Resolution, LER, and Sensitivity Limitations of Photoresist

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This work is part of a SEMATECH-funded program designed to

1. Generate, analyze, and compare multiple resists to an LER model
2. Use the experimental results to verify, expand, and finetune the LER model
3. Use the verified model to determine approaches for “breaking” the Resolution, LER, and Sensitivity (RLS) tradeoff

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At the end of the talk, two ideas for “breaking” the RLS tradeoff will be discussed:

1. Anisotropic acid diffusion

   ➔ Anisotropic deprotection “blur” *NOT EUV Specific*

2. Increased quantum yield *~ EUV Specific*

For a detailed discussion of these ideas see Gallatin, et. al., SPIE 2007.

Agenda

1. Describe the RLS tradeoff
2. Show how it relates to an LER model
3. Describe the experiments done so far
4. Present comparisons of the experimental results to the LER model
5. Discuss the (two) approaches for breaking the RLS tradeoff

See Poster RE-P02: Robert Brainard, et al., for a detailed description of the resists studied

See Poster RE-P04: Patrick Naulleau, et al., for a detailed evaluation of resist resolution metrics

The Resolution, LER, Sensitivity (RLS) Tradeoff

Resist Resolution: PEB Diffusion or Resist "Blur" …. Smaller is better

LER: Line Edge Roughness …................................ Smaller is better

Sensitivity: Dose-to-Size ………………………………. Smaller is better

…BUT data and modeling indicate the following "constraint":

$$\mathit{Blur}^3 \times \mathit{LER}^2 \times \mathit{Dose} \sim \mathrm{Constant}$$

RLS Tradeoff

For a standard chemically amplified resist and process cannot have blur, LER and dose all small at the same time.

"You can't always get what you want"… Mick Jagger

This type of behavior has been found by many researchers:

Lammers, et al., SPIE 2007, Bristol, et al., SPIE 2007, Brainard, et al., SPIE 2004, Gallatin SPIE 2005, …

How Does the LER Model → RLS Tradeoff

LER MODEL contains 3 fundamental processes Gallatin SPIE 2005

1. Exposure: Image intensity ~ Probability distribution for acid release.
   Acid release positions are statistical → Sensitivity
2. PEB: Acids diffuse and deprotect the resist
   PEB diffusion range → Resolution (resist "blur")
3. Development: Spatial distribution of deprotection determines final resist profile
   Line edge statistics → LER

…do the math… →

$$\underset{\substack{\uparrow\\ \text{LER}}}{\sigma_{LER}} \approx \underset{\substack{\uparrow\\ \text{Constant}}}{C} \left(\frac{I}{\partial I}\right)_{edge} \sqrt{\frac{T}{\alpha\, Q\, \underset{\substack{\uparrow\\ \text{Dose}}}{E_{size}}\, \underset{\substack{\nwarrow\\ \text{“Blur “}}}{R^3}}}$$

→ RLS Tradeoff

I = Image intensity
T = Resist Thickness
α = Absorptivity
Q = Quantum Efficiency
R = PEB Diffusion Range

<u>BONUS</u>: Get the explicit analytic form for the frequency content of the LER
Compare predicted content to experiment

EUV LER DATA

- Combined effort of LBL, CNSE, and Rohm and Haas with SEMATECH funding
- Exposures were done on the 0.3 NA MET at Berkeley
- Three different resists with 4 or 5 different base loadings each
  Resist Names: “5435” “5271” “5496”
- Features imaged: 50 nm and 60 nm 1-to-1 lines/spaces
- CD and LER data through dose and focus at each base loading
- LER and PSDs computed from average of left and right edge data at each focus, dose, and base loading condition
- LER computed from both filtered and unfiltered PSD data
  - “Best Dose” is as indicated in the graphs and tables
  - “Best Focus” is set to 0, by definition
- Resist blur values, R, are fit using the analytical PSD formula:
  Resist “blur” R is the only fitting parameter

Example Result: Resist “5435”, Base Loading G, 50 nm 1-1 lines/spaces

LER(unfiltered)

