A Semi-Empirical Resist Dissolution Model for Advanced Lithographies

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Motivation

Need for a development/etch model that meets the following criteria:

Correctness *Correct prediction; at the very least, the model must be able to correctly predict "trends".*

Robust Implementation *As important as correctness for anything involving process exploration and optimization studies.*

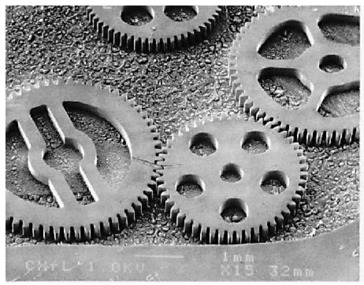
Cross Lithographic Techniques *Must be able to bridge multiple lithographic techniques such as synchrotron and point source based* $1\times$ *x-ray proximity,* $4-5\times$ *EUV projection lithographies, etc.*

Cross Application Domains *From DRAMs to logic to MEMS to novel applications such as Fresnel Zone Plates used for microscopy.*

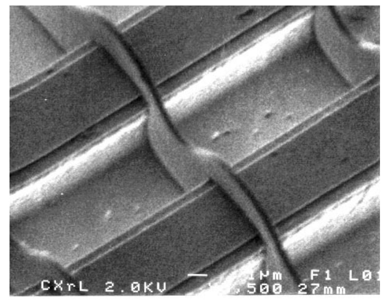
Short "Time to Usability" *Minimal turn-around from acquisition of a new resist to getting reliable results from the model.*

Goals

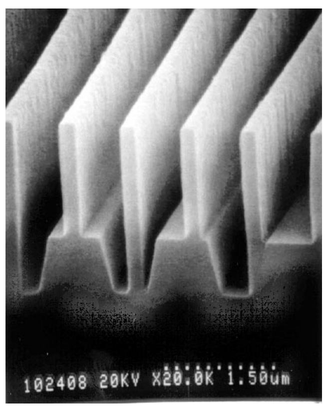
- A robust front-propagation model based on **Level Set Methods** that can be used for 3D pattern transfer.
- Ability to model "real-life" cases such as the following:



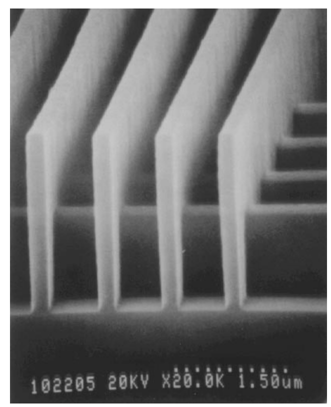
CXrL



CXrL



NTT (K. Deguchi)



NTT (K. Deguchi)

Front propagation algorithms – Issues

Problems:

- Using time-step to evolve surface (**moving grid**)!
- Topological degeneracies (somewhat related to time dependence).

Solution:

- Ask a different question: Given a point, (x, y, z), when does the front reach this point? That is, compute "arrival times" at each grid point and not move the grid itself ($\Rightarrow$ contouring problem).
- Transform the surface evolution to a *Stationary* problem, so that time disappears (Hamilton-Jacobi $\Rightarrow$ Stationary Eikonal Equation).
- Use **Level Set Methods** to solve the Eikonal equation.

Front propagation algorithm using Level Set methods

- Pioneering work by Sethian UC-Berkeley. Highly robust and accurate methods for tracking interfaces moving under complex motions (eg., robotics, fluid dynamics).

- **Selected References**:

Sethian *Level Set Methods: Evolving Interfaces in Geometry, Fluid Mechanics, Computer Vision and Materials Sciences*, Cambridge University Press, 1995.

Mathematical theory of Level Set methods and various applications.

Adalsteinsson and Sethian *A Level Set Approach to a Unified Model for Etching, Deposition and Lithography II: Algorithms and Two-Dimensional Simulations*, J. Comp. Phy., **20**, 128-144 (1995).

Application of Level Set methods in process modeling.

Mathematical model – Equations of motion

- Let $T(x,y)$ be the time at which the boundary crosses (x,y). The boundary $T(x,y)$ then satisfies the equation:

$$|\nabla T|R = 1$$

- Position of the front, Γ at a time t is given by the level set (contour) of value t of the function $T(x,y)$, that is

$$\Gamma(t) = \{(x,y)|T(x,y) = t\}$$

To find the front at time t, simply take the level set (contour) of the function at time t. Solve

$$|\nabla T(x,y,z)| = \frac{1}{R(x,y,z)}$$

Numerical solution to $|\nabla T|$ in 1-dimensional case

- Standard finite difference notation for 1-dimensional ψ_x:

$$D_i^{0x}\psi = \frac{\psi_{i+1} - \psi i - 1}{2h} \quad D_i^{-x}\psi = \frac{\psi_i - \psi i - 1}{h} \quad D_i^{+x}\psi = \frac{\psi_{i+1} - \psi i}{h}$$

ψ_i is the value of ψ at point ih with grid spacing h.

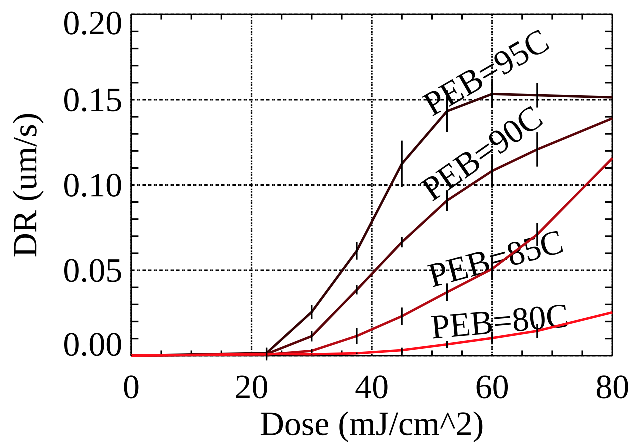
- From Osher and Sethian, the new updated value of gradient:

