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Fabrication antireflection (AR) coatings for P-polarized 193 nm laser light at an incidence angle of 74°

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ABSTRACT

The antireflection coatings for P-polarized light at large incidence angle (68°–75°) are widely used in the ArF excimer laser microlithography light source system and other optical surfaces (e.g., in lenses, prisms, etc.) to suppress undesirable reflections. So the AR coatings for P-polarized 193 nm laser beam at an incidence angle of 74° were designed and fabricated. The results showed that after coating, the residential reflection of the optical components reduced dramatically, which could greatly improve the output efficiency of the optical components in the DUV range.

1. Introduction

The 193 nm ArF lithography technology has been extended to higher resolution below the 22 nm node. So the increasing application of ArF excimer lasers in microlithography results in rigorous requirement for high performance ArF excimer laser light source [1, 2]. The ArF excimer lasers are developed for high output power (>60 W) and frequency (>6 kHz), which makes strict demand on the optical components inside the resonance cavity. These coated components can stand long duration exposure to ultraviolet radiation without significant change in performance. For example, in the line-narrowing-module (LNM) of the ArF excimer laser cavity, the hypotenuse surfaces of the expanding prisms are coated with AR coatings for P-polarized light to reduce the reflectance loss [3, 4]. In order to obtain enough expanding ratio, the incidence angle on the hypotenuse of the expanding prisms needs to be as big as possible. But the residual reflectance loss on the bare substrate could be sufficiently high, and the photons within the resonance cavity will make several round trips within the cavity. Extreme low output efficiency or the failure of the cavity could be a result from these reflectance losses. Considering the increasing difficulty and cost of AR coating processes as the incidence angle goes bigger, the design incidence angles are usually selected between 68° and 75°. The output efficiency and lifetime of the ArF laser cavity are determined by the performance of these AR coatings. So AR coatings for P-polarized 193 nm laser beam at an incidence angle of 74° (P74degAR coatings for short) were designed and fabricated here, and their optical performance was tested and analyzed.

2. Experiments

The P74degAR coatings were deposited using the molybdenum boat evaporation method in a Leybold SYRUSpro 1110 DUV batch coater. The chamber was pumped out to a base pressure less than 2×10^{-6} Pa before the evaporation process started. Lanthanum fluoride (LaF_3) and magnesium fluoride (MgF_2) were used as 'H' and 'L' materials (H, L stand for 'quarter wave' layer thickness). Excimer grade CaF_2 (111) (RMS <0.3 nm) was used as substrates. The substrates and the chamber were conditioned with reactive plasma pretreatment. This pretreatment was applied to remove residual water vapor and hydrocarbons. Deposition temperatures were set to 300 °C, film thickness and deposition rates (0.6 nm/s) were controlled by a quartz crystal sensor.

At first, the single layers are deposited and analyzed to obtain the optical constants. Then the P74degAR coatings are designed on the basis of the calculated optical constants. The optical characteristics (residual reflectance, angle resolved reflection (ARR), transmittance, and angle resolved scattering (ARS)) of the P74degAR coatings were analyzed by a vacuum ultraviolet (VUV) spectrometer (ML 6500 Metrolux) [5]. The spectrometer is designed to determine the transmission, reflection characteristics of optical components in the range from 115 nm to 300 nm using non-polarized or polarized light. This device was purged continuously with N_2 ($>99.999\%$) gas

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to avoid the absorption of oxygen, moisture and organic contamination in the DUV range. The structural properties of the P74degAR coatings were evaluated through observation of top-view images of AFM measurements. A laser calorimeter (Laser Zentrum Hannover) was used to determine the absolute absorption of the coatings [6]. At last, laser resistance tests were carried out to verify the laser resistance.

