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

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Headline:

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Summary:

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

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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, and it also depends strongly on the wavelength or color of the light itself. Use shorter wavelengths of light, and the potential for higher resolutions beckons. From visible-light, to ultraviolet (365 nm), and onward to deep ultraviolet wavelengths (248 and 193 nm), the lithographers who mass-produce semiconductor micro-chips have pushed this trend toward higher resolutions. Lithographers worldwide are now preparing to bring extreme ultraviolet (EUV) optics, operating at 13.5-nm wavelength, 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 taking place 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 beyond lithography, including space telescopes for astronomy, materials science investigations at length scales in the tens of nanometers, and synchrotron beamline optics, among other applications.

While the physics of light focusing is the same for all wavelengths, using EUV light requires many special considerations. Since no useful transparent materials exist for EUV light, this special class of lenses relies on curved mirror surfaces with specially 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 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 set of challenges. Despite numerous technical advances, for EUV optics there remains a fundamental challenge of scale: the quality of a lens must be measured in relation to the wavelength of light it focuses. Therefore the difficulty of making, testing, and aligning these advanced lenses is itself extreme. Optical aberrations arise from surface imperfections and misalignment, and from coating-thickness errors—even angstrom-scale aberrations can cause significant image blurring. Scattering from surface roughness is also a problem that grows worse with shrinking wavelengths.

A decade ago, the lens-making technologies necessary for angstrom-scale surface accuracy over large areas (hundreds of square centimeters) had not yet been developed. With a goal of unprecedented high accuracy, research in advanced visible-light (at LLNL) and EUV (at LBNL) metrology techniques has since been applied to the fabrication and optimization of a series of nine prototype EUV lenses with increasing quality and resolutions down to 12-nm 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 pioneered the development of new ultra-high-accuracy EUV testing techniques. To gain the highest sensitivity, we measure at the operational EUV wavelength of the systems under test (i.e. *at-wavelength*). We use both grating-based lateral-shearing interferometry (LSI),[2] and phase-shifting point-diffraction interferometry (PS/PDI),[3] with a series of carefully conducted null-tests, to achieve RMS accuracy levels down to 0.4 Å for primary aberration terms. The accuracy has been verified repeatedly through high-resolution imaging (i.e. lithographic printing) and by cross-comparison with visible-light interferometry.

For these two interferometers, a *common-path* design 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 ads a narrow aperture in the image plane to transmit the test beam. With image-plane pinholes as small as 25-nm, the PS/PDI requires precise nano-positioning, yet it has become the accuracy standard in our laboratory.

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 coattails of photolithography, and bolstered by newly developed high-accuracy visible-light interferometry techniques[1] and EUV metrology tools, diffraction-limited EUV optical systems able to focus light down to 25-nm or below can be available 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.

References:

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The following is an eps figure. Some parts were rendered at 600 dpi.
Filename: EUV_interferometers2005B2.eps

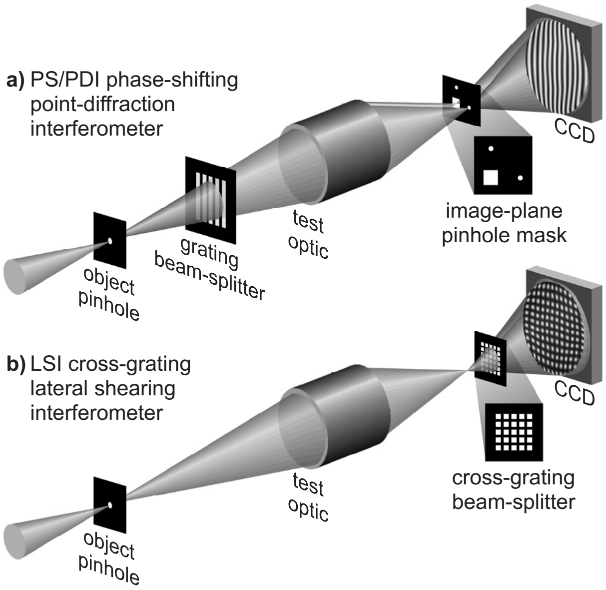

Figure 1. The essential optical elements of the **(a)** PS/PDI and the **(b)** LSI interferometers. Light is incident from the left.