Resist profile control in E-beam lithography

by Sherry J. Gillespie

Imaging studies have confirmed that a desired resist profile can be obtained by selecting the appropriate combination of process parameters: dose, interrupted development, pattern bias, and resist thickness. Bias sensitivity of the resist image to process parameters was measured using a positive diazo resist with nonlinear development characteristics on an IBM EL-3 E-beam tool. Because of superior bias stability, top-edge imaging with undercut profiles in a single-layer resist was found to provide many of the imaging advantages of a multilayer system. Sufficient resolution and image quality are obtained to extend the application of a single-layer resist system to 1-μm lithography.

Introduction

Extending the usability of single-layer resist systems to small dimensions is advantageous because of the higher cost and complexity of alternative multilayer systems. However, a major concern when using a single-layer resist system is bias control of the edge from which the image is to be transferred. (Bias is the deviation of measured width from design width.)

A set of experiments was performed in which the parameters that are crucial to resist profile and bias control were examined. The objective was to determine the feasibility of using single-layer resist at 1-μm geometries.

The resolution-limiting factor in E-beam lithography is electron scattering in the resist, which produces lateral spread in absorbed energy [1, 2]. Electron scattering also affects image width control and causes proximity effects. Computer simulation of electron scattering through Monte Carlo techniques has shown that the top opening of the resist is determined primarily by the shape of the incident beam, while the bottom edge gets contributions from both forward- and back-scattered electrons [3, 4]. The developed resist profile is a result of these scattering effects plus the development characteristics of the irradiated resist in a solvent. The relative sensitivities of the top and bottom edges of the resist profile to changes in process parameters are governed by differences in absorbed energy distributions at these edges. We made a quantitative assessment of these relative sensitivities and, as a result, a preferred mode of imaging was determined.

Profile experiments

The resist system chosen for this study was a positive diazo resist having nonlinear development characteristics. It is similar to the one modeled in [3, 5] but with higher sensitivity gained through the use of an imidazole additive [6]. Exposure was done on IBM's EL-3 E-beam lithography tool [7].

The parameters most influential in determining resist profile were selected for this study. They are incident dose [8], development, pattern bias (beamwidth adjustment) [9, 10], and resist thickness. The beam voltage was fixed at 25 kV because of tool considerations. All other process parameters such as developer concentration and temperature, as well as prebake conditions, were held constant.

Incident dose was varied by adjusting beam dwell time. For this study, all image widths received the same selected value of incident dose, uncorrected for proximity effects. The

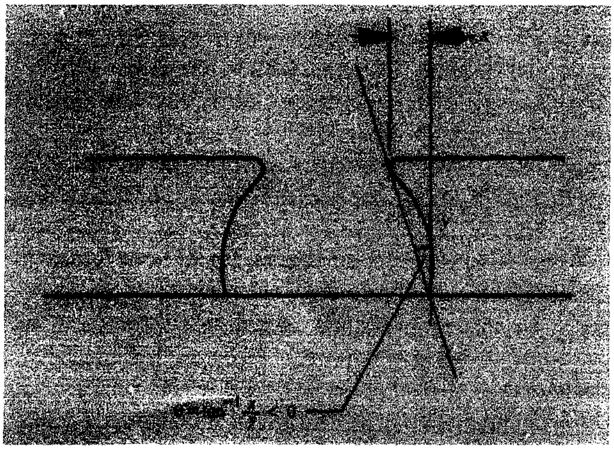


Figure 1

Undercut resist profile characterized by negative sidewall angle θ.

