Construction of a High Frequency and High Reflectance Shutter for a Direct Write EUV Lithography System

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Abstract: Extreme ultraviolet lithography (EUVL) is widely seen as a key technology for future semiconductor mass production. However, due to the short wavelength material properties of EUV, it is strongly absorbed by most materials. Thus if the shutter for a lithography system operates by means of absorption, one must consider the potential temperature rise due to the high energy radiation absorbed by the structure. In this paper, we propose using a high-reflectance shutter so as to resolve temperature-related precision problems in lithography systems. A single-layer molybdenum film is used to greatly reduce the quantity of absorbed radiation energy by the shutter structure (in line with Fresnel equation) by increasing the incidence angle. A green laser is used as the light source to construct an automatic measuring system for reflectance and transmittance to verify the increase of material reflectance by the incidence angle of the photosource. The obtained incidence angle is also be fixed on the multilayered piezoelectric to serve as an actuator, so as to measure the high-frequency echoed signal of the laser photosource. Results show that, when the incidence angle is 83° , the optimum energy reflectance (50%) is obtained and the switching frequency reaches a maximum of 19 kHz, verifying the feasibility of using the reflected energy as the photosource switch. Finally, experiments were conducted in Taiwan's National Synchrotron Radiation Research Center (NSRRC) using EUV as the photosource to measure the reflectance curves of single-layer molybdenum and aluminum films with different thicknesses under different incidence angles. Experimental results show that a high degree of reflection can be produced by the proposed single-layer film structure given a large incidence angle. The reflectance also increased significantly at an incidence angle of 60° for molybdenum while 70° for aluminum, and this relatively high reflection by molybdenum with a smaller incidence angle can be used to facilitate lithography system construction.

Keywords: EUVL; shutter; absorption; reflectance; incidence angle; single-layer film shutter

Introduction

The rapid development of the semiconductor industry requires lithography processes at nano-scale line widths. Extreme ultraviolet lithography (EUVL) is widely seen as a key next generation lithography technology for printing circuits at the 32nm node and below in high volume manufacturing (HVM) environment fabs [1]. In 1996 Henry I. Smith used an array of Fresnel zone plates and matrix-addressed micromechanical shutters to turn individual x-ray beam on or off in response to commands from a control computer. Mechanical issues and material

properties related to the shutter will affect the beam dose and energy control in the EUVL system, making it a key component in EUVL systems [2, 3]. The primary purpose of this paper is to efficiently use EUV radiation energy to achieve appropriate switching motion. However, short wavelength EUV photosource can be absorbed by most materials strongly [4, 5]. Therefore, manufacturing a shutter for a lithography system by means of absorption must consider potential temperature rise due to high radiation energy absorption by the structure, which also produces interference which will result in pattern placement errors and image blurring during exposure [6, 7]. This paper proposes a method by which to replace material absorption with

high reflectance, thus preventing loss of exposure system precision due to photoswitch-related temperature rise in lithography systems [7]. Given the differences between the application of photoswitch and that of photomasks and condenser mirrors (which must adopt a vertical angle for incidence), and to reduce the shutter mass to achieve the high frequency photoswitch [8], this paper uses a single-layer film structure and incidence via an oblique angle to greatly reduce the level of radiation absorbed via the principle of perfect reflection.

Design Theory and Reflector Plate Simulation

Reflector plate theory

Refractive index

Refraction often occurs when lights pass through the border of two different media, thus producing interactions among different particles in the media. Given a plane electromagnetic wave in an ideal interface, (i.e., the interface between the two semi-infinite media), the complex refractive index of the wave with a short wavelength (e.g., EUV) on common materials can be expressed as follows:

$$\tilde{n} = n + i\beta = 1 - \delta + i\beta = 1 - \frac{N_0 r_e \lambda^2}{2\pi} (f_1 - if_2), \quad (1)$$

wherein n is the real part of complex refractive index. β is the extinction coefficient, i.e., the imaginary part of complex refractive index. N_0 is the number of atoms in each unit of volume. r_e is the classical electron radius. λ is the wavelength of incident light and f_1, f_2 are the tomic scattering factors.

