Line Pattern Collapse

Modeling and Prediction in Semiconductor Processing

Derek Bassett[a], Michael Carcasi[a], Wallace Printz[a], Shinichiro Kawakami[b], Yuichiro Miyata[c]

[a]Tokyo Electron America, 2400 Grove Blvd, Austin, TX, USA 78741
[b]TEL Technology Center, America, LLC., 255 Fuller Rd., STE 244, Albany, NY, USA 12203
[c]Tokyo Electron Kyushu, Fukuhara, Koushi-shi, Kumamoto, 869-116, Japan

TOKYO ELECTRON

COMSOL CONFERENCE BOSTON 2012

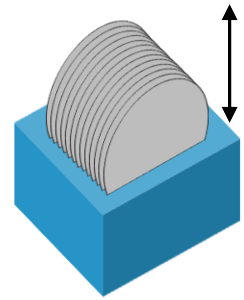
50 Years

Outline

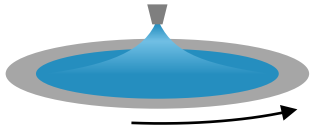
- **Microlithography introduction**
- **Pattern Collapse**
- **Finite Element Model**
- **Results and Conclusions**

Semiconductor Production

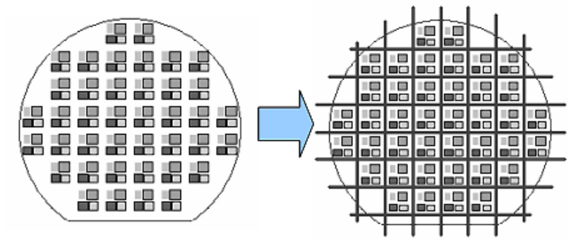
- Semiconductor device manufacturing involves many ‘wet’ processing steps
- Microchips are made by dicing wafers
- Industry aggressively follows Moore’s Law
- As features get smaller, they become weaker and more prone to damage

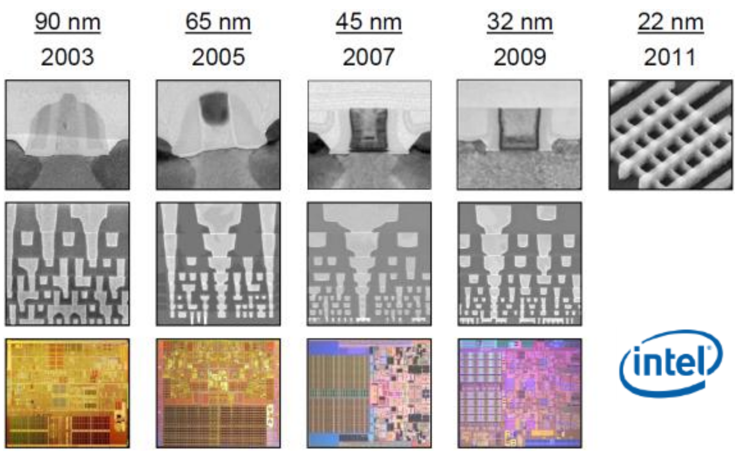


batch process



single wafer process





Intel press release Apr 5, 2012

Basic Microlithography Process

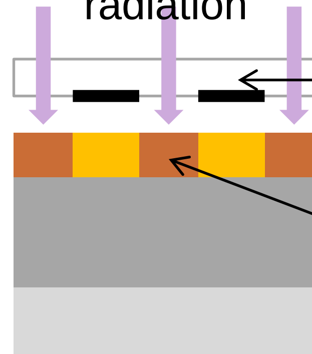
Initial material stack on wafer

photoresist polymer

silicon dioxide

silicon substrate

Expose to radiation



use mask to create pattern

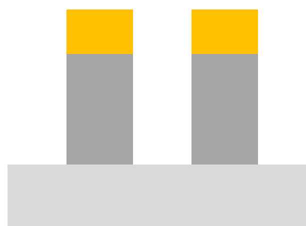
photochemical reaction makes exposed photoresist soluble

