MEMORANDUM

TO: Dr. Roger Bonnecaze

FROM: Cyrus E. Tabery

DATE: May 4, 2000

SUBJECT: A report on shear and bending of a resist beam under the influence of surface tension forces.

Motivation

A model is sought to describe the behavior of high aspect ratio resist features under the influence of surface tension forces. Both bending or plastic deformation failure and adhesive failure have been observed. A qualitative failure mechanism and a quantitative predictive model describing the conditions resulting in failure will facilitate the use of resist patterns in microelectronic and micro-electromechanical devices. Supercritical develop or drying is an option when features of extremely high aspect ratio are required and will eliminate the forces on the resist that result in failure.

Introduction

After develop, all of the gaps between resist features are filled with developer. This liquid causes capillary forces on the resist beams and for large aspect ratios, large stresses are induced which can result in feature collapse. First, the end feature in a group of nested lines is investigated for various pitches and aspect ratios for shear and bending failure. The influence of the end line can propagate through dense lines causing long range deformation of the resist features. Finally, a crack propagation model in conjunction with information concerning the fracture toughness of the resist substrate interface is used to determine when adhesive failure is important. The important parameters and definitions for the model are presented below in Table 1 and Figure 1.

Table 1. A summary of important parameters for the system studied.

Parameter	**Symbol**	**Value**
Resist Modulus	E	$\sim 10^9$ N/m^2
Developer Surface Tension	γ	~70 mJ/m^2
Aspect Ratio	ε	.1-100
Feature Pitch	P	10-10,000 nm
Resist Thickness	εP/2	0.1-10 μm

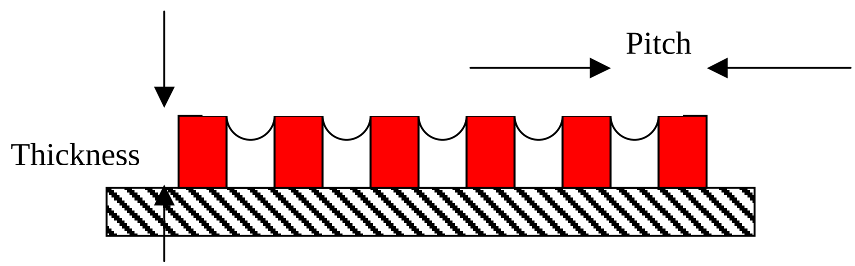

Figure 1. Geometry of resist and liquid system studied.

Theoretical Development

The presence of a curved liquid vapor interface results in a pressure difference across the resist beam. The theory of elastic solids is used to describe the deformation of the resist beam assuming adhesive failure is not important.

Consider the structure shown below in Figure 2. The Young-Laplace equation (1) predicts the pressure on the resist beam for a perfectly wetting fluid.

$$\Delta P = \gamma \nabla \cdot \underline{n} = \frac{\gamma}{R} \qquad (1)$$

This pressure results in a reaction force R, and a moment M_y, on the resist beam of moment of inertia I_y described by equations (2-4).

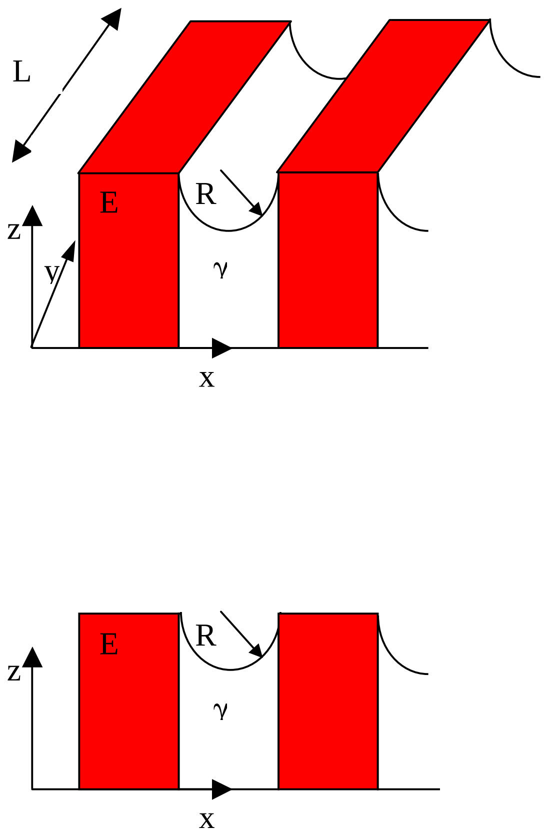

Figure 2. Resist coordinate system.