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Single-boundary reflection and transmission coefficients

Based on the Maxwell equations and boundary conditions, the Fresnel equations of the reflection and transmission of electromagnetic waves in different boundaries can be deduced, thus the Fresnel reflection and transmission coefficients can be defined. Generally, the incidental electric field can be divided into two linearly polarized lights with mutually perpendicular polarizations; the polarized light of the vertical incident plane is called S-polarization, while that of the parallel incident plane and called P-polarization. The Fresnel reflection and transmission coefficients are as follows [9]:

Reflectance:

S-polarization:
$$r_{12}^s = \frac{\tilde{n}_1 \cos \alpha_1 - \tilde{n}_2 \cos \alpha_2}{\tilde{n}_1 \cos \alpha_1 + \tilde{n}_2 \cos \alpha_2}, \quad (2)$$

P-polarization:
$$r_{12}^p = \frac{\tilde{n}_1 \cos \alpha_2 - \tilde{n}_2 \cos \alpha_1}{\tilde{n}_1 \cos \alpha_2 + \tilde{n}_2 \cos \alpha_1}. \quad (3)$$

Transmittance:

S-polarization:
$$t_{12}^s = \frac{2\tilde{n}_1 \cos \alpha_1}{\tilde{n}_1 \cos \alpha_1 + \tilde{n}_2 \cos \alpha_2}, \quad (4)$$

P-polarization:
$$t_{12}^p = \frac{2\tilde{n}_1 \cos \alpha_2}{\tilde{n}_1 \cos \alpha_2 + \tilde{n}_2 \cos \alpha_1}, \quad (5)$$

where n_1, n_2 are the refractive indexes of the two media, α_1, α_2 are the incidence angle and refracted angle respectively, α_2 is determined by Snell's law:

$$\tilde{n}_1 \sin \alpha_1 = \tilde{n}_2 \sin \alpha_2,$$

as shown in Figure 1.

Figure 1. Schematic diagram of single-boundary refraction and reflection.

Reflectance and transmittance of multi-layer film

Given the reflection and transmission coefficients of the N-layer film shown in Figure 2, the reflection coefficient of Layer-i is [10]:

$$r_i = \frac{r_{ij} + r_j e^{2i\beta_j}}{1 + r_{ij} r_j e^{2i\beta_j}}, \quad (6)$$

and the transmission coefficient is:

$$t_i = \frac{t_{ij} e^{2i\beta_j}}{1 + r_{ij} r_j e^{2i\beta_j}}, \quad (7)$$

where $\beta_i = 2\pi d_i \tilde{n}_i \cos \alpha_i / \lambda$ & d_i is the thickness of Layer-i.

Next, the reflection coefficient r and the transmission coefficient t of the last layer can be calculated via iteration, hence the reflectance is:

$$r = |r|^2, \quad (8)$$

and the transmittance is:

$$T = \text{Re} \left\{ \frac{\tilde{n}_s \cos \theta_s}{\tilde{n}_o \cos \theta_o} \right\} |t|^2. \quad (9)$$

Figure 2. Schematic diagram of reflectance and transmittance of multi-layer films.

Simulation of reflectance and transmittance of green laser

This experiment explores the feasibility of producing reflectance by increasing the incidence angle. The photosources (EUV or laser) used are all electromagnetic waves which comply with the Fresnel reflection and transmission coefficients (indicating the specific value of electric fields) to form a square relationship with light intensity when traveling in media of different refractive indexes. Thus the above-mentioned Fresnel equation is used to stimulate the reflectance and transmittance of the reflector plate against the photosource. Given that most materials absorb EUV strongly, in selecting the material for the reflector plate we chose the reflection method to reduce the amount of energy to be absorbed. To use materials

with similar properties as the reflector plate, we used SiO_2 which exhibits high transmittance towards green laser light. Figure 3 shows a schematic diagram of the reflection and transmission rays of the laser from air to glass. Figure 4 (a) shows the curves of reflectance and transmittance from air to glass, in which R refers to the reflectance and T the transmittance, while s and p indicate the polarization directions. The Brewster angle is formed when the incidence angle is about 55° , where the photosource of the p -polarization direction transmits perfectly without reflection. Figure 4 (b) displays the curves of reflectance from glass to air, where the photosource is incident to the sparse medium from intensive ones. It can be seen clearly from the figure that the perfect reflection will occur when the incidence angle is beyond 43.29° .

