# Current status and prospect of extreme ultraviolet resists

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# Semiconductor lithography

| | | | | | 7 nm node | 5 nm node | | | | Å node |
|---|---|---|---|---|---|---|---|---|---|---|
| 年 | 2001 | 04 | 07 | 16 | 19 | 22 | 24 | 26 | 28 | 30 |
| Resolution (nm) | 130 | 90 | 65 | 22 | 20 | 15 | 14 | 12 | 10 | **8** |
| Roughness (nm) | | | | 1.8 | 1.5 | 1.3 | 1.2 | ? | ? | ? |
| Source (wavelength) | KrF 248nm | ArF 193nm | | ArF immersion (+DP) 193nm | EUV 13.5nm | | **EUV (High NA) 13.5nm** | | | **Single Nano** |
| | EB for mask production | | | | | | | | | |

## Most severe problem for realization of EUV lithography

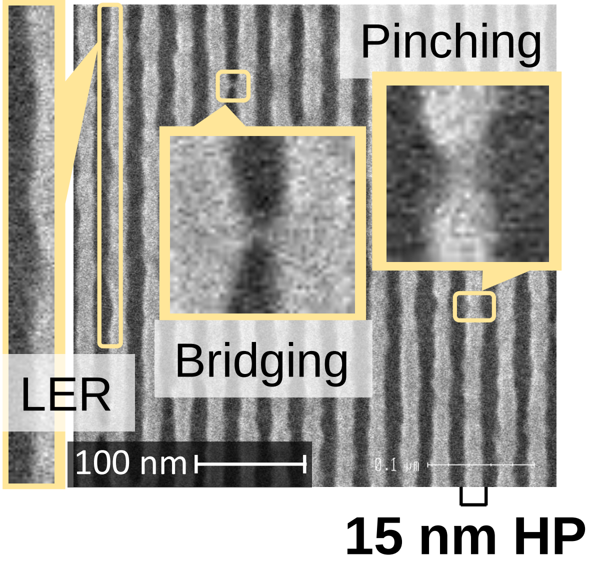
Resolution
(Device performance = Value)

Sensitivity
(Throughput)

Roughness
(Yield)

**Trade-off relationships between resolution, LER/LWR, and sensitivity**

## Most severe problem for realization of high NA EUV lithography



**Stochastic defects**

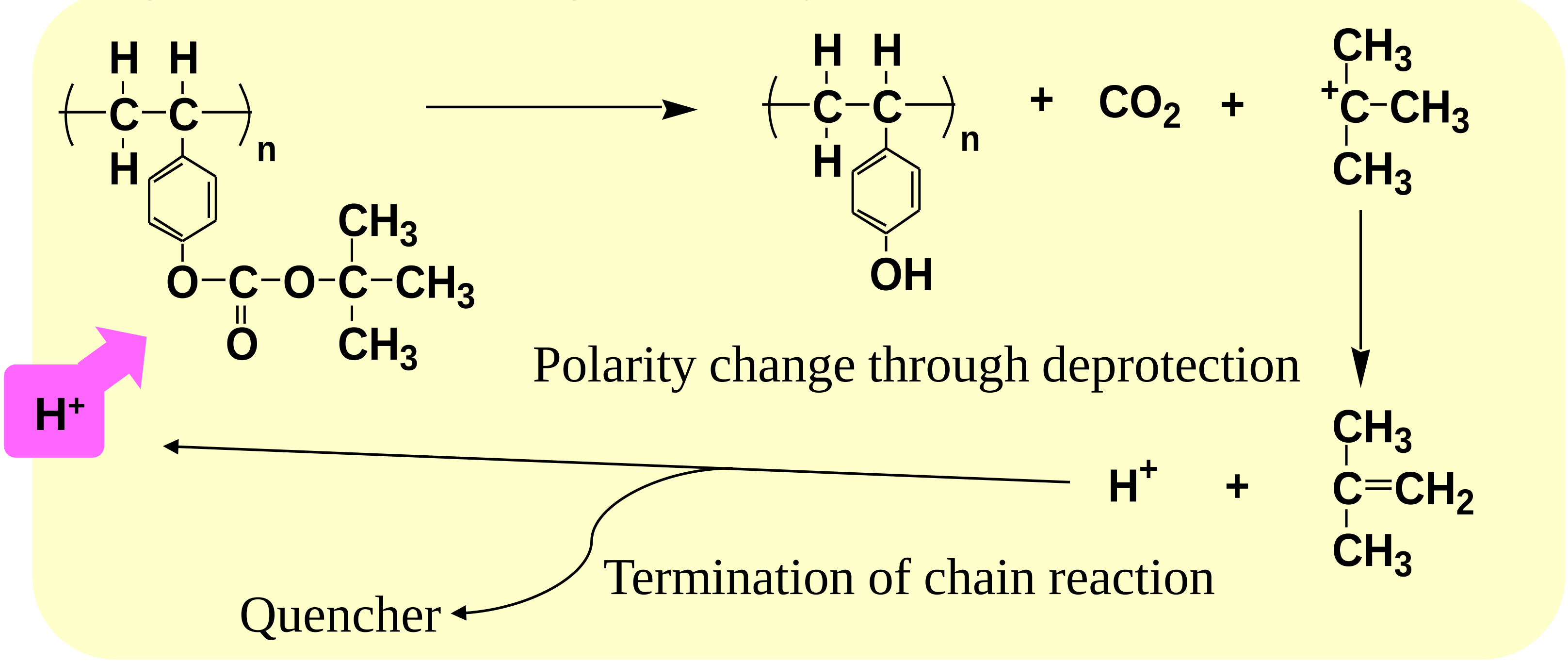
# Concept of chemically amplified resist

