Reflection mode imaging with nanoscale resolution using a compact extreme ultraviolet laser

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Abstract: We report the demonstration of reflection mode imaging of 100 nm-scale features using 46.9 nm light from a compact capillary-discharge laser. Our imaging system employs a Sc/Si multilayer coated Schwarzschild condenser and a freestanding zone plate objective. The reported results advance the development of practical and readily available surface and nanostructure imaging tools based on the use of compact sources of extreme ultraviolet light.

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1. Introduction

As nanotechnology rapidly advances, compact and practical tools capable of imaging at nanometer scales are of growing interest. Several high-resolution imaging techniques currently exist. Compared to electron and scanning tip microcopies, optical microscopy is advantageous in that the sample requires little preparation, images are rapidly rendered and the sample’s environment can be varied (e.g. exposed to an electromagnetic field). In particular, reflection mode optical microscopy provides readily accessible topographic information useful in the characterization of, for example, material surfaces, microelectronic integrated circuits, and lithographic masks. However, the resolution of conventional optical microscopes is limited by the wavelength of the illuminating source. To overcome this limitation several methods based on nonlinear optical effects, interference, and surface techniques, that improve the resolution of optical microscopy beyond the diffraction limit have been developed [1].

Higher resolution can also be achieved by using extreme ultraviolet (EUV) and soft x-ray light. Because in this spectral range the reflectivity of most materials is low, previous research at these wavelengths has typically focused on transmission mode imaging. In transmission mode the best resolution reported thus far, 20 nm, was obtained using 2.07 nm wavelength synchrotron radiation [2]. More compact sources, such as high order harmonic EUV sources [3,4] and laser plasma-based soft x-ray sources [5,6] have demonstrated the ability to resolve feature sizes below 1 μm. The best resolution obtained to our knowledge with a table-top EUV transmission microscope, ~ 120-150 nm, was recently demonstrated using a compact EUV laser as the illumination source [7]. In reflection mode, however, only a few experiments have been reported. A proof-of-principle experiment using a soft-x-ray recombination laser was carried out to demonstrate that differential reflectivity from material surfaces produces sufficient contrast in the EUV region [8]. Additionally, 13 nm synchrotron radiation was successfully used to image lithography masks in this mode [9] and to print features with resolution of 20 nm using annular illumination [10].

In this work we demonstrate the imaging of nanometer-scale features with a reflection mode table-top EUV microscope. The instrument utilizes a compact high average power, high repetition rate, 46.9 nm capillary discharge laser as an illumination source in combination with a Schwarzschild condenser and zone plate objective. The high pulse energy (~ 0.1-0.3 mJ at 4 Hz) of the laser source used in this work allows us to observe features on a 100 nm

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scale with a large field of view and exposures of only several seconds. The feasibility of obtaining reflection mode images with single shot laser illumination is also demonstrated.

2. Experimental setup

The optical system of the EUV microscope is schematically shown in Fig. 1. This reflection mode imaging system consists of a compact capillary-discharge EUV laser, followed by a Schwarzschild condenser that focuses the light onto a sample positioned at 45 degrees relative to the illuminating beam. A freestanding zone plate objective forms a magnified image of the sample onto a back-thinned CCD detector positioned at 90 degrees with respect to the source.

