Analysis of Stochastic Effect in Line-and-Space Patterns Fabricated by Extreme Ultraviolet Lithography

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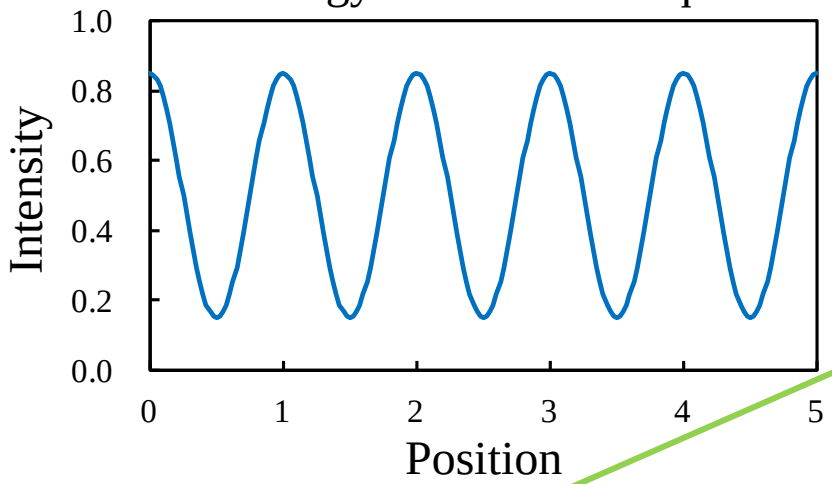
Chemically amplified resist

Typical components: Polymer, Acid generator, Quencher

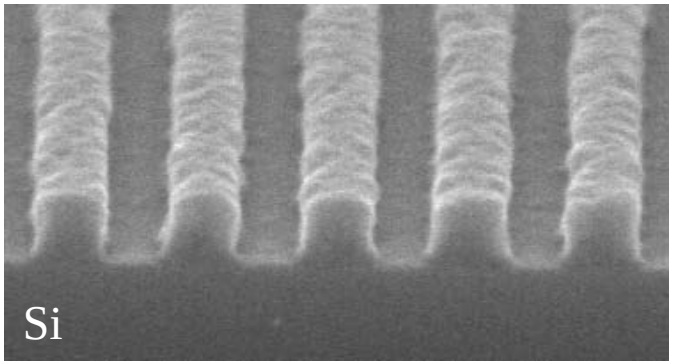
Role: Conversion of energy modulation to binary image

Exposure source

Energy modulation of quantum beam



Resist image



SEM image of resist

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 → Development

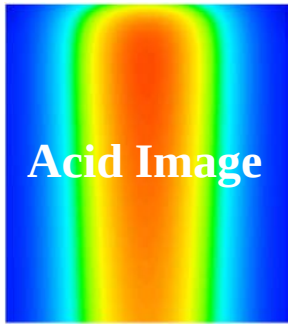
Acid diffusion, deprotection

Dissolution of molecules

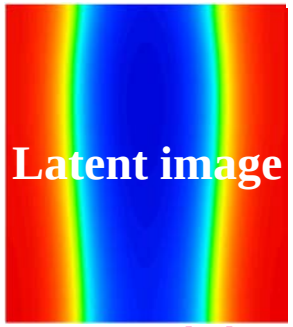
Relationship between LER and chemical gradient

Aerial image

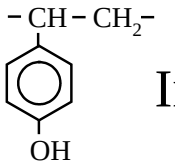
EUV



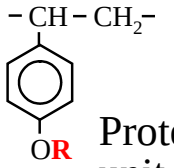
Cross section



Soluble ← Can be controlled

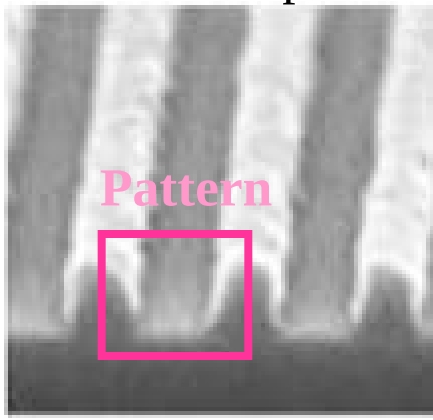


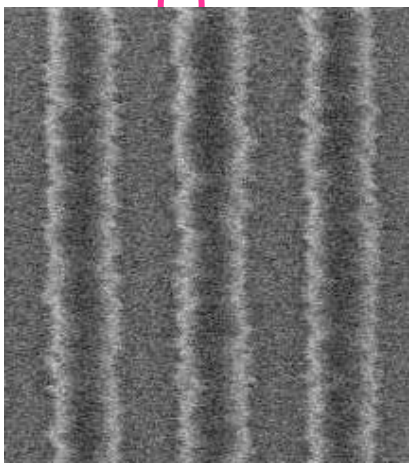
Insoluble



Protected unit

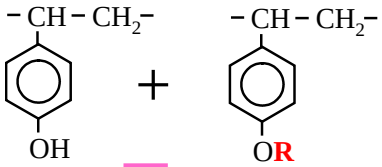
After development





Top-down view

Mixture of soluble and insoluble molecules



Absolutely stochastic
Can not be controlled

(Spatially) partially soluble

LER formation

LER ∝ width of intermediate region $\fallingdotseq \dfrac{1}{\text{Chemical gradient}}$ ➡ $LER \approx \dfrac{f_{LER}}{dm/dx}$

Performance (efficiency) of resist

The number of incident photons is limited because of the sensitivity requirement.

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

④How smoothly are the polymers dissolved in developer?

