UCRL-JC-134880
PREPRINT

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This paper was prepared for submittal to the
44th Annual Meeting of the International Symposium on
Optical Science, Engineering, and Instrumentation
Denver, Colorado
July 18-23, 1999

August 25, 1999

Multilayer coated optics for an alpha-class extreme ultraviolet lithography system

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ABSTRACT

We present the results of coating the first set of optical elements for an alpha-class extreme-ultraviolet (EUV) lithography system, the Engineering Test Stand (ETS). The optics were coated with Mo/Si multilayer mirrors using an upgraded DC-magnetron sputtering system. Characterization of the near-normal incidence EUV reflectance was performed using synchrotron radiation from the Advanced Light Source at the Lawrence Berkeley National Laboratory. Stringent requirements were met for these multilayer coatings in terms of reflectance, wavelength matching among the different optics, and thickness control across the diameter of each individual optic. Reflectances above 65% were achieved at 13.35 nm at near-normal angles of incidence. The run-to-run reproducibility of the reflectance peak wavelength was maintained to within 0.4%, providing the required wavelength matching among the seven multilayer-coated optics. The thickness uniformity (or gradient) was controlled to within ±0.25% peak-to-valley (P-V) for the condenser optics and ±0.1% P-V for the four projection optics, exceeding the prescribed specification for the optics of the ETS.

Keywords: Extreme ultraviolet (EUV) lithography, reflective multilayer coatings, thickness distribution, and uniformity

1. INTRODUCTION

Extreme ultraviolet (EUV) lithography is now one of the leading candidates for next generation lithography (critical dimension below 100 nm) for the integrated circuit industry.[1] Most of the R&D work in EUV lithography is currently performed through a collaborative effort between U.S. national laboratories and a consortium of semiconductor companies.[2,3] Currently, all the EUV lithography imaging studies are performed with a 10× system developed several years ago and upgraded last year with new multilayer-coated reflective optics.[4,5] We are now building an alpha-class EUV lithography system, called the Engineering Test Stands (ETS), which will be a 4× system capable of exposing at least 10 wafer per hour. The design for this ETS system incorporates multiple reflective optics: (1) four condenser optics (C1 to C4) in the illumination system (2) a reflective mask consisting of a patterned absorbing layer on a multilayer mirror; and (3) four precision projection optics (M1 to M4) to image the mask pattern onto a photoresist-coated wafer.[6] Seven of the nine surfaces operate at near-normal incidence and require EUV-reflective multilayer coatings.

The requirements for the multilayer coatings prescribed by the ETS are daunting: reflectances above 65% are required at the operating EUV wavelength (13.4 nm), the thickness distribution must be controlled to within ±0.1% peak-to-valley (P-V), and the wavelength matching of the reflectance response among the optics must be better than 0.05 nm. The rationale behind these coating prescriptions is articulated in more details in the following section (Section 2). This manuscript then briefly describes our recently developed multilayer deposition technology that allowed us to meet the required specifications (Section 3). Finally, it reviews the main results for the two condenser optics C1 and C3 and the four projection optics M1-M4 we have coated (Section 4).

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To be published in SPIE 3767, paper 31

Table 1. Description of the ETS projection and condenser optics.

Optic	M1	M2	M3	M4	C1	C3
Diameter [mm]	165	209	104	170	280	20x39 long
Clear aperture [mm]	±56.2	±78.1	±25.4	±59.0	±130	16x35 long
Best fit radius [mm]	-3055	+1088	-389	+504	+235	+6112
Average incidence angle [Deg]	4.0	6.55	12.0	6.0	12-28	10.65 & 11.85

Note: positive curvature radius = concave; negative curvature radius = convex

The thickness distribution across the individual optics must also be carefully specified. A lack of thickness distribution control leads to a perturbation in amplitude and/or phase of the beam reflected by that mirror. The impact on the ETS imaging performance is quite different depending upon whether the mirror is in the condenser or the projection optics. For example, amplitude effects control multilayer requirements in the condenser. Specifications on the coating thickness distribution control for condenser optics are set by the requirement to deliver a dose to the mask with a uniformity of ±1%. Such uniform dose is needed to ensure that the printed critical dimension (CD) is consistent across the image field at the wafer. For reference, a typical CD uniformity requirement is ±10% across the printed field, leading to an illumination uniformity requirement of ±1%. Working in the context of an illumination uniformity budget, this translates into multilayer thickness distribution control of better than ±0.4% across the condenser elements. This tolerance is placed around the graded thickness prescriptions that are required for the condenser coatings to compensate for the variation in incident angle across the condenser mirrors.

