Stochastic Effects in Resist Processes of Extreme Ultraviolet Lithography

Takahiro Kozawa[1], Julius Joseph Santillan[2], and Toshiro Itani[2]

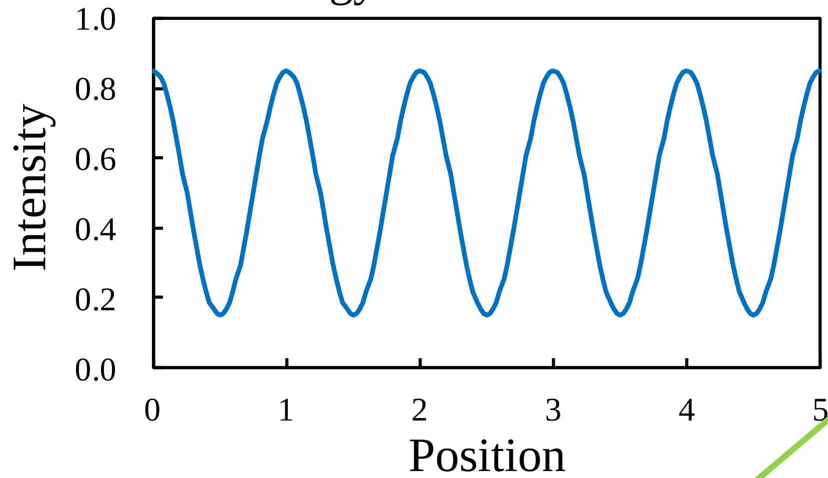
[1]The Institute of Scientific and Industrial Research, Osaka University
[2]EUVL Infrastructure Development Center (EIDEC)

Role of resist materials

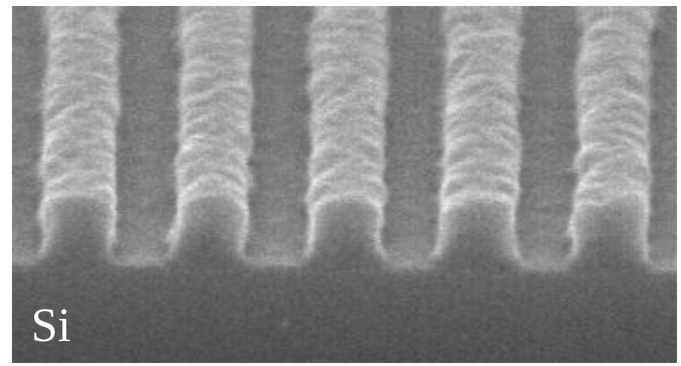
Conversion of energy modulation to binary image

Exposure source

Energy modulation



Resist image



SEM image of resist

Photon/electron interaction with matter

Energy deposition → **Formation of acid image** → (Thermal energy) → **Formation of latent image** → **Development**

Decomposition of acid generator

Solubility change through chemical reaction

Acid diffusion, deprotection

Dissolution of molecules

The conversion process has to be completed in nanometer scale region (<11 nm).

Outline of basic design strategy of chemically amplified resist

The performance of resist materials is determined by the efficiency of conversion processes.

①How many photons can be absorbed?

- Absorption coefficient: ~4 /μm

②How many acids can be generated by a single photon?

- Quantum efficiency: 2-3

③How many dissolution inhibitor (protecting group) can be removed by a single acid during the diffusion of unit length?

- Effective reaction radius: 0.06-0.16 nm
  - Activation energy for deprotection
  - Activation energy for acid diffusion
    - Low-diffusion anion → Anion-bound resist
    - High T_g polymer

④How smoothly are the polymers dissolved in developer?

- Proportionality constant between LER and chemical gradient, f_{LER}: 0.14-0.31
  - Molecular size, protection ratio
  - Development, rinse

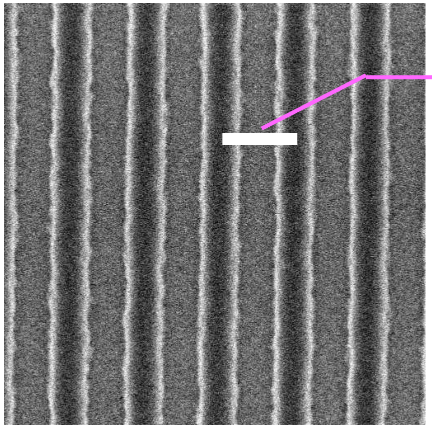
$$LER \approx \frac{f_{LER}}{dm/dx}$$

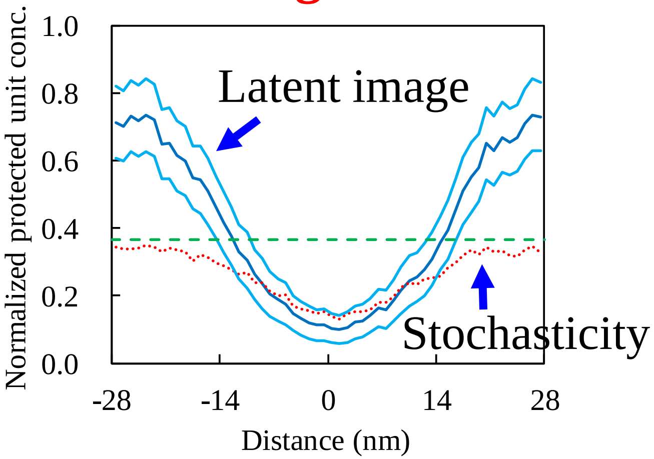
The proportionality constant depends on the stochastic effect.