$$R = \Delta PL\frac{\varepsilon P}{2} \qquad (2)$$

$$M_y = \int_0^z \Delta PLz'dz' = \Delta PL\frac{z^2}{2} \qquad (3)$$

$$I_y = \frac{LP^3}{96} \qquad (4)$$

First, the shear stresses in the beam are considered. This is given by the ratio of the force on a single plane divided by the area of that plane as shown in equation (5). This stress has only a linear dependence with aspect ratio thus shearing failure is unimportant.

$$\tau_{xy} = \frac{\Delta PL(\frac{\varepsilon P}{2} - z)}{\frac{PL}{2}} = \Delta P(\varepsilon - \frac{2z}{P}) \qquad (5)$$

Tensile and compressive stresses are also induced in the beam from the capillary pressure. This stress is linear in x and quadratic in z (the distance from the substrate) as shown in equation (6). This equation can be found in the literature (Namatsu, 1999).

$$\begin{aligned} \sigma_z &= \frac{M_y}{I_y} x = \frac{48\Delta P x z^2}{P^3} \\ \sigma_{\max} &= 12\frac{\gamma}{P}\varepsilon^2 \end{aligned} \qquad (6)$$

This however ignores the fact that any elastic deformation will causes a change in the capillary pressure on the resist beam. This requires treatment of the resist as an elastic solid. The fourth order ODE in equation (7) describes the deformation, v, of the resist beam (Muvdi, 1984). The boundary conditions imposed on the beam are shown in equation (8), which result in a deformation solution shown in equation (9).

$$EI_y \frac{d^4 v}{dz^4} = \Delta PL \qquad (7)$$

$$
\begin{aligned}
&v(z=0)=0 \\
&\frac{dv}{dz}(z=0)=0 \\
&EI_y \frac{d^2v}{dz^2}(z=0)=M_y(z=\frac{\varepsilon P}{2}) \\
&EI_y \frac{d^3v}{dz^3}(z=0)=R
\end{aligned}
\tag{8}
$$

$$
v(z)=\frac{384\gamma}{EP^4}(z^4-2\varepsilon Pz^3+\frac{3}{2}\varepsilon^2P^2z^2) \tag{9}
$$

Now, the maximum deformation at the top of the resist causes a change in the capillary pressure. The new capillary pressure is given in equation (10).

$$
\begin{aligned}
&\Delta P=\frac{4\gamma}{P-v_{\max}} \\
&v_{\max}^{(o)}=3\varepsilon^4\frac{\gamma}{E}
\end{aligned}
\tag{10}
$$

Using this perturbation on the capillary pressure yields a series solution for the maximum tensile stress (12) and the maximum deflection (11). The convergence of the series solution is also shown in equation (11).

$$
\begin{aligned}
&v_{\max}^{(i)}=3\varepsilon^4\frac{\gamma}{E}\sum_{m=0}^{i}\left(-6\varepsilon^4\frac{\gamma}{EP}\right)^{-m} \\
&\sum_{m=0}^{\infty}(-x)^{-m}=x+1
\end{aligned}
\tag{11}
$$

$$
\sigma_{\max}=12\frac{\gamma}{P}\varepsilon^2\left(\frac{1}{1-\frac{3\varepsilon^4\gamma}{PE}-\frac{18\varepsilon^8\gamma^2}{P^2E^2}}\right) \tag{12}
$$

In Figure 3 below, the zero order solution of equation (6) is compared to the full perturbation solution shown in equation (12). Note that for high aspect ratios the errors of the zero order solution are several orders of magnitude. Also note that elastic bending is important over the entire range of aspect ratios studied.