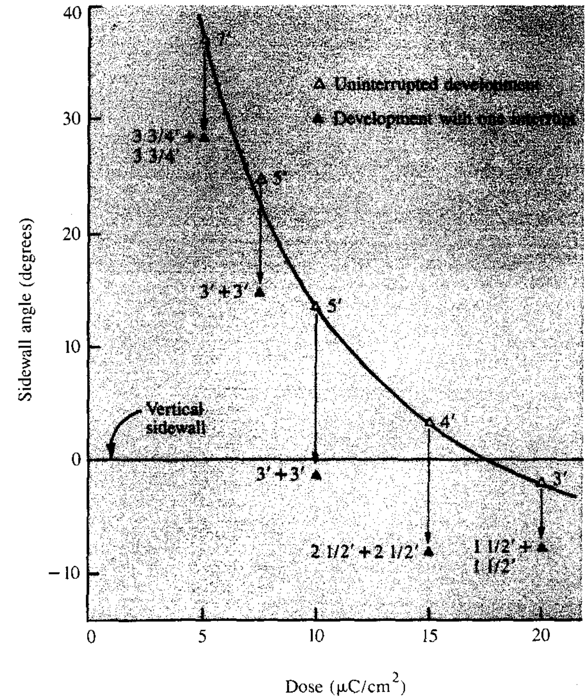


Figure 2

Effect of dose and development on resist profile for a 1.5-μm image. Beamwidth = 1.1 μm using a 0.4-μm pattern bias. Initial resist thickness = 0.8 μm.

process variable that was studied was development with and without interruption. Stopping the development process before completion and then resuming it again results in a different profile than if the total development were uninterrupted [11]. In these experiments, development was quenched at an interrupt by rinsing in water for one minute and drying. The total development time is dictated by the time to open an image to a given width and is not considered a fundamental variable.

The use of pattern bias to control profile was treated as another process variable. When a pattern bias was applied, it was directed so that the beamwidth would be narrower than the desired final image width. Thus, a 1.5-μm image with a 0.4-μm pattern bias would be written with a 1.1-μm beamwidth. Again, development time was adjusted to achieve the desired final image width. Finally, initial resist thickness was treated as a variable for the control of resist profile.

The profile studies were done for isolated, exposed images in a range of widths from 1 μm to 3 μm. Wafers were processed with selected values of the four variables. The top-edge and bottom-edge widths of the resist profiles were measured from SEM micrographs of cleaved samples. Final resist thickness was measured so that the sidewall angle could be calculated. Thickness loss during development affects the final image sidewall angle and, consequently, the profile. Sidewall angle is expressed as the deviation from the normal to the substrate, to allow for easy identification of positively and negatively slopped profiles **(Figure 1)**.

The separate sensitivities of the top and bottom edges of the image profile were determined from the measured values of image widths. The results are presented graphically as relative bias variations of the top and bottom edges.

Results

• *Profile control*

Varying the incident dose affects the resist profile **(Figure 2)**. Increased dose results in a steeper profile with undercut commencing at about 18 $\mu C/cm^2$ for the case of uninterrupted development. Development times were chosen to produce images of roughly equal bias. At the low dose end of the curve, resist thickness loss becomes a significant factor in influencing the profile. Deterioration of the profile occurs, shown by a rapid increase in sidewall angle. Figure 2 also shows the influence of interrupted development on the profile. Points are plotted for a single interrupt with equal development intervals. To equalize the top-edge widths with and without interrupt, it is necessary to slightly increase the total development time with interrupt. In every case where the interrupt was used, the sidewall angle became more negative. Optimal development time intervals can be found for the particular resist system under consideration. Additional interrupts can be used but are found to be less effective in making significant additional changes in the profile.

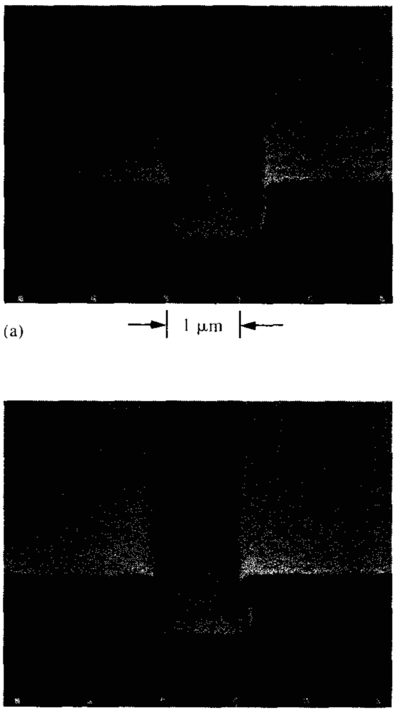


Figure 3

Effect of interrupted development on resist profile for a 0.1-μm image. Beamwidth = 0.6 μm using a 0.4-μm pattern bias. Dose = 15 μC/cm^2; resist thickness = 0.8 μm. (a) Uninterrupted development; (b) development with one interrupt.

