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# Absorber dependence of M3D overlay errors in high-NA and hyper-NA EUV lithography

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## ABSTRACT

The M3D effect causes telecentricity errors at the illumination slit ends, when the dipole illumination is used for vertical L/S. The telecentricity errors at the right and left ends have opposite signs, so they cannot be compensated by changing the sizes of the two poles. The M3D overlay error is defined as the product of the telecentricity error at the illumination slit end and half the depth of focus. The M3D overlay error depends on the scanner NA and the absorber material. When the conventional Ta absorber is used, the error is negligible for NA 0.33 scanners. As NA increases, the M3D overlay error also increases, but the overlay error budget decreases. The M3D overlay error of the Ta mask for NA 0.55 scanners is slightly below the overlay error budget. However, it exceeds the budget for NA 0.75 scanners. The M3D overlay error becomes larger when PSMs are used. The root cause is the large phase distortion at the absorber sidewalls. The M3D overlay error can be reduced by using binary masks. Binary masks are required for hyper-NA lithography.

**Keywords:** EUV mask, overlay error, mask 3D effect

## 1. INTRODUCTION

The numerical aperture (NA) of the current extreme ultraviolet (EUV) scanners is 0.33. To print smaller patterns, high-NA EUV scanners (NA 0.55) were developed. Toward hyper-NA scanners (NA >= 0.75) several simulation studies have been conducted.[1,2] These simulations mainly focus on the image contrast and do not consider the overlay error. In this report, we discuss the overlay error caused by the mask 3D (M3D) effects.

In NA 0.33 optical systems, a well-known example of M3D effects is the two-bar critical dimension (CD) asymmetry, which causes CD difference between two adjacent horizontal spaces.[3] As shown in Fig. 1(a), when the dipole illumination is used, the incident angle of the ray from the small angle pole (SAP) is different from that from the large angle pole (LAP). Due to the M3D effect, the diffraction amplitudes from the two poles are different. The unbalanced diffraction amplitudes cause CD asymmetry at defocused positions. Ref. 3 shows that the CD difference becomes small by changing the sizes of SAP and LAP (Fig. 1(b)). In this way, the M3D effect on horizontal line and spaces (L/Ss) can be compensated by using asymmetric dipole illumination.

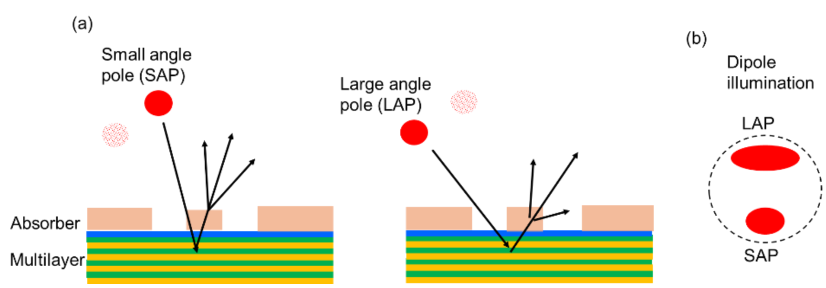


Fig.1 (a) Diffraction amplitudes from the small and large angle poles. (b) Asymmetric dipole illumination.

However, such a compensation scheme cannot be applied to vertical (V) L/S. The root cause is the curved illumination slit. Due to the curved slit, the azimuthal angles are opposite between the right and left ends of the illumination slit (Fig. 2). Therefore, the telecentricity error (TCE) at both slit ends cannot be corrected simultaneously by changing the sizes of the right and left illumination poles.

