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The Fabrication and Testing of Optics for EUV Projection Lithography

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The Fabrication and Testing of Optics for EUV Projection Lithography[1,2]

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Introduction

Extreme UltraViolet Lithography (EUVL) is a leading candidate as a stepper technology for fabricating the next generation of microelectronic circuits. EUVL is an optical printing technique qualitatively similar to Deep UV Lithography (DUVL), except that 11-13nm wavelength light is used instead of 193-248nm. The feasibility of creating 0.1μm features has been well-established using small-field EUVL printing tools, and development efforts are currently underway to demonstrate that cost-effective production equipment can be engineered to perform full-width ring-field imaging consistent with high wafer throughput rates. Ensuring that an industrial supplier base will be available for key components and subsystems is crucial to the success of EUVL. In particular, the projection optics are the heart of the EUVL imaging system, yet they have figure and finish specifications that are beyond the state-of-the-art in optics manufacturing. Thus it is important to demonstrate that industry will be able to fabricate and certify these optics commensurate with EUVL requirements. The goal of this paper is to demonstrate that procuring EUVL projection optical substrates is feasible.

Specifications

EUVL projection systems employ all-reflective configurations in a ring field geometry with the mirror surfaces having stringent specifications on both figure and finish.[3] Nominal specifications for the average allowable figure and finish errors on individual substrates for a 4-mirror EUVL projection optics design are given in Table 1. These multi-mirror systems typically utilize aspheric surfaces to obtain aberration correction, which adds a significant degree of difficulty to the fabrication and testing of the substrates.

The three specification categories listed in Table 1 are tied closely to performance requirements. The figure specification is motivated by the requirement for a high resolution imaging system with low distortion across the image field. If the projection optics are to achieve diffraction-limited performance by Marechal's criterion, the composite wavefront error (at the exit pupil) must be less than $\lambda/14$ rms where λ is the operating wavelength ($\lambda = 13.4$ nm). In the context of our 4-mirror system, each surface should contribute, on the average, no more than 0.5 nm rms of WFE (assuming the errors are uncorrelated), which leads to the average figure error of 0.25 nm rms specified in Table 1. Mid-spatial frequency roughness (MSFR) (spatial periods of 1 μm to 1 mm) causes near-angle scattering where the scattered light remains in the image field. Thus, MSFR causes a background illumination, usually

Table 1. Nominal specifications for EUVL projection optics (4 mirror system).

Error Term	Maximum Error Specification	Defined by integrating the Power Spectral Density (PSD) of surface errors over the following bandlimits:
Figure	0.25 nm rms	$(\text{Clear Aperture})^{-1}$ – 1 mm^{-1}
Mid-Spatial Frequency Roughness (MSFR)	0.20 nm rms	1 mm^{-1} – 1 μm^{-1}
High-Spatial Frequency Roughness (HSFR)	0.10 nm rms	1 μm^{-1} – 50 μm^{-1}

referred to as *flare*, that is superimposed on the desired image. The most prominent effect of flare is to reduce image contrast, which adversely limits the range of acceptable operating conditions (process window) for performing lithography. In addition, if the flare is non-uniform over the image field, then the critical dimensions (CD) of printed features will also exhibit non-uniformity. Modeling efforts indicate that acceptable levels of image contrast and CD variation can be achieved for MSFR levels of 0.2-nm rms, as specified in Table 1. Wide-angle scattering is caused by high-spatial frequency roughness (HSFR) (spatial periods <1 μm) and results in a loss to the system because light is scattered outside of the image field. Wide-angle scattering also decreases contrast by reducing the intensity of the "light" areas of the image field, in comparison with near-angle scattering, which decreases contrast by redistributing energy within the image field.

The Evolution of Optical Fabrication to Meet EUVL Specifications

Figure 1 is a plot of surface errors for the three key specification categories (figure, MSFR, HSFR) versus the year in which they should be achieved in order to meet current program requirements; each of the three lines corresponds to a different category. The three points at 1997 ("Sandia 5x") are the measured values from aspheric surfaces fabricated for another project and represent the state-of-the-art for combined figure and finish at the beginning of our current program. The fact that the MSFR is greater than the figure error is indicative of the impressive level of determinism in the figuring process, while also indicating that finish is often sacrificed during aspheric processing. In comparison, the data point labeled "CRADA" for mid-1996 represents an impressive 0.3 nm rms measured figure error, although finish was not specifically controlled for that optic.[4] The points indicated for 1998 and 1999 are the specifications for optics required in the current effort; the *Intermediate Specifications* in 1998 offer an interim milestone mid-way during the finishing process development that links the state-of-the-art in 1997 with the *Final EUVL Specifications* for 1999. Complete sets of optical elements will be delivered and evaluated for both the intermediate and final specifications.

The two points to the right of 1999 labeled as "Classical Superpolishing" are the levels of MSFR and HSFR that can be produced on flats and spheres by companies that perform "superpolishing", such as for laser gyro components. These points represent a "proof of existence" that demonstrates that optical fabrication methods can indeed attain these levels of finish.