$$|\psi_x| \approx \ [(max(D_i^{+x}\psi, 0)^2 + min(D_i^{-x}\psi, 0)^2)]^{1/2}$$

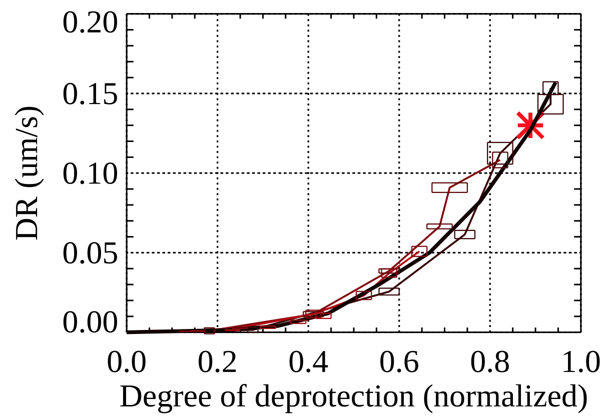
This is known as the “upwind” scheme, which chooses grid points in the approximations in terms of the flow of information.

Simulation input

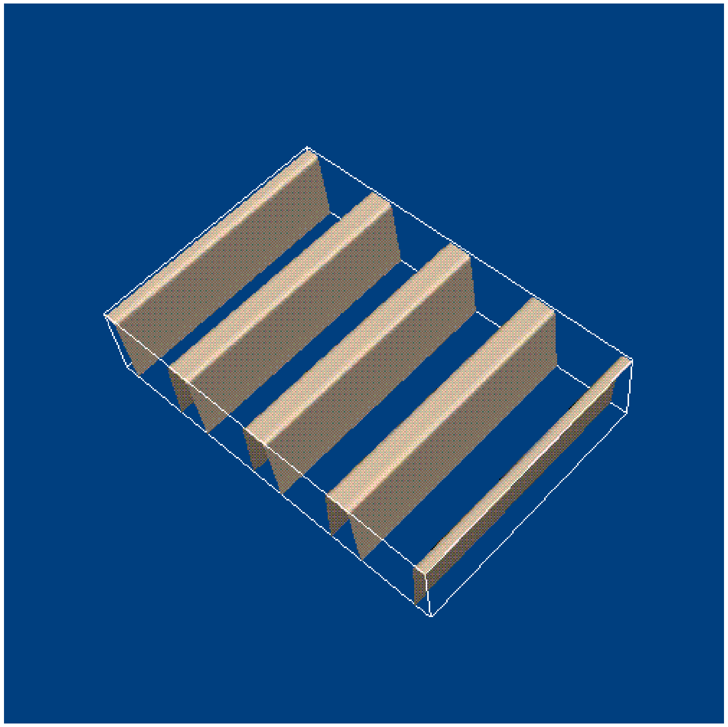
- Local dissolution rate. Data courtesy of Y. Zhu.



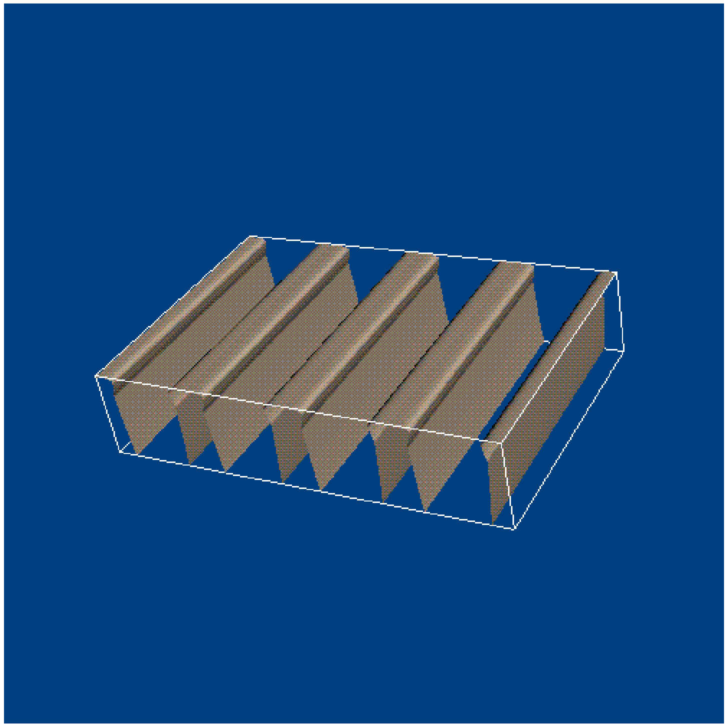
- Modeling of local dissolution rate is performed by a pre-processor (latent image).