Relationship between LER and chemical gradient, f_{LER}

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

← The chemical gradient is determined by ①－③

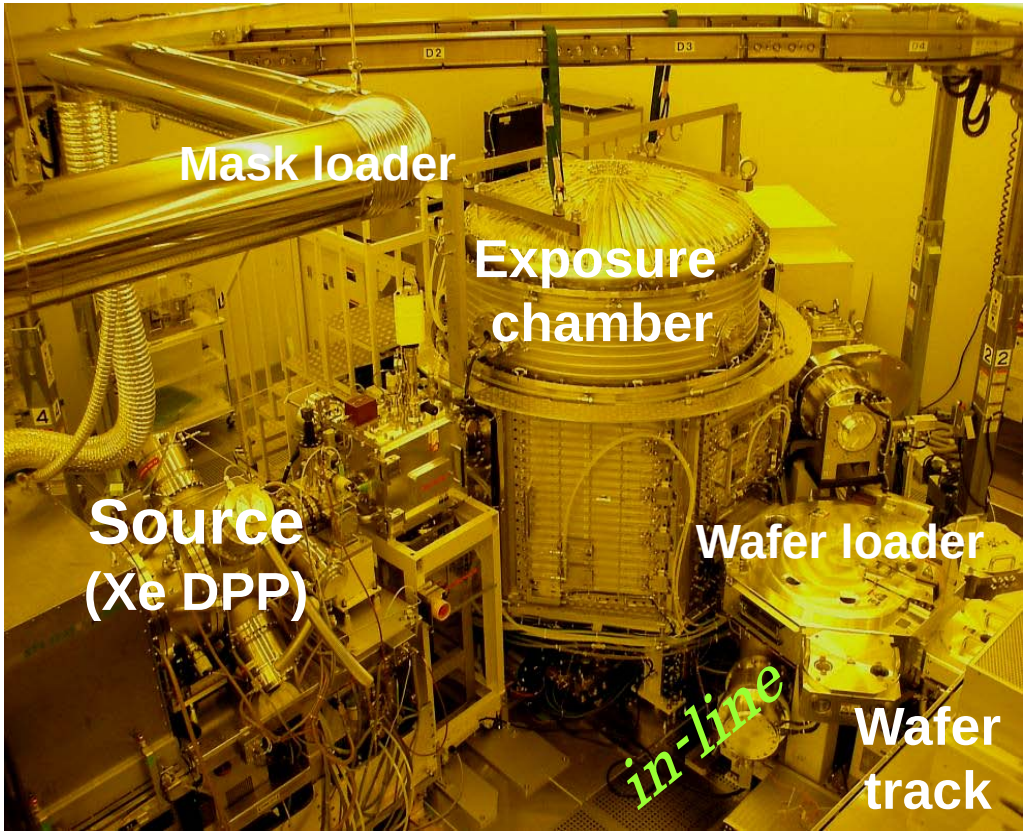
The relationship between LER and stochastic effect is unclear.

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 relationships among LER, chemical gradient, and stochastic effect.

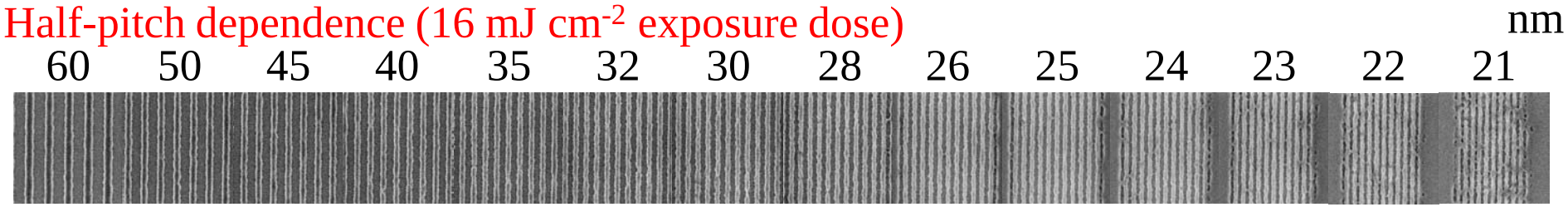
Small Field Exposure Tool : SFET



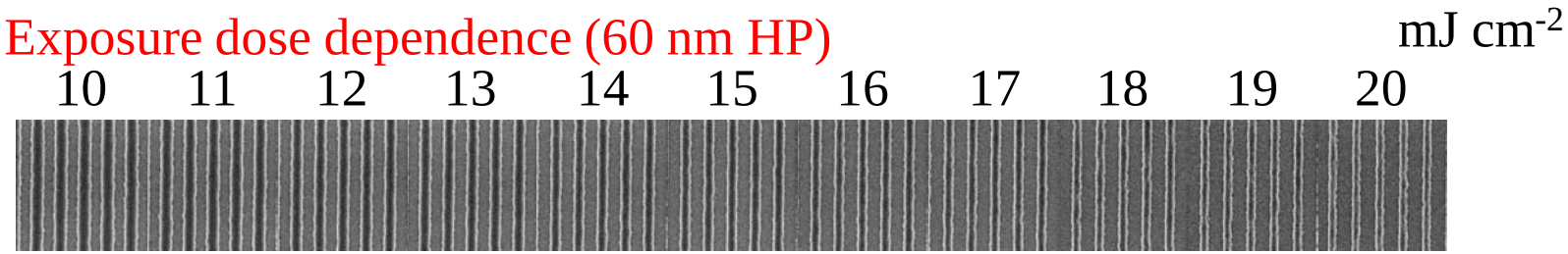
Items	Target Specifications
NA	0.3
Illumination mode	Annular(0.3/0.7), x-slit
Field size	0.2 x 0.6 mm
Magnification	1/5
Wavefront error	＜0.9 nm rms
Flare	＜7%（MSFR）
Source power	0.5W @IF
Wafer size	300 mm

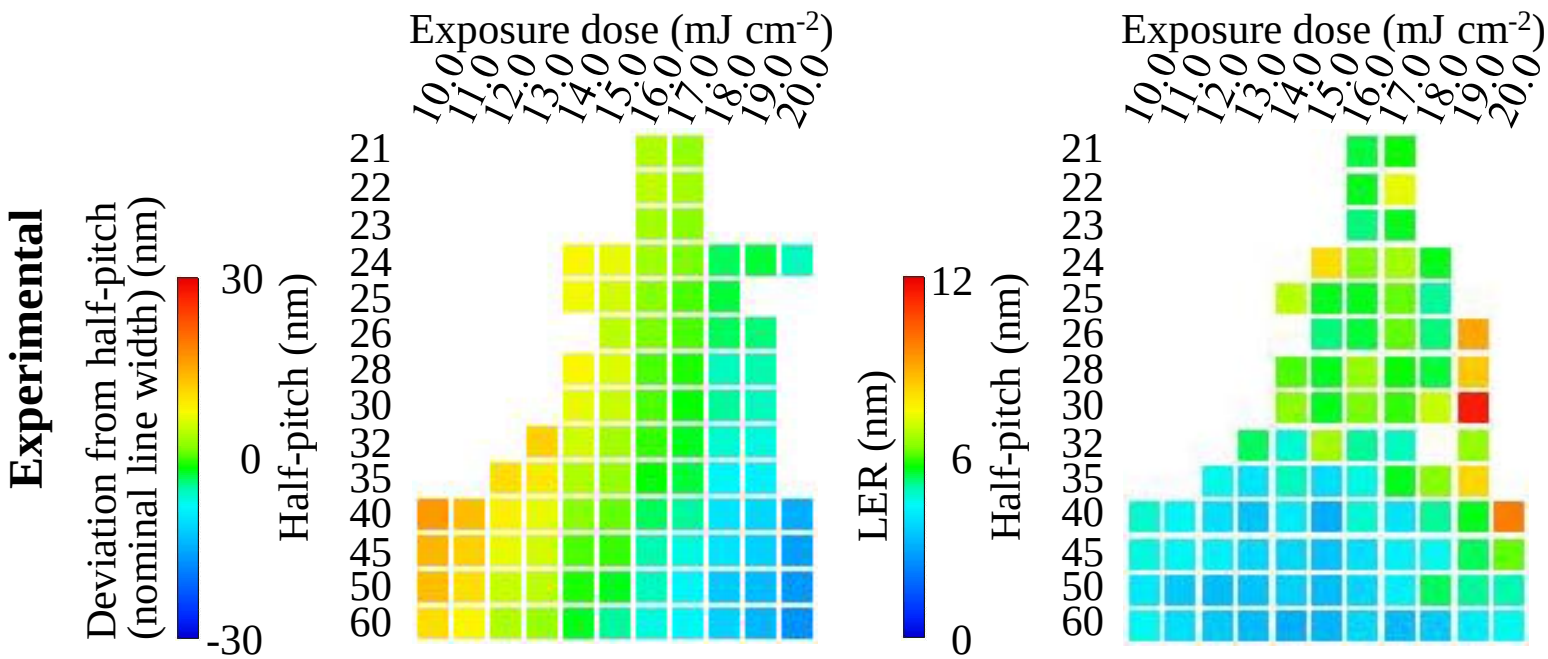
Dose-pitch matrices of EIDEC standard resist