Best Focus: 0

Best Dose: 14.82

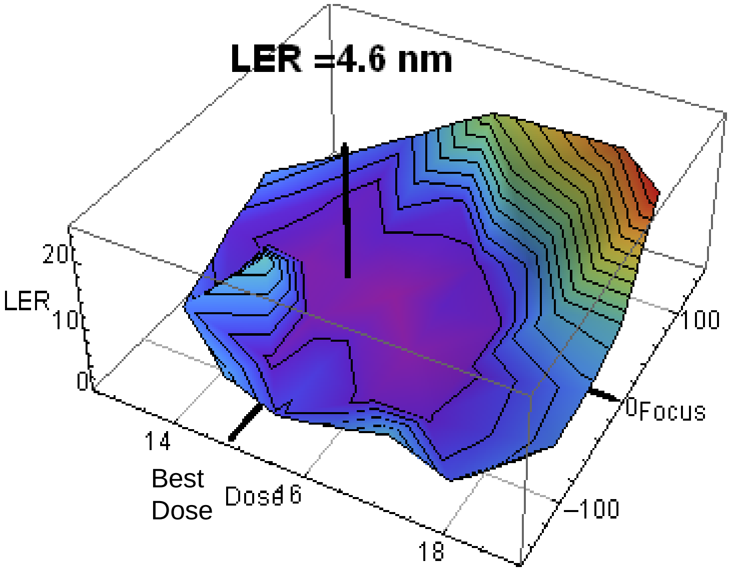
Dose\Focus	−150	−100	−50	0	50	100	150
12.8				5.5	8.8		
13.44		8.4	6.	5.2	5.5		
14.11			11.7	4.4	5.	5.1	7.4
14.82	9.9	5.	4.6	4.6	5.3	8.2	
15.56	6.8	6.3	5.	4.	5.1	5.7	15.8
16.34	8.4	4.9	4.3	5.2	5.1	14.2	
17.15	10.7	5.2	4.7	4.9	8.2		
18.01	7.3	6.5	6.8	10.7	16.5	23.	
18.91	14.7	8.6	8.8	11.5	25.		

R (“blur”)

Best Focus: 0

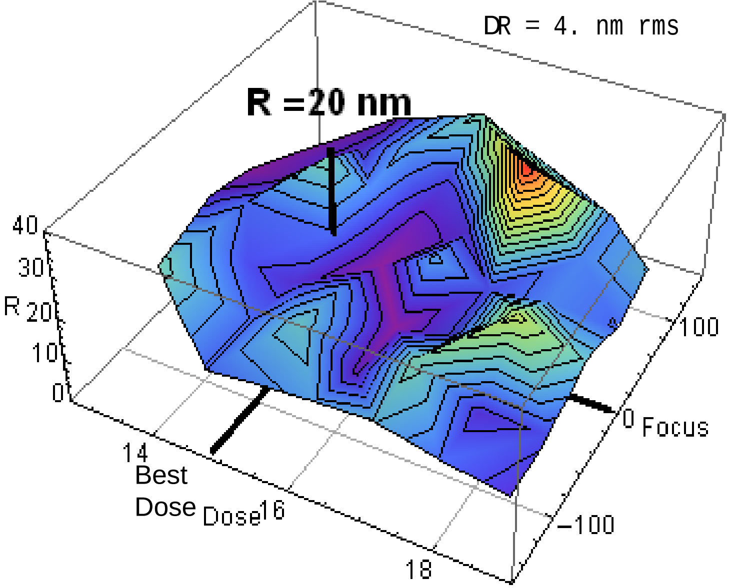
Best Dose: 14.82

Dose\Focus	−150	−100	−50	0	50	100	150
12.8				18	16		
13.44		25	22	20	17		
14.11			19	20	25	18	17
14.82	20	20	18	20	21	22	
15.56	21	24	21	16	17	19	25
16.34	22	17	16	22	18	30	
17.16	23	25	19	19	38		
18.01	20	18	29	21	21	21	
18.91	18	19	24	20	23		



Average R = 21. nm

DR = 4. nm rms



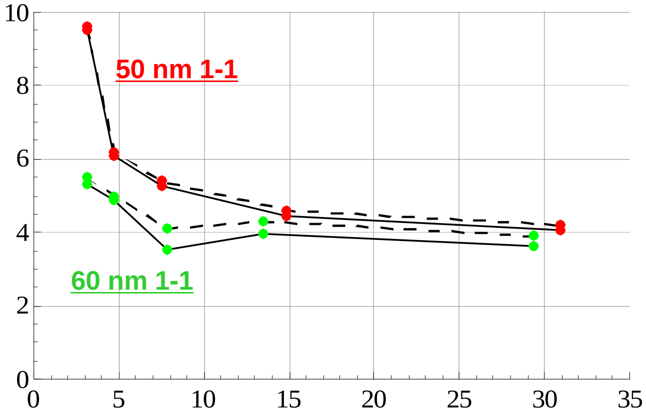
LER versus Dose

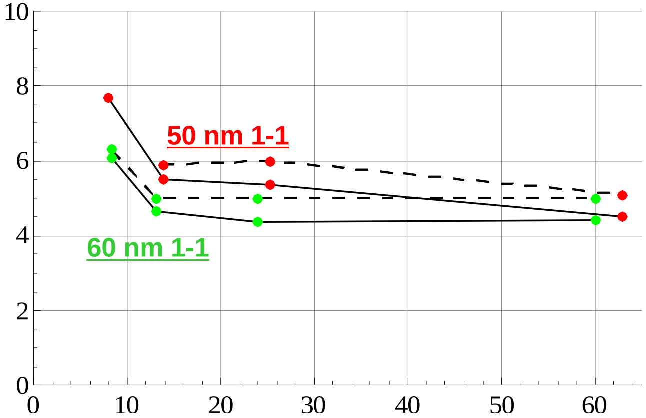
Solid Lines = Filtered LER
(High frequency noise removed from PSD before computing LER)

