Latent Image Created using Selete Small-Field Exposure Tool for Extreme Ultraviolet Lithography

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LER formation mechanism

Initial acid distribution

Aerial image including reflection from substrate and flare
Acid concentration
- Exposure dose — **Process factor**
- Acid generation efficiency — **Material factor**

Shot noise
Specific to EUV, EB
- *Reaction of acid generator with low energy electron (~0eV)*

Catalytic chain reaction (acid diffusion and reaction)

Pre-baking and post-exposure bake conditions (temperature and period) — **Process factor**

Diffusion constant of acid and base quencher
- Glass transition temperature of polymer
- Size of acid counter anion and base quencher
- Residual solvent

Base quencher concentration
Activation energy for catalytic reaction

— **Material factor**

Development and rinse

Development time
Temperature of developer
Strength and molecular size of solvents
Rinse

— **Process factor**

Molecular weight
Molecular dispersion
Rigidity of polymer structure
Polymer aggregation
Crystallization

— **Material factor**

LER

Polymer resist

|| or ∧

Molecular glass resist

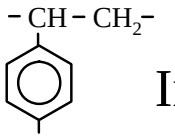
Main cause of LER in state-of-the-art resists

Chemical inhomogeneity at image boundary

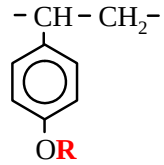
T. Kozawa, S. Tagawa, J. J. Santillan, M. Toriumi, T. Itani, J. Vac. Sci. Technol. B **25** (2007) 2295.

Chemical inhomogeneity at image boundary

Soluble ← Can be controlled

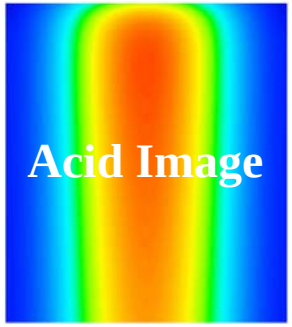


Insoluble

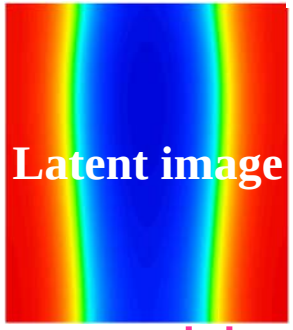


Aerial image

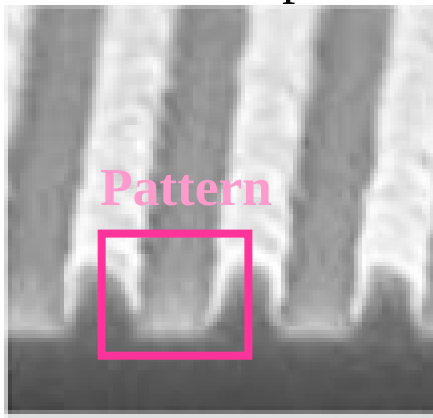
EUV



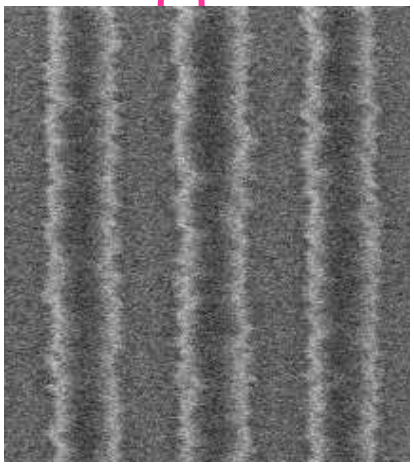
Cross section



After development

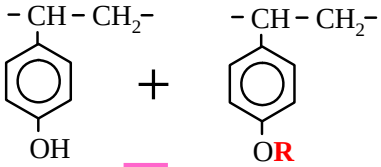


After development



Top-down view

Mixture of soluble and insoluble molecules



Absolutely stochastic
Can not be controlled

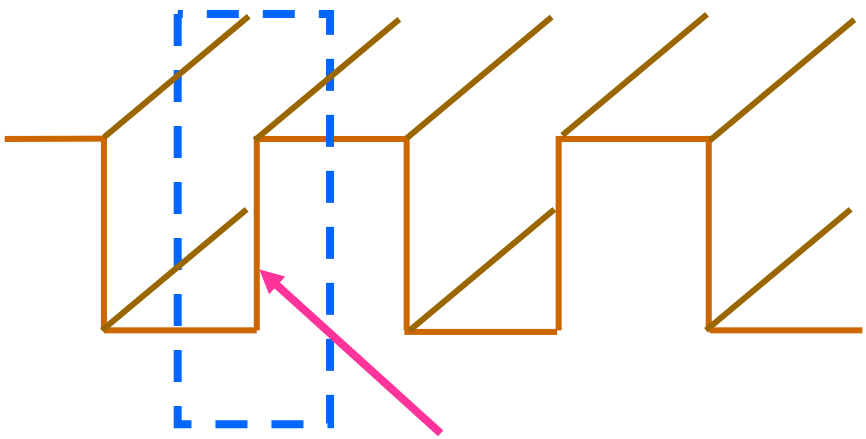
(Spatially) partially soluble

LER formation

LER ∝ width of intermediate region $\fallingdotseq \dfrac{1}{\text{Chemical gradient}}$ ← Good indicator for LER

