3-D Optical Metrology of Finite sub-20 nm Dense Arrays using Fourier Domain Normalization
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Introduction
• Reduced target dimensions require improved resolution and sensitivity.
• Sensitivity to nanometer scale changes can be observed when measuring critical dimensions of 6th-order targets.
• Imaging methods can use all of the phase and frequency information.
• There is a need to reduce overall size of a grating to 900 nm2 with ~20 lines yet acquire more information.
• Targets that are non-repetitive, irregular, or have pitches greater than the wavelength of light scatter multiple (or even a continuum of) frequencies.
• Example: spatial selectivity could enable in-chip measurement.

Our new approach enables rigorous analysis of 3-D focus-resolved and angle-resolved optical images that samples the three-dimensional electromagnetic field above and into finite targets, that scatter a continuum of frequency components.

Simulate a library of scattering profiles.
- Angle-resolved and focus-resolved images
- Choose one in the center of the parameter space and add a systematic and random noise profile shown on the right.
- Concatenate the data sets.
- Perform a standard regression analysis and determine uncertainties.

The Simulation Study

Tool Functions

Advanced Tool Characterization

Fourier Domain Normalization
• The incident illumination is independently normalized.
• The light scattered data used to do the experimental data are normalized in the frequency domain.
• The rest curve shows uncorrected simulation data and the graph shows the reconstructed image following Fourier normalization.

Linear Regression Model
With a Taylor expansion the non-linear regression becomes

\[ y = y_0 + \sum_{i=1}^{n} x_i^2 \]  

With initial set of floating parameters

\[ y = \sum_{i=1}^{n} x_i^2 \]  

By re-parameterization, the model is expressed as

\[ y = \sum_{i=1}^{n} x_i^2 \]  

It can be shown that the generalized least squares estimator of \( \beta \) is now given by

\[ \beta = \left( X^T X \right)^{-1} X^T y \]  

for the best \( K \) parameter estimates

Experimental Sensitivity

Conclusions
• We have rigorously fit complex targets that scatter a broad range of frequencies using focus-resolved scatterfield microscopy.
• A comprehensive approach using Fourier normalization and field corrections was used to rigorously fit the data with no tunable parameters.
• Excellent uncertainties were obtained for the parameter fits shown here by using all of the phase and frequency information.
• This technique was validated for micro-meter-sized dense targets.
• Microscope phase errors are embedded in the normalization.
• Next, we will compare with SEM and then use a Bayesian hybrid metrology formulation to optimize the measurements.

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Simulation/Experiment Fitting Results of a Si Edge

Type B Uncertainty Estimates
1. CCD pixel pitch uncertainty mapped into intensity variation
2. SiOx thickness uncertainty
3. Numerical Aperture size uncertainty 0.12–0.14
4. CBFP Aperture position uncertainty (incidence angle uncertainty)
5. Intensity variation due to through focus increment (4nm)
6. A/10 random phase error with systematic phase errors mapped into intensity variation
7. Tool function repeatability error
8. Parametric modeling errors, physical parameterization

Type B errors are combined with experimental repeatability uncertainties

Uncertainties vs. Fitting Residuals

Fitting Results

Sub-20 nm CD Metrology Target
• Sets of nominally 14nm, 16 nm, and 18 nm lines were fabricated by SEMTECH based on NIST designs.
• Targets are Si on Si with a thin conformal oxide. Two wafers were fabricated using e-beam litho. One was checked and the other has residual SiOx ~ 2-3 nm.
• Line extensions were included to facilitate AFM measurements. Note AFM measurements may have a bias compared to dense area optical measurements.
• Current target sizes as small as 1.75 μm x 6 μm.

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