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Beryllium Based Multilayers for Normal Incidence Extreme Ultraviolet Reflectance

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Abstract

We report the experimental results of beryllium based multilayer mirrors for use in the 11.4 nm region. Mirrors using molybdenum as the high-Z material have demonstrated 68.7% peak reflectance at 11.3 nm.

The need for normal incidence mirrors maintaining reflectance greater than 60% for an industrially competitive Extreme Ultraviolet Lithography (EUVL) system has been well documented. The Molybdenum/Silicon system has emerged as the de-facto standard, where researchers are now routinely fabricating mirrors demonstrating 63% reflectance near 13 nm. However, multilayer mirrors using beryllium as the low atomic number (low-Z) spacer could potentially show similar or better reflectance, and operate at wavelengths down to the beryllium K-edge at 11.1 nm. Besides offering potentially greater reflectance, the beryllium based multilayer mirrors can reflect shorter wavelength light, which potentially offers more desirable resist performance.

We report the peak reflectance measurements from beryllium based multilayer mirrors. The mirrors were fabricated at the Lawrence Livermore National Laboratory and tested at the Center for X-Ray Optics at Lawrence Berkeley Laboratory.

At wavelengths just longer than the silicon L-edge at 12.4 nm, Mo/Si is the near universal choice for normal incidence reflectance in the wavelength region useful for EUVL, with a theoretical peak reflectance about 76%. However, in the region down to 11.1 nm, beryllium based multilayers show theoretical reflectances even greater than that offered by Mo/Si. Using the closed form solution from Rosenbluth, or the iterative approach of Underwood and Barbee, along with the optical constants from Henke et al., one predicts 78-80% peak reflectance using beryllium with Ru, Mo, Rh, or Nb.

We have investigated the Mo/Be, Nb/Be, Ru/Be and Rh/Be systems. The multilayers were deposited in a cryopumped system with the axis of the guns and rotating
arm horizontal to minimize debris. The argon pressure during deposition was 2.5 mtorr. The target to substrate distance is 9.5 cm, and the substrate holder is water cooled and rotates at 0.15-0.25 Hz. The arm rotates back and forth over a range of 240 degrees, with a period of 59 seconds. We control layer thicknesses by modulating the power rather than the arm velocity for these studies. Depending on the power supplies and target materials used, we had a 0.1-0.5 nm layer thickness resolution at the substrate. The substrates were test quality 3" diameter (100) Si wafers.

It is possible that oxygen could become incorporated into the Be during sputtering or that the surface could become oxidized after exposure to air. We deposited a beryllium film onto a beryllium substrate and used Rutherford Backscattering analysis to determine the oxygen content within the film. We determined that there is approximately 3.0 nm equivalent of BeO on the surface, and that it is stable over the time period of these experiments.

We began a systematic investigation of the observed peak reflectance vs. the number of bilayers, $N$, for the Be/Mo system. We determined that Be as the last layer gave a higher reflectance than a comparable deposition ending in Mo. We did not investigate a time dependance for the reflectance of the the Mo-ending multilayer, but would expect a similar degradation as seen in the Mo/Si system$^6$.

Figure 1 shows the peak reflectance vs. number of bilayers. The circles represent the measured data, and the solid line through the data is from a numerical model. The model parameters were $d=5.75$ nm, $\Gamma=0.45$, $0.68$ nm RMS interface roughness, and $3.0$ nm of BeO on the surface. The data levels off at $N=70$ with $R=67.5\%$. A slight degradation in peak reflectance is seen with 80 and 90 bilayers, indicating that interfacial roughness is starting to increase. Also shown on this plot is a dashed curve for ideal interfaces with no surface oxide. This curve asymptotically approaches $R=78.1\%$. We found that the wavelength of peak reflectance changed by 0.3 nm from the center to the edge of the wafer, corresponding to a 0.15 nm d-spacing variation.

After determining that $N=70$ gave the maximum reflectance, we then adjusted $\Gamma$ to 0.36$\pm$0.02. The observed reflectance was $68.7\pm0.2\%$. This was the highest measured reflectance, and the reduced statistical uncertainty results from averaging more points at the wavelength of peak reflectance. We repeated this deposition onto a highly polished silicon wafer, but found no improvement in reflectance. Several of the films, which were stored in air, were remeasured over the four month duration of the experiments. We did not observe any loss in measured reflectance, within experimental error.

Figure 2 shows the reflectance measured from the multilayer referred to in the last paragraph, along with a simulation. Note that the d-spacing which best simulates the measurements is 5.72 nm, which, with no refractive correction would show a peak at 11.44 nm. The observed peak at 11.3 nm indicates the necessity to account for a refractive shift to the wavelength corresponding to peak reflectance. We find excellent agreement between the measured and simulated data.

We also investigated Nb/Be mirrors with 50 bilayer pairs and $\Gamma=0.38$. We observed 57.5$\pm$0.3% for the mirror with Be as the last layer, and a reflectance of 54.0$\pm$0.3% for the mirror that ended in Nb. We did not continue with the Nb based multilayers, since for equivalent conditions, it appeared that the Mo/Be mirrors performed better than the Nb/Be mirrors.
Although the Mo/Be system appeared to be a promising candidate for our design goal of 70%, we wanted to investigate Ru/Be and Rh/Be multilayers. We found an interesting phenomenon with the Ru/Be system. On our initial deposition, we found that the peak reflectance was only 5%. We investigated the hard x-ray diffraction pattern and found that the Bragg peaks were split, indicating severe interfacial roughness and/or compound formation at the interfaces. We have seen in previous work with boron based materials that active cooling of the substrate improves interface quality; we decided to see if active cooling would improve the reflectance of the Ru/Be multilayer. We applied vacuum compatible, thermally conductive paste to the back of the silicon substrate and repeated the run. Under identical run conditions, this 40 bilayer mirror then showed a reflectance of 54%. Increasing the number of bilayers to 70 yielded a reflectance of 63%.

The Rh/Be system indicated interfacial problems even with active cooling. Hard x-ray diffraction scans of several calibration multilayers showed split and asymmetric Bragg peaks. The peak reflectance achieved for this system was 49.5% with 40 bilayers. We did not pursue further studies of this system.

We plan to continue to investigate the material combinations showing most promise for use in an EUVL system. Peak reflectance, bandwidth, angular acceptance, stability, and re-coating issues are parameters we plan to address.

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References

Figure 1. The peak normal incidence reflectance for the Mo/Be system as a function of the number of bilayers, N. The dashed curve is calculated for multilayers with ideal interfaces, and the lower curve results from a modeled interface roughness of $\sigma = 0.68$ nm, $d = 5.75$ nm, $\Gamma = 0.45$ and 3.0 nm of BeO on the surface. The points represent measured data.

Figure 2. The reflectance of a Mo/Be multilayer, $\Gamma = 0.36$, $N = 70$, ending in Be. The measured peak reflectance is 68.7$\pm$0.2% at 11.3 nm (dark line). The dashed line represents the modeled curve, using the parameters $d = 5.72$ nm, $\Gamma = 0.36$, $\sigma = 0.63$ nm, $N = 70$, 3.0 nm BeO on the surface.