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PROGRESS REPORT & PROPOSAL

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

for the second year of

A THREE-YEAR PROGRAM OF MICRO- AND NANO-SYSTEM TECHNOLOGY DEVELOPMENT FOR X-RAY ASTRONOMY

CURRENTLY SUPPORTED BY GRANT NAG5-5105

Submitted by the

CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Estimated cost of the Second Year:

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Submitted: December 12, 1997

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1. INTRODUCTION

The Proposal for the current program of technology development for x-ray astronomy at the MIT Center for Space Research, supported under Grant NAG5-5105, was submitted on February 23, 1996, entitled "A Three Year Program of Micro- and Nano-system Technology Development for X-ray Astronomy" in response to NASA Research Announcement NRA 95-OSS-17 for the High Energy Astrophysics Supporting Research and Technology Program (SR&T). The proposed work was in part a continuation and extension of research previously supported under NASA Grant NAGW-2003.

For many years the work at MIT aimed at the development of new concepts and technologies for space experiments in high-energy astrophysics, but not explicitly supported by flight programs, has been supported through the NASA SR&T Program, in the past through Grant NAGW-2003 and currently through Grant NAG5-5105. This work has yielded new devices and techniques for X-ray astronomy, primarily low-noise, deep-depletion charge-coupled devices (CCDs) for spectrally-resolved X-ray imaging, and high-performance transmission gratings for high-resolution X-ray spectroscopy. Among the most significant recent achievements have been the development by G. Ricker and associates of the X-ray CCD camera flying on *ASCA*, and currently in development for AXAF and Astro-E, and the development by C. Canizares and associates of thick, 200 nm-period transmission gratings employing the phenomenon of phase shifting for high-resolution X-ray spectroscopy up to energies of 8-10 keV that is essential for the operation of the AXAF High Energy Transmission Grating Spectrometer (HETGS). Through the current SR&T grant, the latter technology is now being extended successfully to the fabrication of 100 nm-period transmission gratings, which have twice the dispersion of the AXAF gratings.

We note that, among other outcomes, the modest investments of past SR&T Grants at MIT resulted in the development of the key technologies for fully one-half of the scientific instrumentation on AXAF. In addition, NASA flight programs that have benefited from previous SR&T support at MIT include the *SAS 3 X-ray Observatory*, which carried the first rotation modulation collimator, the Focal Plane Crystal Spectrometer (FPCS) on the *Einstein Observatory*, the CCD cameras on *ASCA* and planned for Astro-E, the High Energy Transient Experiment (HETE), the Solar EUV Monitor on the Solar and Heliospheric Observatory (SOHO), the Medium Energy Neutral Atom imager (MENA) on the Image for Magnetopause-to-aurora Global Exploration (IMAGE) mission, and the recently-approved Two Wide-Angle Imaging Neutral-atom Spectrometers (TWINS) Mission of Opportunity.

The present Proposal is for continuation during CY98 of the three-year program of technology development, for which initial funding in the amount of $300,000 was granted for CY97. A progress report for work completed in CY97 is presented in Section 2. The proposed research for CY98 is described in Section 3, and an estimated budget and cost justification in Section 4.

2. PROGRESS REPORT FOR CY 1997

Since our last progress report we have made significant advancements in the following technology areas in the Proposal: transmission gratings, reflection gratings, and foil x-ray optics. (As described in the amended Proposal and Statement of Work submitted post-award, the extreme ultraviolet interferometric lithography (EUVIL) technology area will not be pursued, due to the difference between the requested and awarded funds.)

2.1 Transmission grating technology (200 nm period).

We have made considerable progress in the technology of so-called "free standing" 200 nm-period gold gratings. Transmission gratings being fabricated in our laboratory for the High Energy Transmission Grating Spectrometer (HETGS) on AXAF are supported by polyimide membranes. While polyimide is strong and easily survives environmental stresses, it absorbs x-rays and thus reduces diffraction efficiency, especially in the energy band below 1 keV. For future x-ray astronomy missions it will be desirable to develop gratings with both smaller periods and improved diffraction efficiencies. The proven high performance and extremely low weight of transmission gratings (HETGS is under 50 lbs) merits further improvements.

For many years we have fabricated "free standing" gratings supported by coarse-period meshes. However, these were intended for laboratory use and were not designed to withstand the thermal and acoustic loads expected for space instrumentation. Our process was labor intensive and yields were low. Grating quality was also poor. In the past year we have improved the strength, efficiency, and process robustness of our mesh-supported grating technology, as detailed in the sections below. These improvements have enabled us to win contracts from the Southwest Research Institute and the Los Alamos National Laboratory to provide UV-filtering gold transmission gratings for the NASA Medium Energy Neutral Atom imager (MENA) on the Image for Magnetopause-to-aurora Global Exploration (IMAGE) mission. The results of these contracts should enable us to resolve many spaceworthyness issues of free standing gratings which will be essential if they are to be proposed for future x-ray astronomy missions.

Specific process improvements made in the past year are listed below. A publication describing details of our improved process is in preparation [7].

Interferometric lithography: Our 200 nm-period gratings are patterned using a method called interferometric lithography (IL), in which 351 nm wavelength laser beams are split, expanded and coherently interfered using beamsplitters and mirrors (see Fig. 1). We made a number of enhancements to our IL system which have improved exposure dose uniformity. More improvements will be implemented over the next year. These improvements allow tighter control of grating parameters such as bar width, which boosts diffraction efficiency by suppressing diffraction into undesired orders. We also completed a study of grating distortion [1].

