A Metrology Scanning Electron Microscope for Traceable Measurements

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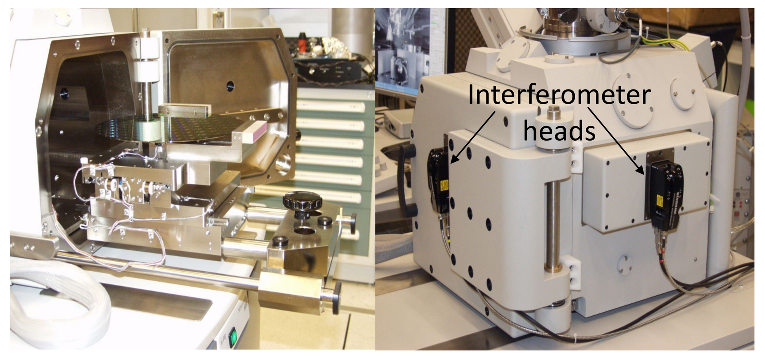
Introduction

The increasing need for traceable nanometer-level metrology has led to the development at the National Institute of Standards and Technology (NIST) of a specialized, metrology scanning electron microscope (M-SEM) having a metrology stage measured by a laser interferometer system. The purpose of the M-SEM is to carry out traceable calibrations of pitch on standard reference materials (SRM) using nanometer-level positioning of the sample under the electron beam in the SEM. The M-SEM will also be used for customer measurements on other reference samples such as those used in integrated circuit and nanotechnology development and production. This paper introduces the metrology, measurement and control system design, uncertainty budget, preliminary results, and the design of a planned reference artifact.

1

Laser Interferometer Sample Stage

The M-SEM uses laser interferometers for sample displacement measurements traceable to the International System of Units (SI). The X-Y sample-stage position is measured while synchronously recording the secondary or backscattered electron output signal of the SEM.



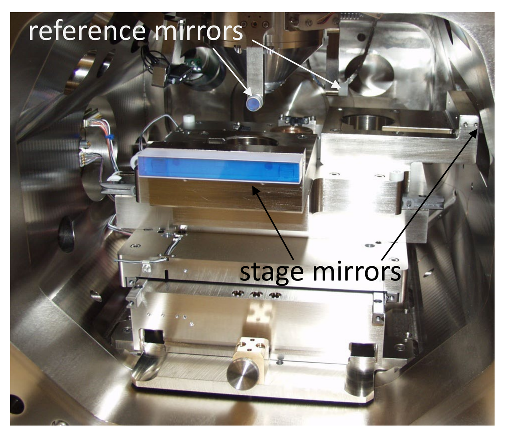
The laser sample stage with a 300 mm wafer.

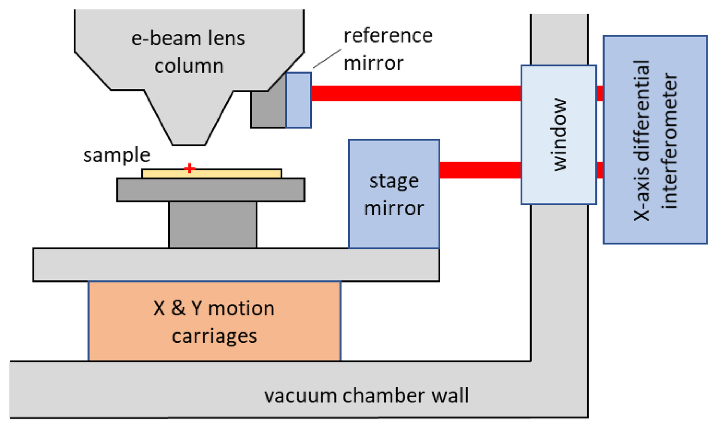
Two laser interferometers with fiber optic beam delivery, on the side and on the heavily reinforced new door of the SEM.

2

Metrology Design

The homodyne interferometer system with phase sensitive photo detectors has 40 pm resolution and uses fiber-optic delivery of the laser light directly to the measurement axes. This results in reduced optical path complexity, lower thermal drift, and a smaller footprint, enabling the interferometer optics to mount directly on the SEM sample chamber. High planarity mirrors are mounted on the SEM column and motion stage in both X-Y directions for differential measurement of sample position with respect to electron optical column. The interferometer system provides sub-nanometer non-linearity and will track velocities up to 1 m/sec with relative positional accuracy of 1×10^{-6}.