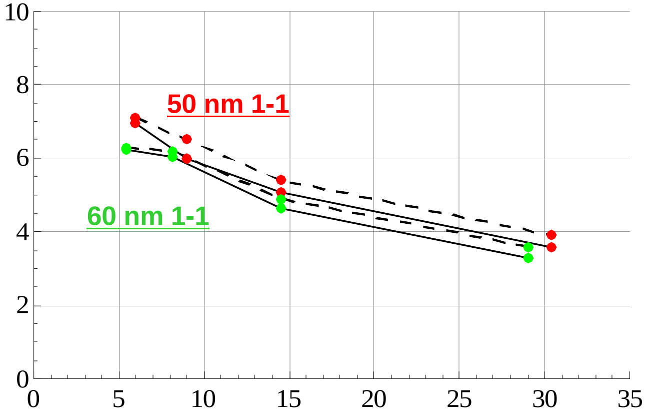
Dashed Lines = Unfiltered LER
(Raw PSD used to compute LER)

Comments

- Difference between filtered and unfiltered LER values ~ 0.5 nm
- Saturation at high dose is clearly evident
- Most of the difference between 50 nm and 60 nm LER comes from the slight difference in image log slope $(I/\partial I)_{edge}$







LER versus Dose
Add saturation to model

Dots = LER Data

Lines = Model fit to the data after incorporating saturation

$$\frac{1}{\sqrt{E_{size}}} \rightarrow \frac{1}{\sqrt{E_{sat}\left(1-e^{-E_{size}/E_{sat}}\right)}}$$

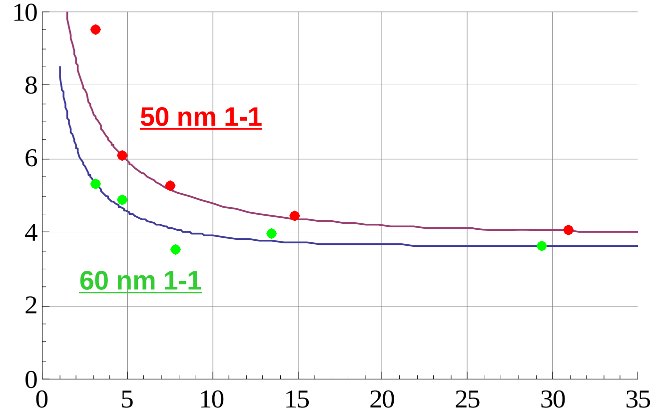
Comments

- Results aren't bad, but more work needs to be done.

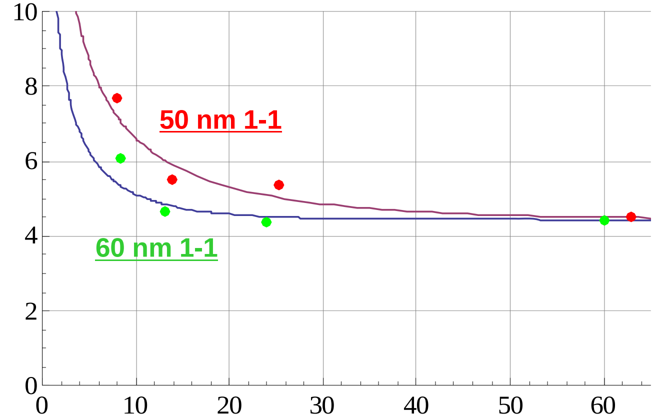
- **Specifically**:

  Match fitting parameter E_{sat} to actual resist parameters, e.g., PAG loading, base loading, absorption, quantum efficiency, etc.

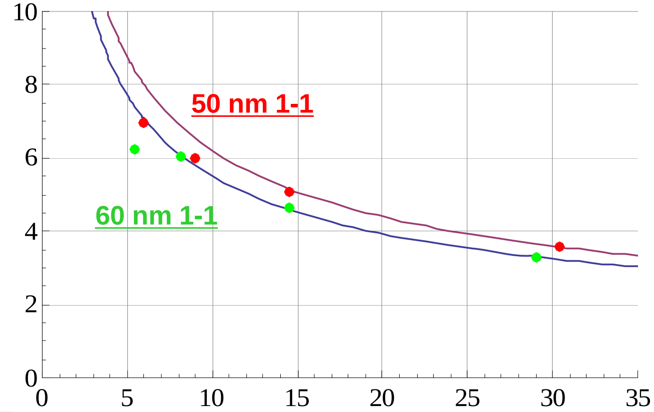
Resist "5435"



Resist "5271"