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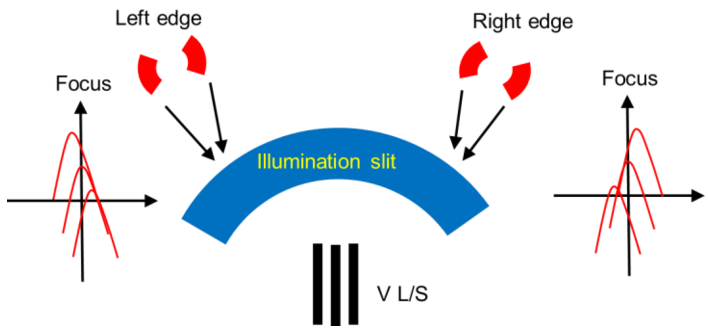


Fig. 2 Illumination slit position dependence of TCE.

In Ref. 4, M3D overlay error was defined as the product of the TCE and half the depth of focus (DOF). When the conventional Ta absorber was used, the error was negligible for NA 0.33 scanners, but it was over 0.5 nm for NA 0.55 scanners. The M3D overlay error was reduced by using high-k absorber.

In this report, we study the absorber dependence of the M3D overlay errors in high-NA and hyper-NA EUV lithography. In Sec. 2, we classify EUV masks depending on the complex refractive index of the absorber. In Sec. 3, we show the NA and absorber dependence of the M3D overlay errors. Sec. 4 is the summary.

## 2. CLASSIFICATION OF EUV MASKS

The reflectance and phase-shift value of an EUV mask oscillate depending on the absorber thickness as shown in Figs. 3. The root cause is the interference of the reflected amplitude A at the absorber surface and the reflected amplitude B which goes through the absorber and reflected inside multilayer (ML). When we ignore the absorber surface reflection A, the relative reflectance $R$ and phase-shift value φ are calculated by the following equations. [5]

$$R \approx \exp(-8\pi k\, t/\lambda), \tag{1}$$

$$\varphi \approx 4\pi(1-n)\, t/\lambda, \tag{2}$$

where $t$, λ, $n$, and $k$ are the absorber thickness, the wavelength, the refractive index, and the extinction coefficient of the absorber, respectively.

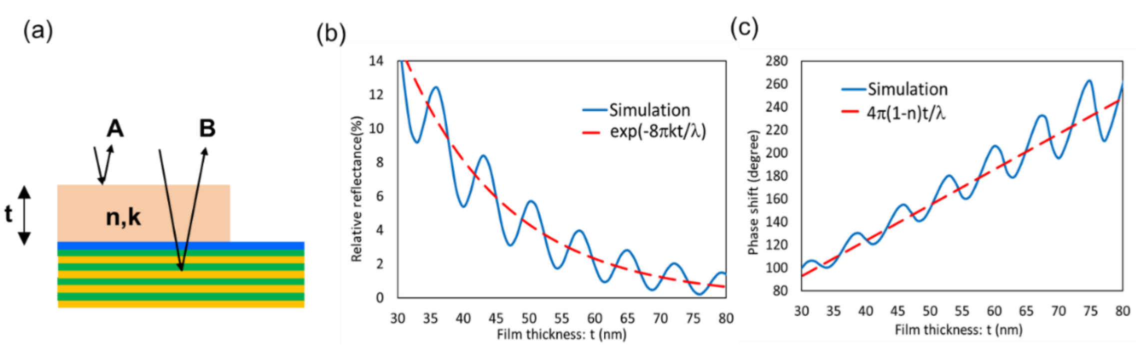


Fig. 3 (a) Reflection at the absorber surface and inside ML. (b), (c) Relative reflectance and phase-shift values of Ta absorber.

In optical lithography, the optical density (OD) of the binary mask is over three. This means that the transmittance is below 0.1 %. In EUV lithography, assuming the absorber thickness $t$ = 50 nm, the relative reflectance is below 0.1 % when the extinction coefficient $k$ is over 0.07. We use this condition as the definition of the EUV binary mask.

