Proposal of plane-parallel resonator configuration for high-NA EUV Lithography

Tsumoru Shintake*\textsuperscript{a}

*OIST: Okinawa Institute of Science & Technology Graduate University
1919-1 Tancha, Onna, Okinawa 904-0495 Japan

ABSTRACT

The mask pattern is created on the multilayer reflection mirror in the EUV lithography. This is the origin of the issues such as the absorber shadowing (mask-3D) and contrast loss at high-NA tool. To solve these issues, this paper presents conceptual discussions on a new configuration which employs rotating mirror (precession beam) to illuminate the mask from normal direction with small tilt angle matches to the numerical aperture: 8.3 deg at 0.55 NA and 11.3 deg at 0.71 NA, both angles are acceptable for multi-layer mirror of the mask. Unlike current EUV machine design, all optical components are axisymmetric and aligned on axis (in-line), and thus form a plane-parallel resonator configuration. x- and y-magnifications are same 4x, and full-field 33 mm x 26 mm may be possible at high-NA as high as 0.71. Annular slit at the back focal plane acts as Fourier spatial filter, which removes 3D components, thus resulting image becomes longitudinally projected mask pattern without shadows. The system becomes a both-side telecentric camera, providing long depth-of-focus and high contrast image. As the objective mirror, Schwarzschild objective or Wolter telescope will be a suitable candidate. Wolter telescope is axisymmetric and lighter than conventional solid concave mirror, therefore, a larger diameter mirror can be fabricated in high precession. After the objective mirror, all diffractions have the same angles to the axis (cone beam) including the illumination beam. A new concept “the generalized interference lithography” will be introduced as the working principle of pattern writing on the wafer.

Keywords: High-NA, EUV lithography, telecentric, interference lithography, no mask 3D effect

1. INTRODUCTION

The anamorphic projection system has been introduced in the next high-NA lithography system [1], which solves the issues such as the absorber shadowing (mask-3D) and contrast loss at high-NA tool, while the printing field is limited to a half. Alternative solution is proposed in this paper: the plane-parallel resonator configuration, which is in-line design, i.e., the lithography mask and the wafer are parallelly arranged through two focusing mirrors. EUV light is injected through an off-axis rotating mirror at the back focal plane and provides off-axis illumination (precession beam) to the mask and bounces back twice (at the mask and the wafer), finally goes out from the resonator through the rotating mirror. The off-axis illumination is essential for high-NA optics, which recovers the high spatial frequency, and improves the edge contrast. The matched annular-aperture is located at the back-focal plane of the projector mirror, which acts as Fourier filter passing only the horizontally scattered waves reflected by the density modulations of 0-th z-order Fourier component of the mask. During single precession of the beam, this system creates 2D image of the normally projected density map of the mask pattern onto the wafer, where the longitudinal variation (3D effect) disappears, and thus the mask-shadowing problem is moderated. The depth-of-focus (DOF) is long, and the image contrast becomes very high. As the objective mirror, Schwarzschild objective or Wolter telescope will be a suitable candidate. Wolter telescope is axisymmetric and lighter than conventional solid concave mirror, therefore, a larger diameter can be fabricated in high precession. If we remove the rotating mirror, the system becomes a resonator cavity, which will provide sensitive tool to verify errors in optical components and day-by-day corrections of mechanical alignments and detecting mask defect.

This paper describes basic configuration, working principle, diffraction physics and introduces a new concept: generalized interference lithography. The technical challenge and drawbacks will be also discussed.

*shintake@oist.jp
2. PROPOSED CONFIGURATION

Figure 1 shows schematic diagram of the proposed lithography system. The mask and the wafer are arranged in parallel along its optical axis, like the plane-parallel resonator configuration. The EUV light is fed through IF (intermediate focus), followed by 90 deg reflecting mirror (not rotating) at the center axis. The two rotating mirrors bring the EUV light on the beam line in parallel to the axis. The convex mirror creates the diverging light, which matches with the illumination size on the mask through the condenser/projection mirrors M1, M1’. Since the imaginary source point S1 of the diverging beam is located at the back focal plane, the beam after M1, M1’ becomes parallel plane wave which illuminates the mask uniformly. The imaginary source point S1 is located off-axis, and thus the beam provides tilted illumination to the mask, which enhances the resolution. The same concept, but static illumination, was used in Zernike’s phase contrast and darkfield microscopy [5].

