Immersion microlithography at 193 nm with a Talbot prism interferometer

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ABSTRACT

A Talbot interference immersion lithography system that uses a compact prism is presented. The use of a compact prism allows the formation of a fluid layer between the optics and the image plane, enhancing the resolution. The reduced dimensions of the system alleviate coherence requirements placed on the source, allowing the use of a compact ArF excimer laser. Photoresist patterns with a half-pitch of 45 nm were formed at an effective NA of 1.05. In addition, a variable-NA immersion interference system was used to achieve an effective NA of 1.25. The smallest half-pitch of the photoresist pattern produced with this system was 38 nm.

Keywords: Immersion, interference, ArF, DUV, Talbot

1. INTRODUCTION

Interferometric lithography has proven to be a useful method to study photoresist materials[4], the impact of polarization state on imaging[6], and to approximate general-purpose projection imaging[9]. All of these experiments benefit from the use of an exposure source of future projection immersion microlithographic systems, as it is imperative for these approaches to provide useful results. The higher NA possible with the immersion system allows for closer inspection of polarization effects, as well as photoresist compatibility with the immersion process.

Interferometric lithography has been used in conjunction with immersion using an ArF source at 193 nm[1], achieving an effective NA of 1.05. Other sources such as UV light sources at 257 nm[7], and VUV light sources at 157 nm[2], have been used. The key requirements placed on the source are spatial and temporal coherence, which have been difficult to obtain with an ArF excimer laser. However, with a compact size Talbot interferometer system the requirements are alleviated, allowing the use of a commercial ArF excimer laser[8].

2. ANALYSIS

Two mutually coherent plane waves impinging onto a substrate surface form sinusoidal intensity distribution with the pitch (Λ) corresponding to

$$\Lambda = \frac{\lambda_{medium}}{2\sin\theta_{medium}} = \frac{\lambda_{vacuum}}{2n_{medium}\sin\theta_{medium}} \qquad (1)$$

where λ_{medium} is the index of refraction of the propagation medium, and θ_{medium} is the angle of incidence, provided both waves are arriving at the same angle to the surface normal. The image pitch remains constant as the waves travel from the immersion fluid into photoresist, following Snell's law, $n_{medium}\sin\theta_{medium} = n_{resist}\sin\theta_{resist}$.

This relationship, when compared to Rayleigh resolution limit for projection lithography

$$\frac{\Lambda}{2} = k_1 \frac{\lambda_{vacuum}}{NA_{eff}} \qquad (2)$$

yields the effective *NA* for immersion interference imaging as $NA_{eff} = n_{medium}\sin\theta_{medium}$, with k_1 equal to 0.25.

In order to best satisfy the mutual coherence requirement, a symmetric Talbot interference system is used, as shown in Figure 1. In this type of interferometer, the length of the arms is equal (at the center of the field). A phase grating acts as the beamsplitter, and only 1st and –1st diffraction orders are used as the interference waves. The turning mirrors are created by depositing a reflective coating onto the prism facets. The angle of the facets, combined with the phase grating pitch, defines the arrival angle at the wafer. The bottom surface together with the wafer forms the fluid gap. The top surface has a quarter wave anti-reflective coating to minimize stray light.

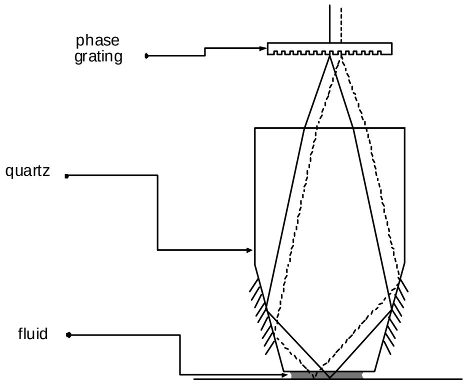

Figure 1. Sketch of the immersion interference system. The symmetric layout allows the use of an excimer laser. Note the center (solid) beam and the off-center (dashed) beam produce interference fringes in the same image plane.

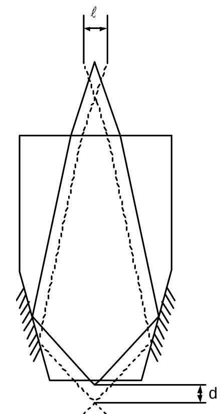

Figure 2. Loss of spatial coherence as image plane moves out of alignment by *d*. Coherence is maintained while $\ell \ll \delta$.