Simulation

Pattern line & space



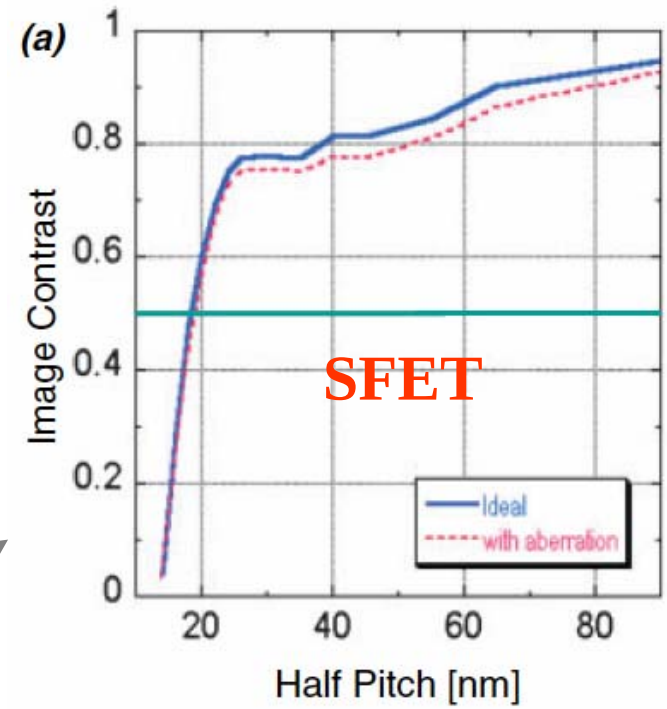
Latent image and chemical gradient

Effective reaction radius for deprotection, *R*

R of typical resist: 0.01~0.5 nm

R = 0.05, 0.1, 0.5 nm

Exposure tool



K. Tawarayama et al. Jpn. J. Appl. Phys. **47** (2008) 4866.

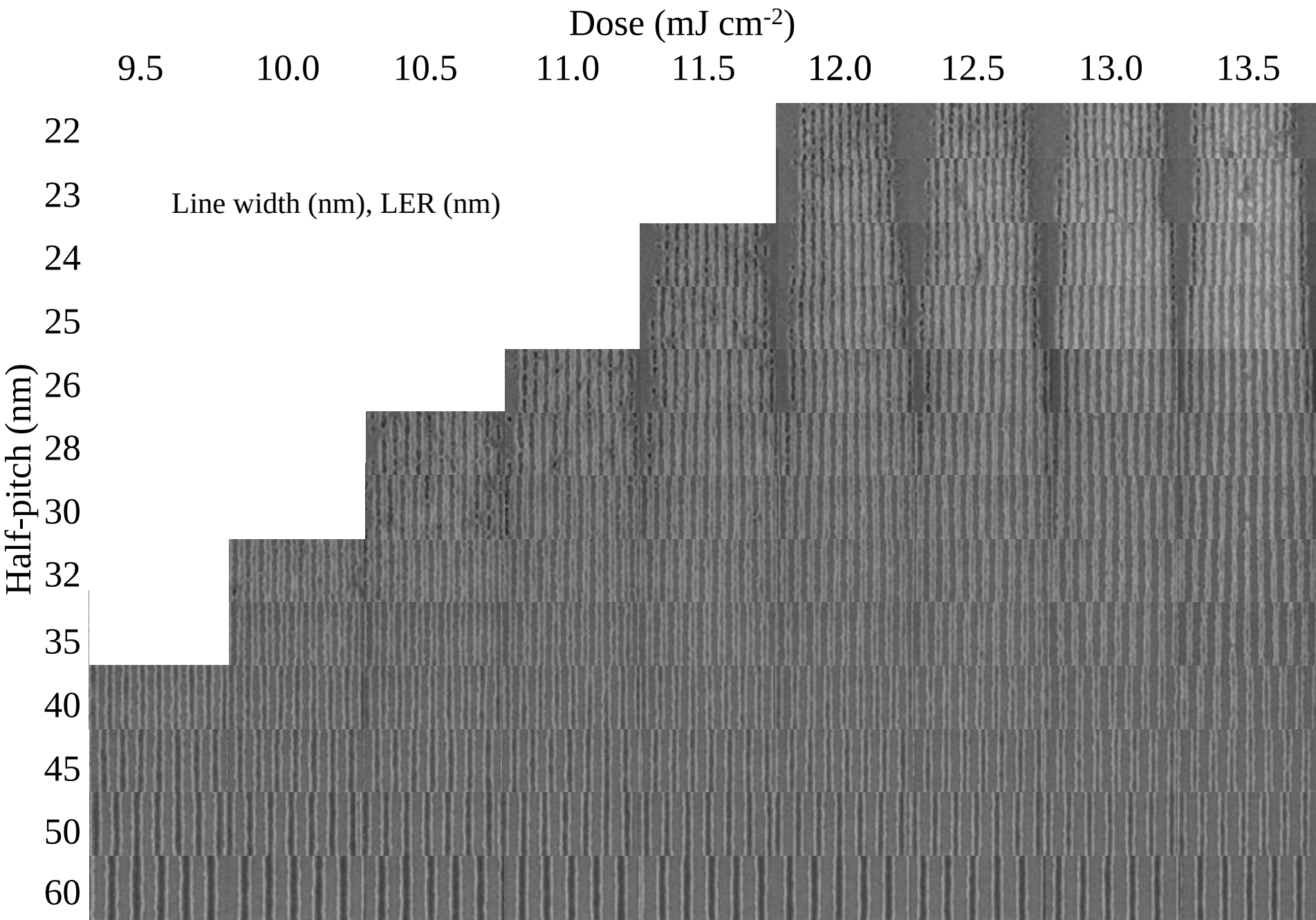
Aerial image of incident EUV

$$I(x,y,z) = A\left\{\frac{1}{2}\left[1 + C\cos\left(\frac{\pi x}{p_{1/2}}\right)\right] + F\right\}\exp(-\alpha|z|)$$

Contrast Flare (10%)

Analysis of SSR3

Resolution-dose matrix



Dissolution point of SSR3

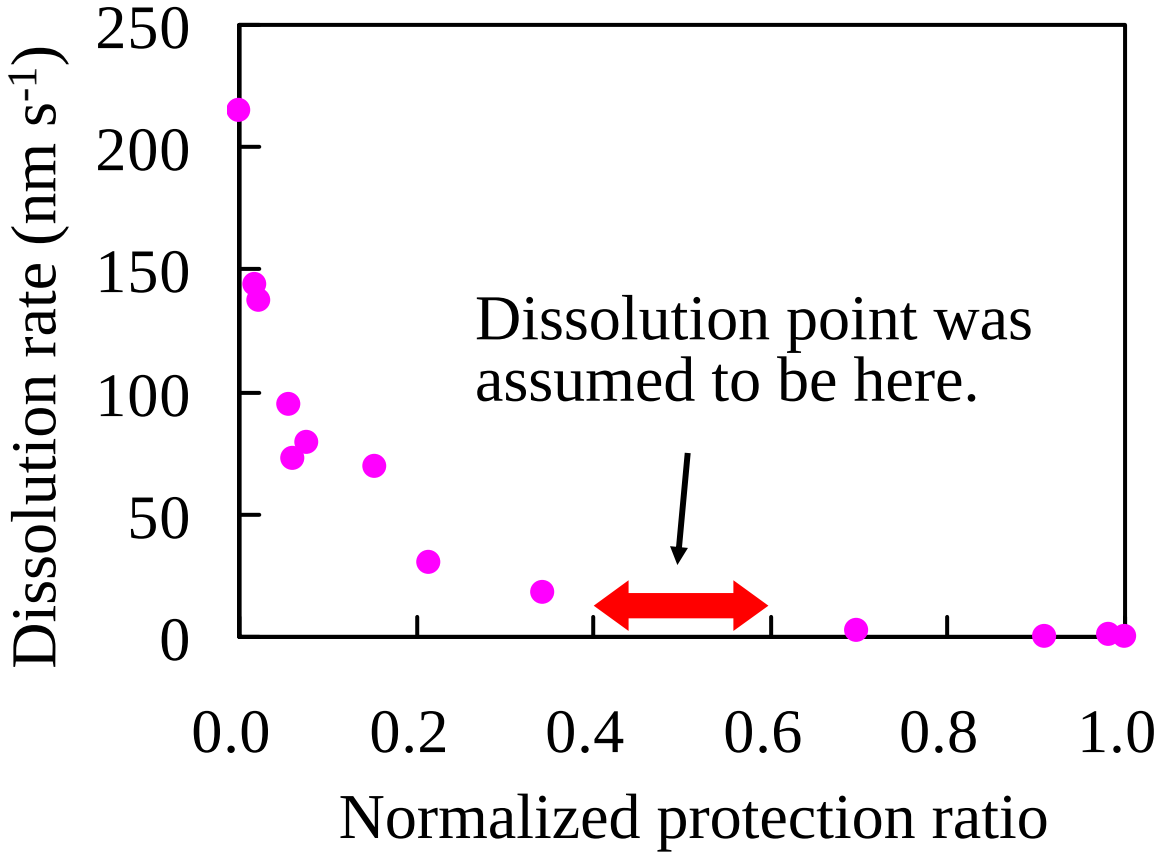
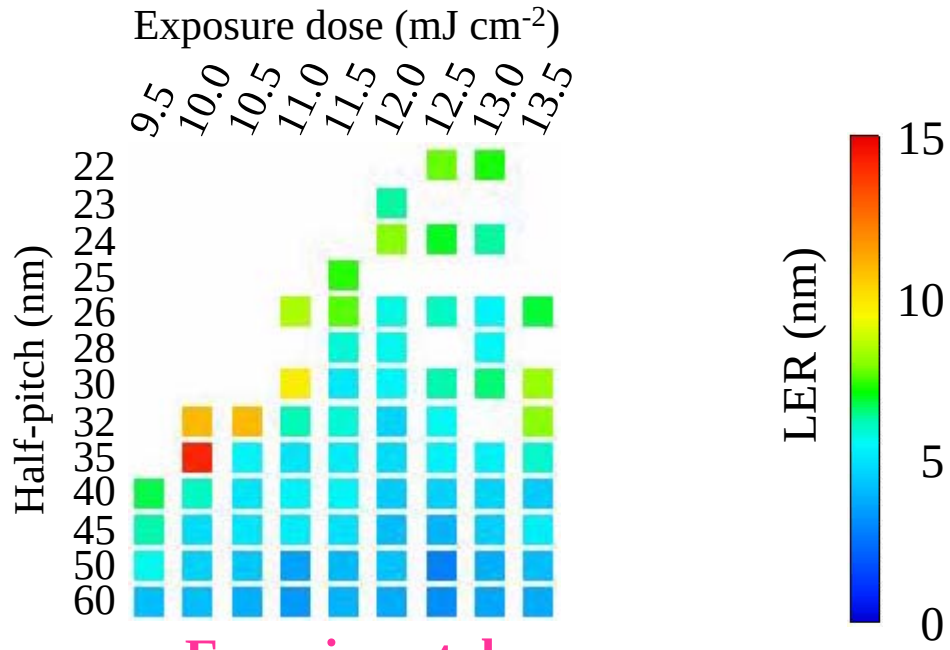


Fig. Relationship between normalized protection ratio and dissolution rate of SSR3. Protection ratio was normalized by initial protection ratio.

