Synchrotron beamline for extreme-ultraviolet multilayer mirror endurance testing

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The lifetime of multilayer mirrors is an outstanding problem on the road to commercialization of extreme-ultraviolet (EUV) lithography. The mirrors are exposed to high-intensity EUV radiation in a vacuum with traces of water vapor and hydrocarbons. The combination of EUV and reactive species leads to chemical degradation of the mirror surfaces—carbon deposition and/or oxidation of the Si surface. In order to understand and quantify these processes, as well as to study mitigation schemes, we have constructed a dedicated synchrotron-based facility with the capability to deliver high-intensity EUV radiation in a variety of trace-gas atmospheres. The facility features a spherical Mo–Si coated mirror and a thin Be foil captured in a gate valve, which serves as both a spectral filter and vacuum seal. We will describe this facility and its performance. [DOI: 10.1063/1.1896225]

Extreme ultraviolet lithography (EUVL) is a leading candidate for next-generation lithography, likely to be in commercial production sometime after 2010.[1] This technology uses Mo–Si multilayer-coated mirrors working near normal incidence to collect radiation from a pulsed source and to reduce and focus an image from a reflective mask onto a resist-coated wafer. A major outstanding issue in the road to commercialization of EUVL is the lifetime of the multilayer mirrors.

Because of the tight alignment tolerances, the vacuum system housing the stepper cannot be baked to reduce the amount of residual water vapor present. Moreover, there is some outgassing of organics from the photoresist. The presence of these reactive species, along with high-intensity ionizing radiation, leads to degradation of the mirror surfaces. The cracking of hydrocarbons, which leads to thin carbon overlayers, can be reversed using reactive oxygen or ozone.[2] Water vapor, however, leads to oxidation of the Si cap layer, which is an irreversible process.

Several schemes have been proposed to avert the damage done to the mirrors by the residual gas/EUV radiation combination. Among these, admission of a low partial pressure of reactive gas and capping layers of noble metals appear very promising. A background of ethanol of the appropriate pressure appears to form a dynamic graphitic monolayer that both getters oxygen from the surface and prevents too large a buildup of cracked hydrocarbons.[3] To date, ruthenium-capped multilayers show very good resistance to oxidation and virtually no reduction in initial reflectivity.[4]

The ability to quantitatively test the lifetimes of mirrors is critical for discovering the proper mitigation schemes. Because the surface damage is believed to be due primarily to secondary electrons rather than direct photon excitation,[5] most long-term testing is currently done with low-energy electron beams.[6] It is desirable, however, to have a long-term testing facility that uses EUV radiation, both for testing purposes and to determine the equivalence between EUV and electron-based damage mechanisms.

We have constructed a facility at the National Institute of Standards and Technology Synchrotron Ultraviolet Radiation Facility (SURF III) electron storage ring. The facility is capable of delivering up to 5 mW of inband radiation to a spot about 0.6 mm by 0.8 mm. We are able to measure incident radiation, reflectivity, and the photoemission from the surface of the sample. We will describe the design of the facility and its performance.

In order to maximize the intensity on the sample, several requirements must be met. Under normal operation SURF III has a large electron-beam size, about 1 mm by 3.5 mm [full-width half-maximum, (FWHM)], so we must have significant demagnification. A large solid angle must be collected, and the focusing and demagnifying must be done by an optic with minimal aberrations. Moreover, the radiation must be in the band of the multilayer reflectivity, so some wavelength selection must occur.

In order to simulate the environment of a stepper, some impurity gases must be introduced into the sample chamber. Mitigating reactive gases may also be necessary. Because the front end of the beamline must be extremely clean and ultrahigh vacuum, very good isolation between the sample chamber and the front end is absolutely essential.

The layout of the beamline is shown in Fig. 1. The only optical element is a multilayer-coated sphere with a 75 mm diameter and 1.5 m radius of curvature. Located 4.5 m from the electron-beam tangent point, it intercepts almost 17 mrad of the output of SURF III. The vertical emittance is about 3 mrad at 13 nm, so all of the vertical emittance is collected. The radiation is incident at an angle of 10° from the normal, and is focused 90 cm from the mirror. The sample is held on an *x*-*y*-*z*, bellows-sealed translation stage within a separate sample chamber. Incident and reflected power are measured using a calibrated Zr-coated, EUV-sensitive Si photodiode and read by a picoammeter. Photoemission from the sample

