

X-Ray/EUV Optics

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X-ray/EUV optics is one of the most exciting and rapidly growing areas of modern optics. Since the resolution limitations imposed on an optical system by Fraunhofer diffraction are directly proportional to the wavelength, focusing and imaging optical systems operating at soft x-ray (1- to 100-Å) and extreme ultraviolet (EUV) (100- to 1000-Å) wavelengths provide the potential for unprecedented spatial resolution. This has been understood and appreciated since the advent of grazing-incidence mirrors and Fresnel zone plate optics over forty years ago. However, fabrication difficulties and limitations imposed by x-ray scattering at grazing incidence have kept the resolution of grazing-incidence optical systems significantly above the diffraction limit. New methods for producing ultrasoother, low-scatter mirrors are being developed and will permit grazing-incidence optics to approach this goal more closely. The recently developed multilayer optical systems can operate at normal incidence and are far less sensitive to x-ray scattering. Since the radiation is reflected by Bragg diffraction, multilayer optics provides the potential for good spectral resolution coupled with superb spatial resolution. Normal-incidence mirrors also provide a much larger collecting area than a grazing-incidence mirror of the same diameter. Important advances in the methods of fabricating multilayer coatings have made it possible to achieve normal-incidence reflectivities approaching 70% at selected EUV wavelengths. These combined properties of high efficiency, low scatter, and inherently good spectral resolution coupled with the potential for ultrahigh spatial resolution are of tremendous value to instrumentation now being developed for astronomy, microscopy, polarimetry, and lithography.

This special section, devoted to x-ray/EUV optics, is somewhat dominated by the work on multilayer optics for imaging systems in the soft x-ray/EUV wavelength regime, even though important and exciting work is continuing with advanced grazing-incidence optics, which are now being developed. It is hoped that this area of x-ray optics can be more adequately represented in a future issue.

Several of the papers in this special section are concerned with the fabrication, characterization, and performance of multilayer mirrors. The first paper discusses the fabrication and test of silicon/silicon oxide and silicon/silicon nitride multilayers with

well-defined Bragg peaks and very narrow bandpasses. These mirrors have high absolute reflectivity in the EUV and very good thermal stability. The multilayers were deposited by a reactive diode rf-sputtering system, and *in situ* kinetic ellipsometry methods were used for monitoring the multilayer deposition. The paper discusses the characterization of the multilayers by grazing soft x-ray reflection tests and EUV reflectivity measurements at normal incidence using synchrotron radiation. Mo/Si multilayers have also been fabricated by electron-beam deposition. The next paper describes methods of improving the reflectivity of electron-beam-deposited multilayers by optimization of the substrate temperature and deposition rate. The results of TEM, x-ray diffractometer, and soft x-ray spectroreflectometer characterizations of the multilayer coatings are provided. Materials for x-ray mirrors designed to operate at wavelengths below 100 Å are discussed in the paper by Kearney et al. An intriguing approach to the fabrication of reflective Fresnel zone plates by means of electron-beam nanolithography on a Mo/C multilayer mirror is described in the next paper. This unique coupling of microfabrication and thin-film deposition technologies makes possible an entirely new type of patterned multilayer optic, capable of focusing x rays with flat optics.

The combination of the low-scattering, large collecting area and spectral discrimination properties inherent in multilayer optics makes them ideal components for soft x-ray/EUV microscope systems. An x-ray microscope designed to operate between the K absorption edges of carbon and of oxygen should yield an instrument ideally suited for producing high-resolution high-contrast images of carbon structures within the aqueous envelope of living cells. Recent progress in the development of this water window imaging x-ray microscope, which has potential applications to fundamental cell biology and cancer research, is discussed. Improvements in the image quality of multilayer x-ray microscopes may be achieved by the use of aspherical mirrors. A theoretical treatment of an aspherical reflecting multilayer microscope to achieve enhanced spatial resolution is discussed. Multilayer optics are not only important to astronomy and microscopy, but they are also beginning to play a valuable role in projection lithography. The paper by

Newnam describes multilayer technology systems as applied to the development of free-electron laser-based EUV projection lithography systems.

The most extensive applications of multilayer optics to date have been in solar x-ray astronomy and many of these applications are discussed. The resolution limitations imposed by the surface topography with respect to spatial frequency errors in multilayer telescope optics are presented. Solar observations with the NIXT telescope and considerations of the available photon fluxes and detector characteristics are used to predict the resolution that should be achievable with sounding rocket-borne multilayer x-ray telescopes.