Typical components: Partially protected polymer, Acid generator, Quencher

Acid generation through the decomposition of acid generators by exposure

$$Ph_3S^+X^- \xrightarrow{h\nu\text{、radiation}} H^+X^-$$

Image formation utilizing acid-catalytic chain reaction



Polarity change through deprotection

Termination of chain reaction

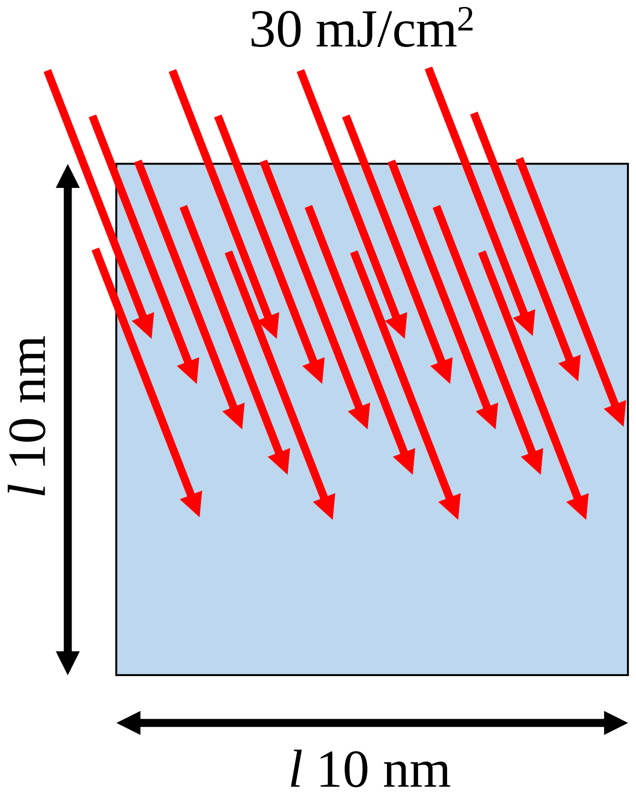
Quencher

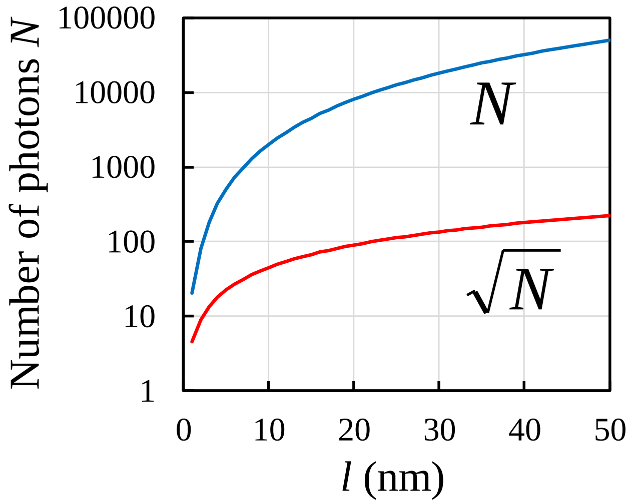
High sensitivity is obtained through acid-catalytic chain reaction.

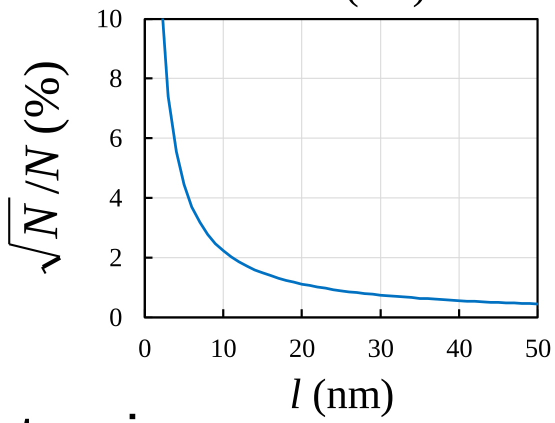
High resolution is obtained through the control of acid diffusion using quenchers.

# Shot noise (EUV lithography)

**Photons carry information for imaging.**







2024 photons

±45 fluctuation (2.2%) ← Shot noise

The number of photons seems adequate???

↓

**However, the information is lost during the imaging process...**

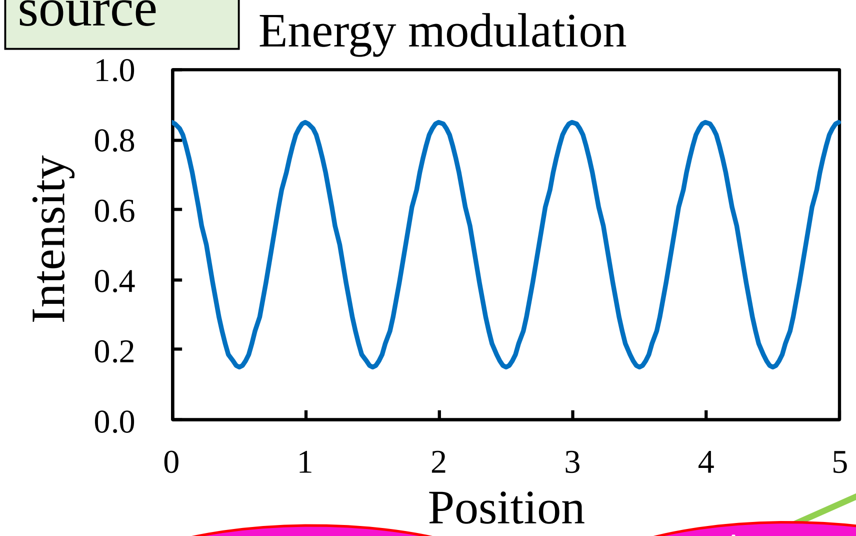
# Imaging process

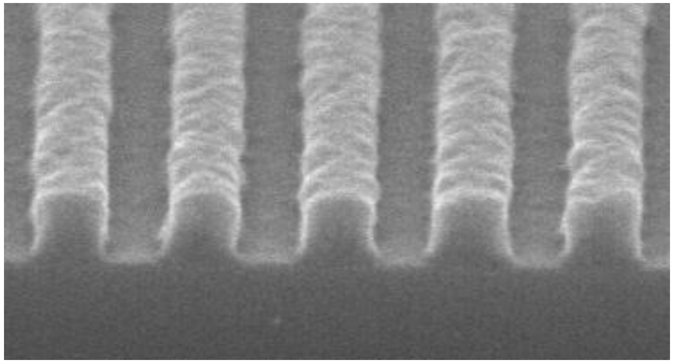
Role of photons: Transfer of information and energy for imaging

