Relationship between photon shot noise and secondary electron blur in line edge roughness formation

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Role of resist materials

Conversion of energy modulation to binary image

Role of photons:
- Transfer of information and energy for imaging

Energy modulation

Exposure source

Intensity

0
0.2
0.4
0.6
0.8
1.0
0 1 2 3 4 5

SEM image of resist

Position

Conversion process

Photon/electron interaction with matter

Energy deposition

Formation of acid image

Thermal energy

Formation of latent image

Solubility change through chemical reaction

Acid diffusion, deprotection

Dissolution of molecules

Development

Resist

image

Exposure

source

Si

SEM image of resist

Conversion of energy modulation to binary image

Photons alone can transfer information.
The energy does not have to be transferred by photons.  

Sensitivity enhancement

Quantum efficiency enhancement

(Increase in reduction potential of acid generator, acid amplification, PSCAR etc.)
Formation mechanism of LER

EUV

Acid image

Latent image

Insoluble

-CH-CH2-

OR

Soluble

-CH-CH2-

OH

After development

Pattern

LER

Decrease in dissolution factor
Decrease in protected unit fluctuation

Increase in chemical contrast

*α: dissolution factor, 0.68 for ESR1
Sensitization mechanism of EUV resists

EUV photon $h\nu$

- Electron
- Photon

Resist

Ionization $h\nu-I_e$

- Ionization
- Next ionization or excitation
- Acid generator

Activation energy for dissociative electron attachment: $\sim 0$

The electron with thermal energy can sensitize acid generators.

Simulation processes

(1) Absorption

(2) Deceleration

\[ E_{th} < E < h\nu - I_e \]

(3) Deceleration

\[ 25 \text{ meV} < E < E_{th} \]

(4) Electron diffusion and reaction

\[ E = 25 \text{ meV} \]

\[ E_{th} : \text{Threshold energy for electronic excitation} \]

\[ I_e : \text{Ionization energy} \]
The electron with thermal energy can sensitize acid generators.

Activation energy for dissociative electron attachment: \( \sim 0 \)

The acid generator molecules nearest to the absorption point were intentionally decomposed in accordance with the quantum efficiency.

Catalytic chain reaction

LER and stochastic defect generation

\( E_{th} \): Threshold energy for electronic excitation

\( I_e \): Ionization energy

\( h \nu - I_e \): Electron attachment

\( h \nu \): EUV photon

\( E < E_{th} \): Thermalization

\( E > E_{th} \): Next ionization or excitation
Comparison between real and ideal case

Fig. Dependence of LER of 11 nm half-pitch line-and-space patterns on exposure dose. The optical contrast was 1.0. The effective reaction radius for deprotection was 0.1 nm.
Fig. Dependence of LER on sensitivity. The optical contrast was 1.0. The effective reaction radius for deprotection was 0.1 nm.
1. Effects of photon shot noise in chemically amplified EUV resists with photodecomposable quenchers, assuming an ideal case.

2. Relationship between photon shot noise and secondary electron blur
Acid generator and photodecomposable quencher molecules nearest to the absorption point were intentionally decomposed in accordance with the quantum efficiency.

Ideal case
Acid generator and photodecomposable quencher molecules are decomposed after thermalization of secondary electrons.

Real case
Acid generator and photodecomposable quencher molecules are decomposed after thermalization of secondary electrons.

$h\nu$: Photon energy
$E$: Electron energy
$E_{th}$: Threshold energy for electronic excitation
$I_e$: Ionization energy
Fig. Representative calculation results of 11 nm half-pitch line-and-space patterns for the quantum efficiencies of 2 and 20. The total sensitizer concentration was 0.2 nm$^{-3}$. 
Fig. The relationships between sensitivity and LER obtained for the quantum efficiencies of 2, 10, and 20 with the total sensitizer concentration of 0.2 nm$^{-3}$. 
Comparison between photodecomposable and conventional quenchers

**Fig. Dependence of LER on the sensitivity.** The numerical values next to “Q” denote the quantum efficiencies. The quencher concentration, PEB time, and dissolution point were optimized to maximize the chemical gradient at the intended boundary for each parameter set. The dashed lines (except for the straight horizontal lines) were calculated, assuming chemically amplified resists with acid generators and conventional quenchers.

The shot noise limit is determined by the total sensitizer concentration, independently of the type of sensitizers (AG or PDQ).

PDQ is equivalent to AG in the role as an information receiver.
AG or PDQ molecules at the distance of $r_s$ from last sensitization (or ionization) point were intentionally decomposed in accordance with the quantum efficiency.

**Assumed case**

Acid generator and photodecomposable quencher molecules are decomposed after thermalization of secondary electrons.

**Real case**

Acid generator and photodecomposable quencher molecules are decomposed after thermalization of secondary electrons.

- $h\nu$: Photon energy
- $E$: Electron energy
- $E_{th}$: Threshold energy for electronic excitation
- $I_e$: Ionization energy
- $r_s$: Sensitization distance
**Sensitization distance**

Fig. Representative calculation results of 11-nm half-pitch line-and-space patterns for sensitization distances of 1 and 3 nm. Dotted lines represent the photon intensity distribution normalized for comparison. Solid and dashed lines were calculated with quantum efficiencies of 2 and 10, respectively. Solid and dashed lines correspond to exposure doses of 36 and 7.2 mJ cm\(^{-2}\), respectively. Total sensitizer concentration is 0.2 nm\(^{-3}\).
Fig. Dependence of LER on the sensitivity calculated at a sensitization distance of 0, 1, 2, and 3 nm. Numerical values next to “Q” denote the quantum efficiencies. Total sensitizer concentration is 0.2 nm$^{-3}$. Dotted lines with open circles represent the photon shot noise limit of LER for a total sensitizer concentration of 0.2 nm$^{-3}$ with a sensitization distance of 0 nm.
1. The role of acid generators is to receive the information carried by photons and to fix it as an acid distribution in the resist film. From the viewpoint of the shot noise limit, the photodecomposable quencher was equivalent to the acid generator in the role as an information receiver.

2. With the increase of sensitization distance, the shot noise limit of LER was significantly increased. At a sensitization distance of 1 nm, the increase in the quantum efficiency to 20 becomes meaningless. At the sensitization distance of 3 nm, the lowest LER for the quantum efficiency of 10 becomes achievable at the same sensitivity with the quantum efficiency of 2. Therefore, the effectiveness of quantum efficiency enhancement depends on the sensitization distance.

3. Upon the application of the quantum efficiency enhancement to the design of chemically amplified resists, the acceptable sensitization distance is significantly short. Consequently, it is important to assess the sensitization distance when a significant enhancement of quantum efficiency is attempted.

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