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Interim Progress Report
This Grant covers MIT support for the technology development of x-ray reflection gratings for the Constellation-X Reflection Grating Spectrometer (RGS). Since the start of the Grant MIT has extended its previously-developed patterning and super-smooth, blazed grating fabrication technology to ten-times smaller grating periods and ten-times larger blaze angles to demonstrate feasibility and performance in the off-plane grating geometry.

In the past year we successfully developed several nanoimprint grating replication methods that achieved very high fidelity replication of master silicon gratings. Grating geometry on the nano and macro scales were faithfully replicated, demonstrating the viability of the process for manufacturing the thousands of gratings required for the RGS.

We also successfully developed an improved metrology truss for holding test grating substrates during metrology. The flatness goal of grating substrates is under 500 nm. In the past, grating holders would cause non-repeatable distortion of >> 500 nm to the substrates due to friction and gravity sag. The new holder has a repeatability of under 50 nm which is adequate for the proposed RGS grating substrates.

Details can be found in the publications and Master's theses listed below:

Publications:
R122. "Nanometer-accurate grating fabrication with scanning beam interference lithography," C.G. Chen, P.T. Konkola, R.K. Heilmann, C. Joo and M.L. Schattenburg, *Proc. SPIE* **4936**, *Nano- and Microtechnology: Materials, Processes, Packaging, and Systems* (SPIE, Bellingham, WA), ed. D.K. Sood, 126-134 (2003).
R124. "Fabrication of saw-tooth diffraction gratings using nanoimprint lithography," C.-H. Chang, R.K. Heilmann, R.C. Fleming, J. Carter, E. Murphy, M.L. Schattenburg, T.C. Bailey, R.D. Frankel and R. Voisin, *J. Vac. Sci. Technol. B* **21**, 2755-2759 (2003).
R125. "Precision microcomb design and fabrication for x-ray optics assembly," Y. Sun, R.K. Heilmann, C.G. Chen, C.R. Forest and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **21**, 2970-2974 (2003).
R126. "Nanometer-level repeatable metrology using the Nanoruler," P. Konkola, C. Chen, R.K. Heilmann, C. Joo, J. Montoya, C.-H. Chang and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **21**, 3097-3101 (2003).
P127. "Thin glass optic and silicon wafer deformation and kinematic constraint," C. Forest, M. Akilian, G. Vincent, A. Lamure and M.L. Schattenburg, *Proc. of the 18th Annual Meeting of the American Society for Precision Engineering*, **30** (ASPE, Raleigh, NC) 39-42 (2003).
R128. "Metrology of thin transparent optics using Shack-Hartmann wavefront sensing," C.R. Forest, C.R. Canizares, D.R. Neal, M. McGuirk, A.H. Slocum and M.L. Schattenburg, *J. Optical Engineering* **43**, 742-753 (2004).

P129. "Grating arrays for high-throughput soft x-ray spectrometers," A.P. Rasmussen, A. Aquila, J. Bookbinder, C. Chang, E. Gullikson, R.K. Heilmann, S.M. Kahn, F. Paerels and M.L. Schattenburg, *Proc. SPIE* **5168**, *Optics for EUV, X-ray, and Gamma-ray* Astronomy (SPIE, Bellingham, WA), eds. O. Citterio and S.L. O'Dell, 248-259 (2004).

P130. "Advances in reflection grating technology for Constellation-X," R.K. Heilmann, M. Akilian, C.-H Chang, C.G. Chen, C. Forest, C. Joo, P. Konkola, J.C. Montoya, Y. Sun, J. You and M.L. Schattenburg, *Proc. SPIE* **5168**, *Optics for EUV, X-ray, and Gamma-ray* Astronomy (SPIE, Bellingham, WA), eds. O. Citterio and S.L. O'Dell, 271-282 (2004).

P132. "Dimensional metrology for nanometer-scale science and engineering: towards sub-nanometer accurate encoders," R.K. Heilmann, C.G. Chen, P.T. Konkola and M.L. Schattenburg, *Nanotechnology* **15**, S504-S511 (2004).

P133. "High fidelity grating replication using thermal nanoimprint lithography," C.-H. Chang, J.C. Montoya, M. Akilian, A. Lapsa, R.K. Heilmann, M.L. Schattenburg, M. Li, K.A. Flanagan, A.P. Rasmussen, J.F. Seely, J.M. Laming, B. Kjornrattanawanich and L.I. Goray, *J. Vac. Sci. Technol. B*, Nov./Dec. 2004 (*in press*).

P134. **"Thin foil reflection gratings for Constellation-X,"** R.K. Heilmann, M. Akilian, C.-H. Chang, C.R. Forest, C. Joo, A. Lapsa, J.C. Montoya and M.L. Schattenburg, *Proc. SPIE* **5488**, *UV-Gamma Ray Space Telescope Systems* (SPIE, Bellingham, WA), eds. G. Hasinger and M.J.L. Turner, 283-290 (2004).