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



Exposure dose dependence (60 nm HP)





(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 **Catalytic chain reaction**

Step 1: Overall fitting – Probability density model

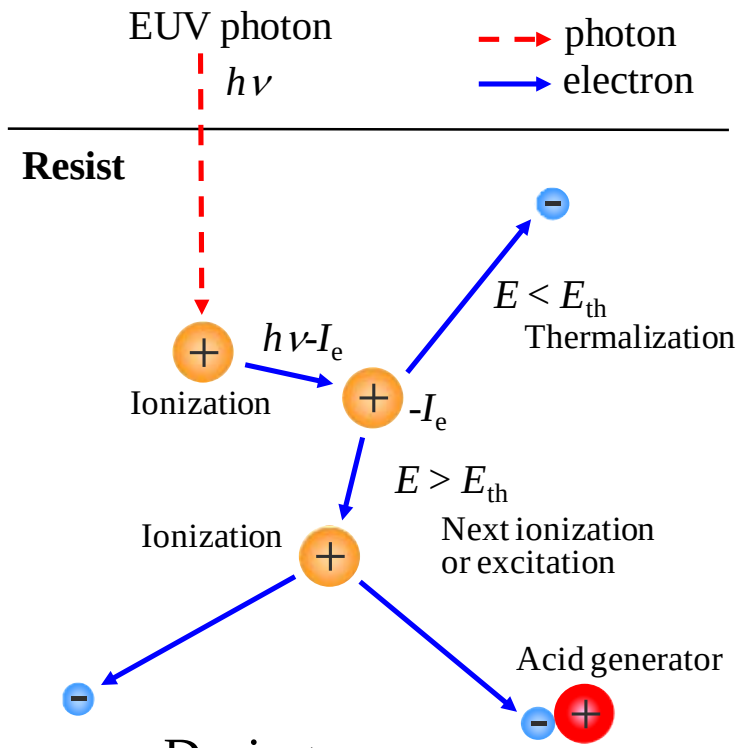
Point spread function Reaction diffusion equations

Step 2: Refitting with Monte Calro acid generation simulation – Hybrid model

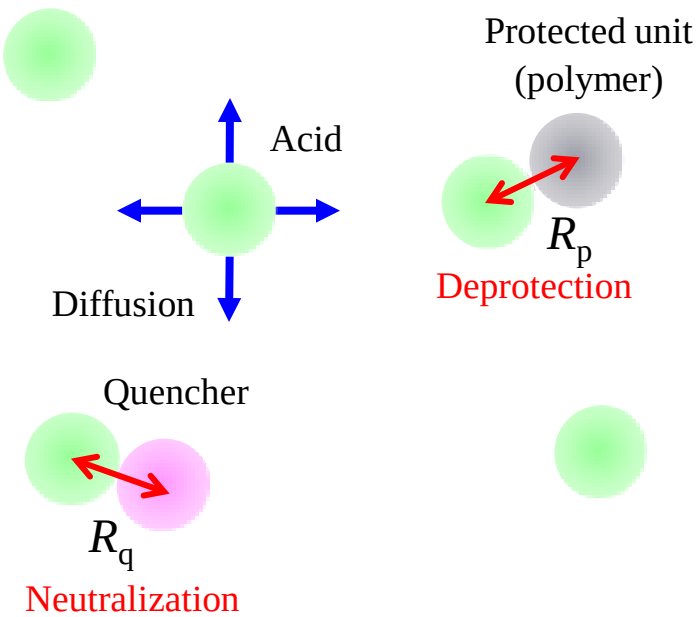
Monte Carlo method Reaction diffusion equations