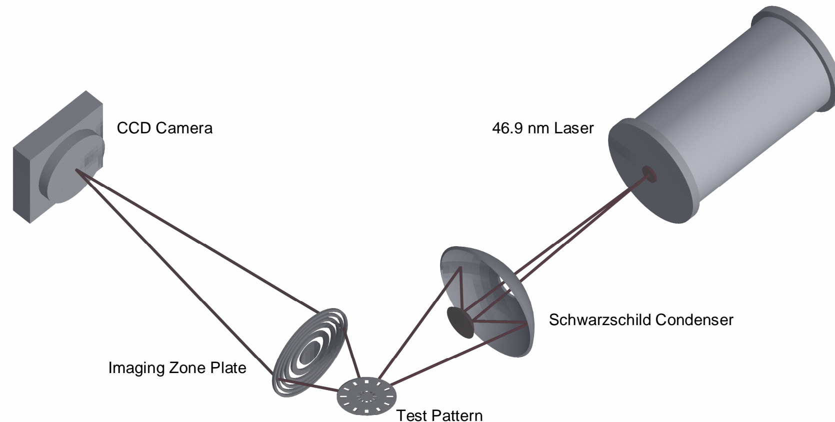

Fig. 1. Schematic representation of the compact extreme ultraviolet microscope.

The Sc/Si multilayer Schwarzschild condenser contains a primary convex mirror of 10.8 mm in diameter and a 50 mm secondary concave mirror. Together these two mirrors produce a hollow cone of 46.9 nm light that is focused onto the sample that is at ~ 5 cm from the output of the condenser. The Schwarzschild condenser has a numerical aperture (NA) of 0.18 and a throughput of only ~ 1%. This low throughput could be improved by at least one order of magnitude using Sc/Si multilayer coatings with the best reflectivity available at this wavelength, ~ 40% [11].

A freestanding zone plate was used as the imaging lens. The freestanding design maximizes throughput, as the use of any substrate material would significantly attenuate the 46.9 nm light. The zone plate was manufactured using electron-beam lithography onto a thin nickel foil attached to a silicon frame. It has a diameter of 0.5 mm, an outer zone width of 200 nm, and a NA of 0.12. The focal distance of the lens is 2.13 mm. To achieve high magnification of the imaging system (~ 480×) the working distance was chosen to be very close to the focal distance of the objective, ~ 2.14 mm.

The illumination source used is a table-top capillary discharge laser that emits radiation at a wavelength of 46.9 nm with a ~ 1.2 ns pulse duration and a spectral bandwidth of $\Delta\lambda/\lambda<1\times10^{-4}$ [12]. An Al_2O_3 capillary 18 cm long was used during most of the experiment, resulting in pulse energy of ~ 0.1 mJ [12]. Although a single laser shot produces a discernable image, most images were acquired by accumulating several shots to improve the signal-to-noise ratio and to illuminate a larger area on the sample. Nevertheless, since the laser can be operated at a repetition rate of several Hz, the exposure time was only several seconds.

The images were collected on a CCD camera with a back-illuminated 1024 x 1024 array of 24x24 μm^2 pixels. During the experiment the camera was thermoelectrically cooled to a

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temperature of -30° C to improve the signal-to-noise ratio. In this work the distance from the zone plate to the detector typically used is ~ 1 m.

Two different samples were imaged. The first consisted of a specially designed nickel test pattern with concentric apertures as small as 100 nm. This sample was produced with the same technique used to fabricate the zone plates. The second sample was a test structure consisting of polysilicon lines patterned on a Si wafer produced for the optimization of the lithography process for chip manufacturing. At a wavelength of 46.9 nm and an incidence angle of 45° the reflectivity of nickel and silicon are ~ 8 % and ~ 5 % respectively.

Coherence effects such as speckle and interference fringes are introduced whenever a laser source is used for imaging. The degree of spatial coherence of the laser used in this work can be modified by selecting the length of the capillary tube. At a capillary length of 36 cm the light is essentially fully coherent [13]. Initially in the experiment we made use of a capillary 27 cm in length, resulting in a high average pulse energy of ~ 0.3 mJ and a relatively high degree of spatial coherence. Using this configuration considerable coherence effects were noticeable. We found, however, that slight displacements of the condenser in the direction perpendicular to the beam during a multi-shot exposure significantly reduces these effects. To further reduce interference effects, the capillary length was decreased to 18 cm producing a lower coherence beam with pulse energy of ~ 0.1 mJ. Under this condition clear images with only a small amount of speckle and other interference effects were observed as can be seen in the figures below. The shorter capillary is preferable for recording images with a single shot exposure since, in this case, the condenser cannot be moved during acquisition. Single shot images were used to adjust different parameters (i.e. focusing of the imaging zone plate and condenser, and sample positioning) in a quasi-real-time manner at a rate limited by the acquisition time of the CCD. After establishing the best focus for a particular area of the sample, multi-shot exposures were used to improve the image quality.