Different parts of the beam are split and recombined with themselves, maintaining spatial coherence. With the image plane set at optimum conjugate position, a beam with infinitesimal spatial coherence distance (δ) can be tolerated. As the image plane moves out of this position, the fringe visibility will reduce as the interfering beams originate from different parts of the incoming bundle, as shown in Figure 2. The fringe visibility is maintained as long as lateral beam distance (ℓ) is small with respect to the coherence distance.

The temporal coherence of the beams is maintained while the lengths of the two arms of the interferometer remain equal within the temporal coherence length (ℓ_c). The inherent symmetry of the design ensures this condition is always satisfied for a centered beam. For the off-center beams, the magnitude of the OPD (optical path distance) difference between the two interferometer arms scales directly with system size. Compact systems are thus advantageous.

The variations in the source wavelength affect the arrival angle, and therefore the pitch of the interference fringes are dependant on the source wavelength according to

$$\Lambda = \frac{\lambda_{vacuum}}{2n_{quartz}\sin\left(2\Theta + \arcsin\left(\frac{\lambda_{air}}{\Lambda_{grating}n_{quartz}}\right)\right)} \qquad (3)$$

where Θ is the angle of the prism vertices acting as turning mirrors. Presence of images with varying pitch leads to beating effects, which have to be controlled by utilizing a line-narrowed source.

The exact OPD and lateral beam misalignment values can be calculated once the dimensions of the system are known, and are presented in the next section.

3. EXPERIMENTAL

Multiple prisms were designed for different image pitch values, as shown in Table 1. An effort was made to keep the length of the prisms less than 50 mm, enabling a compact lithography system. The beamsplitter grating pitch was designed to be 600 nm, which is compatible with current PSM processing to achieve low zero order requirement (less than 1% of total intensity). The prism with the NA of 1.05 was manufactured and used for this experiment.

Table 1. Prism designs created for the Talbot interferometer.

NA	Half-pitch (nm)
0.8	60
1.05	45
1.20	40
1.35	36

The stringent spatial and temporal coherence requirements on the light source used in interference systems make it impossible to utilize a free-running excimer laser. Line-narrowing and resonator techniques have to be used to make this source suitable for interference imaging. A compact ArF excimer laser[8] fitted with an unstable resonator and line-narrowing optics was used.

The spatial coherence distance of the laser beam was calculated by measuring the uncorrectable divergence of the beam, as $\delta = \lambda / \Delta\varphi$, where $\Delta\varphi$ is the divergence angle. The measured value of 0.5 mm was expanded to 2.5 mm via the use of a beam expander. Using a ray tracing algorithm and taking into account the expanded spatial coherence distance, a latitude of 300 μm in image plane positioning was predicted. Within this tolerance the lateral beam displacement remains under 10% of the spatial coherence distance.

The full bandwidth (FWHM) of this source is 6 pm, which provided the temporal coherence length $\ell_c = \lambda^2 / \Delta\lambda$ of 6.2 mm. The interferometer arm length difference was calculated by ray tracing, and was found to be less than 10% of ℓ_c at the imaged spot size of 1 mm.

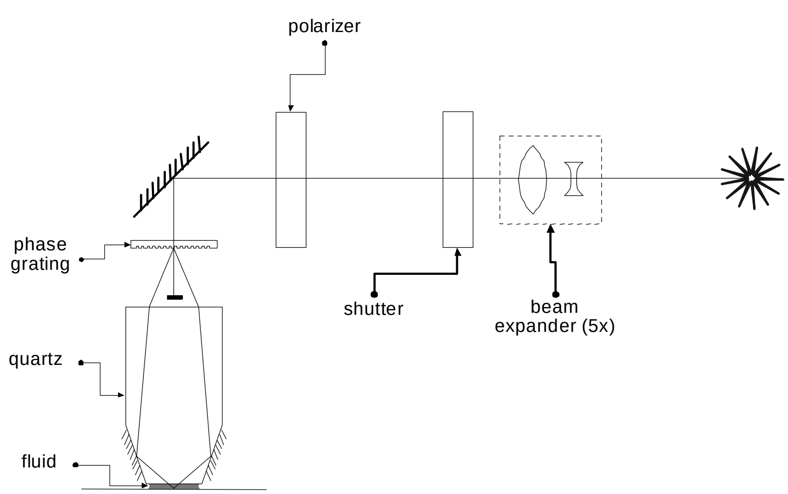

Figure 3. Complete compact Talbot prism immersion lithography system.

While the prism approach alleviates the alignment difficulty, it is fixed in terms of the arrival angle, and produces imaging with only one desired pitch. In order to achieve other pitch values, a variation to the system was used; as shown in Figure 4, and described earlier[1].

