Stochastic Effects in Chemically Amplified Resists for Extreme Ultraviolet Lithography

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Evaluation of resist materials

Exposure experiments

Resolution, Sensitivity, LWR(LER)

The performance of resist materials is generally evaluated by comparing the resolution, LER, and sensitivity.

For example, high sensitivity does not necessarily mean high performance.

The evaluation of the potential capability of resist materials is tricky because of the trade-off relationships between these factors.

It is essential to the evaluation and development of resist materials to extract information from SEM images as much as possible.
Objective

Establishment of scientific foundation and technology for resist evaluation

The stochastic effect in line-and-space patterns fabricated using SFET was analyzed to clarify the relationship of stochastic effect to LER and resist pattern defects.

Small Field Exposure Tool: SFET

<table>
<thead>
<tr>
<th>Items</th>
<th>Target Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0.3</td>
</tr>
<tr>
<td>Illumination mode</td>
<td>Annular(0.3/0.7), x-slit</td>
</tr>
<tr>
<td>Field size</td>
<td>0.2 x 0.6 mm</td>
</tr>
<tr>
<td>Magnification</td>
<td>1/5</td>
</tr>
<tr>
<td>Wavefront error</td>
<td>&lt;0.9 nm rms</td>
</tr>
<tr>
<td>Flare</td>
<td>&lt;7% (MSFR)</td>
</tr>
<tr>
<td>Source power</td>
<td>0.5W @IF</td>
</tr>
<tr>
<td>Wafer size</td>
<td>300 mm</td>
</tr>
</tbody>
</table>
Dose-pitch matrices of EIDEC standard resist

Half-pitch dependence (16 mJ cm$^{-2}$ exposure dose)

Exposure dose dependence (60 nm HP)
Dose-pitch matrices of EIDEC standard resist

Half-pitch dependence (16 mJ cm\(^{-2}\) exposure dose)

Exposure dose dependence (60 nm HP)

Experimental

Deviation from half-pitch (nominal line width) (nm)

Exposure dose (mJ cm\(^{-2}\))

(a) Line width

(b) LER
Analysis procedure

Stochastic effect was investigated using Monte Carlo method. However, Monte Carlo method is not suitable for accurate calculation.

**Acid generation**

- **Step 1:** Overall fitting – Probability density model
  - Point spread function

- **Step 2:** Refitting with Monte Carlo acid generation simulation – Hybrid model
  - Monte Carlo method

- **Step 3:** Analysis with Monte Carlo process simulation – Stochastic model
  - Monte Carlo method

**Catalytic chain reaction**

- **Step 2:** Refitting with Monte Carlo acid generation simulation – Hybrid model
  - Reaction diffusion equations

- **Step 3:** Analysis with Monte Carlo process simulation – Stochastic model
  - Reaction diffusion equations

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**Chemical Reactions and Processes**

- **EUV photon → photon**
  - Ionization
  - Thermalization
  - Next ionization or excitation
  - Acid generator

- **During exposure**
  - **Resist**
    - **Ionization**
    - **E < E_{th}**
    - **Thermalization**
    - **E > E_{th}**

- **During PEB**
  - **Protected unit (polymer)**
    - **Deprotection**
    - **Acid**
    - **Diffusion**
    - **Quencher**
    - **Neutralization**
    - **R_p**
    - **R_q**
Best fit parameters

Effective reaction radius for deprotection: 0.16 nm
Effective quencher concentration: 0.023 nm$^{-3}$
Diffusion constant: 10 nm$^2$ s$^{-1}$ \( (2\text{~to~}6 \text{ nm}^2 \text{ s}^{-1}) \)
Proportionality constant between LER and chemical gradient $f_{\text{LER}}$: 0.22

Dissolution point:

Dependence of dissolution characteristics on pattern size

- Amount of chemical reaction required for dissolution
- Amount of chemical reaction required at 16 nm half-pitch increases by 74%, compared with that at 60 nm half-pitch.
Stochastic effect – 23 nm LS pattern at 16 mJ cm\(^{-2}\) exposure

Photon image | Acid image | Latent image
--- | --- | ---
Top down
Cross section

Photon density (nm\(^{-3}\))
Acid conc. (nm\(^{-3}\))

0 | 0.6

Protected unit conc. (nm\(^{-3}\))

0 | 4

Standard deviation
Average

Normalized absorbed photon density

Normalized acid conc.

