Multilayer facilities required for extreme-ultraviolet lithography

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We have developed a magnetron sputtering system for the deposition of Mo/Si multilayer (ML) coatings onto large-area, figured optics, as required for the imaging system in a practical, extreme-ultraviolet (EUV) lithography tool. Coating uniformity on figured optics is adjusted by implementing contoured, shaped baffles during ML deposition. We have also developed an EUV reflectometer that is capable of measuring the reflectance versus wavelength across the surface of these optics, so that the coating uniformity can be determined with the required precision. We discuss the ML coating uniformity requirements for a practical EUV lithography tool, describe the facilities and techniques we have developed, and present some recent results wherein these facilities and techniques have been used to deposit high-reflectance coatings onto a variety of spherical and aspherical substrates.

I. INTRODUCTION

Extreme-ultraviolet (EUV) lithography is an extension to shorter wavelengths of optical lithography, in which a pattern is transferred from a mask to a wafer with reduction.[1] By operating at short wavelengths (e.g., 13 nm) the limits on image formation due to diffraction are greatly relaxed, enabling the possibility of printing 0.1-μm features over a large field. However, the optics that comprise the imaging system are reflective, and therefore require multilayer (ML) coatings in order to operate with high efficiency near normal incidence in the EUV region.

As a result of the optical characteristics of the MLs, specifically the narrow reflection bandwidth, and by the need to minimize the wavefront distortions introduced by the coatings, stringent requirements must be placed on the variation in ML coating thickness across the surface of each optical element in the imaging system. These coating requirements represent a significant technical challenge, and have resulted in the development of new deposition and metrology facilities and techniques, which we describe here. The facilities include a magnetron sputtering system for depositing Mo/Si ML coatings onto large-diameter, figured substrates with precise coating thickness control, and an EUV reflectometer system capable of measuring reflectance versus wavelength across the surface of these optics. Coating thickness uniformity is adjusted by implementing contoured, shaped baffles during ML deposition to control the spatial distribution of adatoms during deposition.

In Sec. II we discuss the ML coating uniformity requirements for the imaging optics in an EUV exposure tool. In Secs. III and IV we describe the ML deposition and metrology facilities, respectively, and in Sec. V the shaped-baffle technique we have developed for adjusting the coating thickness profile. In Sec. VI we present some recent results wherein these facilities and techniques have been used to deposit high-reflectance coatings onto a variety of spherical and aspherical substrates for EUV lithography.

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II. MULTILAYER COATING UNIFORMITY REQUIREMENTS

The requirements on ML coating uniformity for the imaging system in a practical EUV exposure tool are driven by the need to both maximize wafer throughput and minimize wavefront distortions. The precise specification of these requirements will demand a complete analysis of the overall system requirements, and in particular, a specification of the error budget, which we do not present here. However, we do provide below a rough estimate of the coating uniformity requirements. For this estimate we assume that the operating wavelength of such a lithography tool is 13 nm, i.e., that Mo/Si MLs having >60% peak reflectance near normal incidence are used.[2]

The variation in reflectance with wavelength for a ML depends on both the incidence angle and the ML period.[3] In particular, for a given incidence angle and period, the response of the coating will be highly peaked in a narrow band around a specific wavelength, as shown, for example, in Fig. 1(a) for a Mo/Si ML at normal incidence. Because the imaging camera in a practical EUV exposure tool will be comprised of at least three normal-incidence, figured optics [in order to achieve high-resolution pattern transfer with low distortion over a large field (Ref. 1)], the ML coatings on each optic must be properly matched, therefore, so that the peak wavelengths corresponding to successive reflections will coincide. If the coatings are not matched the reflectance peaks will not coincide, and the throughput will be drastically reduced [Fig. 1(b)]. Furthermore, because the peak of the reflectance curve also shifts with incidence angle, and because the incidence angle will vary, in general, across the surface of each imaging optic, each coating must also be graded (i.e., the thickness must vary with position) in order to achieve the required wavelength matching over the full aperture of the imaging system. That is, light scattered from each point on the mask will be distributed over the entire aperture of the imaging system, so the variation of peak wavelength in the response of the system across the aperture must be minimized.