The data in Fig. 2 show that, with an interrupt, images can be produced at 10 μC/cm^2 with the same sidewall angle as images written by uninterrupted development at 20 μC/cm^2. Thus, resist performance is significantly improved by interrupted development. Interrupted development produces an effective sensitivity enhancement of two times in this case.

Figure 3 illustrates profile modification at a dose of 15 μC/cm^2. The near vertical profile of the 1.0-μm image that is produced by uninterrupted development [Fig. 3(a)] can be transformed into an undercut profile with a single interrupt [Fig. 3(b)]. No measurable resist thickness loss occurs at this dose.

Figure 4 illustrates the profile improvement obtainable at the low dose range. Appreciable thickness loss occurs after development at 5 μC/cm^2 with uninterrupted development [Fig. 4(a)]. The effect of increasing the dose to 7.5 μC/cm^2 and using an interrupt is to reduce the thickness loss to zero and to improve the sidewall angle by 20 degrees [Fig. 4(b)].

Results of using pattern bias to control profile are shown in **Figure 5.** Using a narrower beamwidth to produce the same final result of a 1.5-μm image yields a more vertical profile after development. The effectiveness of pattern bias is limited to the upper dose range with uninterrupted development. At the lower doses, long development time causes significant thickness loss, which deteriorates the profile. Combined with interrupted development, however, the benefits of pattern bias are realized at lower doses (Fig. 5).

Figure 6 shows the results of experiments using initial thickness as a control parameter for resist profile. Images were developed to maintain a top-edge bias difference of no more than 0.1 μm for purposes of comparison of two thicknesses. Note that more negative sidewall angles are produced in the thicker resist. As dose is reduced, this effect is diminished. Again, the use of interrupted development allows one to obtain more leverage from increased thickness at reduced doses.

Figure 7 illustrates the high degree of profile control obtainable in a 1-μm line-space pattern by employing the combined effects of interrupted development, pattern bias, and thick resist at a dose of 20 μC/cm^2. This undercut profile is typical of one that can be used, for example, in metal lift-off work [12].

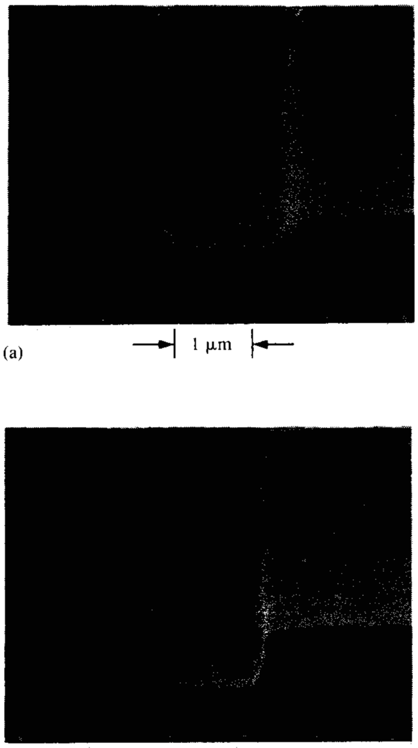
Sensitivity to parameter variation

A high degree of profile control was achieved through selection of appropriate conditions for dose, development, pattern bias, and resist thickness. The next issue to consider is the preferred profile type for maintaining tight tolerance objectives at 1-μm dimensions.

Using the image width measurements, we have been able to quantitatively determine the relative sensitivities of the top and bottom edges of the resist profile to changes in dose, development, and thickness. **Figure 8** shows bias sensitivity to dose variation for the 1.5-μm image. Note that the top edge of the resist is less sensitive to dose variation than the bottom edge. A comparison of Fig. 8(a) with 8(b) shows that the bottom edge sensitivity becomes even greater as resist thickness is increased. This is further illustrated by Fig. 7, where the line width at the top edge remains constant while the pedestal width varies due to proximity effects. Similarly, the top edge is less sensitive to development time variation than the bottom edge **(Figure 9). Figure 10** shows the bias sensitivities of the top and bottom edges to changes in resist thickness. The top edge is seen to maintain relative stability while the bottom edge shows large variation. The incident dose is insufficient to fully open up the 1.5-μm image at 2-μm thickness [Fig. 10(a)], while it is more than sufficient to open up the 3.0-μm image at the same thickness.