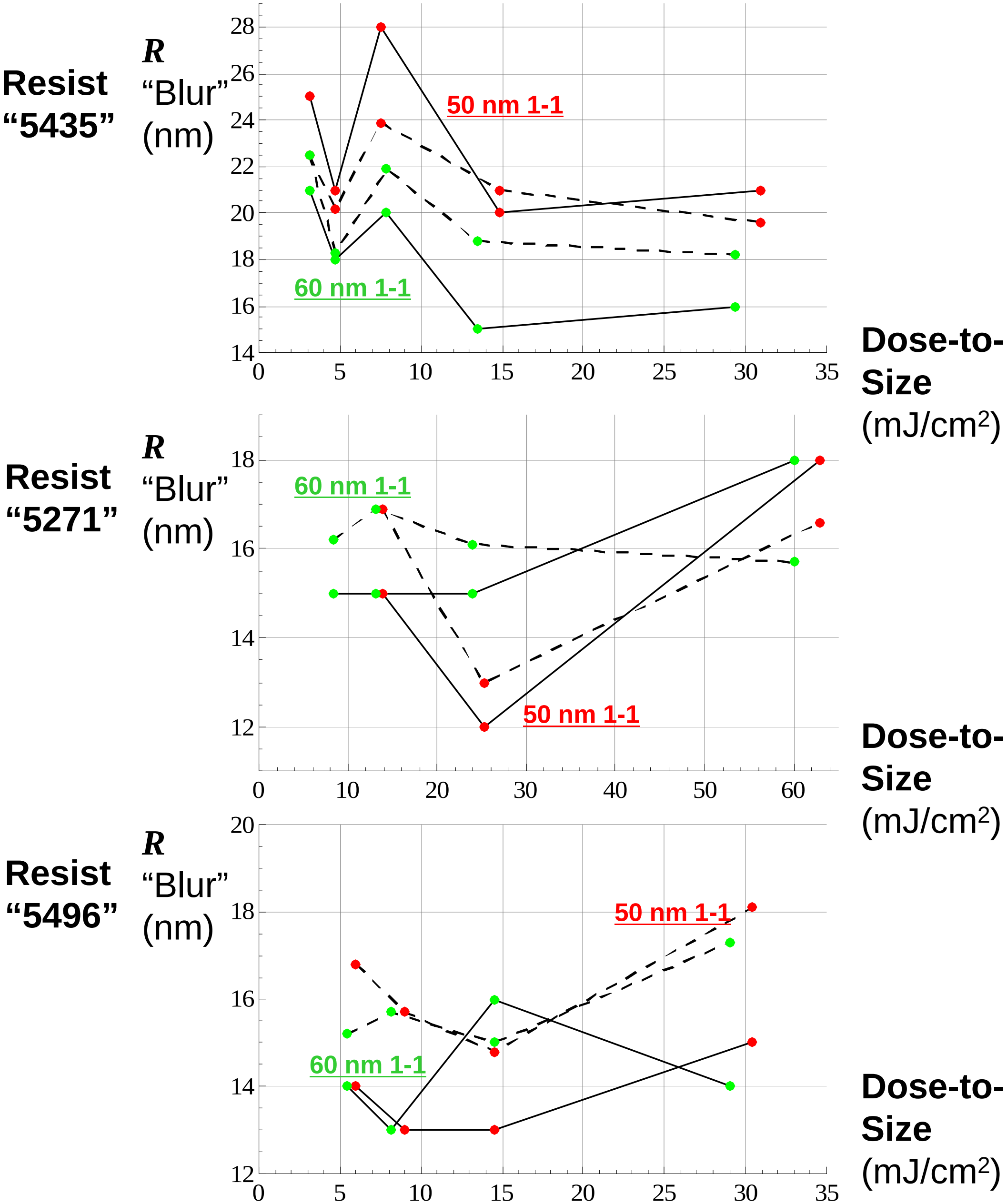
Resist "5496"



Resist “Blur” Value, R, versus Dose

Solid Lines = R **at best dose and focus**

Dashed Lines = **Average** R **over all dose and focus values**



Comments

- 50 and 60 nm “blur” values approximately the same.
- Possibly some systematic variation with dose.
- 1σ variation in R ~ 1 to 4 nm

➔ Difficult to distinguish systematic from random behavior.

"How well does the model PSD shape fit the data PSD shape?"