The reflected light goes back through the same optical components M1, M1’ and form a spot S2 (0-th beam spot) at the back focal plane, which is opposite side of the imaginary source point S1. The diffractions associated with the logic pattern on the mask creates Bragg spots at the back focal plane around S2.

The annular slit is prepared to filter the Bragg diffractions, and rejects unwanted components associated with 3D effect. The 0-th beam and useful Bragg diffractions propagate down to the objective mirror M2 and produce mask image on the wafer. The objective mirror may be Schwarzschild or Wolter telescope. After the objective mirror, the 0-th beam and the Bragg diffractions become plane wave and overlap each other and create interference pattern, like interference lithography as shown in Fig. 2.

![Diagram of lithography system](image)

Fig. 1. Plane-parallel resonator configuration proposed for high-NA EUV lithography optics.

Looking up the annular slit from the downstream, the 0-th beam and Bragg diffractions stay on a ring shape light source, i.e., they are the same radius from the axis, and thus all the light illuminating on the wafer becomes plane wave with the same opening angle, like cone beam. The interference modulation is deep and uniformly activate resist layer on the wafer. During one cycle of rotating mirror, all the required Fourier components will be transferred on to the mask, and there is no missing diffraction spot.

Example machine parameter is summarized in Table-1 for 0.55 NA and 0.71 NA.
Fig. 2. The object wave (diffractions from mask) and the reference wave (illumination) interfere on the mask, create interference fringe, which become the mask pattern. Because of annular slit, ZOLZ (Zero-rh Order Lau Zone) Fourier components arrive to the wafer, thus mask-3D effect disappear.

Table 1. Example machine parameter.

| Numerical aperture | NA | 0.71 | 0.5 |
|--------------------|----|------|-----|
| Wafer field size   | $\Delta x$, $\Delta y$ | 33 mm x 26 mm | = |
| Magnification factor | $M$ | x 4 | = |
| Mask size (diameter) | $M\Delta x$, $M\Delta y$ | 132 mm x 104 mm (Diagonal 168 mm) | = |
| Focal length of projector | $F_1$ | 1000 mm | = |
| Focal length of Wolter telescope | $F_2$ | 250 mm | = |
| Maximum beam angle at exit of Wolter telescope | $\theta_2$ | 45 deg | 30 deg |
| Beam divergence at Wolter telescope | $\theta_{div} = \frac{1}{2} \frac{D_M}{F_1}$ | $\pm 4.8$ deg | $\pm 4.8$ deg |
| Maximum diffraction angle at the mask | $\theta_1 = \frac{\theta_2}{M}$ | 11.3 degree | 7.5 degree |
| Tilt angle of precession beam on the mask | $\theta_T = \theta_1$ | 11.3 degrees | 7.5 degree |
| Wolter telescope diameter at entrance | $D_W = 2F_1\theta_T$ | 392 mm | 261 mm |
| Annular aperture | $R_a = \frac{D_w}{2} = F_1\theta_T$ | 196 mm | 131 mm |
| $W_w = 0.1 \times R_a$ | 20 mm | 13 mm |
| Projector mirror size | $D_p = D_w + D_M$ | 560 mm | 429 mm |
| Depth of focus | $DOF \approx \frac{\lambda}{2NA^2} \frac{R_a}{2w_a}$ | 67 nm | 135 nm |
| Mirror Rotation Speed | = | 20 cycle/sec | = |
| EUV shots per cycle | = | 20 kH EUV Source | 1000 shots |
| Throughput | = | at 100 stamps/wafer | 180 WPH |
3. DIFFRACTION FROM THE MASK