To estimate quantitatively the affect of coating thickness nonuniformity on throughput for a multiple-mirror EUV op-

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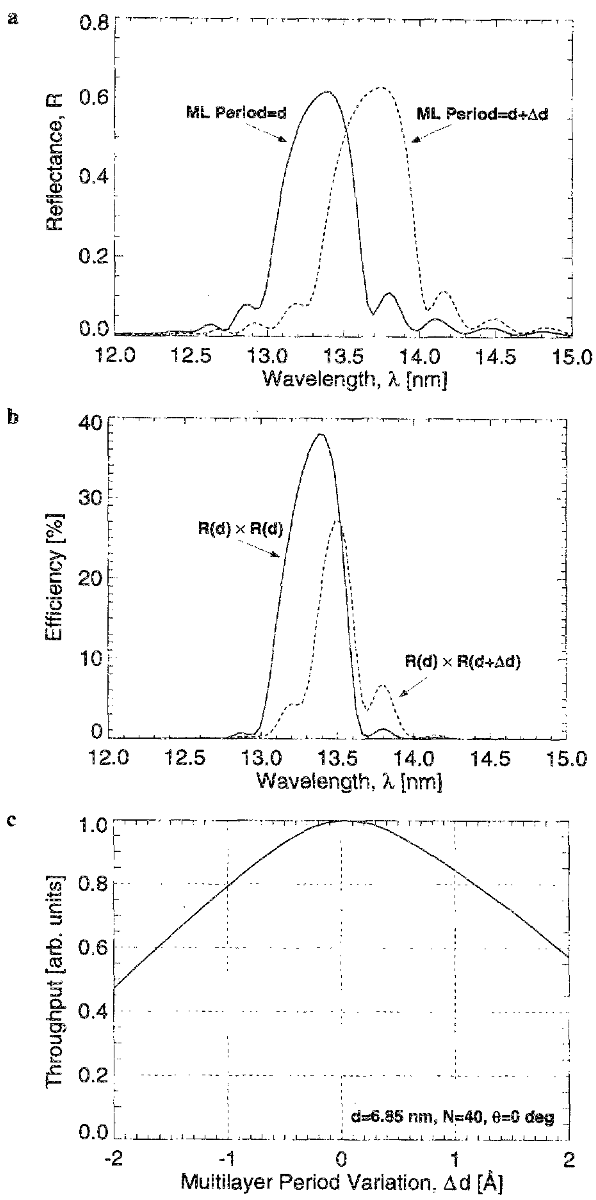

FIG. 1. (a) Reflectance vs wavelength of two Mo/Si ML coatings near normal incidence, whose periods differ by an amount Δd. (b) Efficiency after two ML reflections for the case of matched (solid) and mismatched (dashed) coatings. (c) Integrated throughput (relative) after two reflections vs ML period variation.

tical system, we can compute the relative throughput of the system as a function of the ML period variation, Δd, as follows. (Here, Δd refers to the departure in period from the nominal value, either across the surface of a single mirror, or between successive mirrors in the optical path.) The system throughput will scale with the integrated reflectance—the integral over wavelength of the product of the aperture-averaged reflectance versus wavelength curves for each reflection in the system. For the simplest case, we consider a system comprising only two Mo/Si ML coatings, as in Fig. 1. Although a practical EUV system will certainly include more than two ML reflections, the two ML case can be useful to estimate the tolerance on Δd nonetheless. From Fig. 1(c), we can see that a period variation of 1 Å, for example (i.e., 1.4% for $d=69$ Å), will reduce the system throughput by ~20%. As we add more ML reflections, the loss in throughput will increase, somewhat, depending on the details of the coating mismatch. We could imagine developing a more sophisticated analysis, in which the decrease in system throughput was computed as the variation in ML period between several mirrors was distributed randomly, for instance, but even from the simplest case presented in Fig. 1, it is clear that a period variation of more than 1%–2% will be unacceptable for a practical lithography system where throughput is crucial.

The second (and, as we shall see, more stringent) constraint on ML uniformity is the affect of coating thickness variations on wavefront distortion (WD). For diffraction-limited imaging, we require that the total WD at the image plane be less than some small fraction of the operating wavelength. The total WD includes contributions resulting from the figure errors in each optical surface, plus any WD introduced by the coatings. In order to minimize WD, and thereby achieve diffraction-limited imaging, it will be necessary to keep the WD introduced by the coatings from consuming the entire WD error budget.

ML thickness variations across the surface of a mirror can affect the reflected wavefront in two ways. First, there is a phase shift (relative to a reflection from the underlying substrate) due to the total coating thickness (i.e., due to the optical path difference) which is given by $\Phi=4\pi Nd/\lambda$, where d is the ML period, N the number of periods in the stack, and λ is the wavelength of light; if d varies across the surface of the optic, so does Φ, and this variation in phase shift (i.e., $\Delta\Phi=4\pi N\Delta d/\lambda$) perturbs the surfaces of constant phase in the reflected field. This effect is equivalent to a substrate figure error.[4] The second contribution to the total WD is that due to the phase shift on reflection from the ML, which can be calculated by solving Maxwell's equations for the ML. The relevant quantity here is again the *relative* phase shift on reflection across the surface of the optic, which will arise only from nonuniformities in the coating thickness profile.