Next 5 slides show an example comparison of model PSD to data PSD

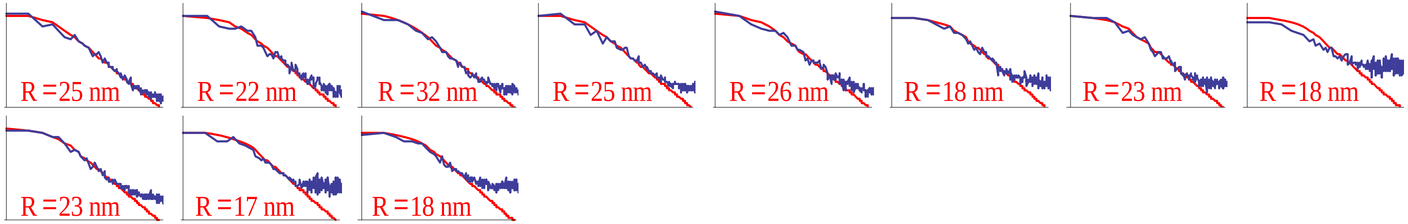
- Resist "5435," 50 nm 1-to-1 lines/spaces
- Plots show model PSD and data PSD at all dose and focus and base loading (dose-to-size) values

  Red curves = Model PSD fit to one parameter, the value of R
  Blue curves = Data PSD

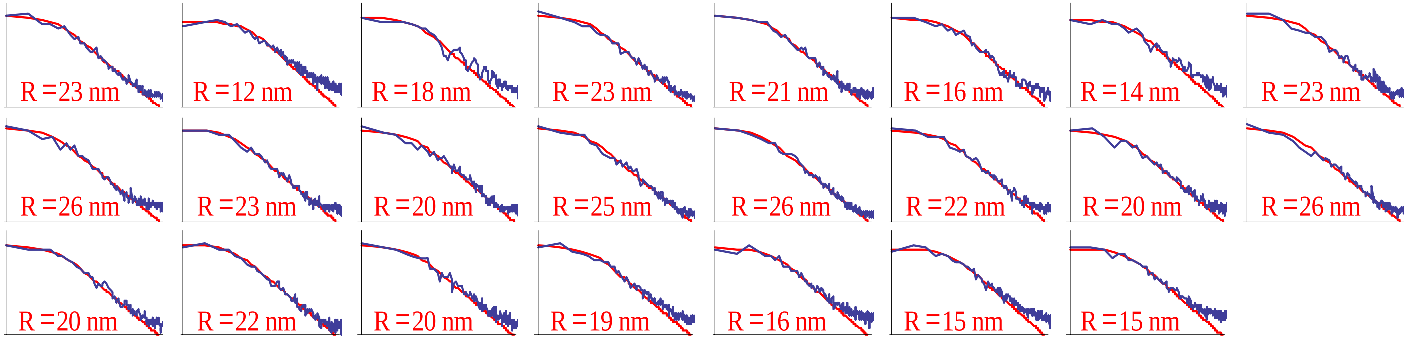
- Results indicate that the PSD **shape** is remarkably stable through dose, focus, base loading, and resist type

Will go quickly through the next 5 slides.
Just look at the general comparison of the model and data PSDs