2.1. Optical constants

The LaF_3 layers usually have a rough surface and many holes or nodular defects inside the layer due to their inherent growing characteristic, which result in high absorption and scatting losses [7]. So the optical characteristics of high index LaF_3 material play a very important role in the 'HL' muti-layers system. Consequently, the precise optical constants (refractive index and extinction coefficient) of LaF_3 are also more difficult to obtain because of its inhomogeneity. A first order bulk inhomogeneity (Schroeder model) was assumed and the thin film software Optilayer' OptiChar part was used to calculate the optical constants of LaF_3. This model implies that the film refractive index changes linearly from the film substrate side to the film ambient side.

It can be discerned from Fig. 1(a) the fitting comparison of the reflectance curves of LaF_3 single layer with and without inhomogeneity, that obviously the LaF_3 material exhibited a negative inhomogeneity (the refractive index decreased as the film thickness increased). Fig. 1(b) shows that the refractive index varies with the thicknesses of LaF_3 single layer, different thickness of LaF_3 single layers give different optical constant results, because the surface mobility of LaF_3 molecules is particularly sensitive to temperature, deposition rate, substrate surface quality and so on, and the LaF_3 film becomes inhomogeneous with increasing thickness [8]. So the refractive index of LaF_3 was carefully chosen and modified according to the required coating thickness during the deposition process. The refractive index of MgF_2 can be obtained through the normal dispersion model. The refractive index (n) and extinction coefficients (k) of LaF_3 and MgF_2 films at using deposition parameters are shown in Table 1.

2.2. Coating design

It is difficult to fabricate AR coatings for P-polarized laser light at oblique incidence; especially at large incidence angle (larger than the Brewster Angle) the reflection reduction efficiency of the stack of quarter-wave layers is reduced dramatically, so that the required number of layers is substantially increased and the thickness and density tolerance on each layer is greatly tightened.

The P74degAR coating was designed bases on the optical constant results as follows: sub/43.7 nm (L), 30.1 nm (H), 50.2 nm (L), 30.1 nm (H), 50.3 nm (L), 30.0 nm (H), 2.2 nm (L)/air. This design concentrated on low residual reflection, high transmittance, and high laser-induced damage threshold (LIDT).

In Fig. 2(a) the diagrams reveal that the P-polarized laser light penetrates throughout almost all the layers without much attenuation. So to reduce the absorption effect of P74degAR coatings, the thickness of the high refractive (LaF_3) material has been designed to a minimum, with overall layer thickness of the high refractive layers of about 90 nm. Fig. 2(b) shows the comparison between 'standard 1/4 design' and 'modified design'. After adjusting the thickness of 'HL' materials, the light path of P-polarized laser in the H material is shorter and the electric intensity is lower than in the 'standard 1/4 design'; the energy burden was shifted to the low material (MgF_2), which could also increase the LIDT. A MgF_2 layer with thickness about 2 nm was used as the last layer to make a smoother surface.

3. Results and discussion

3.1. Reflection and transmission

The reflection and transmission results were from wedge and flat CaF_2 coating samples separately in the same coating batch process. As showed in Fig. 3(a) the residual reflection of P-polarized light at an incident angle of 74° was below 2.3% in the range of 188–195 nm, and achieved the minimum value of 2.0% around 193 nm (about 9.0% in bare substrate). The transmission of the P74degAR coatings including backside reflection was about 86.5% at 193 nm. The single side transmission of the

Table 1
The optical constants of LaF_3 and MgF_2.

Material	n (@193 nm)	k (@193 nm)
CaF_2	1.502	0
LaF_3	1.702	0.00325
MgF_2	1.421	0.000496

