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Multilayer Coatings for the EUVL Front-End Test Bed

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Abstract

Good illumination uniformity at the mask and wafer planes, and high wafer throughput in the EUVL front-end test bed facility at LLNL require graded period multilayer (ML) coatings on several of the optics. The ML deposition was accomplished using a newly developed deposition technique which avoids the use of "uniformity masks" to define the spatial dependence of the ML period variation. The capabilities of the process in providing the specified ML coatings are discussed for both EUVL condenser and imaging systems.

Introduction

The EUVL front-end test bed facility at Lawrence Livermore National Laboratory (LLNL) is an eight-bounce, reflective, EUV optical system designed to evaluate the influence of illumination strategy on the imaging properties of an EUVL exposure tool[1]. The system combines a 3-element Kohler illumination condenser, a reflection mask and a 2-element, four bounce imaging system. Efficient radiation transport requires that the optical response of each element be well matched to the rest of the system: i.e. the optical pass band of each reflective element must be matched to within ± 0.25Å[2]. In the Kohler condenser, the preservation of high radiation transport efficiency and uniformity of illumination at the wafer plane provide the criteria for evaluating condenser performance. Optimum performance is achieved in a design which requires identical, uniform multilayer (ML) coatings on 2 of the elements and a laterally graded ML coating on the third[3]. For the imaging system, the ML coated optics must provide adequate radiation transport and diffraction limited performance[4]. This can be achieved by uniformly coating each of the individual optical elements of the imaging system. However, the individual optics require unique ML coatings; the average angle of incidence of the EUV radiation on each optic determines the appropriate ML period. Providing a ML coated optical system conforming to these requirements represents a significant technical challenge.

Coating specifications

Kohler condenser

A schematic of the Kohler condenser system is illustrated in Fig. 1. It contains three spherical optical elements C1 through C3. Both C1 and C3 have limited angular acceptance and operate near normal incidence. C2 operates over a wider range of incidence angles and requires a graded ML coating.

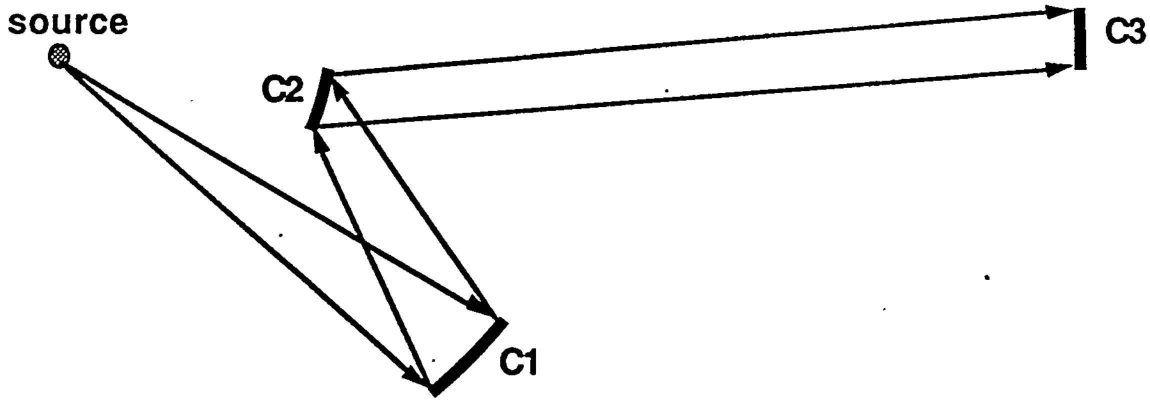

Figure 1. Schematic of the LLNL front-end test bed Kohler condenser system.

Fig. 2 illustrates the symmetry and magnitude of the required ML period gradient for the C2 optic. Contours of constant wavelength response are circles centered on the optical axis. The gradient in the wavelength response in the radial direction is of order 0.1Å/mm and the wavelength of maximum reflectance varies between 130 and 134Å over the optical surface.