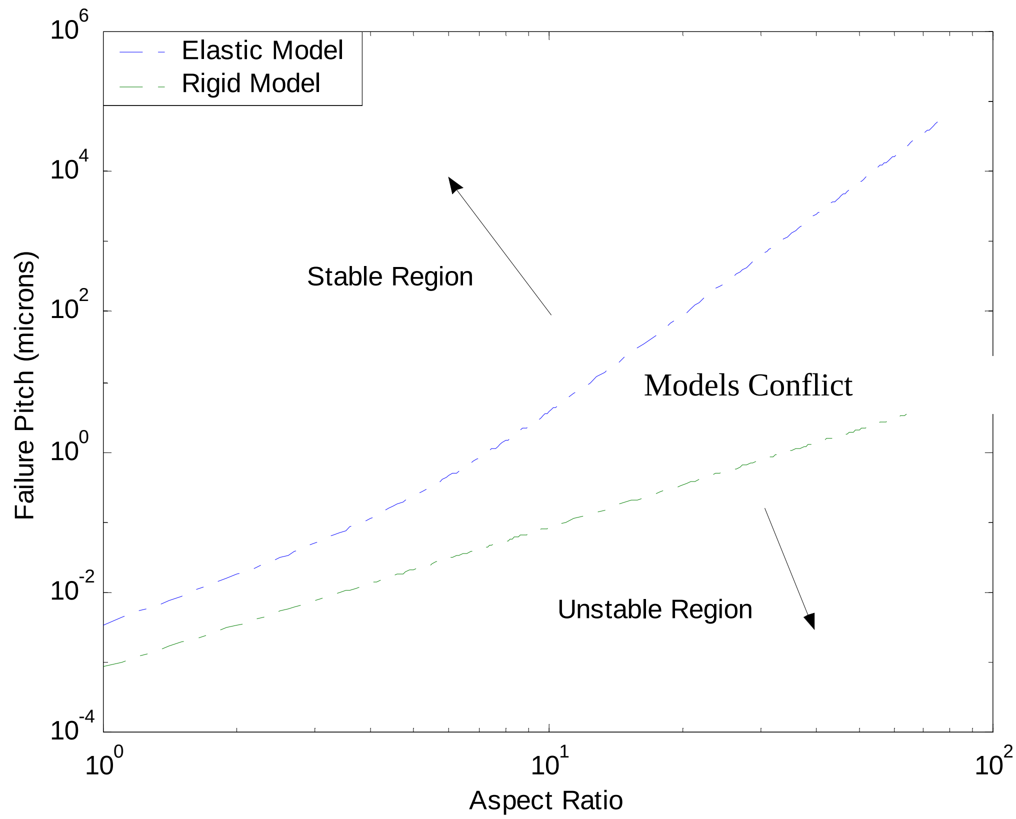

Figure 3. Zero order and perturbation solution for stability for a range of aspect ratios.

An interesting observation was made on resist features that were made of water soluble polymer(Yamada, 2000). Here the resist features failed in bending not only at the end of the line space patterns but the failure propagated through the nested features forming pairs of collapsed features. This is shown in Figure 4.

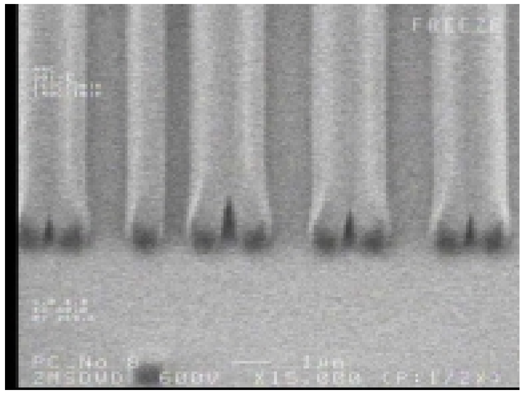

Figure 4. Resist beam bending failure in nested features.

Conclusions

Elastic deformation is important in considering the failure of resist beams under the influence of surface tension. Previous results using a rigid model for the resist beam grossly overestimates the region of stability. Analysis of a simple dimensionless number , the Tabery number, will reveal when elastic deformation of the resist beam will be important. This is shown in equation (13). Large Tabery numbers mean that feature collapse is likely and elastic deformation of the resist beam is important. The critical Tabery number resulting in failure could be measured experimentally.

$$N_{Ta} = \frac{\varepsilon^4 \gamma}{PE} = \frac{Deformation\_scale}{Feature\_scale} \qquad (13)$$

Appendices

References Cited

1. Budynas, R.G. Advanced Strength and Applied Stress Analysis. McGraw-Hill 1977
2. Muvdi, B.B., Mcnabb, J.W. Engineering Mechanics of Materials. 3rd ed. Macmillan Publishing 1984
3. Namatsu, H., Yamazaki, K., Kurihara, K. "Supercritical Drying for Nanostructure Fabrication without Pattern Collapse." Journal for Microelectronic Engineering. Vol 46. 1999.
4. Buckley, D.H. Surface Effects in Adhesion, Friction, Wear, and Lubrication. Tribology Series #5. Elsevier 1981
5. Richards, R.W., Peace, S.K. Polymer Surfaces and Interfaces 3. John Wiley & Sons. 1999.
6. Vakula, V.L., Pritykin, L.M. Polymer Adhesion: Basic Physicochemical Principles. Ellis Horwood. 1991.
7. Yamada S., Rager T., Owens J., Willson C.G., "Design and study of aqueous-processable positive tone photoresists," Proceedings of SPIE Microlithography 2000.

Sample Calculations