Discussion

The experiments show the effects of dose, development, pattern bias, and thickness variations on resist profile. From such experiments, a set of operating conditions (not



(a) Sidewall angle = 36°
Resist thickness loss = 0.4 µm

→| 1 µm |←

(b) Sidewall angle = +16°
Resist thickness loss = 0

→| 1 µm |←

Figure 4

Resist profile modification for a 1.5-µm image. Beamwidth = 1.1 µm using a 0.4-µm pattern bias. Initial resist thickness = 0.8 µm. (a) Dose = 5 µC/cm^2, uninterrupted development; (b) Dose = 7.5 µC/cm^2, development with one interrupt.

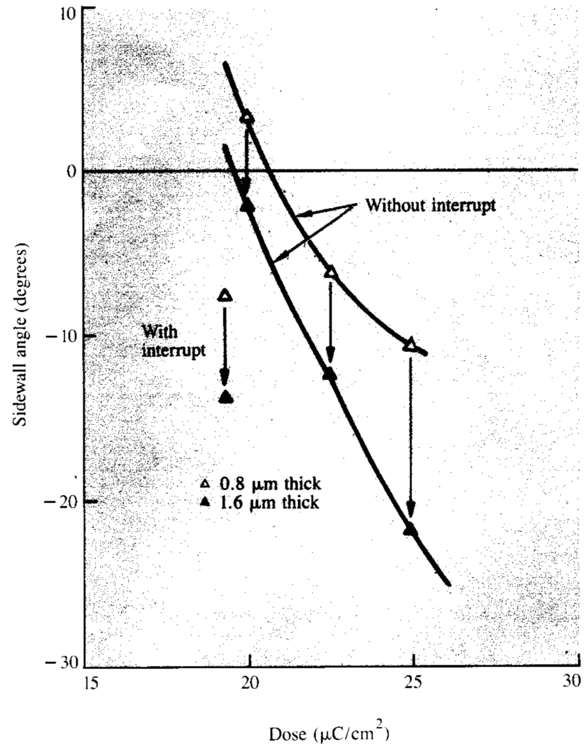


Figure 6

Effect of resist thickness on profile for a 1.5-µm image. Beamwidth = 1.1 µm using a 0.4-µm pattern bias.

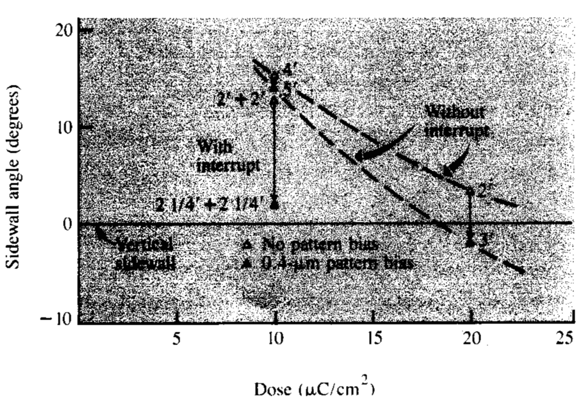
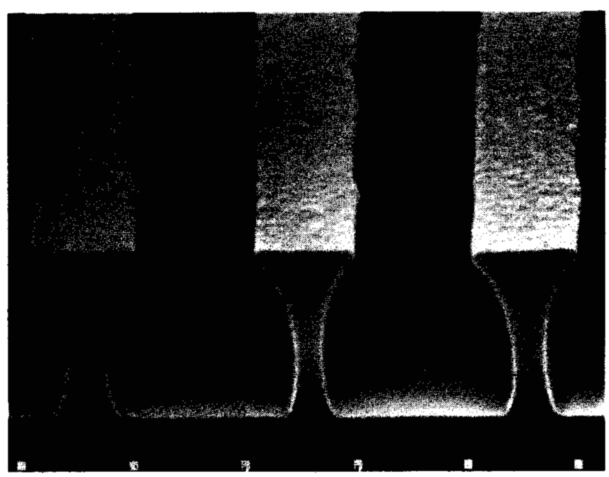


Figure 5

Effect of pattern bias on resist profile for a 1.5-µm image. Initial resist thickness = 0.8 µm.



→| 1 µm |←

Figure 7

Two-micrometer pitch pattern in 1.6-µm-thick resist. Beamwidth = 0.6 µm using a 0.4-µm pattern bias. Dose = 20 µC/cm^2, development with one interrupt.