Role of resist materials: Conversion of energy modulation to binary image

**Exposure source**

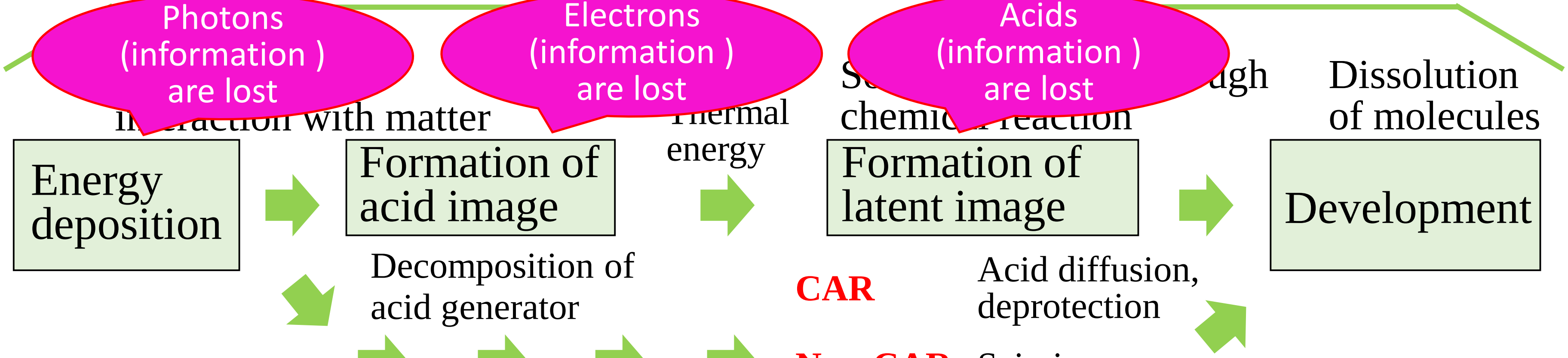
**Resist image**





SEM image of resist

**Conversion process**



Interaction with matter

Energy deposition

Formation of acid image

Thermal energy

Se ugh chemic reaction

Formation of latent image

Dissolution of molecules

Development

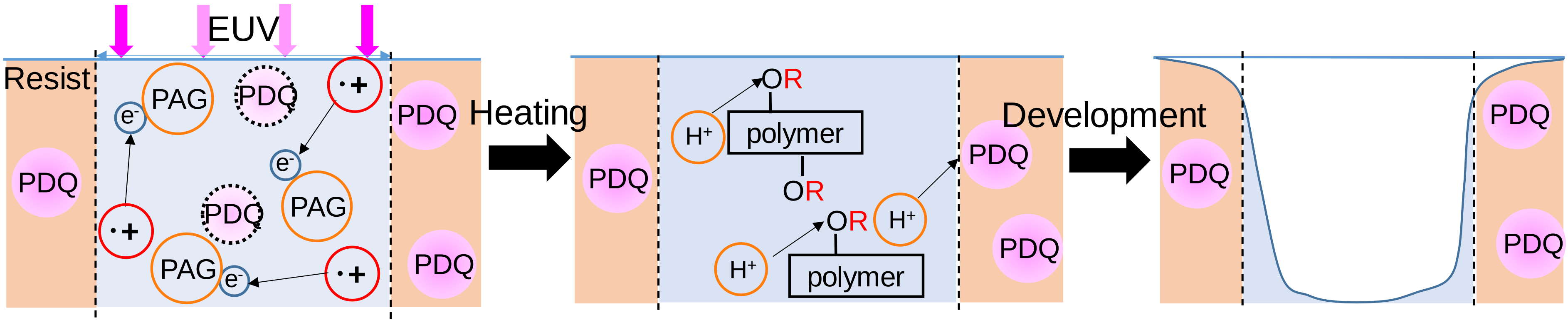
Decomposition of acid generator

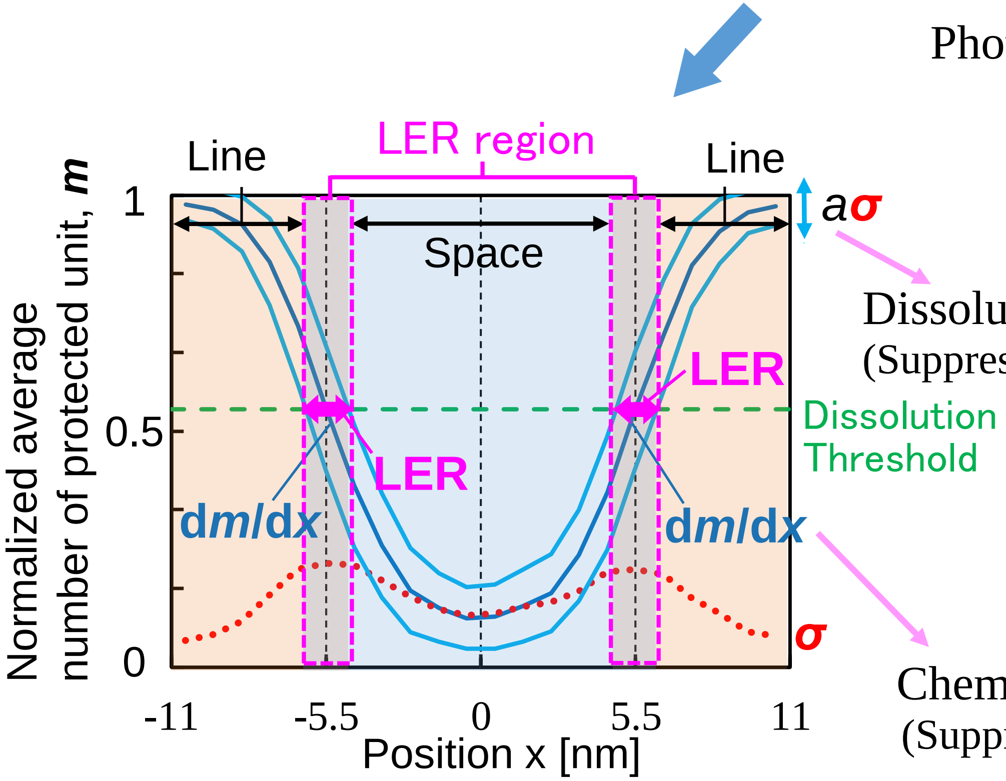
| | |
|---|---|
| **CAR** | Acid diffusion, deprotection |
| **Non-CAR** | Scission |
| **Metal** | Ligand decomposition |

**Understanding the total flow of information and energy is essential to the development of resist materials and processes.**

***Smoothing can be used for the suppression of stochasticity by sacrificing the resolution.**

# Mechanism of LER generation





Photon stochastics

Electron stochastics with diffusion

Acid stochastics with diffusion

Protected unit stochastics

Material stochastics

Dissolution factor (Suppression factor)

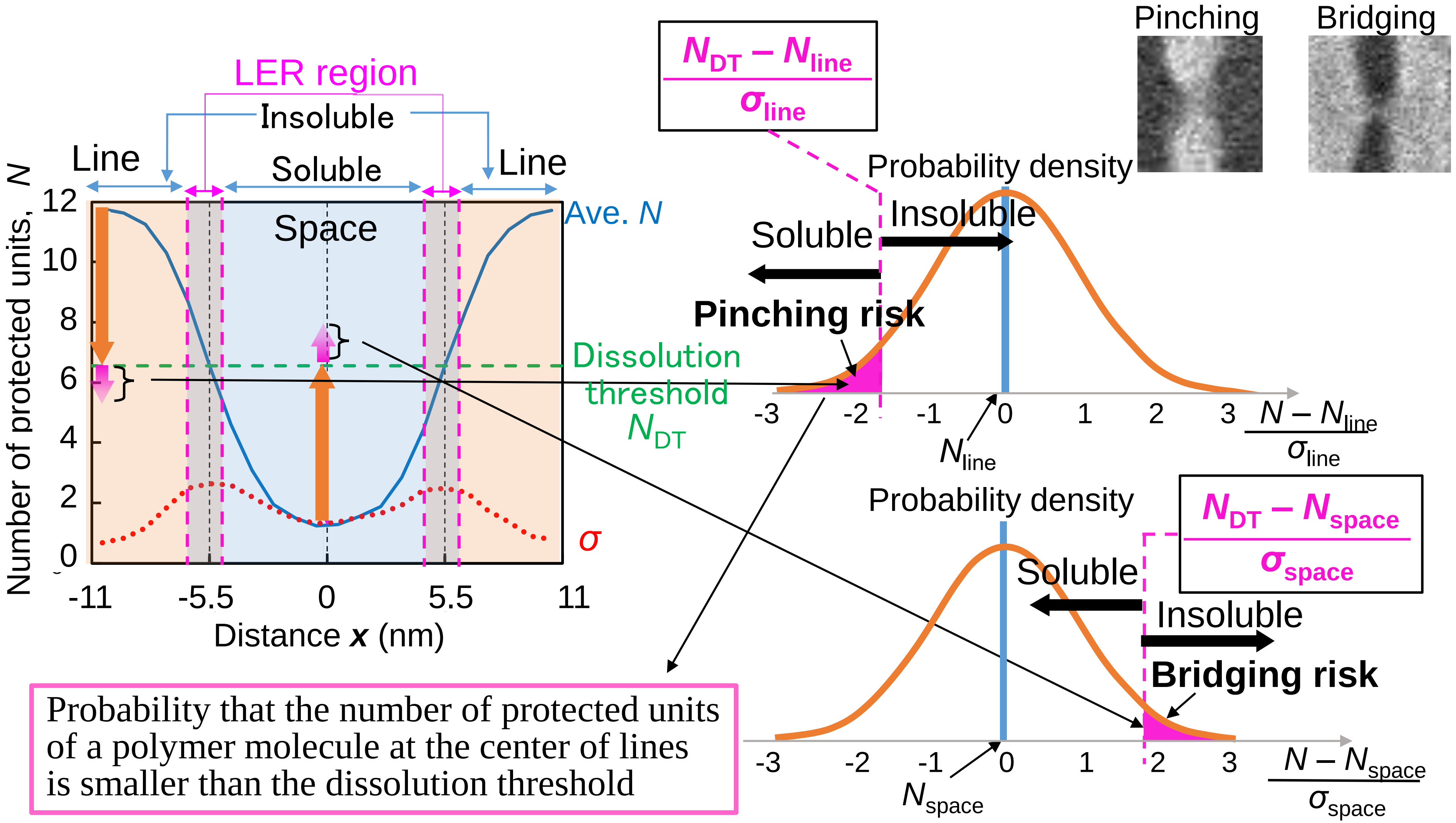
Chemical gradient (Suppression factor)