Analysis of SSR3

Line edge roughness



Experimental

Fitting parameter

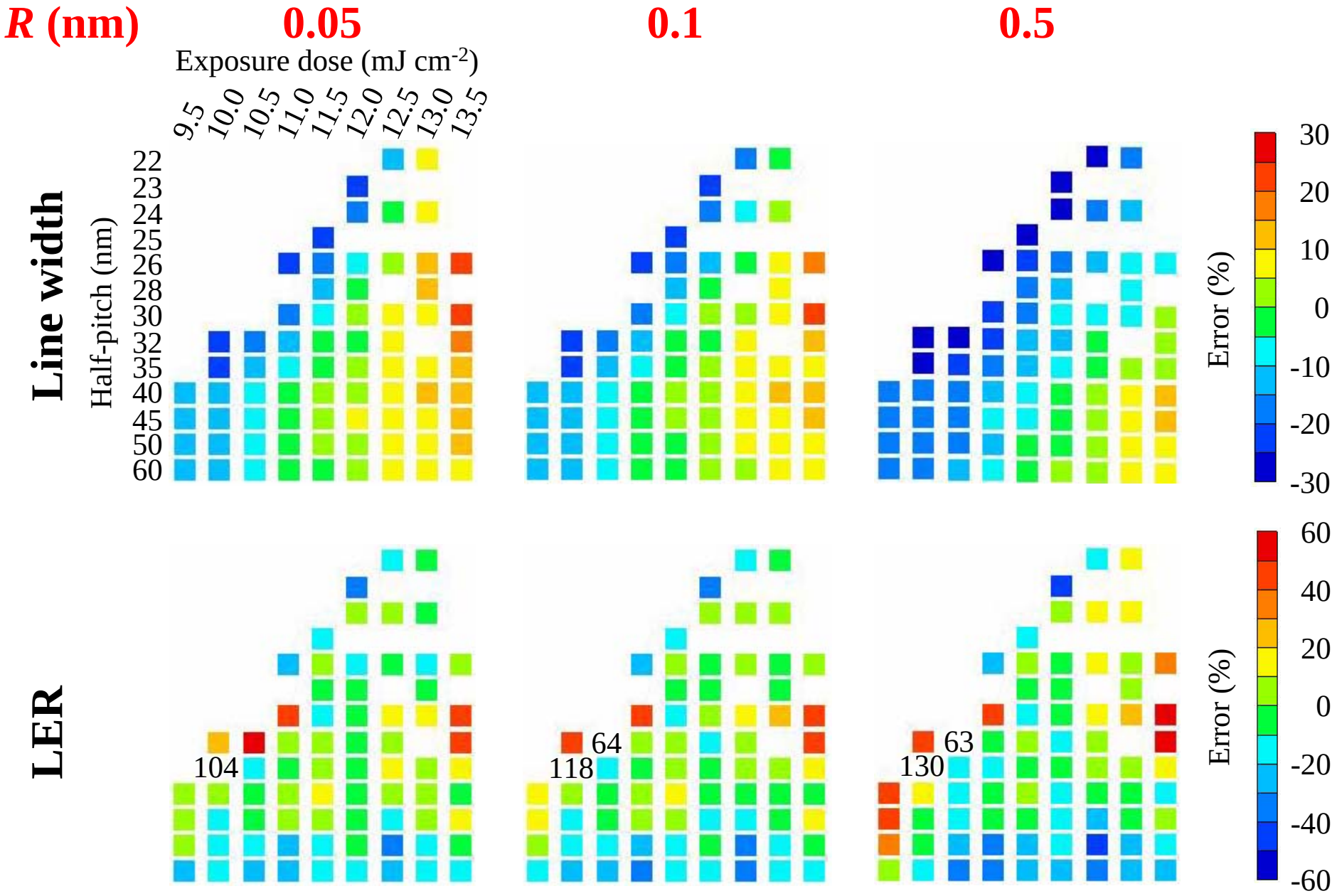
- Acid diffusion length
- Quencher concentration
- Dissolution point

R (nm) 0.05 0.1 0.5

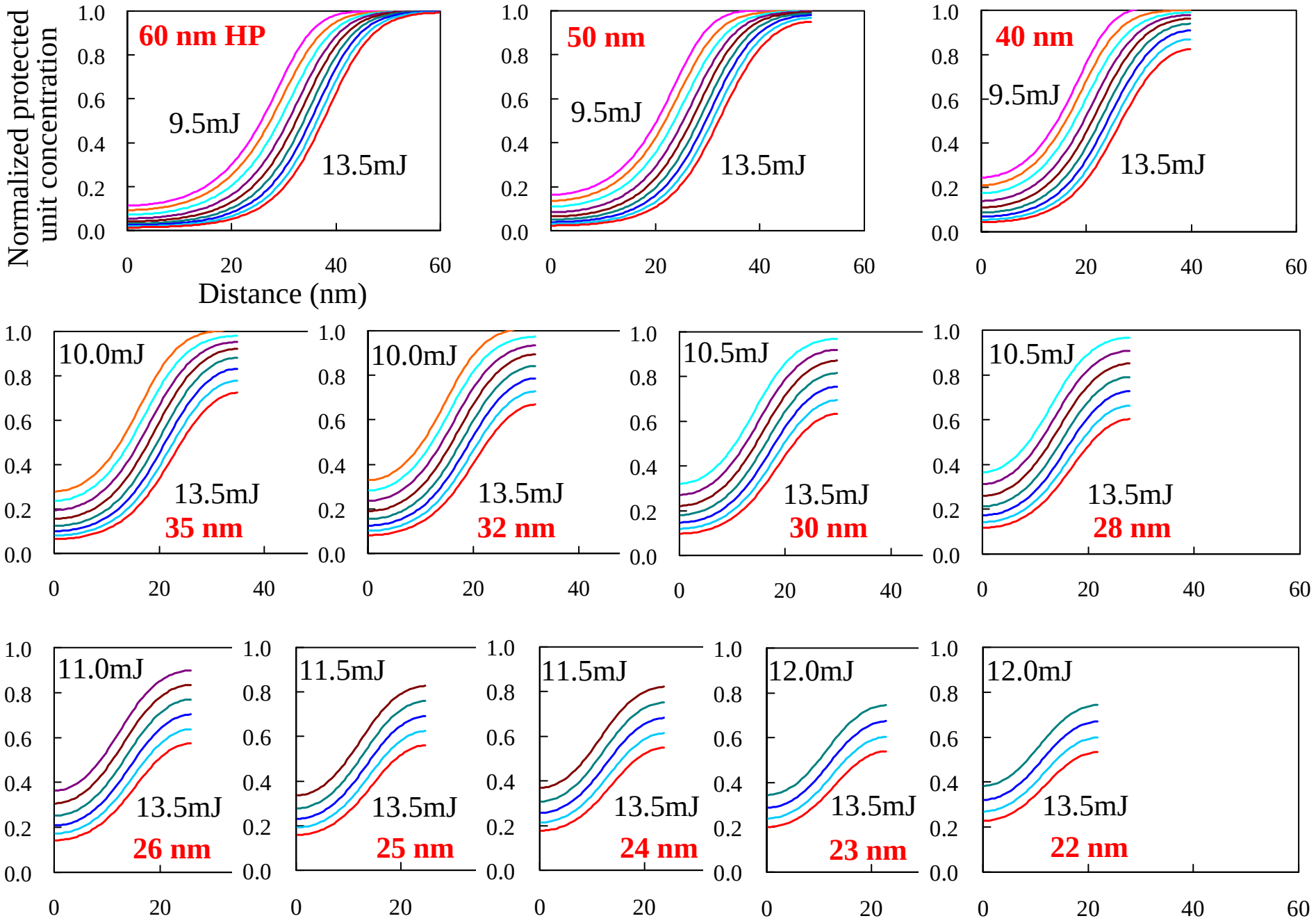
Effective reaction radius for deprotection