Application: $70nm$ lines and spaces

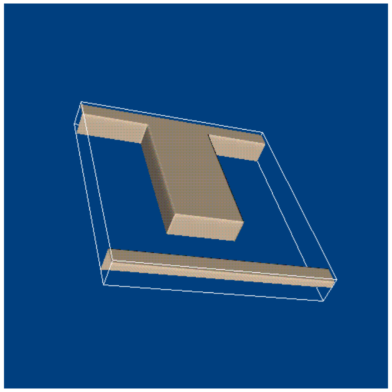


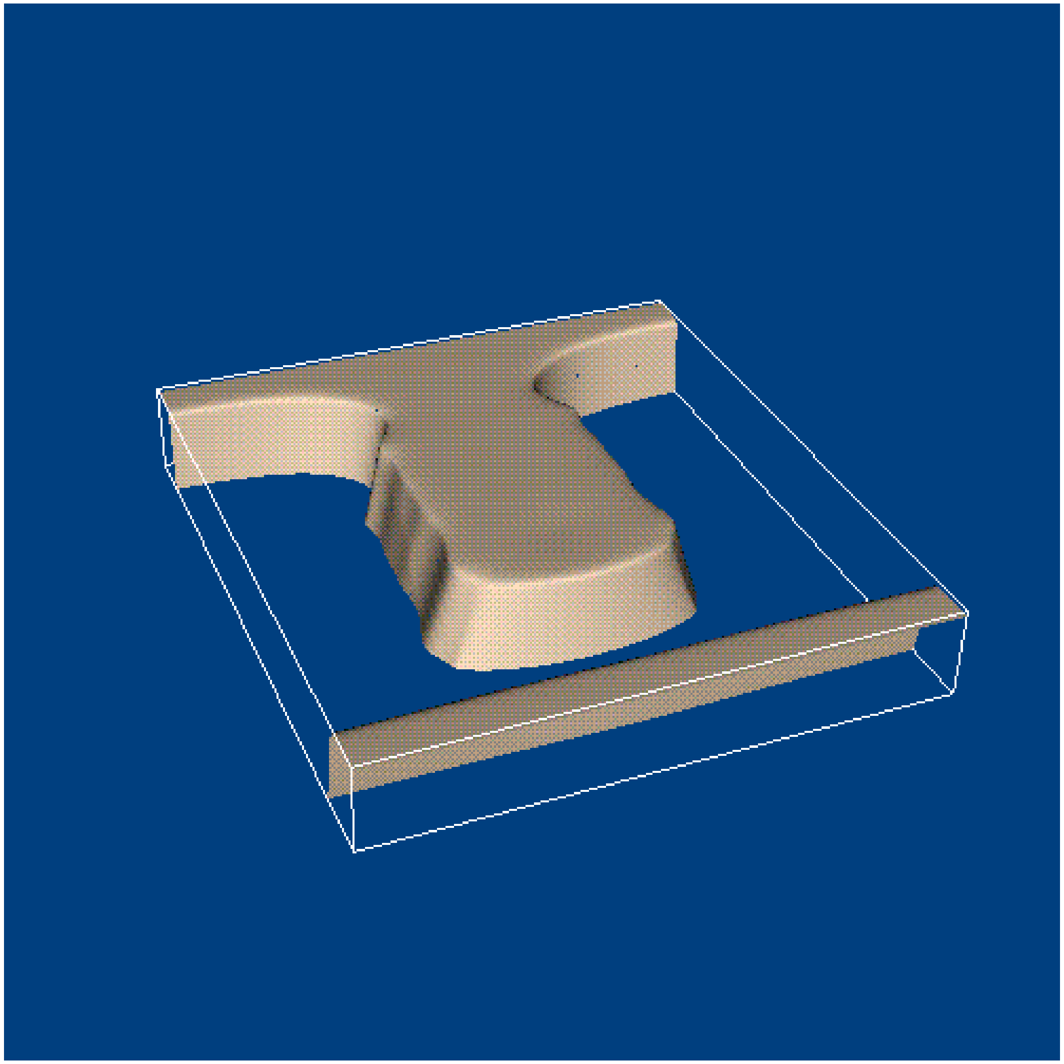
No Surface inhibition effects.



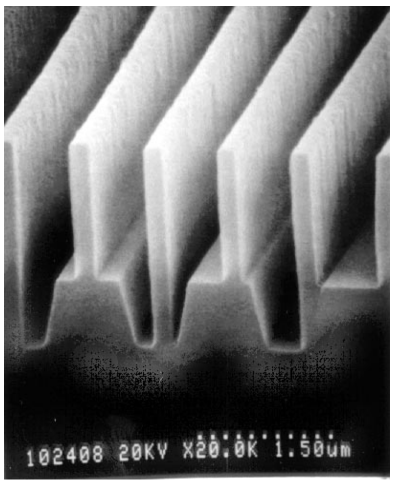
User-defined surface inhibition effects included.

