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A model for multilayer analysis in a coated extreme ultra-violet lithography projection system

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ABSTRACT

Reflection-enhancing multilayer coating is one of the key technologies in Extreme Ultra-Violet Lithography (EUVL). The typical thickness of the Mo/Si multilayer coatings generally adopted in EUVL is about 300 nm, which is much greater than the operating wavelength of 13.5 nm. The EUV is reflected completely back to the vacuum before punching the substrate. This changes the actual reflective surface by dozens of waves and creates extra aberrations. In this study, an equivalent working surface model for multilayer analysis based on the energy conservation principle was developed. Under the premise of the same energy modulation function for real and model film systems, each multilayer film coated optical element with complex energy propagation is transformed into a single surface. Optical design software can be used to assess these virtual surface in terms of estimation and optimization. Finally, the model was applied to a same Schwarzschild system but with different coating solutions. And the best solution was confirmed in which the coating-induced aberrations could be compensated for by image defocus.

1. Introduction

Extreme Ultra-Violet Lithography (EUVL) is one of the most promising technologies in Next Generation Lithography (NGL) [1]. Since nearly all the materials are not transparent for the exposure wave with $\lambda = 13.5$ nm, reflective projection with reflection-enhancing multilayer-coated mirrors must be adopted for EUVL. The typical Mo/Si multilayer consists of 40–60 periods with a total thickness of about 300 nm, which is much greater than the operating wavelength. A finite difference time domain (FDTD) analysis of a typical Mo/Si multilayer film in EUVL projection system demonstrates that the most of the incident light does not penetrate the substrate when the reflectivity of the film is fairly high. There will be a big difference relative to the exposure wavelength between the systems with and without multilayer films in terms of energy modulation. When aberrations are introduced into the projection by these films, the imaging quality is compromised [2–4].

In terms of estimation for a film-coated optical system, commercial optical design softwares such as CODEV [5] and Zemax [6] do not take into account the thickness of the coating or assume that the coating grows into the substrate. Only a film-induced phase shift in $(-\pi, \pi]$ and transmissivity will be adopted into the aberration algorithm [7–9]. In fact, it is also not possible to conduct a precise FDTD analysis of a coated optical system. Wesner [10] and Bal [9] proposed equivalent reflective surface models based on the multilayer-induced phase shift in reflective systems independently of each other. They concluded that the effective incident depth for the multilayer films is proportional to the second-order partial deviation of the induced phase shift to the incident angle [9,10]. Due to the low-order approximation algorithm and considerable asynchronism of the p- and s-polarization phase shift at a large angle of incidence (AOI), the model may fail to address some factors. For example, the effective incident depth may be negative when the AOI is larger than 10° for a typical Mo/Si film.

This paper presents a new equivalent working surface model (EWSE) for a film-coated system analysis and optimization. It is based on conservation of energy principles, regardless of the low-AOI limitation. The equivalent working surface has the same energy modulation function as the corresponding real-coated optical element. The EWSE can simplify the complex physical optical process in films into geometrical tracing optics with a single working surface. Therefore, with the aid of optical design software, analyzing a coated optical system is completed more quickly and intuitively. Using the universal energy conservation principle and basic electromagnetic field theory as the theoretical bases, the EWSE model aids in estimation of other multilayer

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optical systems. This is especially pertinent when the multilayer coatings are much thicker than the operating wavelength, such as in the EUVL projection system.

2. Model of equivalent working surfaces

In this section, basic electromagnetic(EM) field theory is presented firstly as the natural transition to energy analysis in multilayer system, forming the foundation of the EWSE model. The model can then be further adapted.

2.1. Basic electromagnetic theory

According to the basic electromagnetic field theory, when a wave with amplitude ϵ emerges from a vacuum into an absorbing medium, the electric field can be written as [11]

$$\begin{aligned} E(z,\theta_i) &= \epsilon \exp\left[i\omega t - \left(\frac{2\pi N(z)}{\lambda}\right) r(z,\theta_i)\right] \\ &= \epsilon \exp\left[-\left(\frac{2\pi k(z)}{\lambda}\right) r(z,\theta_i)\right] \\ &\quad \times \exp\left[i\omega t - \left(\frac{2\pi n(z)}{\lambda}\right) r(z,\theta_i)\right] \end{aligned} \tag{1}$$

in which the medium depth z is perpendicular to the medium face, with the original point at the incident point of light beam. The propagation path r is the function of AOI θ_i, z and medium distribution. $N = n - ik$ is the complex refractive index in which n and k are the index and extinction factor, respectively. When light enters the medium with depth z, we get

$$\frac{I_s(z)}{I_{s0}} = \exp\left[-\frac{4\pi k(z)}{\lambda} r(z,\theta_i)\right] \tag{2}$$

