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

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# Role of resist materials

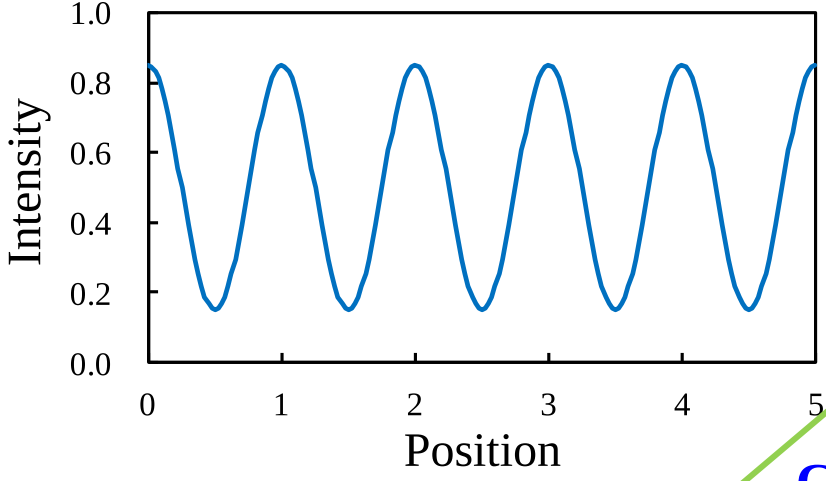
Conversion of energy modulation to binary image