Figure 3. Schematic diagram of reflection and transmission rays from air to glass.

Figure 4. Simulation results of reflectance and transmission from air to glass. (a) Laser beam from air incident on the glass, (b) Laser beam transmission from glass to air.

According to the simulation results, the reflected energy of the second layer (from glass to air) contributes to the reflectance of the first layer (from air to glass). The comparison results are shown in Figure 5. Aside from the initially small reflectance of the first layer, other small reflectances are all produced when the energies are incident on the second layer of medium after being refracted by the first layer. Comparison results in the diagram indicate the reflectance curve reflected back to the first layer makes a little contribution. Analyzing the implications represented respectively through the superposition of results, Figure 6 (a) depicts a schematic diagram which accounts for the reflectance of the first layer only, while Figure 6 (b) accounts for both the reflectance of the first and the second layers.

Based on the analysis above, Figure 7 shows the simulation results corresponding to the two conditions in Figure 6, where Figure 7 (a) shows glass absorption where the reflected energies are mutually interfering, while Figure 7 (b) shows the contribution of the reflection of the second layer to the first under ideal conditions.

Figure 5. Comparisons of the contributions of the first and the second layer to reflectance.

Figure 6. (a) First layer reflectance only; (b) reflectance of both the first and second layers.

(a)

Figure 7. Reflectance simulation results. (a) First layer reflectance only. (b) Reflectance of both the first and the second layers.

Simulations of Reflectance and Transmittance of EUV

In lithography systems, short wavelength reflectors are usually applied to the photomask and condenser lens, thus the photosource must be designed to be perpendicularly incident. However, reflectors are manufactured using at least two kinds of materials, and the cycle must be long enough to realize the desired reflectance. [8] designed a multi-layer structure with respective thicknesses of molybdenum and silicon of 2.7 nm and 4.2 nm, with a cycle of 50, to produce a EUV reflector with a reflectance of about 74% when the incidence angle is 0°. Figure 8 shows the resulting reflectance, transmittance and absorbance by simulating the Mo-Si multi-layer film at different cycles in accordance with parameters taken from the literature. Changes in the reflectance curve along with the cycle shown in Figure 8 (a) clearly show that the reflectance at an incidence angle of 0° tends to improve significantly as the number of cycles increases.

This paper proposes using a single-layer molybdenum film to reduce the amount of radiation energy that the structure must absorb by means of incidence via an oblique angle. Simulations use different thicknesses (i.e., 10, 50, 100, 150 and 200nm) single-layer molybdenum films to compare the curves of reflectance, transmittance and absorbance of EUV at different incidence angles. The reflectance is found to be nearly zero when the incidence angle is 0°, and improves remarkably when the angle exceeds 60°. In addition, from the curve tendency, the same effects can also be obtained if the film thickness exceeds a certain threshold. Therefore, to figure out the minimum film thickness required, the molybdenum films with thicknesses of 10, 15, 20, 25 and 30 nm are compared, as shown in Figure 9, with the 30 nm film showing a saturated curve.

Figure 8. Computed results of reflectance, transmittance and absorbance of Mo-Si multi-layer at different cycles.

Figure 9. Simulation results of reflectance, transmittance and absorbance of single-layer molybdenum film with different thicknesses.

Experimental System

Reflectance Measuring System for Green lasers

As for the measuring method, the experiment defines the angle of the laser beam vertically incident on the specimen as 0° , then rotates the reflector plate through the step-motor with $\theta=0.36^\circ$ according to the automatic measuring equation for echoed signals, and controls the position sensing detector on the rotation stage for synchronous rotation with $2\theta=0.72^\circ$ (i.e., incidence angle + reflection angle), thus ensuring that reflected beam stays within the measuring range of the sensing detector. However, due to the mechanical limitations of the optical measurement system, it is difficult to measure the reflected energy near the specimen on which the ray is vertically incident; therefore, the experiment measures the incidence angle of the origin position from 18° to 90° (i.e., the reflected energy is measured from 36° to 180°). After determining the rotational position of the sensing detector and reflector plate, measurements are taken for 0.1 second at a sampling rate of 1 MHz.