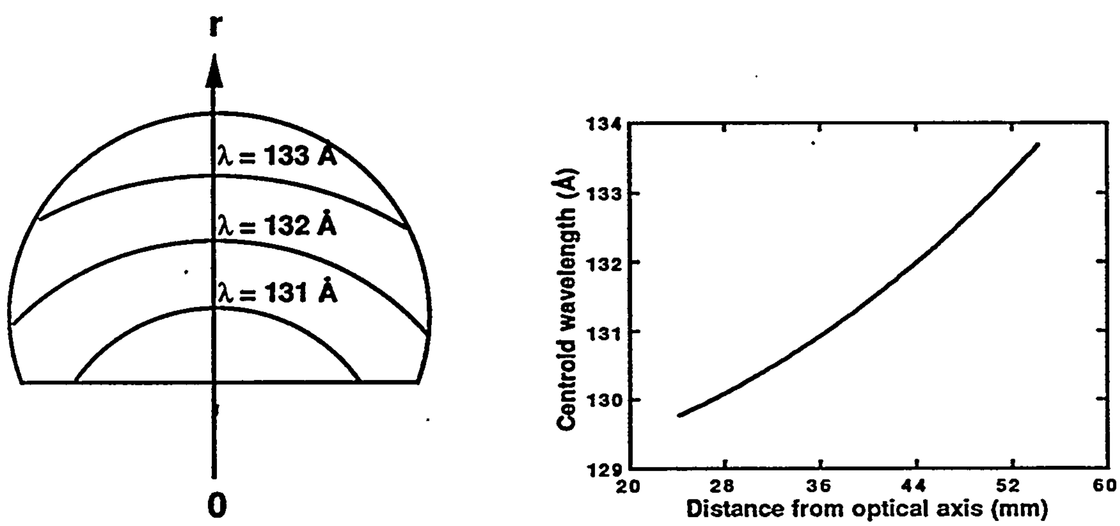

Figure 2. The normal incidence reflectance response required for the ML coating on condenser C2. The graph illustrates the specified wavelength response in the radial direction as a function of distance from the optical axis (0).

Imaging system

In Fig. 3 a schematic illustration of the four-bounce two element imaging system is shown. For each optic, the variation in the incidence angles for both reflections are similar and a uniform ML coating is sufficient. Differences in the average angle of incidence for each optic are accounted for by offsetting the optical response of each element by 0.5Å. This corresponds to a difference of 0.25Å in the ML period of the two coatings.

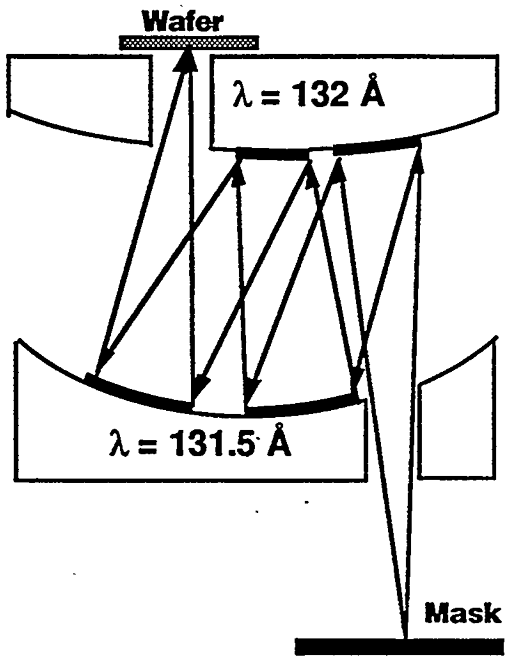

Figure 3. Schematic diagram for the LLNL front-end test bed imaging system.

Coating Technique

Geometrical effects arising from self shadowing, variations in source-substrate distance and angle of incidence can combine to produce spatial variations in the ML period of coatings deposited on curved surfaces that are absent on flat substrates. Consequently, the fabrication of a spatially graded ML coating on a flat substrate, and the fabrication of a uniform ML coating on highly curved substrate pose formally equivalent problems. The traditional approach to this class of coating problem is to tailor the deposition profile using shaped apertures and baffles to adjust the deposition profile in the desired manner. This approach has been used by several groups to tailor the ML period variation of EUV optical elements[5,6,7]. Limitations of the approach are manifold and are related to the requirement that effective aperturing requires the mask to be located in close proximity to the substrate. The most accurate results are obtained when the masks are conformal and accurately replicate the substrate geometry. Typically, defining the correct mask geometry is not possible from first principles and a tedious, iterative calibration procedure is required to derive the correct mask configuration for each coating design on a given substrate. We have developed a technique for the production of spatially graded ML coatings that avoids the use of uniformity masks. The method utilizes programmed variation of the substrate velocity as the substrate transits the boundaries of the deposition source.

Consider the situation illustrated in Fig. 4 below where a circular substrate of radius r_o moves in the x direction over a uniform rectangular deposition source producing a flux Φ_o over the region $r_o < x < L$. Assume that the substrate rotates at angular frequency ω, about its center x_{cm}, such that $\omega r_o >> dx/dt$, the substrate translational velocity.