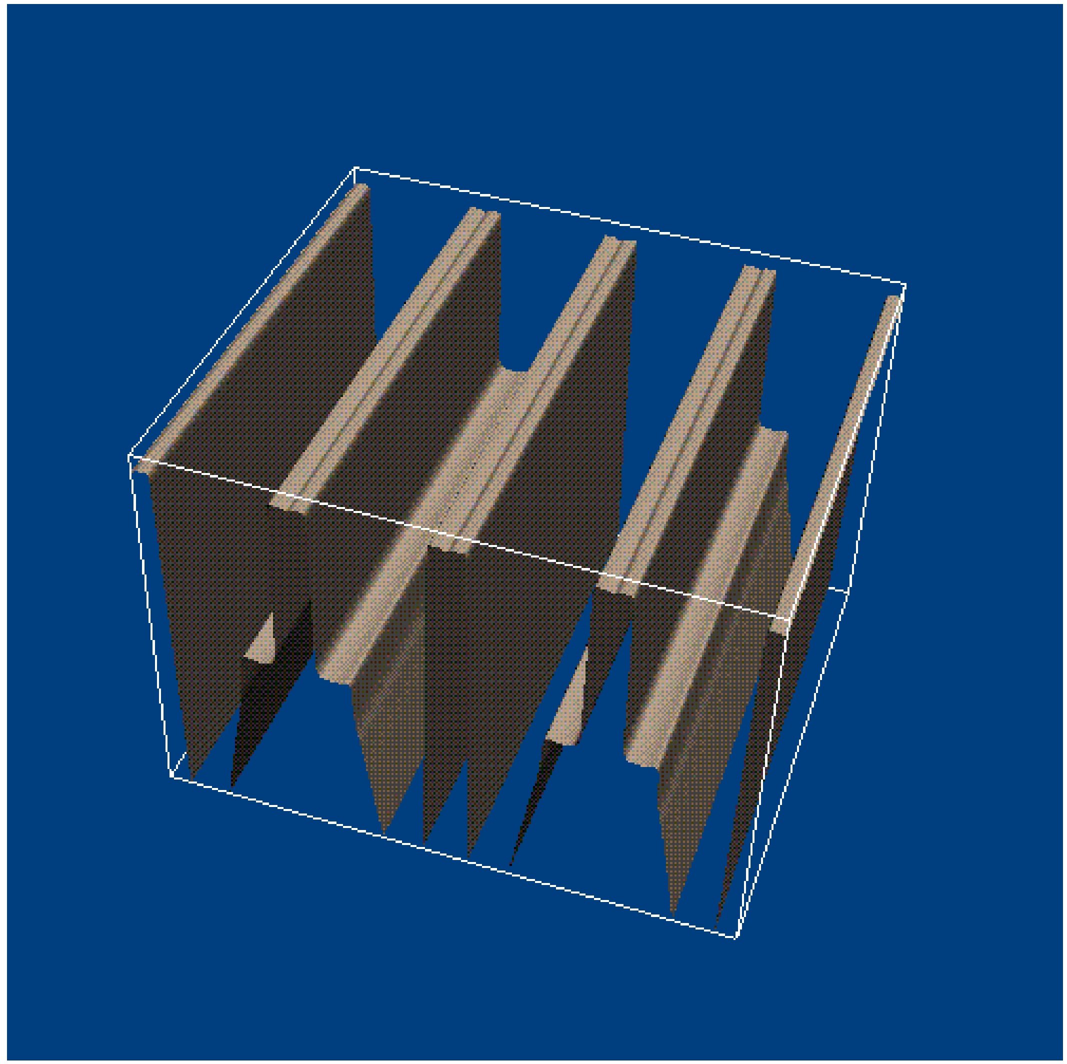
Application: 2D proximity effects



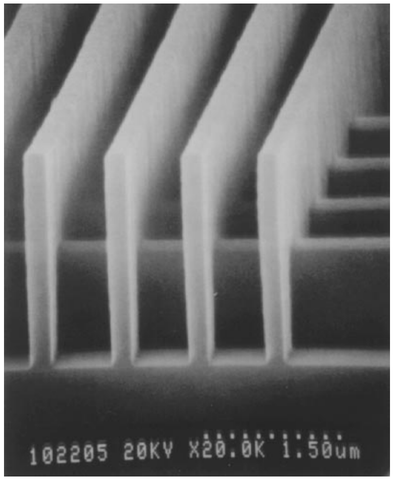


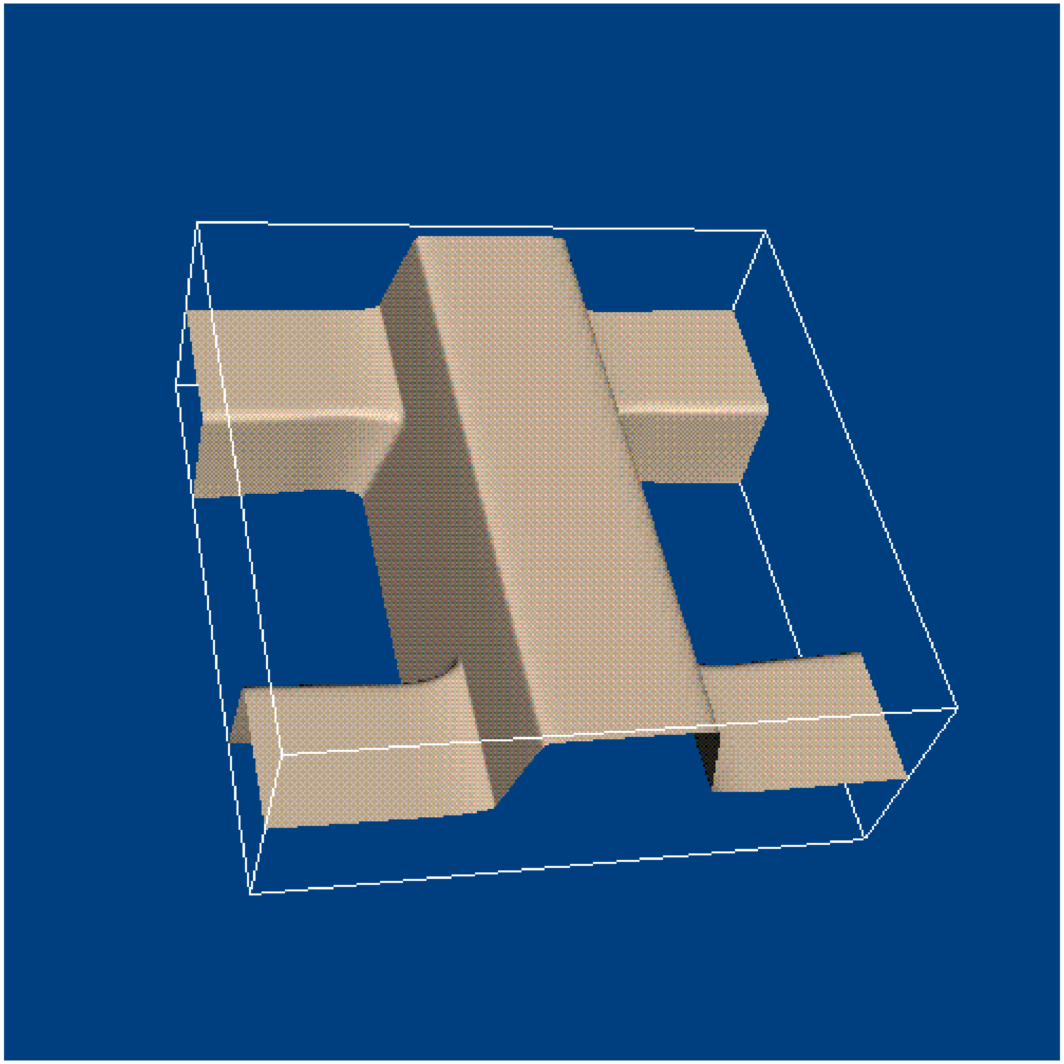
Application: Resist over topography



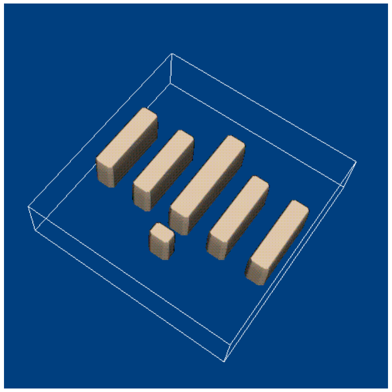


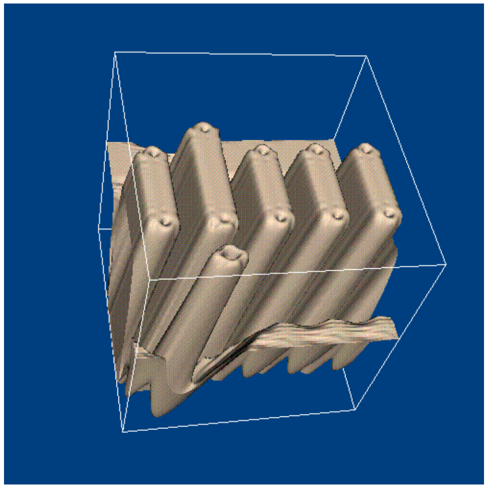
Application: Resist over topography II

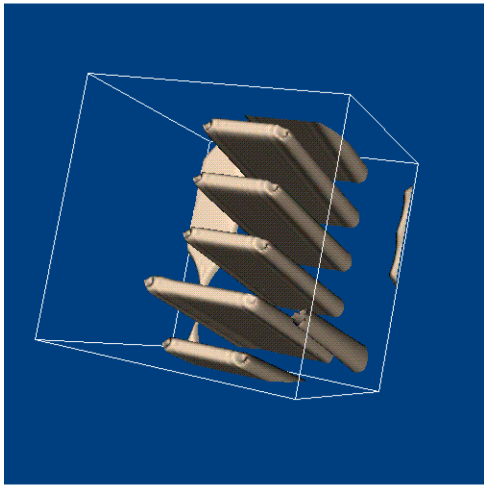


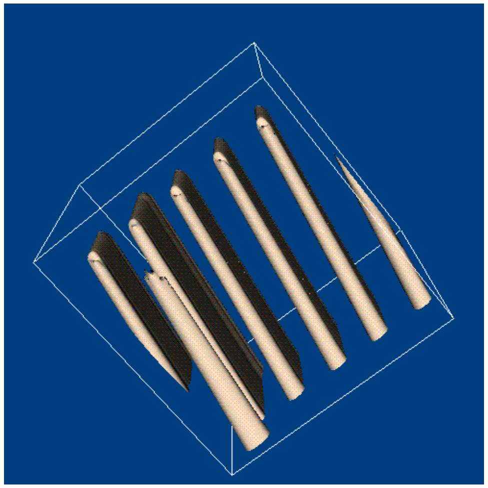