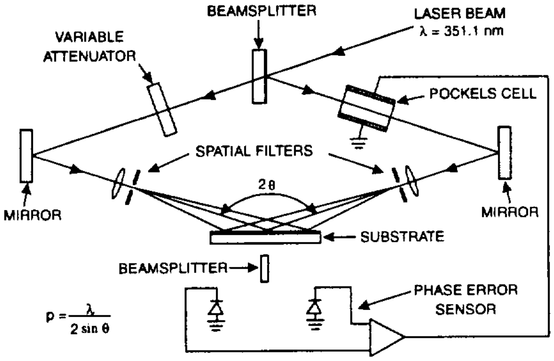
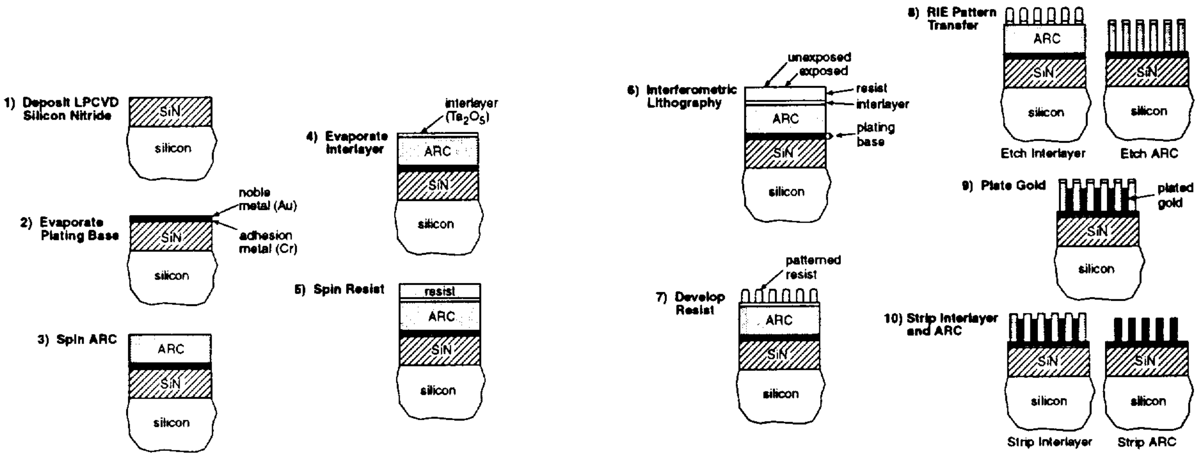


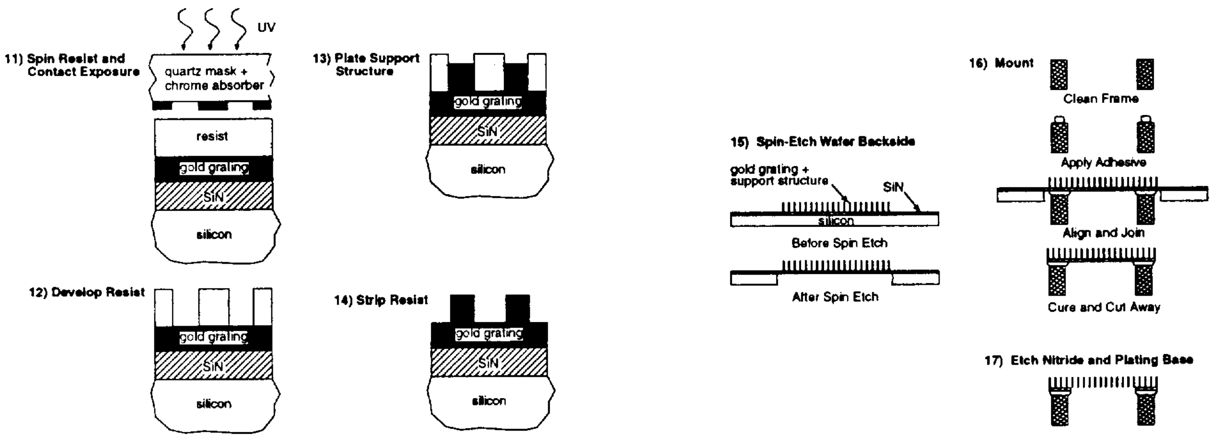
Figure 1. Our "traditional" interferometric lithography system, which can pattern gratings with periods down to 200 nm.

Etch-stop barrier. Our transmission grating fabrication procedures typically utilize an acid etching step at the back end of the process that is used to etch a hole through the substrate silicon wafer. In the case of polyimide-supported gratings, the the polyimide layer serves as the etch-stop. In the case of mesh-supported gratings, the plating-base layer serves as an etch-stop. However, the extremely thin plating base (typically 5 nm of chromium and 20 nm of gold) is mechanically weak, leading to frequent acid break-throughs and subsequent damage. For this reason, we investigated the feasibility of an etch-stop layer which might serve as a barrier to the acid and increase process yield. This layer must etch very slowly in the acid or not at all, must be impervious to acid fumes, must be easily and quickly deposited on wafers, and must be easily removed after the acid etching step is completed. We investigated a number of barrier materials including evaporated gold and chromium, thermal silicon oxide (SiO2), chemical vapor deposited (CVD) silicon nitride (Si3N4) and CVD silicon-rich silicon nitride (SiN). We found that the SiN material gave the best results, and have successfully developed and tested a process using this material (see Fig. 2).



(a) Wafer Preparation (Steps 1-5)

(b) Lithography, Pattern Transfer, Plate & Strip (Steps 6-10)



(c) Pattern Support Structure (Steps 11-14)

(d) Spin Etch, Mount & Etch Backside (Steps 15-17)

Figure 2. *Improved process for fabricating free-standing gold transmission gratings. The use of a silicon nitride etch stop barrier significantly improves grating quality and process yield.*

Barrier/plating base removal. In the past, the plating base layer (typically 5 nm of chromium and 20 nm of gold) was removed from the completed grating by argon-ion milling. (The plating base is normally removed because it strongly absorbs long-wavelength x-rays.) The ion milling process has a number of problems, including very low throughput and poor control of etch rate. We have developed and tested a new process which uses CF4 reactive-ion etching to remove the plating base and etch-stop barrier in one step, significantly improving process throughput and control.

Metal frames: In the past, mesh-supported gratings were fabricated with an integral silicon support frame. While this simplified processing, the extremely fragile single-crystal frames lacked reproducible mechanical dimensions and were poorly aligned to the grating direction. We have adapted technology originally developed for the HETGS gratings to bond mesh-supported gratings to precisely machined, accurately aligned stainless steel frames suitable for flight use. Fig. 3 is a photograph of a completed mesh-supported grating with a frame of the new design.

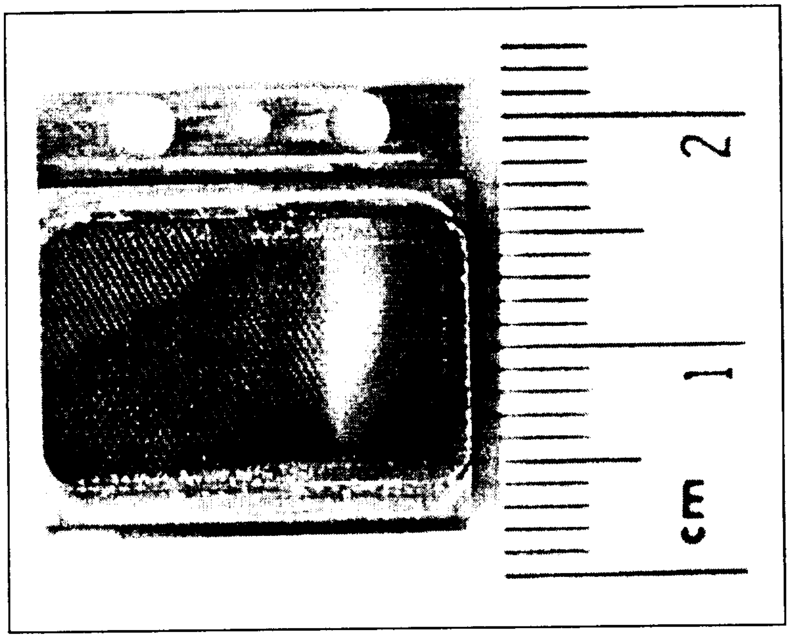


Figure 3. Photograph of free-standing 200 nm-period gold transmission grating bonded to a stainless steel frame, fabricated with our improved process. The 400 micron-period "triangle grid" support structure mesh is visible.