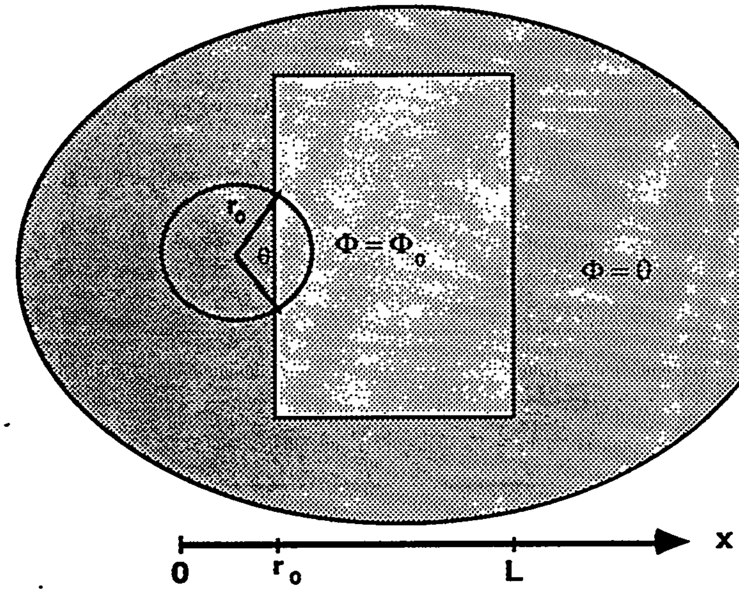

Figure 4. A circular substrate moving in the x-direction transits a uniform rectangular deposition source. The substrate rotates at an angular velocity ω, about its center x_{cm}, such that $\omega r_o >> dx/dt$.

At a substrate position r, the substrate will receive a uniform coating for all x_{cm} satisfying $r_o+r < x_{cm} < L-r$. In the regions $r_o-r < x_{cm} < r_o+r$, and $L-r < x_{cm} < L+r$, the substrate acquires a coating thickness that depends upon the substrate position relative to the boundary. If the substrate resides at a position x_{cm}, for a duration dt', it acquires a coating thickness $\Lambda(r,t')$, given by

$$\Lambda(r,t') = \frac{\Theta(r)}{2\pi}\Phi_0 dt' = \frac{\Phi_0}{\pi}\cos^{-1}\left(\frac{r_0 - x_{cm}}{r}\right)dt' \qquad (1).$$

If the substrate moves from over the region $0 < x_{cm} < L+r_o$, according to the equation of motion $x_{cm} = f(t)$ the substrate will acquire a coating thickness $\Lambda(r)$ given by

$$\Lambda(r) = \Phi_0\left[\frac{1}{\pi}\int_{t_1}^{t_2} dt' \cos^{-1}\left(\frac{r_0 - f(t')}{r}\right) + (t_3 - t_2) + \frac{1}{\pi}\int_{t_3}^{t_4} dt' \cos^{-1}\left(\frac{f(t') - L}{r}\right)\right] \qquad (2)$$

and $x_{cm}(t_1) = r_0 - r, x_{cm}(t_2) = r_0 + r, x_{cm}(t_3) = L - r, x_{cm}(t_4) = L + r$. It is evident that programmed motion of the substrate can be utilized to tailor the coating profile. The ML period variation predicted from Eq. (2) for trapezoidal velocity profiles is shown in Fig. 5. The substrate uniformly accelerates from v_1 to v_2 for $0 < x_{cm}(t) < 2r_o$, and maintains this velocity for $2r_o < x_{cm}(t) < L-r_o$, then decelerates from v_2 to v_1 for $L-r_o < x_{cm}(t) < L+r_o$. The transit velocity v_2 has been adjusted in each case to give a ML period of 70Å at the substrate center. The coating profile is uniform for $v_1/v_2 \approx 1$, and lateral gradients in the

ML period as large as 10Å can be obtained for substrates 50 mm in diameter and velocity ratios $v_1/v_2 \approx 0.1$.