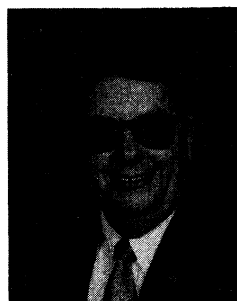
The most complex array of multilayer x-ray/EUV telescopes ever flown is the Multi-Spectral Solar Telescope Array (MSSTA). Several papers in this issue are related to the MSSTA. The x-ray/EUV reflection efficiencies of the assembled Ritchey-Chrétien telescopes were measured at the Stanford Synchrotron Radiation Laboratory (SSRL) and the results of those studies are presented. The EUV and far ultraviolet (FUV) response characteristics of the MSSTA photographic films have been measured at SSRL and at the SURF II synchrotron of the National Institute of Standards and Technology. These tests have revealed that the ultrahigh resolution 649 spectroscopic film has sufficient sensitivity for solar imaging with the MSSTA instruments in the short time available during the sounding rocket mission. A number of exotic thin-film foil filters have been developed to optimize the performance of these telescopes at the wavelengths of selected solar spectral lines. The predicted transmission and the bandpass characteristics for these different filters are presented. Specific absorption edges of the filters can be used to narrow the bandpass of the multilayer telescopes at the wavelengths chosen for investigations of the solar chromosphere, transition region, corona, and corona/solar wind interface. The temperature diagnostic response of the MSSTA telescopes to the optically thin solar plasma has been analyzed and the results presented.

Another paper describes the high-resolution stigmatic EUV spectroheliometer, a sounding rocket instrument using a Gregorian telescope with a toroidal diffraction grating and a multi-anode microchannel array (MAMA) detector. The combination of high spatial and spectral resolution provided by this instrument should allow the fine-scale structure of the chromosphere, transition region, and corona to be observed, providing exciting new information pertaining to the temperature, density, and velocity of specific structures in the outer solar atmosphere.

Grazing-incidence x-ray optics are now being fabricated by a number of techniques including replication. The fabrication and characterization of lacquer-coated replicated grazing-incidence optics are described. Several papers in this special section are devoted to various aspects of polarization phenomena of x-ray, EUV, and FUV radiation. Important techniques for the production and analysis of polarized x rays from synchrotron radiation are described. New information concerning vectorial effects in the x-ray photoemission from cesium iodide is presented. Two papers are concerned with new imaging EUV/FUV polarimeters for measuring vector magnetic fields in the solar corona. With the advent of ultrasmooth normal-incidence optics capable

of operating at soft x-ray/EUV/FUV wavelengths, all-reflecting coronagraphs and polarimeters, which operate without a Lyot stop or occulter, are feasible. These coronagraph/polarimeter instruments allow the solar corona to be imaged simultaneously with emission features on the disk and the Stokes vectors of the linearly polarized light to be measured.

It is clear that the field of x-ray/EUV optics is dynamic and rapidly growing. Advances in grazing-incidence and multilayer x-ray optical systems are making possible exciting new instrumentation, with unprecedented spatial resolution, for astronomy, microscopy, and lithography. Advances in mirror substrate fabrication and multilayer coating technology are allowing us to approach more closely the goal of diffraction limited x-ray optical systems.



Richard B. Hoover is an astrophysicist in the space Science Laboratory of NASA's Marshall Space Flight Center. His work in the field of x-ray optics began in 1967 when he became involved with the Skylab ATM Experiment S-056 grazing-incidence x-ray telescope. He has been principal investigator and coinvestigator on many spaceflight missions utilizing x-ray telescopes, including the Stanford/

MSFC/LLNL Rocket X-Ray Spectroheliograph experiment. In October 1987, this experiment produced the first high-resolution x-ray/EUV images of the solar corona with normal-incidence multilayer x-ray telescope systems. He is coinvestigator for the Stanford/MSFC/LLNL Multi-Spectral Solar Telescope Array (MSSTA), launched on May 13, 1991. The MSSTA obtained high-resolution soft x-ray/EUV and FUV images of the sun including the first H I Lyman α coronal images recorded simultaneously with Lyman α emission from the solar disk. He is currently exploring novel optical configurations for enhanced coronagraph/polarimeter instruments. Mr. Hoover is also principal scientist for the Ultra-High Resolution XUV Spectroheliograph (UHRXS) attached payload instrument, which was selected for flight on the U.S. space station. He has long been interested in microscopy and diatom research and is fabricating a high-resolution multilayer x-ray microscope for use in the biologically important "water window." This microscope could play a significant role in cancer research and fundamental cell biology. He is also developing advanced x-ray/EUV/FUV telescopes and polarimeters, and has authored numerous scientific papers, patents, and monographs.