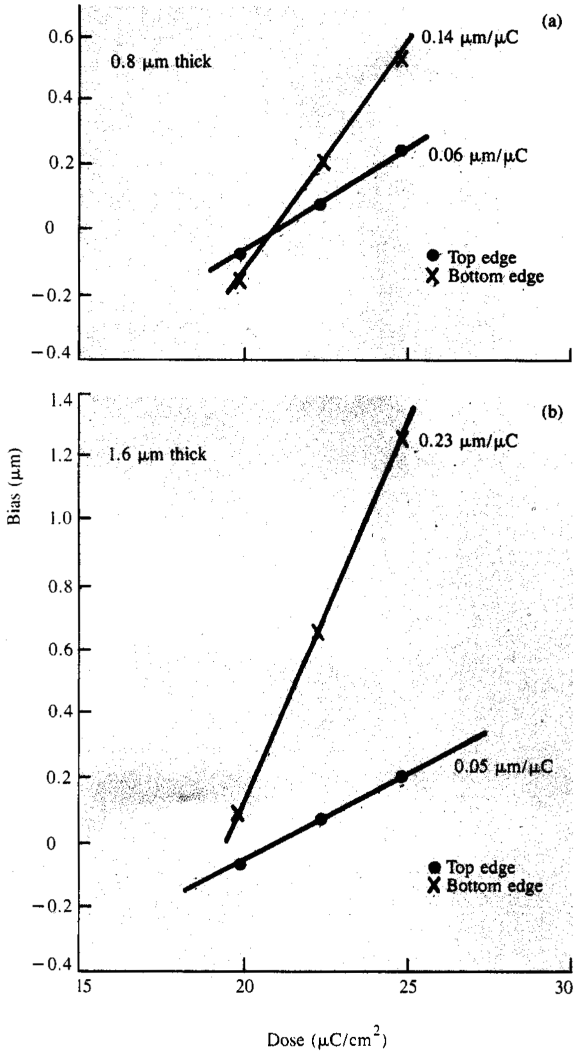


Figure 8

Image width sensitivity to dose for a 1.5-μm image. Beamwidth = 1.1 μm using a 0.4-μm pattern bias. (a) Resist thickness = 0.8 μm, development time = 2.5 min; (b) resist thickness = 1.6 μm, development time = 3 min.

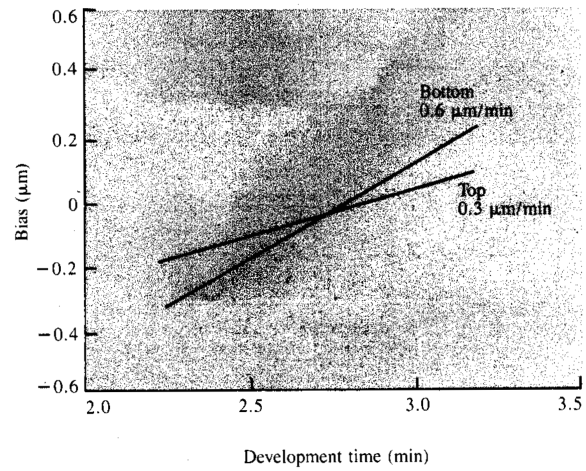


Figure 9

Image width sensitivity to development time for a 1.5-μm image. Beamwidth = 1.1 μm using a pattern bias of 0.4 μm. Dose = 20 $\mu C/cm^2$; resist thickness = 0.8 μm.

necessarily unique) can be obtained to achieve the desired profile. This approach can be used, in general, to experimentally characterize resist systems whose performance depends on a complex combination of parameters. It is particularly applicable where no models are available for individual parameters, such as interrupted development.

The results also show that the top edge of the resist is considerably more stable than the bottom edge with respect to variations in dose, development, and thickness. Process control, therefore, becomes much easier with top-edge imaging. The line edge quality at the top is superior to that at the bottom. Any irregularities in beam illumination, as well as imperfect spot size and butting, are minimized at the top edge. Images are also insensitive to topographical variations. It is desirable to use the top edge of the resist for patterning all process levels. This can be done using the undercut profile with image transfer from the top edge to the substrate through directional etch (RIE) [13–15] or lift-off [12].