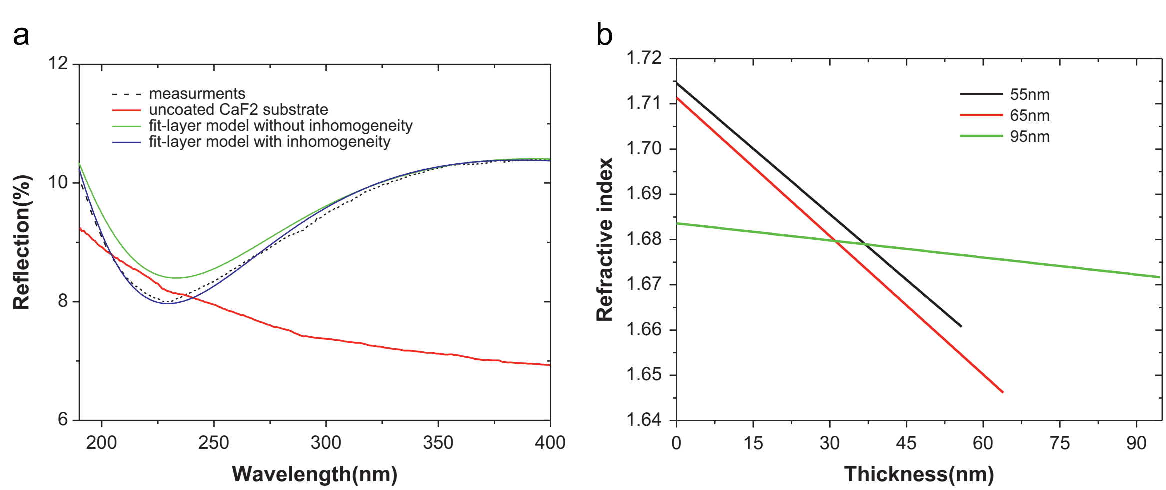

Fig. 1. Reflectance fitting curves of LaF_3 thin films on CaF_2 (a) and refractive index varies with the thickness of LaF_3 single layer at 193 nm (b).

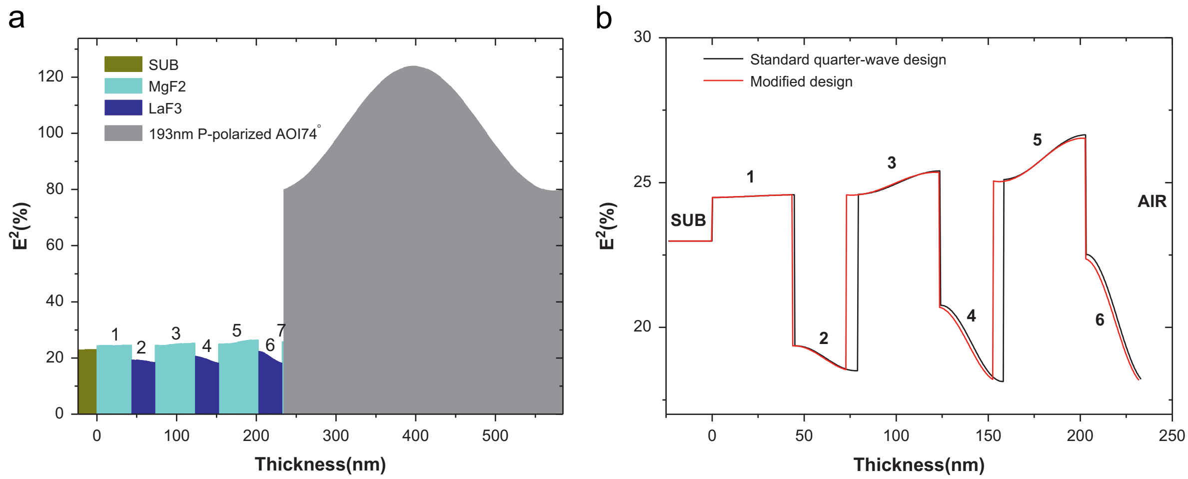

Fig. 2. Electric field distribution in the P74degAR coatings (a) and electric field distribution comparison between 'standard quarter-wave design' and 'modified design' (zoom in) (b).