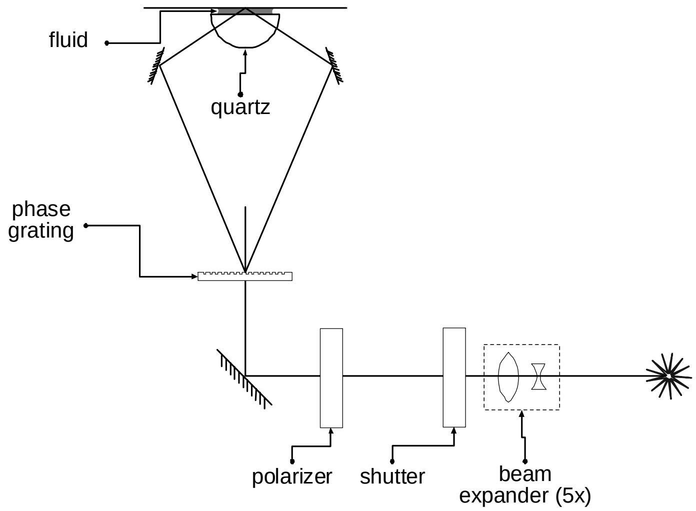

Figure 4. Variable pitch interferometric system, utilizing a half-ball lens. Maximum NA achieved with this system was 1.25 at λ=193 nm.

A phase grating with the pitch of 600 nm was used for all of these setups. The zero order intensity was less than 1% of the full intensity, and was blocked with a beam stop. Shipley XP1020 photoresist was used for all experiments, unless specified otherwise. The thickness of photoresist varied for different pitch images. Shipley AR40 was used as a bottom anti-reflective coating, and TOK ISP3a was used as a protective top coat.

4. RESULTS

The Talbot prism with NA=1.05 was manufactured, and used to print the images presented in Figure 5.

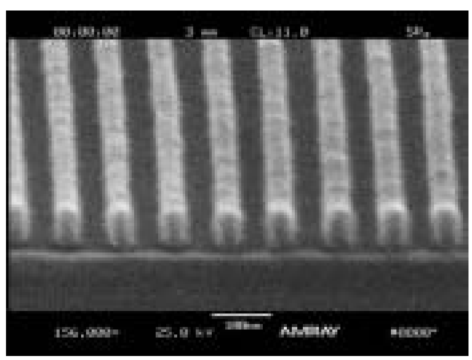

Figure 5. Photoresist lines printed with the compact Talbot prism, NA=1.05, corresponding to a half-pitch of 45 nm.

The variable NA system was used to demonstrate immersion interference imaging with NA values between 0.5 and 1.25, shown in Figure 6 Figure 8 to Figure 10. The images at the NA of 1.25 demonstrate the high contrast inherent to interference imaging, albeit with some line collapse. The line collapse will likely abate with more BARC layer thickness optimization at this extreme NA.

In addition, a KrF immersion interferometer was set up using the Braggmaster laser, as shown in Figure 7.

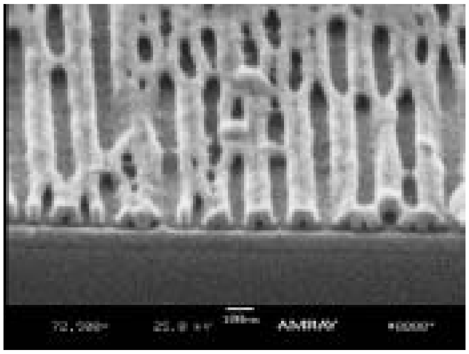

Figure 6. Photoresist lines at NA=1.25, half-pitch of 38 nm, resist thickness 70 nm.

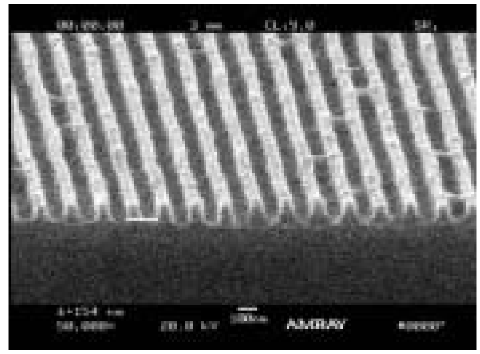

Figure 7. Interferometric imaging at 248 nm, with a KrF excimer laser, at NA=0.5, half-pitch of 125 nm.