Figure 10 shows the experimental structure, in which a green laser is used as the photosource with energy levels of up to about 100 mW. Given that the laser's high energy may exceed the measuring range of the sensing detector, Neutral Density Filters are used to weaken the photosource, and plane convex lenses are used to weaken the initial beam path, whereby the focused spot size is about $150 \mu\text{m}$. In addition, given that most materials are highly adsorbent of EUV and the goal of this paper is to reduce the energy adsorbed by reflection, a SiO_2 with a thickness of $510 \mu\text{m}$ is used as the reflector plate for the experimental system. To increase the distinctiveness of the reflection effects and to differentiate the properties of EUV according to the various materials, in the green laser experiment glass was used to investigate reflectance and transmittance under high transmission conditions.

Figure 10. Framework of measuring system for reflectance and transmittance.

Measuring experiments for reflectance and transmittance with the above-mentioned angles show that the optimum reflection angle results in the highest reflection efficiency. Subsequently, a measuring system for high-frequency echoed signals is designed, as shown in Figure 11, using the same photosource, but prevents excess energy through the iris and by using the objective lens as the focusing lens. The theoretical spot size and the depth of focus can be computed based on a basic theoretical equation, and the ideal working range of the system is the area close to the focal plane shown in the figure.

Figure 11. Framework of experimental measurement system for shutter.

Reflectance Measuring System of EUV

From the simulation result, the effect of high reflectance with low absorbance can only be obtained when the incidence angle of the designed reflector plate exceeds 70° , even given a structure made of a single layer of 30 nm molybdenum. As a result, the complexity of process is reduced along with the quality requirements for the shutter, thus facilitating the future design of high-frequency structures. Similarly, the specular reflection principle (θ - 2θ) in the green laser experiment is also used to measure the variation of reflectance with incidence angle in terms of different film materials (aluminum and molybdenum) and thicknesses (100nm and 200nm) under the EUV wave band. Two materials are compared because aluminum at a thickness of greater than 100nm is often regarded as excellent reflection material for the photosource, but the simulation result reveals that its reflectance of the origin angle is slightly higher than that of molybdenum, as is its absorbance, making it difficult to realize the mechanism design and system assembly. To verify the simulation result, the reflectance measuring experiment was conducted in the National Synchrotron Radiation Research Center (NSRRC), using the BL08A1 to generate

the photosource for the EUV waveband (13.5 nm) in a vacuum of 10^{-9} torr. The experimental set up is shown in Figure 12.

Figure 12. NSRRC BL08A1 EUV reflectance measuring system.

Results and Discussions

Experimental Results of Green Laser Reflex Shutter

Verification Results for Reflectance Measurements

Figure 13 compares the actual measurement results for reflectance and transmittance. The experimental results are found to be similar to the simulated results for the first layer both in terms of the origin angle of reflectance and the curve trend. Moreover, the experimental results show that the P-polarization direction of the photosource is relatively obvious. In addition, given the mechanical limitations for future installations of high-frequency switching experiments, we selected a position with an incidence angle of 83° with a reflectance of 50%.

Figure 13. Experimental results of reflectance and transmittance.

Reflex shutter experimental results

The displacement of the piezoelectric actuator, the focus point size and the initial energy of the green laser must be measured prior to the experiment. However, the travel distance of the piezoelectric actuator is only $18 \mu\text{m}$. Secondly, by fine-tuning the lateral displacement of the 3-axis stage, the focused laser spot can be reflected to the middle of the sensing detector where its diameter

was measured to have a minimum spot size of about $8\ \mu\text{m}$. In addition, the laser's initial total energy was measured about 7.07 V (energy that is directly incident on the sensing detector without any shielding), while the maximum reflected energy averages 3.53 V (i.e., the total reflection energy given the angle). Therefore, when the switching efficiency is 100% (i.e., fully switched on/off), the ideal achievable reflectance is 49.93%.

Figure 14. Experimental picture of green laser shutter.