$$\mathrm{LER} \approx \frac{a\sigma}{|dm/dx|}$$

***σ*** : Standard deviation of the number of protected unit per polymer molecule

T. Kozawa et al., *Appl. Phys. Express* **6**, 026502 (2013).

# Mechanism of pinching and bridging generation

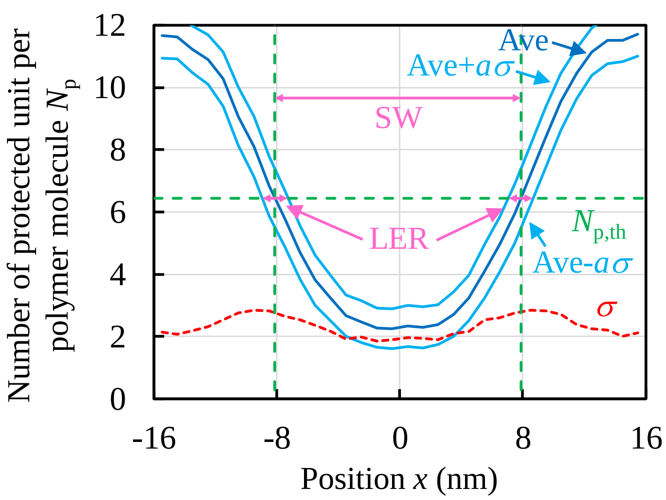


Probability that the number of protected units of a polymer molecule at the center of lines is smaller than the dissolution threshold

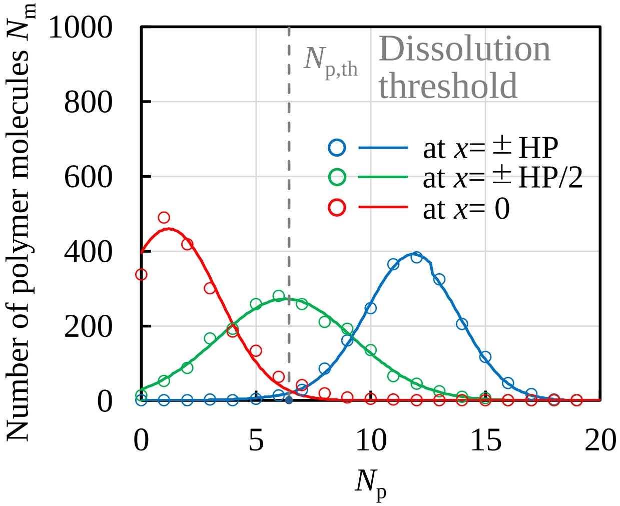
Fig. Defect generation model using the standard deviation ($\sigma$) of the number of protected units connected to a polymer molecule.

**The suppression of both pinching and bridging are required for the fabrication of line-and-space patterns applicable to the device manufacturing.**

# Protected unit distribution



Latent image



Number of polymer molecules with $N_p$

○ Simulation

— Fitting

$N_0$ : 2000

$s$ : 42 mJ cm$^{-2}$

$C_s$ : 0.2 nm$^{-3}$

$r_0$ : 4 nm

$\sigma_i$ : 2

## Protected unit distribution at centers of lines ($x$=±HP)

Fitting equations

$N_p \leq L_+$ (12.5)

$$N_m(x = \pm HP) = \frac{N_0 p_r}{\sqrt{2\pi}\sigma_{\mathrm{line,r}}} \exp\left(-\frac{\left(N_p - N_{\mathrm{line,r}}\right)^2}{2\sigma_{line,r}{}^2}\right) + \frac{N_0 p_u}{\sqrt{2\pi}\sigma_{\mathrm{line,u}}} \exp\left(-\frac{\left(N_p - N_{\mathrm{line,u}}\right)^2}{2\sigma_{\mathrm{line,u}}^2}\right)$$

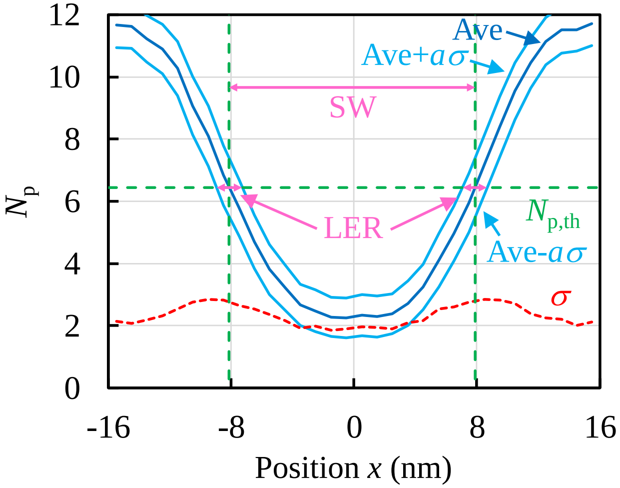
$N_p > L_+$

$$N_m(x = \pm HP) = \frac{N_0 p_u}{\sqrt{2\pi}\sigma_{\mathrm{line,u}}} \exp\left(-\frac{\left(N_p - N_{\mathrm{line,u}}\right)^2}{2\sigma_{\mathrm{line,u}}^2}\right)$$

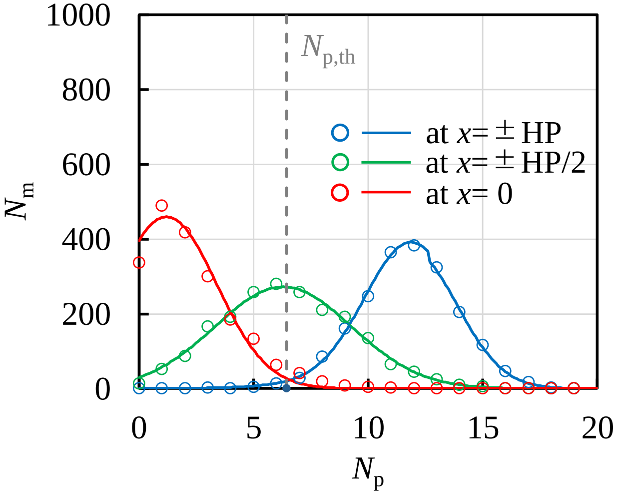
Normalization constants ($p_r$, $p_u$)

$$\frac{p_r}{\sqrt{2\pi}\sigma_{\mathrm{line,r}}} \int_{-\infty}^{L_+} \exp\left(-\frac{\left(N_p - N_{\mathrm{line,r}}\right)^2}{2\sigma^2}\right) dN_p + \frac{p_u}{\sqrt{2\pi}\sigma_{\mathrm{line,u}}} \int_{-\infty}^{\infty} \exp\left(-\frac{\left(N_p - N_{\mathrm{line,u}}\right)^2}{2\sigma_{\mathrm{line,u}}^2}\right) dN_p = 1$$

# Protected unit distribution



Latent image



Number of polymer molecules with $N_p$

○ Simulation

— Fitting

$N_0$ : 2000

$s$ : 42 mJ cm$^{-2}$

$C_s$ : 0.2 nm$^{-3}$

$r_0$ : 4 nm

$\sigma_i$ : 2

## Protected unit distribution at centers of spaces ($x$=0)

Fitting equations

$N_p \neq 0$

$$N_m(x=0) = \frac{N_{p\neq 0}}{\sqrt{2\pi}\sigma_{space}} \exp\left(-\frac{\left(N_p - N_{space}\right)^2}{2\sigma_{space}^2}\right)$$