3.1 Reflection angle at the mask

The mask pattern is created on the multilayer reflection mirror in the EUV lithography. This is the origin of the issues such as the absorber shadowing (mask-3D) and contrast loss at high-NA tool. To solve these issues, in this paper a new configuration is introduced, which employs rotating mirror (precession beam) to illuminate the mask from normal direction with small tilt angle matches to the numerical aperture: 8.3 deg at 0.55 NA and 11.3 deg at 0.71 NA, as shown in Fig. 3. These angles may be acceptable for current mask design, and compatible to the current NXE 3400 tool [6].

In the following sections, the reason why we use ring shape diffractions will be explained.

![Fig. 3](image-url)

Fig. 3. The reflection angles in the proposed high-NA solutions are within the maximum angle in the current design at NA 0.33.

3.2 X-ray diffraction from 3D crystal shows circular patterns

X-ray Bragg diffraction phenomena has been successfully used to analyze the protein structure, known as X-ray crystallography [7]. Fig. 4 shows a typical diffraction pattern from a small protein crystal. By rotating crystal, the circular pattern changes their diameter and the center. Each dot corresponds to Bragg diffractions, from which scientist reconstruct 3D structure of the protein inside the crystal.

Physical origin of this phenomena is that the X-ray does not change its wavelength during Bragg diffraction, thus the wave vector length stays unchanged. The diffraction happens when the X-ray wave exchanges momentum with the atoms inside the crystal. Because the atoms form 3D array inside the crystal, whose interaction kernel is also discretized and acts as the diffraction grating. From the momentum conservation law:

\[ S = k_2 - k_1 \]  

Where \( S \) is the structure factor, and \( k_1, k_2 \) are the incident and the scattered wave vectors. Because the vector keeps the same length,

\[ k_0 = 2\pi/\lambda = |k_1| = |k_2| = \sqrt{k_x^2 + k_y^2 + k_z^2} \]  

(2)
This equation indicates that endpoints of the wave vectors are on a sphere of radius $k_0$, which is called Ewald’s sphere. The protein crystal is formed by translational copy of proteins in x, y and z directions, whose Fourier series also becomes 3D space pattern, which is called reciprocal space. In Fig. 4, the red curve represents Ewald’s sphere, which intersects with multiple layers of lattice index $l = -2, -1, 0, +1$, and thus creates circular lunes in the Bragg diffraction.

![Diagram of Bragg diffractions from a protein crystal.](image)

By using narrow annular slit, we use this component in the proposed EUV lithography. The Fourier component is given by

$$F(S) = \int \rho(r) \cdot \exp(iS \cdot r) \, dv$$

(3)

$\rho(r)$ is the electron density of the object, i.e., the lithography mask. $F(S)$ can be written down in Cartesian coordinate as follows [7].

$$F(S_x, S_y, S_z) = \iiint e^{i2\pi(S_x x + S_y y + S_z z)} \rho(x, y, z) \, dx \, dy \, dz$$

$$= \iiint \rho(x, y, z) \, e^{i2\pi(S_x x + S_y y)} \, dx \, dy \cdot e^{i2\pi S_z z} \, dz$$

(4)

Effect of the longitudinal structure variation is given by the last term. Thinner the reticle will provide broad spread of $F(S)$ in longitudinal direction, and thus high frequency loss becomes less important. While in EUV lithography, to achieve enough contrast, the absorbing layer becomes longer than the wavelength at 13.5 nm, this effect is not negligible. Additionally, the mask absorbing pattern is created on the multilayer coating mirror, as a result, there exists double layer absorber images (real and mirror images), which cause shadowing effect and further complicated longitudinal Fourier components.
If the depth of focus is limited, the out of focus components will be blurred and overlap to the focused image, as a result, lower the contrast. To improve resolution and contrast, we need to obtain projected image of the mask, which is given by Fourier component on 0-th z-order plane. By letting $S_z = 0$,

$$F(S_x, S_y, 0) = \iint \left[ \rho(x, y, z) \, dz \right] \cdot e^{i2\pi(S_x x + S_y y)} \, dx \, dy$$