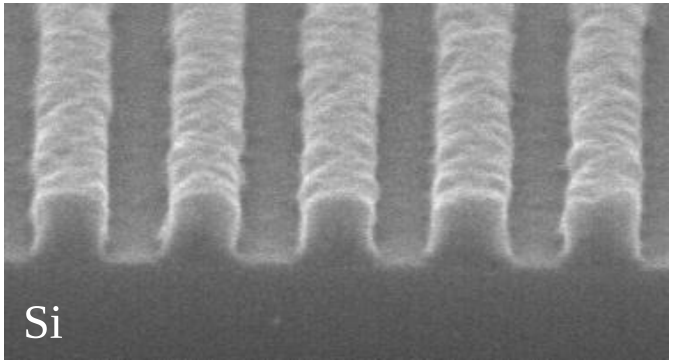
Exposure source

Role of photons:
Transfer of information and energy for imaging

Resist image

Energy modulation





SEM image of resist

**Conversion process**

Photon/electron
interaction with matter

Energy deposition

Formation of acid image

Decomposition of
acid generator

**Thermal energy**

Solubility change through
chemical reaction

Formation of latent image

Acid diffusion,
deprotection

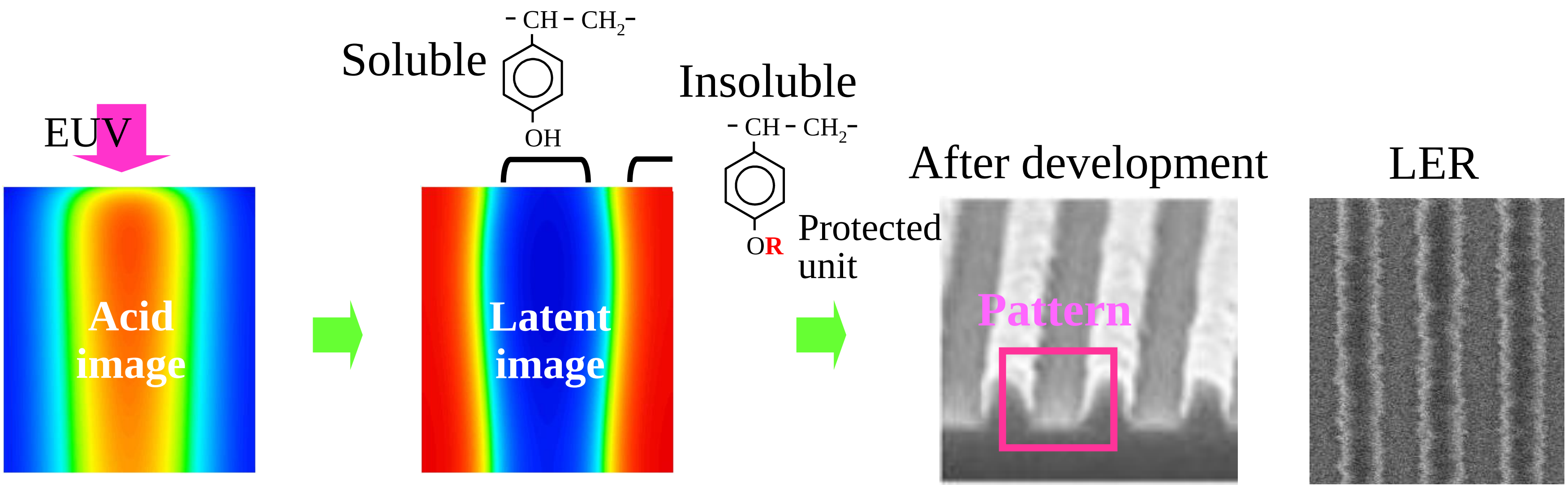
Dissolution
of molecules

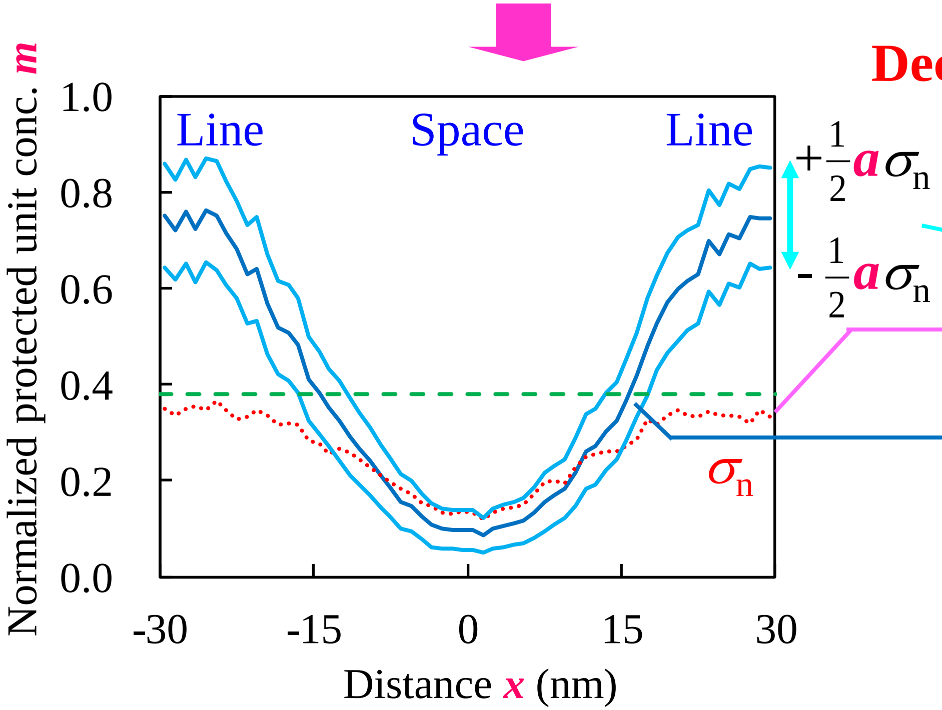
Development

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





**Latent image**

**Decrease in dissolution factor**

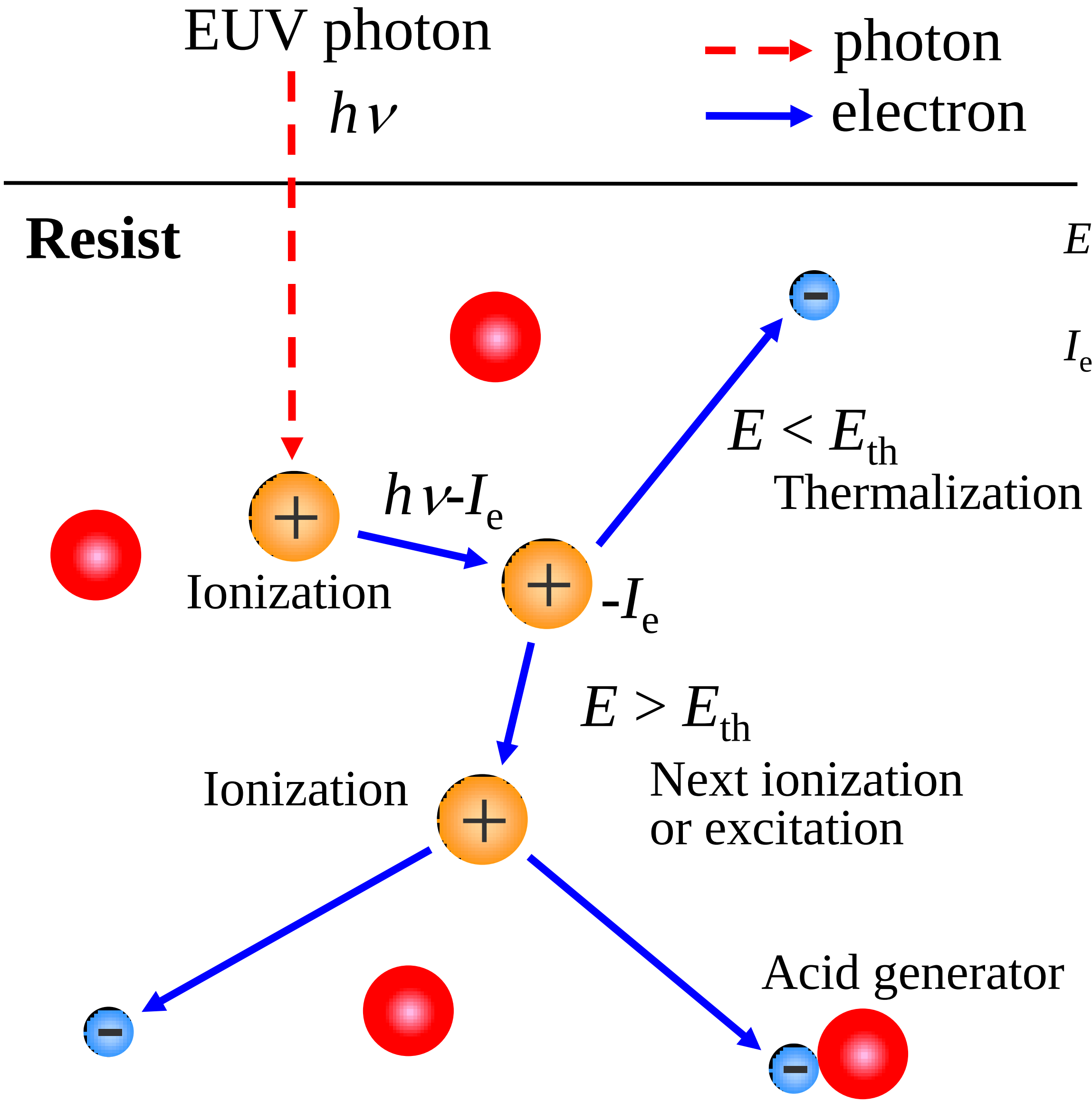
**Decrease in protected unit fluctuation**