Stronger support mesh: In the past, we used a supporting mesh which consisted of a 4.0 micron-period gold grating crossed at 90 degrees with a 150 micron-period gold grating. The highly anisotropic strength of this mesh frequently led to severe grating damage during processing and testing. We have developed an improved supporting mesh geometry, which consists of a 4.0 micron-period grating and a 400 micron-period "triangle mesh" with superior strength (see Fig. 4). In addition, we have sucessfully developed a nickel plating process for the support mesh, which should also significantly improve mechanical stability due to the much higher tensile strength of nickel.

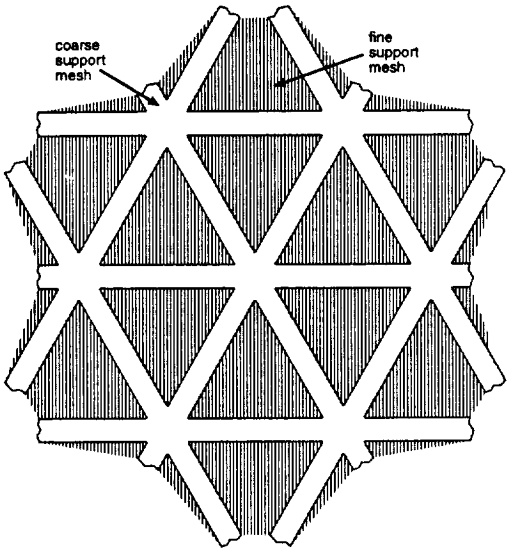


Figure 4. Improved free-standing grating support mesh, consisting of a 400 micron-period "triangle mesh" and a 4.0 micron period fine mesh.

2.2 Transmission grating technology (100 nm period).

We have made a number of significant improvements in the technology of fabricating 100 nm-period transmission gratings. These are fabricated using a method we developed called achromatic interferometric lithography (AIL), in which a 193 nm wavelength laser beam is expanded, split, and coherently interfered using quartz transmission gratings (see Fig. 5). We have made improvements in the basic design of the AIL interferometer which increase image contrast and stability. We devised accurate and rapid alignment techniques. We developed a novel tri-level resist process which significantly improves grating quality and process yield, and have sucessfully fabricated free-standing gold transmission gratings suitable for x-ray spectroscopy (see Fig. 6). Details of our process improvements have been published [2], and so will not be presented here.

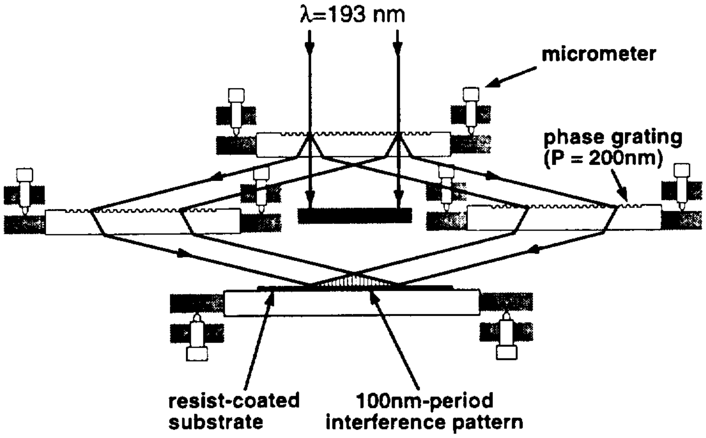


Figure 5. Interferometer configuration for achromatic interferometric lithography (AIL), which is used to pattern 100 nm period gratings. A beam from a ArF excimer laser (193 nm) is split and recombined using quartz transmission gratings.

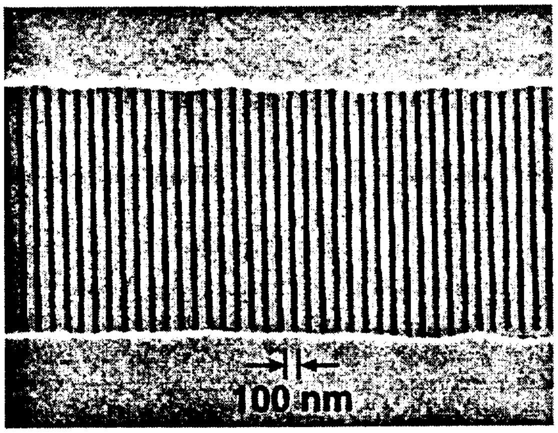
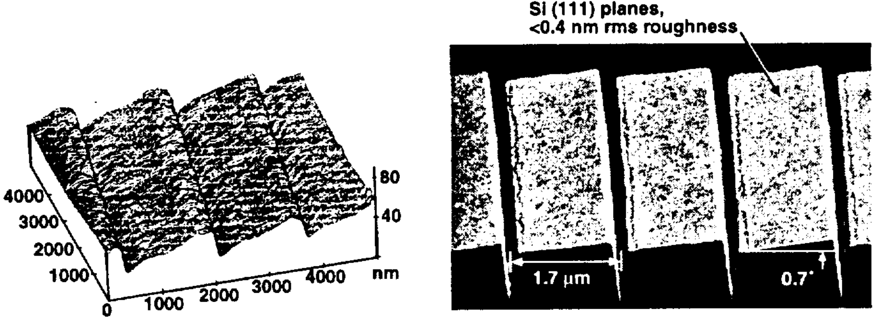


Figure 6. Scanning electron micrograph of a free-standing 100 nm-period gold transmission grating fabricated by achromatic interferometric lithography.