3. Results and discussion

Figure 2 is an image of the Ni test pattern taken in reflection mode at a 45° angle of incidence with a magnification of 480×. The image was obtained accumulating 70 laser shots. To ensure complete illumination of the sample the condenser was slightly defocused and its position was continuously scanned during the acquisition. This scanning also helped to

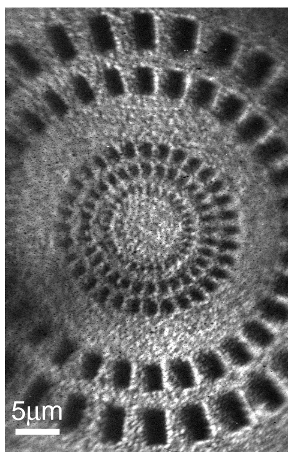

Fig. 2. EUV microscope image of a Ni test pattern image obtained at 45° with a magnification of 480×. For this image 70 laser shots were used with an exposure time of 70 seconds. The inner apertures are ~100 nm in size with ~ 800 nm separation.

reduce coherence effects in the image. As seen in Fig. 2 the 100 nm apertures with ~ 800 nm separation that form the inner ring are discernible. The image was digitally compensated for the horizontal distortion introduced by the angular placement of the sample. Notice that

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because the beam is not at normal incidence with respect to the sample, and the zone plate has a short estimated focal depth of ~3.5 μm, only a central ~ 10 μm wide vertical portion of the image is well defined.

An image of the silicon sample is shown in Fig. 3. The image was taken at an angle of incidence of 45° with a 20 second exposure. In the upper right corner of Fig. 3 (a), 100 nm polysilicon lines separated by 800 nm spaces are discernible, and in the lower right region, 250 nm lines with 250 nm separations are well resolved. Figure 3(b) shows an enlarged view of the 250 nm half-period lines. Even though the 100 nm lines can be seen in Fig. 3(a), their space/line-width ratio appears smaller than the value of eight corresponding to the structure in this sample. This can be attributed to the fact that the finest lines are narrower than the resolution limit of the instrument.

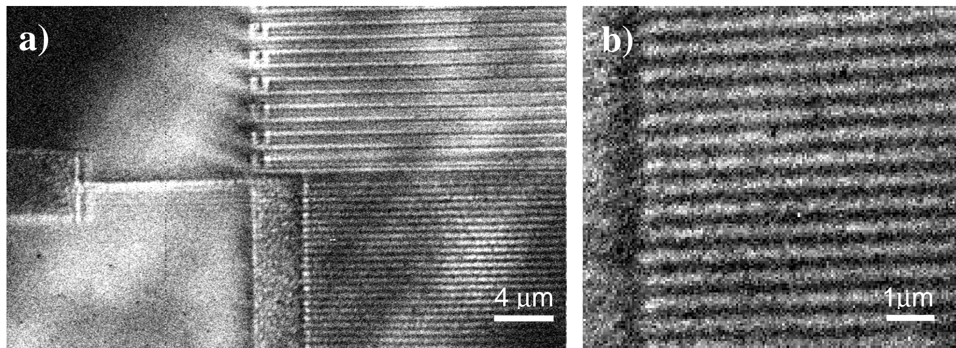

Fig. 3. (a) EUV microscope image of the silicon wafer with 100 nm polysilicon lines separated by 800 nm spaces (top right) and 250 nm half-period lines with equal lines and spaces. This image was obtained with an illumination angle of 45° with 200 nm outer zone objective using a 20 second exposure (20 laser shots) and a magnification of 480×; (b) enlarged view of the 250 nm lines/spaces.