$$LER \approx \frac{a\sigma_n}{dm/dx}$$

**Increase in chemical contrast**

*$a$: dissolution factor, 0.68 for ESR1

# Sensitization mechanism of EUV resists



EUV photon

$h\nu$

photon

electron

**Resist**

Ionization

$h\nu\text{-}I_e$

$-I_e$

$E < E_{th}$

Thermalization

$E > E_{th}$

Next ionization or excitation

Ionization

Acid generator

$E_{th}$: Threshold energy for electronic excitation

$I_e$: Ionization energy

**Simulation processes**

(1) Absorption

(2) Deceleration

$E_{th} < E < h\nu\text{-}I_e$

(3) Deceleration

$25\ \mathrm{meV} < E < E_{th}$

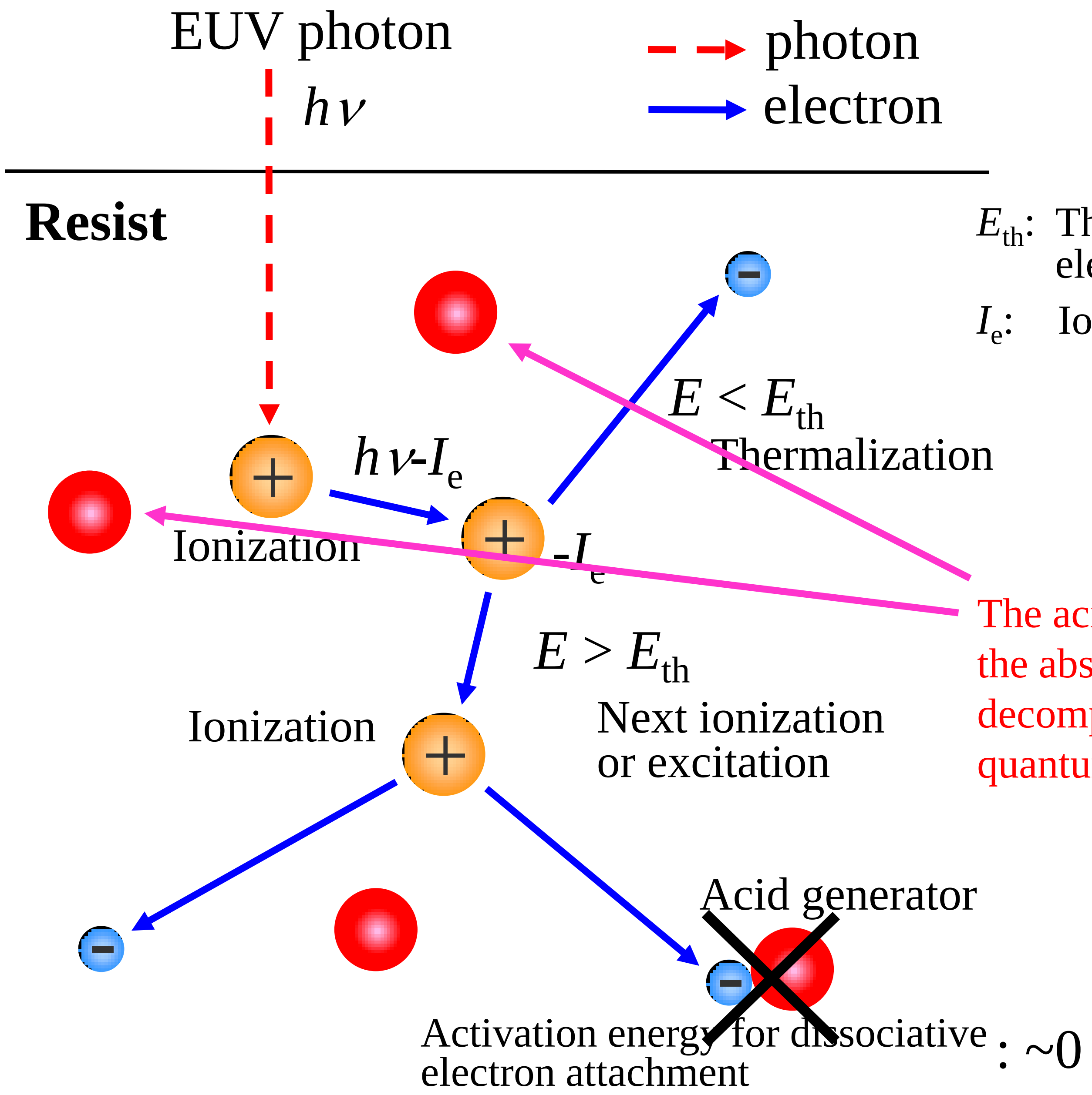
(4) Electron diffusion and reaction

$E = 25\ \mathrm{meV}$

Activation energy for dissociative electron attachment : ~0

The electron with thermal energy can sensitize acid generators.

# Physical limit



EUV photon

$h\nu$

photon

electron

**Resist**

Ionization

$h\nu$-$I_e$

-$I_e$

$E < E_{th}$

Thermalization

$E > E_{th}$

Next ionization
or excitation

Ionization

Acid generator

Activation energy for dissociative electron attachment : ~0

$E_{th}$: Threshold energy for electronic excitation

$I_e$: Ionization energy

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

The electron with thermal energy can sensitize acid generators.

# Comparison between real and ideal case

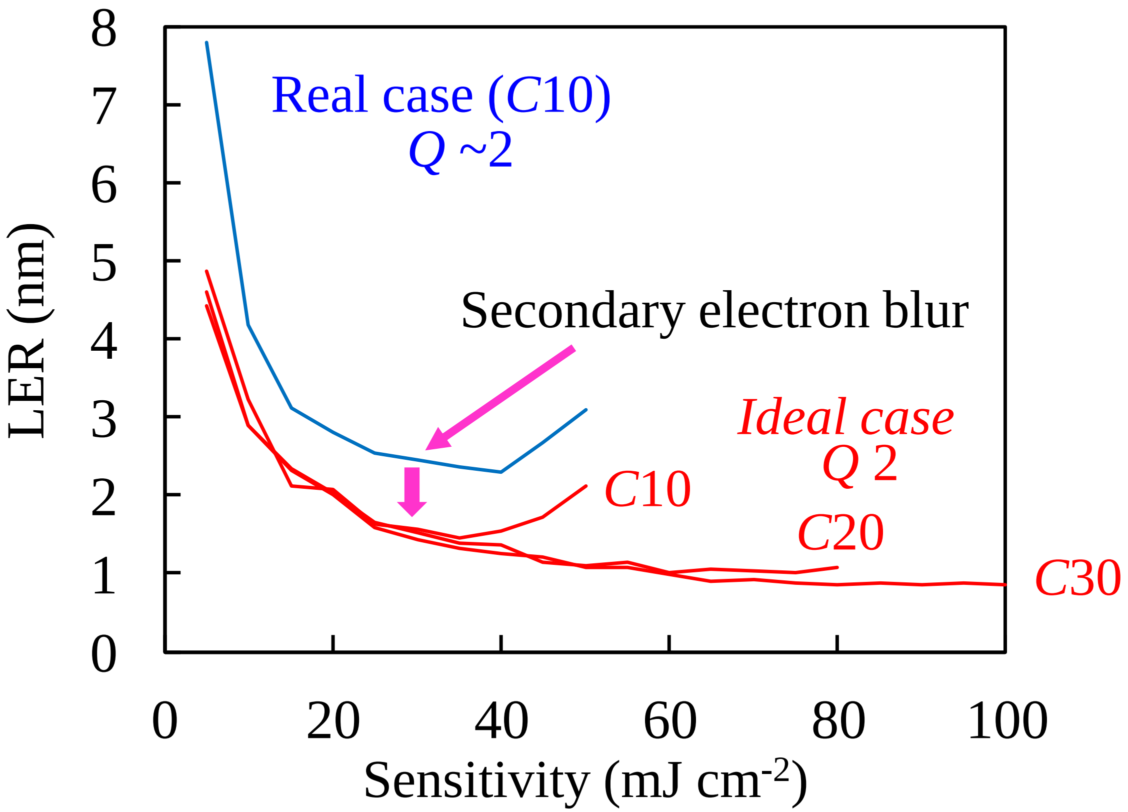


Fig. Dependence of LER of 11 nm half-pitch line-and-space patterns on exposure dose. The optical contrast was 1.0. The effective reaction radius for deprotection was 0.1 nm.