The chemical gradient is determined by ①−③

Concept of resist characterization for stochastic effect

Reconstruction of chemical image





Conventional characterization

SEM image

Resolution
Line edge roughness
Sensitivity
Exposure latitude

Information

Inadequate for material design of 16 and 11 nm node

+

Advanced characterization

Latent image & stochasticity

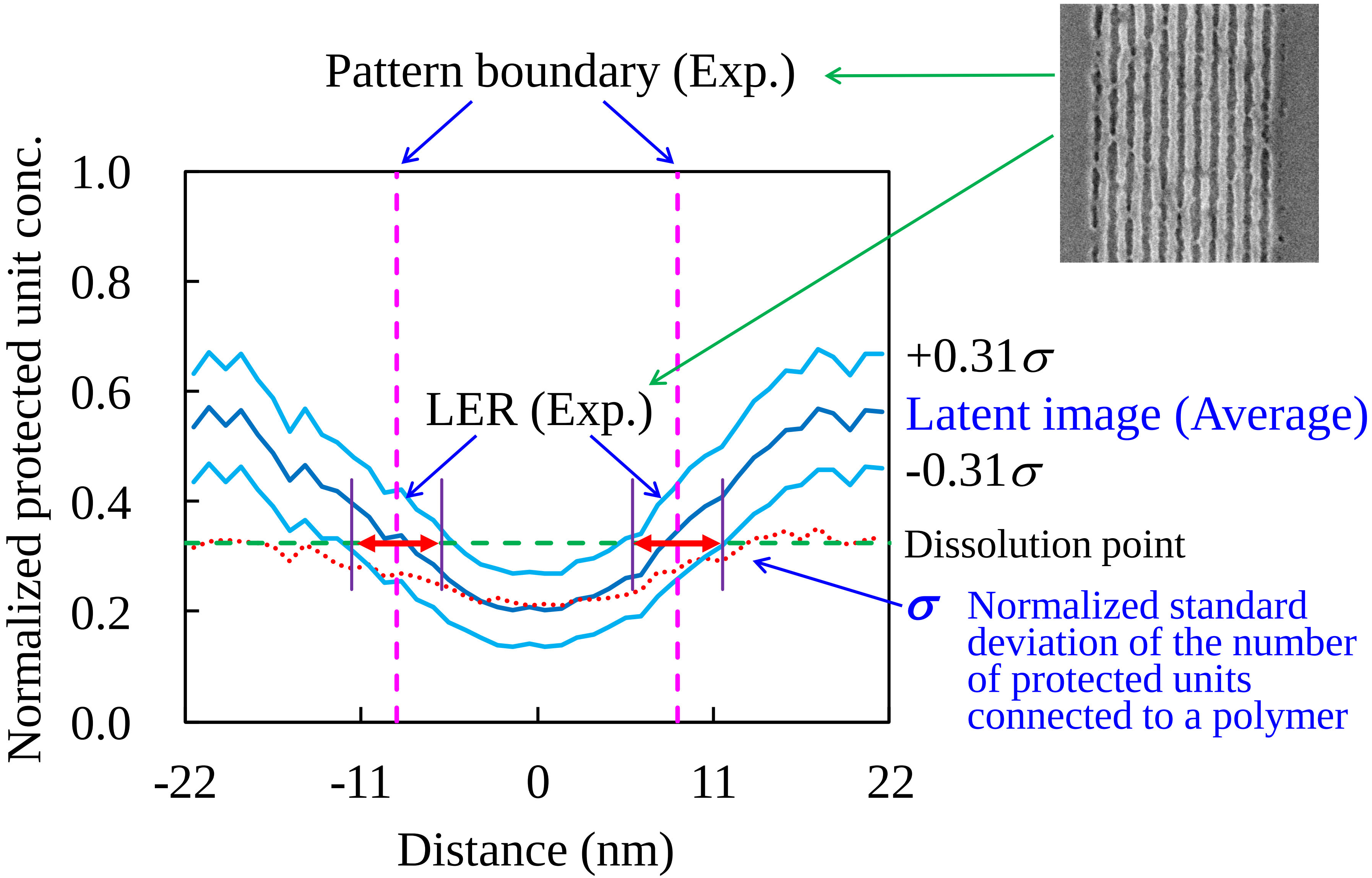
Absorption coefficient
Quantum efficiency
Effective reaction radius
Dissolution point
Dissolution efficiency

Information

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

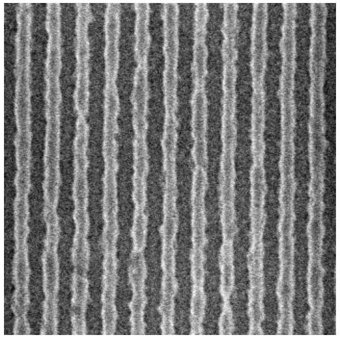
Applied to ESR1 to clarify the stochastic effect

Latent image of 22 nm LS pattern at 16 mJ cm^{-2} exposure



±0.31-±0.37σ fluctuation of protected units contributed to LER formation.

Advanced resist characterization and stochastic effect



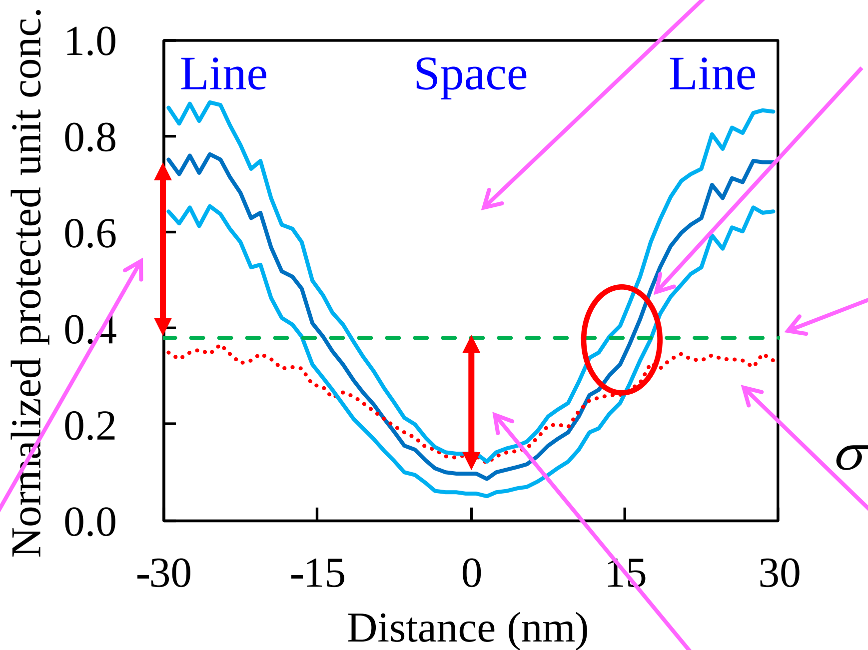
EIDEC Standard Resist

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.

