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Pattern Collapse

Chris A. Mack, *Austin, Texas*

Not long ago, defining what an acceptable resist profile looked like was relatively easy. First and foremost, the feature must have the correct critical dimension (CD) within some given tolerance. The more enlightened lithographers might also specify a minimum acceptable resist height and sidewall angle to ensure good pattern transfer. Today, for lithography below 100 nm, the simplicity of those days seems almost quaint. Two new problems bedevil the already overwhelmed lithographer: line edge roughness and pattern collapse. Saving line edge roughness of the next column, here we will discuss pattern collapse, develop a simple 1D model for collapse, and investigate the impact of collapse on the focus-exposure process window.

Pattern collapse occurs for tall, narrow resist lines when some force pushing against the top of the line causes the profile to bend and eventually break or peal off the substrate (Figure 1). As one might expect, the taller and narrower the line, the easier it would be to push it over. But where does this pushing force come from? After development, the wafer is rinsed with deionized water and then air-dried. As the water dries, surface tension from the receding water will pull on the top of the resist feature. Of course, if the water is symmetrically receding from both sides of the line, the two forces on each side will cancel. If, however, there is an asymmetry and the water from one side of the line dries off faster than the other side, the resultant force will not be zero.

Figure 2a shows what is probably the worst case for generating asymmetric surface tension forces during after-rinse drying: two isolated parallel lines with a small gap between them. The large open areas to each side of the pair quickly dry while the small space between them requires a much longer time for removal of the water. As a result, there will be a point in the drying cycle where the top meniscus of the water in the gap will line up with the top of the resist features, producing a capillary force, driven by the surface tension of water, that will pull the two resist lines towards each other (Figure 2b). If the force is great enough to cause the two resist tops to touch each other, these feature are said to have collapsed. Other patterns of lines and spaces (a five bar pattern, for example) will behave very similarly to this two-bar test pattern for at least the most outside lines.

Tanaka [1] developed a simple cantilever beam mechanical model for this pattern collapse situation. The capillary pressure (force per unit area) along the side of the resist line covered by water is equal to the surface tension σ of the water-air interface divided by the radius of curvature R of the meniscus. The radius of curvature in turn is determined by the contact angle θ of the water-resist interface and the spacewidth w_s. Before any bending occurs, this curvature will be

$$R = \frac{w_s}{2\cos\theta} \tag{1}$$

For a resist thickness *H*, the resulting capillary force per unit length of line is

$$F = \frac{\sigma H}{R} = \frac{2\sigma H \cos\theta}{w_s} \tag{2}$$

As the resist line starts to bend, however, this force increases. The radius of curvature of the meniscus decreases as the two resist lines come closer together, causing an increase in the capillary force.

Since the force caused by the surface tension is always perpendicular to the air-water interface, a contact angle of zero (very hydrophilic case) causes the maximum force pulling the resist line towards the center of the space. Resists tend to be somewhat hydrophobic, so that contact angles between water and resist are often in the 50 – 70° range (though these measurements are for unexposed resist, not the partially exposed and deblocked resist along the profile edge where the contact angle should be less). Note that the capillary force increases with the aspect ratio of the space ($A_s = H/w_s$) and with the surface tension of water, which at room temperature is about 0.072 N/m (72 dyne/cm).

The bending of the resist line can be described as an elastic cantilever beam. The important resist material property of mechanical strength is the Young's modulus, *E*, which is a measure of the stiffness of the resist and is higher for resists with high glass transition temperatures. Resists have been measured to have Young's modulus values in the range of 2 – 6 GPa with the high end of the range corresponding to Novolak resists and the low end of the range for ArF resists [1,2]. Applying a force *F* to a line of width w_l causes that line to move (sway) into the space by an amount δ given by

$$\delta = \frac{3}{2}\left(\frac{F}{E}\right)\left(\frac{H}{w_l}\right)^3 \tag{3}$$

Note that the amount of bending is proportional to the cube of the aspect ratio of the resist line, and thus will be very sensitive to this aspect ratio.