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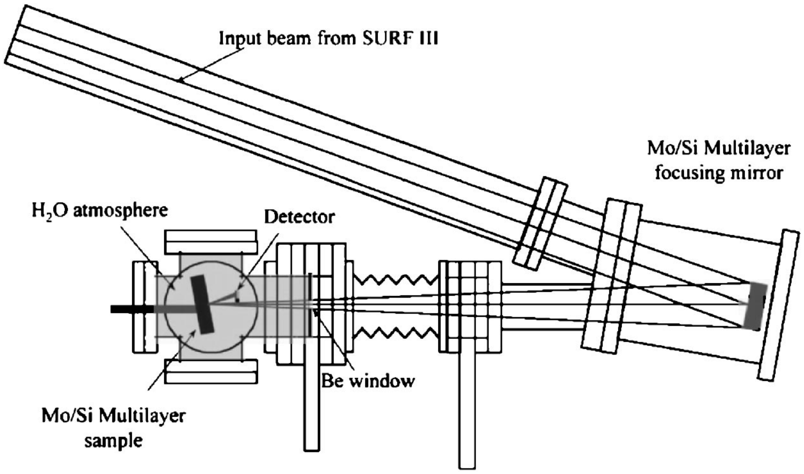

FIG. 1. Layout of multilayer exposure beamline.

surface can be measured by biasing a collector 3 mm from the sample surface and reading the current emitted from the surface of the sample with a picoammeter.

Because we introduce reactive gases into the exposure chamber, there must be good vacuum isolation between it and the upstream parts of the beamline to avoid degradation of the focusing optic and contamination of the beamline and SURF III. This isolation is done in most facilities by differential pumping—that is, a small aperture (or apertures with pumps inbetween) between the sample chamber and the rest of the beamline. However, we must be able to place a monitor photodiode in the incoming beam, so any aperture must be at least 20 cm from the sample. At this distance, our beam is about 2 cm wide, so it is not possible to run with a small aperture. Therefore we use a 0.25 μm Be filter for vacuum isolation. The filter can withstand very little pressure difference, so it must be withdrawn while the chamber is being pumped out. To accomplish this, we mount it in a 75-mm-diam aluminum disk that is captured in the gate of a valve that had originally had a captured window. The filter can tolerate a few pumping cycles in this configuration. Moreover, it can hold off 10^{-3} Pa (10^{-5} Torr) while the pressure on the other side of the filter is still 10^{-7} Pa (10^{-9} Torr). A single filter can withstand several kJ of incident EUV fluence in the presence of 10^{-4} Pa (10^{-6} Torr) of water vapor and sustain just minor pinholes. The pinholes still allow no detected upstreaming of water vapor while allowing less than 1% of out-of-band radiation incident upon the sample. We have recently begun depositing 5 nm of Rh on the surface of the filter to reduce the reactivity of the water-vapor-facing surface.

SURF III is a single-magnet storage ring with a 1.676 m orbital diameter. The radiance is easily calculable, and the characteristics of all of the optical elements are measurable. The estimated spectrum incident upon the sample is shown in Fig. 2. This was modeled using the calculated output of SURF III, the geometry of the beamline, the measured reflectivity of the mirror, and the measured transmittance of the filter. The integrated power with 200 mA stored beam current is calculated to be 6.4 mW, as opposed to the measured incident power of 4.2 mW. Differences in these numbers are most likely due to small differences in geometry, reduced throughput due to baffles, and changes in the properties of the optical components.

The optical configuration of the beamline was modeled using a ray tracing program in order to determine the performance of the system and determine the effects of varying the electron spot size of SURF III and varying the image distance between the focusing optic and the sample. The model predicts a focal spot size of 0.95 mm by 0.85 mm (FWHM).

The beam profile at best focus is shown in Fig. 3. This

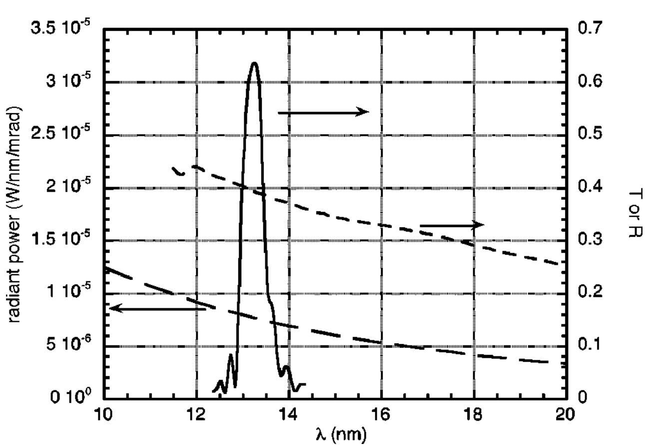

FIG. 2. Reflectance of multilayer mirror (solid line), transmittance of Be filter (short-dashed line), and calculated radiant power of SURF III (long dashes), which are used to calculate the incident spectrum and total throughput of the exposure beamline.