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

Monte Carlo method Monte Carlo method

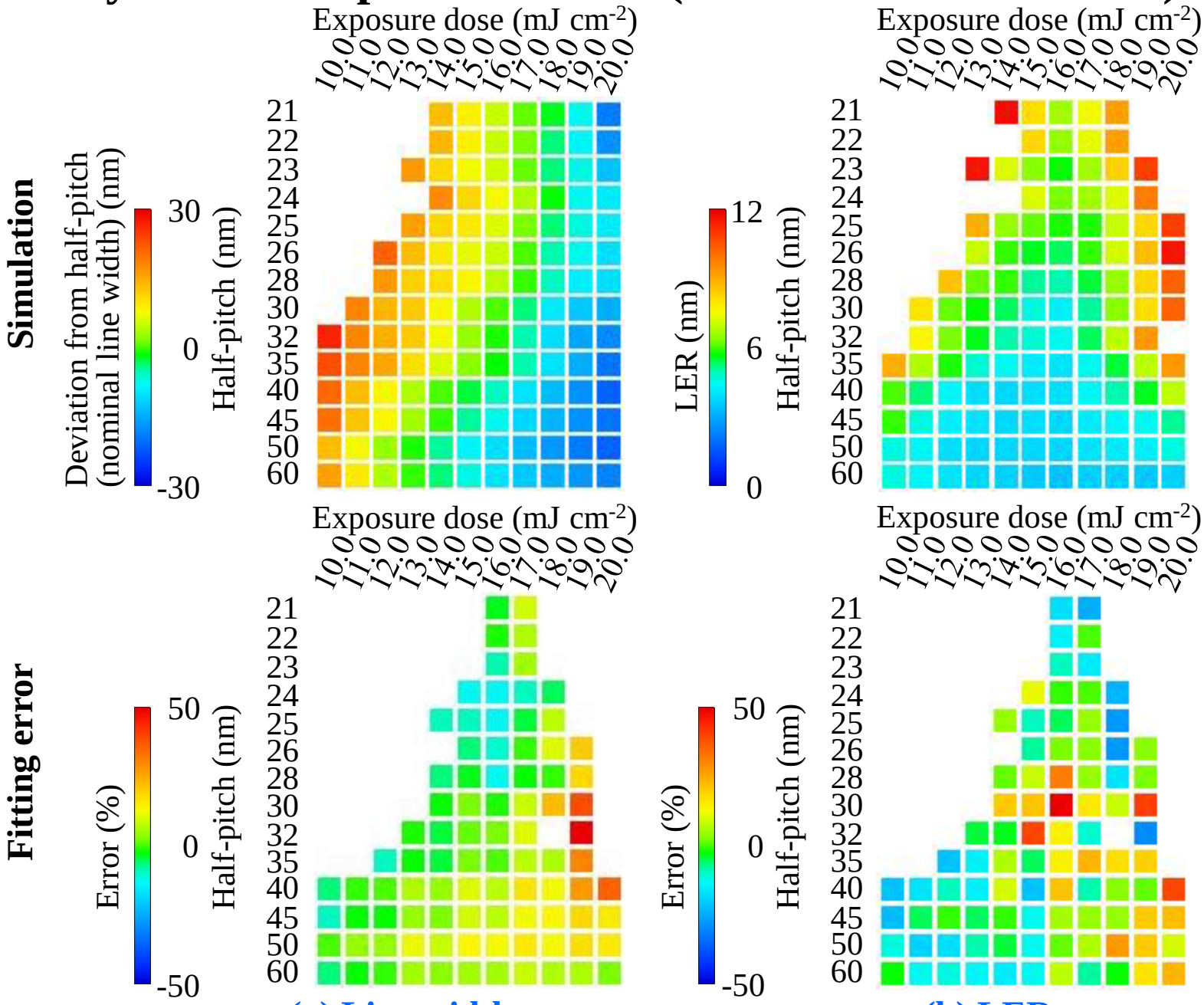


During exposure



During PEB

Analysis of dose-pitch matrices (EIDEC standard resist)