Application: Point source based x-ray lithography

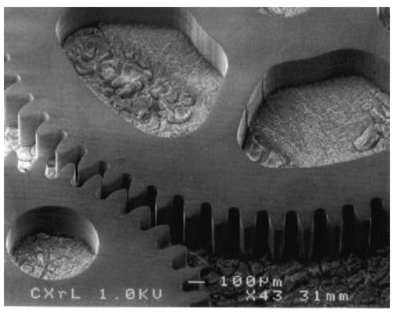


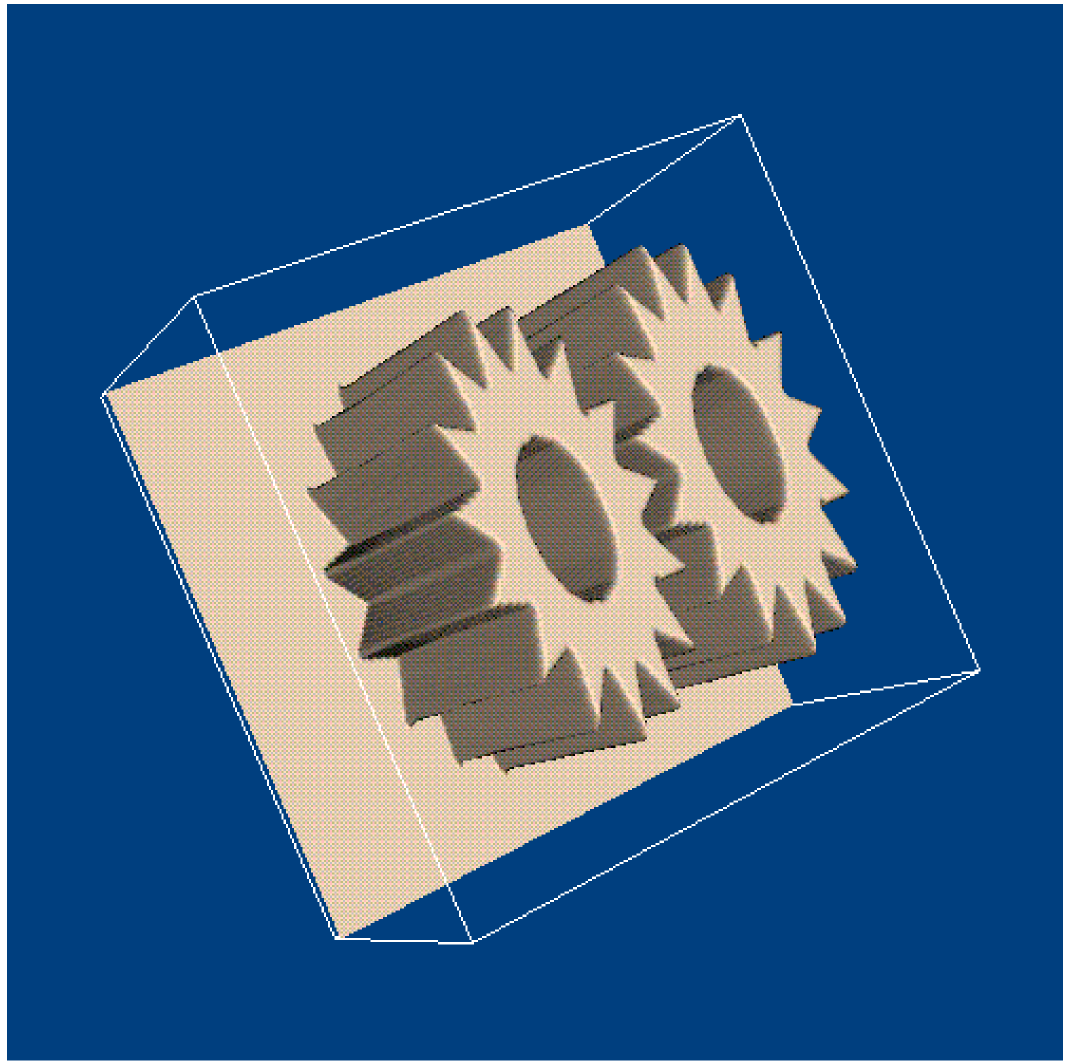




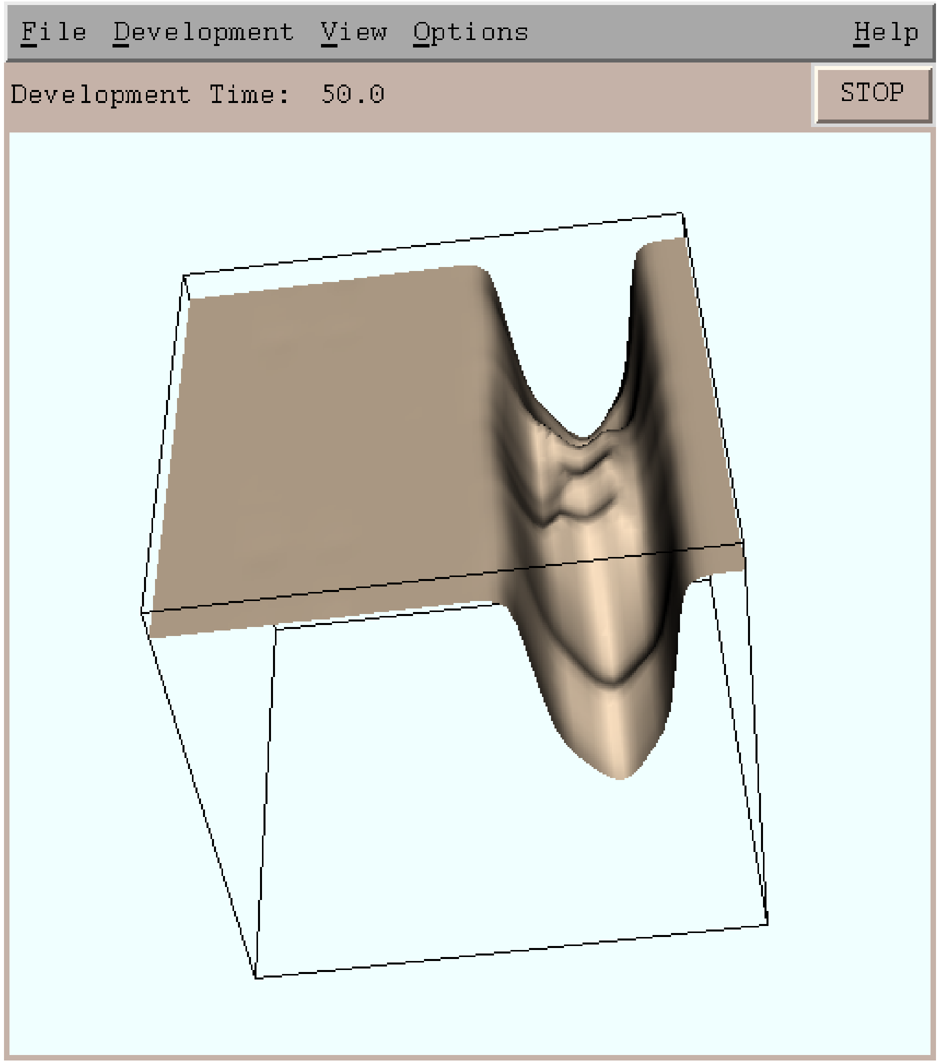


Application: MEMS using LIGA





Virtual Development Tool



Resist parameter extraction

- The model must be tuned for each resist using empirical data.

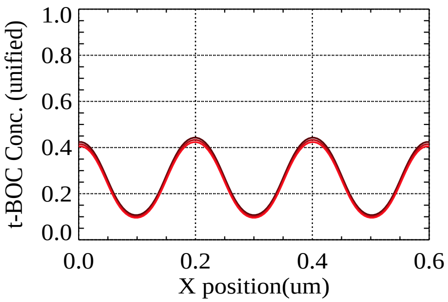
  Dissolution Rate The dissolution rate as a function of time.

  Depth Dependence Needed for predicting “T tops” and “footing” often seen for many chemically amplified resists such as APEX-E.

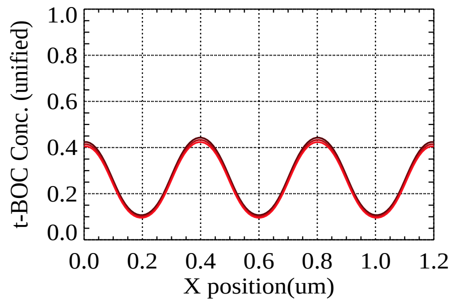
  Feature Size Dependence There is an observed dissolution rate difference for features of different sizes ($\leq 150nm$), but it is unclear how to obtain this data reliably.