Figure 14 shows actual images of photosource transmission (a) and reflection (b), with the reflected spot energy accounting for 49.82% of the total reflected energy. The 50% energy loss (i.e. can't be detected) is caused by scattering where the laser beam incident on the side of glass shutter. Figure 15 shows the experimental results of the high frequency switching of the green laser, in which the green curve indicates the input is 1% of the actuator and the red curve is the detected echo signal. The shape, similar to a square wave near the echoed signals, indicates that the energy indeed results in full on/off switching. However, when the piezoelectricity is operated at high frequencies, the output sine wave is not complete, thus the top of the signal is not flattened. As the frequency increases, no phase difference is generated at 0 V. The experimental results are listed in Table 1. The reflectance of the echoed signal is not equal to that of the ideal signals, because it is impossible to fully shield the energy of the photosource from background interference and the edge energy of the laser Gaussian distribution

Figure 15. The experimental results of green laser switching.

Table 1. Experimental results list.

Input frequency (kHz)	1	5	10
Incidence total energy (V)	6.60		
Maximum reflected energy (V)	3.29		
Ideal reflectance (%)	49.82		
Input voltage (V)	42.22	42.28	42.22
Amplitude of echoed signal (V)	3.19	3.23	3.21
Switching reflectance (%)	48.33	48.93	48.64

Experimental results of EUV reflectance

Figure 16 shows the original data of the experimental results. By comparing the origin angle and maximum total energy, the following three points can be verified:

- (1) The origin angle of reflectance of molybdenum is found to be 65° , while that of aluminum is 75° , which coincides with the simulation result.
- (2) Relatively thicker specimens have a larger absorbance in terms of both molybdenum and aluminum, which is consistent with theoretical conclusions.
- (3) The absorbance of aluminum is greater than that of molybdenum, which is consistent with the simulation results for the imaginary refractive index.

Figure 16. Original data of reflected energy for different samples under EUV wave-band.

However, in the experiment with the green laser model, the correct reflectance and transmittance is computed by the obtained echoed and transmitted signals divided by total energy incident on the sensing detector. Due to the time interval of synchrotron radiation in the EUV reflectance experiments, the total energy of the photosource used in the experiment is not measured. Although a specimen is located horizontally at the energy peak during calibrating, considering the

energy of the photosource shielded by the specimen's thickness, the maximum energy during the experiment is used as total energy of the photosource to compute the reflectance.

Figures 17(a) and (b) compare the experimental result (red) and simulation result (blue) of 200 nm Al and Mo specimens. The experimental aluminum result shows that both the increase trends of the curves and the origin angle of reflectance correspond to the simulation result. However, the experimental molybdenum result shows that the reflectance trend increases, but obvious differences are found between the simulation and experimental results. This discrepancy is due to the experiment selecting the maximum energy obtained as the total reflected energy to compute the reflectance, along with inadequate sensitivity of the sensing detector. Thus the low energy change can't be measured and the curve of the experimental results moves backward. Figure 18 shows the original experimental data for 100 nm molybdenum at a low angle. The measurement value is appropriately 0 before the origin angle of reflectance rises. However, integrating the above findings, experiments prove that molybdenum is indeed a preferable reflecting material for the EUV wave-band photosource, and the increasing trend of reflectance can be applied to replace the multi-cycle plated film to reflect EUV energy. The result can be used to solve the problem presented by the high absorbance of the materials.

Figure 17. Comparison of experimental and simulation results of reflectance of Al (a) and Mo 200nm (b) to EUV.

Figure 18. Measuring of reflectance of Mo 100nm to EUV at low angle.

Conclusions

Using a laser as the photosource and glass SiO_2 as the reflector, we constructed an automatic measuring system for reflectance and transmittance. The reflectance increase for various materials was verified via the incidence angles of the photosource. Several experiments were conducted to confirm experimental reproducibility and reliability. The obtained reflection angle (83°) was used to collocate the multilayered piezoelectric to serve as an actuator, using high-frequency AC signals to drive the piezoelectric elements through the power amplifier. This produced high-frequency displacement which served as the switching focus spot. The high-frequency echoed signals of the laser were measured, indicating the feasibility of using the reflected energy as the photoswitch. Finally, NSRRC and EUV beams were used as actual photosources to explore reflectance curves of single-layer molybdenum and aluminum plated films of different thicknesses under different incidence angles. Results showed that reflectance increases significantly when the proposed single-layer molybdenum film maintains a high incidence angle. The results confirm that a high-reflectance shutter can be used to replace the absorbance in lithography systems.

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