# Information- and energy-deficit region

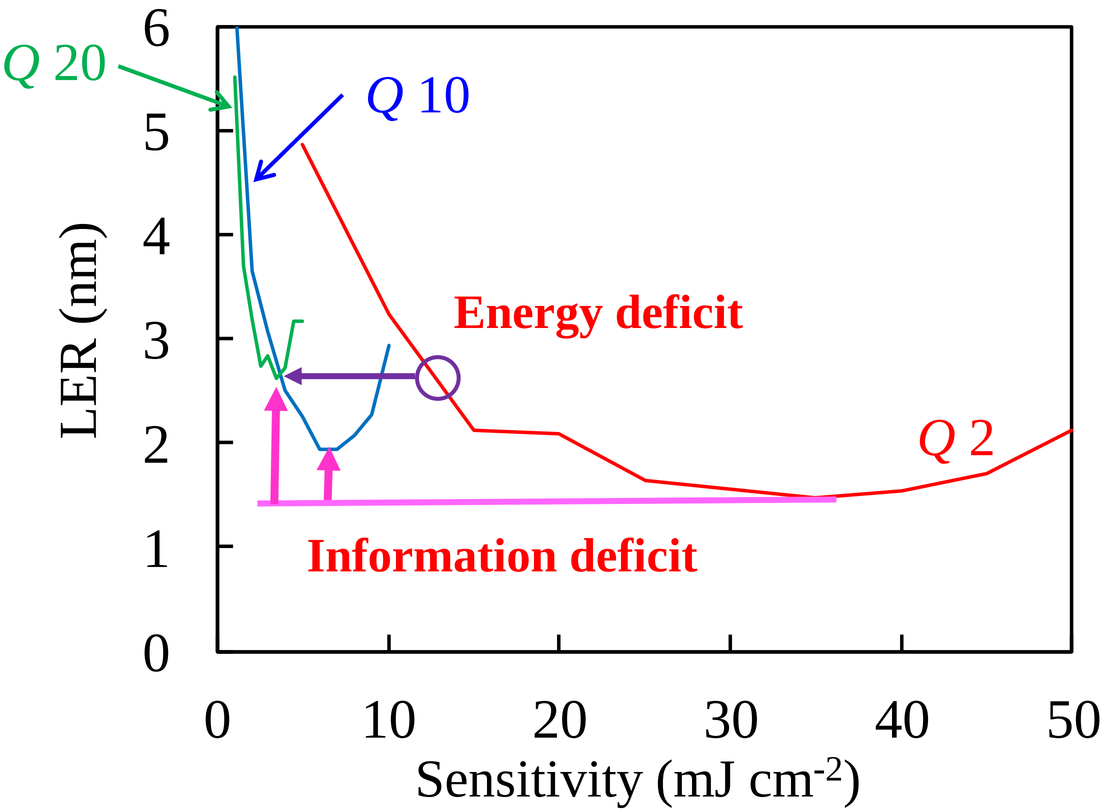
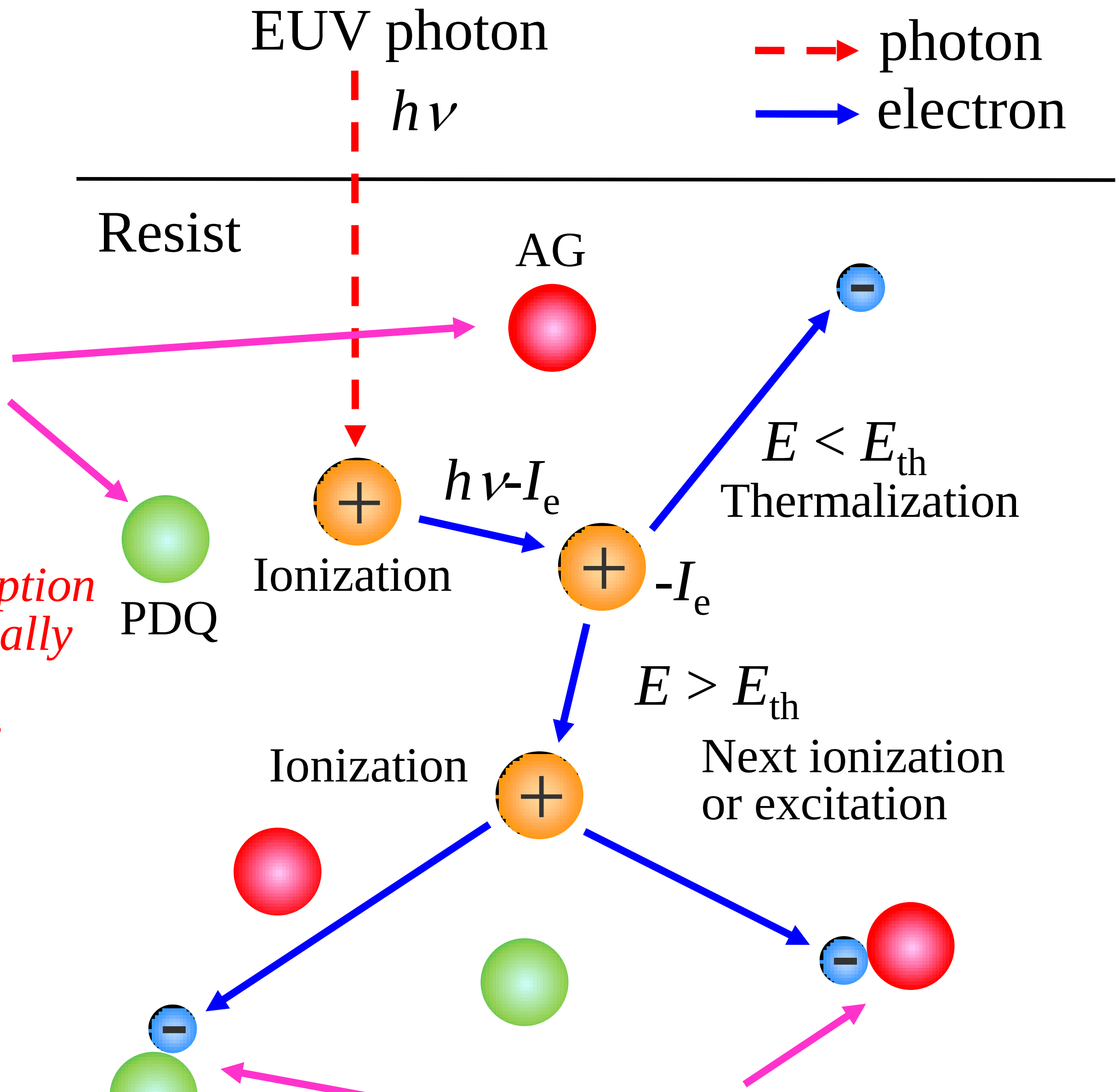