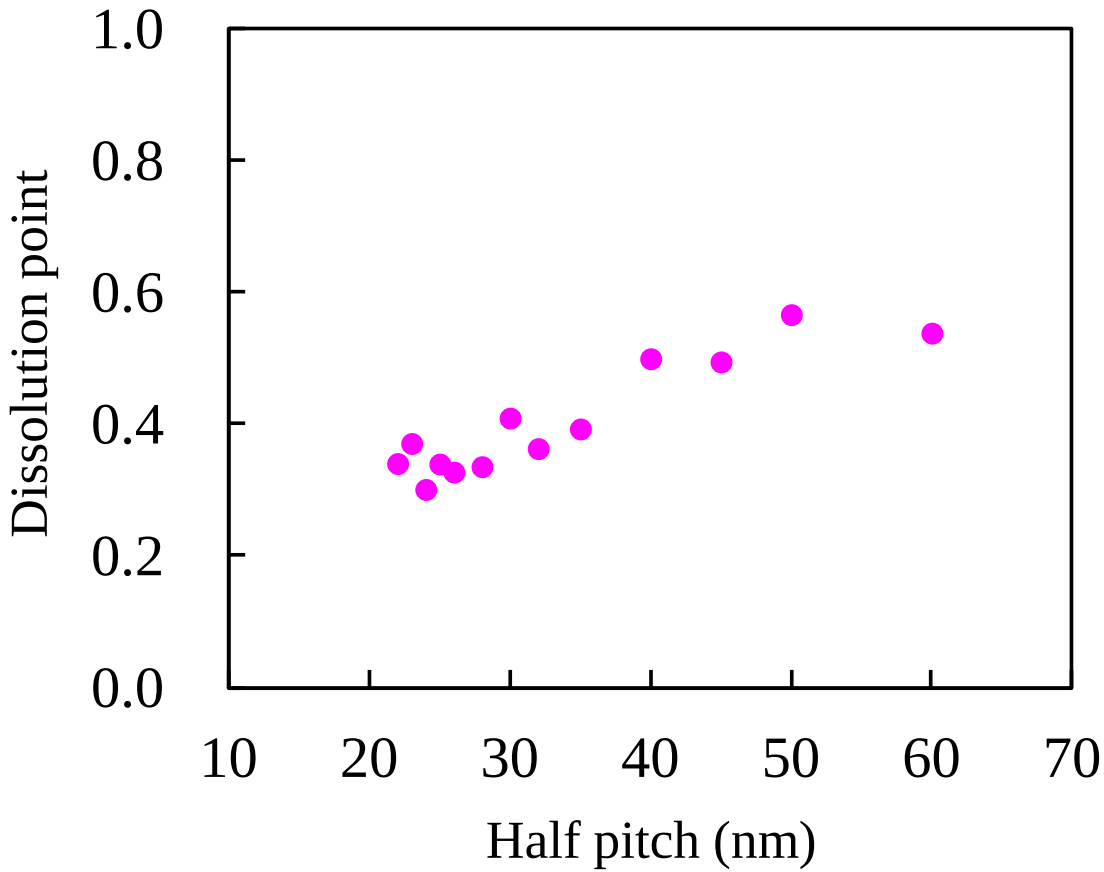


(a) Line width

(b) LER

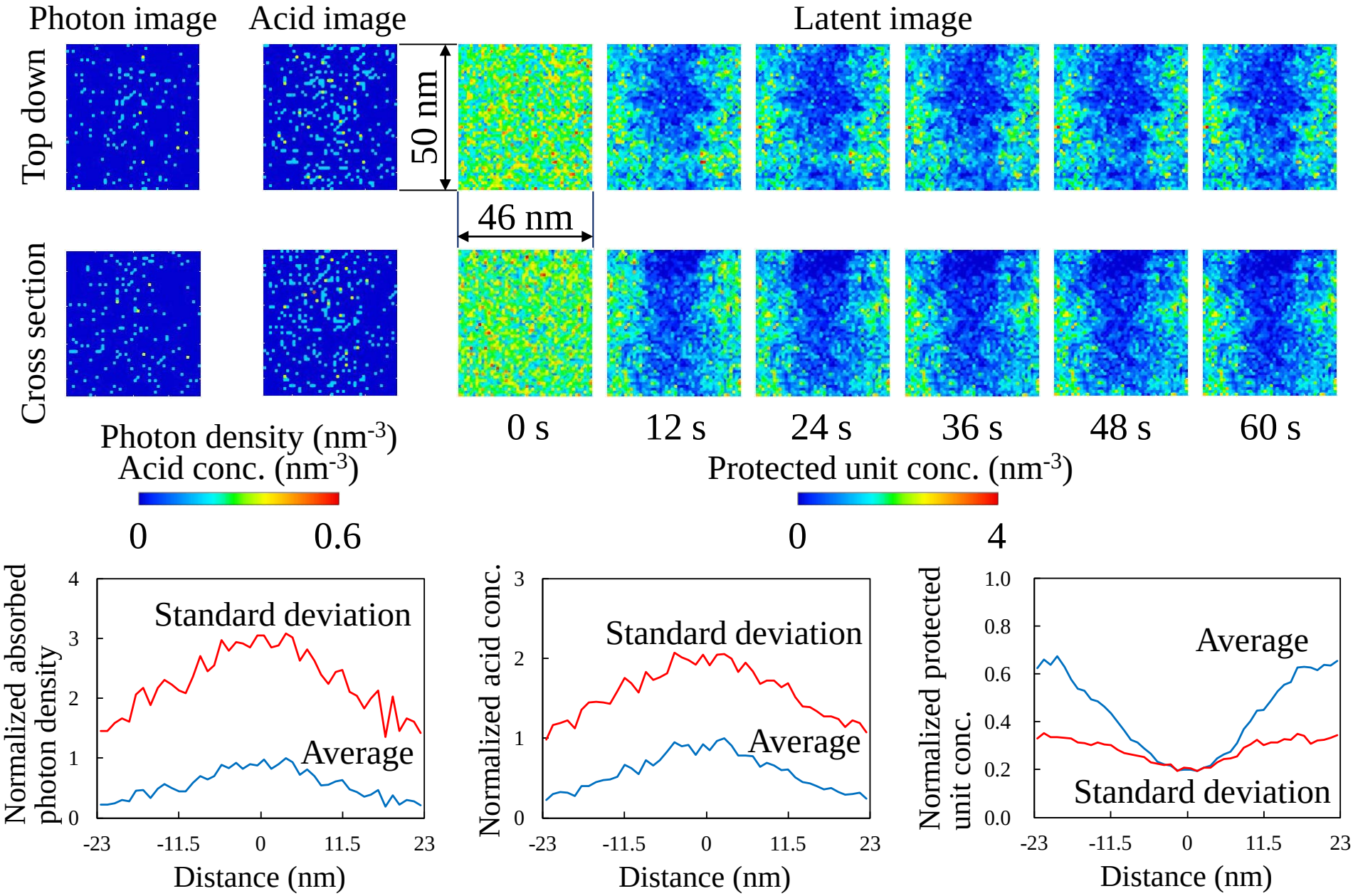
Best fit parameters

Effective reaction radius for deprotection: 0.16 nm
Effective quencher concentration: 0.023 nm^{-3}
Diffusion constant: 10 nm^2 s^{-1}
Proportionality constant between LER and chemical gradient f_{LER}: 0.22
Dissolution point:



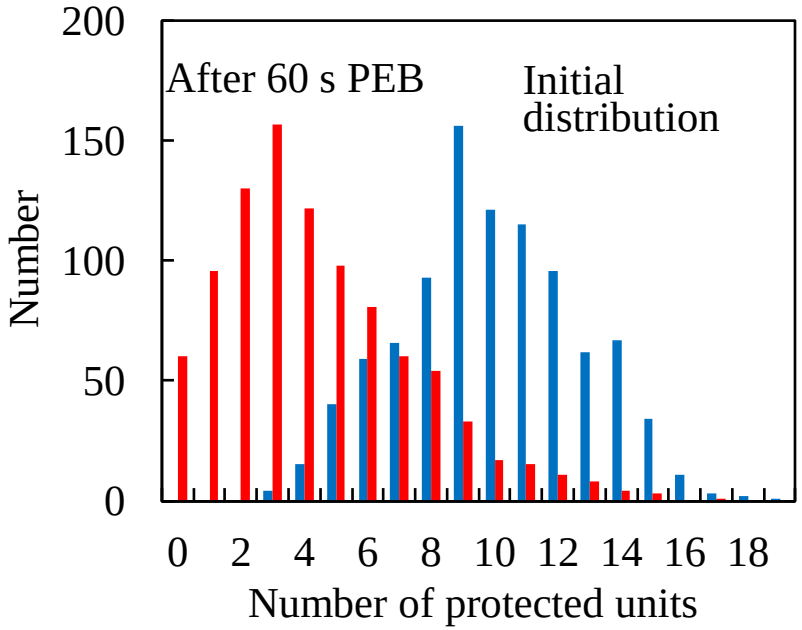
Dependence of dissolution characteristics on pattern size

Stochastic effect – 23 nm LS pattern at 16 mJ cm^{-2} exposure



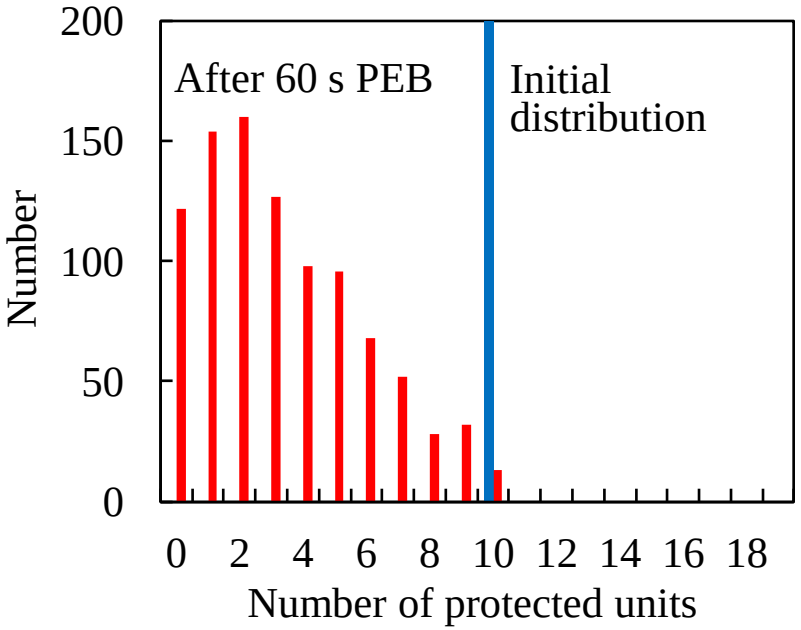
Change of protected unit distribution (23 nm LS, 16 mJ cm^{-2})

