Nanoimaging with a compact extreme-ultraviolet laser

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Images with a spatial resolution of 120–150 nm were obtained with 46.9 nm light from a compact capillary-discharge laser by use of the combination of a Sc–Si multilayer-coated Schwarzschild condenser and a free-standing imaging zone plate. The results are relevant to the development of compact extreme-ultraviolet laser-based imaging tools for nanoscience and nanotechnology. © 2005 Optical Society of America

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Rapid progress in nanotechnology and nanoscience creates the need for new practical imaging tools capable of resolving nanometer-sized features. Short-wavelength light provides an opportunity to develop optical imaging systems with the highest resolution. The best resolution so far, 20 nm, has been obtained in imaging with soft-x-ray synchrotron radiation at 2.07 nm wavelength.[1] Submicrometer resolution was obtained with a soft-x-ray recombination laser,[2] and 75 nm resolution was reported with a low-repetition-rate (several pulses per day) laboratory-sized soft-x-ray laser.[3] There is, however, a need for the development of more compact and practical nanometer-resolution imaging systems. Toward this goal extreme-ultraviolet (EUV) light from high-order harmonic sources was used to demonstrate imaging systems with a resolution of better than 1 μm,[4,5] and soft-x-ray imaging with laser-plasma-based sources has been investigated.[6–8]

In this Letter we report what is to our knowledge the first demonstration of nanometer-scale imaging with a compact capillary-discharge pumped high-repetition-rate EUV laser. Spatial resolution of the 46.9 nm wavelength system is estimated to be 120–150 nm. This is to our knowledge the highest resolution achieved with a compact high-repetition-rate coherent EUV illumination source. The high average power ($\sim$1 mW) and multihertz repetition rate of the Ne-like Ar capillary discharge laser source that we used[9,10] allowed us to perform real-time imaging, for which the image is continuously updated on the computer screen at the rate of the laser pulses.

The imaging system is schematically illustrated in Fig. 1. It consists of a compact capillary-discharge 46.9 nm laser, a Sc–Si multilayer-coated reflective condenser, a zone-plate objective, and a CCD detector. The condenser, the imaged sample, and the objective were mounted onto motorized translation stages that were assembled inside a vacuum chamber connected to the EUV laser source with standard vacuum fittings. The illumination source is a compact capillary-discharge Ne-like Ar laser emitting at a wavelength of 46.9 nm with a pulse duration of $\sim$1.2 ns. Its short wavelength, narrow spectral bandwidth, high photon fluence, and beam directionality make this source well suited for microscopy. The spectral bandwidth of the laser is $\Delta\lambda/\lambda < 10^{-4}$.[9] The laser's output pulse energy and degree of spatial coherence depend on the capillary discharge length. For this experiment the laser was equipped with an 18 cm capillary discharge tube that provided an average pulse energy of $\sim$0.1 mJ. This choice of capillary length was made to ensure a sufficient photon

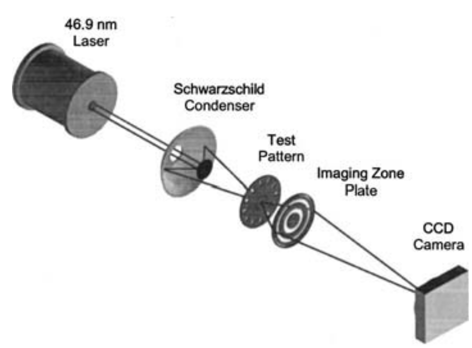

Fig. 1. Schematic representation of the EUV imaging system.

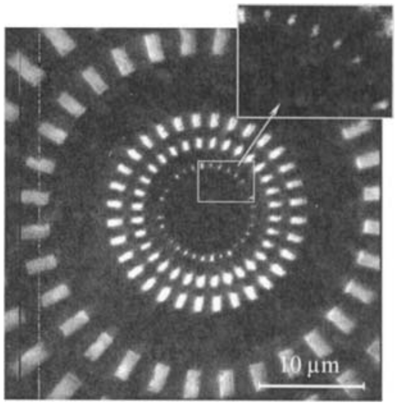

Fig. 2. Image of a ring test pattern obtained with a compact 46.9 nm capillary-discharge laser and a zone-plate-based imaging system with 200 nm outer zone width and 470× magnification. The orifices that compose the central ring of the test pattern have a width of ~100 nm. The exposure time was 10 s (10 laser shots).

flux while the coherence is kept relatively low[11] to prevent diffraction fringes and speckles in the images. The far-field laser beam profile has an annular shape with a peak-to-peak divergence of ~4.6 mrad. For most measurements the laser was operated at a 1 Hz repetition rate. The beam diameter was ~12 mm at the entrance of the microscope condenser, situated 1.6 m from the capillary exit. The background Ar plasma light was filtered with a 100 nm thick aluminum filter.