5. CONCLUSIONS

The Talbot system enables immersion interferometric imaging at the 193 nm and 248 nm wavelength of ArF and KrF excimer lasers. Furthermore, the complexity of the interference system is greatly reduced when a compact Talbot prism is used in combination with a commercially available line-narrowed excimer laser fitted with an unstable resonator. Using this approach, imaging at NA=1.05 and a half-pitch of 45 nm was demonstrated. In addition, a variable NA half-ball prism system with the same source allowed imaging with the effective NA of 1.25.

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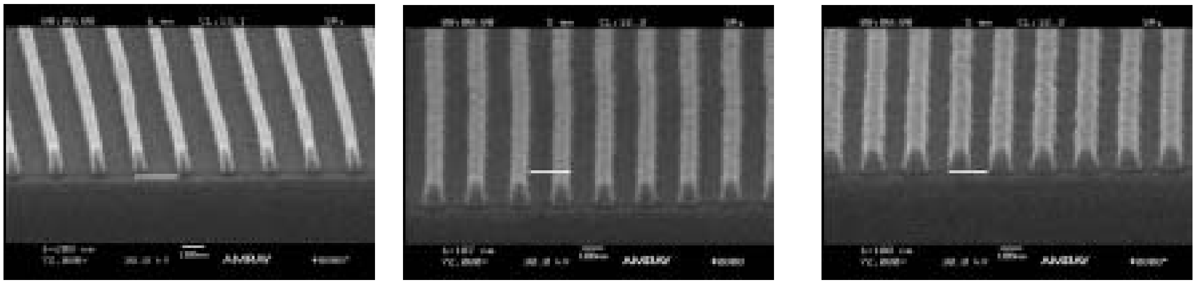
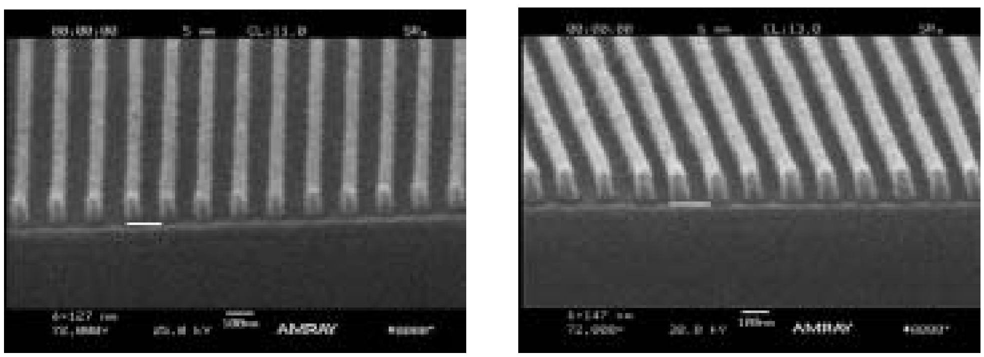
A. APPENDIX



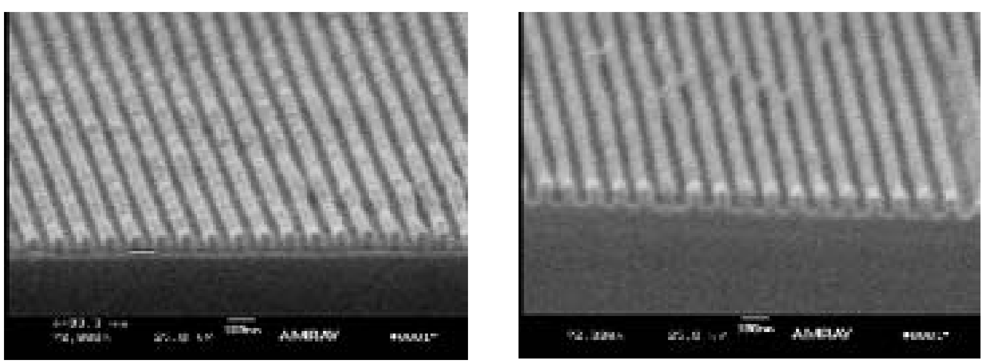
(a) (b) (c)

Figure 8. Images of the periodic pattern with NA=0.5, corresponding to a half-pitch of 98 nm. Varying duty ratio is produced at different dose levels. Duty ratios of 3:1 (a), 1.5:1 (b), and 1:1 (c) have been produced.



(a) (b)

Figure 9. Images of resist features with NA=0.7, corresponding to a half-pitch of 70 nm.



(a) (b)

Figure 10. Images of resist features with NA=1.0, (a) using Shipley photoresist, and (b) using TOK ILP photoresist.