, and the periodic arrangement of the cells. Thus, a case-by-case analysis is necessary. When the defect is much larger than a single cell, which is a very common case of mask contamination, the technique will still provide...
defect tolerance but only to a certain extent. The general trend is that the reconstruction quality decreases with the size of the defect. On the other hand, the defect is less evident for more distant Talbot planes. For example, a mask with an obstruction nine times larger than a single cell will render prints with satisfactory quality at the third and higher order Talbot planes.

V. SUMMARY

In summary, we have demonstrated a lithography technique which is defect tolerant. Two different sizes of defects were investigated: a single cell (defect to mask area ratio of 0.01%) and an entire row of cells (defect to mask area ratio of 1%). Despite the defect purposely planted within the mask, the prints at the first Talbot plane are devoid of defect signs, as observed both with AFM and SEM. Furthermore, there was no measurable loss of resolution at the defect site. The results obtained are in good agreement with both analytical and numerical calculations. We envision that the technique presented here has the potential to be applied in extreme ultraviolet nanopatterning.

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