where I_s is the intensity of energy at depth z. If coordinate z is beyond the medium, and I_s was obtained out of the medium, I_s is called transmissive intensity. $I_{s0} = \frac{1}{2} Re(\mathbf{N})\epsilon^2$ is the incident intensity at the medium surface. Subscript s means that the intensities are obtained from the plane perpendicular to the *Poynting's vector*. Eq. (2) shows that, due to the absorption of medium, different I_s values indicate different energy propagation paths. When we replace the medium in Eq. (2) with the multilayer coating on the optical substrate, the relationship between I_s and $I_{s\ 0}$ can be represented in various ways, such as reflectivity, transmissivity and absorptivity. Therefore, the propagation path or depth of light in the coating can be obtained from the coating's performance under the constraints of the energy conservation principle. This is the theoretical basis for our new equivalent working surface model, EWSE.

2.2. Framework for the EWSE model

This section discusses the framework for the EWSE model. Fig. 1 presents the translation from the real film element to the EWSE model element. Fig. 1(a) also shows the structure and energy transfer of a typical real reflection-enhancing multilayer coating with reflectivity R and transmittance T. First, a substrate is plated alternately with two unique materials, whose thicknesses correspond to the work wavelength. The complex multiple reflections and transmissions between the interferences are expressed as a continuous, dashed line. The gray level and size of the arrows indicate the amount of light intensity. Film absorption is not shown.

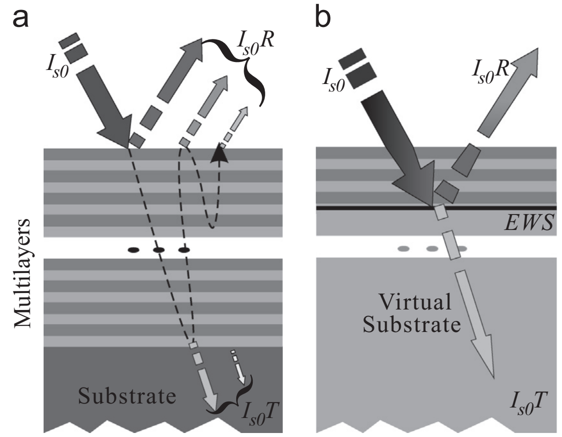

Fig. 1. (a) Schematic diagram and energy transfer of real multilayer coating (b) equivalent working surface model based on the energy conservation principle (EWSE).

Fig. 1(b) illustrates the EWSE model with the same energy modulation function as the real coating stacks shown in Fig. 1(a). EWS represents the equivalent working surface. In reflective systems, this can be considered as the reflective surface, just like a virtual mirror with the same R and the same T as the real coating. The distance between the coating face and the EWS, and the EWS and the substrate surface are the effective incident depth(EID) and the additional thickness(AT) of the coating, respectively. Incident and reflective light is absorbed by the media in EID, while the transmissive intensity in virtual substrate does not change. In this way, the effect of the film is considered as a change in the working surface and a loss of energy. Because energy conservation is the cornerstone of the EWSE model, the EID naturally involves a loss of energy. Therefore, only the change in the working surface taken into account when estimating a coated system with EWSE. The complex energy transfer based on physical optical theory in real film is transformed into brief geometrical ray-tracing optics and the virtual mirror can be shared with commercial optical design softwares such as ZEMAX and CODE V. This allows for easy and efficient estimations and optimizations of coated systems for the most part.

Next, we describe the theoretical derivations of EWSE. To be more efficient, we lay out the framework of the EWSE model first. The two details below will be considered later in Section 2.3

1. The multiple, complex reflections and transmissions in EID;
2. The fact that some light is reflected back to the incident medium in advance.

First, a beam with intensity of $I_{s\ 0}$ is directed at the film-coated optical element. When the beam arrives at the film before touching the EWS, it is absorbed by the media, and we assume that the multilayer media in EID has an attenuation factor C_{att}, which is the ratio of output and input intensities. According to the principle of energy conservation, for an infinitesimal area element δ S in EWS, we can express the energy transfer shown in Fig. 1(b) as

$$[I_{s0}(\delta S\ \cos\ \theta_i)C_{att} - I_{st}(\delta S\ \cos\ \theta_t)]C_{att} = I_{sr}(\delta S\ \cos\ \theta_r) \tag{3}$$

with θ_i, θ_t, and θ_r being the angles of incidence, transmission and reflection, respectively. Reflectivity R and transmittance T of the coating can be easily achieved through theoretical calculation or measurement. With the aid of basic definitions or equations, such as $R = I_{sr}/I_{s0}$, $T = I_{st}\ \cos\ \theta_t/(I_{s0}\ \cos\theta_i)$ and $\theta_r = \theta_i$, Eq. (3) can be simplified as

