The history of R & D is full of unexpected benefits—situations in which work done for one purpose turns out to be useful for others, some of which may have a more immediate economic payback than the original project. One recent example is the intensive development work on optics for extreme UV (EUV) microlithography. This technology, which has breakthrough potential for the semiconductor and nanotechnology industries, places extreme demands on our ability to apply, measure, and polish optics ranging from flats to complex aspherical surfaces.

Although EUV lithography is still a developmental technology for chipmaking, the optical fabrication methodologies developed and optimized by our teams over the last decade are paying dividends in a range of extreme-precision optical applications, including longer-wavelength (UV) lithography and inspection, and astronomy and other low-scatter, extreme-resolution imaging applications.

The industry has long known that the demands of semiconductor lithography optics provide a significant driver for continuous improvement of optical manufacturing and metrology. Indeed, the ultimate EUV lithography requirements drive the requirement to polish and measure optical surfaces to 0.1 nm rms (see figure 1). These technology and metrology advances not only further the science of precision optics but provide more economical manufacturing solutions and greater confidence for the end user.

Developing the capability to produce EUV optics to the required surface figure, mid-frequency error, and surface roughness required a much more rigorous understanding than previously available of the physics and chemistry
of the optical manufacturing process. It also required improvements to computer-controlled fabrication and metrology technology. To meet these requirements, we developed proprietary computer-controlled optical surfacing (CCOS) technology and complimentary metrology that enables optical-surfacing accuracy to better than 0.1 nm rms. These new technologies also enable more economical and precise manufacturing of aspheric surfaces, and can be applied to novel optical designs to minimize wavefront errors.

**Frequency Counts**

The surface errors that cause an optical surface to deviate from the nominal can be divided into three regimes. Low-spatial-frequency errors (figure errors), normally characterized by Zernike polynomials, cause distortion in the system wavefront, yielding blurry images. Mid-spatial-frequency errors cause small-angle scattering of light (flare), which reduces image contrast. Finally, high-spatial-frequency errors scatter light over larger angles, reducing energy throughput in an optical system.

ASML Optics recently completed two sets of 10X Schwarzschild optics for use in an EUV camera system used at the Lawrence Berkeley National Laboratory. The configuration consists of two spherical elements: a 15-mm convex primary that is fabricated from fused silica and a 90-mm concave secondary that is fabricated from Zerodur (see figure 2).

The specifications for the 10X optics covered spatial periods ranging from the full aperture to 0.00002-mm. To fully characterize the surfaces, the team used a series of metrology instruments, including a Fizeau interferometer (clear aperture to about 0.3 mm), a mid-frequency proprietary interferometer called the sub-aperture surface-height interferometric measuring instrument (SASHIMI, for the 5-mm to 0.3-mm band), a phase-measuring microscope (PMM, using a 10X and 50X objective to cover the 0.3-mm to 0.001-mm band), and an atomic force microscope (AFM, for about 0.002-mm to 0.00001-mm band). We developed the SASHIMI instrument to bridge the gap between figure metrology and PMM and provide surface information over the relevant waveband.

A power-spectral density (PSD) plot is a quantification of the surface error as a function of frequency. We create a PSD by applying a fast Fourier transform to the surface data from each metrology instrument. Ideally the PSD plots from the various metrology instruments overlap to permit seamless stitching of instrument data into a single composite curve from which we obtain the surface error values by numerical integration (see figure 3).

**Figure 2** The Schwarzschild design consists of a 15-mm convex primary and a 90-mm concave secondary (inset). Photo credit: ASML Optics

**Figure 3** Combining data from multiple metrology tools across the full spatial frequency range (left) yields the composite PSD plot (right).
Shrinking the Scale

Accurate interferometric metrology is the cornerstone of precision optical fabrication, giving confidence to both the manufacturer and the customer regarding the quality of optical products. The requirements for many of today's optics are beyond the inherent accuracy of commercial out-of-the-box interferometers; however, calibrating the interferometer relative to a known standard provides a common method for performance verification. The accuracy of the standard thus becomes the limiting factor. Most commercially available standards are limited to about \( \lambda /20 \) (at \( \lambda = 632 \text{ nm} \)) peak-to-valley accuracy levels.

By applying the same CCOS technologies used to make the EUV optical components, to the production of optical calibration standards, ASML has reduced artifacts in those standards by a factor of five. These standards, developed to support the testing requirements for lithography optics, are fabricated to the extreme-precision level of better than 1 nm rms (\( \lambda /632 \text{ rms} \); see figure 4, Figure 5). This is an example of developments in one application benefiting another: technology refined for EUV lithography has dramatically improved optical metrology calibration. This absolute standard can extend the accuracy of optics beyond \( \lambda /150 \) peak-to-valley.

ASML Optics is also applying these standards, fabrication and metrology technologies to the wavefront correction of large-field optics that may potentially be used in a leading space agency program to secure images of planets orbiting nearby stars, exploring a method for producing such large-aperture, high-performance systems rapidly and economically. We have completed a hardware demonstration in which a nominally flat complex aspheric mirror 120-mm in diameter statically corrects the high-order aberrated wavefront error of an 120-mm-diameter off-axis parabolic mirror to 0.5 nm rms.

Metrology data showed the parabolic mirror wavefront error was dominated by spherical aberration before special figuring, and by 3-50 cycles/aperture error after special figuring (see figure 6). These mid-spatial-frequency errors would have required multiple polishing and test cycles to correct, particularly since in the real system multiple mirrors would need correction, adding production time and cost. An interferogram taken with the single corrector mirror in place shows the level of

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**Figure 4** Surface metrology data from 4-in. metrology flat shows 0.75 nm rms figure error without power removed (right) and 0.34 nm rms figure error (left).

**Figure 5** Overlapping PSDs from several metrology instruments (top) yield composite PSD (bottom).
Finding a Tight Focus

Noreen Harned might have been a high school physics teacher today, but a summer job years ago sent her in a different direction.

After earning a BS in physics at the State University of New York, Stony Brook (SUNY) in 1973, followed by an MS in 1974, Harned got a teaching appointment at SUNY, and also taught in a public high school in Beverly, MA. During the summer break of her second year, she took a temporary research job at the now-defunct AVCO Everett Research Laboratory (Everett, MA).

“I thought I would be doing it just for a summer. It turned out I really, really liked it,” she says. “I enjoyed the entire environment—not only the research, but the stimulation of the people I was working with.”

At the end of the summer, AVCO offered Harned a full-time position, and she accepted. At AVCO she began to focus on optics, particularly high-energy lasers. From 1999 to early 2003, Harned was responsible for Silicon Valley Group’s program to develop equipment for extreme-UV (EUV) lithography, the next-generation method for making semiconductor chips. Now, as vice president of marketing, technology, and business development at ASML, Harned’s focus has broadened again, as she tries to set strategic directions for both the EUV business and the company’s optics business unit.

—Neil Savage