Objective

The formation of line-and-space patterns was calculated by applying the knowledge obtained with the advanced characterization in order to clarify the stochastic effects at 11nm node.

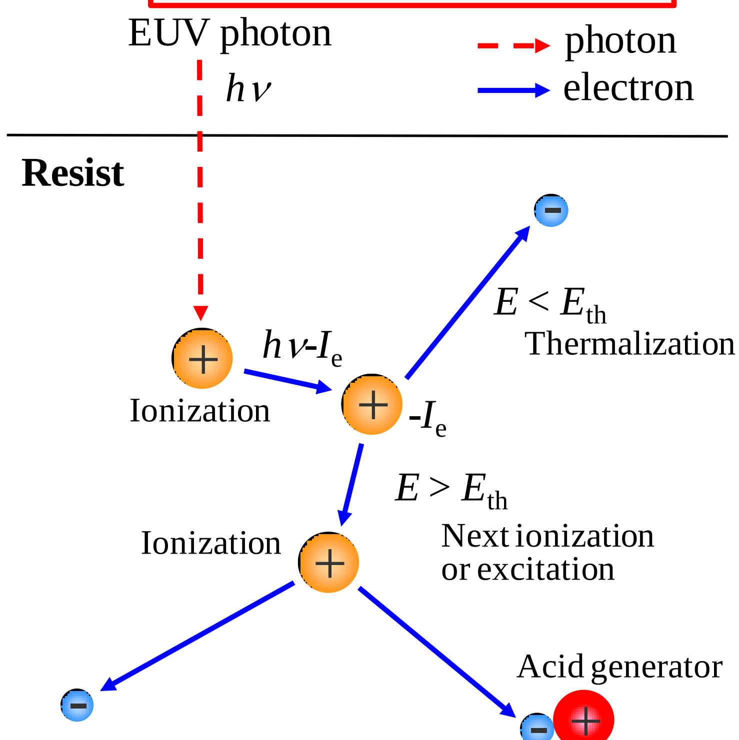
Terminology and assumption

1. The distribution of the protected units connected to a polymer molecule is hereafter called the protected unit distribution.
2. The standard deviation of the number of protected units connected to a polymer molecule is called “standard deviation” in this study.
3. The dispersion of the molecular weight (4000) of resist polymer (the completely deprotected polymer) was assumed to be 1 for simplicity.
4. The average number of protected units connected to a polymer molecule was assumed to be 10.
5. $\pm 0.34\sigma$ (an average value of 0.31 and 0.37) protected unit fluctuation was assumed to contribute to LER formation.
6. The optical images with contrast of 1 and without flare were assumed.

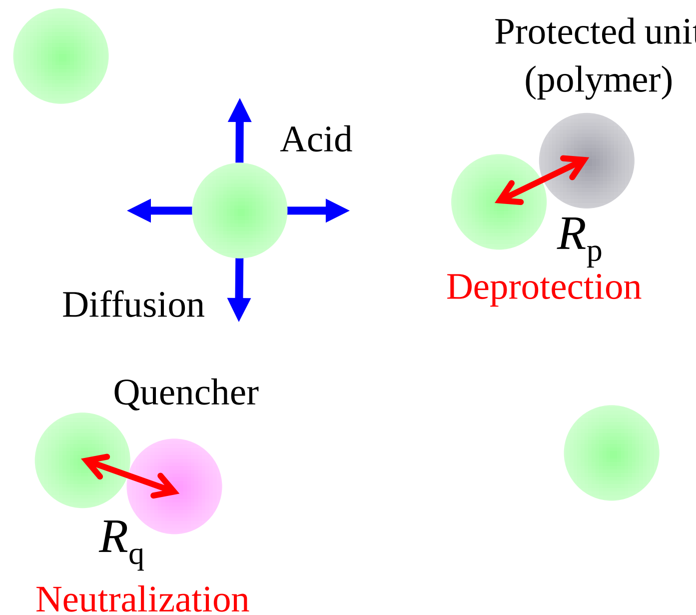
Simulation method

Optimum process parameters were determined using the hybrid model.
Using the obtained parameters, the stochastic model was applied to the study on stochastic effects.

Acid generation	**Catalytic chain reaction**
1. Probability density model	
Point spread function	Reaction diffusion equations
2. Hybrid model	
Monte Carlo method	Reaction diffusion equations
3. Stochastic model	
Monte Carlo method	Monte Carlo method



