Theoretical study on stochastic effects in chemically amplified resist process for extreme ultraviolet lithography

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Outline

- Background / Purpose of this work
- Advanced resist characterization
  - Stochastic defect generation and LER
  - Summary
- Material design for 16 and 11 nm node
  - What is the problem?
  - Basic strategy
  - Effect of molecular weight
  - Effect of protection ratio
- Summary
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Background

Establishment of scientific foundation and technology for resist evaluation

Trade-off relationship

- Resolution
- LWR(LER) Sensitivity
- Sensitivity
- Resolution
- Trade-off

Resist RLS trade-off will remain an issue in future <11nm nodes.

Interaction:
- Photon / electron and matter
- Molecule

Chemical reaction:
- Solubility change
- Dissolution

Molecule

Exposure:
- Acid image
- Acid generator decomposition
- Latent image
- Acid diffusion, deprotection

Energy deposition

Pattern formation

Resist pattern formation process
Purpose of this work

Need for scientific foundation and technology for resist evaluation:

- Establish resist characterization technology
- Obtain material design pointers for 16 and 11 nm node

Deeper understanding of fundamental resist characteristics.
Feedback to EUV resist material and process development.
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Summary
Resist characterization

Reconstruction of chemical image

Conventional characterization
- SEM image
- Resolution
- Line edge roughness
- Sensitivity
- Exposure latitude

Information

Inadequate for material design for 11 nm node

Advanced characterization
- Latent image & stochasticity
- Absorption coefficient
- Quantum efficiency
- Effective reaction radius
- Dissolution point
- Dissolution efficiency

Information

Extraction of chemical information from SEM images is essential to efficient resist development.

New resist characterization technology (2012)
& Material design for 16 and 11 nm node (2013)
Relationship between stochastic effects and protected unit fluctuation

Distance (nm)

1.77$\sigma_n$ 0.36$\sigma_n$

1.67$\sigma_n$ 0.06$\sigma_n$

1.74$\sigma_n$ -0.35$\sigma_n$

1.64$\sigma_n$ -0.72$\sigma_n$

10 mJ cm$^{-2}$

11 mJ cm$^{-2}$

12 mJ cm$^{-2}$

13 mJ cm$^{-2}$

m is the normalized protected unit concentration.

$\sigma_n$ is the normalized standard deviation of the number of protected units connected to a polymer molecule.

No image

Space started to appear.

Bridges
Relationship between stochastic effects and protected unit fluctuation

Pinching started to appear. Bridges were eliminated.
Relationship between protected unit fluctuation and pattern defects

Space

Start of dissociation

Half-open

Elimination of bridge

Line

Start of pinching

Start of disconnection

Definition of “Difference in σ unit”

\[
\frac{(m-m_{DP})}{\sigma_n}
\]

Difference between protected unit concentration and dissolution point
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Advanced Resist Characterization

Latent image was successfully reconstructed from SEM image using a Monte Carlo simulation.

Chemical information was also obtained.

The acid diffusion length was approximately 10 nm in the high resolution region.

±0.31-±0.37 $\sigma_n$ fluctuation of protected units contributed to LER formation.

$LER = \frac{0.68\sigma_n}{dm/dx}$

The resolution dependence of dissolution point was estimated.

The fluctuation of protected unit was estimated.

To eliminate pinching within 6.1 $\mu$m length, 1.2-1.6$\sigma_n$ difference is required.

To eliminate bridges within 6.8 $\mu$m length, 1.5-2.0$\sigma_n$ difference is required.
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Half pitch dependence of stochastic defect generation

Threshold for the elimination of stochastic defect generation in “a SEM image”

Probability for stochastic defect generation rapidly increased with the reduction of half-pitch.

22 nm HP

16 nm HP

11 nm HP
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Basic strategy of material design for 11 nm node

The suppression of stochastic effects (LER and stochastic defect generation) is an urgent task for the realization of 11 nm fabrication.

\[ LER = \frac{0.68\sigma_n}{dm/dx} \]
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Effect of molecular weight

Fig. Latent images of 11 nm line-and-space pattern and standard deviation of the number of protected units connected to a polymer molecule and histograms of the number of protected units at $x=\pm p_{1/2}$, $\pm p_{1/2}/2$, and 0. The protection ratio was 30%. $N_L$, $N_S$, and $N_{DP}$ represent the average number of protected units connected to a polymer molecule at $x=\pm p_{1/2}$, 0, and $\pm p_{1/2}/2$, respectively. The exposure dose was 30 mJ cm$^{-2}$. 

LER
Pinching
Bridge

$\frac{(N_L-N_{DP})/\sigma_L}{(N_{DP}-N_S)/\sigma_S}$
The increase of molecular weight is effective for the suppression of stochastic effects. The increase of minimum dissolution unit and the increase of the probability for the polymer aggregation lead to defect suppression. The relationship between molecular weight and stochastic effects can be expressed as:

\[ LER = \frac{0.68\sigma}{dm/dx} \]
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Effect of protection ratio

Fig. Latent image of 11 nm line-and-space pattern and standard deviation of the number of protected units connected to a polymer molecule and histograms of the number of protected units at $x = \pm p_{1/2}$, $\pm p_{1/2}/2$, and 0. The molecular weight was 4800. The exposure dose was 30 mJ cm$^{-2}$. 
The relative standard deviation was decreased with the increase of protection ratio.

Optimum protection ratio was 40-60% in terms of the suppression of stochastic effect.

Why was the stochastic effects increased at the high protection ratio region?
Decrease of quantum efficiency due to protection of proton source

Transient absorption spectra of PHS radical cation and phenoxy radical

Relationship between acid yield and protection ratio

Proton generation

Hydrogen bonding

Deprotonation efficiency

\approx 1
For the suppression of LER and the stochastic defect, it is essential to increase the protection ratio without decreasing the quantum efficiency.
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Summary - Material design for 16 and 11 nm node -

1. How many photons can be absorbed?
   Absorption coefficient: ~4 /μm

2. How many acids can be generated by a single photon?
   Quantum efficiency: 2-3

3. How many dissolution inhibitor (protecting group) can be removed by a single acid during the diffusion of unit length?
   Effective reaction radius
   - Activation energy for deprotection
   - Activation energy for acid diffusion
     - Low-diffusion anion → Anion-bound resist
     - High T_g polymer

4. How smoothly are the polymers dissolved in developer?
   Relationship between LER and chemical gradient, \( f_{LER} \)
   - Molecular size, protection ratio, dispersion
   - Development, rinse

Resist design

\[ LER = \frac{0.68 \sigma_n}{dm/dx} \]

Advanced resist characterization is useful for evaluating these factors.
Acknowledgement

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