Accurate and efficient simulation of resist images generated by advanced lithographic systems using the Extended Nijboer-Zernike (ENZ) diffraction theory

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Optical Lithography Simulations
Introduction to optical lithography

• Process to transfer a geometric pattern from a photomask onto a light-sensitive chemical layer

• Main application is found in the chip industry where complex lithographic systems are used to transfer a chip design pattern onto a silicon wafer (for example using ASML wafer steppers)

• Current state-of-the-art is 32nm lithographic fabrication process. This is 6x smaller than the wavelength of the wafer illumination (193 nm)!
Optical Lithography Simulations
Optical lithography: driving forces & constraints

• Lithographic community is constantly pushing to further decrease the minimum printable feature size. This to enhance computer performance and increase memory capacity. Consequently lithography operates at the very edge of what is technologically possible.

• Error tolerances in optical lithography are extremely small as a single defect in the pattern transfer can result in a completely useless chip. While at the same time throughput should be large enough to repay the extremely large investments involved in chip manufacturing.

Mask with small defect
Faulty image at wafer
Optical Lithography Simulations

Lithography simulations, why bother?

In Lithography simulations play an essential role:

- First of all simulations are extensively used to design and predict the performance of lithographic systems.

- But simulations are also instrumental in obtaining the mask design that produces the best possible chip pattern on the wafer. Nowadays, the mask layout is obtained through an iterative procedure and the final layout generally show little resemblance with wafer image it tends to produce!
Optical Lithography Simulations
Why is lithographic simulation such a difficult task?

Specific requirements and challenges:
- Many optical components contribute to the image quality (Extended source, projection optics, waferstack).
- Extremely small tolerances in the order of a few nanometers require extremely accurate simulations (computationally expensive and large memory demands).
- Scale mismatch, nanometer features are produced through an aperture several centimeters in diameter.
- Sub-wavelength image formation requires fully electromagnetic and vectorial treatment
- **Image formation in a non-uniform space**
Optical Lithography Simulations

Current status

The modeling approaches used for many decades in lithographic simulation are no longer sufficient.

Although many model adjustments have been proposed in recent years that are sufficient to overcome the issues at the current lithographic node, most of them are based on phenomenological observations instead of the correct underlying physical mechanisms at work. Thus they will most likely fail again for future nodes.

Truth is that, by entering the nanometer world, we are now in a totally different regime and it would be best to come up with a new model instead of keep patching-up the old one.
Optical Lithography Simulations

Proposed alternative optical model

The recently developed Extended Nijboer-Zernike (ENZ) theory of diffraction provides a convenient analytic relation between the pupil distribution and the image generated by an optical system.

Main Characteristics:
- Fully vectorial
- Accurate and potentially fast analytic solution to the diffraction integral.
- Applies very few approximations
Optical Lithography Simulations

ENZ-based imaging

Fields components in exit pupil:

Simulated image

Exit pupil

Image space

Analytic ENZ relation

Optical Lithography Simulations

• ENZ-imaging model vs. common Fourier based imaging

ENZ-imaging:
• Novel method
• Isolated objects
• Potentially fast using tabulation
• Highly accurate#
• Current work to include image formation in stratified media

Fourier-imaging:
• Established widespread method
• Periodic objects
• Fast using FFT
• Some concern about accuracy (applied approx.)

Multilayer ENZ-imaging

• Schematic representation of the configuration under consideration:
Multilayer ENZ-imaging

- Effective pupil: Homogeneous imaging
Multilayer ENZ-imaging

- Effective pupils: half-space imaging
Multilayer ENZ-imaging

- Effective pupils: 3-layer image space
Multilayer ENZ-imaging

- Insert effective backward and forward propagating distributions into Debye Diffraction integral
- Apply ENZ semi-analytic solution!

\[
E_2(r, \phi, f) = \frac{-in_1s_0^2}{\lambda_0} \left[ \exp \left( \frac{-if}{u_{0,h}} \right) \int \int_C \frac{E_h^f(\rho, \theta + \pi)}{(1 - s_0^2\rho^2)^{1/2}} \times \exp \left\{ \frac{if}{u_{0,h}} \left[ 1 - (1 - s_0^2\rho^2)^{1/2} \right] \right\} \exp \left\{ i2\pi \rho \cos(\theta - \phi) \right\} \rho \, d\rho d\theta \right.

+ \exp \left( \frac{if}{u_{0,h}} \right) \int \int_C \frac{E_h^b(\rho, \theta)}{(1 - s_0^2\rho^2)^{1/2}} \times \exp \left\{ \frac{-if}{u_{0,h}} \left[ 1 - (1 - s_0^2\rho^2)^{1/2} \right] \right\} \exp \left\{ -i2\pi \rho \cos(\theta - \phi) \right\} \rho \, d\rho d\theta \right]
\]
Multilayer ENZ-imaging example 1:

- Three models to represent a lithographic stack

(water immersion lithography; $\lambda=193\text{nm}$, $\text{NA}=1.368$)
Multilayer ENZ-imaging example 1:

- Single water-photoresist interface
Multilayer ENZ-imaging example 1:

- Simple stack including highly reflective substrate
Multilayer ENZ-imaging example 1:

- Advanced lithographic stack with Anti Reflective Coating (ARC)
Multilayer ENZ-imaging example 2:

- High-capacity optical data storage with Solid Immersion Lens:
Conclusions & Discussion

• Accurate simulation of advanced lithographic systems is very challenging for the current and future nodes
• Extensions of existing models or introduction of new more comprehensive models is required
• We are developing a novel imaging method based on the Extended Nijboer-Zernike theory
• Latest developments include the ability to compute images formed in a stratified image space.
• Additional advantages introduced by the ENZ method include the efficient optimization of the multilayer stack in image space and additional information on aberrations introduced by the layer-interfaces.
Questions?

Visit:
http://www.nijboerzernike.nl

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