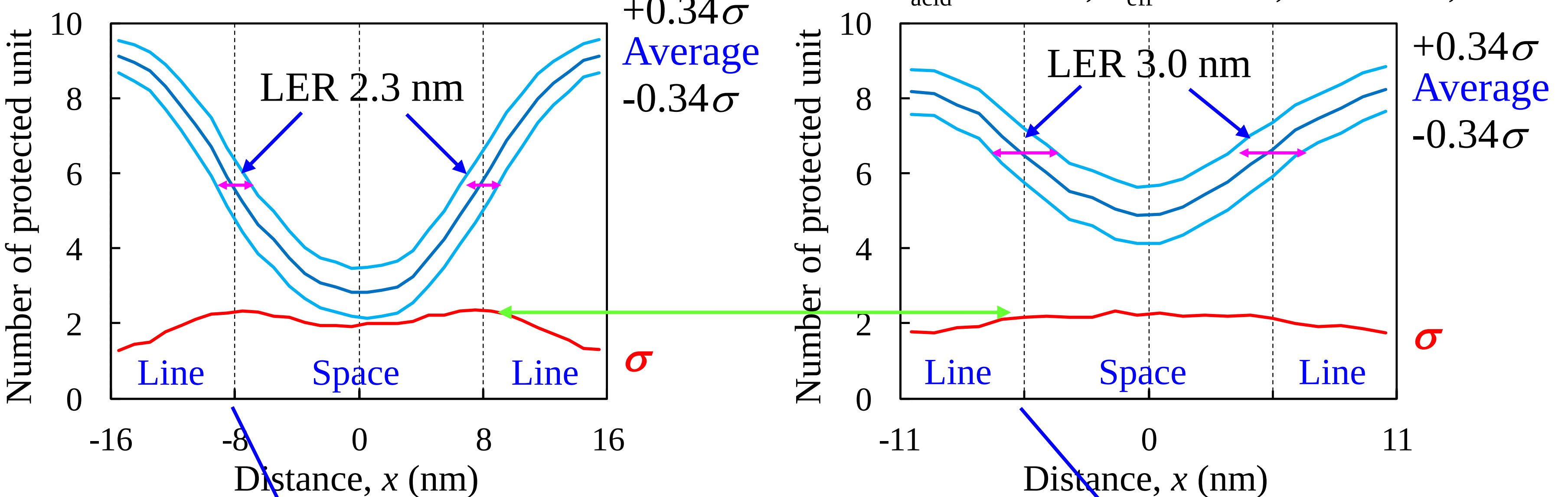
During exposure



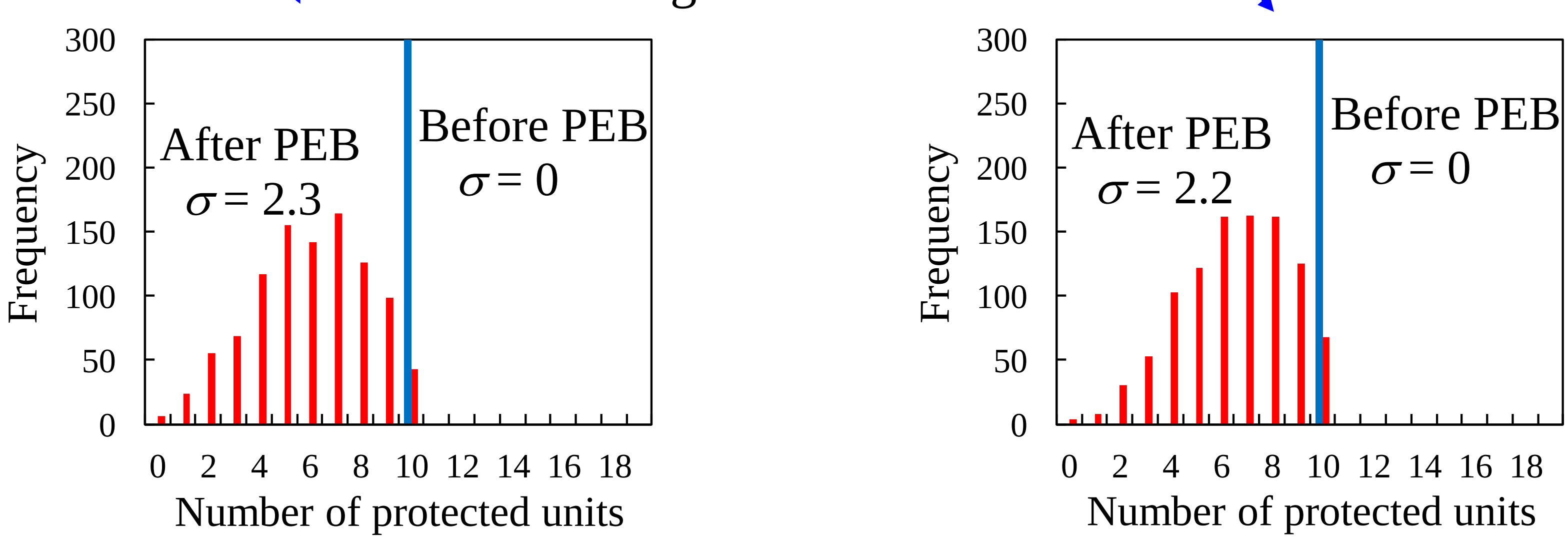
During PEB

Latent images (current resists) predicted at 16 and 11 nm node

C_{acid}: 10 wt%, R_{eff}: 0.1 nm, Contrast 1, no flare



Latent image with standard deviation



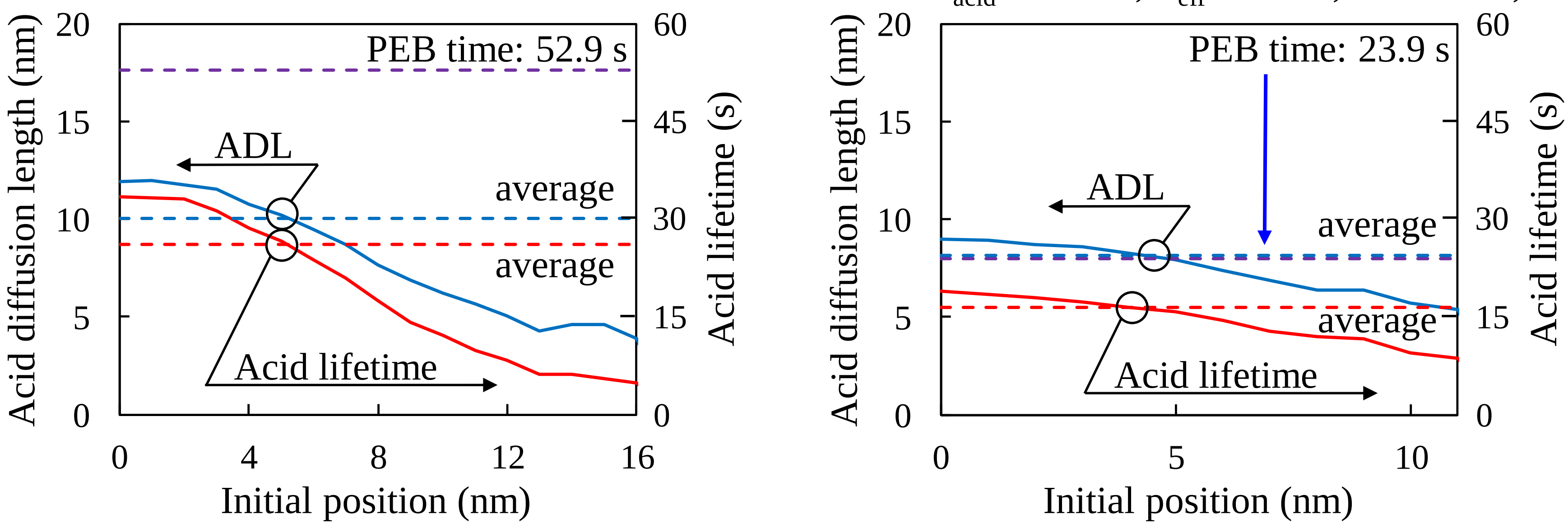
Distribution of the number of protected units connected to a polymer