The phase-shift value of the optical phase shift mask (PSM) is $\pi$. However, in the case of the EUV PSM, the effective phase-shift value depends on the pattern pitch due to the M3D effect as shown in Ref. 6. For convenience, we define the reflectance of the EUV PSM as the reflectance when the phase-shift value is $\pi$ as follows.

$$R_{\pi} = \exp\left(-2\pi k/(1-n)\right) \quad . \tag{3}$$

Even though the transmittance of the optical PSMs is 6 %, there have been innumerable attempts to develop higher transmittance PSMs. Well known drawback of the high transmittance PSM is that the sidelobes become larger as the transmittance increases. The sidelobe can be suppressed, to some extent, by applying the optical proximity correction (OPC). The allowable value of the PSM transmittance depends on the pattern layout. In the case of random logic pattern the maximum transmittance might be ~10% due to the complicated OPC. OPC of DRAM memory cells is much simpler and PSM with 15% transmittance could be used. In general, the allowable range of the PSM reflectance $R_{\pi}$ is 5-15%. This means

$$0.3 < \frac{k}{(1-n)} < 0.5 \quad . \tag{4}$$

Figure 4 shows the classification of EUV masks. The extinction coefficient of Ni absorber is over 0.07,[7] and the mask with Ni absorber is an example of EUV binary masks. The mask with TP1 absorber in Ref. 8 is an example of EUV PSMs. The complex refractive index of TP1 satisfies Eq. (4). The mask with Ta absorber is neither a binary mask nor a PSM. The optical properties of the mask with Ta absorber are between those of a binary mask and a PSM.

| | n | k |
|---|---|---|
| Ta | 0.957 | 0.034 |
| Ni | 0.948 | 0.073 |
| TP1 | 0.91 | 0.032 |

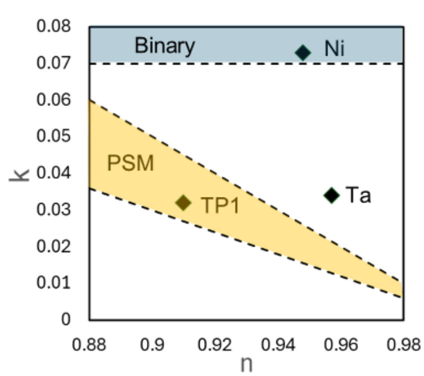


Fig. 4 Classification of EUV masks.

It has been pointed out that high-k absorbers reduce TCE, and low-n absorbers increase TCE.[5] The origin of TCE in PSMs is not purely geometrical. It is caused by the wave nature of light. In the case of PSMs, the incident wave is distorted at the side walls of PSMs as shown in Fig. 5. The phase distortion induces M3D effects such as TCE. In the case of binary masks, the phase distortion is small. Therefore, TCE of binary masks is smaller than that of PSMs.

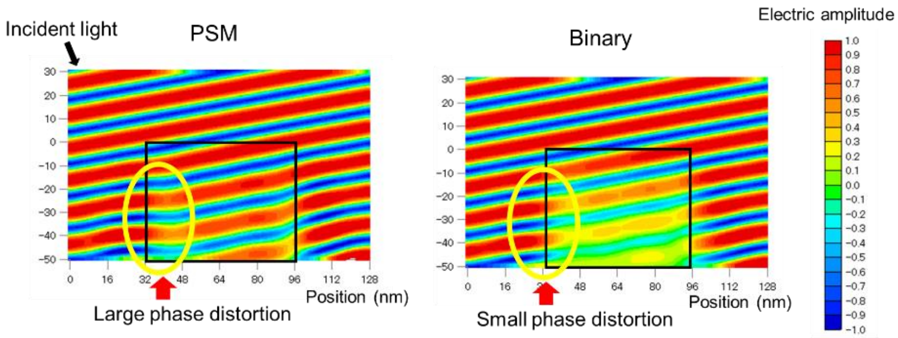

Fig. 5 Phase distortion of incident waves at the sidewalls of absorbers.