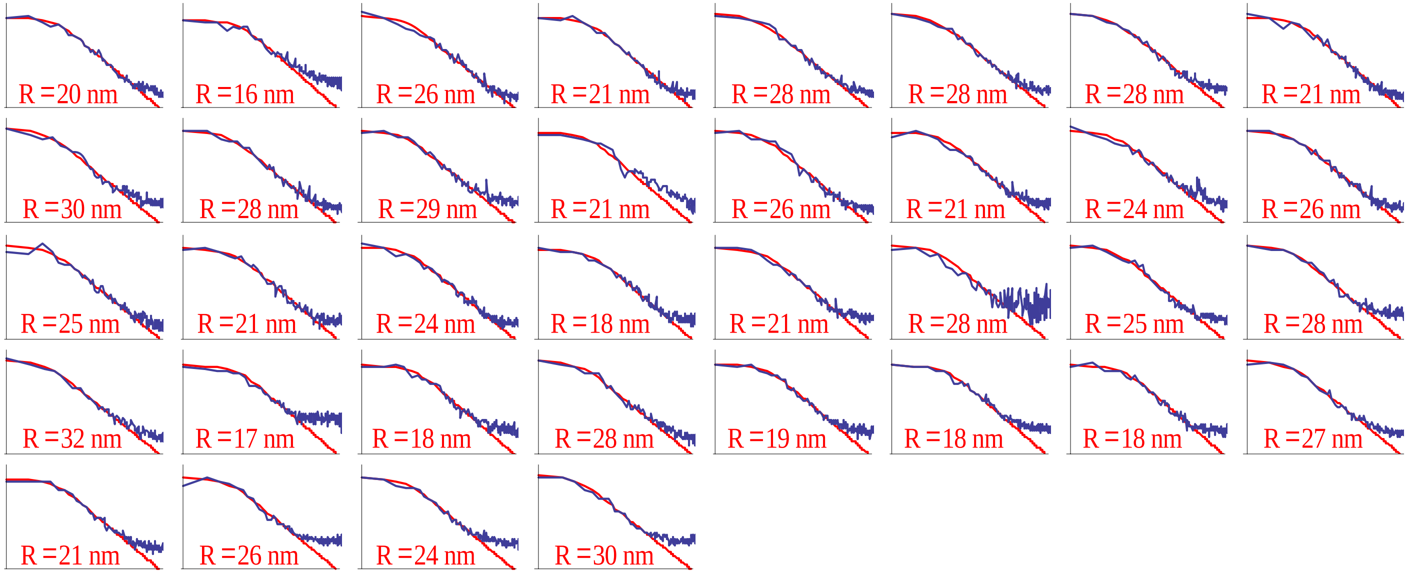
Resist 5435
Dose-to-Size = 3.09mJ/cm^2



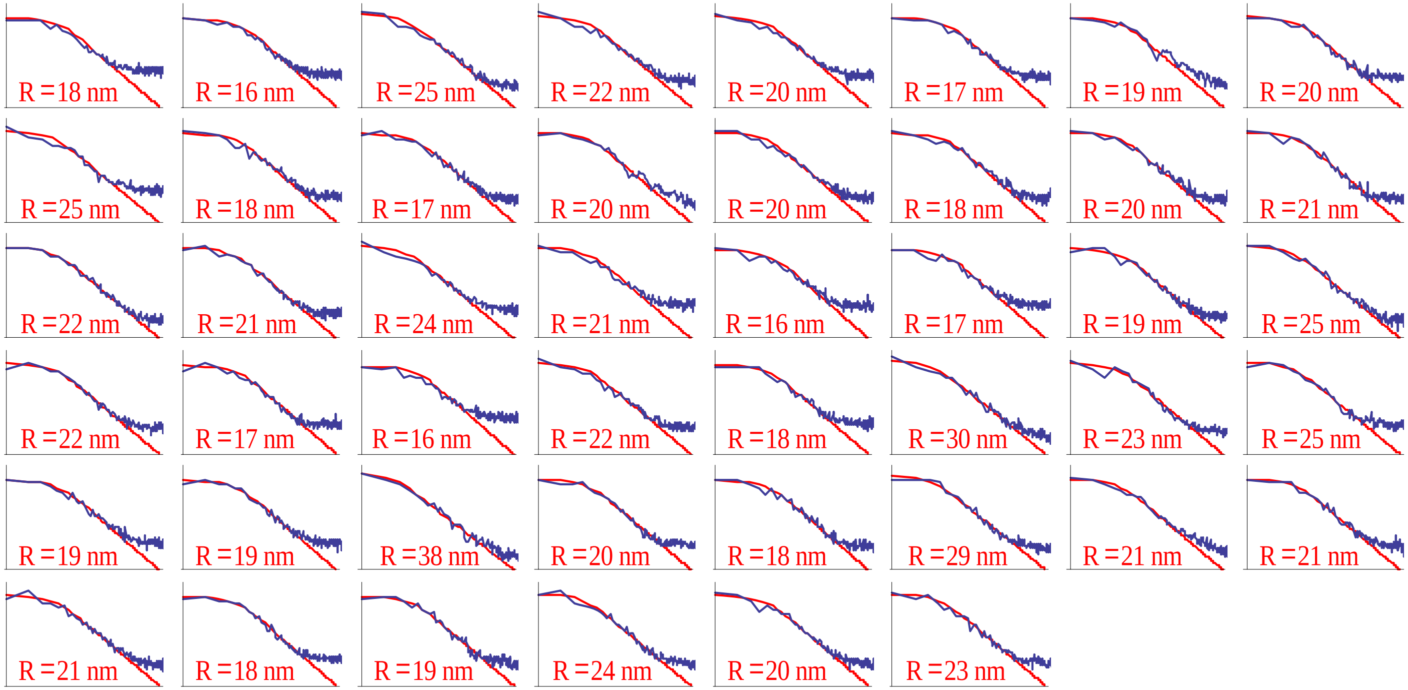
Resist 5435
Dose-to-Size = 4.73mJ/cm^2



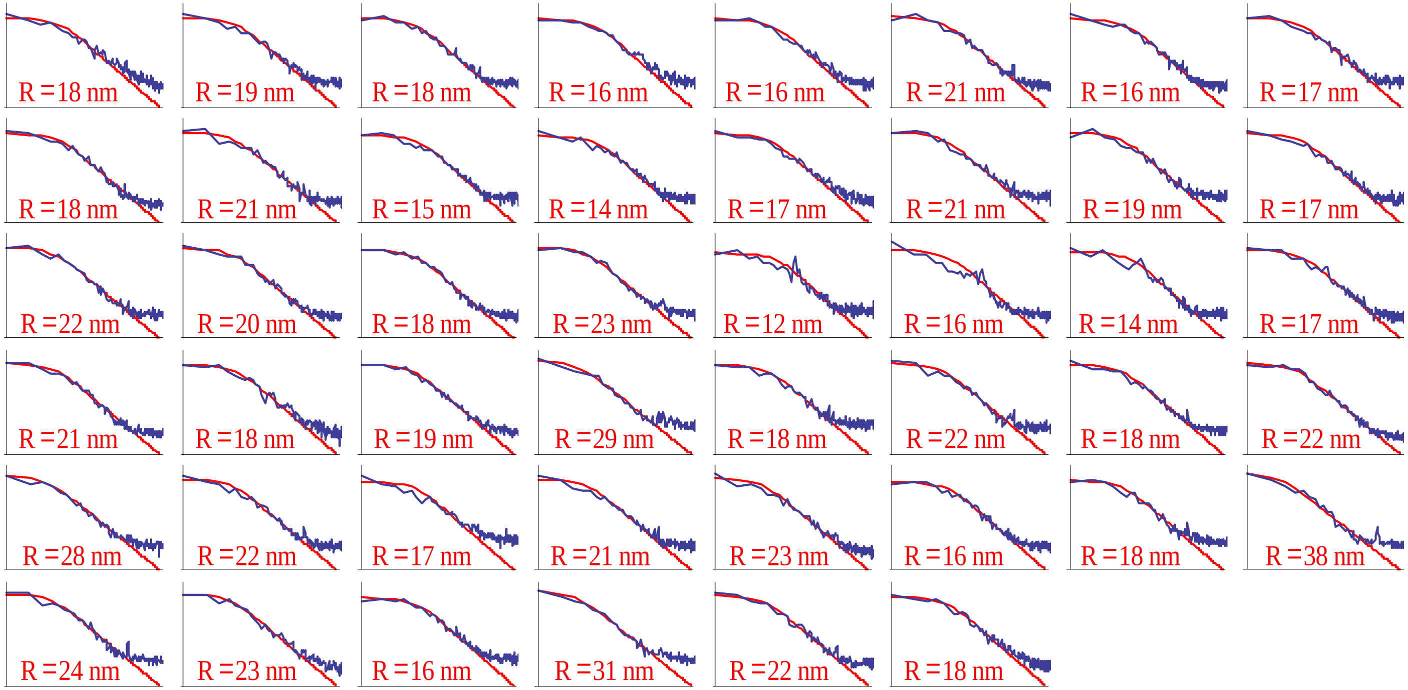
Resist 5435
Dose-to-Size = 7.50mJ/cm^2



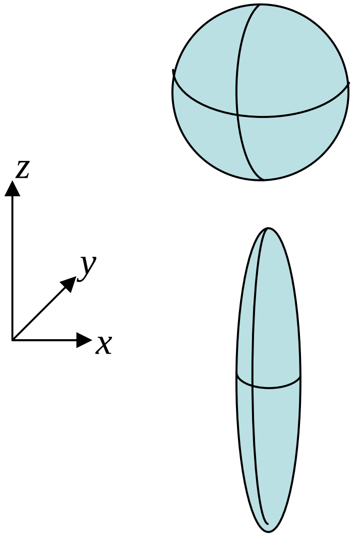
Resist 5435
Dose-to-Size = 14.82mJ/cm^2



Resist 5435
Dose-to-Size = 30.87mJ/cm^2



1. Anisotropic Resist “Blur”



➔ Spherical Deprotection Blur: $R_x = R_y = R_z$

$$\text{Volume} \sim R_x R_y R_z$$

➔ Anisotropic Deprotection Blur:

Shrink in x and y

$$R_x \to \frac{R_x}{s} \qquad R_y \to \frac{R_y}{s}$$

Expand in z

$$R_z \to s^2 R_z$$

s = Scaling Factor

$$s \geq 1$$

$$\text{Volume} \sim \frac{R_x}{s}\frac{R_y}{s} s^2 R_z = R_x R_y R_z$$

…do the math…