There is a growing effort in the optics community to improve aspheric fabrication technology in order to meet the future needs of EUVL. As part of our efforts in identifying and reducing program risks, we are assessing this rate of improvement by purchasing optical substrates from commercial supplier(s) using specifications that become increasingly stringent, as shown in Figure 1.

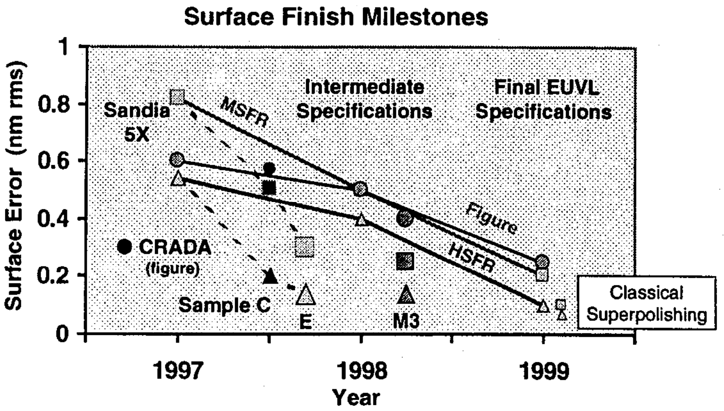

Figure 1. This timeline depicts how figure and finish specifications for EUVL are evolving to support current program requirements. Data points for Samples C and E indicate that developments in aspheric manufacturing are rapidly approaching EUVL program goals (material: Zerodur M).

Our test and evaluation samples have been obtained from commercial source(s) and have all been fabricated using aspheric processing methods, although the surface contours are flat or spherical in order to simplify inspection. Some of the substrates have had simultaneous figure and finish specifications, while others have concentrated on improving finish while using aspheric methods. In all cases, the required specifications have been met.

The results for two of the developmental samples are shown in Figure 1. Sample C is a spherical substrate fabricated using aspheric methods with specifications for figure, MSFR, and HSFR. The key observation is that even while maintaining figure quality to 0.6-nm rms, the values of MSFR and HSFR dropped to 0.51 nm rms and 0.20 nm rms, respectively. The goal of flat Sample E was to focus aspheric processing development on improving surface finish, without a stringent specification on figure. The MSFR value of 0.30-nm rms and HSFR value of 0.14 nm rms are plotted on the timeline in Figure 1. Both of these values are closely approaching the final EUVL specifications.

An important milestone was achieved by the fabrication of the initial element of our 4-mirror projection system to the *Intermediate Specifications* shown in Figure 1. Mirror M3 is a spherical Zerodur M substrate that was fabricated using the aspheric methods developed with the developmental samples. Aspheric finishing techniques were used instead of traditional spherical polishing methods because of their demonstrated determinism in meeting stringent figure requirements. For comparison, the figure and finish tolerances that were achieved are indicated in Figure 1, by the three symbols to the right of the *Intermediate Specifications*. A figure error of 0.4 nm rms, MSFR of 0.22 nm rms, and a HSFR of 0.14 nm rms were achieved, which are significantly below the specified values. Completion of this element demonstrates the feasibility of meeting stringent specifications using aspheric methods. As this manuscript is being written, the other elements of this set are being completed.

Calculation of Surface Errors

As noted in the definition of the specifications given in Table 1, the relevant parameter is the rms power obtained by integrating the 2-D power spectral density (PSD) over an appropriate band of spatial frequencies. The use of 1-D PSDs is well described in the literature, particularly in relating light scattering to surface statistics.[5] However, the calculation of statistics from the 2-D PSD is relatively uncommon, although there is a trend for its increasing application. In order to calculate the relevant surface statistics, we calculate the 2-D PSD, and then delineate a circular region within the frequency domain with a radius of the Nyquist frequency (or an ellipse if the Nyquist frequencies are different in the x and y directions).[6] We then integrate the 2-D PSD in the annular region that includes the spatial frequencies that are relevant. For example, we would integrate between the frequencies of 1/mm to 1/μm in order to assess the MSFR. Measurements may be required from more than one instrument in order to span a sufficiently wide frequency region. PSDs calculated from surface roughness measurements have shown excellent agreement with PSDs inferred from angle-resolved scattering data.[7]

Metrology for EUVL Optics

The bandwidths of the three specification categories given in Table 1, figure, MSFR, and HSFR, correspond approximately to the bandwidths measured by three types of instruments: full-aperture phase-shifting interferometry, phase-shifting interferometric microscopy, and atomic-force microscopy (AFM), respectively. Thus, power spectral densities can be assembled that cover an extremely wide spatial frequency band, i.e. CA^{-1} to 0.1 nm^{-1}. Figure 2 shows the average radial PSD for M3 that shows the contributions over about six orders of magnitude of spatial