- Only the dissolution rate function is essential for $1st$ order modeling. Rest are used for “fine tuning”.

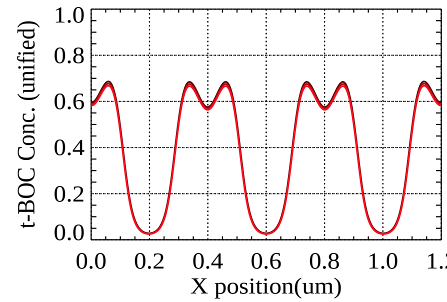
Limitations – effect of resist dimension



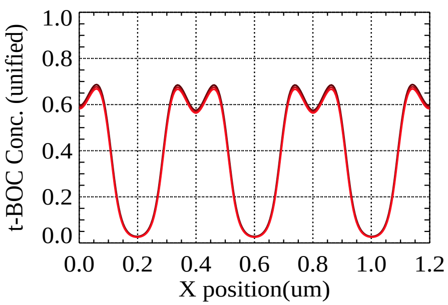
0.1 μm CD t-BOC profile



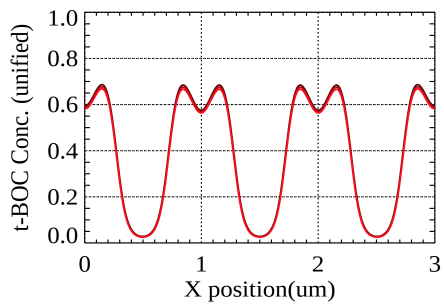
constructed 0.2 μm CD t-BOC profile



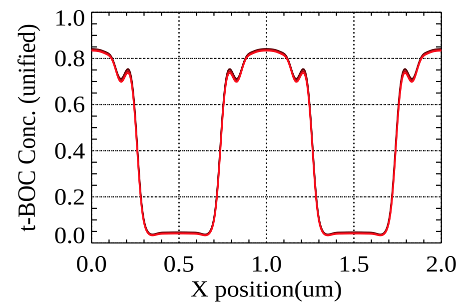
0.2 μm CD t-BOC profile



0.2 μm CD t-BOC profile

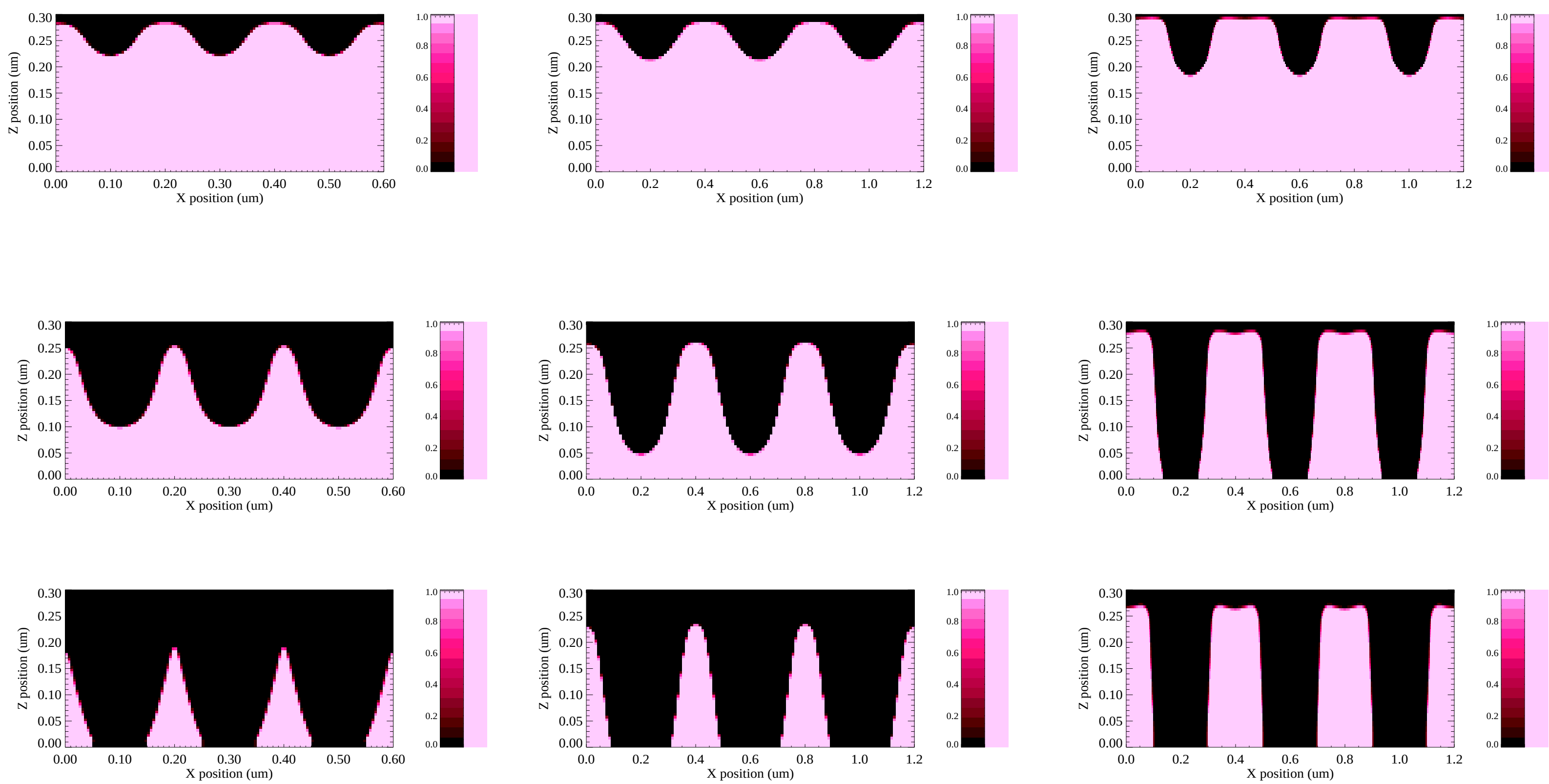


constructed 0.5 μm CD t-BOC profile



0.5 μm CD t-BOC profile

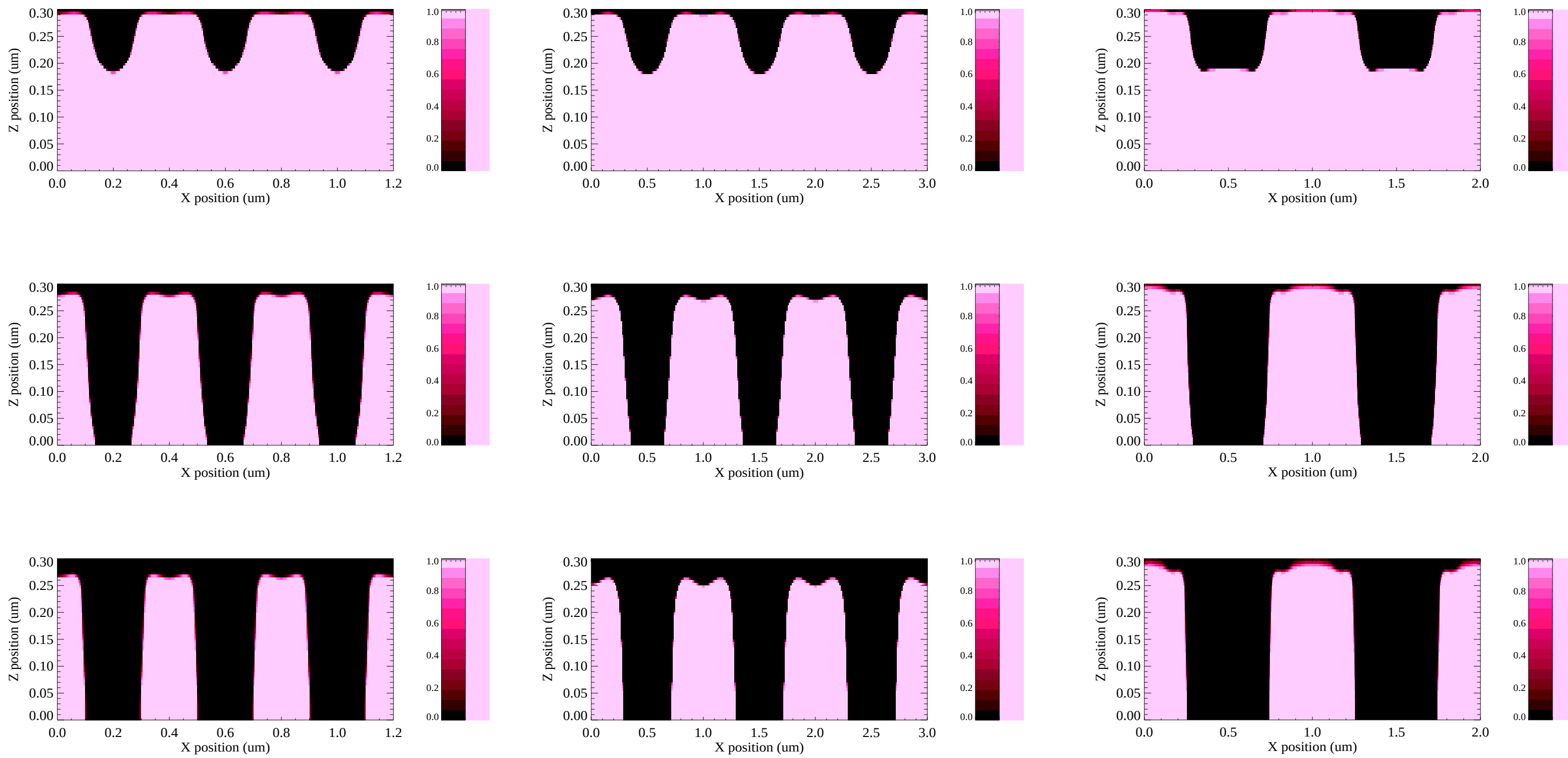
Effect of resist dimension – Y. Zhu model



0.1 μm CD *Constructed 0.2 μm CD* *0.2 μm CD*

Time evolution of the resist: only difference of the input between 1st and 2nd column is the scaling (shape is the same).

Effect of resist dimension – Y. Zhu model



0.2 µm CD *Constructed 0.5 µm CD* *0.5 µm CD*

Time evolution of the resist: only difference of the input between 1st and 2nd column is the scaling (shape is the same).

Summary and discussion

- Two different implementations based on level sets:
  - *time-dependent solution, and*
  - *fast marching set or steady-state solution*

- Demonstrated extendibility to multiple application domains.

- Need better characterization of dissolution rate function for better prediction of the resist front as a function of time (eg., depth dependence of dissolution rate, surface effects, etc).

- Need for “intelligent” topography descriptor for modeling complex geometries.

- Natural extension to etching models.

Conclusions

- New dissolution model using front-propagation algorithm based on level set methods by Sethian:
  - Numerically robust for fronts moving under complex conditions.
  - Accurate determination of front position at any time.
  - Topological changes such as cusps, corner development, etc., are naturally handled by the algorithm.
- The faster steady-state solution is sufficient for most resist dissolution modeling needs.
- The algorithmic aspect of “wave-front” photoresist development over a large range of dimensions is solved.

Future Work

- Implementation of local properties such as variations in the developer concentration.

- Extraction of the *front speed*, F, as a function of dose, depth, material properties, etc., for more accurate prediction.

- Heuristics to better handle complex geometries.

- Calibration to experimental results remains the most important challenge.

- Anisotropic etching model.