2.3 Reflection grating technology.

Future x-ray astronomy missions are likely to utilize thin foil x-ray optics because of their extreme light weight and large collecting area. Unfortunately, their image quality is typically much poorer than can be achieved by monolithic optics such as on AXAF, and thus dispersive (grating) spectrometers used with them have low resolution, unless impractically small periods are used. Steve Kahn and coworkers have pioneered the use of grazing-incidence reflection gratings, which have tremendously higher dispersion than transmission gratings, on the foil-optic XMM mission. The high dispersion allows the spectrometer to achieve high spectral resolution even with focusing optics of low resolution.

The XMM gratings were fabricated by epoxy replication from master ruled gratings. The ruling process proceeds line-by-line by burnishing an aluminum-coated substrate with a diamond stylus. The process is extremely slow and produces gratings with rough surfaces and undesirably rounded groove profiles. The replication process further degrades grating quality. The end result is gratings with significantly lower efficiency and higher amounts of scattered light than predicted theoretically (see Fig. 7a).



(a) Mechanically Ruled **(b) Anisotropically Etched**

Figure 7. Three-dimensional atomic force microscope (AFM) images of grazing incidence, blazed, reflection gratings. (a) Mechanically ruled master grating (Bixler et al., Proc. SPIE 1549, 420-428 [1991]). Note the roughness and curvature of the ruled grating. (b) Anisotropically etched grating using new process.

We proposed a new method for fabricating master gratings by interferometric lithography using specially-prepared silicon wafers cut 0.7 degrees off of the [111] plane, followed by anisotropic chemical etching which does not etch [111] planes (see Fig. 8). This results in groove profiles which are atomically smooth (see Fig. 7b). Process development has been successfully completed and several test gratings were fabricated and tested. We measured grating efficiencies that were ~35% greater than that of the best available ruled masters of comparable design (see Fig. 9). Details of our fabrication process and preliminary x-ray test results were published [6], and so will not be presented here.

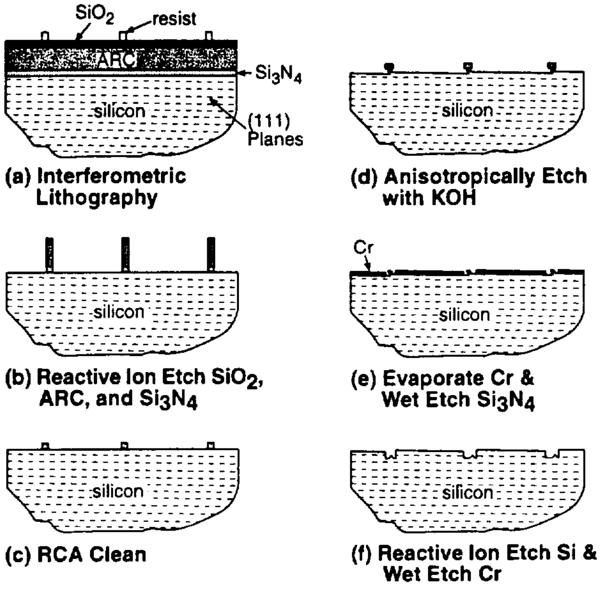


Figure 8. Schematic representation depicting the process for fabricating super-smooth x-ray reflection gratings. Note the trenches between the blaze facets. Because only the upper portion of the blaze facet is illuminated, the trenches do not decrease efficiency.

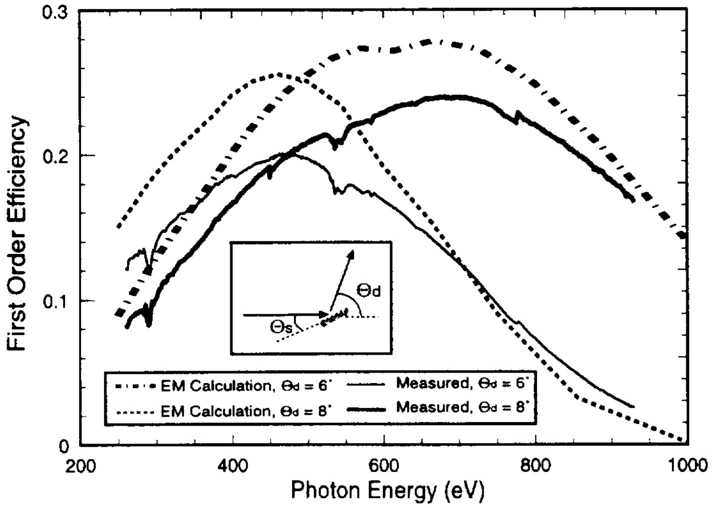
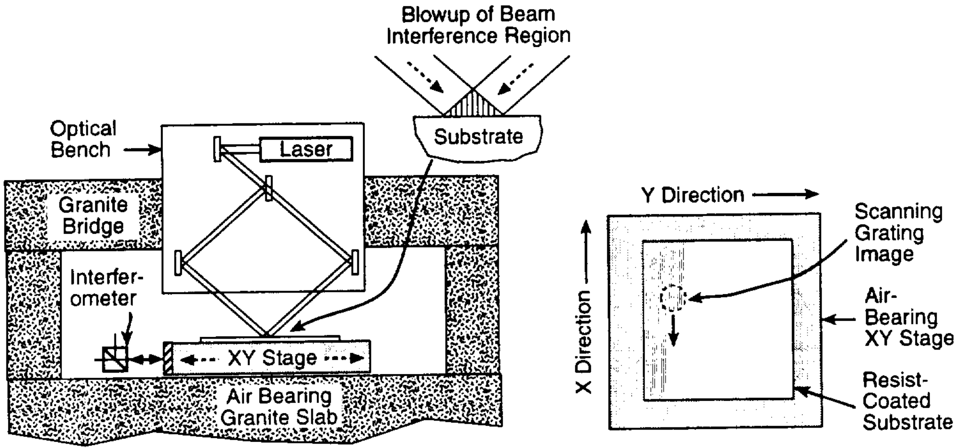


Figure 9. Comparison of x-ray diffraction efficiencies measured at Lawrence Berkeley Laboratory with the results of electromagnetic finite element calculations were performed at Columbia University.

2.4 Scanning-beam interferometric lithography.

We proposed to develop a revolutionary new and powerful interferometric lithography technique, called *scanning-beam interferometric lithography* (SBIL). This method is depicted in Figure XXX. Whereas traditional IL utilizes large static beams on the wafer (see Fig. 10), SBIL utilizes small interfering beams and a precision X-Y air bearing stage to scan a small grating image over the substrate. The advantages of the SBIL method include tighter control of grating period (i.e., lower distortion), improved image dose control, larger substrates, and the capability of chirped (variable) periods. These improvements will be essential to fabricating the high performance reflection and transmission gratings that will be required for future x-ray astronomy missions.



a) Scanning beam interferometer. b) Grating scanning method.