Simulation

Error distribution

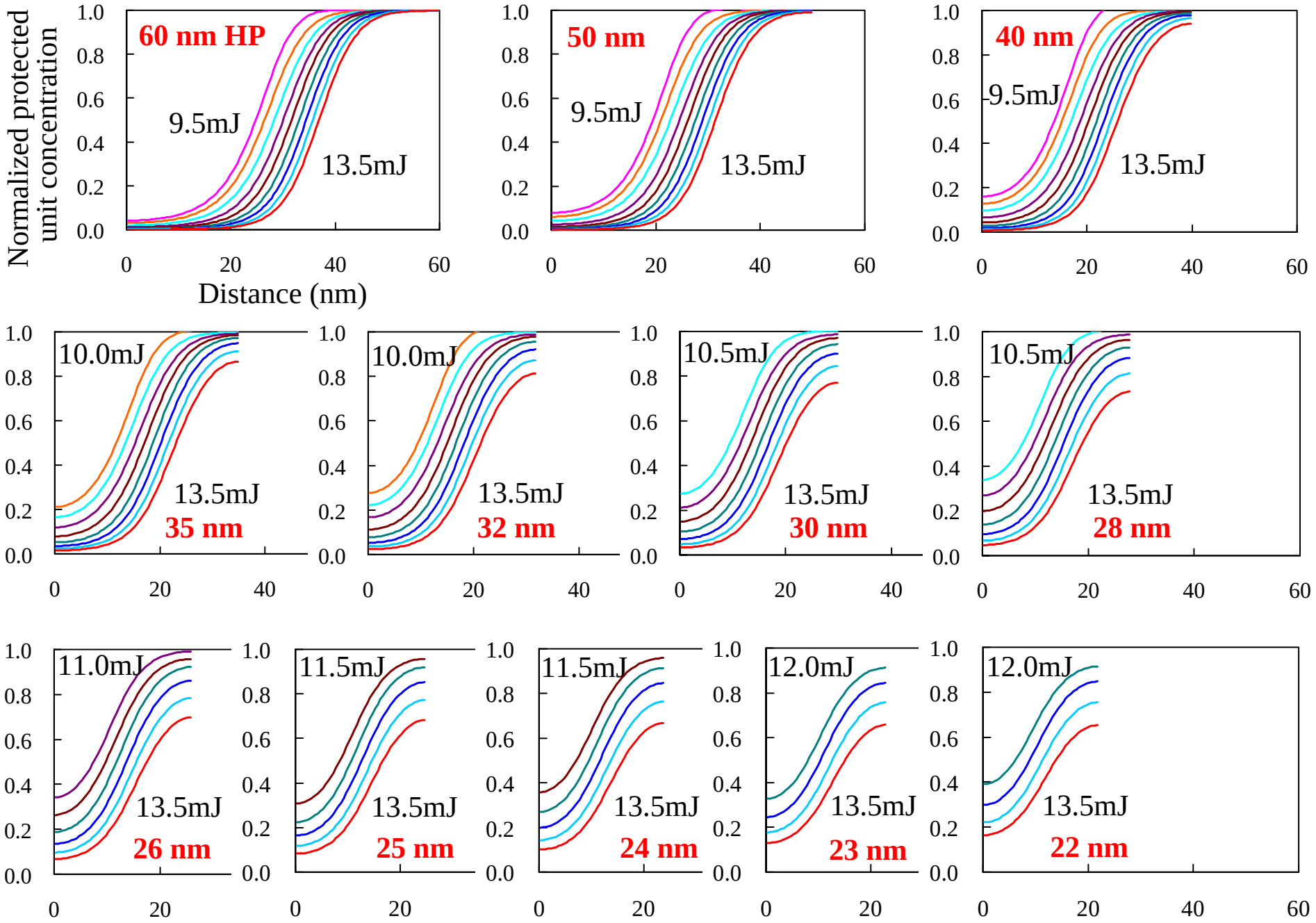


Latent image (*R*=0.05nm)



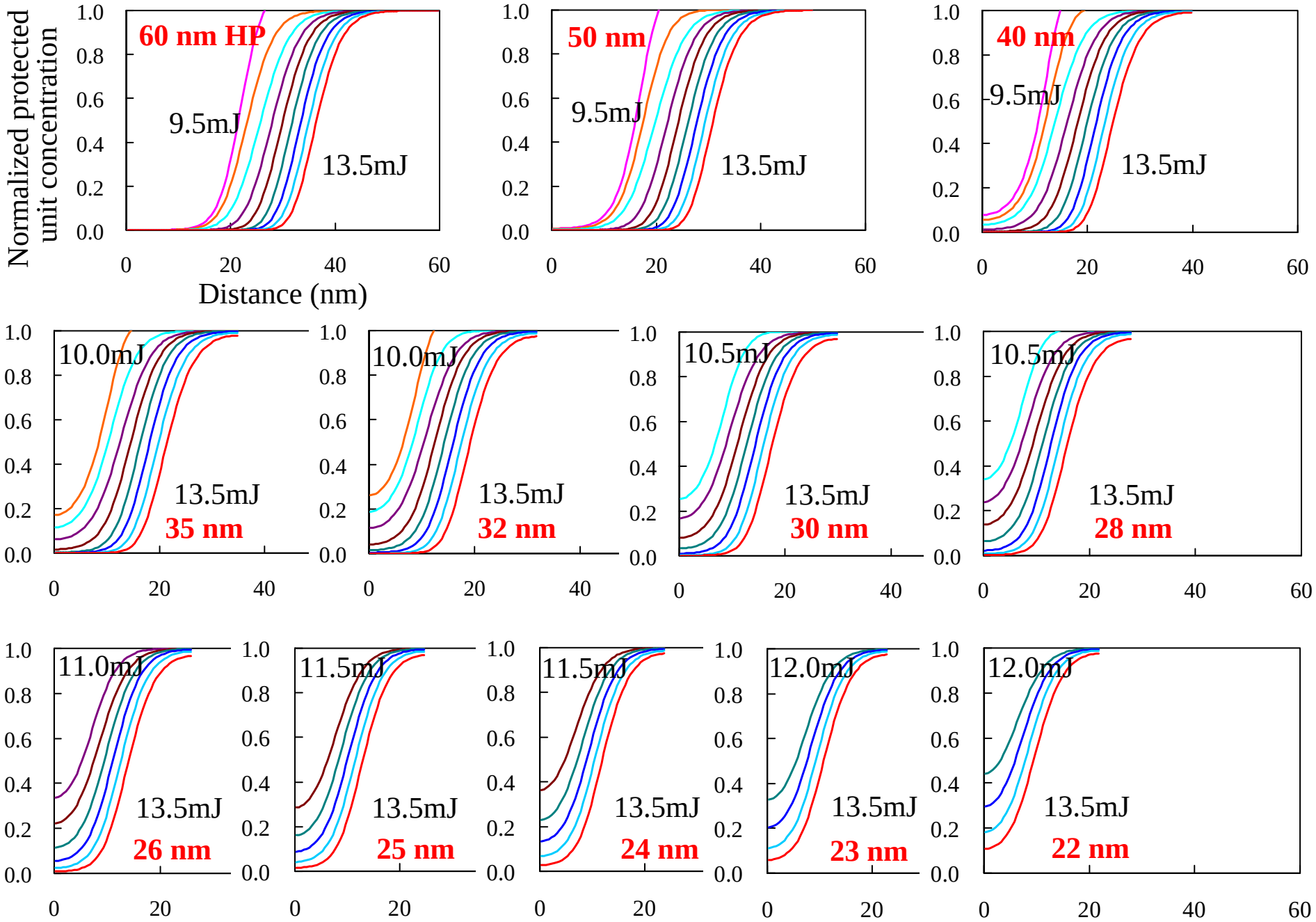
Analysis of SSR3

Latent image (*R*=0.1nm)