We can calculate the relative phase shift as a function of ML period variation as follows. Figure 2(a) shows a plot of the phase shift on reflection versus wavelength for two different MLs having periods d, the nominal period, and $d'=d+\Delta d$, where Δd is again the period variation. At the peak of the reflectance curve for the nominal ML, the phase shift is exactly 180°, while at this same wavelength, the phase shift for the second ML differs from the first by an amount $\Delta\Phi$. As we vary Δd, we can see that $\Delta\Phi$ will also vary; this variation in $\Delta\Phi$ is thus a complicated function of wavelength and Δd. Shown in Fig. 2(b) is the variation in $\Delta\Phi$ vs Δd at the peak wavelength for the nominal ML. Also shown is the phase shift due to the total coating thickness, as described above. It is clear from this plot that the phase shift resulting from the total coating thickness is always much greater than phase shift due to reflection from the ML. We can also see that even a small thickness variation will result in a large phase shift, and will therefore perturb considerably the reflected wavefront. As mentioned above, the amount of wavefront distortion due to the coating that can be tolerated will depend on a detailed analysis of the system error budget.

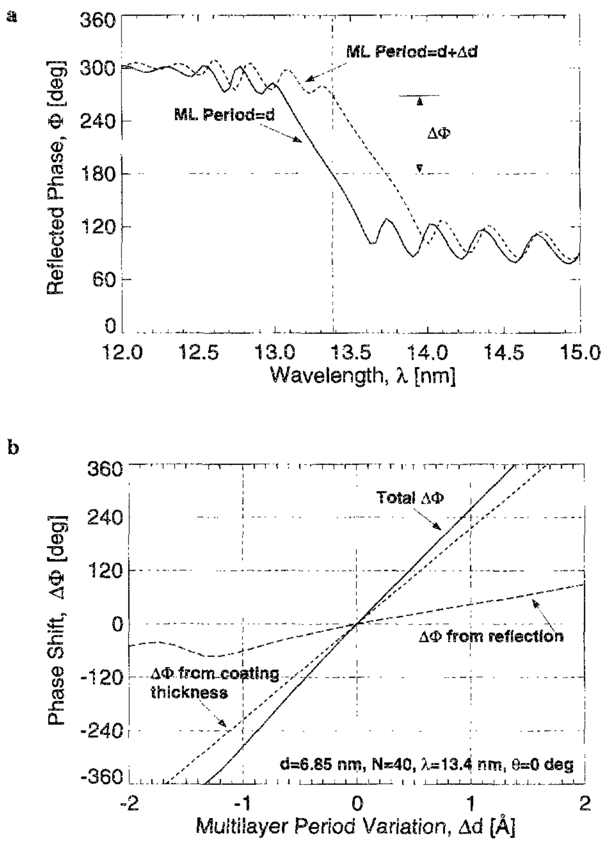

FIG. 2. (a) Phase shift on reflection for two Mo/Si ML coatings near normal incidence, whose periods differ by an amount Δd. (b) Phase error introduced by a ML coating; due to variation in phase shift on reflection (dashed); due to phase shift resulting from optical path difference corresponding to total coating thickness (dotted); and total phase shift (solid).

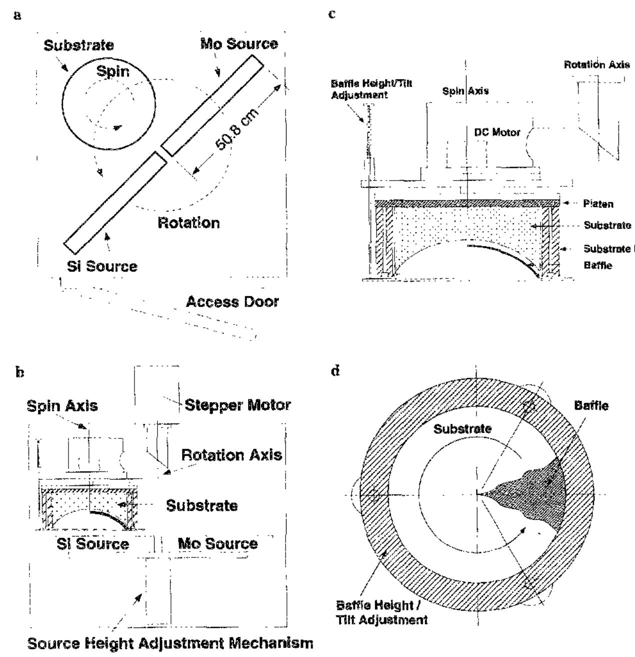

FIG. 3. (a) Top and (b) side view of magnetron sputtering system for ML deposition onto large substrates. (c) Baffle mechanism detail. (d) Bottom view of baffle mechanism.

