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Patterning of nanodot-arrays using EUV achromatic Talbot lithography at the Swiss Light Source and Shanghai Synchrotron Radiation Facility

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A B S T R A C T

Achromatic Talbot lithography (ATL) at extreme ultraviolet (EUV) wavelengths has been used to produce one or two-dimensional periodic patterns over large areas. In this work, an ATL transmission mask was used to perform EUV exposures at 13.5 nm and 8.8 nm illumination wavelengths at two different synchrotron facilities, to study the broadband nature of the method and the used mask as well as to investigate the influence of illumination parameters and experimental arrangements. The experiments were performed at the Swiss Light Source (SLS), PSI, Switzerland, and at the Shanghai Synchrotron Radiation Facility (SSRF), P. R. China. Achromatic Talbot lithography was proven to be a simple and robust interference lithography scheme for producing large area and high resolution patterns suitable for different wavelengths and for a variety of EUV sources and setups.

1. Introduction

There has been an enormous amount of interest in the nanostructures of various materials and particularly towards potential applications for future electronic devices [1]. Extreme ultraviolet (EUV) lithography at the 13.5 nm wavelength is the best industry candidate for producing next generation electronic devices [2]. Nonetheless, before EUV lithography is introduced into high volume manufacturing many new EUV resists require development and evaluation with EUV light [3]. EUV interference lithography is not only a useful method for research and development of EUV materials and technologies, but it also enables the fabrication of large area high resolution periodic nanostructures [4,5]. Achromatic Talbot lithography (ATL), also known as achromatic spatial frequency multiplication (ASFM), is a very robust, highly efficient, and simple technique to produce highly dense, high-resolution periodic nanostructures down to 15 nm feature size [6,7]. This method is suitable for broadband EUV sources, i.e. the majority of EUV sources, and for low intensity or brightness sources, since the aerial image is generated using the interference from all transmitted diffraction orders, allowing large area patterning with high throughput via step-and-repeat exposures [7].

In this study, ATL masks have been fabricated at the Laboratory of Micro and Nanotechnology (LMN) at the Paul Scherrer Institute (PSI) in Switzerland. The masks are transmission masks of nickel absorbers on silicon nitride membranes. The highly efficient ATL masks were then first tested at the X-ray interference lithography (XIL) beamline of the Swiss Light Source (SLS) in PSI and subsequently at the IL beamline of the Shanghai Synchrotron Radiation Facility (SSRF), P. R. China, to elucidate and compare the performance of the two beamlines for high-resolution patterning.

2. Theory and calculations

Talbot first noticed that periodic patterns were produced at fixed distances from a diffraction grating upon which monochromatic coherent light was incident [8]. These patterns are self-images of the diffraction grating, produced at repeating Talbot distances at every integer multiple of z_T (Eq. (1)) from the mask [9]:

$$z_T = \frac{2p^2}{\lambda} \tag{1}$$

where p is the grating period and λ is the illumination wavelength (Fig. 1).

When the incident light has a spectral bandwidth of $\Delta\lambda$, the Talbot images due to different incident wavelengths overlap at a certain

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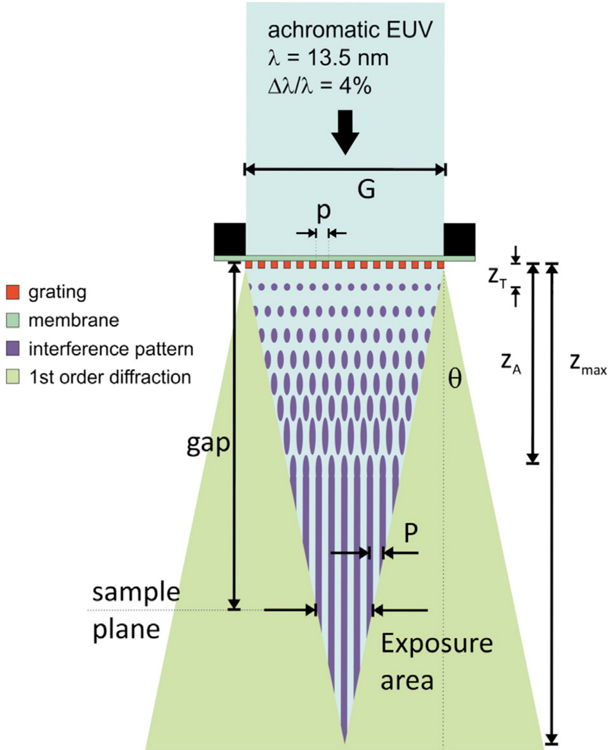

Fig. 1. Scheme of achromatic Talbot lithography. Self-images of the diffraction grating are produced at the Talbot distance z_T from the grating, after which they smear out and eventually become stationary images at the achromatic Talbot distance z_A.