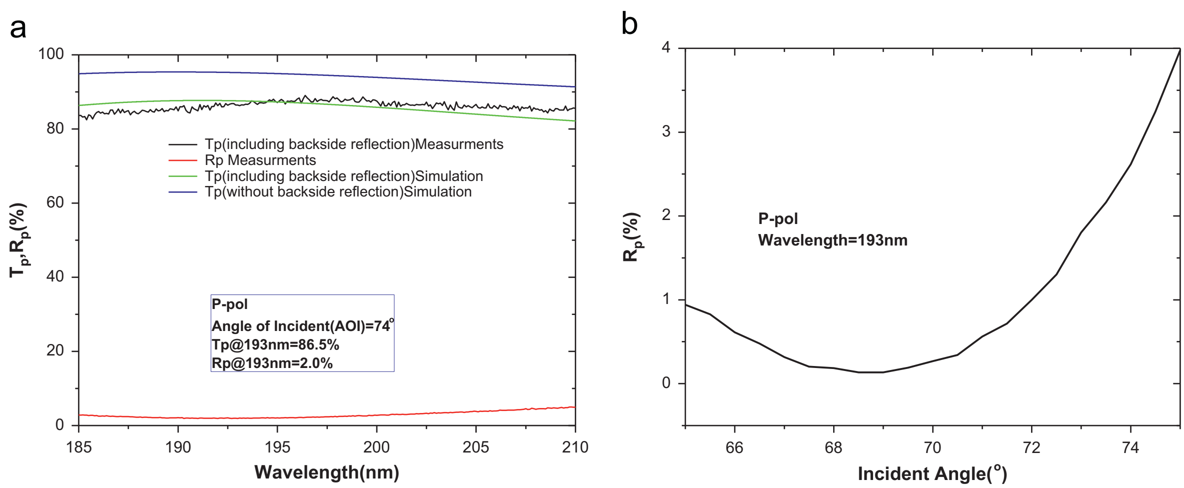

Fig. 3. Residual reflection (a) and angle resolved reflection (ARR), (b) spectra of the P74 degAR coatings.

P74degAR coating was about 95.2% at 193 nm deduced from the theory (about 90.6% in bare substrate).

The angle resolved reflection (ARR) method was applied to test the P-polarized AR coatings for AOI tolerance from 65° to 75°. It is impossible to make the residual reflection minimum at 74° in the angular curve because of the large incidence angle. The R_p value increases sharply as the incident angle becomes bigger. It can be discerned from Fig. 3(b) that in the case of deviations of $\pm 1°$ from the optimal angle of incidence 74°, the P74degAR multilayer system's residual reflection was lower than 3.9% in the angle range between 73° and 75°. The minimum residual reflection is at an AOI of approximately 66°–71°, and the residual reflection is less than 0.5% in this range.

3.2. Absorption and scattering

Unfortunately, there are no instruments available for absorption or scattering measurements for oblique incident at the wavelength of 193 nm.So we evaluate the optical losses of the P74degAR coatings through other methods. The absorption test was carried out in the laser calorimeter system, by using normal incidence of the ArF laser beam [9,10]. The irradiation was carried out at the wavelength of 193 nm with a fluence of 1.58 mJ/cm^2 and a repetition rate of 1 kHz. The heating and cooling time was set to 120 s and 560 s, respectively. The absorption measurement

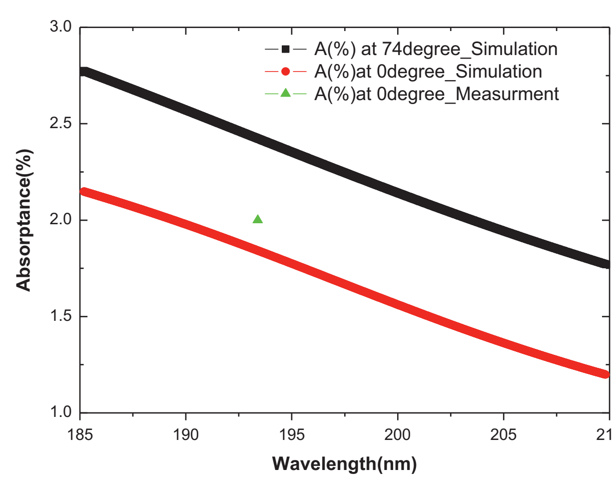

Fig. 4. Laser absorption results of the P74deg AR coatings.

results of the P74degAR coatings and bare substrate obtained in the case of normal incidence are, respectively, about 2.3% and 0.3%, separately. So the absolute absorption of the P74degAR coatings in the case of normal incidence is about 2.0%.