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Measurement and Control System

A computerized measurement and control system was developed to operate at a high data throughput. Fast scanning of the SEM minimizes the inter-frame drift due to environmental effects. The maximum data acquisition rate for the combined SEM column detector, the SEM horizontal and vertical raster scan signals and the X-Y laser stage position is 3 MHz. The SEM scan and detector data are collected using data acquisition hardware while the stage position data are simultaneously acquired through a custom-programed floating point gate array (FPGA) board that interfaces to the interferometer hardware. Complete synchronization of the hardware (and thus data acquisition process) is achieved by generating a master clock signal within the FPGA which, in turn controls the analog SEM column data acquisition.

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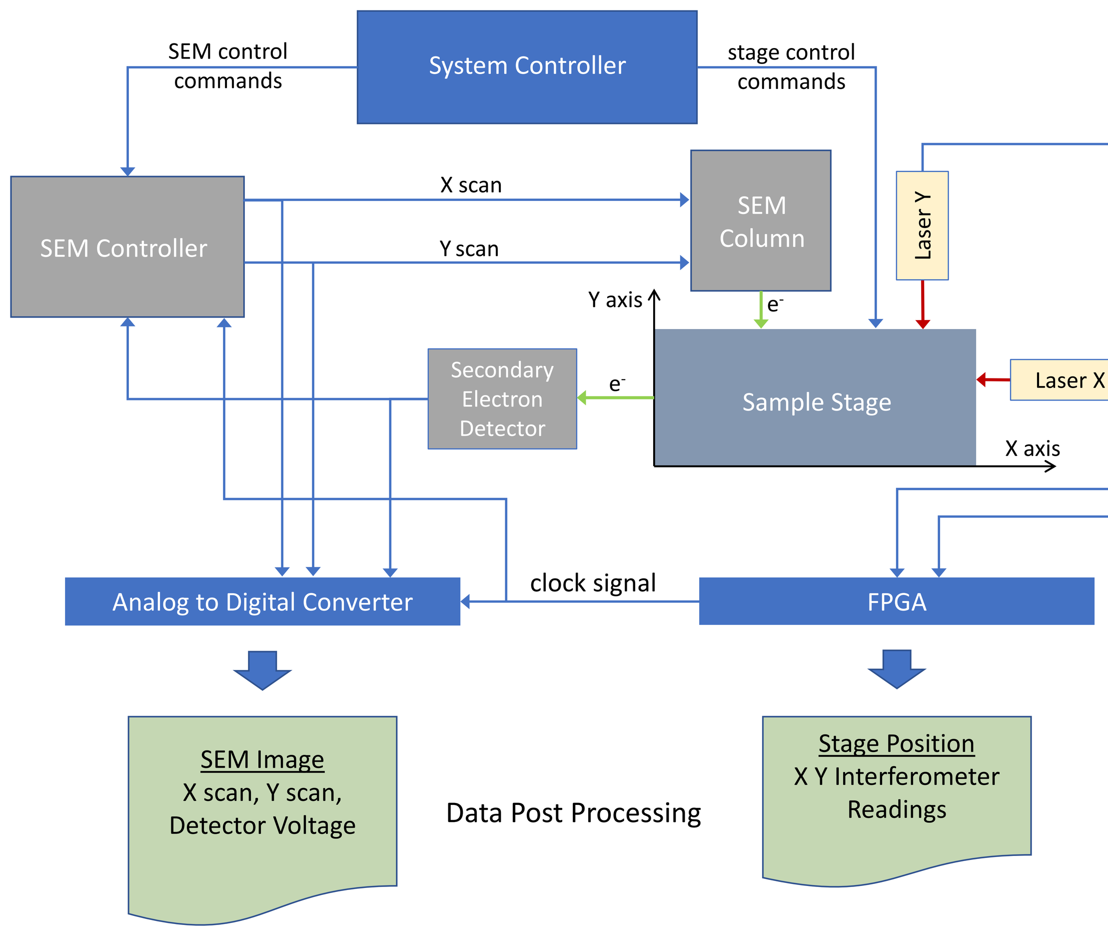
Measurement and Control System Layout



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Measurements

Two measurement methods are implemented: 1) Image magnification calibration, where a set of images at constant magnification are collected as a feature is moved systematically within the field of view by translating only the interferometrically-measured sample stage. The position of the feature (pixel coordinates) is correlated with the interferometer-measured X-Y position of the stage to calibrate the field magnification scale or pixel size. 2) Spot mode metrology, where the primary electron beam is stationary, and the sample is moved under the beam while recording secondary electron detector signal and X-Y position of measurement stage. The spot mode method is applicable to long distances of up to 100 mm.