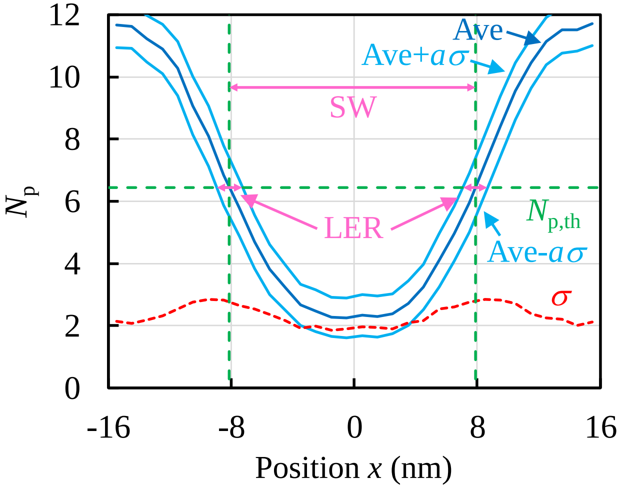
$N_p = 0$

$$N_m(x=0) = N_{p0}$$

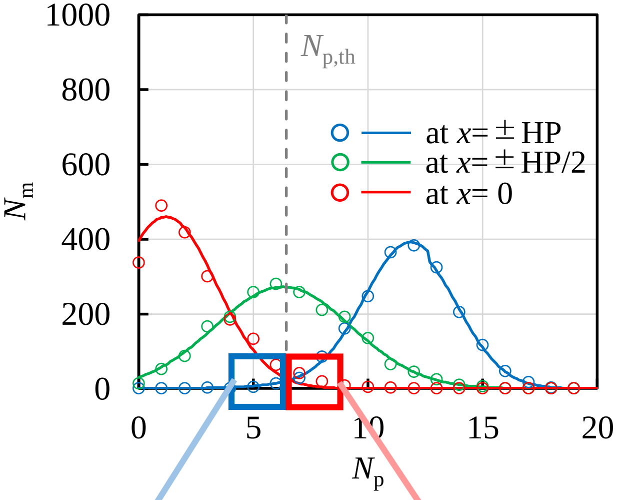
Normalization constant ($N_{p\neq 0}$)

$$N_{p0} + \frac{N_{p\neq 0}}{\sqrt{2\pi}\sigma_{space}} \int_{0.5}^{\infty} \exp\left(-\frac{\left(N_p - N_{space}\right)^2}{2\sigma_{space}^2}\right) dN_p = N_0$$

# Defect risk



Latent image



Number of polymer molecules with $N_p$

○ Simulation
— Fitting

$N_0$ : 2000
$s$ : 42 mJ cm$^{-2}$
$C_s$ : 0.2 nm$^{-3}$
$r_0$ : 4 nm
$\sigma_i$ : 2

**$R_p$ 1.38 × 10$^{-2}$** **$R_b$ 1.31 × 10$^{-2}$**

## Pinching risk $R_p$

Probability that a polymer molecule has protected units smaller than the dissolution threshold at lines

$$R_p = \frac{1}{N_0}\int_{-\infty}^{N_{p,th}} N_m(x = \pm HP)\,dN_p$$

$$= \frac{p_r}{\sqrt{2\pi}\sigma_{line,r}}\int_{-\infty}^{N_{p,th}} \exp\left(-\frac{\left(N_p - N_{line,r}\right)^2}{2\sigma^2}\right)dN_p + \frac{p_u}{\sqrt{2\pi}\sigma_{line,u}}\int_{-\infty}^{N_{p,th}} \exp\left(-\frac{\left(N_p - N_{line,u}\right)^2}{2\sigma_{line,u}^2}\right)dN_p$$

## Bridging risk $R_b$

Probability that a polymer molecule has protected units larger than the dissolution threshold at spaces

$$R_b = \frac{1}{N_0}\int_{N_{p,th}}^{\infty} N_m(x = 0)\,dN_p$$

$$= \frac{N_{p\neq 0}}{N_0\sqrt{2\pi}\sigma_{space}}\int_{N_{p,th}}^{\infty} \exp\left(-\frac{\left(N_p - N_{space}\right)^2}{2\sigma_{space}^2}\right)dN_p$$

# Meaning of bridging risk $R_b$

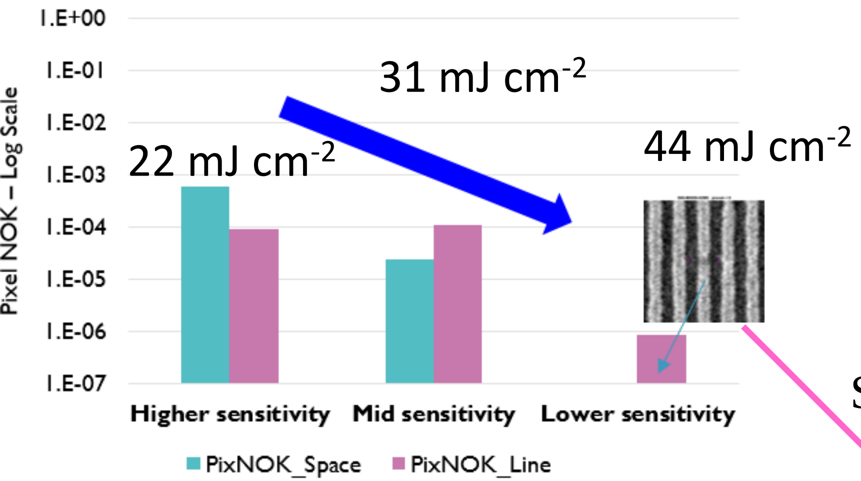
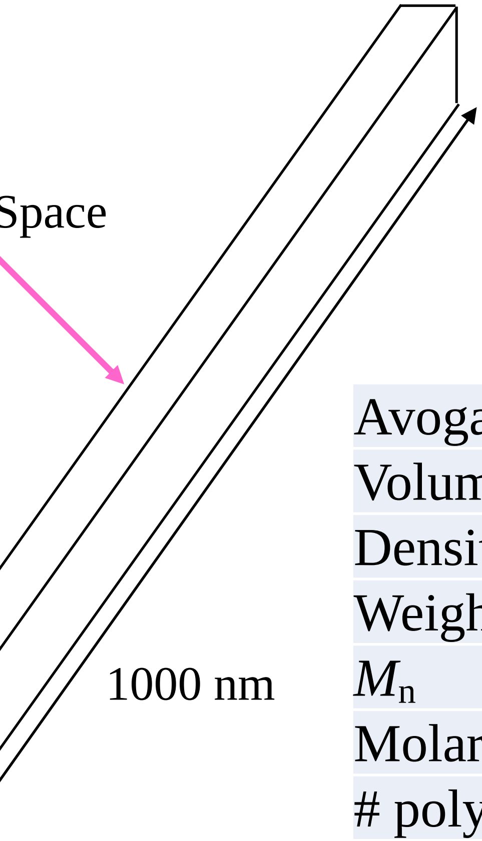
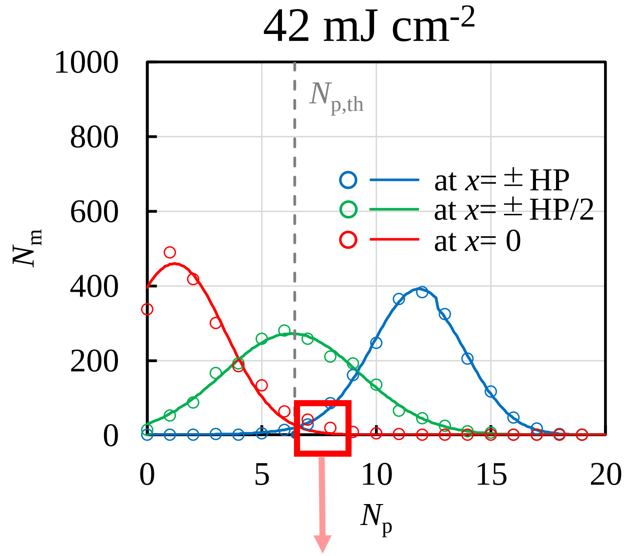