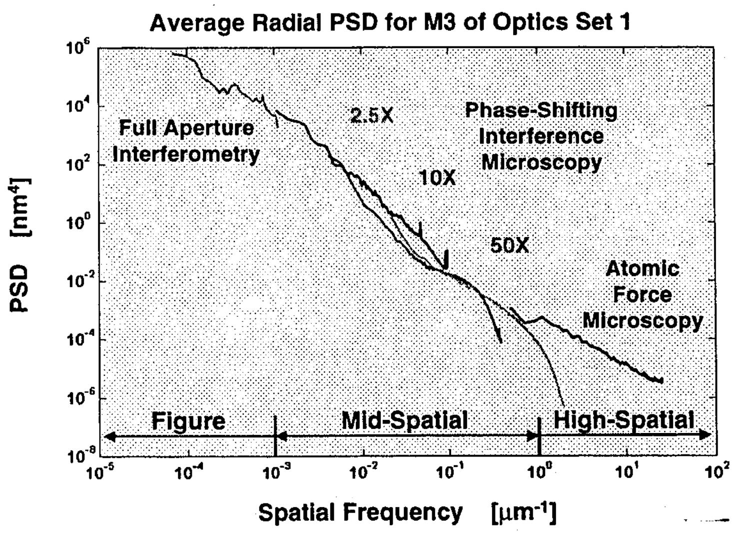

Figure 2. Power Spectral Density for M3 comprises PSDs measured using five different instruments of magnifications.

frequency. Three magnifications were used with the phase-shifting interferometric microscope for measuring the MSFR. It is outside of the scope of this summary to provide a comprehensive discussion of these types of measurements. However, the measurement of figure accuracy is an especially important issue, because of the need to measure absolute accuracy with respect to the optical design.

We have designed and built a phase-shifting diffraction interferometer (PSDI) for measuring the figure accuracy of EUVL mirror substrates.[8] Errors in the reference have been minimized by using two arbitrarily perfect spherical wavefronts: one serves as the measurement wavefront and is incident on the mirror surface under test and the other serves as the reference wavefront. The calculated deviation from sphericity for reference waves generated with a diffracting aperture are of order 10^{-6} waves (visible). Control of their relative amplitude and phase provides contrast adjustment and phase shifting capability. The PSDI has been successfully applied to measuring aspheric surfaces with low fringe density or to more general aspheric surfaces by stitching together regions that are independently measured with low fringe density. This concept has been implemented in several ways using lithographically generated apertures or single mode optical fibers.

Conclusion

The optics industry is currently attaining figure and finish values near those required for EUVL aspheres. The rate at which finishing performance is improving will enable a projection optics system to be assembled for meeting current EUVL program requirements.

Notes and References

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[2] For additional references and an expanded description of many topics mentioned in this summary, see: Taylor, J. S., Sommargren, G. E., Sweeney, D. W., and Hudyma, R. M., "The fabrication and testing of optics for EUV lithography", in *Emerging Lithographic Technologies II*, Proc. SPIE vol. 3331, pp. 580-590 (1998).

[3] Sweeney, D. W., Hudyma, R. M., Chapman, H. N., and Shafer, D. R., "EUV optical design for a 100-nm CD imaging system", in *Emerging Lithographic Technologies II*, Proc. SPIE vol. 3331, pp. 2-10 (1998).

[4] Kestner, R., "Precision asphere fabrication and metrology to tolerances <1 nm rms", paper presented at the OSA Optical Fabrication and Testing Topical Meeting, Boston, May 1-3, 1996; note that this measured value represents a comparison with respect to the vendor's interferometric reference, not a definitive statement of accuracy.

[5] Church, E. L. and Takacs, P. Z., "Specification of glancing- and normal-incidence x-ray mirrors", *Optical Engineering*, vol. 34, no. 2, pp. 353-360 (Feb. 1995).

[6] The 2-D PSD is the squared magnitude of the 2-D Fourier transform of the surface errors and is calculated as:

$$S(f_x, f_y) = \frac{L_x L_y}{M^2 N^2} \left| \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} z(x_m, y_n) e^{-2\pi i m \Delta x f_x} e^{-2\pi i n \Delta y f_y} \right|^2$$

where $z(x,y)$ is the distribution of surface errors over the x,y plane

L_x, L_y are scan lengths in the x and y directions

f_x, f_y are spatial frequencies in the x and y directions

M, N are the number of equi-spaced samples in the x and y directions

Δx, Δy are the sample spacings for x and y

[7] Gullikson, E. M., "Nonspecular scattering for normal-incidence EUV optics", in *Emerging Lithographic Technologies II*, Proc. SPIE vol. 3331 (1998) to be published.

[8] Sommargren, G. E., "Phase shifting diffraction interferometry for measuring extreme ultraviolet optics", in *Extreme Ultraviolet Lithography, Trends in Optics and Photonics* (TOPS), vol. IV, G. D. Kubiak and D. R. Kania eds., Optical Society of America, pp. 108-112 (1996).