Randomly protected polymer



Histogram of the number of protected unit connecting to a polymer

Monodisperse polymer



Histogram of the number of protected unit connecting to a polymer

Change of standard deviation

After 60 s PEB

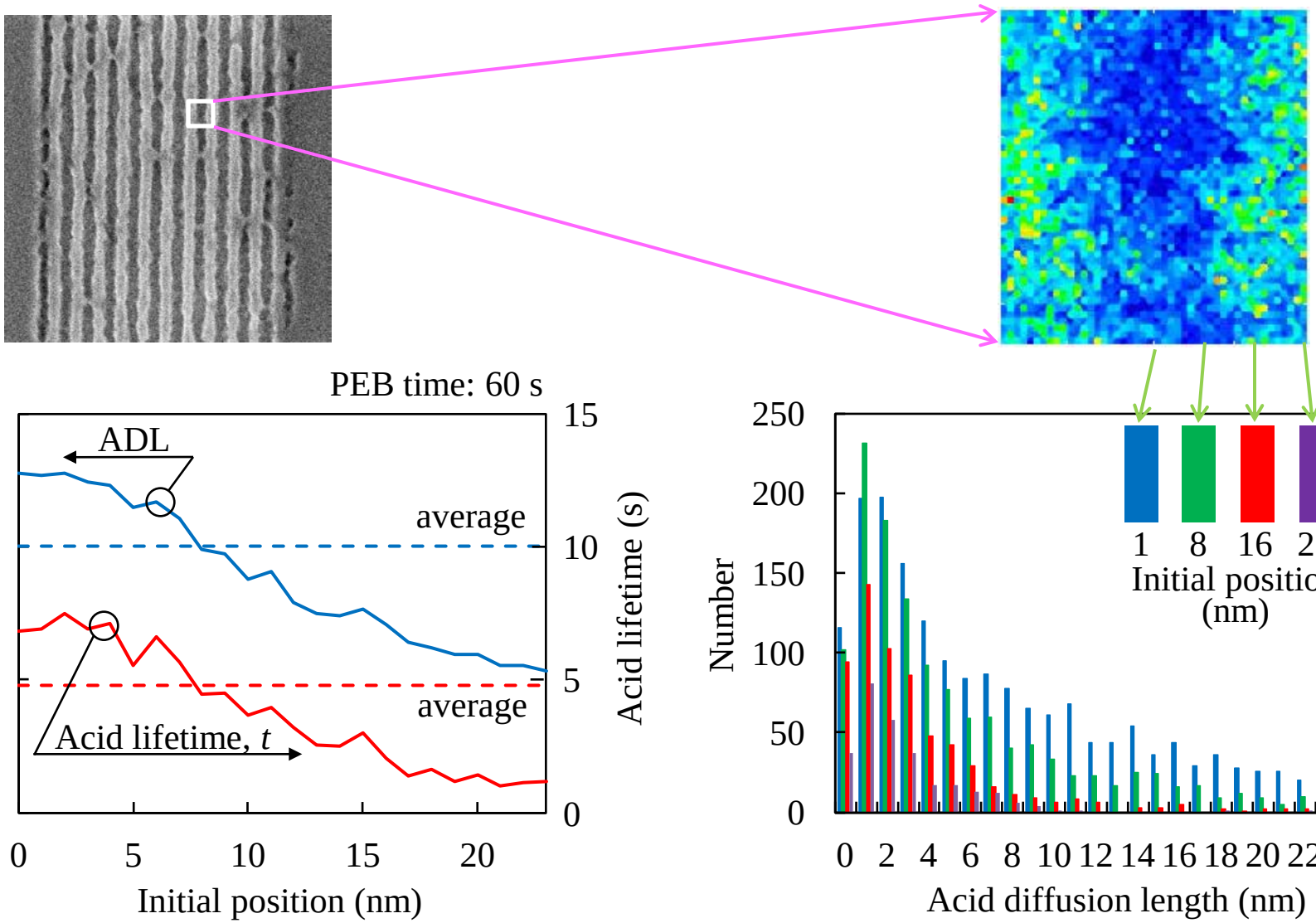
3.0 → 3.0

After 60 s PEB

0 → 2.6

The protected unit dispersion of the real resist polymer is between the cases shown here.

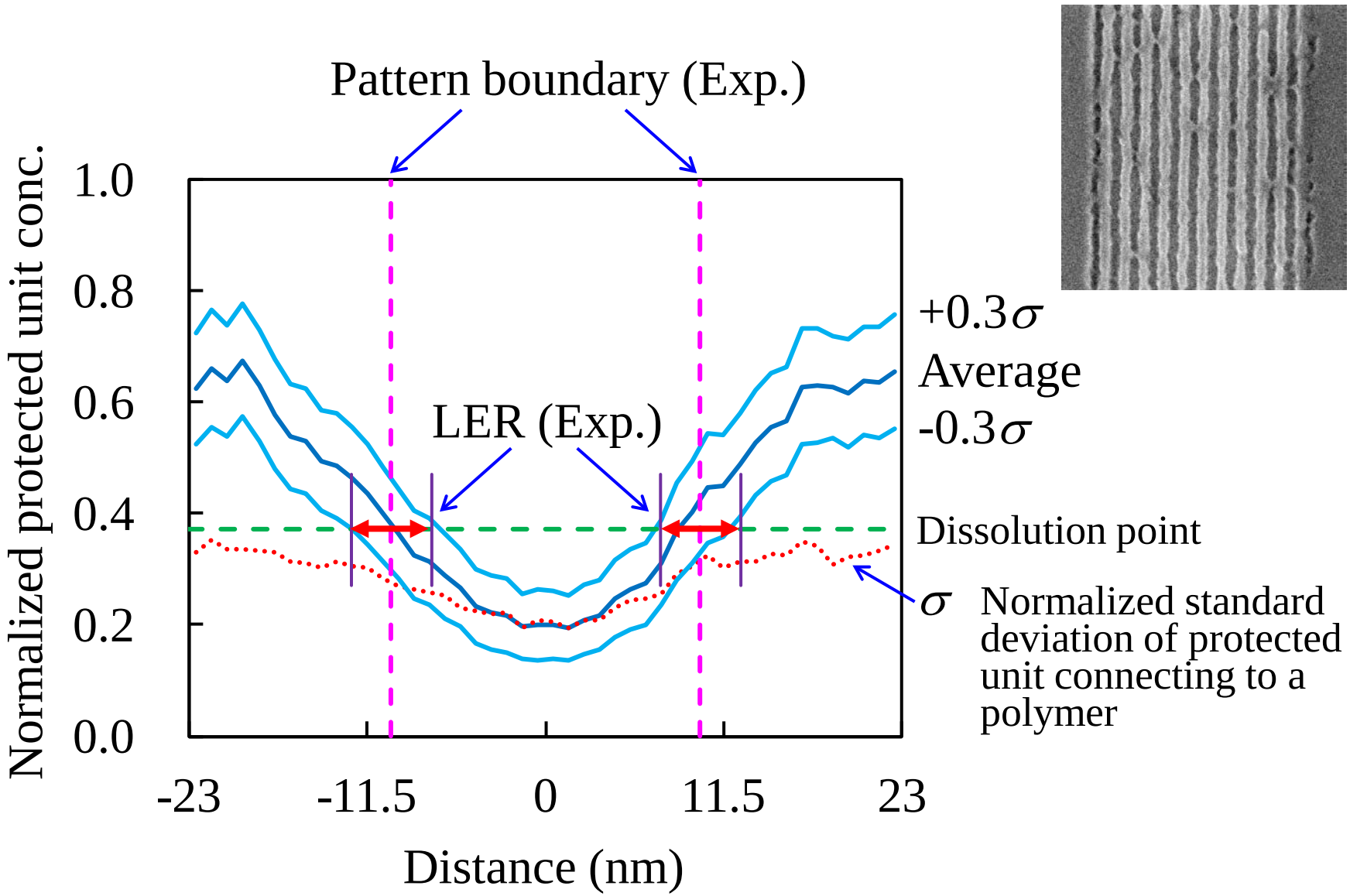
Acid diffusion length of 23 nm LS pattern at 16 mJ cm^{-2} exposure