The ETS optical system was designed to perform well with uniform coatings on the four projection optics. Phase errors caused by multilayer thickness variations are equivalent to wavefront errors that degrade the image quality of the optical system. Ideally, the multilayers should not degrade the residual wavefront error of the design and should effectively become "invisible" to the optical performance. The impact of multilayer thickness variations can be measured as degradation against the residual aberration of the optical design. For the ETS, the PO Set 1 specification allows a wavefront degradation of ~25% compared to the design residual, while the PO Set 2 specification allows a wavefront degradation of ~10% compared to the design residual. This translates into multilayer thickness control of ±0.25% P-V for the first set of optics and ±0.1% P-V for the second set. The P-V specification encompasses the total coating error from the target prescription. However, some forms of the coating error are compensable. A quadratic, or spherical, figure error induces a tilt and a focal shift that are easily compensated during optical alignment. Non-spherical figure errors, however, induce wavefront errors that cannot be corrected. We have therefore specified an *added figure error* of 0.14 nm root mean square (RMS) and 0.11 nm RMS for sets 1 and 2 respectively, which are the values derived after subtracting the quadratic components of the coating thickness distributions. Since the residual wavefront error of the optical design is so small, the resolution and CD uniformity of the ETS is not impacted at these levels of coating non-uniformity.

3. MULTILAYER DEPOSITION

The Mo/Si multilayers were deposited in a DC-magnetron sputter system previously described.[7,8] Briefly, in this deposition system two substrates are held face down by spinner assemblies mounted on a rotating platter and swept over rectangular sputter sources with a controlled rotation velocity of the platter. Major upgrades of the hardware and the electronic controls were performed in order to handle the large size and weight of the ETS optics with the required precision. These upgrades were largely based on the results of a study of the sensitivity of the deposition rates to changes in process variables such as power, pressure, flow rate, substrate-to-target distance, and platter velocity. These data were useful in identifying those variables that required improved levels of control, which was instrumental in determining where to focus our system upgrade efforts.

The desired uniform or graded thickness distribution on a given optic is achieved by modulating the velocity of the substrate while it passes through the sputter flux. If, for example, the system produces a coating too thin at the edge of the optic with a constant platter velocity, a more uniform coating is obtained by reducing the velocity while the substrate enters and leaves the deposition zones, when the substrate edges are being coated. The optimized platter velocity modulation recipe is rapidly determined with computer software which predicts the film thickness uniformity for any given platter velocity modulation recipe. This technique is applicable to both curved (concave and convex) and flat optics. The effect of substrate curvature is accounted for within the deposition model. The system can be used to obtain precisely graded coatings as well as uniform coatings.

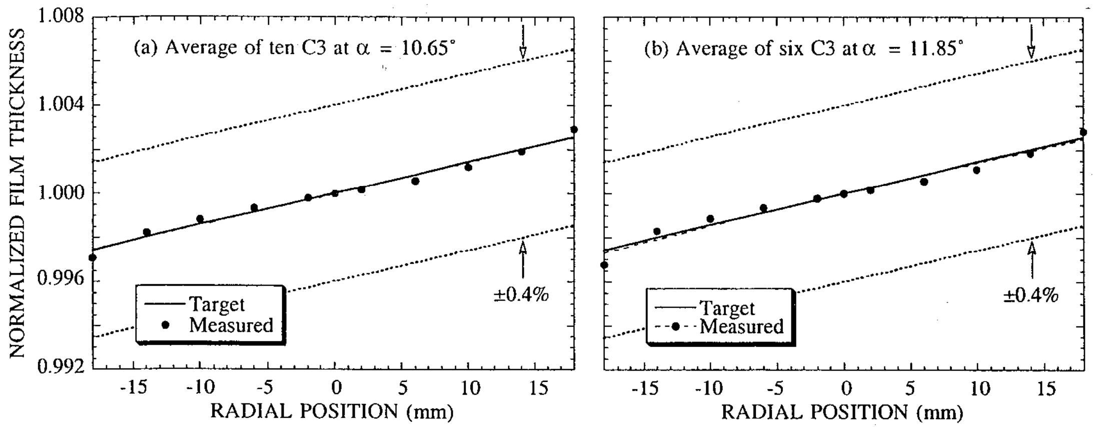

Fig. 3. Average normalized thickness distribution of (a) ten C3 optical elements to be used at 10.645° and (b) six C3 optical elements to be used at 11.850°. The solid circles are the measured values, the solid line is the targeted thickness profile, and the dotted lines are the boundaries of a ±0.4% tolerance zone. Note that one element was coated first with a 10.645° incidence multilayer and then over-coated to provide an extra spare mirror for 11.850°.