As the resist line bends, the pulling of the line by the capillary force is countered by a restoring force caused by the stiffness of the resist. Eventually a 'tipping point' is reached where the increasing capillary force exceeds the restoring force of the resist and the line collapses. Tanaka calculated this critical point to occur when

$$\frac{E}{\sigma} \le \frac{4}{w_s} A_l^3 \left[3A_s\cos\theta + \sin\theta + \sqrt{9A_s^2\cos^2\theta + 6A_s\cos\theta\sin\theta} \right] \tag{4}$$

where A_s is the aspect ratio of the space and A_l is the aspect ratio of the line (H/w_l). If the contact angle is less than about 80° and the aspect ratio of the space is high (that is, we are in an interesting regime where pattern collapse is likely to be a problem), the square root can be approximated with the first terms of a Taylor series to give a somewhat more approachable result:

$$\frac{E}{\sigma} \le \frac{8}{w_s} A_l^3 \left[3A_s \cos\theta + \sin\theta \right] \qquad (5)$$

Equation (5) tells us what affects pattern collapse and therefore what we can do to try to reduce pattern collapse. Resist chemists could make the resist stiffer by increasing the Young's modulus E (similar to increasing T_g, the glass transition temperature), something that is hard to do without altering other very important resist properties. The water-air surface tension can be reduced by adding surfactant into the rinse liquid. Surfactants can easily reduce the surface tension by a factor of 2 or 3 [2]. Contact angle of water to the resist also influences collapse. The worst case (maximum value of $3A_s\cos\theta + \sin\theta$) occurs at an angle of $\tan^{-1}(1/3A_s)$ which is generally less than 10º. Thus, hydrophilic resists produce greater pattern collapse. Making the resist more hydrophobic will help (this, incidentally, is also a goal for immersion lithography). The aspect ratio of the space is important, but is less so for hydrophobic resists (small $\cos\theta$). The space width has a direct impact on collapse, with smaller spaces increasing the capillary force and thus the likelihood of collapse. By far the most critical factor is the aspect ratio of the line. Since the tendency to collapse increases as the line aspect ratio cubed, small changes in this factor can have big consequences.

Putting some numbers into the equation, ArF resists will have E/σ in the range of about 35 nm^{-1} assuming no surfactants in the water. Assuming a 60º water-resist contact angle, consider a 100 nm space with a space aspect ratio of 3. The maximum aspect ratio of the line will be 4.3 (a 70 nm linewidth before the line collapses). If the space were shrunk to 50 nm keeping the space aspect ratio at 3, the maximum line aspect ratio drops to 3.4 (a 44 nm linewidth). As another example, when printing a pair of 45 nm equal lines and spaces in a resist of thickness 141 nm, overexposure will cause the patterns to collapse before they reach a 10% CD error. Pattern collapse can become a process window limiter before CD, sidewall angle, or resist loss reach their specifications.

Equation (5) can also predict the tendency towards pattern collapse as a function of line/space duty cycle. To simplify, assume that the contact angle is small enough that ignoring the $\sin\theta$ term in equation (5) produces very little error (this approximation is not so bad, even for a 60º contact angle). For this case, a given pitch equal to $w_s + w_l$ will have the minimum tendency to collapse when the linewidth is 50% bigger than the spacewidth (a 3:2 linewidth to spacewidth ratio). All other duty cycles will have an increased chance of pattern collapse. For a fixed duty cycle, the likely hood of collapse goes as the resist thickness to the fourth power, and as one over the pitch to the third power.

The two-dimensional model used here is really a worst case since it assumes very long lines and spaces. For shorter lines that are connected to another resist feature at one or both ends, the other features can give support to the line, inhibiting the twisting that would be required to make the line collapse. However, it is likely that CMOS device levels like poly and metal 1 will always have some patterns that will behave close to the worst case presented here. And the trend towards smaller feature sizes and constant or even greater aspect ratios will only make the problem of pattern collapse worse in the future.

References

1. T. Tanaka, et al., “Mechanism of Resist Pattern Collapse during Development Process”, Jpn. J. Appl. Phys., Vol. 32, Part 1, No. 12B (Dec. 1993) pp. 6059 – 6064.

2. J. Simons, et al., “Image Collapse Issues in Photoresist”, *Advances In Resist Technology and Processing XVIII, Proc*., SPIE Vol. 4345 (2001) pp. 19 – 29.