Preliminary spot-mode measurements have been made on grating artifacts with 500 nm, 700 nm, and 1 μm pitches by traversing their full 100-μm fields. A representative estimated uncertainty budget for average pitch measurements from these data is shown in Table 1. Individual uncertainty components are combined as root sum of the squares. The uncertainty arising from the measurement of the 00 μm distance is $[(5\times10^{-7} \times 100\ \mu m)^2 + (1\ nm)^2]^{1/2} = 1$ nm; a relative uncertainty of 1×10^{-5}. (All uncertainties are reported with a coverage factor k = 1.) However, the overall average pitch measurement uncertainty is overshadowed by the sample-related components totaling 30 nm, a relative uncertainty of 3×10^{-4}. The uncertainty for this preliminary measurement was dominated by the crude, unmeasured alignment of the sample with the measurement axis resulting in a large cosine error uncertainty.

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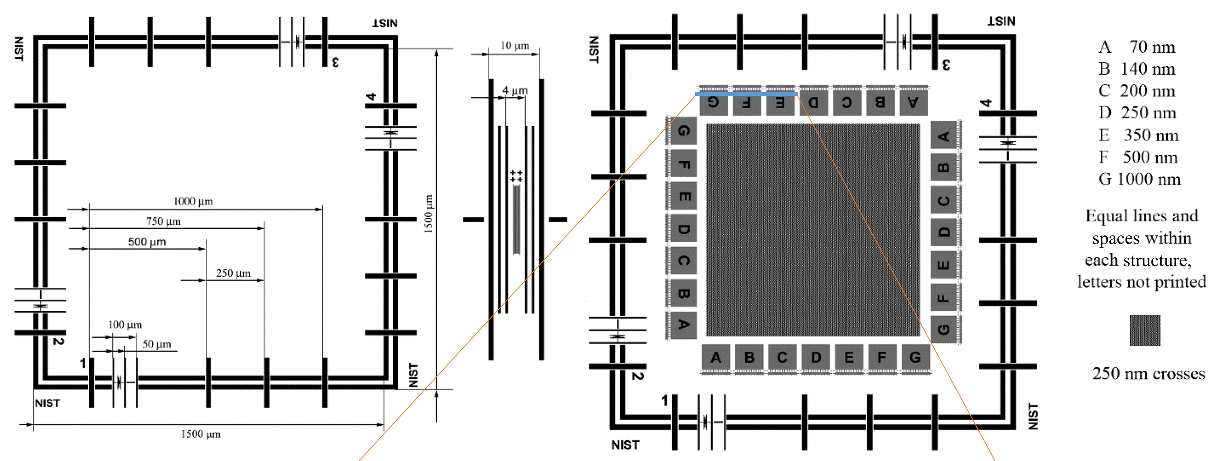
NIST Standard Reference Material

NIST Standard Reference Material (SRM) 8820 is under development for accurate, traceable scale calibrations for SEMs, atomic force microscopes and optical microscopes. SRM 8820 has pitches ranging from 1.5 mm to 70 nm.

SRM 8820 status: die produced; statistical measurements completed; SI-traceable calibration pending



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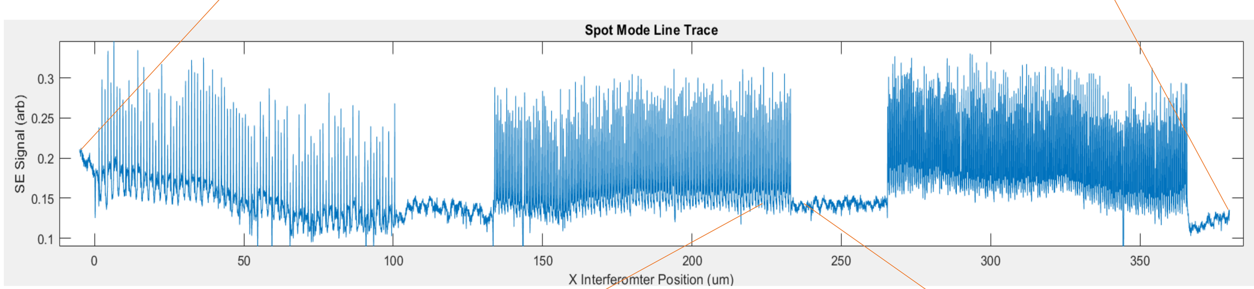
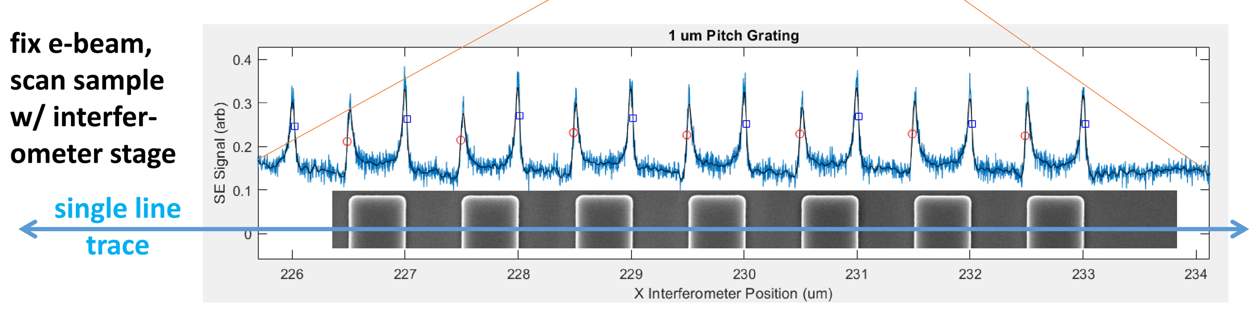
Spot Mode Preliminary Measurement Results