Remove exposed photoresist

wet cleaning process dissolves photoresist

wafer must be dried afterwards

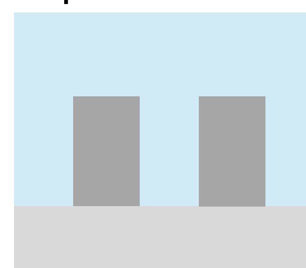
Etch through feature



uses plasma or chemical process

remaining resist creates pattern

Remove remaining photoresist



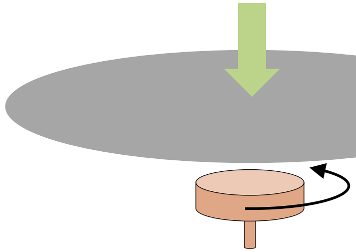
wet cleaning process dissolves remaining photoresist

wafer must be dried afterwards

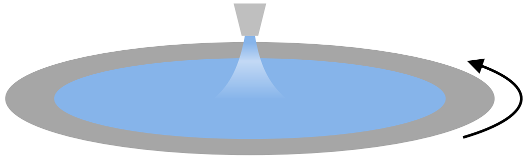
Modern CPU production requires 40~50 lithography steps, and ~100 or more wet cleaning steps.

Single Wafer Wet Process

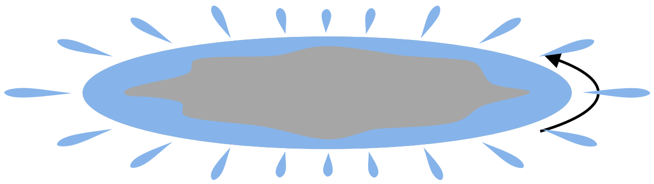
300mm wafer is placed onto a spin chuck that allows it to be spun at desired speed



Chemical solution or washing liquid is dispensed onto wafer surface while wafer spins

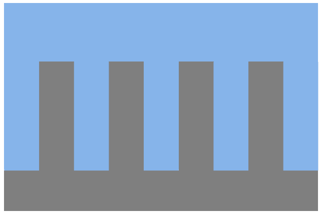


After process is complete, wafer is spun rapidly (~2000 RPM) to dry the wafer

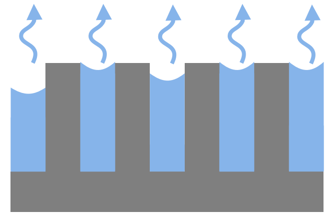


Macro-scale process, nano-scale problems
Multiscale modeling problem

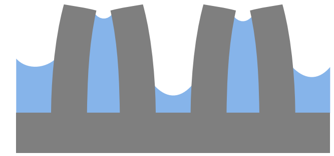
Wafer Drying and Pattern Collapse



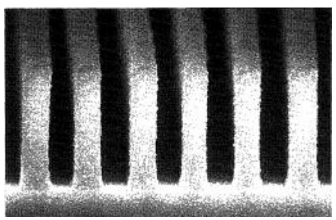
Fluid on wafer



Evaporation of fluid

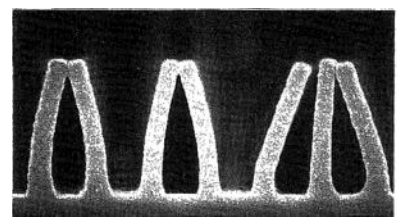


Bending of features



Structure returns to unstressed position

Good



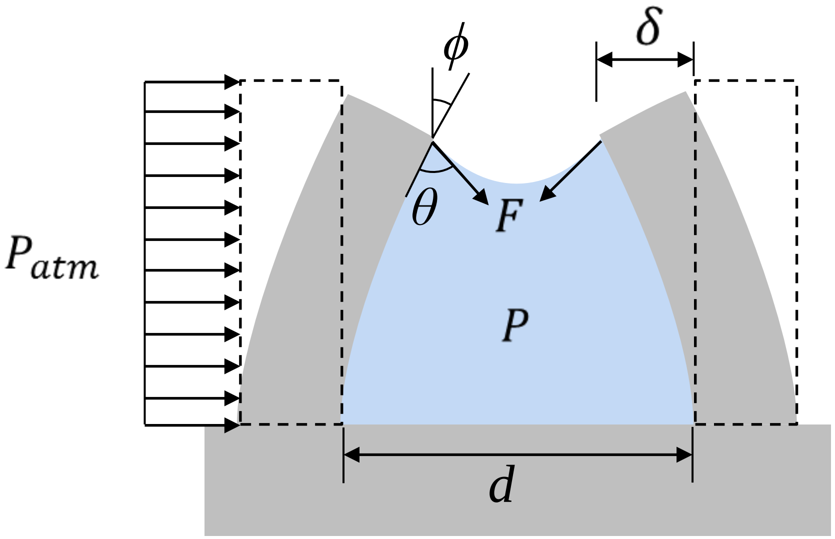
Features touch, van der Waals forces dominate