Finally, we have projected image reconstructed at the wafer as follows.

$$\sigma(x, y) = \iint F(S_x, S_y, 0) \cdot e^{-i2\pi(k_x x + k_y y)} \, dk_x \, dk_y$$

In this integration, $F(0, 0, 0)$ is the illuminating beam, which acts as the reference wave. $F(k_x, k_y, 0)$ are the object waves interfere with illuminating beam, create interference fringes.

There existed the precession method in X-ray crystallography [2], which was used to collect $F(k_x, k_y, 0)$ components through the annular slit and precession motion of the crystal. This instrumentation was widely used to identify the crystal structure in early days in the crystallography, while not any more used because of emerging alternative advancing computerized method. The precession method was also successfully used in electron crystallography to remove dynamical diffractions [3,4]

### 3.3 Normal and tilt illumination to the mask (UV transparent mask)

For the simplicity of discussion, here we assume the lithography mask is transparent, and illuminating from top. Figure 5 shows the reciprocal space (Fourier space) of the wave diffraction from the mask for normal and tilt illuminations. In the normal illumination, the incident wave vector $k_1$ is scattered by angle $\theta$ into $k_2$. At higher angle, the scattering vector moves away from xy-plane, and thus the wave-structure coupling becomes lower as a result lowering the edge contrast. In case of the tilt illumination, the incident wave vector $k_1$ has tilt angle $\theta$, and scattered into $k_2$ vector in the opposite direction by $2\theta$. The scattering vector $\mathbf{s}$ lies on xy-plane, thus the wave-structure coupling becomes high and produce high edge contrast. The scattering vector length is twice longer, thus resolution become twice higher. In the conventional UV lithography, the tilt illumination has been used to enhance the edge contrast in this reason [8].

The double circle in Fig. 5 represents the annular slit, which lies on xy-plane normal to z-axis. As we learned in the previous section, the intersection circle to Ewald’s sphere is related to ZOLZ diffraction, i.e., Fourier component at $z = 0$. When a narrow slit is used, the longitudinal components become small, and thus the 3D effect disappear from the projected image.

![Fig. 5. Normal and tilt illumination through the transparent mask.](image-url)
From the longitudinal frequency spread, we may estimate the depth of focus as follows.

\[
DOF \approx \frac{\lambda}{2NA^2} \frac{\theta}{2\Delta \theta} \approx \frac{\lambda}{2NA^2} \frac{R_a}{w_a}
\]  

(7)

where \(R_a\), \(w_a\) is the radius and the width of the aperture, respectively. Typically, DOF becomes more than five times longer than conventional system. Narrower width of the annular aperture will provide longer DOF. It must be optimized in experimentally, considering optical alignment errors and the source size.

### 3.4 Beam precession

In the previous section, we discussed the tilt illumination on one direction, where a part of Fourier components scatters the beam. To uniformly illuminate the mask and covers all the diffraction spots within the resolution rim, we perform the beam precession as shown in Fig. 6.

During the beam motion, the diffraction pattern shifts as keeping the diffraction center \((0,0)\) on the illumination spot. We must note that the diffraction pattern does not rotate around the axis, but it shifts. After one cycle of precession, multiple diffraction patterns are accumulated as Fig. 6 (b). The diffractions which pass through the annular slit propagate down to the objective lens.

![Beam precession](image)

**Fig. 6. Beam precession**

In the EUV lithography, the same physics works, while the illumination must be upward. \(k_i\) is reflected illumination from the multi-layer mirror. We have mirror image of the absorber layer, which modulate the longitudinal distribution of Fourier component.
4. PLANE PARALLEL RESONATOR CONFIGURATION

4.1 Feeding light into the resonator

As shown in Fig. 7, the wafer and the mask acts as mirror, the system becomes the plane-parallel resonator. If we place a laser medium inside the optical path, it will work as the laser oscillator. We do not have such laser medium at EUV wavelength, we must inject light from some point.

