Reflecting at 30.4 and Antireflecting at 58.4 nm

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Abstract: We investigated how antireflection (AR) using thin film interference can be achieved in the EUV for multilayer mirrors. This may not been much investigated since AR is not usually needed. AR is not as straightforward as in the visible and neighboring frequencies for several reasons. No materials are entirely transparent in the EUV (indeed materials commonly used in the visible are among the most opaque). The optical constants are not known as well (particularly for compounds), and the antireflection layers can decrease the desired reflection from the multilayer at the "called for" energy. Incorporation of impurities can also be a problem. Nevertheless AR has a role to play in some circumstances.
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1. Introduction

Seven years ago the IMAGE spacecraft was successfully launched and functioned for over 5 years studying the various plasma filled regions surrounding the earth (ionosphere to magnetosphere) in wavelengths from radio through EUV. We designed and coated mirrors for the Extreme Ultraviolet Imager (EUVI) instrument, which was one of about four observational components of the IMAGE Mission. IMAGE, which stands for Imager for Magnetopause to Aurora Global Exploration, was a NASA funded Medium Explorer (MIDEX) program) [1].

The Extreme Ultraviolet Imager was designed to study the distribution of cold plasma in Earth's plasmasphere by imaging the distribution of He+ ions through their emission/scattering at 30.4 nm [1]. The He+ 30.4 nm emission was a natural choice for remote sensing of the plasmasphere. He+ is the most abundant ion in the plasmasphere capable of scattering light. The He+ 30.4 nm feature is, in principle, easy to measure because it is the brightest ion emission from the plasmasphere, it is spectrally isolated, and the nearby background is negligible. We produced a set of U/Si multilayer (ML) mirrors with reflectance peaked at 30.4 nm for 14.5 ± 3.5 [2]. In conjunction with aluminum filters to block lines far from the peak an acceptable image was produced. Al blocks the brightest contaminating emissions, hydrogen Lyman alpha (H Lyα) from the geocorona and interplanetary medium, but not the He 58.4-nm (21 eV) feature, the brightest line from neutral helium. This is because aluminum is mostly transparent above 15 eV. We sought and, to a large measure, succeeded in blocking the 58.4-nm (21 eV) line by antireflection [2].

2. Development

Producing surfaces which deliberately exhibit antireflection beyond the UV is unusual. In the EUV and/or soft x-ray, near-normal incidence reflection is usually very low without the use of multilayer reflectors and MLs naturally are narrow band reflectors. Antireflection of neighboring frequencies is not commonly needed. However, there is often a reflectance of several percent for many materials for energies up to 20-25 eV. So the ML we produced naturally reflected some 58.4nm light. We found a decade ago that a very thin top layer of uranium oxide of the proper thickness provides some antireflection of 58.4nm EUV light without significantly lowering the 30.4 nm reflectance. However other schemes, including designs based on genetic algorithm designs were not successful at that time [3].

We returned to the design of 30.4 nm ML by examining some of the material pairs proposed or used for 30.4 nm in the last decade to see if any were high reflectors than U/Si and if any are more amenable to producing a reliable AR. We also produced and measured the reflectance of simplified (3-layer) reflectors which a GA program indicated would have low reflectance at 58.4 nm.

3. Experimental/ computational

The layer pairs suggested in the literature include, SiC/Mg [4], Mo/Si [5], and Ir/Si [6] with near-normal reflectances of: unknown, 25% and 16%, respectively [4-6]. In addition, Larruquert investigated novel ways to obtain high reflectances in the EUV using stacks composed of more than two materials [7]. Some of the material pairs predicted or produced reflectances higher than that of U/Si when tuned for normal reflectance. These materials were added as data to a genetic algorithm program to design mirrors for 30.4 nm and 58.4 nm, though we did not have access to Ir as a thin film material at our lab.

The first mirrors calculated were stacks with the fewest number of layers possible (3) to produce interference *antireflection* at 58.4 nm for near-normal incidence. We then prepared and tested representative mirrors. Since roughness can also produce low reflectance the reflectance of the surfaces were also measured at other energies near 58 nm. We sought so confirm that we had achieved a reflection minimum, not just low reflectance.

All films were deposited by magnetron sputtering. All targets were nominal 10-cm diameter. The uranium (U-238) target was depleted uranium bought from Manufacturing Sciences (Oak Ridge, TN). The thorium target was cut and machined from a thorium ingot. The 10-cm diameter, heavily doped silicon target was purchased from CERAC. The sputtering was done in a chamber evacuated to a base pressure of less than $3x10^{-6}$ torr with a Cryotorr 8 cryopump. The chamber was then backfilled to a pressure of $2.8x10^{-3}$ torr with ultrahigh purity (99.999% pure) argon passed through an UltraPure (NuPure Corporation) line filter which removed residual N2, O2, H2O, and H2. A plasma was generated in the argon by applying a potential (about 400 V for U and 550 V for Si) between the target and dark space shield. A magnetic field confined the plasma to the area near the target. Argon ions striking the target sputtered U or Si atoms from the surface. These accumulated on the mirror surface at a rate that was calibrated by x-ray diffraction (XRD) measurements on test samples.

Substrates were pieces broken from 100 orientation polished single crystal silicon wafers. The substrates and the multilayers samples were characterized using low angle x-ray diffraction (LAXRD), atomic force microscopy (AFM), x-ray photoelectron spectroscopy (XPS), variable angle spectroscopic ellipsometry (JA Woollam, Inc. M2000) and, in some case, transmission electron microscopy (TEM).

We measured the reflectivities of the test samples at 30.4 and 58.4 nm after their fabrication. The measurement system consisted of a McPherson 629 hollow cathode source filled with He and connected to a McPherson Model 225 1-meter scanning monochromator. Typical operating conditions for the hollow cathode source were a base pressure of $2x10^{-6}$ torr, He pressure of 0.35 torr, and a current of 0.25 amps. The operating pressure in the monochromator was kept below 10^{-4} torr. The monochromator used a Pt-coated grating blazed for 42.0 nm at near-normal incidence. In addition to the reflectivity measurements at BYU, we also measured the mirrors in the LBL EUV calibration facility at wavelengths of 30.4 nm.

Results, with figures, will be presented at the conference. Antireflection, deliberately producing low reflectance over a wavelength range by interference, is not as straightforward as in the visible and neighboring frequencies, but it is worthwhile to understand. One of the complications may be that materials are not entirely transparent in the EUV. Oxides, fluoride and other materials commonly used in the visible are among the most opaque about 30 eV. It is the first-row elements like oxygen which are particularly absorbing at such energies. Optical constants are also not known as well (particularly for compounds) in the lower energy portion of the EUV as in the visible, but are being investigated elsewhere. Oxygen impurities may also be a problem.

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