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

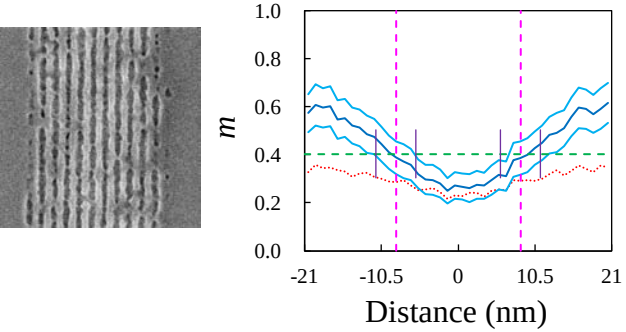
Histogram of acid diffusion length distribution

Latent image of 23 nm LS pattern at 16 mJ cm^{-2} exposure

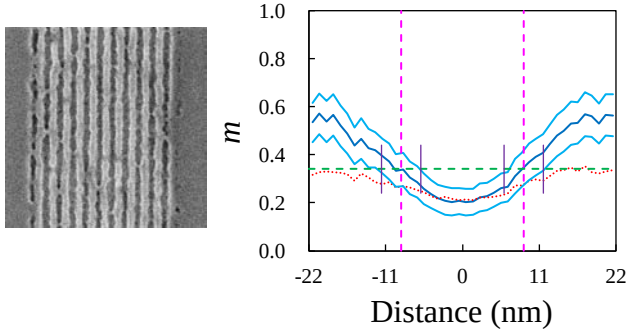


±0.3σ fluctuation of protected units was estimated to contribute to the LER formation of 23 nm LS pattern with 16 mJ cm^{-2} exposure dose.

