Extreme ultraviolet interferometry: measuring EUV optical systems with sub-Å accuracy

K. A. Goldberg[1], P. Naulleau[1], P. Denham[1], S. B. Rekawa[1]
K. Jackson[1], P. Batson[1], E. H. Anderson[1], D. T. Attwood[1,2], J. Bokor[1,2]
[1]Center for X-Ray Optics, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[2]EECS Department, University of California, Berkeley, California 94720, USA

INTRODUCTION

The semiconductor manufacturing industry has selected extreme ultraviolet (EUV) lithography as the leading candidate for circuit fabrication with critical dimensions below 70 nm, beginning approximately in the year 2007. Current photo-lithography technologies use much longer ultraviolet light wavelengths and achieve critical dimensions as small as 130-nm. Research conducted during the past decade has demonstrated the feasibility of every aspect of EUV lithography, but some major challenges for its implementation still remain. Using such a short wavelength of light, dramatically reduces the error budget for the fabrication and assembly of projection lenses that focus and demagnify EUV images. The suggested RMS wavefront-error tolerances for EUV optical systems are in the $\lambda_{EUV}/50$ range (0.25 nm). The error tolerances on the individual mirrors that make-up such lenses are even tighter. Building optics of this unprecedented high quality is only possible if accurate measurement tools are available.

The EUV interferometers operating on ALS beamlines 12.0.1.2[1,2] and 12.0.1.3[3] have been designed to measure sub-angstrom-sized aberrations in EUV optical systems. In 2002, scientists from LBNL's Center for X-Ray Optics (CXRO) measured the second of two lithographic quality large-field EUV projection lenses.[4,5] These optics were designed an produced by a collaboration of Lawrence Berkeley, Lawrence Livermore (LLNL), and Sandia National Laboratories (SNL), funded by an industry consortium called the EUV LLC, which is comprised of Intel, AMD, Micron Technology, Motorola, IBM, and Infineon.

The optics are assembled and aligned using a state-of-the-art visible-light interferometer at LLNL,[6] and are then transported to the Advanced Light Source for measurement at EUV wavelengths. Because the EUV mirror coatings are specifically designed for high reflectivity in a narrow EUV wavelength range, measurements performed "at-wavelength" give essential feedback about the performance of the optic. EUV testing also provides an opportunity to validate the measurements made with visible-light interferometry. Through a careful comparison of the EUV and visible-light measurements, systematic measurement differences can be identified and resolved, and the accuracy of both systems can be improved.

A NOVEL EUV INTERFEROMETER DEVELOPED FOR ULTRA-HIGH-ACCURACY

Designed for exceptionally high-accuracy, the interferometers operating at Beamline 12.0 use the high brightness and coherence properties uniquely available at an ALS undulator beamline. Diffraction from tiny "pinhole" apertures placed at the foci of EUV beams, produces nearly perfect spherical waves that serve as reference waves in the interferometer. The interferometer compares these spherical reference waves to the aberrated waves produced by the optical system under test. Differences smaller than a tenth of an angstrom can be observed; the interferometer's reference-wave accuracy has been measured to be in the half-angstrom range.

Where high-brightness EUV light is available, the phase-shifting point-diffraction interferometer (PS/PDI)[7,8,9] has emerged as the high-accuracy system measurement tool of choice. A schematic of the optical design of the PS/PDI is shown in Fig. 1. Open-stencil pinholes smaller than 100-nm diameter are used to test the latest high-quality EUV optics. A coarse grating beam splitter placed before the test optic divides the beam into multiple diffractive orders that are brought to spatially separated foci in the image-plane. One beam, the *test* beam, containing the aberrations of the test optical system, is allowed to pass through a large window in an opaque mask placed in the image-plane. A second beam, the *reference* beam, is spatially filtered by a pinhole smaller than the diffraction-limited resolution of the test optic, and becomes the spherical reference wave. These two beams overlap to produce an interference fringe pattern that is detected by an EUV CCD detector. The interference pattern may be interpreted as a coherent comparison of the aberrated test beam with the nearly-perfect spherical reference beam; the fringe pattern thus reveals the aberrations in the test optic. Translation of the grating beam splitter is used to introduce a controlled relative phase-shift between the test and reference beams, allowing phase-shifting interferometry techniques to be employed.

The PS/PDI now serves as the accuracy standard for other EUV system metrologies, including visible-light interferometry and alternate EUV interferometry methods being pursued by the CXRO and others.