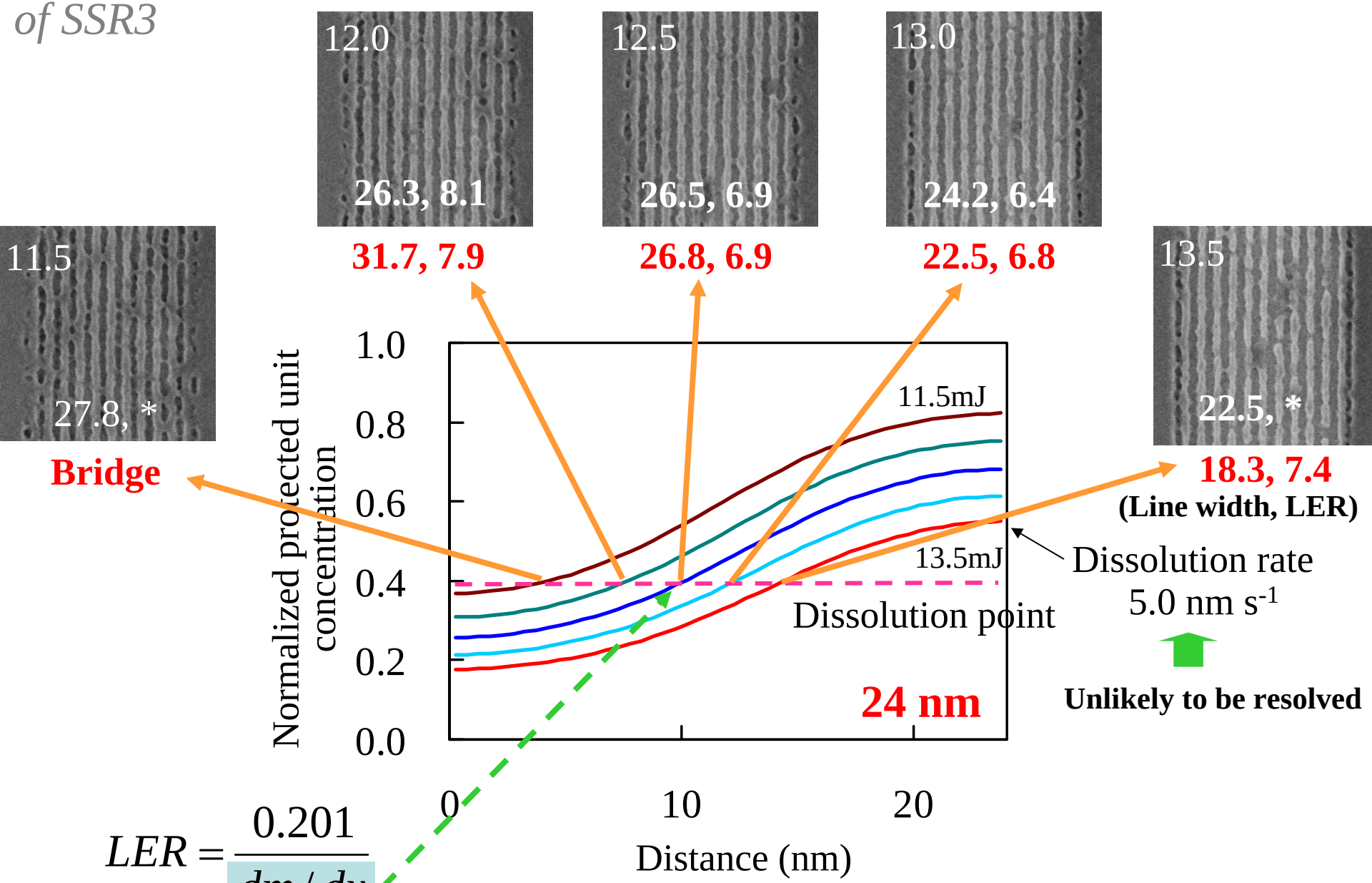
Analysis of SSR3

Latent image (*R*=0.5nm)



Analysis of SSR3

Comparison between latent and real images (*R*=0.05)



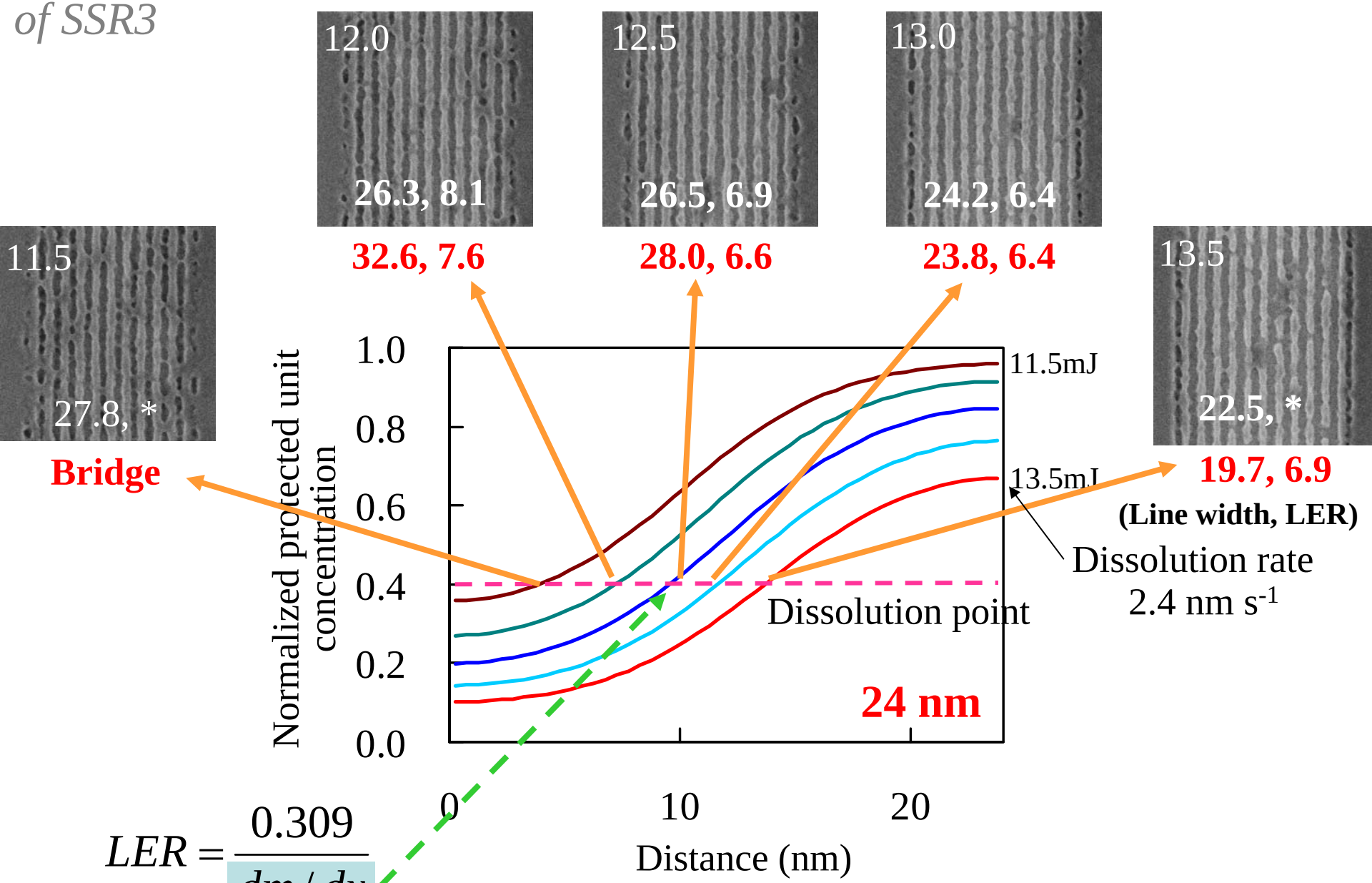
$$LER = \frac{0.201}{dm/dx}$$

Chemical gradient

Unlikely

Analysis of SSR3

Comparison between latent and real images (*R*=0.1)