Fifteen C3 elements were coated with a linear gradient in the long direction and uniformly in the short direction. We therefore have two complete sets of six elements plus spares. Figures 3(a) and 3(b) show the average normalized thickness distribution of C3 optical elements to be used at 10.645° and 11.850°, respectively. The measured values are, once again, well within the ±0.4% tolerance zone. The average peak position (centroid) value is 13.277 nm and 13.291 nm for the 11.850°- and 10.645°-design, respectively, with an average reflectance of 66%.

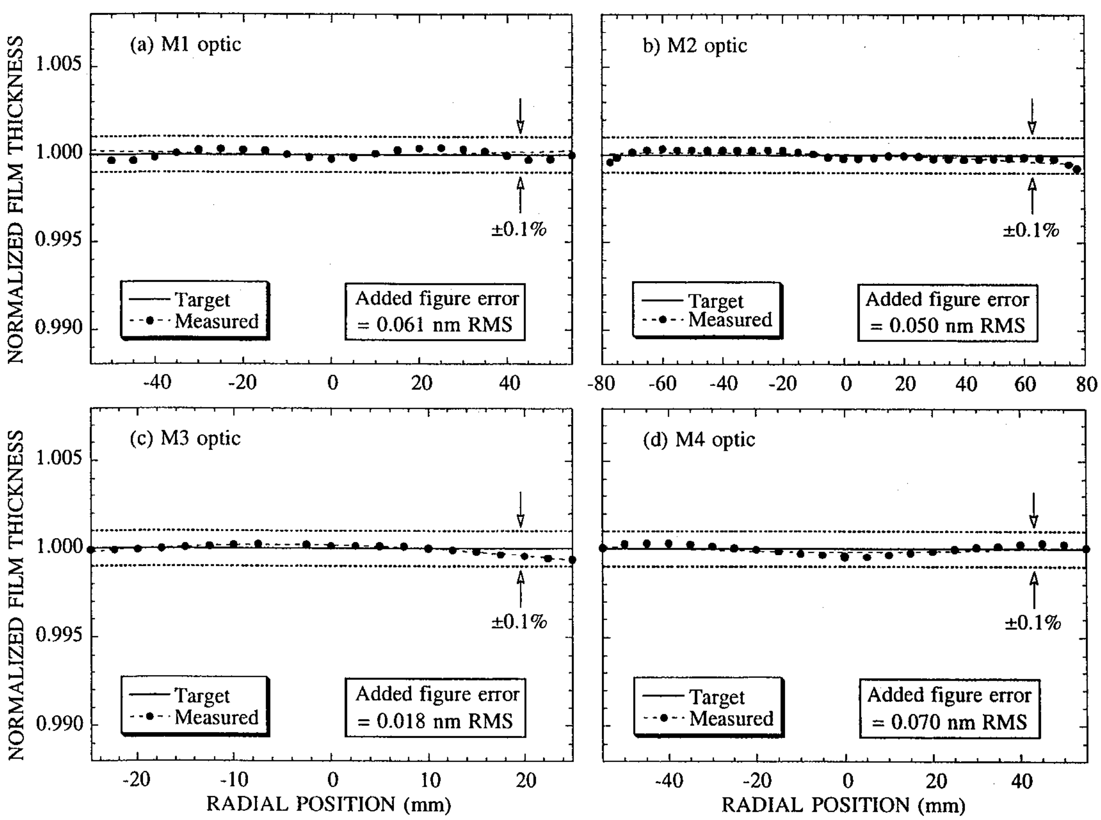

Fig. 4. Normalized thickness distribution of all four projection optics. The solid circles are the measured values, the solid line is the targeted thickness profile, the dotted lines are the boundaries of the ±0.1% tolerance zone, and the dashed lines are second degree polynomial fits to the measured data points.

ACKNOWLEDGMENTS

The authors thank G. B. Wells for his assistance in the maintenance and operation of the multilayer deposition systems and S. B. Ratti for the preparation of the surrogates. We also thank K. Wilhelmsen, G. Hensley, and T. Janusik for the deposition system electronics and controls upgrade, and A. Edge, G. Howe, G. Heaton, R. Levesque, and D. Mueller for the deposition system mechanical upgrade. The authors also acknowledge the support of E. M. Gullikson and F. Scholz in the EUV reflectance measurements at the LBNL. This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48. Funding was provided by the Extreme Ultraviolet Limited Liability Company (EUV LLC) under a Cooperative Research and Development Agreement.

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