Bad

Defect causes device failure

Images from T. Tanaka, M. Morigami, and N. Atoda, “Mechanism of Resist Pattern Collapse during Development Process”, *Jpn. J. Appl. Phys.* **32** pp 6059 (1993).

Physics of Surface Tension



Laplace Pressure

$$\Delta P = P_{atm} - P = \frac{2\gamma\cos(\theta - \phi)}{d - 2\delta}$$

Surface Tension

$$F_x = \gamma\sin(\theta - \phi)$$

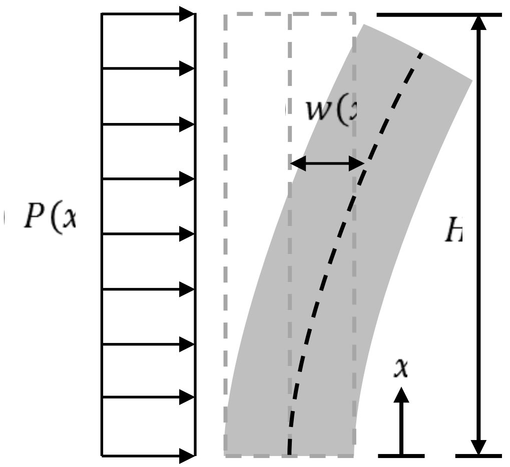
- Two separate effects from surface tension: Laplace pressure ΔP and force at the contact line F_x
- Laplace pressure is inversely proportional to the gap width $d - 2\delta$, so the force on the sides *increases* as the gap gets smaller
- Surface tension force pulls at the feature edges and contributes to feature collapse even when the contact angle is 90°

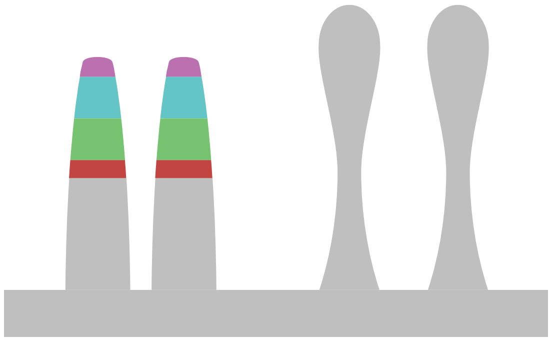
Traditional Modeling Methods

- Euler beam equation used for modeling
- Combine with surface tension model to predict when collapse occurs
- Analytic solution
  - Simple to use
  - Rectangular prism only
- Numerical solution
  - Curved shapes
  - Multiple materials
  - Symmetric shapes only

Euler-Bernoulli Equation

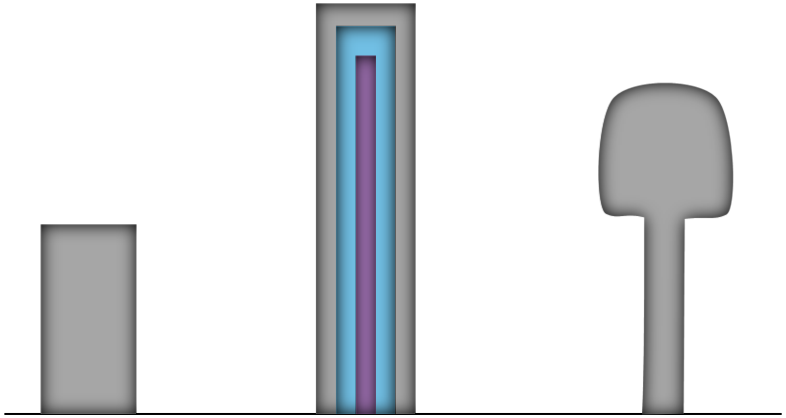
$$\frac{d^2}{dx^2}\left(EI\frac{d^2w}{dx^2}\right) = P(x)$$