16 nm HP, 20 mJ cm^{-2}

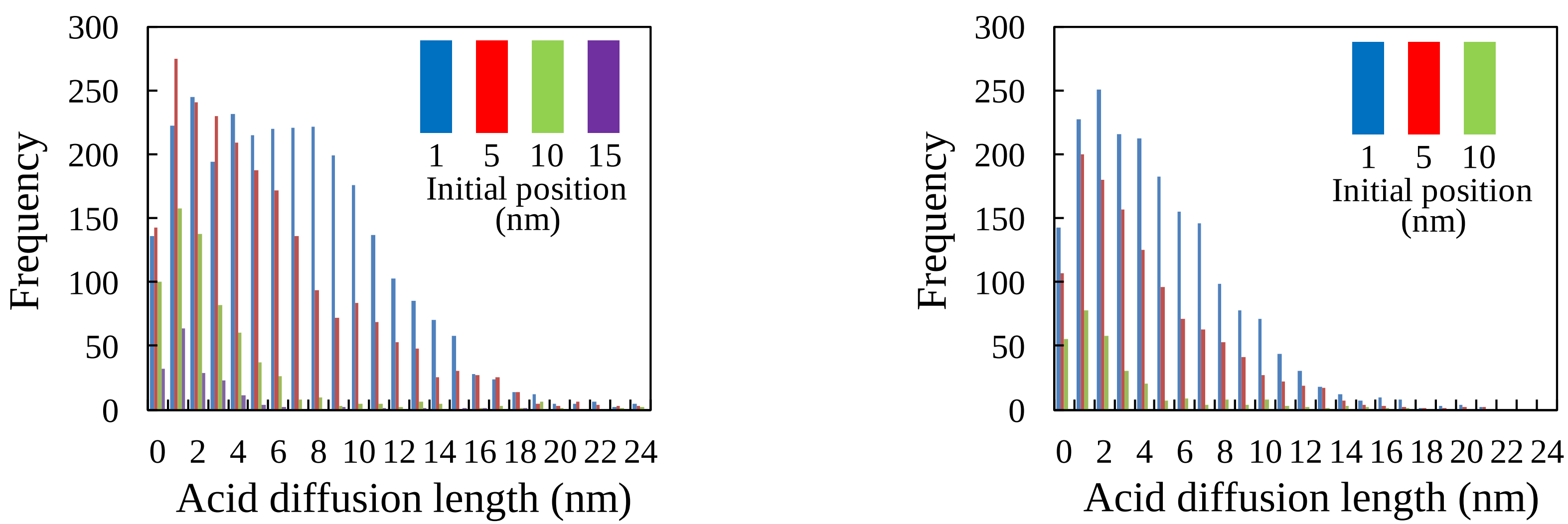
11 nm HP, 20 mJ cm^{-2}

Stochastic effects in acid diffusion at 16 and 11 nm node

C_{acid}: 10 wt%, R_{eff}: 0.1 nm, Contrast 1, no flare



Dependence of acid diffusion length and lifetime on the initial position of acids