$$LER \sim 1/s$$

$$\text{Horizontal Blur} \sim 1/s$$

$$\text{Dose} = \text{Fixed}$$

Improved LER and resolution

Fixed dose

Anisotropic diffusion explicitly breaks the RLS tradeoff.

2. Quantum Yield = Q

248 nm and 193 nm photons release acids ➔

Energy required to release an acid is at most ~ 5 to 6 eV.

EUV photon has 92 eV of energy ➔

Each EUV photon has enough energy to release at least 92 eV/5 eV~18 acids

"acid bottleneck" Neureuther, et al., JVST B 2006

DATA: $Q_{DUV} \sim 1/3$ ➔ 1 in 3 absorptions results in acid release

Brainard, et al., SPIE 2004

$Q_{EUV} \sim 2$ ➔ EUV is not close to using its energy efficiently

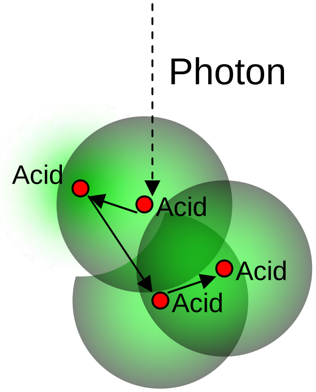
BUT Not all acids can be released in the same position ➔ adds blur

