First stage in the development of a soft-x-ray reflection imaging microscope in the Schwarzschild configuration using a soft-x-ray laser at 18.2 nm

D. S. DiCicco, D. Kim, R. Rosser, and S. Suckewer

Princeton Plasma Physics Laboratory and Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey 08543

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We present results that demonstrate the proof of principle of a soft-x-ray reflection imaging microscope in the Schwarzschild configuration. A soft-x-ray laser operating at 18.2 nm was used as the x-ray source. Mo/Si multilayer mirrors with a normal-incidence reflectivity of ~20% per surface at 18.2-nm wavelength were used in the Schwarzschild objective.

The main interest in developing a soft-x-ray reflection imaging microscope is its potential application to the high-resolution inspection of lithographic products and the observation of surfaces (or membranes) of biological cells. Significant efforts are being made in the United States and elsewhere to produce integrated circuits with a 0.25-μm feature size, which is resulting in an increased demand for the detection of defects in production masks and circuits with a precision of 0.1 μm or better. Also, many scientists in the biological community are interested in gaining a better understanding of the structure and dynamics occurring at cell membranes. A soft-x-ray reflection microscope, which benefits from a revolution in x-ray technology,[1] could address these needs.

Although reflectivities of materials in the soft-x-ray spectral region are generally low, there is a significant variation in the reflectivity from material to material. One may take advantage of this inherent contrast mechanism by building a microscope that images heterogeneous specimen surfaces by means of reflection. This principle may also be applied to biological cells that have been labeled with a high-Z material (e.g., gold). The differential reflectivity between constituent elements (carbon, oxygen, and nitrogen) and labeling materials should provide a good contrast image.

Three optical configurations have been investigated for use in high-resolution x-ray imaging: Wolter,[2,3] zone-plate,[4] and Schwarzschild configurations.[5] The Schwarzschild configuration, unlike a zone-plate configuration is an achromatic system. The Schwarzschild configuration also makes it possible to construct an objective with no spherical aberration, astigmatism, or coma.[6]

Several attempts have recently been made to develop x-ray optical systems based on Schwarzschild objectives.[7–10] These experiments have used a synchrotron[8,10] or laser-produced plasmas[7,9] as x-ray sources. The Schwarzschild optics have been used in various ways: as imaging optics,[7] as a demagnifier,[8] and as focusing optics.[9] A multilayer-coated Schwarzschild objective with a synchrotron x-ray source has also been used to form the probe beam for a scanning photoelectron microscope.[10] Spatial resolutions of 0.2–0.5 μm have been demonstrated in the x-ray experiments, while the photoelectron microscope has demonstrated a resolution of 2–3 μm.

In this Letter we present an important step toward the development of a new idea, the soft-x-ray reflection imaging microscope.[11] A soft-x-ray laser developed in 1984 at Princeton University[12] was used as the x-ray source. The Schwarzschild optics used in our experiments were manufactured by T.R. Optics, Ltd.[13] The optics were polished to a very high surface finish (~0.5-nm rms surface roughness). The Schwarzschild objective is made of a large concave mirror and a small convex mirror. The diameter of the concave mirror is 66.3 mm, and its radius of curvature is 68.5 mm. The convex mirror is 14.5 mm in diameter with a radius of curvature of 23 mm. The objective has a numerical aperture of 0.4 and a focal length of 14 mm. The multilayer coating and the measurement of its reflectivity[14] were done by the Advanced Optics Group of the Lawrence Livermore National Laboratory. The multilayer coating consists of 15 layer pairs of molybdenum and silicon whose thicknesses are ~3 and ~9 nm, respectively, with a measured normal incident reflectivity of $R \approx 20\%$ at 18.2 nm.

