Testing EUV optics with EUV light: if you can measure it, you can make it

Kenneth Goldberg

Optical systems for extreme ultraviolet (EUV) wavelengths can now reach diffraction-limited quality due to advances in optical fabrication, coating, and testing at accuracies measured in tenths of a nanometer. Driven by the demands of semiconductor photolithography, these ultra-high-accuracy interferometric testing methods, which measure EUV optics at their operational wavelengths, produce some of the highest resolution optical systems ever made.

For centuries, lenses have been used to form images with light. The sharpness, or resolution, of those images depends on the quality and other physical properties of the lenses. It also depends strongly on the wavelength (color) of the light itself. Use shorter wavelengths of light, and the potential for higher resolutions beckons. The lithographers who mass-produce semiconductor microchips have pushed this trend toward higher resolutions, moving from visible-light, to ultraviolet (365nm), and onward to deep ultraviolet wavelengths (248 and 193nm). Lithographers are now preparing to bring extreme ultraviolet (EUV) optics, operating at a wavelength of 13.5nm, into widespread use.

With this transition (slated for 2009–13) will come a generation of lenses operating at the physical limits of diffraction: they will be among the highest-quality commercial optical systems ever produced. Research in the construction, testing, and operation of these lenses has been underway at Lawrence Berkeley (LBNL) and Lawrence Livermore National Laboratories (LLNL) for more than a decade. Now this technology is available for other short-wavelength applications, including space telescopes for astronomy, materials science investigations at scales in the tens of nanometers, and synchrotron beamline optics.

While the physics of focusing light is the same for all wavelengths, using EUV light takes special considerations. Since there aren’t any useful transparent materials for EUV light, these lenses rely on curved mirror surfaces with tailored resonant-reflective multilayer coatings formed from alternating layers of molybdenum and silicon, just a few nanometers thick: nearly 70% reflectivity can be achieved with Mo/Si multilayers near normal incidence. EUV lens designs are similar in concept to optical reflector telescopes, with multiple concave and convex mirrored surfaces. Furthermore, EUV optics must operate in vacuum, due to sub-mm absorption lengths in air. Ultra-high vacuum (UHV) cleanliness preparations are also necessary to prevent the build-up of carbon contamination that can absorb light and rob EUV optics of their efficiency.

The fact that EUV wavelengths are 14 times smaller than those used by current lithographic tools presents its own challenges. Despite numerous technical advances, scale remains the funda-
mental issue for EUV optics: the quality of a lens must be measured in relation to the wavelength of the light it focuses. Therefore it is extremely difficult to make, test, and align these advanced lenses. Optical aberrations arise from surface imperfections and misalignment, and from coating-thickness errors: even aberrations of tenths of a nanometer can cause significant image blurring. The problem of scattering from surface roughness also grows worse with shrinking wavelengths.

A decade ago, the lens-making technologies necessary to produce surfaces accurate to a tenth of a nanometer over areas of hundreds of square centimeters had yet to be developed. Since then, research in advanced visible-light (at LLNL) and EUV (at LBNL) metrology techniques has been applied to the fabrication and optimization of a series of nine prototype EUV lenses with increasing quality and resolutions down to 12nm half-pitch.\(^1\) Interferometry is the most widely-applied and important class of coherent measurement techniques for optical systems. Using a laser or other coherent light source, wavefront aberrations acquired upon propagating through a test lens are compared interferometrically with an unaberrated reference wave. Producing and calibrating reference waves of sufficiently high quality proves to be the greatest measurement challenge.

Borrowing ideas in optical testing that predate the advent of lasers, our group at LBNL has developed ultra-high-accuracy EUV testing techniques. Using a laser or other coherent light source, wavefront aberrations acquired upon propagating through a test lens are compared interferometrically with an unaberrated reference wave. Producing and calibrating reference waves of sufficiently high quality proves to be the greatest measurement challenge.

Both these interferometers share a common-path design that reduces sensitivity to vibration, and accommodates short EUV coherence lengths. With advantages in efficiency and simplicity of alignment, the LSI is self-referential: the aberrated test wave is compared with two orthogonally-displaced copies of itself at once, enabling test wave reconstruction from directional-derivative measurements.\(^2\) The PS/PDI uses high-quality pinhole spatial filters in the object and image planes to generate spherical reference waves. Along with the insertion of a grating beamsplitter to produce multiple beams, the PS/PDI adds a narrow aperture in the image plane to transmit the test beam. With image-plane pinholes as small as 25nm, the PS/PDI requires precise nano-positioning, yet it has become the accuracy standard in our laboratory.

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We believe these testing methods are broadly applicable to the advancement of short-wavelength optical systems. Beyond synchrotron sources, these techniques should be adaptable to alternative EUV and soft x-ray light sources now under development. Riding the coat-tails of photolithography, and bolstered by newly developed high-accuracy visible-light interferometry techniques\(^3\) and EUV metrology tools, diffraction-limited EUV optical systems able to focus light down to 25nm or below are possible today.

P. Naulleau of SUNY Albany, E. Anderson and D. Attwood of LBNL, and J. Taylor of LLNL, among many others, have been instrumental in this work.

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Dr. Goldberg received an A.B. degree in Physics and Applied Mathematics, and a Ph.D. in Physics from the University of California, Berkeley. His primary research interests include the application and development of optical techniques at EUV wavelengths, including ultra-high accuracy interferometry, EUV lithography research, synchrotron radiation, and optical system modeling. He has presented at numerous SPIE lithography conferences, served on several program committees, and co-chaired the 1999 SPIE Annual Meeting conference on EUV Multilayers and Gratings.

References


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