Figure 10. *Depiction of the scanning-beam interferometric lithography (SBIL) concept. a) The interferometer utilizes a fixed interferometric image and an X-Y air bearing stage to scan the image over the substrate. b) Method by which a small image is scanned to cover a large substrate.*

We are nearing completion of a year-long design study and vendor selection process. This process has involved a detailed study of large number of technical documents and textbooks, discussions with experts, and numerous vendor visits. Technical topic areas in the study include: high resolution distance measuring interferometry, optical heterodyne interferometry, turbulence compensated interferometry, high speed active optics (piezo, acousto-optic and electro-optic), high-speed air bearing stages, active vibration isolation systems, environmental control systems, and high-speed VME-bus electronic control systems.

One conclusion of this study is that while the system required to demonstrate the SBIL concept is more complicated and expensive than originally envisioned, it is technically feasible and still well within the cost and time constraints of the supported work. A detailed conceptual design of the system in the form of a patent disclosure is nearing completion, including over 40 figures. A thorough vendor review process has been completed, including vendor factory visits, and bids solicited. At this point all bid materials are in hand, and we are nearing completion of the vendor selection process. We anticipate awarding contracts in the next couple of months. All major subsystems should be delivered to our laboratory by the end of second quarter 1998, and after an integration phase we should be able to begin system testing in the third quarter.

2.5 Foil x-ray optics.

In the Proposal we described a new concept for foil mirror assembly which utilized photolithographically-defined and plasma etched foil retainer clips of superior accuracy, rather then the electro-discharge machined (EDM) structures that are the current state-of-the-art. However, available resources precluded work on this topic this year beyond the point of a limited number of vendor inquiries. (We plan to pursue this concept next year, but with a different approach. See Section 2.)

Instead, we report progress with two alternative foil optic designs, one of which we have abandoned after detailed computer modelling, and the second which we are just beginning to work on.

Traditional foil optic designs generally utilize two very different foil fabrication methods, the first being electroforming onto high precision mandrels followed by foil separation, and the second which utilizes vacuum forming of thin aluminum foils onto rough but accurate mandrels, followed by smooth surface replication by epoxy casting. In late 1996 we developed a new foil optic concept which utilized pre-figured silicon foils fabricated by plasma and chemical etching (PACE) technology, which were then bent into the hyperbolic and parabolic shapes required for Wolter Type II optics. The idea was developed into a complete fabrication and assembly concept and presented at MIT, Columbia University, the Harvard-Smithsonian Astrophysical Observatory (SAO), and a NASA workshop [P9, P10]. The idea attracted a great deal of interest, and a collaboration with SAO (with Harvey Tanenbaum and Lester Cohen) was initiated with the aim of studying feasibility through finite-element computer modelling.

The results of months of detailed modelling and analysis were not encouraging. Two problems arose. First, the available computer codes were not able to accurately predict the final shape of the bent optic, due to the extreme aspect ratio of the thin plates in the model, and the fact that the bending drives the problem into a strongly non-linear regime. Presently this seems to be an insurmountable problem. High modelling accuracy is essential because this guides the PACE figuring of the pre-bent silicon foils. The second problem is that the required bending stresses in the silicon were much too large for comfort, and cast doubt on the launch survivablity of the assembled structure.

We were rather discouraged after this fruitless effort. However, several months ago we learned about some very exciting work being performed by Chuck Hailey's group at Columbia University involving slumped glass foils for hard x-ray optics. The Columbia approach is to slump thin sheets of special high-strength glass into precision mandrels. They have published work showing accurate replication of the mandrel with this method, achieving ~1 arcminute figure. We immediately realized that by pre-figuring glass sheets byPACE etching or other methods, figures approaching one arcsecond might be achieved. We have initiated a collaboration between MIT, SAO, Columbia, and a major optics vendor to study the feasibility of this concept.

2.6 Publications and presentations of supported work since last progress report.

Publications

1. "Analysis of distortion in interferometric lithography," J. Ferrera, M. L. Schattenburg, and H. I. Smith, *J. Vac. Sci. Technol. B* **14**, 4009-4013 (1996).

2. "Large-area achromatic interferometric lithography for 100 nm-period gratings and grids," T. Savas, M. L. Schattenburg, J. M. Carter, and H. I. Smith, *J. Vac. Sci. Technol. B* **14**, 4167-4170 (1996).

3. "A diffractive-optic telescope for x-ray astronomy," D. Dewey, T. H. Markert, and M. L. Schattenburg, in *Multilayer and Grazing Incidence X-ray/EUV Optics III*, (*Proc. SPIE* **2805**), eds. R. B. Hoover and A. B. C. Walker (SPIE, Bellingham, WA) (*in press*).

4. "Iridium and gold optical constants from foil transmission measurements over 2,00-12,000 eV," B. Harris, D. E. Graessle, J. J. Fitch, J. Juda, R. L. Blake, E. M. Gullikson, and M. L. Schattenburg, in *Multilayer and Grazing Incidence X-ray/EUV Optics III*, (*Proc. SPIE* **2805**), eds. R. B. Hoover and A. B. C. Walker (SPIE, Bellingham, WA) (*in press*).

5. "A one-dimensional demonstration of spatial-phase-locked electron-beam lithography," J. Goodberlet S. Silverman, J. Ferrera, M. Mondol, M. L. Schattenburg, and H. I Smith, *Microelectronic Engineering*; also in *Proceedings of the International Conference on Micro- and Nano-Engineering 96, Glasgow, Scotland, September 22-25, 1996*, eds. S. P. Beaumont and C. D. W. Wilkinson (North-Holland, Amsterdam) (*in press*).

6. "Super-smooth x-ray reflection grating fabrication," A. E. Franke and M. L. Schattenburg, *J. Vac. Sci. Technol. B*, Nov./Dec 1997 (*in press*).

7. "An improved free-standing transmission grating fabrication process," J. van Beeke and M. L. Schattenburg (*in preparation*).

Master's Thesis

T1. "Fabrication of extremely smooth nanostructures using anisotropic etching," Andrea E. Franke, Master of Science in Electrical Engineering and Computer Science, MIT, 1997.

T2. "Interferometric lithography and selected applications," Maya F. Farhoud, Master of Science in Electrical Engineering and Computer Science, MIT, 1997.

Presentations

P1. "Analysis of distortion in interferometric lithography," J. Ferrera, M. L. Schattenburg, and H. I. Smith, poster presented at the *40th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Atlanta, Georgia, May 28-31, 1996 (*paper C8*).