Fig. Dependence of LER on sensitivity. The optical contrast was 1.0. The effective reaction radius for deprotection was 0.1 nm.

# Objective

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



**Ideal case**

*Acid generator and photodecomposable quencher molecules nearest to the absorption point were intentionally decomposed in accordance with the quantum efficiency.*

**Real case**

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

$h\nu$: Photon energy

$E$: Electron energy

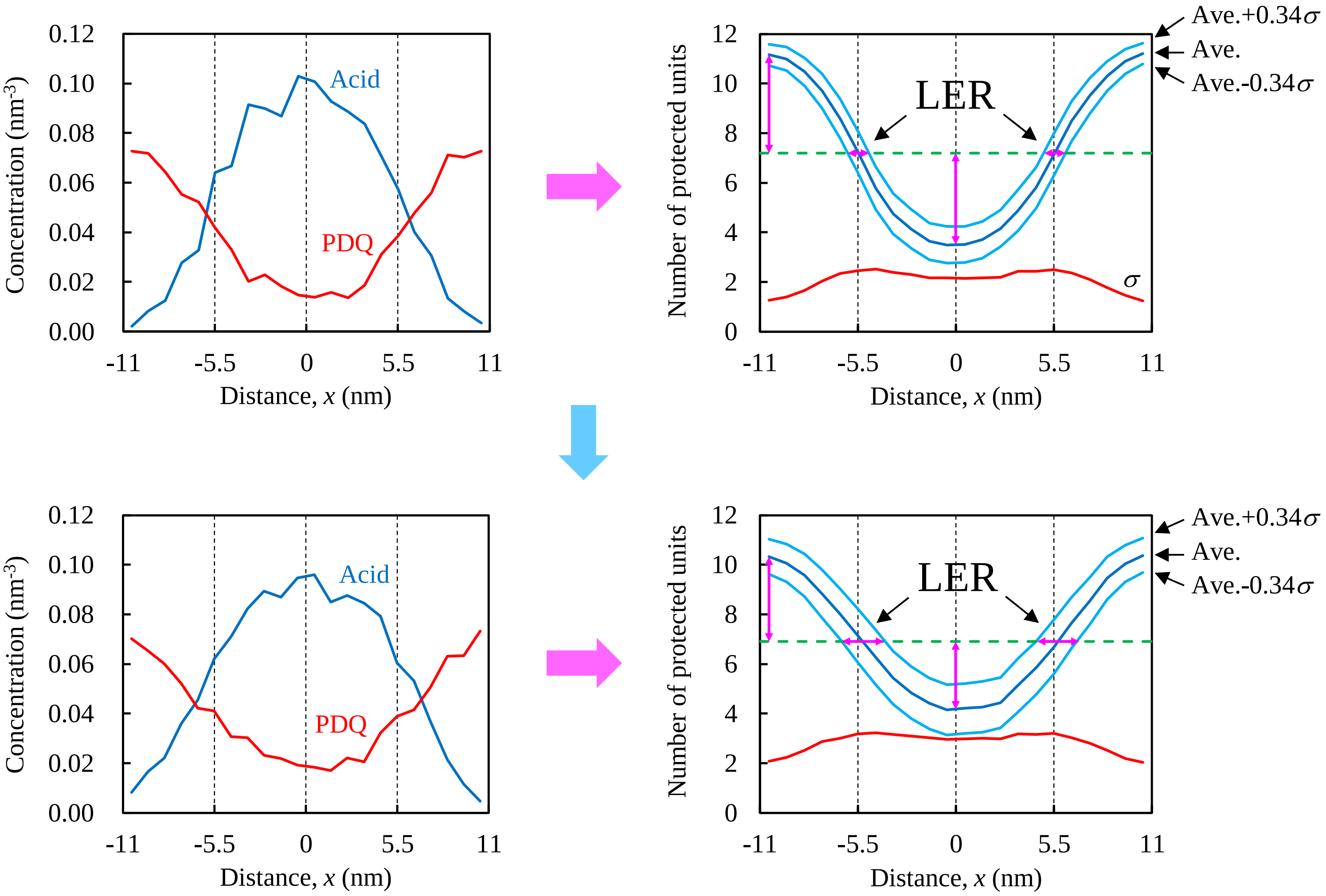
$E_{th}$: Threshold energy for electronic excitation

$I_e$: Ionization energy

# Photodecomposable quencher

***Q* 2**
36 mJ cm$^{-2}$

***Q* 20**
3.6 mJ cm$^{-2}$



Acid and PDQ distribution
after exposure

Protected unit distribution
after PEB

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$^{-3}$.