## 3. NA AND ABSORBER DEPENDENCE OF M3D OVERLAY ERRORS

As shown in Fig. 2, the root cause of the TCE of V L/S is the different azimuthal angles of the right and left poles at the illumination slit ends. The difference increases as NA increases (Fig. 6). Also, the aspect ratio of the mask pattern increases as NA increases. For these two reasons, TCE of V L/S increases as NA increases.

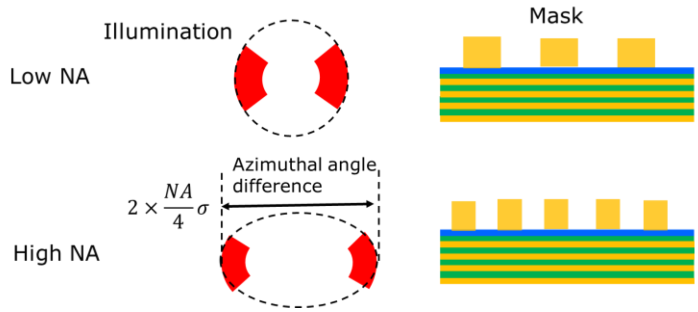

Fig. 6. Illumination shapes and mask patterns in low and high NA EUV lithography.

According to Ref. 4, we define the M3D overly error as the product of the TCE at the illumination slit end and half the DOF.

$$\text{M3D overlay error} = \text{TCE at the illumination slit end} \times \tfrac{1}{2}\text{DOF} \quad (5)$$

The DOF for scanners with NA 0.33, 0.55, and 0.75 scanners is estimated to be 100, 36, and 20 nm, respectively.

Figure 7 shows the NA and absorber dependence of M3D overlay errors. We assume the absorber thicknesses for Ta, binary mask (Ni) and PSM (TP1) are 60, 40 and 40 nm, respectively. The mask patterns are V L/S. We use the dipole illumination $\sigma_{in}/\sigma_{out} = 0.55/0.95$ with the opening angle 90 degrees. We set the azimuthal angle at the illumination slit end to 18 degrees. [9]

In Fig. 7 the overlay error budget is estimated by CD/5/$\sqrt{3}$, where CDs for NA 0.33, 0.55 and 0.75 are 14, 9 and 6 nm, respectively. According to Ref. 10, the total overlay error is CD/5, and we assume the error budget of the M3D overly error is $1/\sqrt{3}$ of the total overlay error. The overlay error budgets for NA 0.33, 0.55 and 0.75 are 1.6, 1.0 and 0.7 nm, respectively. The overlay error budget decreases as NA increases.

The M3D overlay error depends on the scanner NA and the absorber material. When the mask with Ta absorber is used, the error is negligible for NA 0.33 scanners. It is slightly below the overlay budget for NA 0.55 scanners. However, it exceeds the budget at some HPs for NA 0.75 scanners. The M3D overlay error becomes larger when PSMs are used. The M3D overlay error can be reduced by using binary masks.

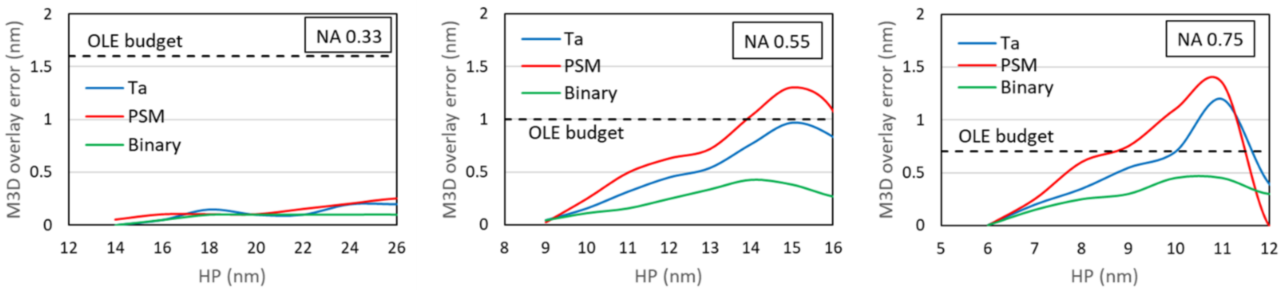


Fig. 7 NA and absorber dependence of M3D overlay errors.