P2. "Large-area achromatic interferometric lithography for 100 nm-period gratings and grids; with novel applications," T. Savas, M. L. Schattenburg, J. M. Carter, and H. I. Smith, presented at the *40th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Atlanta, Georgia, May 28-31, 1996 (*paper A3*).

P3. "A diffractive-optic telescope for x-ray astronomy," D. Dewey, T. H. Markert, and M. L. Schattenburg, presented at the *SPIE Conference on Multilayer and Grazing Incidence X-ray/EUV Optics III*, Denver, Colorado, August 4-9, 1996 (*paper 2805-29*).

P4. "Iridium and gold optical constants from foil transmission measurements over 2,00-12,000 eV," B. Harris, D. E. Graessle, J. J. Fitch, J. Juda, R. L. Blake, E. M. Gullikson, and M. L. Schattenburg, poster presented at the *SPIE Conference on Multilayer and Grazing Incidence X-ray/EUV Optics III*, Denver, Colorado, August 4-9, 1996 (*paper 2805-44*).

P5. "The HETG Spectrometer," M. L. Schattenburg, MIT Center for Space Research Friday Lunch Seminar, Cambridge, Massachusetts, September 20, 1996 (*invited*).

P6. "A one-dimensional demonstration of spatial-phase-locked electron-beam lithography," J. Goodberlet S. Silverman, J. Ferrera, M. Mondol, M.L. Schattenburg, and H.I. Smith, presented at the *International Conference on Micro- and Nano-Engineering 96*, Glasgow, Scotland, September 22-25, 1996 (*paper K.3*).

P7. "Super-smooth x-ray reflection grating technology," A. Franke and M. L. Schattenburg, poster presented at the *High Throughput X-ray Spectroscopy Workshop*, Cambridge, Massachusetts, September 30-October 1, 1996.

P8. "Interferometric Lithography and its Applications," J. Carter, M. Farhoud, J. Ferrera, A. Franke, T. Savas, M. L. Schattenburg, and H.I. Smith, poster presented at the *50th Anniversary Celebration of the MIT Research Laboratory of Electronics*, Cambridge, Massachusetts, November 1, 1996.

P9. "A research program leading to a 1 arcsec foil mirror x-ray telescope," M. L. Schattenburg and C. R. Canizares, presented at the *Structure and Evolution of the Universe Technology Workshop*, College Park, Maryland, December 2-3, 1996.

P10. "A research program leading to a 1 arcsec foil mirror x-ray telescope," M. L. Schattenburg and C. R. Canizares, *Harvard-Smithsonian Astrophysical Observatory Special Seminar*, Cambridge, Massachusetts, December 6, 1996 (*invited*).

P11. "Super-smooth x-ray reflection grating technology," A. Franke and M. L. Schattenburg, poster presented at the *Structure and Evolution of the Universe Technology Workshop*, College Park, Maryland, December 2-3, 1996.

P12. "Fabrication of super-smooth x-ray reflection gratings," A. Franke and M. L. Schattenburg, poster presented at the *MIT Microsystems Technology Laboratories Annnual Review*, Dedham, Massachusetts, January 17, 1997.

P13. "Interferometric lithography: techniques and applications," M. L. Schattenburg, *1997 IEEE-LEOS Spring Short-Course Series: Optical Grating Technology and Applications*, Lexington, Massachusetts, March 18, 1997 (*invited*).

P14. "Super-smooth x-ray reflection grating fabrication," A. E. Franke and M. L. Schattenburg, poster presented at the *41st International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Dana Point, California, May 27-30, 1997 (*paper C59*).

P15. "An inverted x-ray mask configuration compatible with pellicle protection," M. H. Lim, M. L. Schattenburg, and H. I. Smith, presented at the *41st International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Dana Point, California, May 27-30, 1997 (*paper J5*).

P16. "Spatial-phase locked electron beam lithography using a global fiducial grid," G. Goodberlet and M. L. Schattenburg, *Etec Corporation Seminar*, Hayward, California, June 10, 1997.

P17. "Patterned Magnetic Media for Ultra High Density Data Storage," M. S. Farhoud, *University of Aachen - RWTH Institute*, Aachen, Germany, July 3, 1997 (*invited*).

P18. "Magnetic storage media defined by submicron lithography," M. F. Farhoud, H.I. Smith, M. Huang, D. Twisslemann, C. A. Ross, M. L. Schattenburg, J. M. Bae, and K. Youcef-Toumi, poster presented at the *MIT Materials Processing Center "Materials Day" Symposium*, Cambridge, Massachusetts, October 20, 1997.

P19. "Fabrication of freestanding gratings for the MENA atom imager," J. van Beek, *Center for Space Research Seminar*, Cambridge, Massachusetts, October 31, 1997 (*invited*).

3. PROPOSED RESEARCH PROGRAM

In CY98 we propose to extend and build upon work completed in CY97 in three general areas: transmission grating technology, reflection grating technology, and foil mirror optics.

3.1 Transmission grating technology (200 nm period).

Many years of SR&T support and several flight hardware programs have brought our polyimide-supported and free-standing transmission grating technology a high level of maturity (see Section 2.1). However, grating quality and process yield still continue to suffer from relatively poor dose control during the interferometric lithography (IL) step. This poor control is attributed to the use of spatial filters in each of the interfering arms, which are necessary to ensure uniform, phase-coherent beams interfering on the substrate. The spatial filters consist of short focal length lenses followed by 5 micron-diameter pinholes. Air turbulence and thermal drifts in the long beam paths from the laser to the interferometer are responsible for focal spot dither at the focus of the spatial filters, and thus random dose variations at the wafer plane. In CY98 we propose to build a adaptive optical system designed to detect beam drift at the spatial filters, and drive piezo-controlled mirrors to lock the beams in the interferometer, thus eliminating dose variation problems. A breadboard version of this system has been built and tested, but now needs to be applied to our production IL system.

3.2 Transmission grating technology (100 nm period).

Virtually none of the recent improvements in our 200 nm-period grating fabrication process (described in Section 2.1) have been applied to our 100 nm-period process. The 100 nm-period gratings are considerably more fragile and more challenging to fabricate than 200 nm period gratings, and would benefit significantly from the improved etch barrier, stronger mesh, and mefal frame technology. In CY98 we propose to develop a new 100 nm period grating process using these new process improvements.

3.3 Reflection grating technology.

At this point the process development phase of our super-smooth reflection grating work has been completed (see Section 2.3). Fabricated “master" reflection gratings were provided to the High Energy Astrophysics group at Columbia University and the Center for X-ray Optics at the Lawrence Berkeley Laboratory for x-ray efficiency and scattering testing. Preliminary test results were published [6]. Working with our collaborators, we propose to complete more detailed testing and modelling of fabricated gratings.