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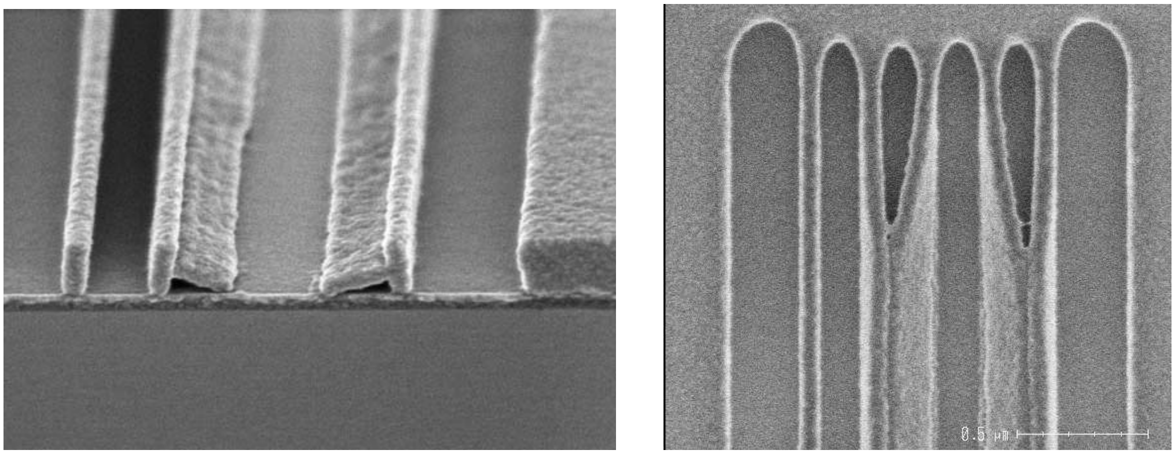

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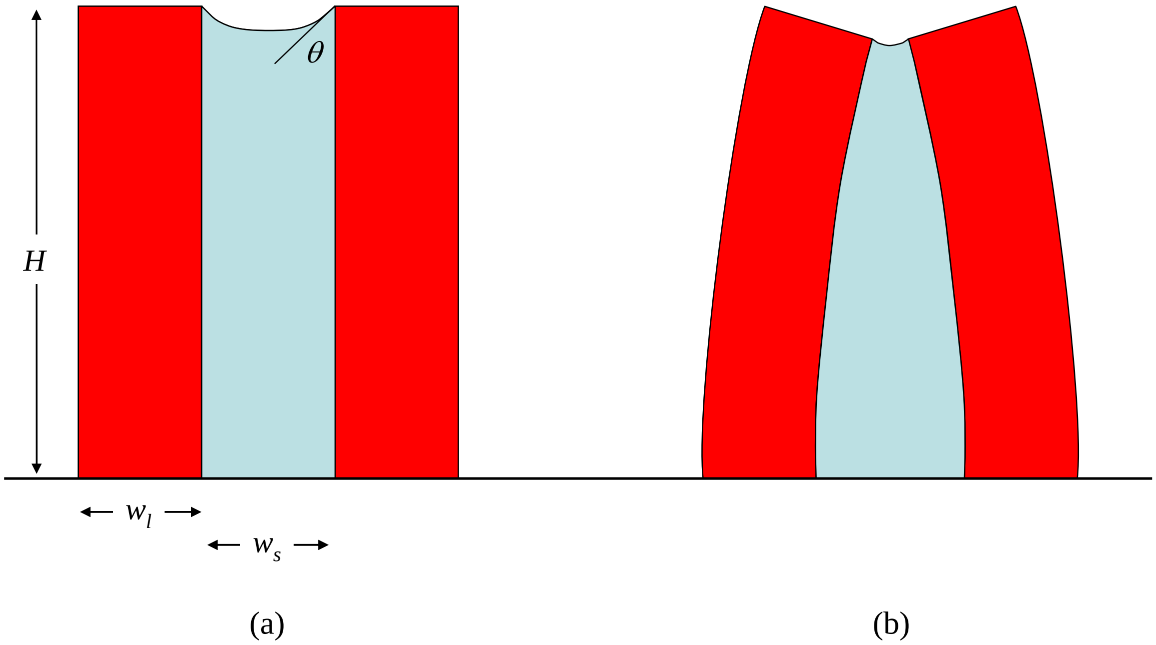

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