Figure 9. Pitch 32 nm dense lines-space. Defect counts as pixels not ok for the three resists under examination at the optimum CD target. The inspected area is 268 μm$^2$ equivalent to 4800 spaces and lines inspected. The resist with lower sensitivity (resist C) shows only one failure on one line (see SEM image above) and no nano-bridge failures (i.e. below the detection limit of 1E-7). D. D. Simone et al. Proc. SPIE 10583, 105830G (2018).



~5000 polymer molecules at bottom



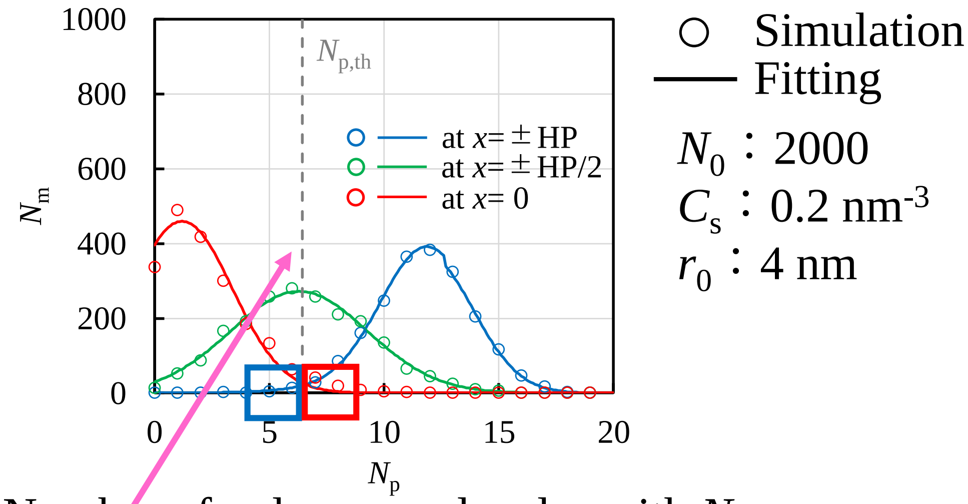
**$R_b$ 1.31 × 10$^{-2}$**

| | |
|---|---|
| Avogadro's number | $6.02\times10^{23}$ mol$^{-1}$ |
| Volume | 512000 nm$^3$ |
| Density | 1.2 g cm$^{-3}$ |
| Weight | $6.144\times10^{-16}$ g |
| $M_n$ | 4800 |
| Molarity | $1.28\times10^{-19}$ mol |
| # polym. molecules | **77100** |
| $V_{polymer}$ | 6.64 nm$^3$ |

We do not need to worry about an isolated insoluble polymer.
We should consider that insoluble polymers happen to coexist near with this probability.

$$\text{Bridging probability} = f(R_b)\ \sim R_b^{\,n}$$

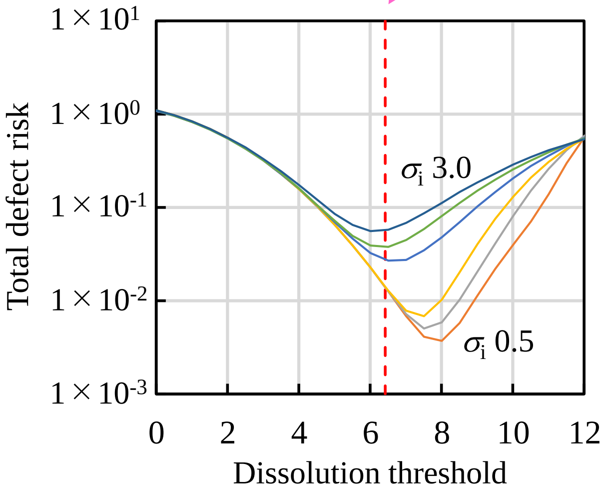
# Total defect risk $R_t$



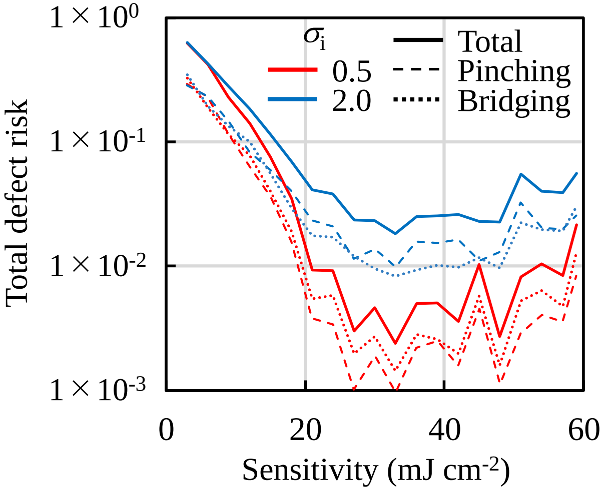
$N_0$ : 2000
$C_s$ : 0.2 nm$^{-3}$
$r_0$ : 4 nm

Number of polymer molecules with $N_p$

$$R_t = \boxed{R_p} + \boxed{R_b}$$

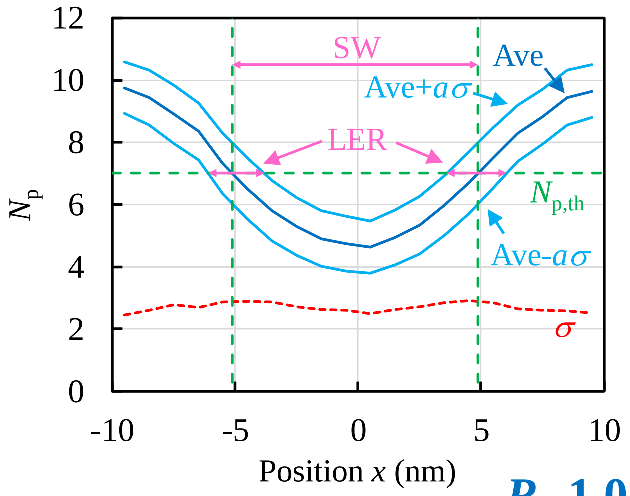


Dependence of total defect risk on dissolution threshold



Dependence of minimum total defect risk on sensitivity

# Dependence of defect risk on sensitizer concentration



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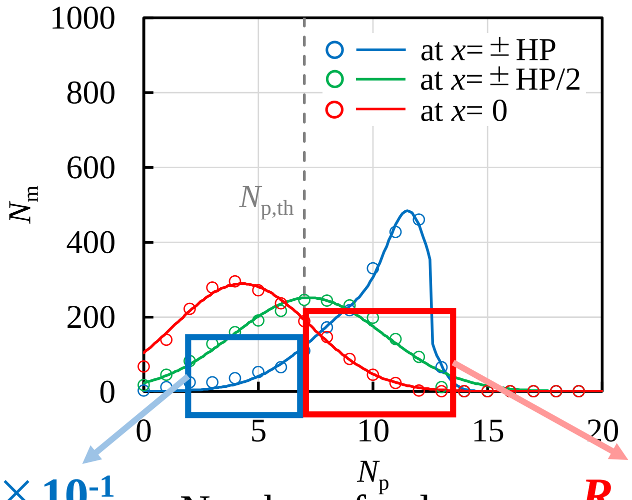


