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13. ABSTRACT (Maximum 200 words) The supported research applied interference lithography technology as a tool for metrology in the sub-100 nm (nanometer) critical dimension (CD) linewidth regime. To accomplish this goal MIT built a novel lithography tool called the Nanoruler. The tool uses the principle of scanning-beam interference lithography to pattern gratings with 400 nm period on 300-mm diameter wafers. MIT demonstrated a phase accuracy during writing and reading gratings with the Nanoruler of 2.1 nanometers, 3 sigma. This demonstrates that gratings can be used as a dimensional metrology tool with accuracy exceeding laser interferometers. The accuracy of gratings written by the Nanoruler far exceed gratings patterned heretofore by other techniques, such as electron beam lithography or ruling. A 300 mm-diameter wafer can be patterned in under 20 minutes with the Nanoruler, compared to hundreds of hours using electron-beam lithography to many weeks using diamond ruling.				
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FINAL PROGRESS REPORT

ARO Research Agreement DAAD19-02-1-0204
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Statement of the problem studied.

The supported research applied interference lithography technology as a tool for metrology in the sub-100 nm (nanometer) critical dimension (CD) linewidth regime. Semiconductor industry roadmaps show CDs shrinking to under 35 nm within 10 years. This requires mask image placement metrology accuracy of under 2 nm. There are currently no industry length-scale calibration standards at any level of accuracy that may be used to ensure metrology tool accuracy to this scale. Instead, the industry relies on various self-referencing schemes which are inaccurate, expensive, time consuming, and ineffective. Many other industrial and military electronics applications would issue from such super-accurate gratings, including encoders and integrated optoelectronic devices. Under this program, MIT developed technology to produce image placement metrology standards. The goal of the first year of the effort was to achieve sub-5 nm accuracy.

Summary of the most important results

MIT completed the construction and testing of a novel lithography tool called the Nanoruler, which is capable of writing and reading large gratings with unprecedented accuracy. MIT demonstrated the writing and reading of gratings on 300 mm-diameter substrates with a phase stability and repeatability of well under 3 nm, 3 sigma.

The Nanoruler utilizes the principle of scanning-beam interference lithography (SBIL), which involves the interference of small beams to create a grating "image," and then scanning a substrate under the image using a high-performance air-bearing stage. Stage and fringe phase errors are measured using heterodyne digital phase meters and locked out by use of acousto-optic phase shifters driven by a digital frequency synthesizer and high-speed digital controls. The Nanoruler is housed in a special environmental chamber to ensure the extremely tight environmental stability required to achieve nanometer fringe stability. Typical system positional stability during a period of 1 min has been demonstrated to be 2.1 nm, 3 sigma. The Nanoruler is capable of patterning gratings and grids with periods down to 200 nm on 300 mm-diameter substrates.

One of the significant accomplishments of the Nanoruler was to demonstrate that large, nano-accuracy gratings can be used as optical encoders to replace interferometers in lithography and metrology stages, thereby

wringing out a large source of CD and overlay errors. Stage error is an important component of overlay and CD budgets. In reading mode, the Nanoruler is designed to read the position and map the phase of gratings written by itself or other tools. In this mode, it thus performs essentially as an optical encoder with a precision and stability of ~2 nm.

Papers published in peer-reviewed journals.

- R110. "Analysis of vector Gaussian beam propagation and the validity of paraxial and spherical approximations," C.G. Chen, P.T. Konkola, J. Ferrera, R.K. Heilmann and M.L. Schattenburg, *J. Optical Society of America A* **19**, 404-412 (2002).
- R111. "Beam alignment and wavefront metrology for scanning beam interference lithography," C.G. Chen, R.K. Heilmann, C. Joo, P.T. Konkola, G.S. Pati and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **20**, 3071-3074 (2002).
- R112. "Nanometer-accurate fringe metrology using a Fresnel zone plate," C. Joo, G.S. Pati, C.G. Chen, P.T. Konkola, R.K. Heilmann, M.L. Schattenburg, A. Liddle and E.H. Anderson, *J. Vac. Sci. Technol. B* **20**, 3075-3079 (2002).
- R113. "A generalized scanning beam interference lithography system for patterning gratings with variable period progressions," G.S. Pati, R.K. Heilmann, P.T. Konkola, C. Joo, C.G. Chen, E. Murphy and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **20**, 2617-2621 (2002).
- R123. "Spatial phase locking with shaped beam lithography," J.G. Hartley, T.R. Groves, H.I. Smith, M.K. Mondol, J.G. Goodberlet, M.L. Schattenburg, J. Ferrera and A. Bernshteyn, *Rev. Sci. Instrum.* **74**, 1377-1379 (2003).