However, we can safely assume that the allowed ML coating thickness variation across the surface of each imaging optic will be less than ±0.4 Å (i.e., ±0.6% for $d=69$ Å, $N=40$), which would be equivalent to a peak-to-valley figure error of $\sim\lambda/4$.

From this analysis, we may conclude that the ML deposition system must (a) be capable of controlling the coating thickness across the surface of figured optics to better than ±0.6%, and (b) because it is impractical to coat all the optical components in the complete EUV system during a single coating run, achieve a run-to-run repeatability of better than 1%–2%.

III. MULTILAYER DEPOSITION SYSTEM

We deposit ML films by dc magnetron sputtering in an argon atmosphere. Planar targets, measuring 50.8×8.9×0.6 cm, are used, containing either solid Si of 99.999% purity or Mo of 99.9% purity. The magnetrons (VacTec, Inc.) are mounted along the diagonal of the square vacuum chamber, and face upward, as shown in Figs. 3(a) and 3(b). The substrate is mounted facing downward on a platen that spins as it rotates over each magnetron source thereby building up the ML one layer per pass. The target-to-substrate distance, which is usually set to 90 mm, is adjusted by a lead-screw mechanism that positions both magnetrons vertically, in order to accommodate substrate thicknesses as large as ~15 cm. The substrate spin motion, which is used to enhance coating uniformity, is driven by a dc motor, and operates at approximately 235 rpm, whereas the rotation motion is driven by a computer-controlled stepper-motor with gear reduction, and operates at any desired rotation rate between 0.000 03 and 5.5 rpm. The individual layer thicknesses in the ML are thus adjusted by controlling the rotation speed, while keeping the intrinsic source deposition rates constant by maintaining constant source power and gas pressure. Stainless-steel shielding is used to limit the angular range of deposition, and thus serves to minimize cross-contamination between the two sources. The temperature of the substrate is not controlled during deposition.

Located between the target and the substrate is the baffle [Figs. 3(b)–3(d)] used in conjunction with the spin motion to adjust the coating thickness profile. The baffle is attached to a mechanism that rotates along with the substrate, that is, the baffle maintains a fixed position relative to the center of the substrate, but the substrate spins about its own center as the whole mechanism rotates over the target. The baffle mounting mechanism provides three vertical adjustments for precise and repeatable positioning (height and tilt) of the baffle relative to the substrate. We have found this adjustment mechanism to be crucial to achieving precise coating profiles with good repeatability. An array of tapped holes for substrate mounting is machined into the platen; as exemplified in Fig. 3(c), the substrate is attached to the platen by a holder that is specific to the substrate geometry. The platen is easily removed from the deposition system to allow for precise

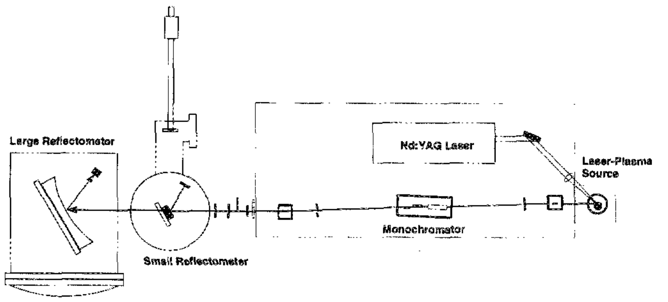

FIG. 4. Top view of EUV reflectometer system.

centering of the substrate. The platen can accommodate substrates as large as 35 cm in diameter.

The deposition chamber is evacuated to a pressure of 0.4 Torr with a rotary piston pump. High vacuum is then achieved using a cryopump (CTI model CT-10.) The base pressure of this system is in the mid-10^{-8} Torr range. We maintain precisely the argon pressure during deposition with a closed-loop feedback system consisting of a mass-flow controller (MKS model 2259C) and a capacitance manometer (MKS model 390HA), using Ar of 99.998% purity. To achieve high-quality Mo/Si coatings, the Ar pressure is maintained as low as possible, typically 1.5 mTorr.[2] Power to each magnetron source is supplied by a 1 kW power supply (Advanced Energy model 2011), operated in the regulated power mode at 200 W. The power supplies are ramped to full power over a period of 2 min, with an additional 20-min warm-up period prior to film growth.