A Sc–Si multilayer-coated Schwarzschild objective with 0.18 numerical aperture was used as a condenser. Each of the two mirrors that compose the objective had a reflectivity of ~10% at 46.9 nm, resulting in a total condenser throughput of ~1%. This parameter can be improved, and the exposures that we report below could be significantly reduced by use of readily available coatings with reflectivities of 40%–50% at this wavelength.[12] The diameter of the small (primary) mirror of 10.8 mm is well matched to that of the laser beam at the objective location. The large (secondary) mirror, which sets the numerical aperture for illuminating the test sample, has a diameter of 50 mm. The condenser produces a hollow cone of EUV light that illuminates the selected sample. The microscope objective consisted of a free-standing imaging zone plate with a numerical aperture of 0.12. It was manufactured by electron-beam lithography into a 200 nm thick nickel film attached to a silicon frame. The imaging zone plate had a 0.5 mm diameter and an outermost zone width of 200 nm. Images produced by the zone plate were detected by a thermoelectrically cooled CCD camera with a backilluminated 1024×1024 array of 24 μm ×24 μm pixels. The CCD was positioned 0.53, 0.99, or 1.60 m away from the imaging zone plate to produce microscope magnifications of 250×, 470×, or 750×, respectively.

We imaged a specially designed transmission test sample that contains circular patterns of small openings; the smallest features are ~100 nm in size. This test sample was fabricated in a nickel foil by electron-beam lithographic techniques.[13] The same techniques were also used to write a free-standing zone-plate test pattern with outer zones of 200 nm lines and spaces. This test pattern is similar to the zone plate used as the objective in the imaging system. Figure 2 shows an image of the test pattern obtained in transmission mode with a magnification of 470×. To acquire this micrograph we focused the illumination beam to a 20–30 μm diameter spot on the sample. The image was obtained with 10 laser shots, for a 10 s exposure at a 1 Hz laser repetition rate. Under these conditions a good-quality image was produced, with the smallest, 100 nm, holes in the center of the pattern clearly discernible.

The spatial resolution of the microscope was evaluated on the images of the 200 nm line/space zone-plate test pattern [Fig. 3(b)] and on numerical simulation of the imaging system. The zone plate offers a set of alternating absorbing and transmitting zones with a periodicity that gradually decreases from the center to the periphery [Fig. 3(a)], reaching a 200 nm zone width at the edge [Fig. 3(b)]. Periodic structures

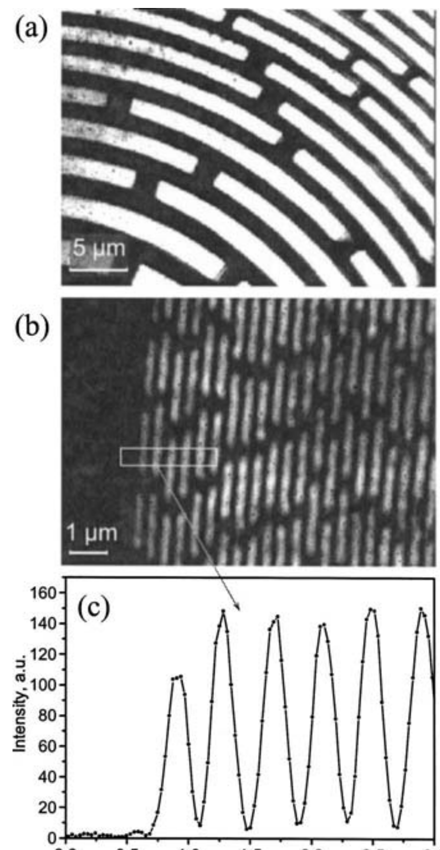

Fig. 3. Transmission mode images, obtained at 46.9 nm, of a free-standing zone-plate test pattern with outermost zones of 200 nm opaque and clear rings: (a) middle area (250× magnification), (b) outer region (750× magnification) with 200 nm outermost zones. (c) Image cross section obtained within the rectangle outlined in (b). The average modulation of the image is 94%, suggesting that the spatial resolution of the microscope is significantly better than 200 nm. Both images were obtained with 10 s exposure times.

such as this are often used to determine microscope resolution, which is done by reducing the period of the structure until the modulation of the corresponding image is reduced to some value, taken here to be 26.5% (Rayleigh-like modulation[14]). Modulation for the 200 nm zone-plate test pattern [Figs. 3(b) and 3(c)], determined by averaging 75 nearby areas of the image, was found to be 94%, suggesting that the resolution of the imaging system is significantly better than 200 nm. An accurate determination of the resolution requires imaging of smaller periodic structures that were not available at the time of the experiment. However, the simulations[15] indicate that the spatial resolution of the microscope is in the 120–150 nm range. To better match the assumption of the incoherent source that was made in the simulations, we operated the laser in a low-coherence regime, obtained by use of a short plasma column length (18 cm).[11] The imaging system described in this Letter can also be adapted for imaging in reflection mode with only minor modifications.

In conclusion, we have, for the first time to our knowledge, demonstrated nanoscale imaging with a compact high-repetition-rate EUV laser. The spatial resolution of the imaging system is estimated to be in the 120–150 nm range. These results demonstrate the feasibility of practical EUV imaging systems based on compact EUV laser sources for nanometer-scale metrologies and diagnostics. The combination of compact EUV lasers with state-of-the-art zone-plate optics has the potential for further improvements in the near future. We expect that the use of a recently demonstrated high-repetition-rate tabletop Ni-like Ag laser at 13.9 nm[16] will result in even better, sub-50-nm, spatial resolution.

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