We also propose to perform test replications of our reflection gratings using conventional techniques, such as epoxy casting. Conventional ruled gratings are known to “wear out” after repeated replication, presumably due to the deformation of the soft aluminum during mold release. This phenomena increases costs and degrades grating quality. Since silicon is much harder than aluminum, it is thought that this phenomena will not occur.

We also propose to test methods of thinning silicon reflection grating substrates using plasma and chemical backside etching methods. If a low-cost method of patterning and thinning silicon reflection gratings can be developed, it could potentially obviate the need for replication.

3.4 Scanning-beam interferometric lithography.

At this point the detailed design study and vendor selection process for the SBIL system is nearly finished; completion of this phase is expected by year's end. We will then place contracts for the major system components, with deliveries expected in the second quarter of CY98. After the system is installed and integrated, we plan a period of system testing, with the goal of fabricating constant period gratings on large substrates by year's end. Because the system turned out to be considerably more complicated to design and build than originally anticipated (see Section 2.4), we do not propose to fabricate variable period gratings in CY98, but rather to demonstrate this in the last year of the Program (CY99).

3.5 Foil x-ray optics.

We proposed to develop new methods of fabricating the precision grooved structures which accurately retain individual foils. Our original idea was to use lithographically-defined masking and deep-etch reactive-ion plasma etching technology (DERIE) to fabricate the individual retainer grooves. Using this method, the goal was to reduce foil assembly tolerances from the present ~20 micron state-of-the-art down into the sub-micron regime. These further improvements will be essential to move the focal quality of foil optics from the present ~1 arcminute level down to the few arcsecond level.

In the past year we studied the feasibility of this method, and several alternative high-precision schemes, but only at the level of paper studies and vendor inquiries. Resource restrictions precluded further work beyond these steps (see Section 2.5). However, we have concluded that the DERIE process is not the most promising candidate for patterning retainer grooves, due primarily to the restrictive set of materials etchable with this method.

In CY98 we propose to evaluate the most promising groove-forming candidate: deep-UV excimer laser ablative machining. At this point we have had extensive discussions with several vendors who sell complete excimer laser cutting systems and also provide fee-based cutting services. The capabilities of these tools are extremely promising, particularly the high speed and accuracy of the cuts. In CY98 we propose to procure test cuts from several vendors and evaluate them for accuracy using scanning-electron microscopy and other appropriate metrology. We propose to build a foil optic assembly structure utilizing these improved retainer grooves to test the feasibility and improved accuracy of this new method.

3.6 Statement of Work.

1) Build and test beam locking electronics in our 200 nm-period interferometric lithography system.

2) Apply improved etch barrier, stronger mesh, and metal frame technology to our 100 nm-period grating fabrication process.

3) Test fabricated reflection gratings with x-rays and compare to detailed modelling. (This work is in collaboration with colleagues at Columbia University and Lawrence Berkeley Laboratory).

4) Test conventional epoxy replication methods with fabricated reflection gratings.

5) Test backside thinning methods with fabricated reflection gratings.

6) Complete design of SBIL system and place orders for system components.

7) Assemble and integrate SBIL system and test by fabricating constant-period gratings.

8) Procure test cuts of foil optic assembly structure grooves by excimer laser ablative machining.

9) Evaluate foil retainer groove quality by SEM analysis and other metrology.

10) Build test foil optic assembly structure which utilizes the improved retainer groove technology.

Appendix A: KEY PERSONNEL

Claude R. Canizares *(Principal Investigator)*

Professor Canizares is the Bruno Rossi Professor of Experimental Physics at MIT. He received three degrees in physics from Harvard University: A.B., 1967; A.M., 1968; and Ph.D., 1972. He came to MIT as a postdoctoral fellow in 1971 and joined the faculty in 1974 as an assistant professor. In 1978, he became an associate professor and was promoted to professor of physics in 1984. Professor Canizares has been Director of the Center for Space Research since 1990 (he served as Deputy Director 1989-1990) and head of the Astrophysics Division within the Department of Physics (1988-1992). He is currently the principal investigator of the AXAF High Energy Transmission Grating Spectrometer and is a member of the ASCA (ASTRO-D) science team. He was Co-investigator on the Einstein Observatory (HEAO-2) and Senior Project Scientist for the Focal Plane Crystal Spectrometer (FPCS) Experiment and directed the FPCS operations and data analysis efforts. His main research interests are high resolution spectroscopy and plasma diagnostics of supernova remnants and clusters of galaxies, cooling flows in galaxies and clusters, X-ray studies of dark matter, X-ray properties of quasars and active galactic nuclei, and gravitational lenses. He also carries out related optical studies of X-ray emitting objects. Previously, he worked with data from the OSO-7 and SAS-3 satellites concentrating on the study of time-variable galactic sources. He has served on numerous NASA advisory committees, was chair of the Space Science Advisory Committee, is a member of the NASA Advisory Council and is currently chair of the Space Studies Board of the National Research Council. He was a member of the Astronomy and Astrophysics Survey Committee of the National Academy of Sciences and was elected a Fellow of the American Physical Society in 1990 and a member of the National Academy of Sciences in 1993 and elected a Corresponding Member of the International Academy of Astronautics and a Fellow of the American Association for the Advancement of Science in 1996. He received the Goddard Medal of the American Astronautical Society in 1997. Professor Canizares has authored or coauthored more than 135 scientific papers. He has served on the MIT Committee on Educational Policy, the Committee on Undergraduate Admissions and Financial Aid, the Special Committee on the Writing Requirement, the Committee on the Freshman Year Program, the Wellesley-MIT Joint Committee, as Vice-Chair of the Faculty Advisory Committee to the Corporation on the Presidential Search and was Chair of the Committee on Nominations.

Most Recent Publications

Metal Concentration and X-ray Cool Spectral Component in the Central Region of the Centarurus Cluster of Galaxies, Y. Fukazawa, T. Ohashi, A.C. Fabian, C.R. Canizares, Y. Ikebe, K. Makishima, R. Mushotsky and K. Yamashita, *Publications of the Astronomical Society of Japan, Initial Results from ASCA,* **46,** No. 3, L55, 1994.

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First Results From ASCA Observations of theLarge Magellanic Cloud Supernova Remnant Sample, C.R. Canizares, J.P. Hughes, D. Helfand, U. Hwang, M. Itoh, R. Kirshner, K. Koyama, T. Markert, H. Tsunemi, and J. Woo, in the *Proceedings from the Conference "New Horizon of X-ray Astronomy-First Results from ASCA"*, F. Makino and T. Okashi (eds), Universal Academy Press, Tokyo, p. 119, 1995.