P135. "The Constellation-X RGS options: raytrace modeling of the off-plane gratings," K.A. Flanagan, J.E. Davis, R.K. Heilmann, A.M. Levine, M. McGuirk, G.R. Ricker, M.L. Schattenburg, M. Wise, A. Rasmussen, J.A. Bookbinder, M.D. Freeman, T.J. Gaetz, D. Jerius, D. Nguyen, W.A. Podgorski, P.B. Reid, W.C. Cash, A.F. Shipley, D.J. Gallagher, P. Huang and S.P. Jordan, *Proc. SPIE* **5488**, *UV-Gamma Ray Space Telescope Systems* (SPIE, Bellingham, WA), eds. G. Hasinger and M.J.L. Turner, 515-529 (2004).

P136. "Thin optics constraint," M. Akilian, C. Forest, A. Slocum, D. Trumper and M.L. Schattenburg, *Proc. of the 19th Annual Meeting of the American Society for Precision Engineering*, Vol. **34**, 209-212 (2004).

P137. "Measuring two-axis stage mirror non-flatness using linear/angular interferometers," J. Montoya, R.K. Heilmann and M.L. Schattenburg, *Proc. of the 19th Annual Meeting of the American Society for Precision Engineering*, Vol. **34**, 382-385 (2004).

R138. "Repeatable and accurate assembly of x-ray foil optics," C.R. Forest *et al.*, J. Precision Engineering (*in preparation, Nov. 2003*).

R139. "Performance metrics and fringe locking control system design for scanning beam interference lithography," P.T. Konkola, C.G. Chen, R.K. Heilmann, C. Joo, J.C. Montoya, C.-H. Chang and M.L. Schattenburg, J. Precision Engineering (*submitted July 20, 2004*).

R141. "Thin optic constraint," M. Akilian, C.R. Forest, D.L. Trumper, A.H. Slocum and M.L. Schattenburg, *J. Precision Engineering* (*in preparation*).

R142. "Describing anisotropic out-of-plane deformation on (110) cubic materials using Zernike polynomials," C.-H. Chang , M. Akilian and M.L. Schattenburg, *J. Precision Engineering* (*in preparation*).

Presentations:

P258. "Nanometrology in nanomanufacturing," M.L. Schattenburg, *NASA Tech Briefs - Nanotech 2003 Conference*, Cambridge, Massachusetts, Oct. 23-24, 2003 (*invited*).

P259. "Thin glass optic and silicon wafer deformation and kinematic constraint," C. Forest, M. Akilian, A. Lapsa, G. Vincent, A. Lamure and M.L. Schattenburg, *18th Annual Meeting of the American Society of Precision Engineering*, Portland, Oregon, Oct. 26-31, 2003 (*paper III-2*).

P260. "Reflection grating development update," R.K. Heilmann, M. Akilian, C.-H. Chang, C.R. Forest, C. Joo, J.C. Montoya, A. Torkaman and M.L. Schattenburg, *Constellation X Mission Facility Science Team Meeting*, NASA Goddard Space Flight Center, Greenbelt, Maryland, Nov. 20, 2003.

P261. "The MIT Nanoruler: a tool for patterning large high-accuracy gratings," M.L. Schattenburg, *University of Rochester, Laboratory for Laser Energetics, Workshop on Large Scale MLD Gratings for OMEGA EP*, Rochester, NY, December 16, 2003 (*invited*).

P262. "The Space Nanotechnology Lab: high resolution x-ray optics with nanometer precision," R.K. Heilmann, MIT IAP symposium *Frontiers of Astronomy, Astrophysics, and Space Science*,

Cambridge, Massachusetts, Jan. 20, 2004.

P263. "The metrology crisis in nano manufacturing," M.L. Schattenburg, *National Nanotechnology Initiative Interagency Workshop on Instrumentation and Metrology for Nanotechnology*, National Institute of Standards and Technology, Gaithersburg, Maryland, Jan. 27-29, 2004 (*invited*).

P264. "Fabrication of saw-tooth diffraction gratings using nanoimprint lithography,"C.-H. Chang, R.K. Heilmann and M.L. Schattenburg, poster presented at the *Microsystems Technology Laboratories Student Research Review*, Waterville Valley, New Hampshire, Jan. 28-29, 2004.

P265. "Dimensional metrology for nanoscale science and engineering," R.K. Heilmann and M.L. Schattenburg., *IEEE Conference on Nanoscale Devices and System Integration*, Miami, Florida, Feb. 15-19, 2004 (*invited paper F2*).

P266. "Fabrication of saw-tooth diffraction gratings using nanoimprint lithography," C.-H. Chang, J.C. Montoya, C. Joo, M. Akilian, A. Lapsa, R.K. Heilmann, M.L. Schattenburg, M. Li and A. Rasmussen, poster presented at the *MIT Photonics & Roadmapping Spring Conference*, Cambridge, Massachusetts, May 3-4, 2004.