# Information- and energy-deficit region -Photodecomposable quencher-

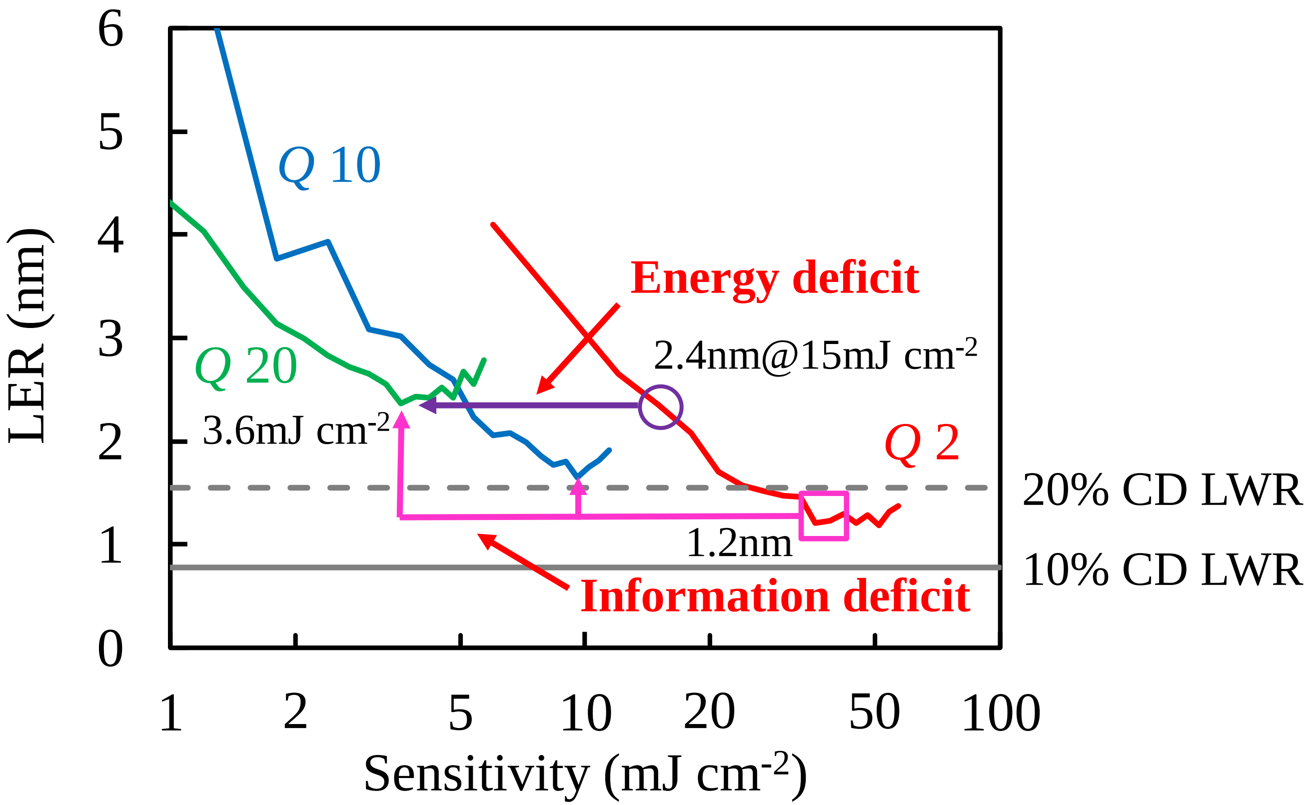
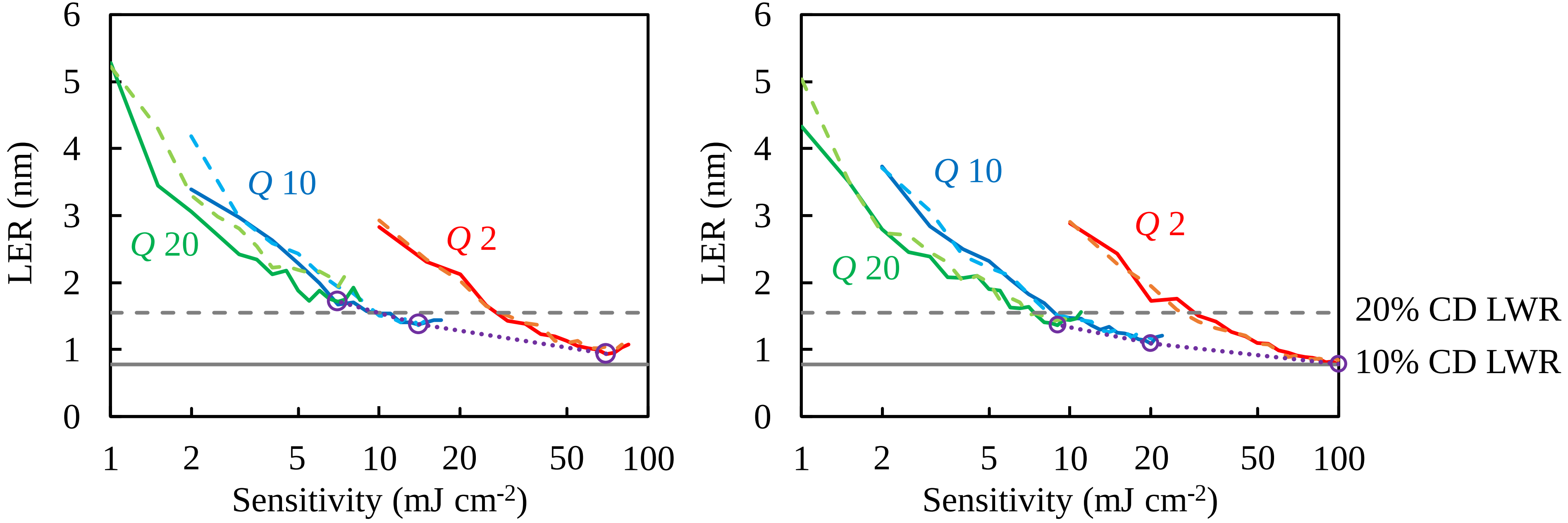


Fig. The relationships between sensitivity and LER obtained for the quantum efficiencies of 2, 10, and 20 with the total sensitizer concentration of 0.2 nm$^{-3}$.