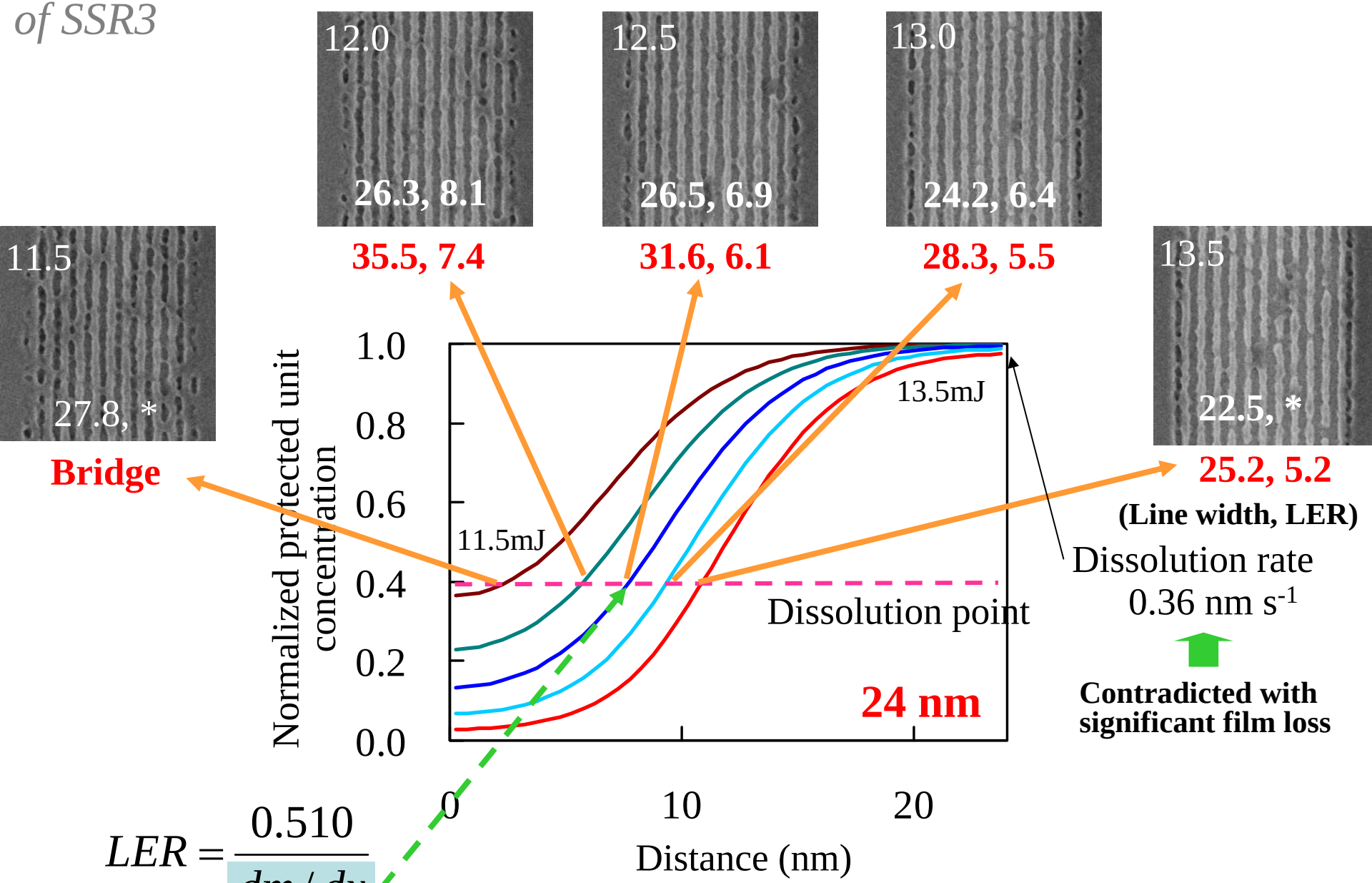


$$LER = \frac{0.309}{dm/dx}$$

Most likely

Analysis of SSR3

Comparison between latent and real images (*R*=0.5)

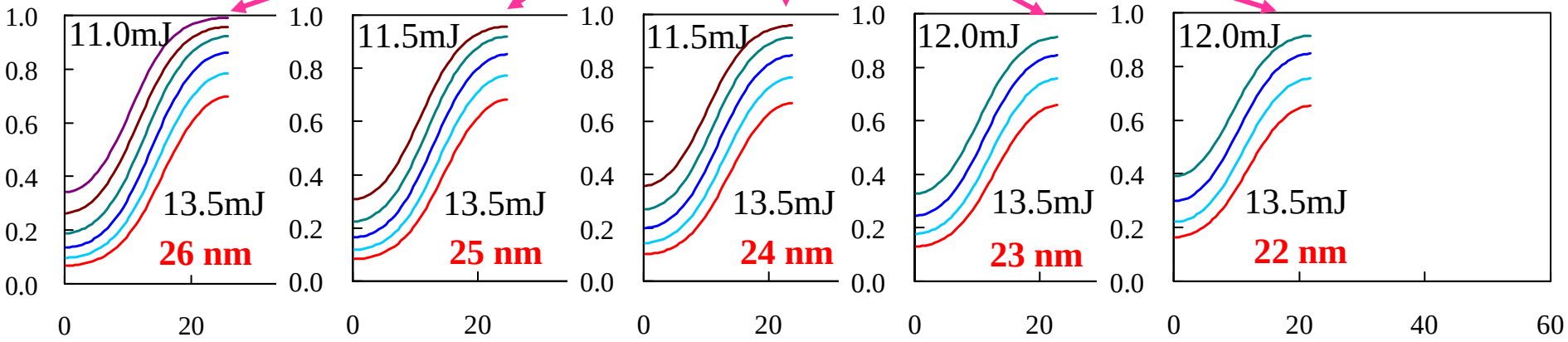


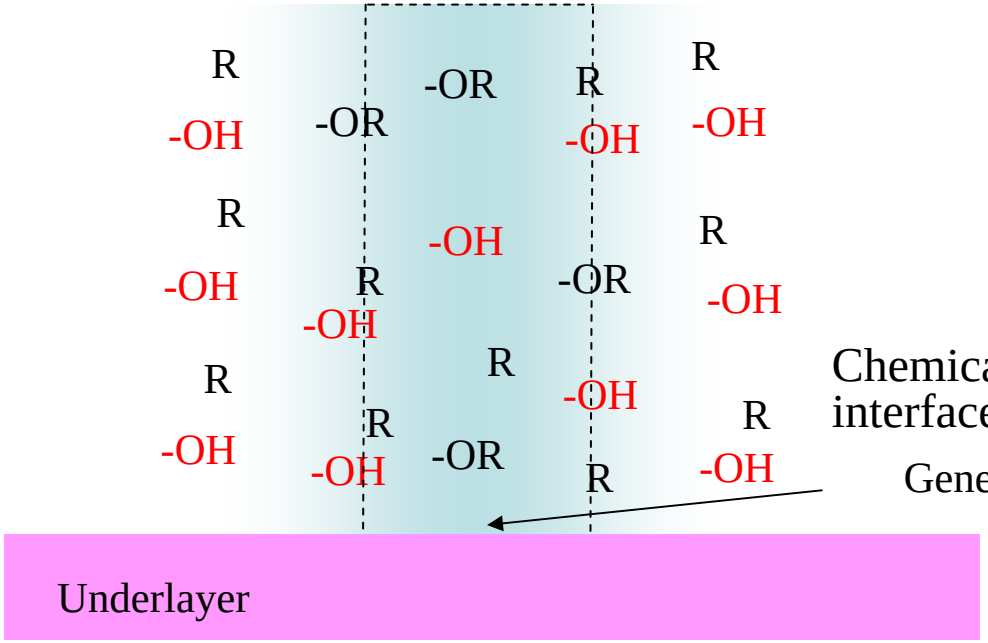
$$LER = \frac{0.510}{dm/dx}$$

Not good fit

Analysis of SSR3 Latent image below 26 nm half-pitch

Intermediate region reaches the center of resist pattern.