P267. "Metrology for nanometer scale science and engineering," M.L. Schattenburg, R.K. Heilmann and H.I. Smith, presented at *The 1st China-US Symposium on Nano Science and Technology*, Beijing, China, May 17-20, 2004 (*invited*).

P268. "The MIT Nanoruler: A tool for patterning large high-accuracy gratings," M.L. Schattenburg, Institute for Laser Engineering, Osaka University, Osaka, Japan, May 22, 2004 (*invited*).

P269. "High fidelity grating replication using thermal nanoimprint lithography," C.-H. Chang, J.C. Montoya, M. Akilian, A. Lapsa, R.K. Heilmann and M.L. Schattenburg, *48th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, San Diego, California, June 1-4, 2004 (*paper 6B5*).

P270. "Thin foil reflection gratings for Constellation-X," R.K. Heilmann, M. Akilian, C.-H. Chang, C.R. Forest, C. Joo, A. Lapsa, J.C. Montoya and M.L. Schattenburg, presented at the *SPIE Symposium on Astronomical Telescopes and Instrumentation 2004 -- Space Telescope Systems (UV-Gamma) (AS02)*, Glasgow, Scotland, June 21-25, 2004 (*paper 5488-82*).

P271. "The Constellation-X RGS options: raytrace modeling of the off-plane gratings," K.A. Flanagan, J.E. Davis, R.K. Heilmann, M. McGuirk, G.R. Ricker, M.L. Schattenburg, M. Wise, A. Rasmussen, J. Bookbinder, M. Freeman, T. Gaetz, D. Jerius, D. Nguyen, W. Podgorski, P. Reid, W. Cash, A. Shipley, D. Gallagher, P. Huang, and S. Jordan, presented at the *SPIE Symposium on Astronomical Telescopes and Instrumentation 2004 -- UV-Gamma Ray Space Telescope Systems, Glasgow, Scotland*, June 21-25, 2004 (*paper 5488-31*).

P272. "Nanometer precision metrology and constraint of thin optics for a high resolution x-ray telescope," M. Akilian, C.-H.Chang, C. Chen, C.R. Forest, R. Heilmann, C. Joo, P. Konkola, J. Montoya, Y. Sun and M.L. Schattenburg, Institute for Experimental Physics, Technische Universität Graz, Graz, Austria, July 15, 2004 (*invited*).

P273. "Large-area gratings for nanometer-accurate positioning and metrology," R.K. Heilmann and M.L. Schattenburg, *Center for Functional Nanomaterials Seminar*, Brookhaven National Laboratory, Upton, NY, July 21, 2004 *(invited)*.

P274. "Space Nanotechnology Laboratory," M.L. Schattenburg, *MIT Center for Space Research Advisory Committee Review*, Cambridge, MA, Sept. 20, 2004.

P275. "The Nanoruler: A tool for rapid high-precision patterning of large-area gratings," R.K. Heilmann, C.G. Chen, P.T. Konkola and M.L. Schattenburg, poster presented at the *R&D 100 Award Ceremony*, Chicago, Illinois, Oct. 14, 2004 (*invited*).

P276. "Advances in x-ray reflection grating technology," M. Akilian, C.-H. Chang, R. Heilmann, J. Montoya and M.L. Schattenburg, *Constellation-X Mission Facility Science Team Meeting*, NASA Goddard Space Flight Center, Greenbelt, Maryland, Oct. 14-15, 2004.

P277. "Thin optics constraint," M. Akilian, C. Forest, A. Slocum, D. Trumper and M.L. Schattenburg, *19th Annual Meeting of the American Society of Precision Engineering*, Orlando, Florida, Oct. 24-29, 2004 (*Poster 2, Equipment, Machines & Instruments - Design & Testing*).

P278. "Measuring two-axis stage mirror non-flatness using linear/angular interferometers," J. Montoya, R. Heilmann and M.L. Schattenburg, *19th Annual Meeting of the American Society of Precision Engineering*, Orlando, Florida, Oct. 24-29, 2004 (*Poster 5, Metrology - Analysis & Modeling*).

P279. "Metrology for nanometer scale lithography," M.L. Schattenburg and R.K. Heilmann, *Materials Research Society Symposium on Progress in Semiconductor Materials IV — Electronic and*

Optoelectronic Applications, Boston, Massachusetts, Nov. 30, 2004 (*invited paper C3.4*).

Master's Theses:

TM11. Chih-Hao Chang, *Fabrication of Extremely Smooth Blazed Gratings*, Master's Thesis, Department of Mechanical Engineering, June 2004.

TM12. Mireille K. Akilian, *Thin Optic Surface Analysis for High Resolution X-ray Telescopes*, Master's Thesis, Department of Mechanical Engineering, Sept. 2004.