NIRT: GOALI - An Electron-Beam Based Microscale Nano-Manufacturing Platform with 1-nm Accuracy (CMMI-0609241)

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Introduction

Scanning electron-beam lithography (SEBL):

- arbitrary patterning
- sub-10-nm resolution
- ideal for nanomanufacturing if not for 3 problems

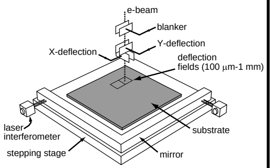
Problems in standard SEBL:

1. poor pattern-placement accuracy,
2. low throughput, and
3. high cost-of-ownership

Key Challenges:

1. Open loop operation (no direct knowledge of beam position, yet many factors introduce position errors)
2. Current-density limited electron beam and time consuming stabilization, calibration, and alignment
3. Costly precision electronics, electron-optics, and stages. High cost of electromagnetic, thermal, and vibration isolated facilities.

Standard SEBL System

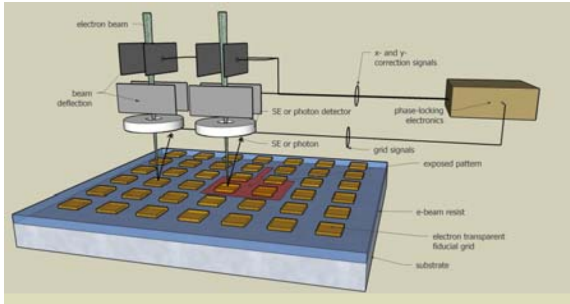


Standard SEBL systems deflect a focused electron-beam over a small region to write nanoscale patterns. This approach provides arbitrary patterning and sub-10-nm resolution, but suffers from poor pattern placement, low throughput, and high cost of ownership.

Key Innovations:

1. **Spatial-phase locking for closed-loop control.** Beam position is controlled based on the signal from an electron - transparent, metrologically accurate, fiducial grid. ➡ **1-nm placement accuracy.** System cost reduced by relaxed requirements for precision engineering, components, isolation, and stabilization.
2. **Multiple micro-fabricated electron-optical systems** for parallel arbitrary patterning. ➡ **Scalable throughput.** No longer limited by current in single beam. Column cost minimized by batch fabrication with wafer scale process.

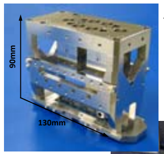
Micro-Column Array SEBL with Spatial-Phase Locking



Multiple-electron beam (two shown) nanomanufacturing system based on spatial-phase locked electron-beam lithography (SPLEBL). Each electron optical system is microfabricated by Novelx, Inc. in a batch MEMs process. As the electron-beams scan across the substrate they interact with an electron-transparent fiducial grid. The grid produces a secondary electron or photon signal whose phase can be detected to provide feedback control of the beam position.

Novelx Inc. Micro-Column SEBL Array

- High current density, low-voltage (1 to 2kV) electron optical systems
- Batch fabricated using wafer scale process.
- 4-column array using thermal field emission sources (two sources installed as shown at right)
- 126x17x9mm monolithic column footprint
- All high-speed electrostatic deflection and blanking.
- Each column capable of independent writing. (Spallas, Silver, and Muray, 2006)



4-column array for parallel lithography

Single column test-bed system for spatial-phase-locked e-beam lithography

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▬ Publication resulting from NIRT award.

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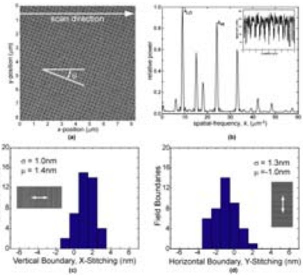
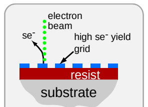
Nanometer-Level Precision using Spatial-Phase Locking with a Single Electron Beam

- **SEBL System**: Raith 150, operating at 10keV, converted for raster-scan exposure with custom phase-locking electronics.
- **Fiducial grid**: **(a)** 8-nm thick aluminum on SiO_2 fiducial grid . Grid rotated with respect to scan direction to provide feedback control for both axes.
- **Phase-locking**: **(b)** Spatial-frequency spectrum of the fiducial grid. The two critical frequency components (k_{HI} and k_{LO}) used for determining x- and y- position errors are labeled. Inset: sample signal from grid.
- **Pattern-Placement Results: (c,d)** Measured x-axis and y-axis stitching errors at the boundaries of each deflection field. Insets contain electron micrographs of a representative pattern at the field boundary. The gap between the lines was intentionally introduced to identify the boundary.