Under the conditions just described, the effective deposition rates for Mo and Si are approximately 1–3 Å/s, depending on the shape of the baffle. For peak reflectance at $\lambda=13$ nm near normal incidence, ML films containing 40 periods of ~2.5-nm-thick Mo layers and ~4.4-nm-thick Si layers are used; the precise period is determined, of course, by the application, i.e., by the incidence angle and specific peak wavelength desired. At these deposition rates, the total deposition time can thus range from ~1–2 h, depending on the diameter of the substrate.

Prior to depositing the ML coatings, a 10-nm carbon film is usually deposited onto the substrate (in a separate coating run), in order to enable the possibility of later removing the Mo/Si coating by wet etching, using a technique described previously.[5] Carbon coating is performed by replacing the Si target with a C target of 99.999% purity. The deposition rate for C is typically 0.2 Å/s, for the deposition conditions just described.

IV. EUV REFLECTOMETER

The EUV reflectometer system is shown schematically in Fig. 4. The major components of this system are the light source, the monochromator, and the two reflectometers. The system as originally constructed included only the first reflectometer, and was designed primarily for versatile measurement capability on small (<75 mm in diameter) samples. The second, larger reflectometer was added principally for measuring ML coating profiles on large-diameter figured substrates. The light source, monochromator, and small reflectometer have been described previously,[6] so only the salient features of these components will be described here.

EUV radiation is generated using a laser-plasma source. A frequency-doubled Nd:YAG laser is used (Spectra-Physics model GCR-170), which produces ~500 mJ per 10-ns pulse at $\lambda=532$ nm, with a repetition rate of 10 Hz. The laser is focused to a ~100-μm spot onto a cylindrical, solid copper target, creating a plasma that emits radiation from the IR to the x-ray region. Using focusing mirrors, a varied-line-space grating monochromator (Hettrick Scientific model HIREFS-170), and a 1-μm-thick Be filter, a collimated, monochromatic EUV pencil beam of ~1 mm in diameter is delivered to either of the two reflectometer chambers. The intensity of the beam is measured before and after reflection from the substrate with a Si diode x-ray detector (IRD model AXUV-100). The detector signal is measured with a gated integrator/boxcar averager which is triggered by the laser pulse. The shot-to-shot variations in the source intensity are removed from the data by monitoring a small portion of the beam before it strikes the substrate, using a microchannel plate detector, and then using this signal to normalize the signal from the diode.

The large reflectometer (Thermionics Northwest) utilizes the very same platen as for the deposition system. In this system, however, the platen and substrate are oriented vertically. Access to the chamber is through a 50-cm-i.d. hinged door having a double O-ring seal; a slider mechanism was developed to simplify platen mounting and dismounting, as these tasks can be extremely difficult, especially for large and heavy substrates. The reflectometer chamber is evacuated to 0.1 Torr using a dual-vane rotary pump. High vacuum is achieved with a cryopump (CTI model On-board 8.) The base pressure of the system is in the low$-10(-9)$ Torr range.

The large reflectometer provides four independent motions: two translational motions of the substrate in the horizontal plane, one normal and the other parallel to the substrate surface; rotation of the substrate about the vertical axis (i.e., incidence angle θ); and rotation of the detector about the substrate (i.e., scattering angle 2θ). Measurements can be made from grazing to near normal (3°) incidence. Scans as long as 35 cm along the surface of the substrate are possible.

The entire reflectometer system is computer controlled, so that automated reflectance scans may be performed. The typical scan used to characterize the optics for EUV lithography consists of measuring the reflectance versus wavelength at several positions on the surface of the figured substrate. Depending on the complexity of the scan, and the size of the substrate, such a measurement may take anywhere from 15 min to several hours. The ML coating thickness profile is determined from the reflectance versus wavelength data by fitting the measured curves to a model where the ML period is the adjustable parameter.[6]

V. SHAPED-BAFFLE TECHNIQUE

The key to achieving the desired coating thickness profile across the surface of a figured substrate is the use of a shaped baffle. The baffle works by shadowing a portion of the spin-