Manuscripts submitted, but not yet published.

- R124. "Nanometer-level repeatable metrology using the Nanoruler," P. Konkola, C. Chen, R. Heilmann, C. Joo, J. Montoya, C.-H. Chang and M.L. Schattenburg, *J. Vac. Sci. Technol. B* Nov./Dec. 2003 (*in press*).

Papers published in conference proceedings.

- R108. "Progress towards a general grating patterning technology using phase-locked scanning beams," M.L. Schattenburg, C.G. Chen, R.K. Heilmann, P.T. Konkola and G.S. Pati, *Proc. SPIE 4485, Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research IV*, eds. A.M. Larar and M.G. Mlynczak, 378-384 (2002).
- R114. "Effects of varying incident angle on the contrast of the fringe metrology using a Fresnel zone plate," C. Joo, G.S. Pati, C.G. Chen, P.T. Konkola, R.K. Heilmann and M.L. Schattenburg, *Proc. of the Seventeenth Annual Meeting of the American Society for Precision Engineering*, **27** (ASPE, Raleigh, NC), 83-88 (2002).
- 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).

Papers presented at meetings but not published.

- P206. "Nanometrology research at MIT," M.L. Schattenburg and H.I. Smith, *University of Central Florida, School of Optics/CREOL Seminar*, Orlando, Florida, February 19, 2002 (*invited*).
- P207. "Nanometrology research at MIT," M.L. Schattenburg and H.I. Smith, *International SEMATECH -- Metrology Council Meeting*, Austin, Texas, February 26, 2002 (*invited*).
- P208. "The critical role of metrology in nanotechnology," M.L. Schattenburg, *Mechanical Engineering Department Seminar*, Cambridge, Massachusetts, March 1, 2002 (*invited*).
- P209. "Grating-based nanometer metrology," M.L. Schattenburg, C. Chen, C. Joo, R.K. Heilmann, P.

- Konkola, G.S. Pati and H.I. Smith, *Defense Advanced Research Projects Administration - Advanced Lithography Program Review*, New Orleans, Louisiana, April 9-11, 2002.
- P212. "Beam alignment and wavefront metrology for scanning beam interference lithography," C.G. Chen, R.K. Heilmann, C. Joo, P.T. Konkola, G.S. Pati and M.L. Schattenburg, *46th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Anaheim, California, May 28-31, 2002 (paper 10B4).
- P213. "Nanometer-accurate fringe metrology using a Fresnel zone plate," C. Joo, G.S. Pati, P.T. Konkola, C.G. Chen, R.K. Heilmann, E.H. Anderson and M.L. Schattenburg, *46th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Anaheim, California, May 28-31, 2002 (paper 10B5).
- P214. "A generalized scanning beam interference lithography system for patterning gratings with variable period progressions," G.S. Pati, P.T. Konkola, C.G. Chen, C. Joo, R.K. Heilmann and M.L. Schattenburg, *46th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Anaheim, California, May 28-31, 2002 (poster PG7).
- P215. "Nanoaccuracy in nanolithography," H.I. Smith and M.L. Schattenburg, presented at the *US-Korea Nanofabrication Workshop*, Hanyang University, Seoul, Korea, June 3-5 (2002).
- P225. "Nanotech research at MIT," C.G. Chen, *Victoria State Department of Regional Development*, Melbourne, Australia, August 26, 2002 (invited).
- P226. "The Space Nanotechnology Laboratory," M.L. Schattenburg, poster presented at the *Summer School on: Nano and Giga Challenges in Microelectronics Research and Opportunities in Russia*, Department of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia, September 10-11, 2002 (invited).
- P227. "Fabrication of ultra-high accuracy diffraction gratings for nanometrology and spectroscopy applications." P. N. Lebedev Physical Institute of the Russian Academy of Sciences (FIAN), Moscow, Russia, September 11, 2002 (invited).
- P228. "The critical role of metrology in nanotechnology," M.L. Schattenburg, presented at the *Symposium on: Nano and Giga Challenges in Microelectronics Research and Opportunities in Russia*, Palace of Science of the Russian Academy of Sciences, Moscow, Russia, September 12-13, 2002 (invited).
- P231. "Interference fringe locking using Fresnel zone plates," C. Joo, G.S. Pati, C.G. Chen, P.T. Konkola, R.K. Heilmann and M.L. Schattenburg, presented at the *17th Annual Meeting of the American Society of Precision Engineering*, St. Louis, Missouri, October 20-25, 2002 (paper V-4).
- P234. "Scanning beam interference lithography," P. Konkola, presented at Brion Technologies, Inc., Mountain View, California, November 1, 2002 (invited).
- P236. "Nanometer-accurate grating fabrication with scanning beam interference lithography," G.C. Chen, P.T. Konkola, R.K. Heilmann, C. Joo and M.L. Schattenburg, *Conference on Nano- and Microtechnology: Materials, Processes, Packaging, and Systems -- part of SPIE International Symposium on Smart Materials, Nano- and Micro-Smart Systems*, Melbourne, Australia, December 16-18, 2002 (paper 4936-28).
- P238. "Environmental enclosure for the Nanoruler," M.L. Schattenburg, P. Konkola, C.-H Chang and C. Joo, *Buildings for Advanced Technology Workshop*, National Institute of Standards and Technology, Gaithersburg, Maryland, January 14-16, 2003 (invited).
- P239. "Nanoaccuracy: an essential element of nanotechnology," J.T. Hastings, M.L. Schattenburg, P. Konkola, E.E. Moon and H.I. Smith, *Japan-US Symposium on Tools and Metrology for Nanotechnology*, Cornell University, Ithaca, New York, January 21-24, 2003 (invited).
- P242. "Design and analysis of a scanning beam interference lithography system for patterning gratings with nanometer-level distortion," P.T. Konkola, *Ph.D. Defense, MIT Department of Mechanical Engineering*, Cambridge, Massachusetts, April 3, 2003.
- P243. "The importance of metrology in nanofabrication," M.L. Schattenburg, *MIT Microsystems Technology Laboratories – Microlunch Seminar*, Cambridge, Massachusetts, April 8, 2003.
- P244. "The role of nanometer-level accuracy and precision in nanomanufacturing," H.I. Smith and M.L. Schattenburg, *First International Symposium on Nanomanufacturing*, Cambridge, Massachusetts, April