As showed in Fig. 4 the deviation between simulation results from the software (Optilayer' Optilayer part) and measurement value was less than 0.3%. The absolute absorption of this coating system for P-polarized 193 nm laser beam at an incidence angle of 74° deduced from the simulation curve is about $(2.4 \pm 0.3)\%$ (2.47% in theory). Further analysis of the absorption of the P74degAR coatings from Optilayer' Optilayer for each layer (layer 1–7, from substrate to air, respectively) is displayed in Fig. 5; the main absorption is caused from LaF_3 and the layers closer to the air have higher absorption because of the electric intensity going stronger toward the layer–air interface direction.

The structural properties of the P74deg AR coatings were evaluated through observation of top-view images of AFM measurements. The microtopography of the P74degAR coatings observed at different positions in 1 μm × 1 μm scan areas is displayed in Fig. 6(a) and the average of the RMS roughness was about 1.2 nm. With the method angle resolved scattering (ARS) of VUV spectrometer, as showed in Fig. 6(b), the scattering characteristic of the test samples can be investigated. The ARS measurements are normalized to the incident power.

There is no strict form solution for the scattering of muti-layer coatings except for a few extreme cases; the total scattering (Ts) loss can be approximated by the formula as [11]

$$Ts = 2\pi \int ARS(\theta_s)\sin\theta_s d\theta_s$$

In this case, the total scattering is less than 5×10^{-3}. However, based on the analysis above, we can get a qualitative conclusion: optical loss of the P74degAR coating comes almost from the absorption. However, as high incidence angle AR coating this optical loss is inevitable due to the effects of strong absorption in the DUV range. A summary of the optical characteristics of P74deg AR coatings is listed in Table 2; we can see that the effective optimization goal of P74degAR coating is to lower the absorption of the LaF_3 materials.

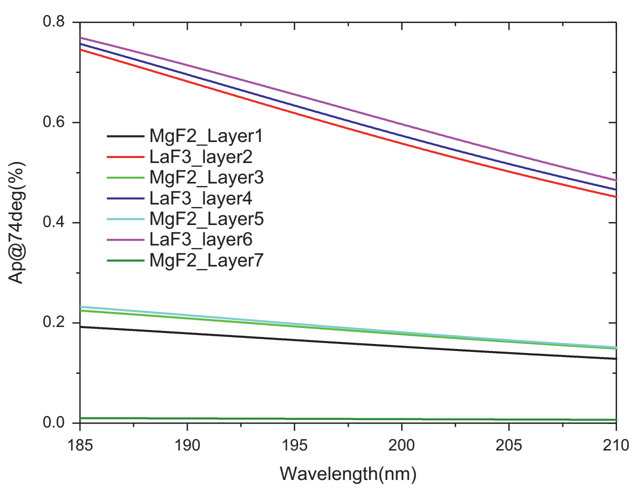

Fig. 5. Absorption of the P74deg AR coatings for each layer.

3.3. Stability and endurance test

The spectrum measurements were performed as deposited and repeated several times within one month. UV cleaning was performed before each measurement. In Fig. 7 we can see that the optical performance of this AR coating is very stable. The resident reflection at the working wavelength of 193 nm hardly changes within a month (from 2.0% to 2.1%), and the slight wavelength shift to the longer wavelengths is about 1 nm.

Laser resistance tests were carried out using laser pulses with energy densities of approximately 25 mJ/cm^2, after millions of shots, the P74degAR coatings show no layer degradation, tears, or other degradations, which verified the laser resistance of this coatings.

