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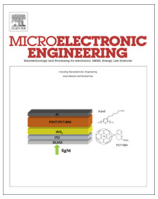

Focus position and depth of two-dimensional patterning by Talbot effect lithography

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ABSTRACT

The Talbot effect is a self-imaging phenomenon enabling lens-less imaging. The interval of the focus position is called the Talbot distance. To maintain pattern fidelity, the accurate focus position of the self-imaging needs to be known. The depth of focus based on Rayleigh's criterion is analytically a quarter of the Talbot distance. In a hexagonal array of a fine pitch, the Talbot distance derived from 2nd-order approximation is inaccurate. The analytically accurate expression of the Talbot distance for hexagonal arrays is shown in imaging of low-order diffraction rays.

1. Introduction

In the latest semiconductor lithography for mass production, ArF projection tools are widely employed. They have sufficient capability to transfer sub-100 nm patterns. Nevertheless, the reduction of the cost per bite is always a concern of semiconductor manufacturers [1]. If the pattern transfer were done without projection optics and were comparable in quality to the projection optics, it would be a great boon.

In 1836, Talbot observed a curious effect in experiments on diffraction of a grating [2,3]. The optical intensity periodically changes along the optical traveling direction. This Talbot effect, or self-imaging enables lens-less imaging [4,5]. The periodical length is called the Talbot distance. Interest in this effect has been increasing recently with a view to applications in lithography [6–14].

The pattern transfer by the Talbot effect is a kind of proximity lithography. We have reported some simulation results for the lens-less exposure method using a 193 nm ArF excimer laser source [13,14]. Those results showed promising resolution would be obtained. In this report, we discuss the depth of focus (DOF) and accurate imaging position of two-dimensional arrays. First, DOF, which is a crucial reference in practical use, is calculated based on Rayleigh's quarter wavefront aberration criteria. Moreover, the correlation to the Talbot distance is shown. Second, the resolution-limit resist patterns are simulated in a square grid hole array and a hexagonal grid hole array. The Talbot distance of a hexagonal grid array by low diffraction orders such as 0-th and ±1-st order diffractions is shown by an accurate analytical expression.

2. Imaging plane and focus depth

The Talbot self-imaging plane appears periodically at every Talbot distance along the traveling direction of the rays. When the imaging quality is considered, the depth of focus (DOF) is a crucial issue. Because the Talbot distance indicates the distance of the positions of the maximum intensity of the optical distribution along the direction where the rays travel, it should be related to the DOF. Here, we consider using the Rayleigh criteria often used in the discussion of the diffraction-limited depth of focus. Based on the Rayleigh criteria, DOF is assumed to be a defocus amount of wavefront aberration of one-quarter of the wavelength.

If the object pitch is p and the wavelength of the illumination is λ, the Talbot distance of the periodic distance of self-imaging is expressed as follows [3,7,14]:

$$Z_T = \frac{2p^2}{\lambda}, \quad p >> \lambda, \tag{1}$$

for the imaging composed of low and high diffraction orders, and

$$Z_{T'} = \frac{p^2}{\lambda}\left(1 + \sqrt{1 - \left(\frac{\lambda}{p}\right)^2}\right), \quad p \approx \lambda, \tag{2}$$

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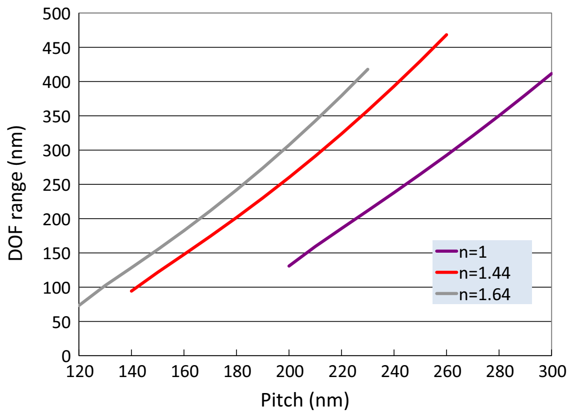

Fig. 1. The relationship between the pattern pitch and DOF range at 193 nm wavelength of an ArF excimer laser for 3 types of indices, namely, air, water, and high-index organic material.

for the imaging composed of only 0-th and ±1-st diffraction orders.