Figure 8 shows the normalized image log slope (NILS) and dose of V L/S. The dose is defined by the inverse of the threshold image intensity. For NA 0.33 scanners, the PSM has the highest NILS. However, the binary mask has the highest NILS for NA 0.55 and 0.75 scanners. The results could be different for other patterns such as hole patterns. In general, the higher the NILS, the larger the dose.

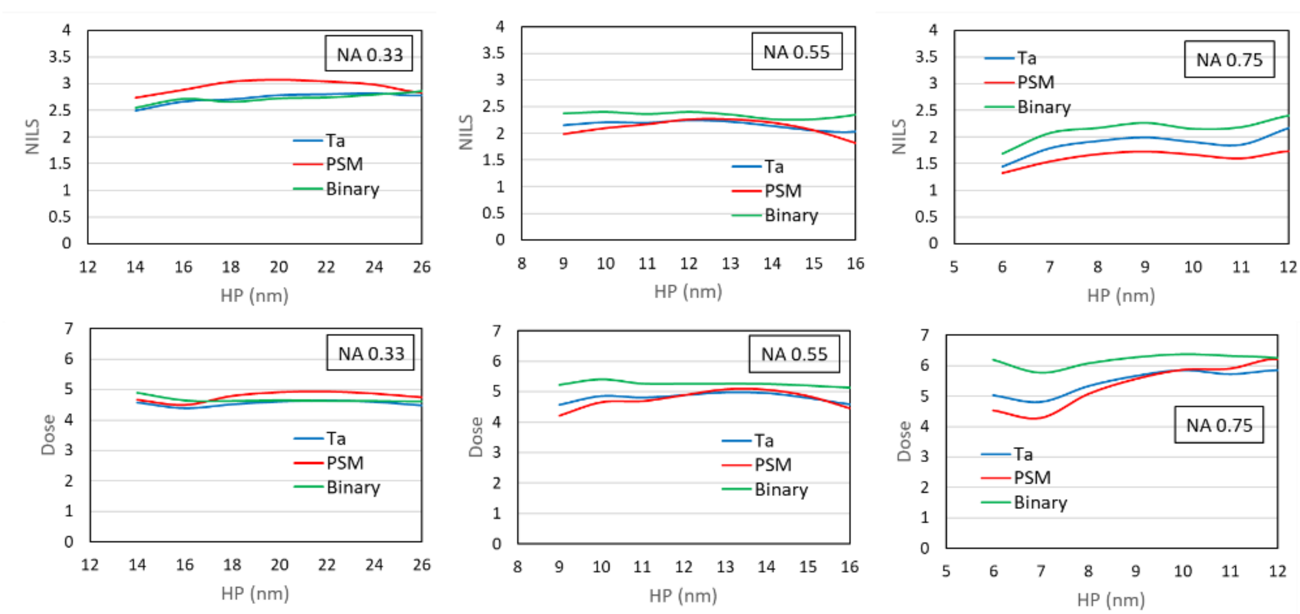


Fig. 8 NA and absorber dependence of NILS and dose of V L/S.

## 4. SUMMARY

The M3D overlay error depends on the scanner NA and the absorber material. When the conventional Ta absorber is used, the error is negligible for NA 0.33 scanners. As NA increases, the M3D overlay error also increases, but the overlay error budget decreases. The M3D overlay error of the Ta mask for NA 0.55 scanners is slightly below the overlay error budget. However, it exceeds the budget for NA 0.75 scanners. The M3D overlay error becomes larger when PSMs are used. The root cause is the large phase distortion at the absorber sidewalls. The M3D overlay error can be reduced by using binary masks. Binary masks are required for hyper-NA lithography.

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