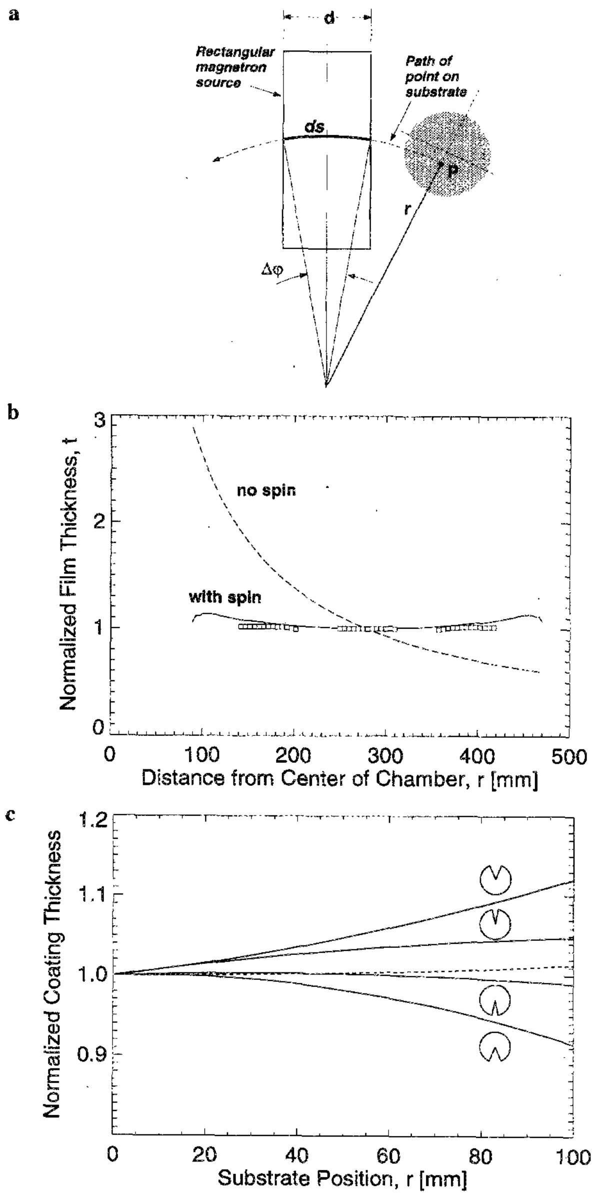

FIG. 5. (a) Coordinate system used for coating thickness analysis. (b) Coating thickness vs distance from center of deposition chamber for the case of nonspinning (dashed) and spinning (solid) flat substrates. Experimental data for spinning substrates are shown as squares. (c) Measured coating thickness on flat substrates for two simple, triangular baffle shapes (opaque area=30° or 45°, as indicated by the drawings,) and at two different orientations relative to the center of rotation.

ning substrate during deposition, in order to adjust the relative deposition rate across the substrate surface. The technique, which is similar to other baffle techniques reported previously,[3] can be understood as follows.

We consider first the case of a flat, *nonspinning* substrate rotating with angular velocity ω past a rectangular magnetron source of width d, that delivers a uniform flux, f [e.g., (Å/s)], of adatoms to the substrate. The coordinates for this example are shown in Fig. 5(a). The thickness $t(r)$ of the film deposited at a point P on the substrate located a distance r from the center of rotation is equal to the flux divided by the velocity, integrated along the path of this point over the source:

$$t(r)=\int \frac{\text{flux}}{\text{velocity}}\, d\ \text{path}$$

$$=\int \frac{f}{r\varpi}\, ds=\frac{f}{\varpi}\,\Delta\varphi(r)=\frac{2f}{\varpi}\arctan\left(\frac{d}{2r}\right),$$

where we have used $\tan(\Delta\varphi/2)=d/2r$. This curve is shown in Fig. 5(b) as the dashed line. The film thickness profile is neither uniform (i.e., it varies with r) nor isotropic in the plane of the substrate.

We now consider the same situation, but suppose that the substrate is spinning rapidly about its center. In this case, the rapid spin causes the thickness profile to be isotropic (i.e., symmetric about the spin axis), and much more uniform as a result of the averaging due to the spin motion. The analysis here is more complicated; the results are shown as the solid line in Fig. 5(b), and agree closely with what we have actually measured (squares) on a flat substrate. (Indeed, the small differences between the theoretical and experimental curves in this simple case alerts us to the many deficiencies of our model.)

We can now understand qualitatively, at least, what affect a baffle will have on the coating profile. Depending on its shape and its orientation relative to the center of rotation, the baffle modifies the way in which this "spin-averaging" is performed. That is, the point P will now spend some of its time in the shadow of the baffle, so the coating thickness at that point will be reduced. We can thus adjust the relative coating thickness at any distance from the substrate center simply by varying the width of the baffle at that distance. For example, shown in Fig. 5(c) are several experimental coating profiles obtained on flat substrates for two different triangular baffle sections, and with two different baffle orientations. We see that the coating thickness can be made to either increase or decrease relative to the thickness at the center of the substrate. We can imagine more complicated baffle shapes as well, so that the coating profile can be adjusted to take on any functional form that we might require.