- Assume acids are released along random walk path with steps spaced by $\rho^{-1/3}$

Q released acids ➔ Extra "exposure" blur $r \sim (Q-1)^{1/2} \rho^{-1/3}$

2. Quantum Yield = Q

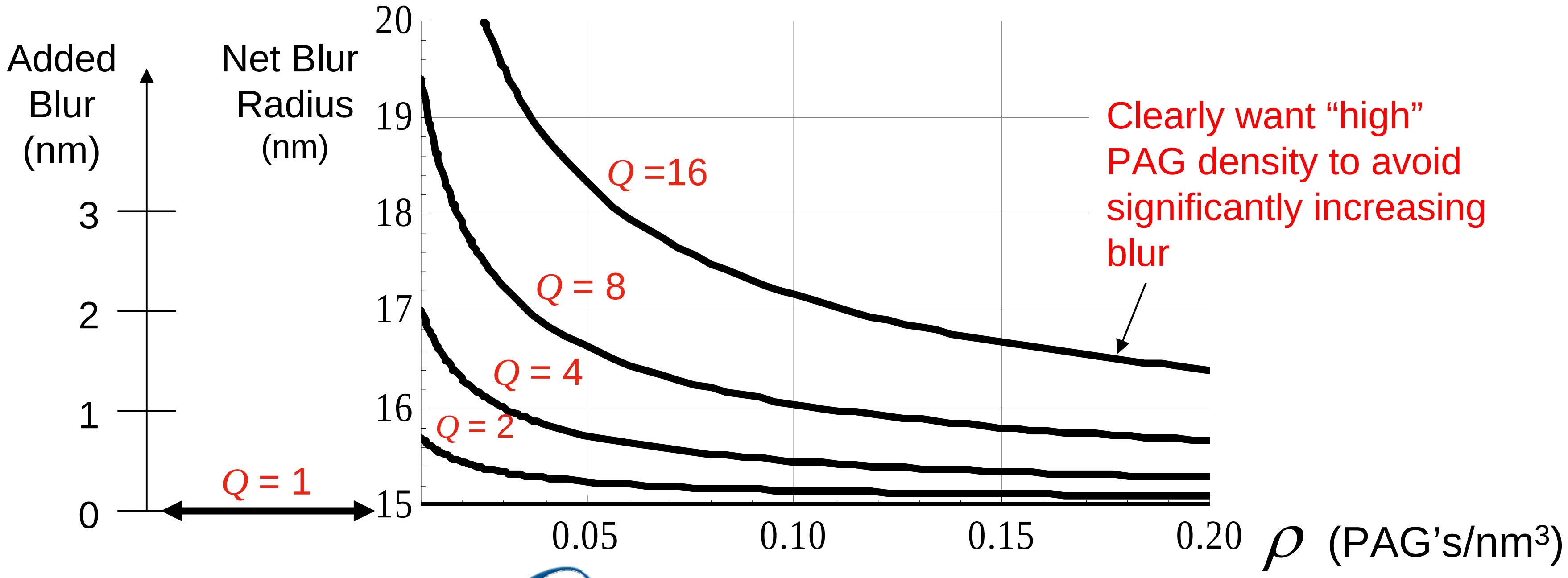
Combine deprotection "blur" from each acid with the random walk distribution of released acids → "Net Blur Radius"



$$Net\ Blur\ Radius \sim \sqrt{R^2 + r^2} = \sqrt{R^2 + (Q-1)\rho^{-2/3}}$$

R = Deprotection blur radius
= FWHM/2 ~ 15nm

Spatial distribution of Q released acids



Clearly want "high" PAG density to avoid significantly increasing blur

2. Quantum Yield = Q

$$LER \propto \frac{1}{\sqrt{\alpha\, Q\, E\, R^3}}$$

Increase Q and Decrease E with $Q\,E$ = constant

- Explicit gain in sensitivity
- If net “blur” = $R_{net} \sim R$ no change in resolution
- No change in LER

Increased quantum yield can break the RLS tradeoff.

NOTE: Some recent experiments show decreasing E and decreasing LER with increasing PAG loading

Choi, et al., SPIE 2007
Leunissen, et al., MNE 2005.

Conclusions and Future Tasks:

- RLS tradeoff predicts that for a ***standard*** chemically amplified resist and process you *cannot* get high resolution, low LER and low sensitivity all at the same time.
- Both anisotropic dissolution and increased quantum yield are good candidates for "breaking" the RLS tradeoff

> "If you try sometimes you just might find you get what you need."
> Mick Jagger

- Future:
  1. Continue verification, expansion, and finetuning the RLS model based on experimental results.
  2. Need to consider non-mean-field behavior. Smith, Biafore, Robertson, SPIE 2007
  3. Determine feasibility of implementation.

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