$$C_{att}^2 - T \cdot C_{att} - R = 0$$

Solving this equation

$$C_{att} = \frac{T + \sqrt{T^2 + 4R}}{2} \tag{4}$$

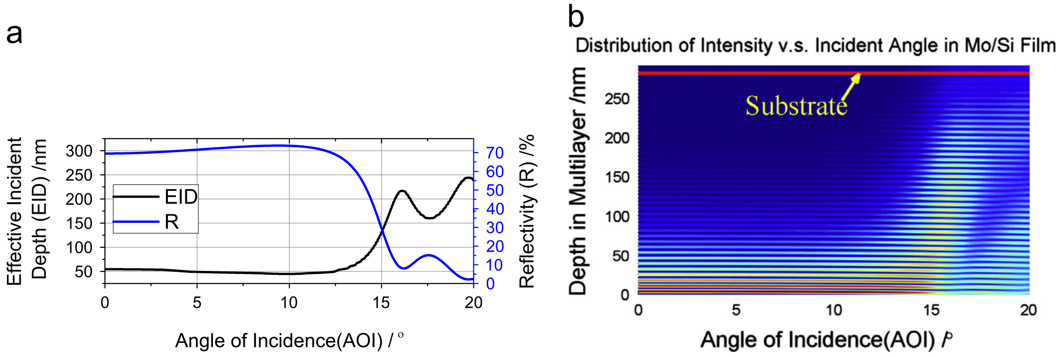

Fig. 2. (a) Reflectivity and effective incident depth (EID) curves of a typical Mo/Si multilayer coating vs. the angle of incidence (AOI) with $\lambda = 13.5$ nm; (b) Electromagnetic field distribution vs. AOI in films with $\lambda = 13.5$ nm.

According to the definition of the attenuation factor noted previously, with Eq. (2) in integration form, when $I_{s\ 0}$ propagates to the EWS, C_{att} can also be represented as:

$$C_{att} = \frac{I_s(z = EWS)}{I_{s0}} = \exp\left[-\frac{4\pi}{\lambda}\int_0^{D'} k(z, \theta_i)\, dz\right] \tag{5}$$

in which λ is the operating wavelength, D' is the EID and k is the distribution of the extinction factor. $I_s(z = EWS)$ is the intensity characterized at the EWS in Fig. 1(b). We can find D' according to Eqs. (4) and (5) through numerical or analytic methods. In this way, the rudiment of EWSE is connected to the specifications of film through C_{att}.

2.3. Updating the model

As noted previously, for the smooth production of EWSE model from the basic EM theory, the two issues enumerated above is retaken into account in this section. Some updates of D' are necessary for the EWSE model to be more reasonable and accurate.

In general, outgoing energy decays exponentially as the propagation path increases linearly as shown in Eq. (2). The physical propagation path (D') without consideration of multi reflections between layers must be amplified than the geometrical incident depth (D'') to account for multi reflections. With R' being the reflectivity between layers in films, the amplification must be only related to R'. The larger the R', the larger amplification will be. Therefore, we define the relationship between D' and D'' as $D'' = D'/f(R')$. The relationship between energy decay(C_{att}) and propagation path is exponential and R' indicates the reconstruction of energy transfer path, Therefore, we believe that the relationship between D'' and D' induced from R' should be exponential as well. In other words, $f(R')$ should be in exponential form. From all of the above, we get $D'' = D'/\exp(R')$, i.e.

$$D'' = D' \exp(-R') \tag{6}$$

On the other hand, some of the light related to film surface reflection R_0 did not go through the EID as predicted by Eq. (2). This was because of the reflections backward to the vacuum in advance. This makes D'' larger than the real incident depth. Therefore, the amendment is shown as

$$D = (1 - R_0)D' \exp(-R') \tag{7}$$

The theoretical derivation of our EWSE model proved to be a successful way of finding the effective incident depth of light in multilayer-coating. The complex interference effect in multilayer can be transformed into brief geometrical optics with an equivalent working surface. As shown in Fig. 2, a typical EUV reflection-enhancing Mo/Si multilayer film revealed data related to energy modulation from the EWSE model. The film is designed for a 5° incident angle with 40 periods, with a periodic thickness of 7.02 nm, and Γ of 0.4 (the thickness ratio of Mo to the period) [12]. Fig. 2(a) shows the reflectivity and EID of the film, which varies according to the AOI. It is evident that the EID varies with the AOI-based change of reflectivity synchronously and sensitively, but with opposite trends. A comparison of the electromagnetic field distribution to the AOI in the film is shown in Fig. 2(b) [13]. This shows good agreement with the EID results in Fig. 2(a). When the EID increases, more energy goes into the film and less is reflected back to the vacuum. In addition, the other two wavelengths (266 nm and 632.8 nm) have been applied to the Mo/Si multilayer, too. The FDTD results also show good agreement with our predictions from this model without the limitation of a low AOI.