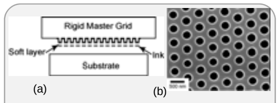


Objectives for Multi-Column Spatial-Phase Locked EBL

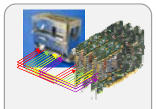
1. **A high signal-to-noise ratio grid that does not perturb the nano-patterning process.**
2. **A means to transfer the grid to each work-piece while retaining nanometer accuracy.**
3. **A phase-locking system suitable for a micro-column SEBL array.**



Objective 1. SPLEBL requires an grid that emits secondary electrons when struck by a primary electron. The grid must not strongly scatter primary electrons.



Objective 2. (a) Inking and stamping using a hybrid rigid/soft master grid offers one possibility for transferring the fiducial grid to each work piece. (b) Near-field optical patterning techniques using rigid masks are also under development. SEM micrograph shows a grid transferred using such a technique.

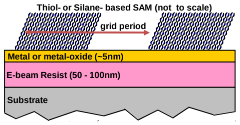


Objective 3. Spatial phase locking algorithms implemented in a field-programmable gate array (Xilinx Virtex 4 FPGA) using an easily parallelized single board solution.

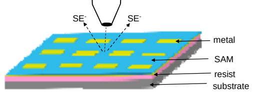
High SNR Fiducial Grid for μ-column SPLEBL

Motivation: Micro-column spatial-phase locking requires a fiducial grid that provides high SNR and minimal electron scattering at low (<5keV) beam energies.

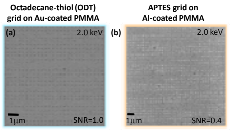
Key Innovation: Self-assembled monolayer fiducial grids with low atomic mass strongly modulate secondary electron yield while minimizing electron scattering. (Samantaray and Hastings, 2008)



The self-assembled monolayer is stamped onto a metal or metal oxide coated electron-beam resist. This configuration produces a electron transparent grid with high signal-to-noise ratio.

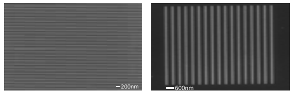


The patterned self-assembled monolayer modulates secondary electron yield from the grid. Electron scattering in the SAM is negligible; thus, electron scattering is uniform across the sample. Scattering can be minimized by using a low atomic number metal interlayer.



400-nm period molecular fiducial grids. **(a)** ODT mono-layer (bright regions) on Au coated PMMA. **(b)** Organo-silane (APTES) layer (dark regions) on Al coated PMMA.

Patterning through the Fiducial Grid



74± 1 nm Cr lines (200 nm pitch)
100-nm of PMMA with Cu-based grid. (5keV)

219±3 nm PMMA lines (600 nm pitch).
50-nm of PMMA, Al-based grid. (2keV)

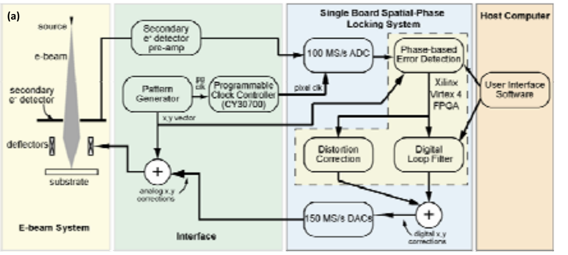
- Current APTES/Al grid removal process and 2keV exposure broaden lines significantly ⇒ need thinner resist and etchant that does not attack exposed resist.

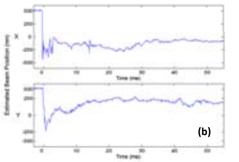
- Alkanethiol (ODT) on gold grids (control experiment) ➡ excellent SNR but unacceptable electron penetration and scattering from Au
- Alkanethiol (ODT) on copper grids ➡ better e⁻ penetration, reduced scattering ,but unacceptable SNR
- Organosilane (APTES) grids on partially oxidized aluminum ➡ excellent SNR (approaching ODT/Au) with minimal electron scattering.

Parallelizable Phase Locking for μ-column Arrays

Motivation: The current spatial-phase locking system exposes 8 Mpixels/s using a general purpose microprocessor and 10 Msample/s DACs and ADCs. For high-throughput nanomanufacturing with micro-column arrays we need a parallelizable system that can run at up to 80Mpixels/s.