The Unusual Quasar PG1407+265, J.C. McDowell, C.R. Canizares, M. Elvis, A. Lawrence, S. Markoff, S. Mathur, and B.J. Wilkes, *Ap.J.*, (in press) 1995.

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The Twisting X-ray Isophotes of the Elliptical Galaxy NGC720, D.A. Buote, and C.R. Canizares, *Ap.J.*, **468**, 184, 1996.

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The Nature of X-ray Emission and Mass Distributions in Two Early-Type Galaxies, D.A. Buote, and C.R. Canizares, *Ap.J.*, **474**, 650, 1997.

Mark L. Schattenburg

Born 1956; Ph.D. MIT, 1984; MIT Postdoctoral Associate, 1984; MIT Scientific Research Staff, 1985; MIT Research Scientist, 1990, MIT Principal Research Scientist, 1996.
Dr. Schattenburg holds a B.S. degree from the University of Hawaii in 1978 and a Ph.D. from MIT in 1984. He is Director of the Space Microstructures Laboratory and Associate Director of the NanoStructures Laboratory. His principal work has been in the area of micro/nanofabrication technology, x-ray lithography, x-ray optics/instrumentation, and x-ray astronomy. Early in his career he participated in the mission planning and operations, data reduction, and analysis for the MIT experiment on the HEAO-2 (*Einstein*) x-ray satellite. Most recently he has developed techniques of nanostructure fabrication that are applicable to advanced instrumentation in x-ray astronomy. He currently leads the group responsible for the fabrication of nanometer period x-ray transmission gratings for the Advanced X-ray Astrophysics Facility (AXAF), scheduled for launch by NASA in 1998. He has published over 70 papers and holds three patents. He is a member of the American Vacuum Society, the American Astronomical Society, and the Society for Photo-Optical Instrumentation Engineers (SPIE).

Selected recent publications

"Fabrication of high energy x-ray transmission gratings for AXAF," M. L. Schattenburg, R. J. Aucoin, R. C. Fleming, I. Plotnik, J. Porter, and H. I. Smith, in *EUV, X-ray, and Gamma-Ray Instrumentation for Astronomy V* (*Proc. SPIE* **2280**), eds. O. H. W. Siegmund and J. Vallerga (SPIE, Bellingham, WA), 181 (1994).

"Extreme ultraviolet polarization and filtering with gold transmission gratings," E. E. Scime, E. H. Anderson, D. J. McComas, and M. L. Schattenburg, *Applied Optics* **34**, 648 (1995).

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"Analysis of distortion in interferometric lithography," J. Ferrera, M. L. Schattenburg, and H. I. Smith, *J. Vac. Sci. Technol. B* **14**, 4009 (1996).

"Large-area achromatic interferometric lithography for 100 nm-period gratings and grids," T. Savas, M. L. Schattenburg, J. M. Carter, and H. I. Smith, *J. Vac. Sci. Technol. B* **14**, 4167 (1996).

"A diffractive-optic telescope for x-ray astronomy," D. Dewey, T. H. Markert, and M. L. Schattenburg, in *Multilayer and Grazing Incidence X-ray/EUV Optics III*, (*Proc. SPIE* **2805**), eds. R. B. Hoover and A. B. C. Walker (SPIE, Bellingham, WA) (*in press*).

"Super-smooth x-ray reflection grating fabrication," A. E. Franke and M. L. Schattenburg, *J. Vac. Sci. Technol. B,* Nov./Dec 1997 (*in press*).

Henry I. Smith

Professor Smith is the Joseph F. and Nancy P. Keithley Professor of Electrical Engineering at MIT. He was born in Jersey City, New Jersey on May 26, 1937. He received the B.S. in Physics from Holy Cross College in 1958, and the M.S. in Physics from Boston College Graduate School in 1960. From 1960-1963 he was in the Air Force stationed at Air Force Cambridge Research Laboratories where he did work in geophysics and microwave ultrasonics. In 1963 he returned to Boston College, obtaining the Ph.D. in solid state physics in 1966. He remained at Boston College as an Assistant Professor of Physics until 1968 when he joined MIT Lincoln Laboratory. At Lincoln Laboratory Dr. Smith worked on surface-acoustic-wave devices and pioneered the development of techniques for fabricating submicrometer structures. In 1980 he left Lincoln Laboratory to pursue full-time teaching and research at MIT where he was appointed a Professor of Electrical Engineering. In January 1990 he was named to the Joseph F. and Nancy P. Keithley Chair in Electrical Engineering. Prof. Smith currently directs the NanoStructures Laboratory at MIT. In recent years his research has emphasized nanofabrication, electronic devices, quantum-effects in sub-100 nm structures, and device fabrication for all-optical communication.

Prof. Smith and his coworkers are responsible for a number of innovations in nanostructures technology and applications, including: conformable photomask lithography, x-ray lithography, the phase-shift mask, the attenuating phase shifter, spatial-phase-locked electron-beam lithography, achromatic interferometric lithography, interferometric alignment, graphoepitaxy, subboundary entrainment, sub-100 nm Si MOSFETs, and a variety of quantum-effect structures such as lateral-surface-superlattices, planar-resonant-tunneling field-effect transistors, and single-electron transistors.

Prof. Smith is a Fellow of the IEEE and a member of the National Academy of Engineering, APS, AVS, OSA MRS and Sigma Xi. He has been a visiting scientist at: University College, London (1972); Thompson CSF, Paris (1974); The Norwegian Institute of Technology (1976); Nippon Telegraph and Telephone Corporation, Atsugi, Japan (1990); and the University of Glasgow (1990). He holds over 25 US patents and has published over 300 technical articles.

Selected Recent Publications

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T.A. Savas, M.L. Schattenburg, J.M. Carter, and H.I. Smith, "Large-Area Achromatic Interferometric Lithography for 100nm-Period Gratings and Grids; With Novel Applications," J. Vac. Sci. Technol. B 14, 4167-4170 (1996).

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J. Goodberlet, J. Ferrera, M. Farhoud, V.Z. Chan, and H.I. Smith, "Extending Spatial-Phase-Locked Electron-Beam Lithography to Two Dimensions," submitted to Japanese Journal of Applied Physics, (1997).

Appendix B: ESTIMATED BUDGET

The amount requested for the second year of the Program is $305,000. This amount is identical to the amount requested in our original proposal, as amended post-award. We anticipate no changes to this amount. Since the detailed cost breakdown and justification was submitted at the time of the award, it will not be included here.