If we now consider a figured substrate, complications arise that limit the utility of the analysis just presented. In particular, our assumption of a uniform flux is invalid. Furthermore, for magnetron sputtering, adatoms strike the substrate surface with a range of incidence angles, so deposition takes place around corners, even behind the baffle. In other words, the baffle does not really act like a simple shadow mask. Therefore, in order to achieve the required sensitivity of coating profile on baffle shape, we have found it necessary to use shaped baffles that are contoured to the figure of the substrate, as in Fig. 3 that are designed to maintain a constant separation from the spinning substrate (typically, 0.75±0.05 mm) and thereby minimize deposition behind the baffle.

Contoured baffles are formed using a hydraulic press. A steel mandrel assembly, having the same contour as the substrate to be coated, is first machined using an NC lathe. The mandrel consists of two halves, one convex, the other concave, and the two sections are aligned together with stainless-steel pins. A flat aluminum baffle, having been pre-

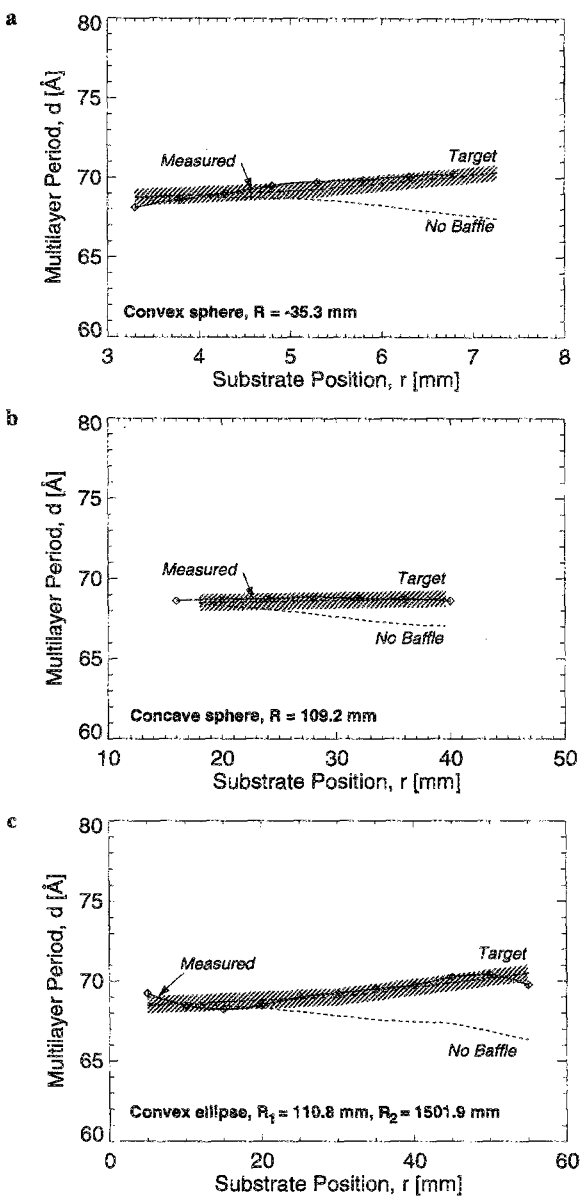

FIG. 6. Measured ML coating thickness on the spherical primary (a), spherical secondary (b), and ellipsoidal condenser (c) mirrors that comprise a 10× reduction Schwarzschild exposure system for EUV lithography. The radii of curvature are indicated. The measured coating thickness profiles (symbols) are within the targeted profiles of ±0.5 Å (shaded regions) from the nominal profile (dashed lines) over the clear aperture in each case. The coating profiles obtained without baffles are shown as dotted lines.

viously machined from 0.05-mm stock to the desired shape, is placed between the two halves of the mandrel, and is aligned relative to the mandrel with additional steel pins. The mandrel assembly is then installed in the jaws of the press, and a pressure of ~3000 psi is applied for ~30 s, forming the contoured baffle.

An iterative procedure is used to design the specific baffle shape that will produce the required coating profile on a figured substrate. That is, a ML coating is deposited onto a test substrate (i.e., an inexpensive, low-quality version of the actual substrate), using a baffle shape that represents a best guess, and the resulting coating profile is measured using the EUV reflectometer. The baffle shape is then modified accordingly, until the desired coating profile has been achieved, at which point the actual high-quality, figured substrate is coated.