Moving from the Gauss imaging point, defocus imaging point is generated by the diffracted rays of diffraction angle of θ. From the Rayleigh criteria, DOF is expressed as follows [15]:

$$\mathrm{DOF} = \pm\frac{\lambda}{4n(1-\cos\theta)} = \pm\frac{\lambda}{4n\left(1-\sqrt{1-\sin^2\theta}\right)} \tag{3}$$

Here, n is the refractive index of the space around the focus point. When the object pitch is p and the diffraction angle is θ, $\sin\theta = \lambda/(np)$. From Eq. (3), DOF is expressed as follows:

$$\mathrm{DOF} = \pm\frac{\lambda}{4n\left(1-\sqrt{1-\left(\frac{\lambda}{np}\right)^2}\right)}. \tag{4}$$

Fig. 1 shows the relationship between the pattern pitch and DOF range at 193 nm wavelength of an ArF excimer laser for 3 types of indices, namely, air, water, and high-index organic material. Mask pattern is resolved if 1-st order diffraction ray is generated. Therefore resolvable pitch is larger than λ/n. It is shown that the 200 nm pitch pattern has about 130 nm DOF range in air and 260 nm DOF range in water. In addition, the 140 nm pitch pattern is resolvable in water immersion and then it has about 95 nm DOF range. The 120 nm pitch pattern is resolvable in high-index immersion and then it has about 70 nm DOF range, for example. Diffraction angle of the diffraction ray translates into the incident angle at the imaging point. Therefore, NA of the Talbot self-imaging corresponds to the diffraction angle from the source grating, that is, $\mathrm{NA} = n\sin\theta$. Eq. (3) can be expressed using NA:

$$\mathrm{DOF} \approx \pm\frac{\lambda}{2\mathrm{NA}^2}, \quad \sin\theta << 1. \tag{5}$$

This is a well-known equation in photolithography. Now $\sin\theta = \lambda/(np)$, Eq. (1) can be inserted into Eq. (5). Then,

$$\mathrm{DOF} = \pm\frac{Z_T}{4}. \tag{6}$$

Eq. (6) can be derived from Eqs. (2) and (3) as well.

3. 2-Dimensional patterning by Talbot lithography

We discuss the 2-dimensional (2D) patterning by Talbot lithography, based on numerical simulations such as hole arrays on a square grid and on a hexagonal grid.

3.1. Simulation parameters for 2D pattern

The mask structure assumed for simulation is shown in Fig. 2. The wavelength of the collimated light source is 193 nm. The substrate to which the pattern is transferred is assumed to have the layers shown in Fig. 3. The bottom antireflective coating (BARC) layer is 40 nm thick on silicon substrate. The resist layer is 80 nm thick on the BARC. The refractive indices are assumed to be quartz (1.563, 0.0), Cr (0.842, −1.647), Si (0.883, −2.778), BARC (1.71, −0.42) and resist (1.71, −0.016). In the following simulations, the material between the mask and the transferred layers is assumed to be air. The aerial imaging and diffracted rays are simulated by the finite-difference time-domain (FDTD) method. Resist profile simulation is performed by projection lithography assuming NA ~ 1, coherency ~ 0, which is equivalent to proximity lithography, a Fresnel mask and x–y polarization. Considering the simulation tools and CPU time available, these assumptions are legitimate from the view point of practicability. Here, the simulation was implemented by commercially available simulators of Panoramic Technology EM-Suite for the aerial image and Synopsys Sentauras Lithography for the resist profile simulation.

3.2. Pattern transfer of 2D array on square grid by the Talbot effect

The pattern transfer performance of a Cr mask by the Talbot effect is simulated for a hole array on the 2D square grid shown in Fig. 2. The hole pattern pitch is 200 nm. Fig. 4 shows the intensity of diffracted rays from the mask when the y-polarized ray illuminates the mask. Coordinates show the value of $\sin\theta$ of the x and y directions in the case of the diffraction angle θ. The red circle indicates the position at which the $\sin\theta = 1$. If the diffraction rays are within the red circle, the mask pattern can be resolved. The diffraction pattern of the square grid is a superposition of x-directional patterns and y-directional patterns. Therefore, the optical resolution limit and the Talbot distance are the same as for line-and-space patterns.

3.3. Pattern transfer of 2D array on hexagonal grid by the Talbot effect

The pattern transfer performance of a Cr mask by the Talbot effect is simulated for the hole array on the 2D hexagonal grid

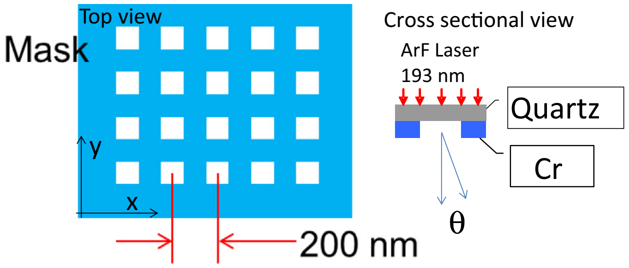

Fig. 2. The mask structure of hole array on the 2D square grid assumed for simulation.

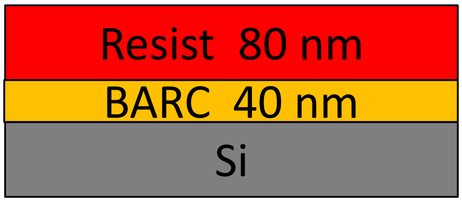

Fig. 3. The substrate to which the pattern is transferred is assumed to have the layers.