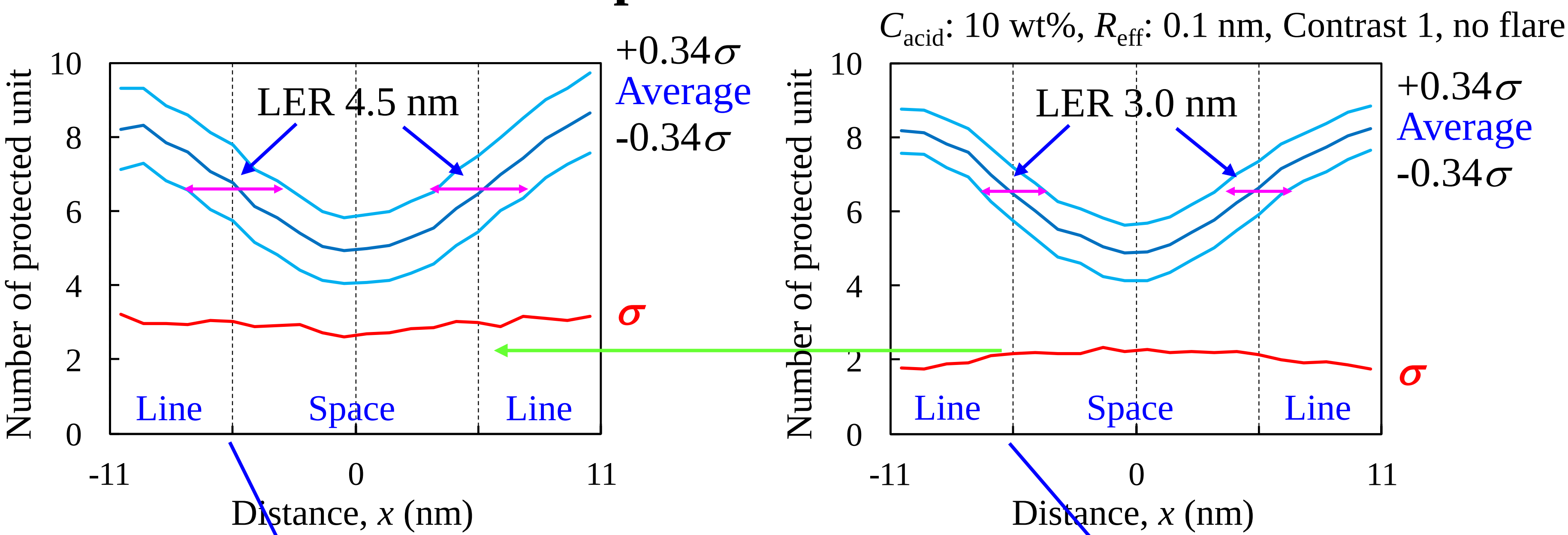


Histogram of acid diffusion length distribution

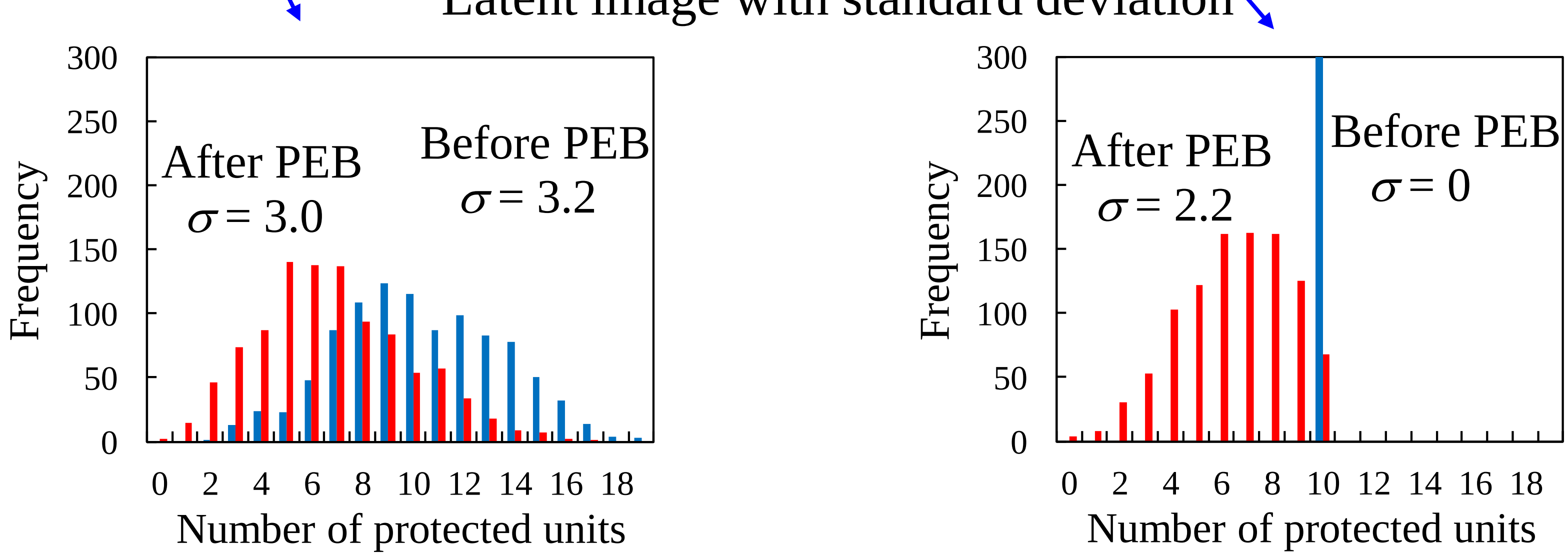
16 nm HP, 20 mJ cm^{-2}

11 nm HP, 20 mJ cm^{-2}

Effect of initial dispersion on LER at 11 nm node



Latent image with standard deviation

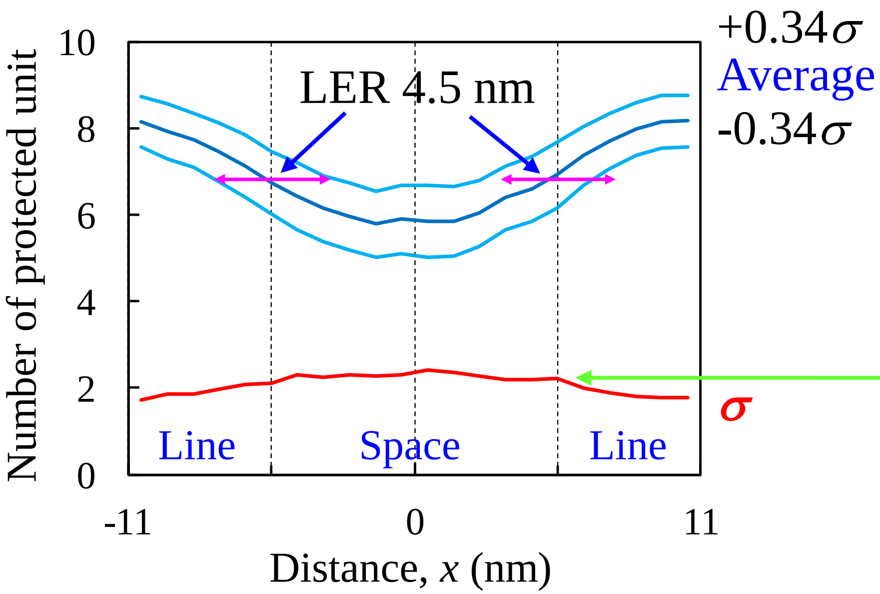


Distribution of the number of protected units connected to a polymer

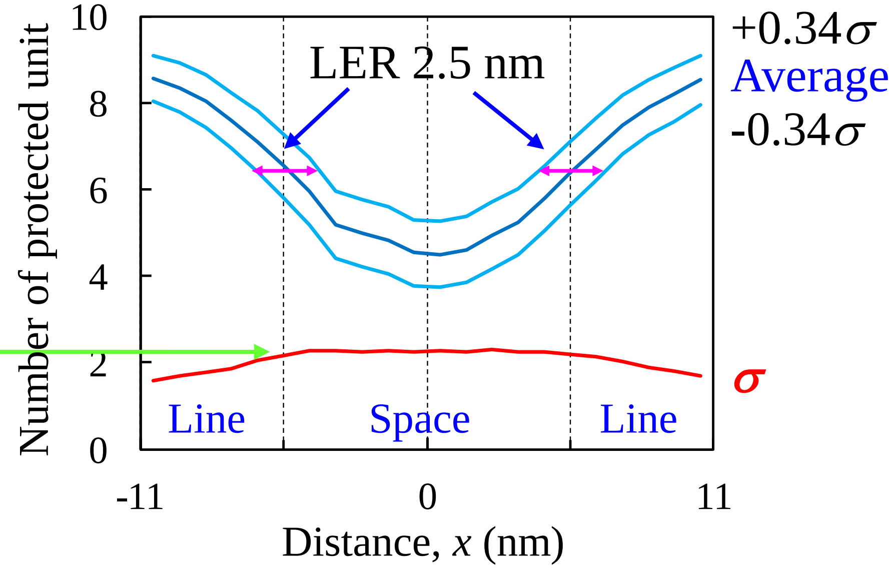
11 nm HP, 20 mJ cm^{-2}

11 nm HP, 20 mJ cm^{-2}

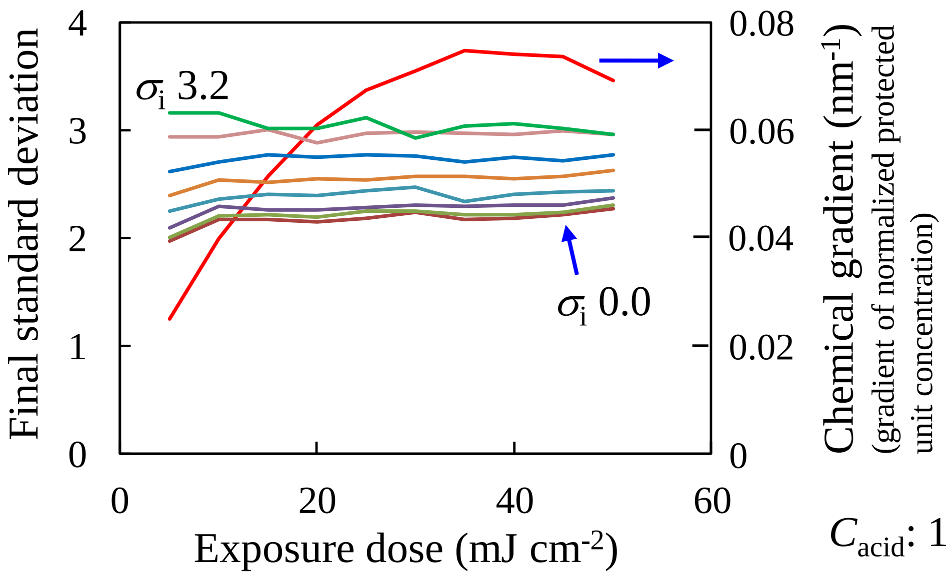
Dose dependence of protected unit fluctuation at 11 nm node



11 nm HP, 5 mJ cm^{-2}



11 nm HP, 35 mJ cm^{-2}