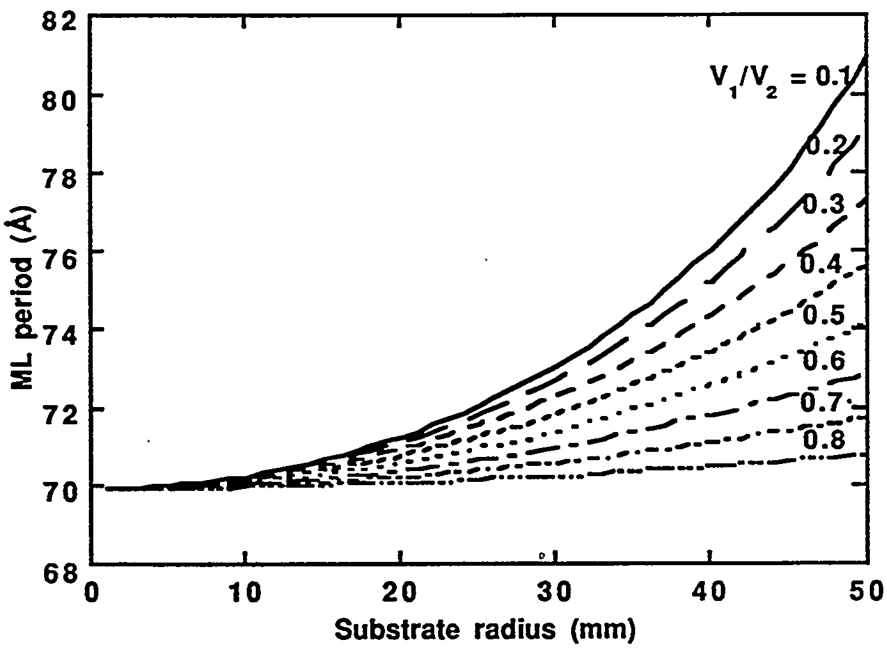

Figure 5. ML period variation from Eq. (2) assuming trapezoidal velocity profiles.

Multilayer Deposition

Mo/Si Multilayer coatings were deposited using dc magnetron sputtering in an Ar plasma. The deposition system and deposition parameters have been described previously[8]. Briefly, it is a cylindrical chamber arranged in a dual source, sputter-up configuration, with the magnetron sources arrayed diametrically on the chamber base-plate. Substrates are held by a platter which rotates sequentially over the two sources to produce the ML coating. The platter can accommodate two substrate carriages and the rotational drive system allows programmed, on-the-fly modification of the substrate transit velocity of each carriage over both deposition sources. This permits simultaneous deposition of structurally distinct ML coatings on each substrate. With this configuration the three condenser optics could be coated in a single deposition cycle. Similarly, ML coatings for the dual element imaging system were deposited in a single coating run.

A series of ML deposition experiments were undertaken to quantify the effects of parametric variation of the substrate motion on ML structure. An iterative cyclic process of ML deposition and at-wavelength characterization of the ML coating was employed to calibrate the deposition conditions for both the condenser and imaging systems. The condenser optics have large radii of curvature and Si wafers were used to tailor the ML coating profiles for the condenser optics. In contrast, the imaging optics are highly curved convex and concave surfaces 78 mm in diameter with radii of curvature of 137 mm; here meaningful calibration could only be accomplished using surrogate replicas that closely approximated the surface figure of each of the imaging optics. Subsequent to characterization the surrogates were stripped of the coating using a reactive ion etch process that permits removal of the Mo/Si MLs without consequential damage of the substrate surface[9], permitting them to be reused in subsequent calibration runs.

Results

The EUV reflectance of each optical surface was determined in a series of point by point measurements at the TGM beamline at the BESSY synchrotron. Briefly, the measurements were performed with a beam divergence of 0.3 mrad, a spot size at the sample surface of 200 μm and a spectral resolution, $\lambda/\Delta\lambda$ = 160 at a wavelength of 13 nm. A detailed description of the facility has been published previously[10]. In Fig. 6 we show the measured spatial dependence of the EUV reflectance of condenser element C2 plotting the centroid of the reflectance maximum in the radial direction vs. distance from the optical axis. The ML coating conforms to the specified wavelength response to within ± 0.5Å. This implies a ML period accuracy of ± 0.25Å.