24-26, 2003 (*invited*).

- P245. "Beam Alignment and Image Metrology for Scanning Beam Interference Lithography – Fabricating Gratings with Nanometer Phase Accuracy," C.G. Chen, *Ph.D. Defense, MIT Department of Electrical Engineering and Computer Science*, Cambridge, Massachusetts, April 29, 2003.
- P247. "Nano-metrology using the Nanoruler," M.L. Schattenburg, P. Konkola, C. Chen, R.K. Heilmann, C. Joo, J. Montoya and C.-H. Chang, *Defense Advanced Research Projects Agency (DARPA) - Advanced Lithography Program Review*, Santa Fe, New Mexico, May 5-8, 2003.
- P249. "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, *47th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Tampa, Florida, May 27-30, 2003 (*paper 2B3*)
- P258. "Nanometrology in nanomanufacturing," M.L. Schattenburg, *NASA Tech Briefs - Nanotech 2003 Conference*, Cambridge, Massachusetts, Oct. 23-24, 2003 (*invited*).

Student Master's and Ph.D. Thesis

- Dr. Carl Gang Chen, *Beam Alignment and Image Metrology for Scanning Beam Interference Lithography – Fabricating Gratings with Nanometer Phase Accuracy*, Ph.D. Thesis, Department of Electrical Engineering and Computer Science, April 2003.
- Chulmin Joo, *Image Grating Metrology using a Fresnel Zone Plate*, Master's Thesis, Department of Mechanical Engineering, August 2003.
- Dr. Paul Thomas Konkola, *Design and Analysis of a Scanning Beam Interference Lithography System for Patterning Gratings with Nanometer-Level Distortion*, Ph.D. Thesis, Department of Mechanical Engineering, April 2003.

Participating scientific personnel.

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- Dr. M. L. Schattenburg, Principal Research Scientist, CSR
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Graduate Students

- C. G. Chen, Research Assistant, Electrical Engineering (Ph.D. April 2003)
C. Joo, Research Assistant, Mechanical Engineering (M.S. August 2003)
P. T. Konkola, Research Assistant, Mechanical Engineering (Ph.D. April 2003)
J. Montoya, Research Assistant, Electrical Engineering

Patents

- "A method for interference lithography utilizing phase-locked scanning beams," M. L. Schattenburg and P. N. Everett, U.S. Patent Ser. No. 09/711,019 (*pending*).
- "Spatial phase locking with shaped electron beam lithography," J.G. Hartley, T.R. Groves, J. Ferrera, J.G. Goodberlet, M.K. Mondol, M. L. Schattenburg and H.I. Smith, U.S. Patent (*pending*).