# Comparison between photodecomposable and conventional quenchers



Total sensitizer concentration 0.3 nm$^{-3}$

— AG + PDQ 0.3 nm$^{-3}$
– – 0.3 nm$^{-3}$ AG + Conv.Q

Total sensitizer concentration 0.4 nm$^{-3}$

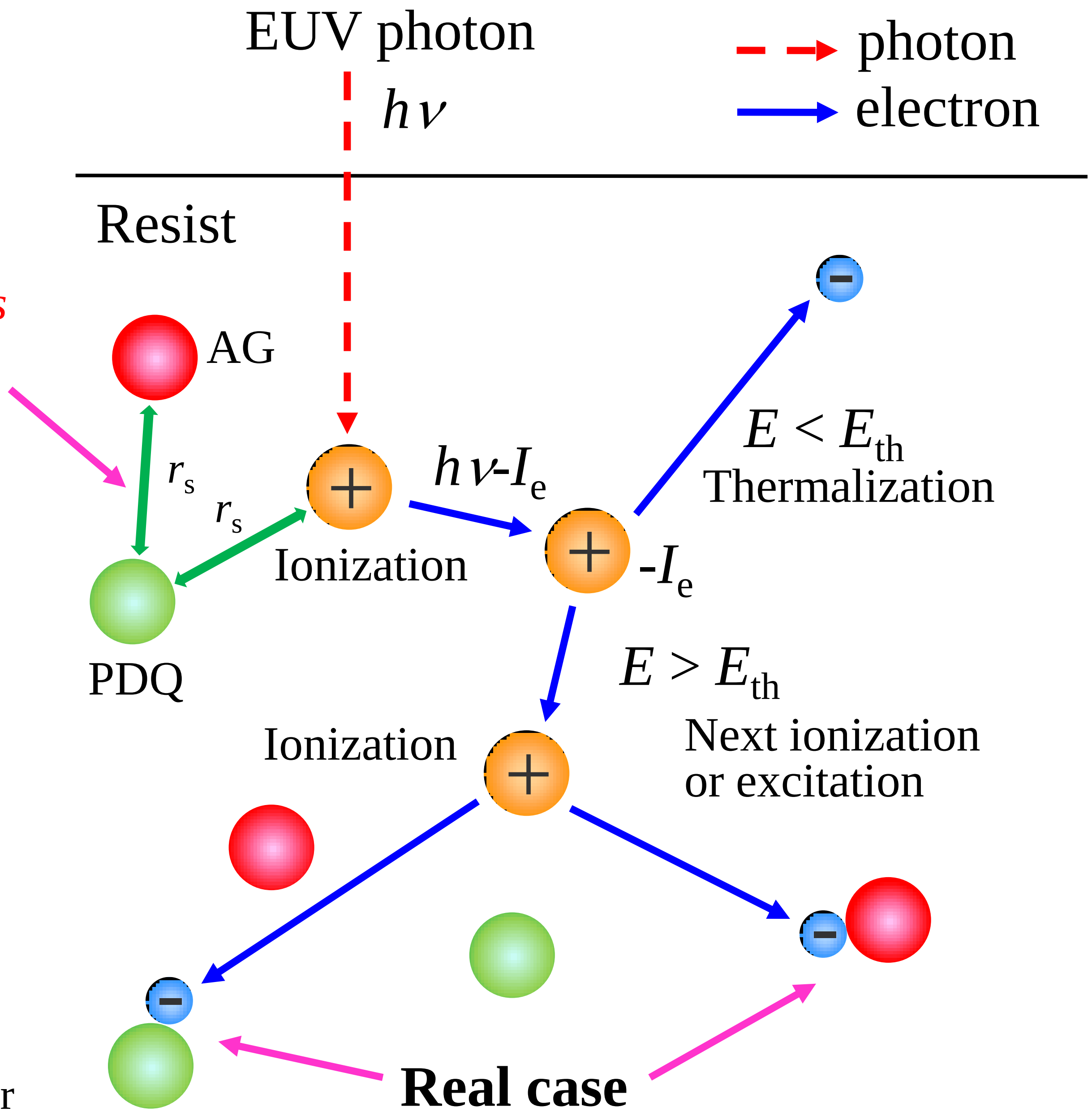
— AG + PDQ 0.4 nm$^{-3}$
– – 0.4 nm$^{-3}$ AG + Conv.Q

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.