Normalized protected unit conc.

Absorbed photon image | Acid image | Latent image
Acid diffusion length in EIDEC standard resist

Dependence of acid diffusion length and lifetime on the initial position of acids (23 nm HP, 16 mJ cm\(^{-2}\))

The optimum acid diffusion length for 16 nm L&S patterns has been reported to be ~10 nm.


EIDEC standard resist has the potential for resolving 16 nm features with HQ EUV images.
The fluctuation of protected unit concentration leads to the fluctuation of the crossing point between latent image and dissolution threshold.
Relationship between protected unit fluctuation and LER

±0.31-±0.37σ fluctuation of protected units contributes to LER formation.
Relationship between latent and SEM images of 30 nm L&S patterns

10 mJ cm$^{-2}$

Normalized protected unit conc.

0.0 0.2 0.4 0.6 0.8 1.0

-30 -15 0 15 30

Distance (nm)

1.77σ 0.36σ

Dissolution point

Average

-0.31σ

1.67σ 0.06σ

Dissolution point

11 mJ cm$^{-2}$

Normalized protected unit conc.

0.0 0.2 0.4 0.6 0.8 1.0

-30 -15 0 15 30

Distance (nm)
Relationship between latent and SEM images of 30 nm L&S patterns

12 mJ cm\(^{-2}\)

13 mJ cm\(^{-2}\)
Relationship between latent and SEM images of 30 nm L&S patterns

14 mJ cm$^{-2}$

Normalized protected unit conc.

Distance (nm)

Dissolution point

1.56$\sigma$

0.88$\sigma$

Line  Space  Line

15 mJ cm$^{-2}$

Normalized protected unit conc.

Distance (nm)

Dissolution point

1.25$\sigma$

1.32$\sigma$

Line  Space  Line

1.56$\sigma$

0.88$\sigma$

Line  Space  Line
Relationship between latent and SEM images of 30 nm L&S patterns

![Graph showing normalized protected unit concentration vs. distance (nm) for different light doses](image)

- **16 mJ cm$^{-2}$**
  - **Line**: 1.09σ
  - **Space**: 2.10σ
  - **Dissolution point**: +0.31σ, Average, -0.31σ

- **17 mJ cm$^{-2}$**
  - **Line**: 0.74σ
  - **Space**: 3.00σ
  - **Dissolution point**: +0.31σ, Average, -0.31σ

**Relationship**: The graphs illustrate the relationship between latent and SEM images of 30 nm Line & Space patterns for two different light doses. The normalized protected unit concentration is plotted against distance (nm), with labeled features indicating significant differences at 1.09σ, 2.10σ, 0.74σ, and 3.00σ. Dissolution point markers are also shown at +0.31σ, Average, and -0.31σ for both doses.
Relationship between latent and SEM images of 30 nm L&S patterns

18 mJ cm$^{-2}$

Normalized protected unit conc. vs. Distance (nm)

- Line: 0.47σ
- Space: 3.57σ

+0.31σ Average
-0.31σ Dissolution point

19 mJ cm$^{-2}$

Normalized protected unit conc. vs. Distance (nm)

- Line: 0.30σ
- Space: 5.05σ

+0.31σ Average
-0.31σ Dissolution point

675 nm

Line
Line
Space
Line
Relationship between latent and SEM images of 30 nm L&S patterns

The same analysis was applied to the other SEM images.
Relationship between stochastic effect and resist pattern defects

**Space**

- **Start of space appearance**
- **Half open**
- **Elimination of bridge**

**Line**

- **Appearance of severe line shrinkage**
- **Appearance of line break**

**Definition of “Difference in \( \sigma \) unit”**

\[
\frac{(C_p - C_{DP})}{\sigma}
\]

Difference between protected unit concentration and dissolution point
Summary – 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 σ fluctuation of protected units contributed to LER formation.

The resolution dependence of dissolution point was estimated.

The fluctuation of protected unit (stochastic effect) was estimated.

To eliminate line shrinkages within 6.1 μm length, 1.2-1.6σ difference is required.

To eliminate bridges within 6.8 μm length, 1.5-2.0σ difference is required.
Acknowledgement

This work was partially supported by the New Energy and Industrial Technology Development Organization (NEDO).