Protected unit fluctuation (standard deviation) does not significantly depend on exposure dose when the process is optimized to maximize chemical gradient for each exposure dose.

C_{acid}: 10 wt%, R_{eff}: 0.1 nm, Contrast 1, no flare

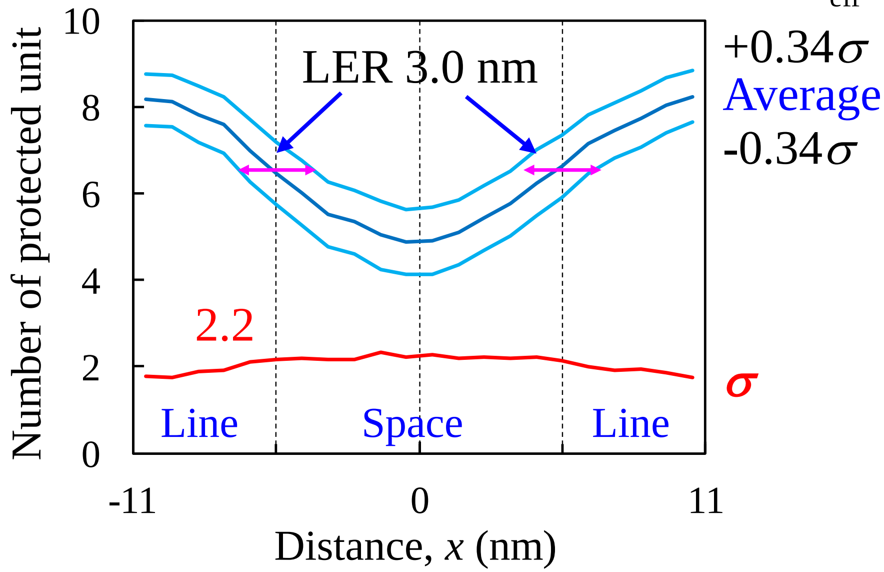
Dose dependence of protected unit fluctuation and chemical gradient. Initial standard deviation σ_i was changed from 0.0 to 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.2.

Effects of acid generator concentration at 11 nm node

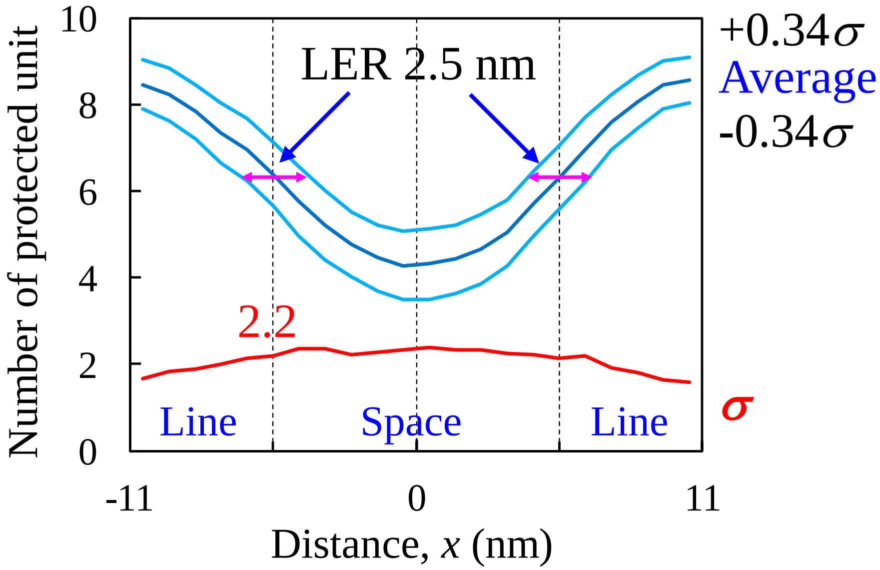
R_{eff}: 0.1 nm, Contrast 1, no flare

Exposure dose:

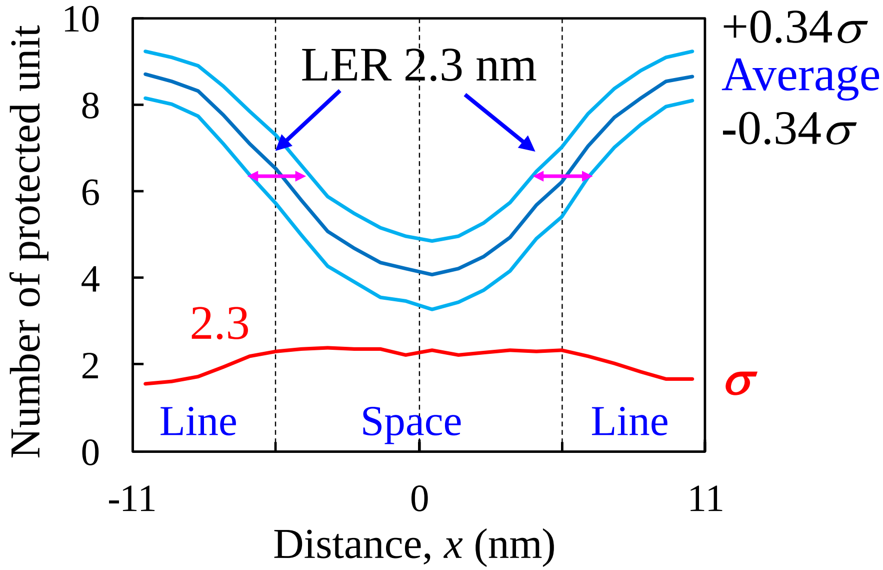
20 mJ cm^{-2}



10 wt%, ϕ_{acid} 2.0



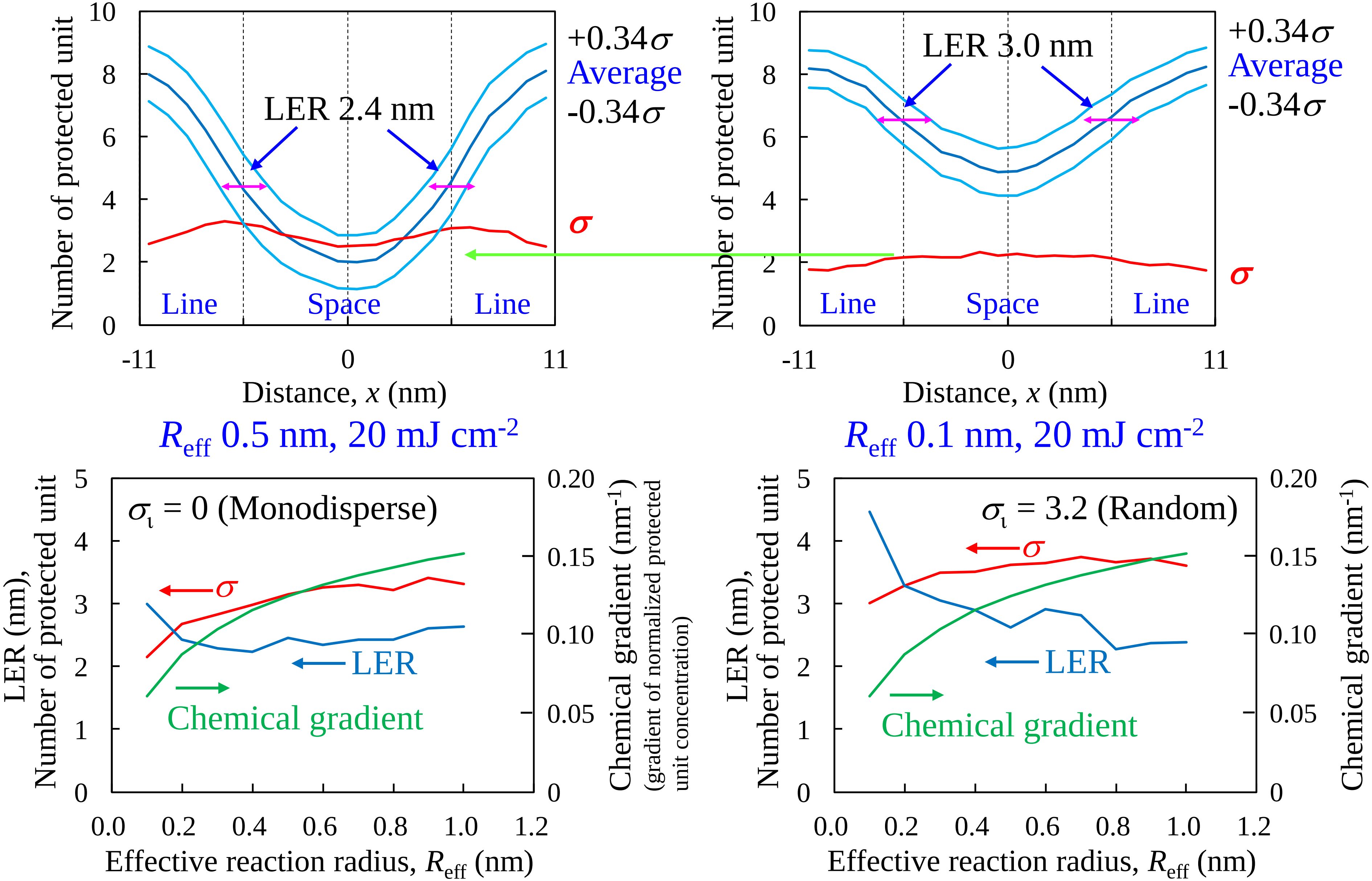
20 wt%, ϕ_{acid} 2.5



30 wt%, ϕ_{acid} 2.8

Effect of effective reaction radius for deprotection at 11 nm node

C_{acid}: 10 wt%, Contrast 1, no flare



Dependence of protected unit fluctuation on effective reaction radius

Conclusion

1. Protected unit fluctuation does not depend on exposure dose (>5mJ cm^{-2}) and acid generator concentration (>5 wt%) at 11 nm node.
2. Protected unit fluctuation after PEB depends on the initial polymer condition.
3. Protected unit fluctuation increases with the effective reaction radius for deprotection.
4. Because of severe requirement for resist processes, not only chemical contrast but also stochastic effects should be taken into account in the design of next generation resists.

Acknowledgement

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