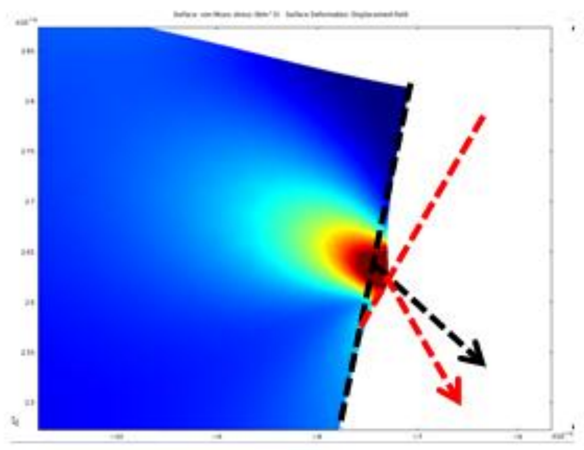




Limitations of Euler-Bernoulli Beam Model

- Beam equation is not accurate for aspect ratio $AR < 8$
- Difficult to model laminar materials
- Inaccurate with sudden changes in feature width
- Model does not incorporate local deformations
- Photoresist polymer structures are typically
  - $AR = 2$ or less
  - Soft outer shell
- **Conclusion**: New model needed for more accurate solution



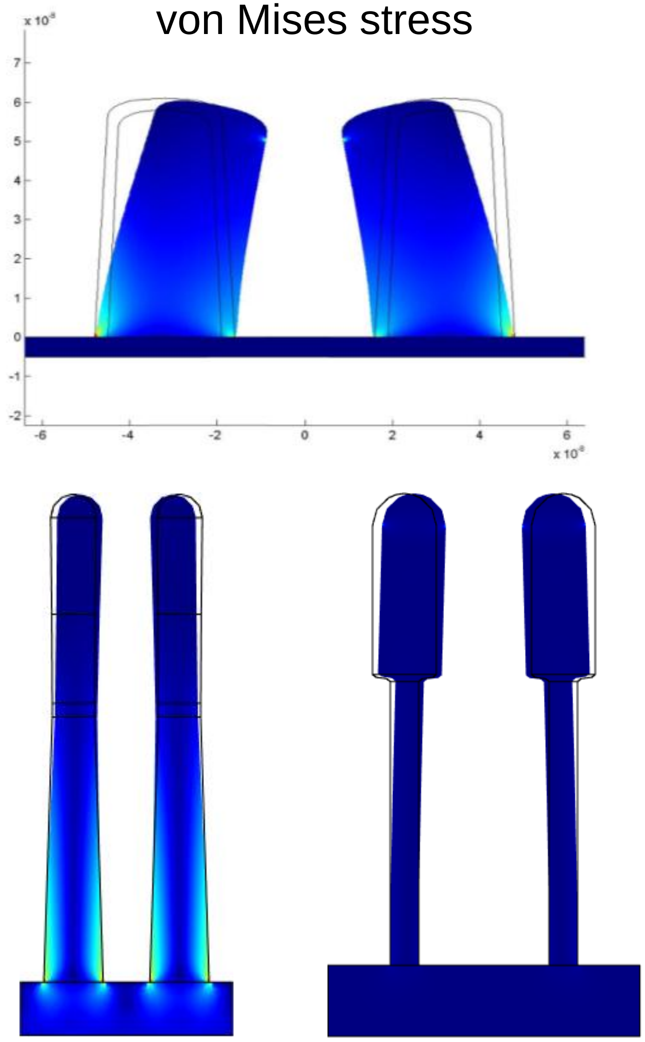


soft material deforming at contact line

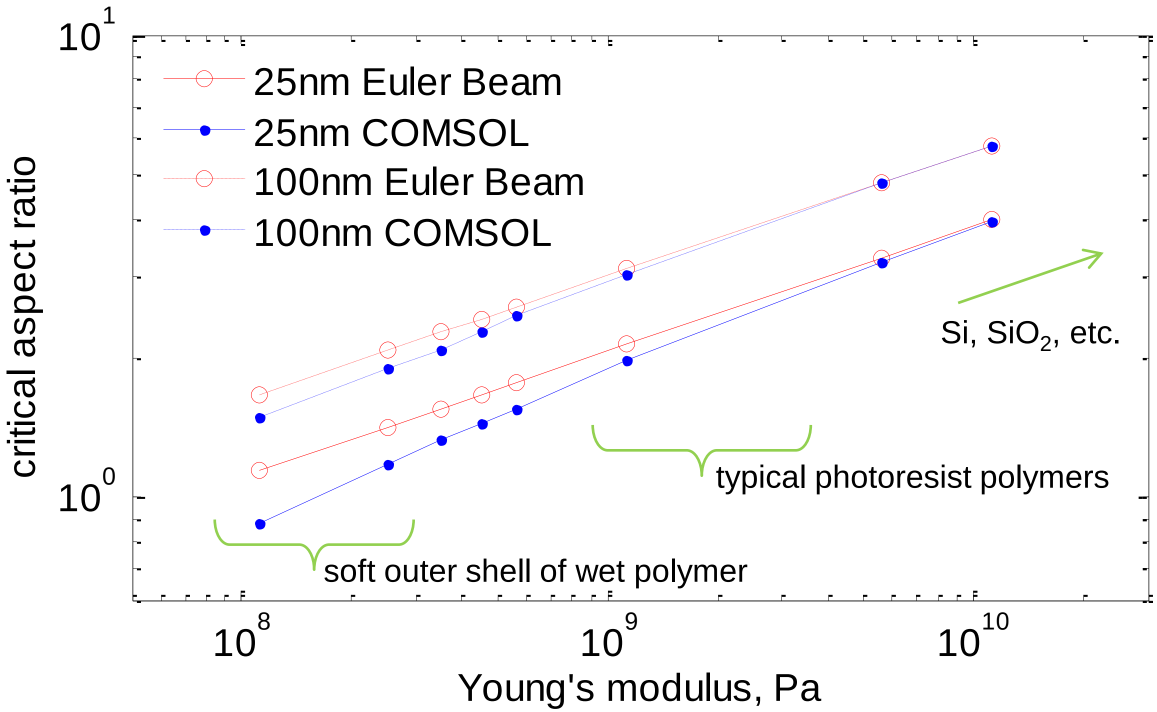
Finite Element Model

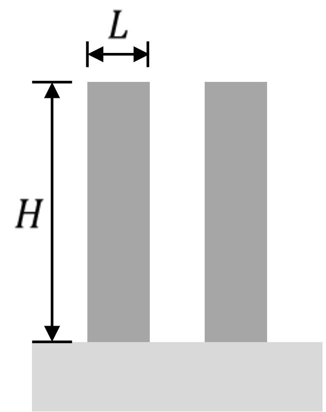
- Use COMSOL to build FE model of feature
  - Linear elastic material model
  - Geometric nonlinearity
  - Moving mesh interface (ALE)
- Capillary forces as boundary conditions
  - No need to solve Navier-Stokes and free-surface problem
  - Surface tension force distributed over an area comparable to molecular scale and falls off with distance
- Move contact line down
  - Simulate evaporation of liquid
- Use convergence results to determine feature stability
  - Convergence of solution implies stability
  - Non-convergence implies collapse of feature