The Schwarzschild objective was used in two sets of experiments. The purpose of the first set of experiments was to test the objective in a transmission imaging configuration. The goal of the second set of experiments was to demonstrate the principle of a soft-x-ray reflection microscope. Figure 1 shows the experimental setup in which the transmission imaging experiments were performed. The 18.2-nm soft-x-ray laser has a rather large divergence (5–10 mrad)[12] as a result of the single-pass amplification (it does not have cavity mirrors around the gain medium). A one-to-one transfer ellipsoidal grazing-incidence mirror was used to collect and

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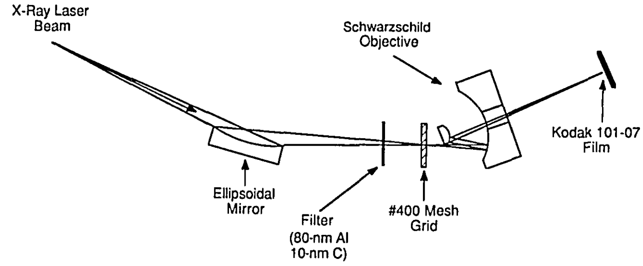

Fig. 1. Experimental layout in the transmission imaging configuration. The Schwarzschild mirror system was tilted at 15° off axis because the numerical aperture of the focusing ellipsoidal mirror is smaller than that of the central obstruction of the Schwarzschild mirror system.

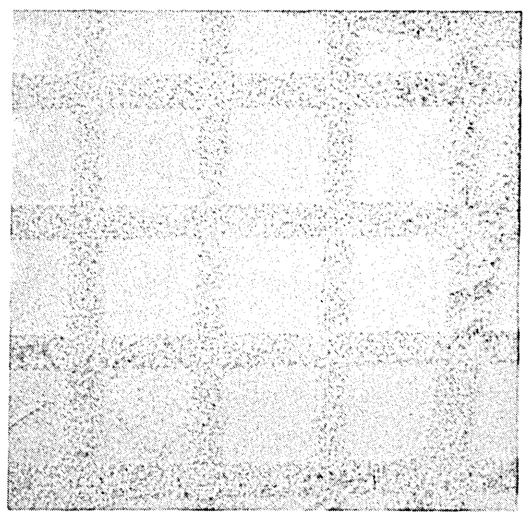

Fig. 2. Photograph of image of a TEM #400 copper grid with a magnification of 22 recorded on Kodak 101-07 x-ray film in the transmission imaging configuration.

focus the 18.2-nm radiation onto a copper transmission electron microscope (TEM) 400-mesh grid. The transfer mirror was fabricated from an aluminum substrate that was diamond turned to an ellipsoidal shape, plated with nickel, and finally coated with rhodium. The mirror assembly has four translators for precise control of the mirror position. The numerical aperture of this ellipsoidal mirror is 0.1. Since the numerical aperture of the central obstruction of the Schwarzschild mirror system used in this experiment is larger (0.17) than that of the ellipsoidal mirror, the Schwarzschild mirror system was tilted at 15° off axis. An 80-nm-thick aluminum filter, with 10 nm of carbon as the base film, was placed before the copper grid (period 63 μm) to block VUV, UV, and visible light. The transmission of the filter is ~50% at 18.2 nm. The grid was illuminated by light passing through the filter and imaged by the molybdenum/silicon multilayer-coated Schwarzschild mirror system with a magnification of 22 onto Kodak 101-07 x-ray film. Figure 2 shows the recorded picture. After we obtained the image as shown in Fig. 2, we intentionally reversed the x-ray film to double check that the exposure was due to x rays. Any longer-wavelength light (especially visible light) passing through the aluminum filter in front of the TEM grid would have exposed the reversed x-ray film (the film backing is thick enough to absorb the 18.2-nm radiation before it reaches the emulsion surface). We did not observe any exposure with the film reversed. Owing to the much lower beam energy of the 18.2-nm soft-x-ray laser than at its best performance, multiple shots (eight) were required to record a picture with the level of contrast shown in Fig. 2. The specimen field of view is 1.3 mm × 0.7 mm. The image was scanned with a densitometer to produce the trace shown in Fig. 3. The spatial resolution was found to be ~0.7 μm at 25–75% contrast. However, we should stress here that this proof-of-principle experiment was not set up to produce a high-resolution image.

