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Introduction

Standard SEBL System

Scanning electron-beam lithography (SEBL):

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

Problems in standard SEBL:

- poor pattern placement accuracy
- low throughput, and
- high cost-of-ownership

Key Challenges:

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

Key Innovations:

- Spatial-phase locking for closed-loop control.** Beam position is controlled based on the signal from an electron-transparent, metrologically accurate, fiducial grid.
- Multiple micro-fabricated electron-optical systems for parallel arbitrary patterning.**

1-nm placement accuracy. System cost reduced by relaxed requirements for precision engineering, components, isolation, and stabilization.

Scalable throughput. No longer limited by current in single beam. Column cost minimized by batch fabrication with wafer scale process.

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 SiO₂ 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_x and k_y) 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.

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 (~100Msamples/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 1 μ m-period grid with an extremely low area dose of 0.05 μ C/cm² and high sample rate (40Mpixels/s).

Micro-Column Array SEBL with Spatial-Phase Locking

Multiple-electron beam (two shown) nanomanufacturing system based on spatial-phase locked electron-beam lithography (SPEBL). 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.

Objectives for Multi-Column Spatial-Phase Locked EBL

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

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

Objective 2. Ink 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.

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)

Vector-scan SPEBL

Motivation: Most SEBL, for research and prototyping purposes uses a vector-scan exposure strategy. All previous work on real-time SPEBL 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)

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 for parallel lithography

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)

High SNR Fiducial Grid for μ -column SPEBL

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)

Thiol- or Silane-based SAM (not to scale)

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

Patterning through the Fiducial Grid

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

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

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) displays 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 an e-beam resist.

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