von Mises stress



Euler Beam vs FE Simulations



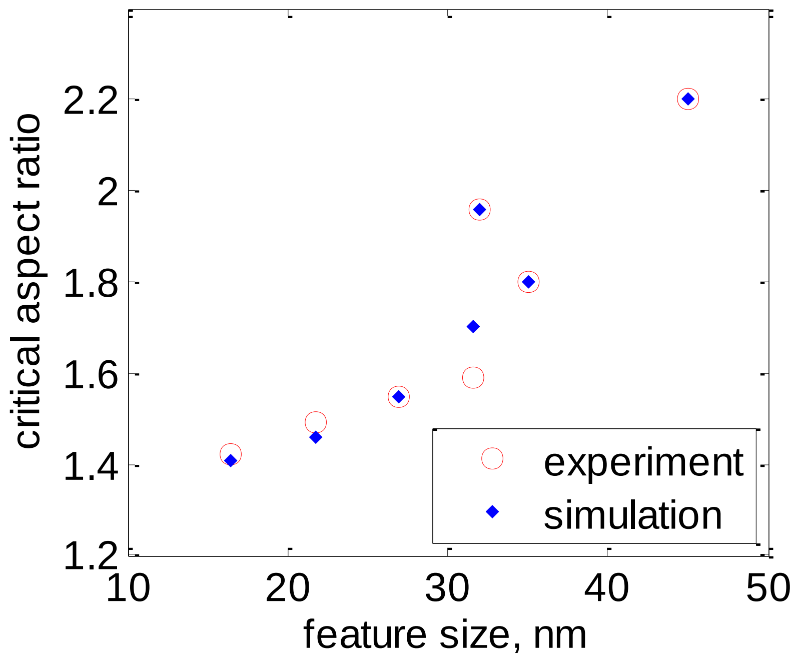


$$AR = \frac{H}{L}$$

- Compared Euler beam simulations and FE simulations by finding maximum stable aspect ratio AR for a given critical dimension L and material Young's modulus
- Results show that accuracy of Euler beam simulations decreases as material gets softer and as size decreases
- **Conclusion:** FE simulations should be used for small photoresist features

Verification of Finite Element Model

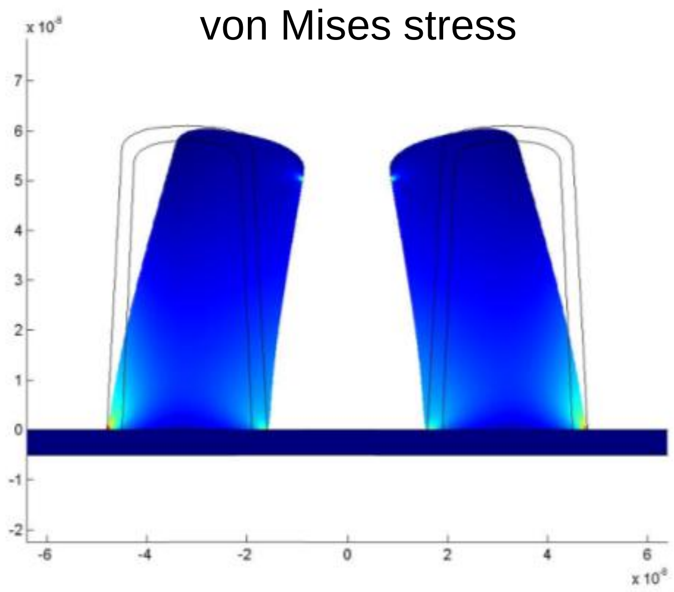
- Experimental data was obtained from literature for polymer resist features of various sizes
- FE simulations were conducted to mimic the experimental parameters
- Successfully verified the critical aspect ratio for collapse by simulation
- **Conclusion**: FE model may be used for prediction of pattern collapse in future work



Experimental data from Yoshimoto, K., Higgins, C., Raghunathan, A., Hartley, J., Goldfarb, D., Kato, H., Petrillo, K., Colburn, M., Schefske, J., Wood, O., Wallow, T., *"Revisit Pattern Collapse for 14nm Node and Beyond"*. Proc. SPIE 7972, (2011).

Conclusions

- COMSOL model able to accurately model line pattern collapse
- Better accuracy than other models for small and soft resist polymer features
- Can use to predict feature stability for future smaller structures



Model Building Summary

- **Advantages of using COMSOL**
  - Simple to include user-defined equations and BC's
  - Easily scriptable with MATLAB
- **Simulation time**
  - 10 seconds per run
  - Thousands of runs required to make plots
  - Total solution time = 1 to 2 days
- **Project time**
  - Six months
- **Strategies for successful model**
  - Start simple, gradually increase complexity
  - For very long formulas, write in text editor and then paste into COMSOL
  - Be sure you can reproduce results from analytic/asymptotic models
  - First build model in COMSOL, then export as MATLAB file

Questions