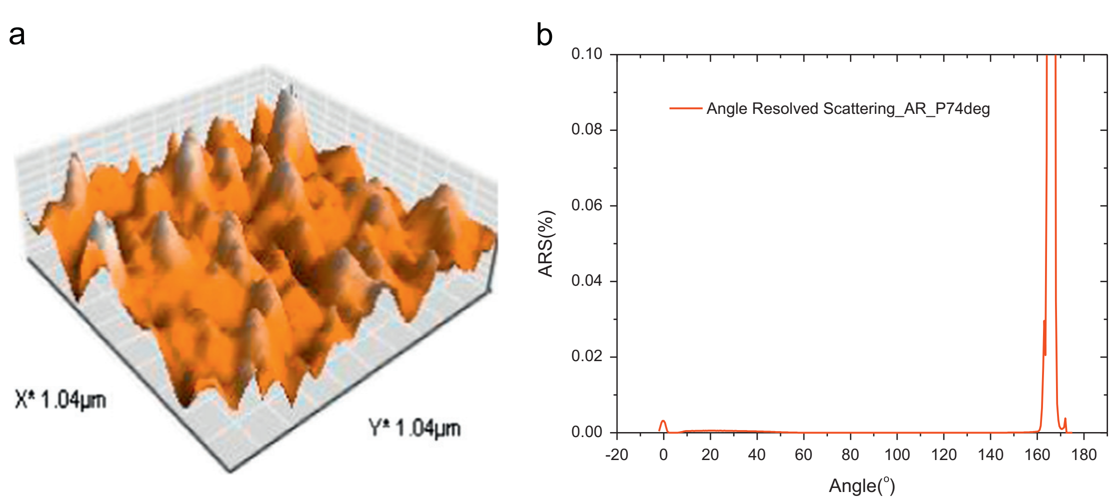

Fig. 6. AFM top view of P74deg AR coating (a) and angle resolved scattering (ARS) of P74deg AR coating (b).

Table 2
Optical characteristics of P74degAR coatings.

Sample	States	Reflection (%)	Transmittance (%)	Absorption (%)	Scattering (%)	Total (%)
P74degAR coatings	$\lambda = 193$ nm, P-pol, AOI = 74°	2.0 ± 0.5	95.2 ± 0.5	2.4 ± 0.3	$< 5 \times 10^{-3}$	100.1 ± 0.5

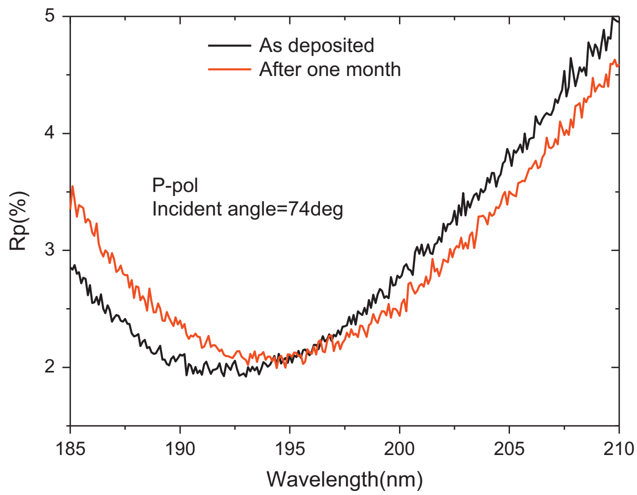

Fig. 7. Long term stability of P-polarized AR coatings for an angle of 74° at 193 nm.

4. Conclusions

The results showed that the P74degAR coatings have good spectral characteristics, long term stability and laser endurance. After coated with the P74degAR coating, the reflectance loss for P-polarized ArF lasers incident upon the bare optical surfaces at 74° is reduced from 8.8% to 2.0%. So the reduction effect of on the optical components surfaces effect is obvious. The impact of this improvement is a significant enhancement in laser output efficiency and lifetime of the laser cavity.

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