EUV photon

$h\nu$

photon

electron

Resist

## Assumed case

*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.*

AG

$r_s$

$r_s$

PDQ

Ionization

$h\nu$-$I_e$

-$I_e$

$E < E_{th}$

Thermalization

$E > E_{th}$

Next ionization
or excitation

Ionization

## Real case

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

$h\nu$: Photon energy

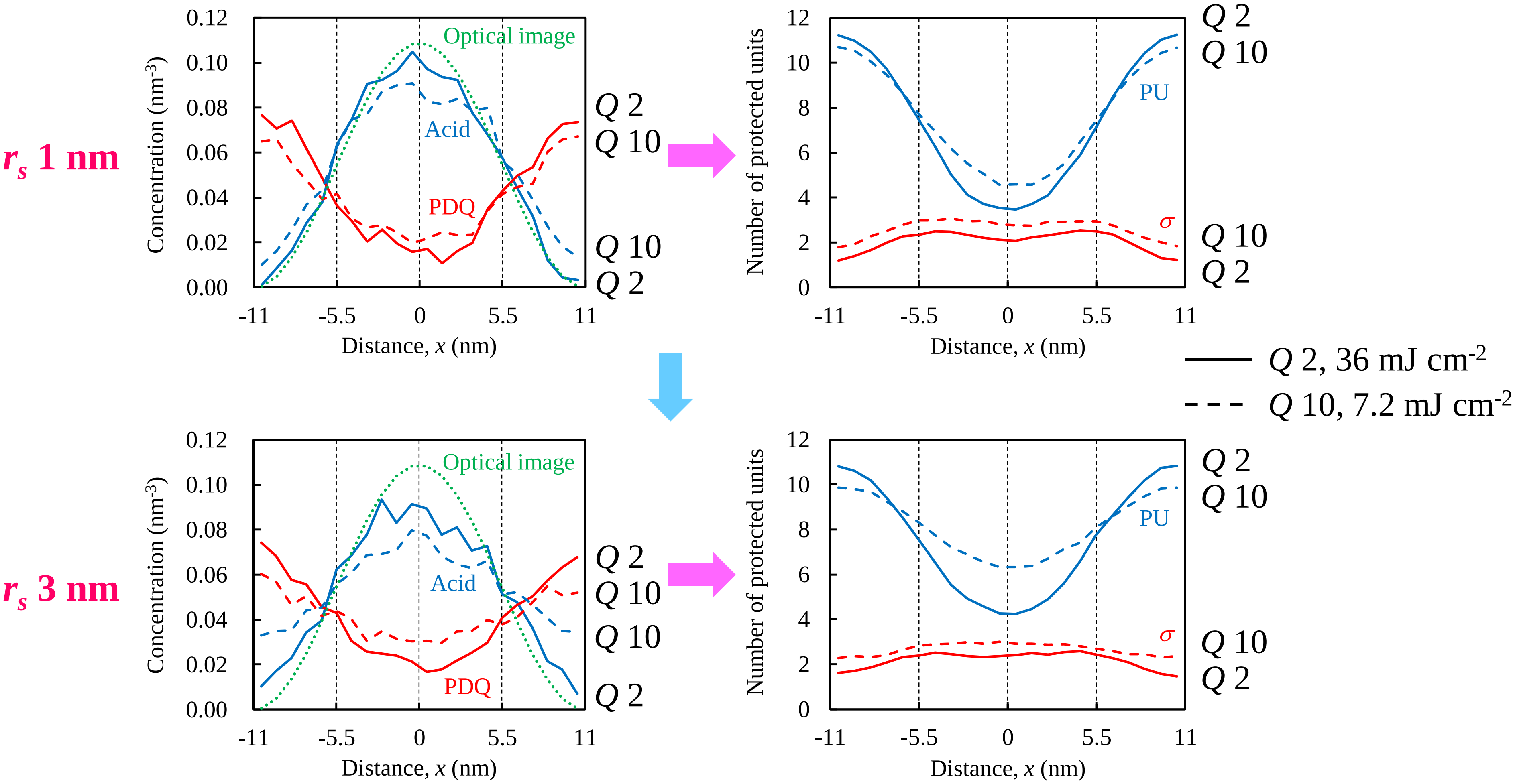
$E$: Electron energy

$E_{th}$: Threshold energy for electronic excitation

$I_e$: Ionization energy

$r_s$: Sensitization distance

# Sensitization distance

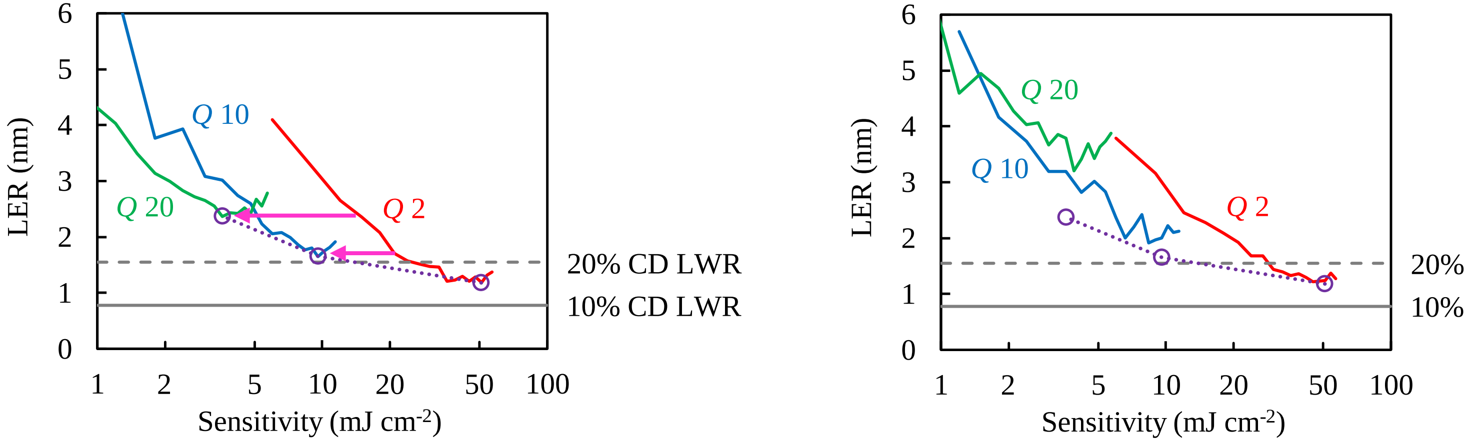


Acid and PDQ distribution after exposure

Protected unit distribution after PEB

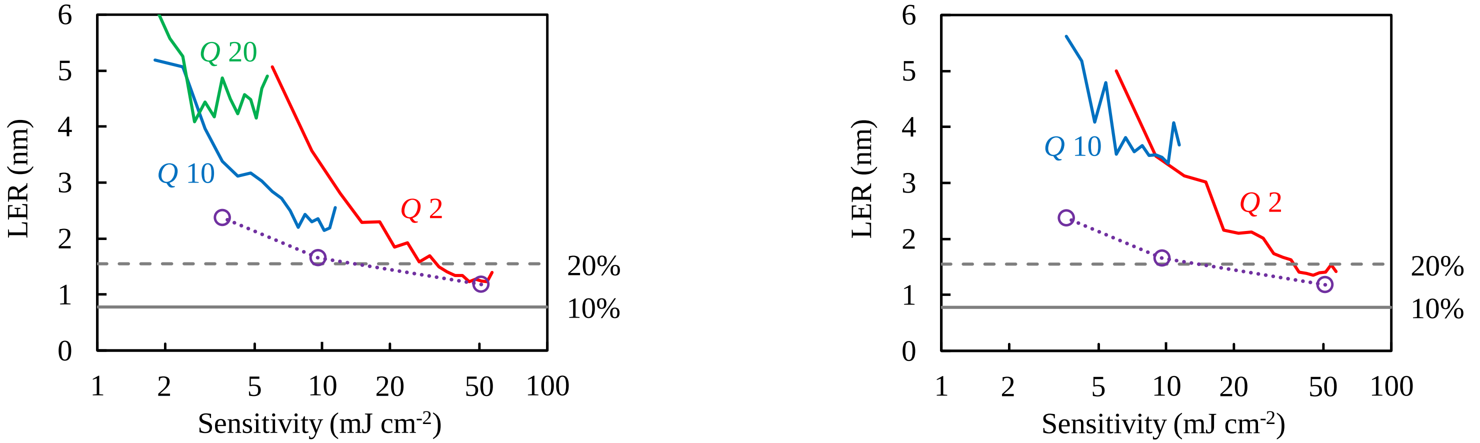
Fig. Representative calculation results of 11-nm half-pitch line-and-space patterns for sensitization distances of 1 and 3 nm. Dotted lines represent the photon intensity distribution normalized for comparison. Solid and dashed lines were calculated with quantum efficiencies of 2 and 10, respectively. Solid and dashed lines correspond to exposure doses of 36 and 7.2 mJ cm$^{-2}$, respectively. Total sensitizer concentration is 0.2 nm$^{-3}$.

# Shot noise limit



**$r_s$ 0 nm (ideal case)**

**$r_s$ 1 nm**



**$r_s$ 2 nm**

**$r_s$ 3 nm**

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.

# Summary

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.

# Acknowledgement

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