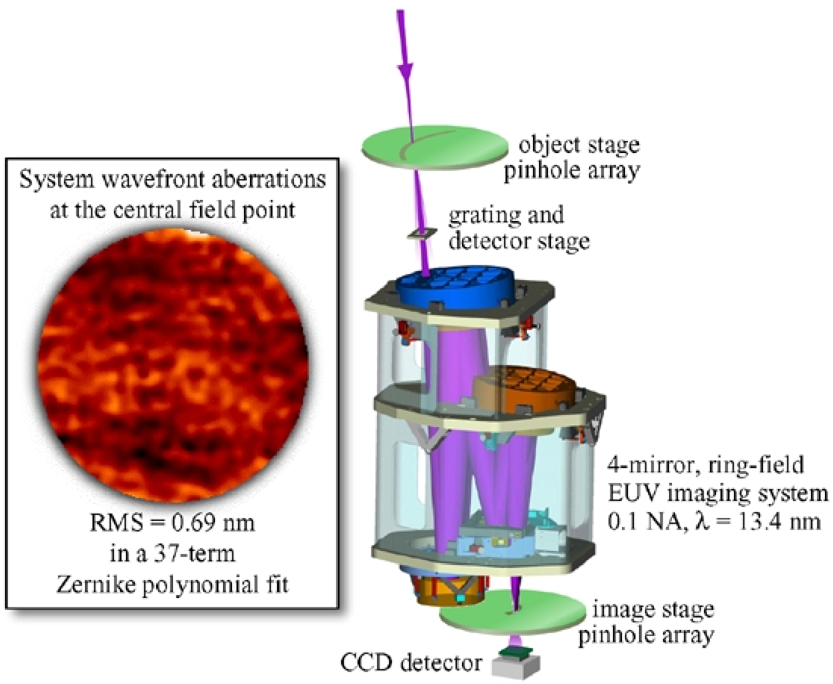

Figure 1. The extreme ultraviolet phase-shifting point diffraction interferometer (EUV PS/PDI) constructed at Beamline 12.0.1.3 for the measurement of lithographic quality projection optics for EUV lithography. The interferometer spatially filters coherent EUV light from ALS to produce reference wavefronts of exceptionally high spherical accuracy. System wavefront quality measurements are made across the large field of view. The aberration data is used to align the four-mirror system, and to predict imaging performance.

AN ACCURACY STANDARD FOR EUV OPTICS TESTING

In the future, as the quality and resolution of EUV optical systems improves, the demands on accurate wavefront metrology become ever higher. The high accuracy afforded by the EUV interferometry performed at ALS Beamline 12.0 can serve a major role in the development of alternate measurement techniques, both visible-light and non-synchrotron-based EUV methods. Since the ultimate proof of the accuracy of lithographic optical system testing comes from printing-based tests, the beamline's illumination system has been modified to accommodate printing experiments as well. These experiments are the subject of a separate abstract in this compendium.

REFERENCES

1. D. T. Attwood, P. Naulleau, K. A. Goldberg, E. Tejnil, C. Chang, R. Beguiristain, P. Batson, J. Bokor, E. M. Gullikson, M. Koike, H. Medecki, and J. H. Underwood, "Tunable coherent radiation in the soft x-ray and extreme ultraviolet spectral regions," *IEEE Journal of Quantum Electronics* **35** (5), 709-720 (1999).
2. K. A. Goldberg, E. Tejnil, S. H. Lee, H. Medecki, D. T. Attwood, K. H. Jackson, and J. Bokor, "Characterization of an EUV Schwarzschild objective using phase-shifting point diffraction interferometry," *Proc. SPIE* **3048**, 264-270 (1997).
3. K. A. Goldberg, P. Naulleau, P. J. Batson, P. Denham, J. Bokor, and H. N. Chapman, "EUV Interferometry of a Four-Mirror Ring-Field EUV Optical System," *Proc. SPIE* **3997**, 867-873 (2000).
4. P. Naulleau, K. A. Goldberg, E. H. Anderson, P. Batson, P. E. Denham, K. H. Jackson, E. M. Gullikson, S. Rekawa, and J. Bokor, "At-wavelength characterization of the extreme ultraviolet Engineering Test Stand Set-2 optic," *J. Vac. Sci. & Technol. B* **19** (6), 2396-2400 (2001).
5. K. A. Goldberg, P. Naulleau, J. Bokor, and H. N. Chapman, "Honing the accuracy of extreme ultraviolet optical system testing: at-wavelength and visible-light measurements of the ETS Set-2 projection optic," *Proc. SPIE* **4688-38**, (2002), *to be published*.
6. H. N. Chapman and D. W. Sweeney, "A rigorous method for compensation selection and alignment of microlithographic optical systems," *Proc. SPIE* **3331**, 102-113 (1998).
7. H. Medecki, E. Tejnil, K.A. Goldberg, and J. Bokor, Opt. Lett. **21** (19), 1526-28 (1996).
8. E. Tejnil, K.A. Goldberg, S. H. Lee, H. Medecki, P.J. Batson, P.E. Denham, A.A. MacDowell, and J. Bokor, *J. of Vac. Sci. & Technol. B* **15** (6), 2455-2461 (1997).
9. K. A. Goldberg, "Extreme Ultraviolet Interferometry," doctoral dissertation, University of California, Berkeley, 1997.

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For additional information: Kenneth Goldberg, Center for X-Ray Optics, Ernest Orlando Lawrence Berkeley National Laboratory. Email: KAGoldberg@lbl.gov. Telephone: 510-495-2261.