We choose the injection point near the back-focal plane as shown in Fig. 7. Th injected beam through 90-deg reflection mirror runs to M1, followed by focusing with M1, and becomes plane wave illuminating on the mask with tilt angle. Reflected beam focused by M1 and forms spot at the back focal plane, goes through the annular slit, without loss. The objective lens M2 focus the beam and provides plane wave to the wafer. The reflected beam is focused back to the back-focal plane through annular slit and goes out from the resonator. This is the single path resonator, thus there is no resonant effect. We rotate the injection mirror around the axis, and uniformly illuminate the mask for 360 deg around the axis.

![Plane-Parallel Resonator Configuration](image)

**Fig. 7.** Plane-parallel resonator configuration with EUV light injection at back-focal plane.

The beam path represents the center of the beam, refer to Fig. 8.

4.2 Wave propagation in the system

Fig. 8 (a) is the simplified diagram of the proposed lithography system. Fig. 8 (b) is sometimes called 4f-system because the focus points of two lenses are commonly shared, and the object and the screen are located at the focus points. If the light is monochromatic, it becomes Fourier transform system, i.e., Fourier transform of the object is created at the back-focal plane, followed by real image on the screen.

Fig. 8 (c) is the proposed system. The light source located at the back focal plane emits spherical wave, which becomes plane wave and illuminates the mask. The reflected wave propagates down to M1, M2 and create real image on the wafer together with diffraction from the mask. We eliminate the unwanted diffractions associated with 3D component at the back-focal plane, i.e., Fourier space.
5. GENERALIZED INTERFERENCE LITHOGRAPHY

The proposed system writes the mask pattern by the same mechanism as the interference lithography. Figure 9 (a) is the conventional interference lithography, where a laser beam splits into two beams through a half mirror, followed by reflection mirrors and overlap on the wafer and create interreference pattern normal to the wafer. This method has been widely used to write precise fine pitch pattern on the mask to test various performance of the lithography technology. Modulation depth (fringe contrast) is generally high (~100%), and whose pitch is well defined by the wavelength and crossing angle of two beams [9]. The fringe pitch (dark-to-dark) is given by

\[ g = \frac{\lambda}{2 \sin \theta}, \]

where \( \theta \) is the opening angle of beam to the axis.

Figure 9 (b) shows a thought experiment of two hole slit in the 4f Fourier transform system. The beam splits into two or more beams due to Bragg diffraction. We place a slit with two holes at the back focal plane, where 0-th beam passes through the left hole, and one of the Bragg diffractions will path the right hole. Those two beams will overlap on the wafer and create the interference pattern same as Fig. 9 (a).

Fig. 9 (c) is the proposed system; we may call it “generalized interference lithography” in this paper. As discussed in the previous sections, we choose the desired Bragg diffractions using annular slit, as a result all the diffractions arriving to the wafer have the same opening angle \( q \) to the axis and create interference patterns perpendicular to the wafer. We must note that the diffractions distributed around the axis, thus the azimuthal angle to 0-th beam is difference on each diffraction. During the one cycle of beam precession, the required interference patterns are accumulated inside the resist layer as the photo-activation. The activated pattern is normal to the wafer surface, and the height is long enough to cover the resist layer thickness. The transverse density distribution represents projected mask pattern.
6. CONCLUSIONS

The discussion in this paper is conceptual and simplified. To realize this system, we need R&Ds on the following issues and questions.

(1) Can we make a vibration free rotating mirror in high precession?
(2) Can we correct the orbital error at the rotating mirror by dynamically feedback?
(3) Polarization changes as the mirror rotates. Can we handle the reflectivity dependence on the polarization?
(4) Number of mirrors is less. Can we correct geometrical aberrations?
(5) Can we realize objective mirror to precisely focus a large hollow beam?

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