Linearized scatterometry for detecting EUV phase deviations

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The need for actinic phase scatterometry

• Actinic phase metrology needed, scatterometry uniquely suited
  • Must be actinic to be sensitive to phase @13.5nm
  • Must measure patterned area to capture M3D/thick-object scattering
  • Scatterometry hardware much simpler than actinic phase imaging
Computational approach is a challenge

- Scatterometry follows RCWA (Rigorous Coupled-Wave Analysis)
  - Computation for ~160 illumination conditions takes a few minutes
  - Numerical optimization would take hours/days with no guarantee of success
    - Local minimum and/or flaws in parametrization

Measured, $y$

RCWA, $y_0$
Linearization greatly simplifies things

• Predict deviations in phase from a linearized approximation
  • Nominal RCWA already very close to measurement: $\delta y = y - y_0$
  • Random perturbations of nominal RCWA to learn linearization: $\Delta \phi \approx w^* \delta y$

• One-time computation, then fast + guaranteed solution at runtime

Deviation, $\delta y$  Learned filter, $w$
How to solve for the filter $w$?

• Goal: solve for $w$ such that $\Delta \phi \approx w^* \delta y$

• Solution: simulate $N$ random perturbations of nominal RCWA
  • Randomly perturb model parameters like layer thickness and mask CD
  • Deviation of scatterometry measurement $\Delta Y$ ($N$-column matrix)
  • Deviation of in-image phase at nominal illumination $\Delta \Phi$ ($N$-element vector)
  • Numerically stable solution for $w$: $w = (\Delta Y^* \Delta Y + \alpha I)^{-1} \Delta Y^* \Delta \Phi$
  • Leave-one-out cross validation to prevent overfitting

• At runtime: estimate change in pattern phase with linear projection
RCWA can learn to interpret scattering data

- Simulated performance on 8 different features
- $w^* \delta y$ correlation with true phase compared to raw magnitude $||\delta y||$
Nominal scattering signal from RCWA

Nominal signal, $y_0$

$p=560\text{nm}, D=25\%$

Diffraction orders
Measured signal

Measured signal, $y$

$p = 560\text{nm}, D = 25\%$

$\theta = 2^\circ$

$\theta = 4^\circ$

$\theta = 6^\circ$

$\theta = 8^\circ$

Diffraction orders

-3

-2

-1

0

1

2

3

13\text{nm} \quad \lambda \quad 14\text{nm} \quad \lambda \quad \lambda \quad \lambda$
Deviation of measurement from nominal

Deviation signal, $\delta y$

$p = 560 \text{nm}, D = 25\%$

$\theta = 2^\circ$

$\theta = 4^\circ$

$\theta = 6^\circ$

$\theta = 8^\circ$

Diffraction orders

13nm $\lambda$ 14nm $\lambda$ $\lambda$ $\lambda$
Weights learned from RCWA

Optimized weights, $w$

$p = 560\text{nm}, D = 25\%$

$\theta = 2^\circ, \theta = 4^\circ, \theta = 6^\circ, \theta = 8^\circ$

Diffraction orders

$\lambda = 13\text{nm}, \lambda = 14\text{nm}, \lambda$
D=50%: nominal $y_0$ and learned $w$

$p=160$  $p=280$  $p=440$

$y_0$  

$w$
D=33%: nominal $y_0$ and learned $w$

$p=240$  $p=420$  $p=660$

$y_0$  $w$
D=25%: nominal $y_0$ and learned $w$

$p=320$

$p=560$