Once the Schwarzschild objective was shown to function properly, the optics were rearranged to the reflection imaging configuration shown in Fig. 4. The 18.2-nm laser beam was aligned to a reflection object that was constructed by evaporating gold onto a polished glass surface through a TEM 200-mesh grid. The angle of incidence of the 18.2-nm laser beam to the reflection object was limited by our vacuum chamber adjustment to 70° (or an angle of 20° between the reflection surface and the incident beam), at which the reflectivities of gold and a glass are calculated to be ~35% and ~1.5%, respectively. The difference in the reflectivity at this angle between gold and glass is large enough to produce a

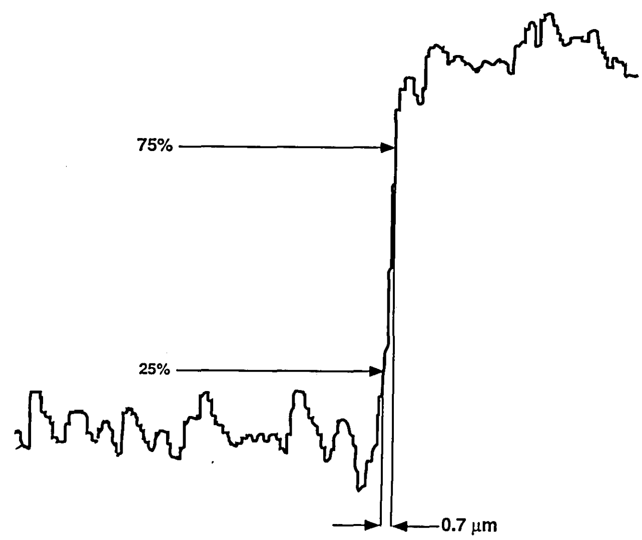

Fig. 3. Densitometer scan of the image shown in Fig. 3. A spatial resolution of 0.7 μm is demonstrated at 25–75% contrast.

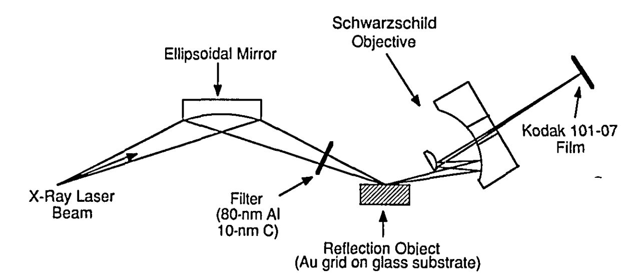

Fig. 4. Experimental layout in the reflection imaging configuration. The angle between the reflection surface and the incident beam is set to be 20°. The Schwarzschild mirror system was tilted at 15° off axis.

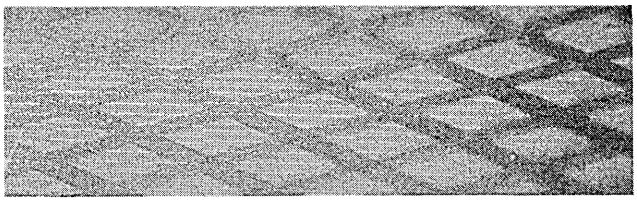

Fig. 5. Photograph of image of a reflection object in the reflection imaging configuration. The reflection object was constructed by evaporating gold onto a polished glass surface through a TEM #200 grid. The image was recorded on Kodak 101-07 x-ray film. The dark lines represent the glass part of the reflection object, while the white areas represent the gold part. The magnification was 16 in this case.

good contrast image. A positive print of the image of the reflection object recorded on Kodak 101-07 x-ray film is shown in Fig. 5. The dark lines represent the glass part of the reflection object, while the white areas represent the gold part.

In conclusion, we have verified the operation of our Schwarzschild objective using an 18.2-nm laser. The same optics were used to demonstrate the feasibility of a soft-x-ray reflection microscope that relies on differential reflectivity from material surfaces for contrast. Further efforts are already under way to increase the magnification from 16 to 100, to obtain higher resolution, and to incorporate a CCD detector to replace the x-ray film.

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D. S. DiCicco and R. Rosser are also with Princeton X-ray Laser, Inc., 1-H Deerpark Drive, Monmouth Junction, New Jersey 08852.

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