distance. This occurs when the Talbot distance of one image due to the minimum incident wavelength equals the Talbot distance of a subsequent image due to the maximum incident wavelength (Eq. (2)):

$$\frac{2np^2}{\lambda - {}^{\Delta\lambda}/_{2}} = \frac{2(n+1)p^2}{\lambda + {}^{\Delta\lambda}/_{2}} = z_A \quad (2)$$

where n is an integer for every subsequent self-image starting from the grating plane. Solving for n, substituting back into Eq. (2), and assuming ${}^{\lambda}/_{\Delta\lambda}$ is much larger than 1/2 gives the achromatic Talbot distance z_A (Eq. (3)). Beyond this distance, self-images of the grating smear and overlap in the z-direction and the aerial image becomes z-invariant beyond z_A [10]:

$$z_A = \frac{2p^2}{\Delta\lambda} \quad (3)$$

This is the minimum distance that is needed to obtain a z-stationary aerial image. As seen in Eq. (3), the bandwidth of the source turns into an advantage by providing an aerial image of very large depth-of-focus. As the self-images are due to the interference from all transmitted diffraction orders, all of the transmitted intensity contributes to the aerial image, and therefore exposures are highly efficient in comparison for example to multiple-beam interference lithography. Furthermore, the whole aerial image can be patterned, giving large-area patterning capabilities in comparison to multiple-beam interference lithography where only the interference patterns due to first or second order diffraction is recorded while the exposed areas due to zeroth order diffraction are not patterned. For a line/space diffraction grating, the resulting line/space pattern has a pitch that is 1/2 of the mask grating period, while for a dot/hole diffraction grating, the resulting dot/hole array pattern has a pitch that is $1/\sqrt{2}$ of the mask grating period rotated by 45° [10]. We note that for both dot and hole array diffraction gratings, a dot array is obtained using negative resist.

From the definition of z_A presented above, it is clear that the grating periodicity and the bandwidth of illumination influences the achromatic Talbot distance. In addition, it should be noted that the aerial image in ATL is a result of interference of diffraction orders from the same grating. As the diffraction orders diverge from each other when moving away from the grating, the overlapping area of diffraction orders and thereby the area of the interference decreases. The diffraction angle θ of a grating with period p and with illumination wavelength λ is calculated by the Bragg equation:

$$\frac{\lambda}{p} = \sin\theta. \quad (4)$$

Given the diffraction angle, the field size can be calculated from the gap between mask and sample plane, or vice versa:

$$\tan\theta = \frac{G - x}{2z} \quad (5)$$

where x is the side length of the patterned area, G is the side length of the grating, and z is the gap distance between mask and sample plane. As the distance of the sample plane from the mask increases, the patterned area x^2 approaches zero at the maximum distance z_{max}. For small diffraction angles, z_{max} is given by combining Eqs. (4) and (5) to give:

$$z_{max} = G \times \frac{p}{2\lambda}. \quad (6)$$

For ATL, the distance between the mask and the sample plane should therefore be larger than the achromatic Talbot distance but smaller than the maximum distance (Fig. 1). This distance should be kept short in order to maximize the size of the patterned area. For a diffraction grating with period 150 nm and a size of $100 \times 100\ \mu m^2$, the calculations for the relevant ATL parameters are given in Table 1.

3. Materials and methods

Achromatic Talbot lithography was performed at the XIL-II beamline, Swiss Light Source, Paul Scherrer Institute, Switzerland, and the IL beamline, Shanghai Synchrotron Radiation Facility, P. R. China, using the same ATL mask. In general, EUV radiation produced from an undulator source is filtered harmonically and spatially by sets of mirrors and pinholes. The XIL-beamline at the SLS has an undulator source filtered by a pinhole to produce spatially coherent light of tunable wavelength/energy (70–500 eV) and a 4% bandwidth (Δλ/λ). The details are described elsewhere [11]. The SSRF is a third generation 3.5 GeV synchrotron source, the first of its kind in China. The IL beamline at the SSRF is a branch of the soft X-ray spectromicroscopy beamline (STXM) [12], and uses an elliptically polarized undulator (EPU) source. By using the same EPU the energy range can be tuned from 85 eV to 150 eV. The beamline layout has been described in detail elsewhere [13]. A four-knife slit placed about nine meters in front of the mask acts as an intermediate light source with high spatial coherence. For

Table 1
Calculations for EUV exposure at PSI and SSRF using $100 \times 100\ \mu m^2$ ATL mask with 150 nm period (i.e. $G = 100\ \mu m$, $p = 150$ nm).

Parameter	Equation	PSI	SSRF λ_1	SSRF λ_2
Illumination wavelength	λ	13.5 nm	13.5 nm	8.8 nm
Image period (45°)	$P = \frac{p}{\sqrt{2}}$	106 nm	106 nm	106 nm
Spectral bandwidth	$\Delta\lambda/\lambda$	4%	3%	3%
Monochromatic Talbot distance	$z_T = \frac{2p^2}{\lambda}$	3.3 μm	3.3 μm	5.1 μm
Achromatic Talbot distance	$z_A = \frac{2p^2}{\Delta\lambda}$	83.3 μm	111 μm	170 μm
Maximum distance	$z_{max} = G \times \frac{p}{2\lambda}$	556 μm	556 μm	852 μm