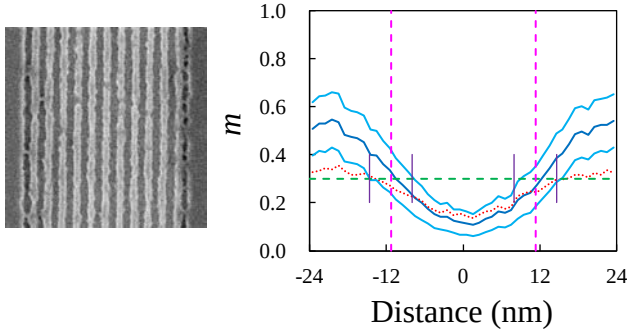
Representative analysis results



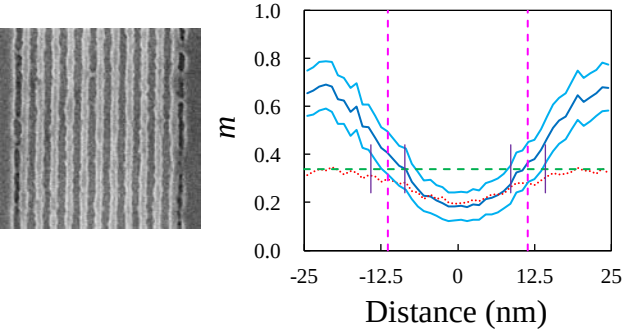
21 nm HP, 16 mJ cm^{-2}



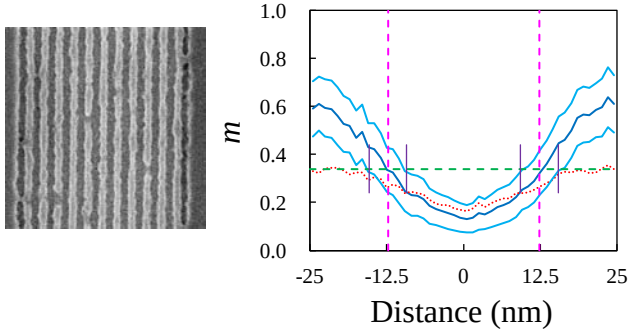
22 nm HP, 16 mJ cm^{-2}



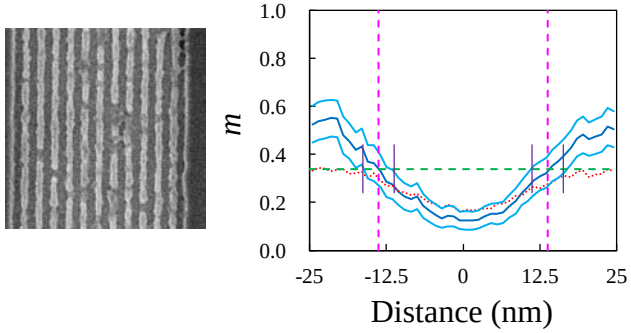
24 nm HP, 17 mJ cm^{-2}



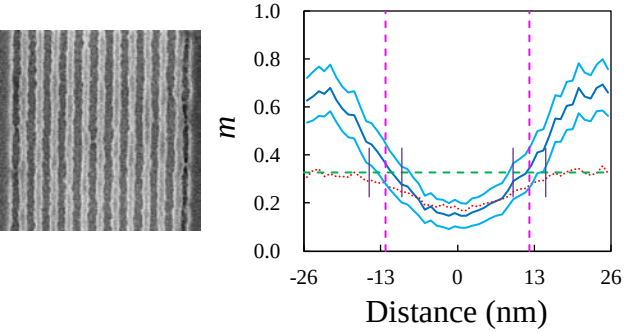
25 nm HP, 16 mJ cm^{-2}



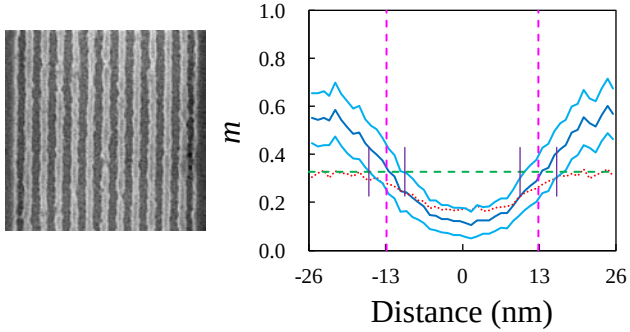
25 nm HP, 17 mJ cm^{-2}



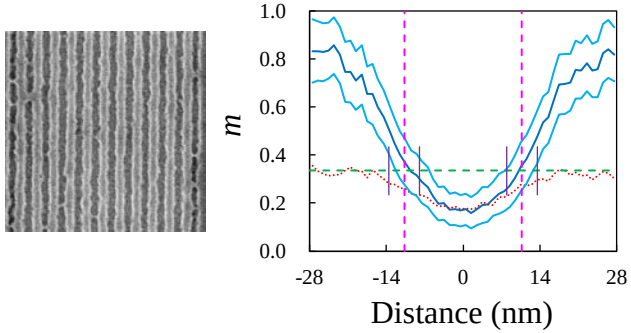
25 nm HP, 18 mJ cm^{-2}



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



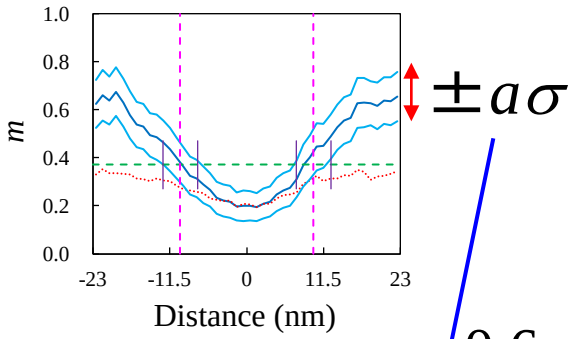
26 nm HP, 17 mJ cm^{-2}

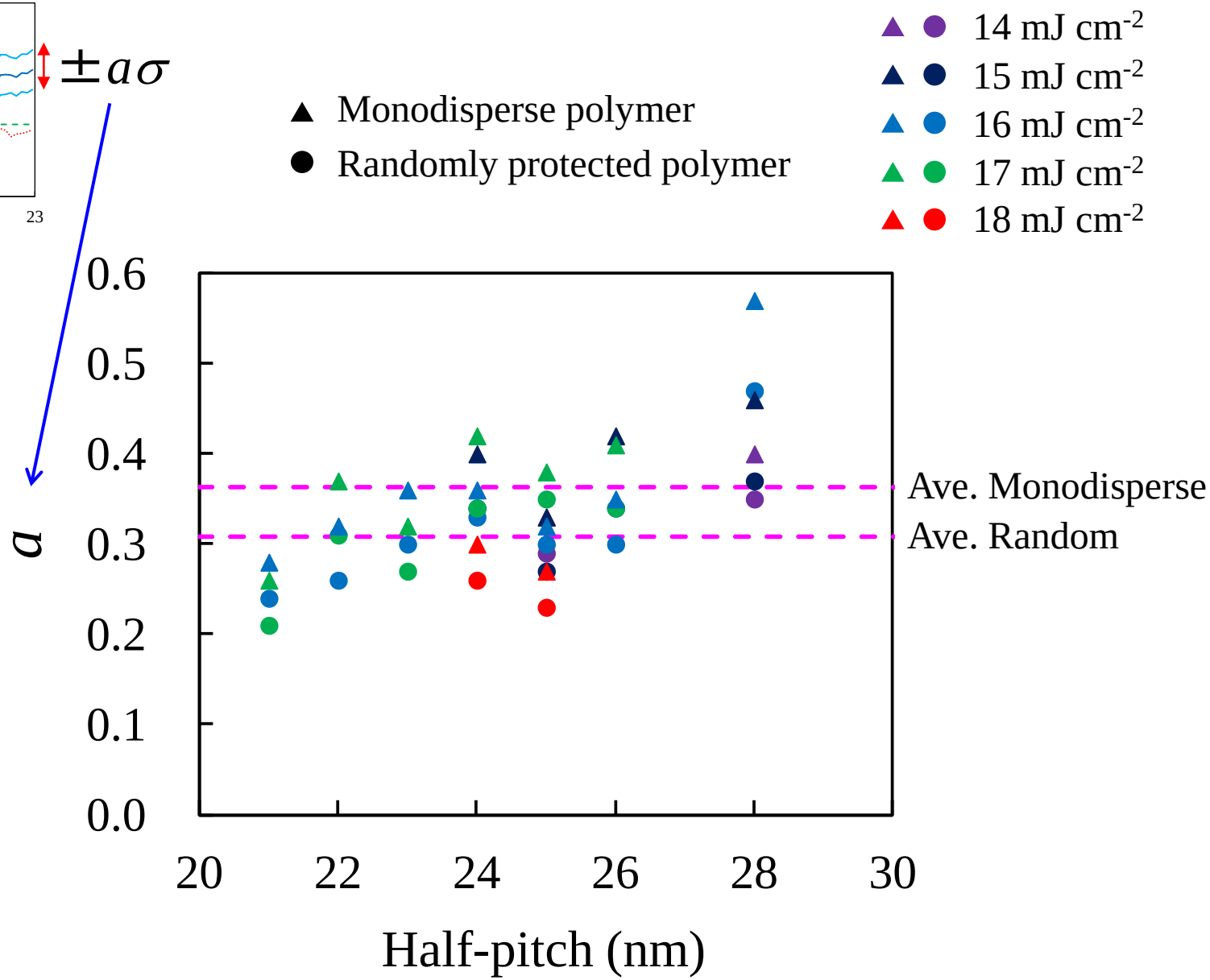


28 nm HP, 15 mJ cm^{-2}

m: normalized protected unit concentration

Relationship between protected unit fluctuation and LER





±0.31~ ±0.36σ fluctuation of protected units contributes to LER formation.

Summary

- Stochastic effect in line-and-space patterns fabricated with SFET was analyzed using a Monte Carlo simulation.
- The dependence of acid diffusion length on the initial position of acids was clarified.
- The relative standard deviation of acid distribution was smaller than that of absorbed photon distribution. The relative standard deviation of protected unit distribution was even smaller than that of acid distribution.
- $\pm 0.31 \sim \pm 0.36\sigma$ fluctuation of protected units was estimated to contribute to LER formation.

Acknowledgement

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