Number of polymer molecules with $N_p$

○ Simulation

— Fitting

$N_0$ : 2000

$s$ : **42 mJ cm$^{-2}$**

$C_s$ : 0.2 nm$^{-3}$

$r_0$ : 4 nm

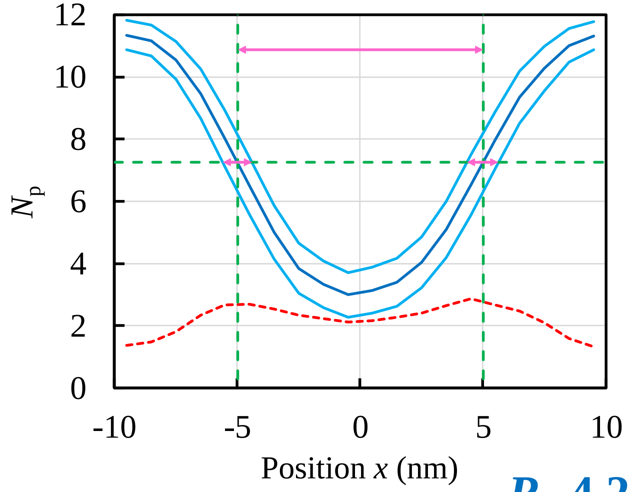
$\sigma_i$ : 0.5

**$R_p$ 1.03 × 10$^{-1}$**

**$R_b$ 2.06 × 10$^{-1}$**

$C_s$ 0.2 nm$^{-3}$

$C_s$ 0.5 nm$^{-3}$



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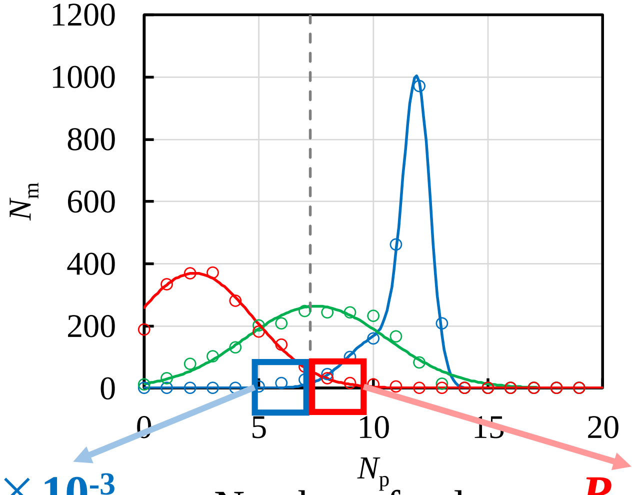