Chemical condition at the interface significantly changes.

Generation of byproduct and free volume

Dose dependence (26 nm L&S)

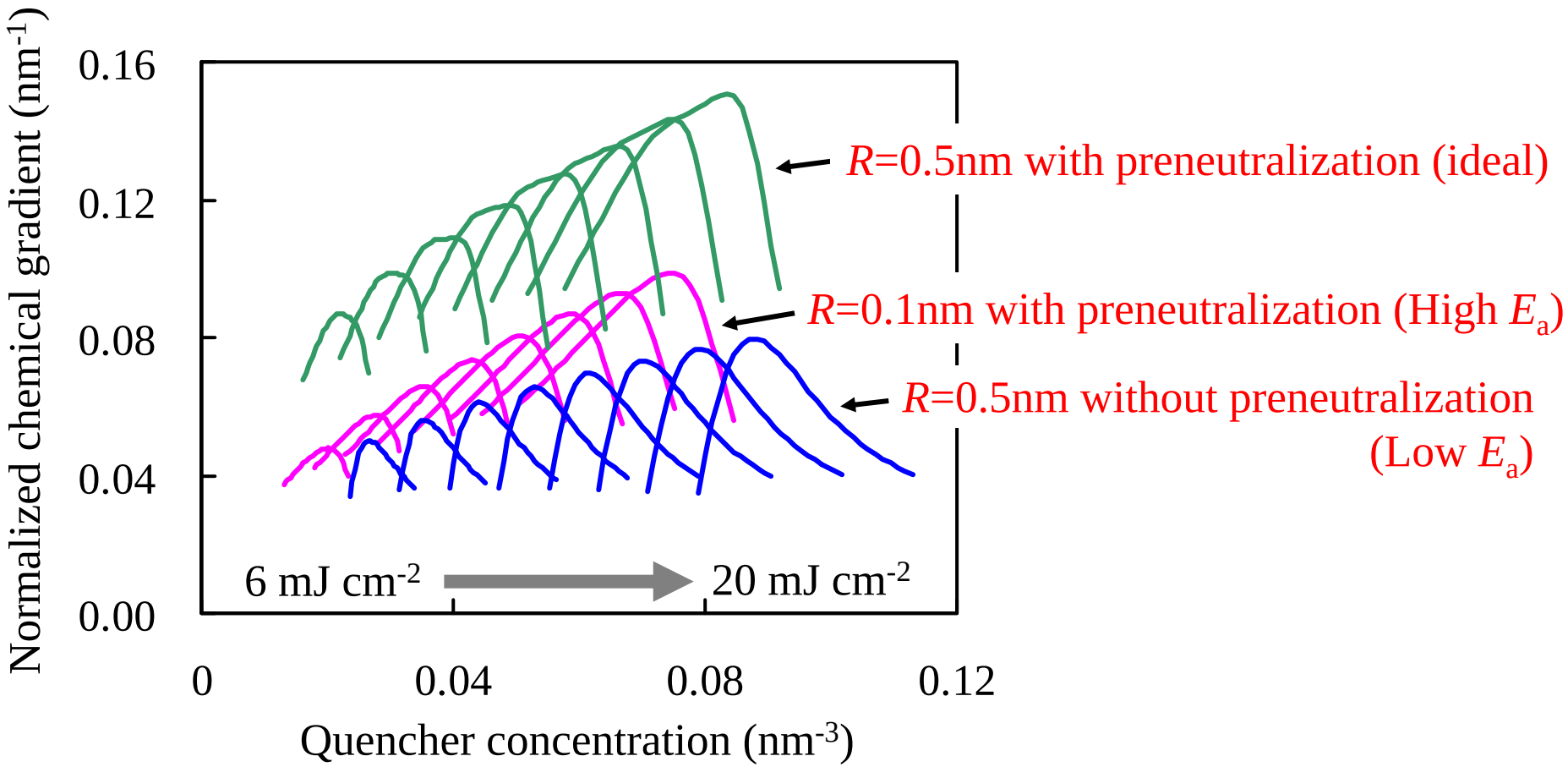


Fig. Exposure dose dependence of relationship between quencher concentration and maximum chemical gradient at the half-depth of the boundary between solubilized and insoluble regions. The half-pitch is 26 nm. The exposure dose was varied from 6 to 20 mJ cm^{-2} with a step of 2 mJ cm^{-2}. The chemical gradient was normalized by the initial concentration of protected units.

Half-pitch dependence (10 mJ cm^{-2})

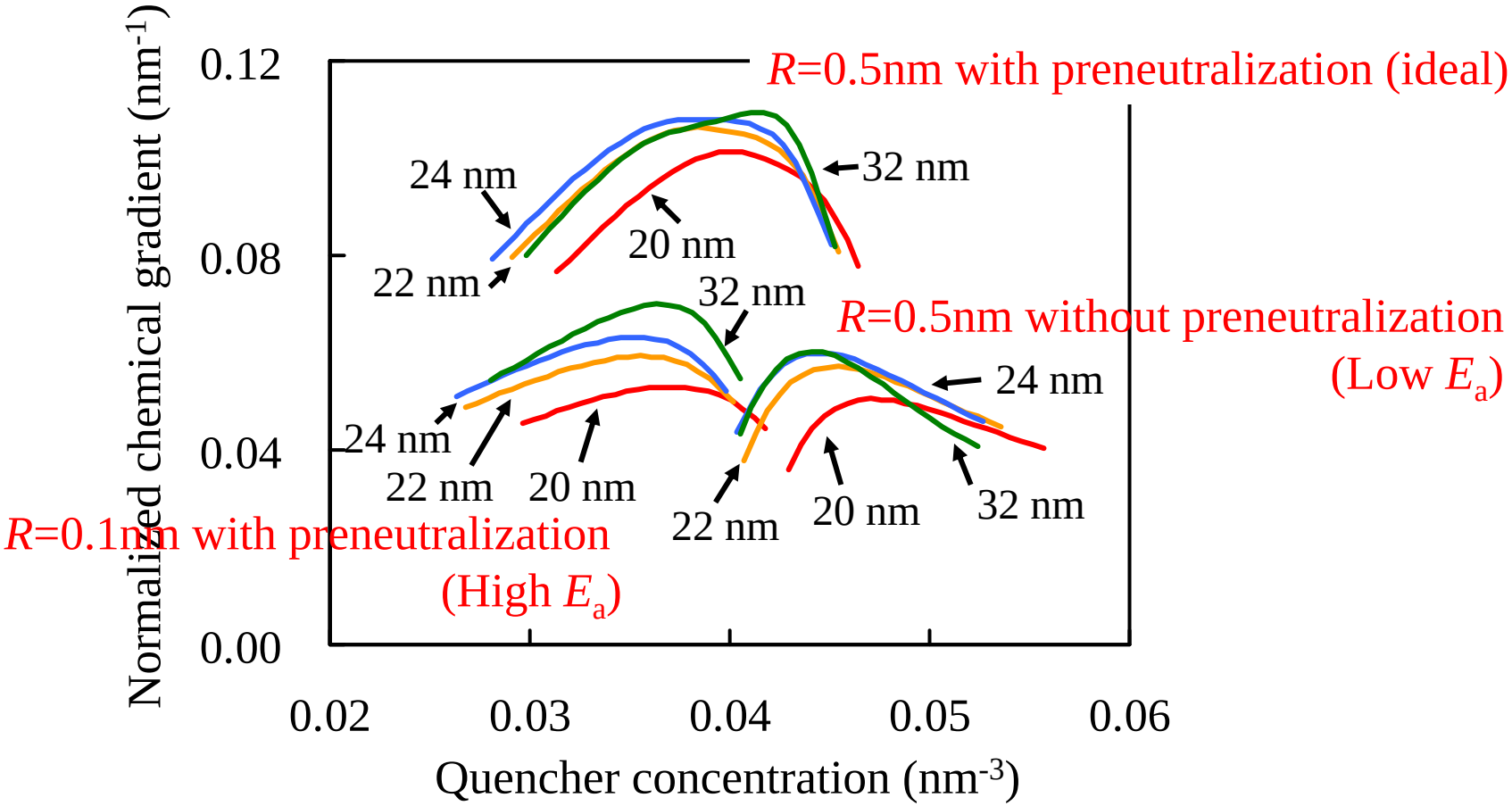
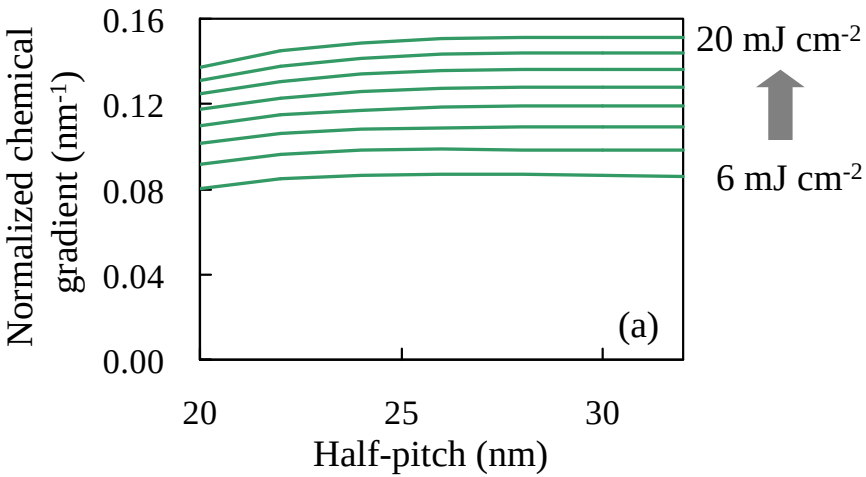
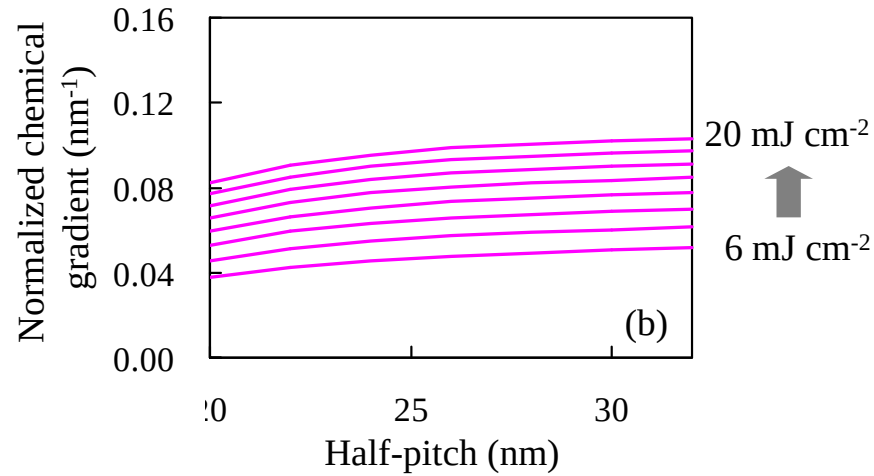