fix e-beam, scan sample w/ interfer-ometer stage

single line trace



Preliminary data measuring gratings in spot mode: 2μm, 1 μm, and 700 nm pitch

- Preliminary average pitch over full 100-μm grating field: 1000.0 nm ± 0.3 nm
- Expected avg. pitch uncertainty 1000.00 nm ± 10 pm (relative $u_c = 1\times10^{-5}$, k=1)

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Uncertainty Budget for 100-μm Scan, 1-μm Average Pitch Measurement				
Source	Uncertainty			Notes
	(× L)	(nm)	Type	
Instrument				
Interferometer scale	$< 5 \times 10^{-7}$		B	laser frequency & alignment
Periodic nonlinearity		< 1	B	fringe interpolation error
Abbe error		< 0.1	B	1 mm Abbe offset; ± 0.1 μrad pitch and yaw for L < 100 μm
Thermal drift		< 0.1	B	primary e-beam drift in 1 s measurement time for L = 100 μm
Subtotal	$< 5 \times 10^{-7}$	**< 1**		
Sample				
Grating alignment to measurement axis	$< 3 \times 10^{-4}$		B	cosθ; θ < 25 mrad
Line position uncertainty		3	A	includes both sample and measurement variability
Thermal expansion	6×10^{-6}		B	temperature = (20 ± 2) °C ; $CTE_{Si} = 3 \times 10^{-6}\ K^{-1}$
Subtotal	$< 3 \times 10^{-4}$	**3**		

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Summary

- At present, preliminary spot-mode grating pitch measurements are being made with the metrology SEM, for testing.
- Final adjustments to the instrument and measurement methods are being carried out to verify measurement uncertainty values for calibration.
- Once validated for traceable measurements, the metrology SEM will first be used to calibrate NIST Standard Reference Material SRM 8820.
- A customer calibration service is also planned.

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Appendix A: Metrology SEM

- Variable landing energy, variable vacuum (ESEM, VPSEM)
- Field emission electron gun, better than 1 nm ultimate spatial resolution
- Large sample capability (200 mm and 300 mm wafers and 6" photomasks) with 100 mm by 100 mm measurement coverage
- Large and diverse set of samples can be measured without conductive coating
- Special high-performance laboratory/cleanroom
- Used for traceable calibrations

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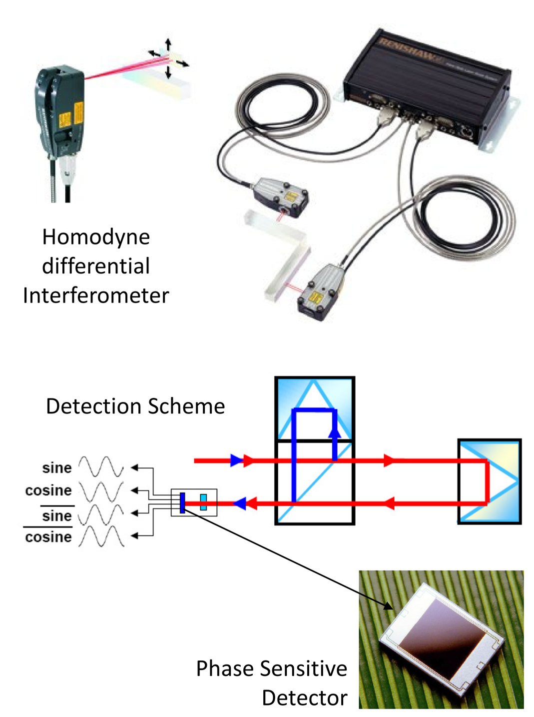
Appendix B: Ultra-Precise Laser Interferometry

- The fiber-optics deliver laser light directly to the measurement axes, no beam splitters, benders and adjustable mounts are needed.
- Reduced optical path complexity, thermal drift and footprint. Simpler alignment and installation.
- The interferometer system provides resolution of 40 picometers.



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