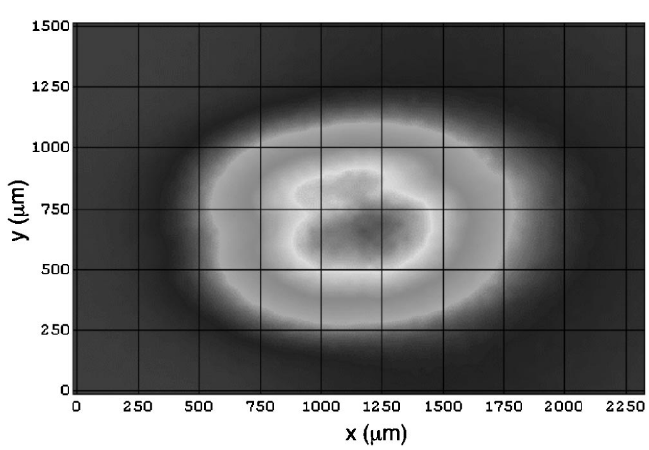

FIG. 3. Measured beam size at the sample plane, obtained using a Nd:YAG scintillator crystal with a 0.5 mm period reticle.

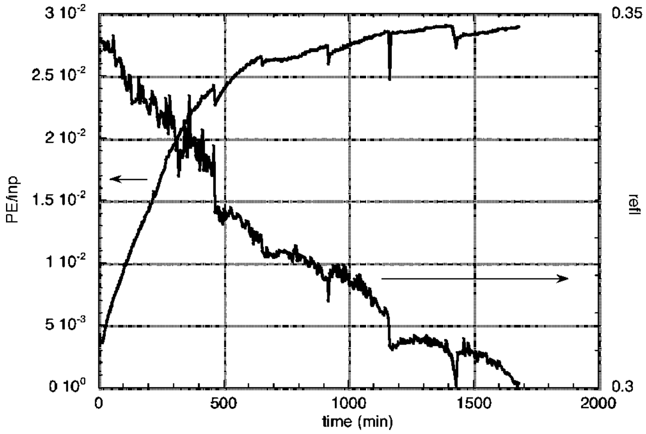

FIG. 4. Reflectance (squares) and normalized photoemission (circles) from a MoSi multilayer test sample.

image was obtained using a Nd: yttrium–aluminum–garnet (YAG) scintillator crystal with a 0.5 mm period reticle. From this we estimate that 75% of the incident power falls within an ellipse of 0.6 mm by 0.8 mm. This compares favorably with the estimated spot size of 0.95 mm by 0.85 mm obtained by ray tracing. The discrepancy between the model and experimental observations are assumed to be due to uncertainty in determining the electron-beam tangent point to collection optic distance and collection optic angle of incidence.

Data obtained during a 30 h exposure of a standard Mo/Si multilayer mirror are shown in Fig. 4. This figure shows the real-time reflectivity and secondary electron emission from the multilayer exposed within a water atmosphere of 2×10^{-4} Pa (2×10^{-6} Torr). The initial measured reflectance of 34.7% seems startlingly low. However, since the illumination is not with monochromatic radiation, this does not represent a peak reflectivity, but an integrated reflectivity over the band pass of the beamline. This multilayer has a peak reflectivity of 61.9%, from which we would predict a measured reflectance of 43.5% if the peak wavelength of the sample occurred at the peak throughput of the beamline. However the peak of this multilayer is at somewhat longer wavelength than the peak throughput of the beamline, leading to the reduction in the measured value. Note also that the electron emission goes up with time while the reflected signal goes down. The increase in electron yield is due to oxidation of the Si capping layer and is typical behavior, and may be a useful indicator of reduction in multilayer performance. The 30 h exposure caused a relative reduction in reflectivity of nearly 13%, which is significant considering the current EUV stepper designs include eight or more normal-incidence reflections. Reflectivity degradation at the rate shown in Fig. 4 is too significant for the use in a commercial stepper. Characterization of degradation of this type is the reason for the development of the beamline described in this note; it is an essential tool for the development of radiation-hardened long-lifetime optics for use in EUVL.

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