VI. EXAMPLES

The shaped, contoured baffle technique just described has been used successfully to deposit high-reflectance Mo/Si MLs onto a variety of figured substrates for EUV lithography. To illustrate, Figs. 6(a)–6(c) are plots of the ML coating thickness profile versus substrate position (measured from the substrate center) for the two spherical optics that comprise the imaging system, and the ellipsoidal condenser optic of a 10× reduction Schwarzschild exposure tool. The targeted coating uniformity for these optics was specified to be ±0.5 Å (i.e., ±0.7%) over the clear aperture, and as can be seen from the figure, this goal was achieved in each case. There are, in fact, a total of five ML reflections in this system, including the reflection mask and a flat turning mirror; the ML coating uniformity for each surface was within the required tolerance. The imaging characteristics of this system are described in Ref. 7. The shaped baffle technique is currently being used to deposit ML coatings onto the imaging optics for a 1:1 ring-field camera.[8] The primary mirror in this system is 25 cm in diameter, and represents the largest substrate coated to date using the facilities described above.

VII. CONCLUSIONS

The ML coating thickness variations that can be tolerated in a multiple reflection EUV lithography system are very small; for Mo/Si MLs designed for normal incidence near 13 nm, we estimate that the ML period cannot differ from the nominal value (which itself depends on the incidence angle) by more than a fraction of an angstrom across the surface of each optic, in order to minimize wavefront distortions, and each optic must be matched with all the others in the system in order to maximize throughput. The ML deposition system used to deposit these coatings onto EUV optics must therefore be capable of adjusting the coating thickness across the surface of figured optics with a precision of better than ~1%, and achieve a run-to-run repeatability of better than 1%–2%.

We have described the ML deposition system and EUV reflectometer system that have been developed in order to meet these coating requirements on large-diameter, figured substrates. The ML coating thickness profile is adjusted by the use of contoured, shaped baffles. This technique has been used successfully to deposit high-reflectance Mo/Si ML coatings onto a variety of spherical and aspherical substrates.

ACKNOWLEDGMENTS

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[1]R. R. Freeman and R. H. Stulen, AT&T Tech. J. November/December 1991, pp. 37–48.
[2]D. L. Windt, R. Hull, and W. K. Waskiewicz, J. Appl. Phys. 71, 2675 (1992).

[3]W. K. Waskiewicz, D. L. Windt, J. E. Bjorkholm, L. Eichner, R. R. Freeman, T. E. Jewell, W. M. Mansfield, A. A. MacDowell, L. H. Szeto, D. M. Tennant, D. L. White, and O. R. Wood II, in *OSA Proceedings on Soft X-Ray Projection Lithography*, edited by J. Bokor (Optical Society of America, Washington, D.C., 1991), Vol. 12, pp. 97–100; J. B. Kortright, E. M. Gullikson, and P. E. Denham, Appl. Opt. Appl. **32**, 6961 (1993).

[4]In the case of optical surfaces for which the incidence angle varies appreciably across the surface, such that a graded ML coating is required, there will be a perturbation to the wavefront even for a perfect coating. In certain cases, it may be possible to compensate for this phase error by defocusing the optic; otherwise it may be necessary to compensate by modifying the design of the mirror to account for the coating thickness variation.

[5]K. Early, D. L. Windt, W. K. Waskiewicz, O. R. Wood II, and D. M. Tennant, J. Vac. Sci. Technol. B **11**, 2926 (1993).

[6]D. L. Windt and W. K. Waskiewicz, Proc. SPIE **1547**, 144 (1991).

[7]D. A. Tichenor, G. D. Kubiak, M. E. Malinowski, R. H. Stulen, S. J. Haney, K. W. Berger, L. A. Brown, W. C. Sweatt, J. E. Bjorkholm, R. R. Freeman, M. D. Himel, A. A. MacDowell, D. M. Tennant, O. R. Wood II, J. Bokor, T. E. Jewell, W. M. Mansfield, W. K. Waskiewicz, D. L. White, and D. L. Windt, Appl. Opt. **32**, 7068 (1993).

[8]A. A. MacDowell, J. E. Bjorkholm, K. Early, R. R. Freeman, M. Himel, P. P. Mulgrew, L. H. Szeto, D. W. Taylor, D. M. Tennant, O. R. Wood II, J. Bokor, L. Eichner, T. E. Jewell, W. K. Waskiewicz, D. L. White, D. L. Windt, and F. Zernike, Appl. Opt. **32**, 7072 (1993).