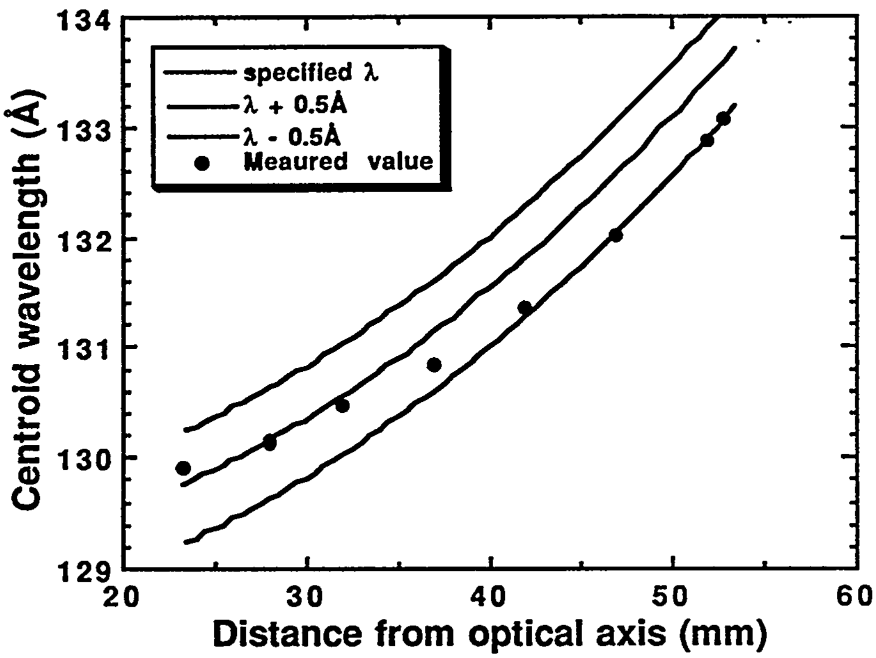

Figure 6. Comparison of the measured spatial dependence of the NIR response at 13 nm of condenser optic C2 with the coating specifications. The ML period variation of the coating conforms to the specifications within 0.25Å.

In Fig. 7 the measured spatial variation of the EUV reflectance of the individual convex and concave elements of the imaging system is shown. The wavelength of the centroid of the reflectance maximum is plotted vs. position on the individual mirror surfaces. The shaded regions indicate variation of ± 0.125Å in the optical response about the specified value for each surface.

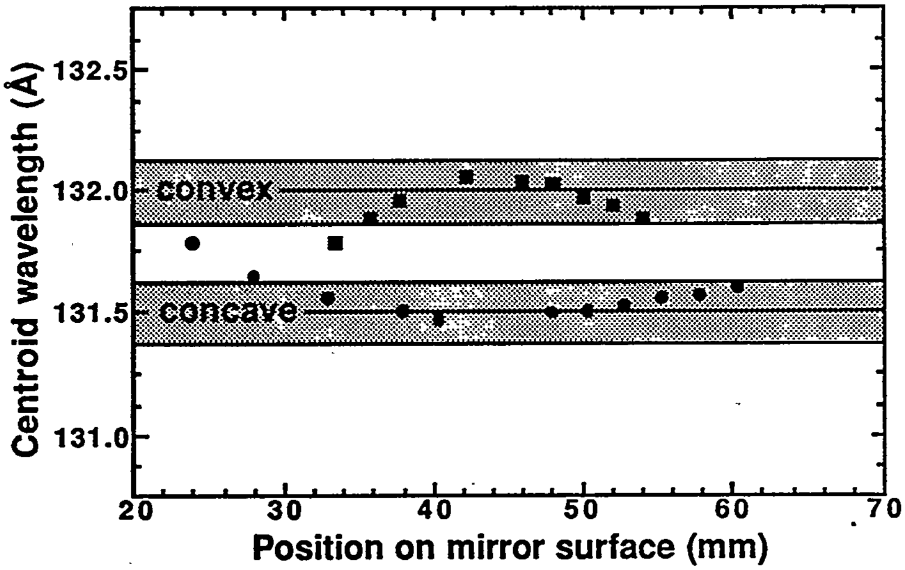

Figure 7. Measured variation in the centroid wavelength response of the individual imaging optics of the LLNL EUVL front-end test bed facility. The shaded regions correspond to an error of ± 0.125Å in the centroid wavelength.

Conclusions

ML coatings for EUVL optics have been fabricated utilizing a newly developed deposition technique which relies upon controlled variation of the substrate velocity over the source boundaries to produce the spatial variation of the ML period. Consequently, the method avoids the shortcomings of conventional deposition techniques that rely upon the use of apertures, masks and baffles to define the coating profile. The method has been employed to provide spatially graded ML coatings required for the Kohler illumination system and uniform coatings required for the highly curved imaging elements. The optical response of the coated elements of the EUVL front-end test bed conform to specifications to better than ±0.25Å.

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