Fig. Half-pitch dependence of relationship between quencher concentration and maximum chemical gradient at the half-depth of the boundary between solubilized and insoluble regions. The exposure dose is 10 mJ cm^{-2}. The half-pitch was varied from 20 to 32 nm. The chemical gradient was normalized by the initial concentration of protected units.

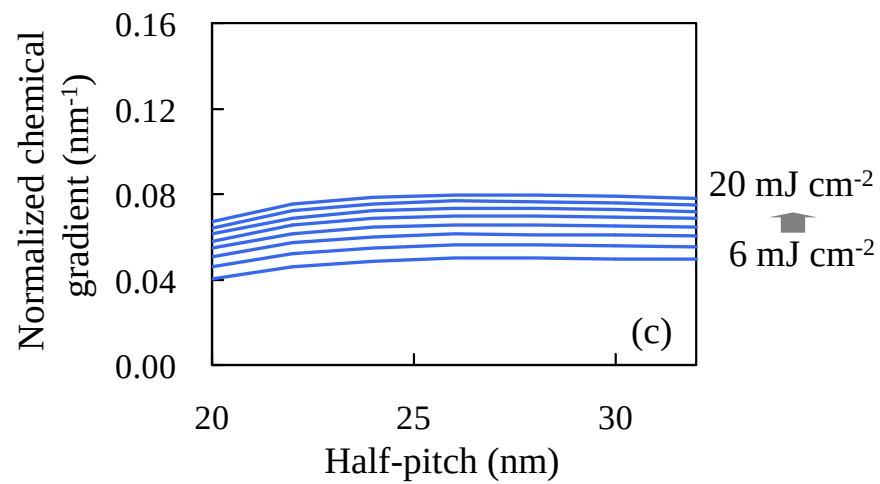
Trade-off relationship



R=0.5nm with preneutralization (ideal)



R=0.1nm with preneutralization (High E_a)



R=0.5nm without preneutralization (Low E_a)

Fig. Dependence of the highest chemical gradient on half-pitch in (a) ideal, (b) high-*E*a, and (c) low-*E*a resists. The exposure dose was varied from 6 to 20 mJ cm^{-2} with a step of 2 mJ cm^{-2}. The chemical gradient was normalized by the initial concentration of protected units.

Mechanism of pattern collapse

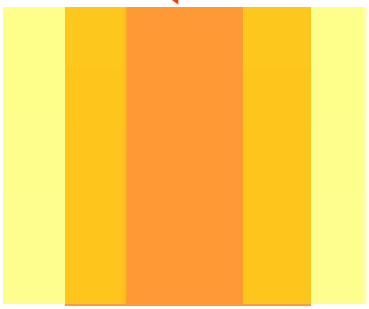
Stress

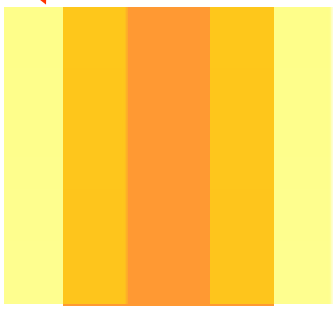
Solvent penetration, partial dissolution, swelling

A cause of long range LER

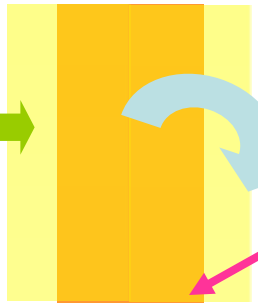
Rigid core

If the width of intermediate region is not reduced with the reduction of half-pitch,





Surface tension



Collapse

Reduction of adhesion force

45 nm

32 nm

26 nm

Intermediate region

the pattern is highly susceptible to pattern collapse.

For SFET annular illumination, pattern collapse is often observed below 26 nm half-pitch.

The limit of the chemical gradient for standing features at ~25 nm is 0.06 – 0.08 nm^{-1}.

Relationship between LER and chemical gradient

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

$$m = \frac{C_p}{C_{p0}}$$

Resist screening experiment using SFET

(T. Itani, Microelectronic Eng. **86** (2009) 207.)

Sensitivity: ~14 mJ cm^{-2}

LWR@32nmHP: 4-7 nm.

Simulation

d*m*/d*x*@32nmHP: 0.068~0.085 nm^{-1}

with 14 mJ cm^{-2} exposure dose

f_{LER} ~ 0.3-0.6 (0.309 for SSR3)

To achieve <1nm LER

d*m*/d*x* should be >0.3-0.6 nm^{-1} + molecular glass resist technology

Summary

We clarified the latent images created in SSR3 upon exposure to annular illumination of SFET. The relationship between chemical gradient and LER was clarified. Also, the relationship between pattern collapse and latent image was made clear. The increase of pattern formation efficiency is required to reduce LER without increasing exposure dose and to avoid pattern collapse. Many methods for the enhancement of chemical gradient has been investigated at each process stage. The integration of chemical gradient enhancement technologies becomes the key to the development of next-generation resist materials.