Table 1
AOI distribution within the respective clear apertures of primary (M1) and secondary (M2) mirrors of the Schwarzschild EUVL projection system.

Mirror	Angle variation	Mean angle
M1	2–8°	5°
M2	0.6–1.9°	1.25°

Table 2
Three sets of Schwarzschild projection system with/without different coatings.

Mirror	Set 1	Set 2	Set 3
M1	N	U	G
M2	N	U	U

N, no film; U, Uniform film; G, graded film [16].

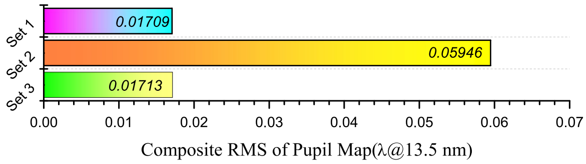

Fig. 3. Composite RMS of pupil map (λ@13.5 nm)of the three POs with/without different coating solutions.

3. Application and discussion

Films have been widely used as an energy modulation tool in the modern optical system to achieve unique energy modulation [14,15]. This can significantly affect the modulation function of some ultra-high precision imaging systems, such as lithography projection objectives (POs). In this study, we used a Schwarzschild projection for EUV lithography research to explain the energy modulation of different films with the EWSE model.

The reflectivity of Mo/Si multilayer is known to be highly dependent on AOI and its period. Table 1 details the AOI of the EUV lithography PO for the multilayer selection. For an ultra-small exposure field, the bandpass of the AOI at each point in the mirrors is close to 0°. Therefore, it is not shown in the table. To show the difference between the none-coated/ bare system Set 1, the last two sets of differently coated POs in Table 2 were analyzed with EWSE model to illustrate the different effects of films. The main steps are outlined below:

- Tracing the full angle information within the clear apertures (CAs) of M1 and M2, respectively;
- Calculating out the EID distribution EID(r) where *r* is radial axis of CAs;
- Identifying the EWSs of coated mirrors by adding ATs to the substrates through high precision algorithm (fitting error$\sim$1E$-$12 mm RMS).
- Optimizing the mechanical alignment variables and estimating the equivalent coated system with CODE V.

Differently coated Set 2 and Set 3 were compared with the diffraction-limited bare Set 1, as shown in Fig. 3. Results show that, when the primary mirror M1 is coated with optimal graded film, the energy modulation of the film can be compensated for completely by the focus shift. On the other hand, the image of Set 2 with the uniform multilayer film-coated M1 was not recovered and could not meet application needs.

A small exposure field Schwarzschild projection is only used for basic research. However for high volume manufacturing, industrial EUV lithography projections with large arc exposure fields and high NA must be adopted. Therefore, the AOI of a mirror is complex: (*a*) the bandwidth of AOI of chief rays over the whole mirror is about 20° at most; and (*b*) the bandwidth of AOI at each point in mirror may reach 8°(generally for the fifth mirror in a 6-mirror EUV lithography projection[17]). According to the EWSE model, the EWS will vary at a single point in the mirrors which can be confusing. In this situation, we can clarify by using the conception of instantaneous clear aperture (ICA) referred to in Ref. [18].

The ICA is the footprint of beams ejected from a single field point on a mask. The union of ICAs of the all field points is the CA of each mirror. Drawing on the experience of optical design, we can estimate the image quality of each typical field point. The corresponding equivalent system for each field point can be built from the information of AOI and coordinates in the ICA based on the EWSE model. Then the estimations in both aberration and exposure uniformity in field can be accomplished with optical design software. For any field point, the equivalent system is unique, regardless of the others. Therefore, this study showed that the EWSE model is suitable for use in estimation for advanced projections with more complex AOIs.

4. Conclusion

This study developed a method for accurate and intuitive analysis of coated systems. Specifically, we proposed a novel equivalent working surface model (EWSE) based on the energy conservation principle from electromagnetic field theory. The EWSE model turns a multilayer with multi-interface into a single equivalent working surface in terms of the energy modulation function of the film. Therefore, interference is transferred into brief geometrical optics, eliminating confusion. Combined with optical design softwares, various film coated Schwarzschild systems were estimated and optimized more easily and intuitively. Results show that, compared with bare system, the system with an optimized graded film coated primary mirror can be recovered via image defocus without obvious image degradation, but not vice versa with uniform film. This proves the validity of the EWSE model. And the results can be applied to direct the integration of the system. With the aid of ICA, each point in the FOV will has its own equivalent system, and can be estimated independently. Thus, this study demonstrates that the EWSE model is applicable for industrial EUV Lithography projections with high NAs and large FOVs.

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