These results are supported by theoretical models for energy absorption in the resist [1, 2]. The top edge, which has a narrow distribution of absorbed energy, is relatively insensitive to changes in dose. The bottom edge, however, having a broad energy distribution, is highly sensitive to dose variation. The variability of the bottom edge with thickness change is understandable. The bottom edge sensitivity is a result of both the wide distribution of energy from backscattered electrons and the lateral spread of the forward beam with depth into the resist.

The present study shows that interrupted development is a significant control parameter. It effectively enhances the contrast of the resist by taking advantage of the nonlinear dissolution characteristics or "induction effect." Interrupted development makes undercut possible at lower doses. This effect is desirable since dose on the EL-3 is a function of beam dwell time (higher doses have a negative effect on tool throughput). Pattern biasing is necessary for controlling image bias since it is effective in compensating for beam-edge slope [9]. Pattern biasing is also effective in altering resist profile since it allows for some overdevelopment. Its applicability becomes limited when linewidths become so narrow that beam intensity is reduced. Increased resist thickness also allows undercut to be more readily obtained. The thicker the resist, the broader the range of lateral scattering from the forward beam and, hence, the larger the relative energy absorption between the bottom and top edges of the resist. Enhanced undercut in thick resist has been reported for a linear resist system as well [16]. This effect diminishes as dose is reduced.

The results of these experiments have implications for the application of proximity correction algorithms [17]. Although dose compensation can be used to equalize the bias for a range of linewidths at either edge, it cannot alter the relative sensitivities to changes of the top and bottom edges. Proximity correcting for the bottom edge cannot be expected to give satisfactory results. A set of correction parameters that are optimal at the bottom edge for one thickness of resist are not optimal for another. A better approach would be to apply dose compensation only as necessary to maintain undercut for top-edge imaging.

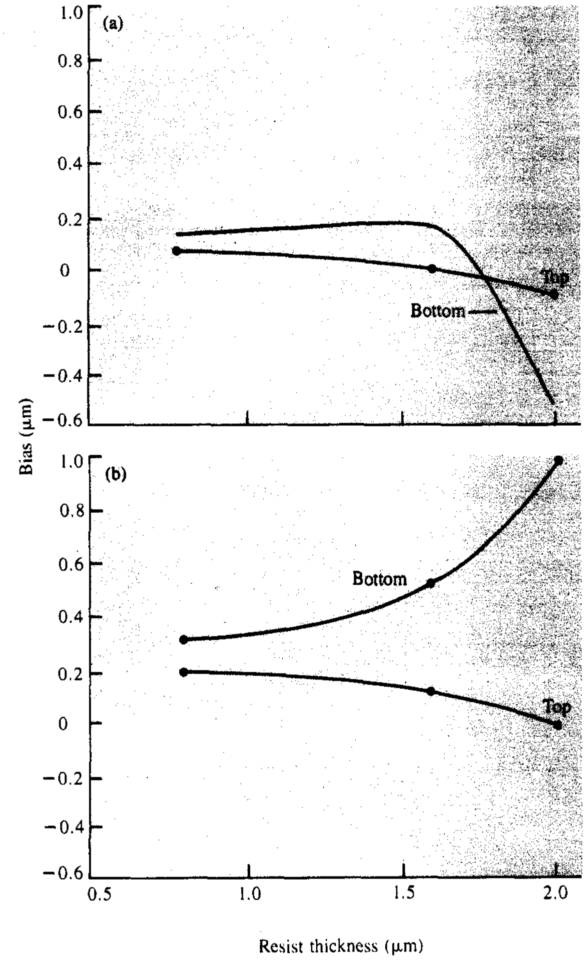


Figure 10

Image width sensitivity to resist thickness. Dose = 20 $\mu C/cm^2$, development time = 3 min. (a) Image width = 1.5 μm, beamwidth = 1.1 μm using a 0.4-μm pattern bias; (b) image width = 3.0 μm, beamwidth = 2.6 μm using a 0.4-μm pattern bias.

Conclusion

Resist profile control is achieved in a positive nonlinear resist through the appropriate combination of dose, development, pattern bias, and thickness. The preferred resist profile is undercut, where pattern transfer is achieved from the top edge. By using top-edge imaging in a single-layer resist, many advantages are realized that are usually associated with the more complex multilayer systems. In combination with directional etching or lift-off, top-edge imaging meets the requirements for 1-μm lithography.

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