Key Innovation: Integrated, single board implementation of spatial-phase locking using a FPGA and high speed (~100Msample/s) A/D and D/A converters. (Yang and Hastings, 2008)





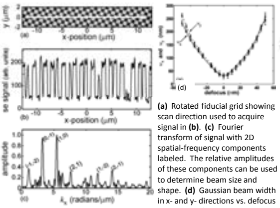
(a) Schematic of the integrated spatial-phase locking system suitable for either raster or vector scan exposures and compatible with high-throughput multi-column systems. The system is implemented on a single board using a Xilinx Virtex 4 field-programmable gate array (FPGA). The current implementation runs at 40Mpixels/s. Streamlining FPGA design will accommodate the full exposure speed of a Novelx micro-column system (80Mpixels/s/column). **(b)** Correction signal from the high speed spatial-phase locking system while monitoring the beam position with respect to a 1μm-period gold grid with an extremely low areal dose of 0.051μC/cm² and high sample rate (40Mpixels/s).

Advanced Feedback Control Algorithms

Feedback control for Beam Shape

Motivation: Changes in beam shape and size during exposure lead to critical dimension errors.

Key Innovation: The fiducial grid signal contains information about beam shape as well as position. A signal processing algorithm that extracts beam size, astigmatism, and rotation from the fiducial grid signal allows real-time feedback control of beam shape during exposure. (Hastings, 2006)

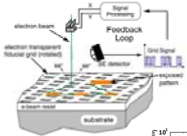


(a) Rotated fiducial grid showing scan direction used to acquire signal in **(b)**. **(c)** Fourier transform of signal with 2D spatial-frequency components labeled. The relative amplitudes of these components can be used to determine beam size and shape. **(d)** Gaussian beam width in x- and y- directions vs. defocus determined from experimental fiducial grid signals.

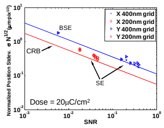
Vector-scan SPLEBL

Motivation: Most SEBL for research and prototyping purposes uses a vector-scan exposure strategy. All previous work on real-time SPLEBL used a raster scan strategy.

Key Innovation: New signal processing algorithm allows arbitrary sampling/exposure sequence. Control system parameters can be pattern dependent if necessary. (Yang and Hastings, 2007)

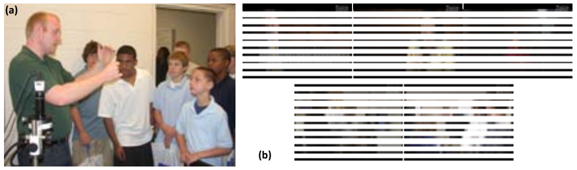


Spatial-phase locking for vector-scan SEBL using an intentionally rotated fiducial grid. In vector scan SEBL sparse patterns are be exposed using complicated deflection strategies (spiral, flyback, or serpentine shape filling). This approach requires more sophisticated signal processing and control algorithms.



Normalized standard deviation of experimental x and y position errors vs. SNR. Also shown are the theoretical limits of estimation precision, or Cramer-Rao bounds (CRB), based on phase estimation in Gaussian white noise.

Nanomanufacturing Education and Outreach



(a) A group of middle school students visiting U.K.'s Center for Nanoscale Science and Engineering. The students are listening to a graduate student (J. Alexander) explain how an AFM operates. The students had just finished a demonstration using the electron-beam lithography system located immediately behind them. **(b)** Images for Research Channel documentary on the Hastings research group in which the NIRT nanomanufacturing work is prominently featured. Clockwise from top left: Dr. Hastings introduces the research, graduate student Yugu Yang explains her role, Dr. Chandan Samantaray (post-doc) explains his work on fiducial grids, Dr. Hastings demonstrates e-beam lithography for U.K. Honors program students, and Dr. Samantaray, undergraduate Donald Keathley, and Dr. Hastings measure the thickness of a metal film on e-beam resist.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 0601351. Facilities and technical assistance were provided by the University of Kentucky Center for Nanoscale Science and Engineering (CeNSE) which is supported by National Science Foundation EPSCoR award No. 0447479. We acknowledge Dr. Chuck May and Brian Wajdyk for valuable technical assistance, and we thank Dr. Timothy Savas and Thomas O'Reilly (MIT Nanostructures Laboratory) for fabricating the fiducial grids used for the vector-scan experiments.