Number of polymer molecules with $N_p$

$N_0$ : 2000

$s$ : **85 mJ cm$^{-2}$**

$C_s$ : 0.5 nm$^{-3}$

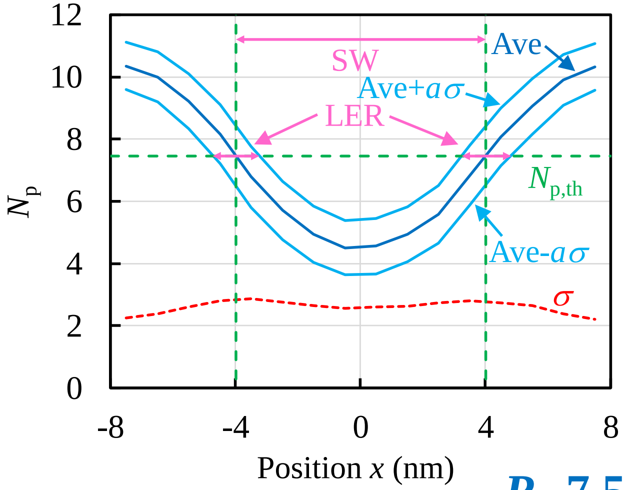
$r_0$ : 4 nm

$\sigma_i$ : 0.5

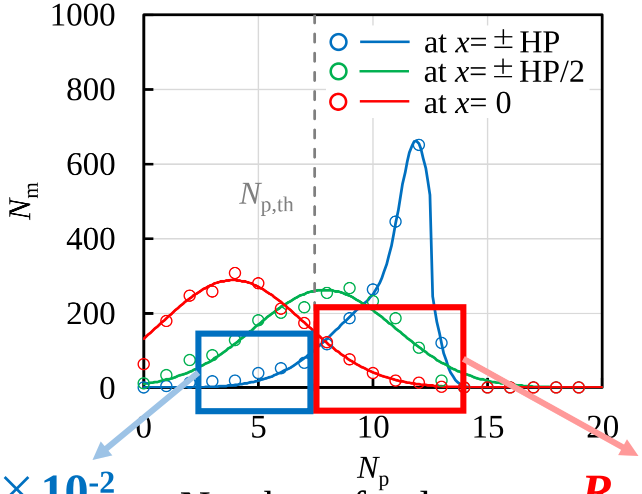
**$R_p$ 4.27 × 10$^{-3}$**

**$R_b$ 3.46 × 10$^{-2}$**

# Dependence of defect risk on thermalization distance



Latent image



**$R_p$ 7.50×10$^{-2}$**

$r_0$ 4 nm

Number of polymer molecules with $N_p$

**$R_b$ 1.45×10$^{-1}$**

○ Simulation

— Fitting

$N_0$ : 2000

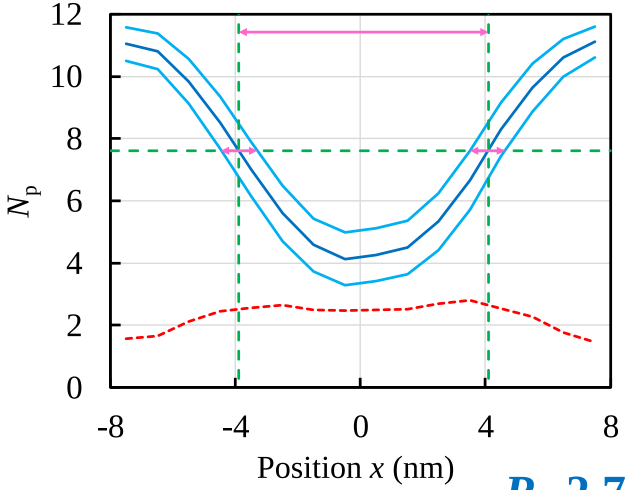
$s$ : 90 mJ cm$^{-2}$

$C_s$ : 0.5 nm$^{-3}$

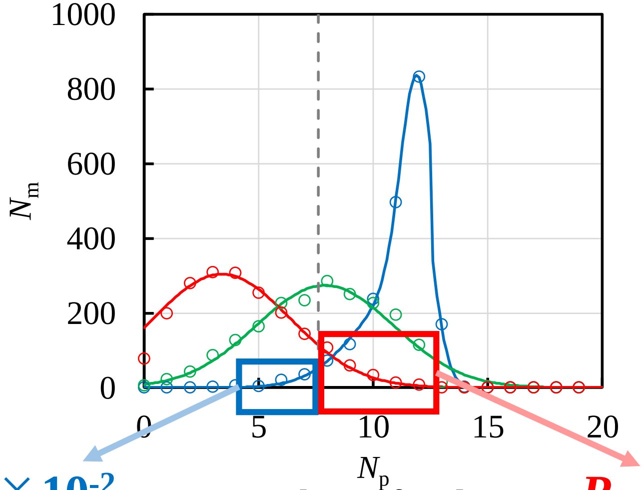
$r_0$ : 4 nm

$\sigma_i$ : 0.5

$r_0$ 2 nm



Latent image



**$R_p$ 2.79×10$^{-2}$**

Number of polymer molecules with $N_p$

**$R_b$ 9.48×10$^{-2}$**

$N_0$ : 2000

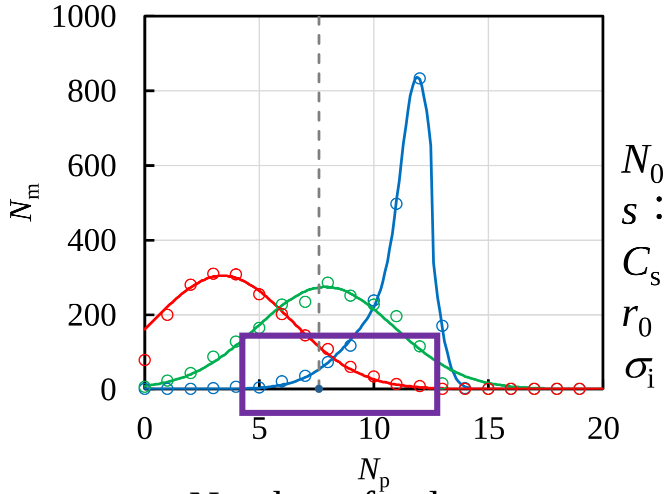
$s$ : 100 mJ cm$^{-2}$

$C_s$ : 0.5 nm$^{-3}$

$r_0$ : 2 nm

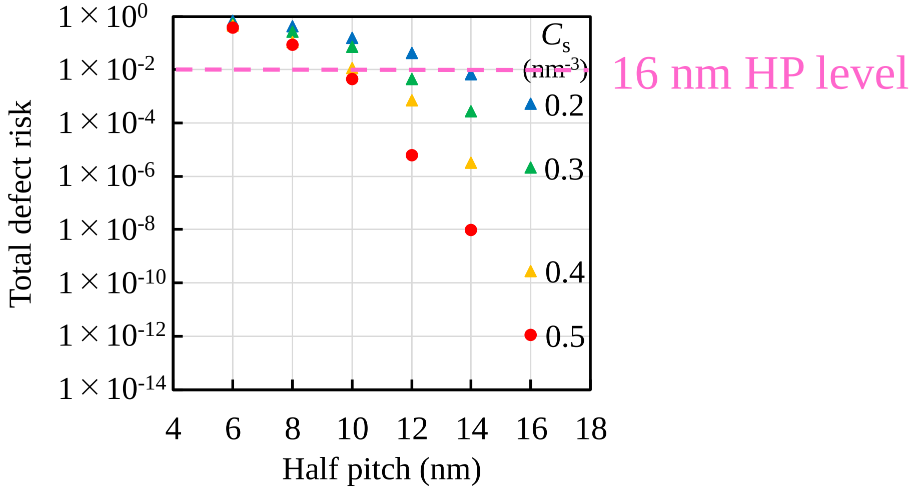
$\sigma_i$ : 0.5

# Half-pitch dependence of total defect risk

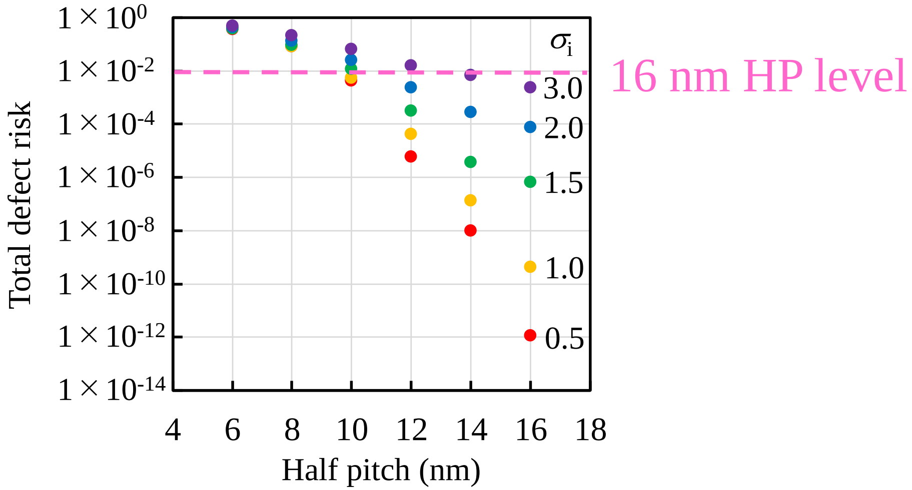


$N_0$ : 2000
$s$ : 100 mJ cm$^{-2}$
$C_s$ : 0.5 nm$^{-3}$
$r_0$ : 2 nm
$\sigma_i$ : 0.5

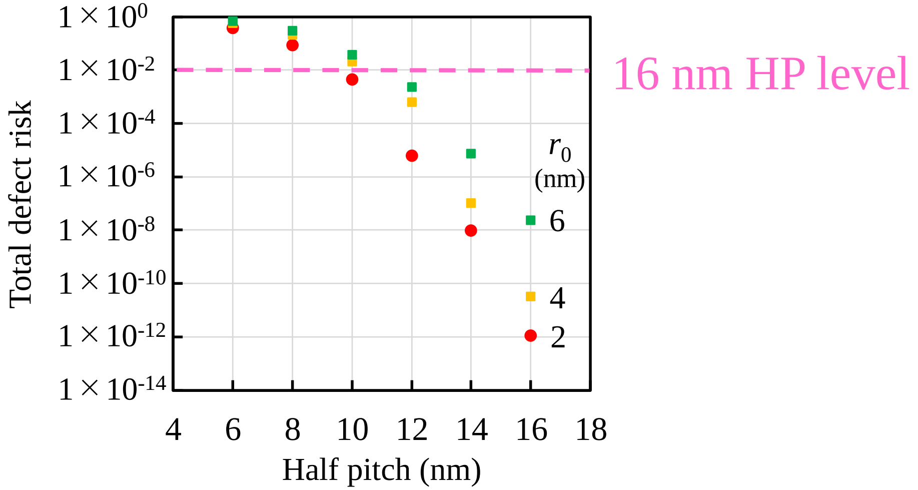
Number of polymer molecules with $N_p$



Sensitizer conc. dependence
($r_0$ 2 nm, $\sigma_i$ 0.5)



Initial standard deviation dependence
($r_0$ 2 nm, $C_s$ 0.5 nm$^{-3}$)



Thermalization distance dependence
($C_s$ 0.5 nm$^{-3}$, $\sigma_i$ 0.5)

# Summary

- ✓ The EUV lithography has been applied to high-volume production of semiconductor devices since 2019.
- ✓ The trade-off relationships between resolution, LER/LWR, and sensitivity were the most severe problem for the realization of EUV lithography.
- ✓ The suppression of stochastic defects is the most serious issue for the development of next-generation EUV lithography (High NA).
- ✓ The total defect risks exponentially depended on HP, $r_0$, $C_s$, and $\sigma_i$.
- ✓ It is possible to reduce the defect risk of 10 nm half-pitch to current 16 nm level.
- ✓ The control of interaction between resist and underlayer in the developer is important for the suppression of stochastic bridging.