The spatial resolution of an imaging system is often measured using periodic structures (gratings) with high contrast and sufficiently small period. Here the resolution is defined as the half period of a dense (1:1) pattern that results in a 26.5 % modulation of the image [2] (Rayleigh-like modulation). Analysis of the image in Fig. 3 shows that the modulation obtained for the 250 nm half-period lines is better than 60 %, thus suggesting that the resolution of the imaging system is better than 250 nm. An accurate determination of the microscope's spatial resolution in reflection mode requires imaging of smaller periodic structures with high reflection contrast that were not available at the time of the experiment. However, the spatial resolution of the same instrument in transmission mode was estimated to be in the 120-150 nm range [7]. We expect that the reflection mode resolution is similar.

The potential of the imaging system described here for a single shot mode is demonstrated in Fig. 4. In this mode the coherence effects were not mitigated by the scanning of the condenser position due to the very short (1.2 ns) duration of the laser pulse. Therefore with a longer plasma column of 27 cm that corresponds to a regime of relatively high coherence the image is affected by speckle (Fig. 4(a)). With a shorter, 18 cm, plasma column the spatial coherence of the source is significantly lower, thus resulting in a better quality image (Fig. 4(b)). It should be emphasized that the images shown in Fig. 4 were obtained with a very low, ~ 1 %, throughput condenser. We expect that throughput can be increased by a factor of 10 with improved coatings. The single shot mode of operation has proved to be extremely helpful for quick alignment of the imaging system with the laser running at 1 Hz repetition rate. This result demonstrates the feasibility of the development of a laser based high resolution EUV microscope capable of obtaining images of surfaces in quasi-real time regime at a rate mainly limited by the readout of the CCD detector.

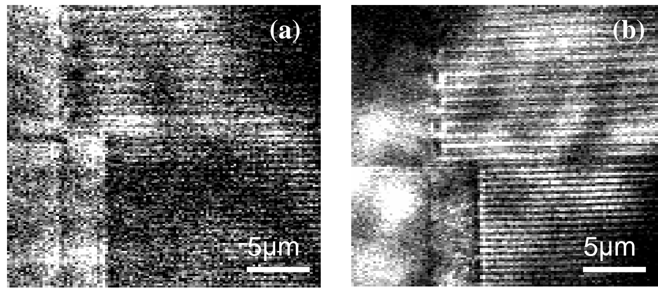

Fig. 4. Single shot EUV microscope images of a silicon wafer with polysilicon lines obtained with (a) 27 cm and (b) 18 cm discharge capillary lengths. Shorter capillary length results in reduced coherence and improved image quality. The images were taken at 45° reflection angle with the 200 nm outer zone width objective zone plate.

4. Conclusions

In conclusion, we have achieved high resolution reflection mode imaging using a compact EUV microscope composed of a table-top EUV laser, a Schwarzschild condenser, and a freestanding zone plate objective. Images of both a nickel test pattern and a silicon wafer with features as small as 100 nm were obtained. Even though the reflectivity of these materials at 46.9 nm is low, the high photon flux of the EUV laser allowed us to obtain good quality images with exposures lasting only several seconds. The use of improved Sc/Si coatings on the condenser mirrors will readily allow high quality images to be obtained using a single laser shot with large field of view and better contrast. Moreover, the use of a zone plate with 50-100 nm outer zone widths should allow sub-100 nm resolution [2]. The combination of the above mentioned improvements may allow the development of a compact sub-100 nm resolution EUV microscope capable of inspecting surfaces in a quasi-real-time manner at a rate limited by the acquisition time of the CCD. These results and the recent demonstration of compact high repetition rate extreme ultraviolet laser sources operating in the gain-saturation regime at wavelengths as short as 13.9 nm [14] will likely enable the fabrication of compact diagnostic tools to probe surfaces with sub-100 nm features for nanotechnology, lithographic mask inspection, and material characterization.

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