The International Society
for Optical Engineering

This paper was published in the proceedings of
Metrology, Inspection, and Process Control for Microlithography XV,
SPIE Vol. 4344, pp. 200-207.

Characterization of Optical Proximity Correction Features

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ABSTRACT

One-dimensional linewidth alone is an inadequate metric for low-k1 lithography. Critical Dimension metrology and analysis have historically focused on 1-dimensional effects but with low-k1 lithography it has increasingly been found that the process window for acceptable imaging of the full 2-D structure is more limited than the process window for CDs alone. The shape and area of the feature have become as critical to the proper patterning as the width. The measurement and analysis of Critical Shape Difference (CSD) of patterned features must be an integral part of process development efforts. Adoption of optical proximity correction (OPC) and other Optical Extension Technologies increases the need for understanding specific effects through the pattern transfer process. Sub-resolution features on the mask are intended to compensate the pattern so that the resulting etched features most accurately reflect the designer's intent and provide the optimum device performance. A method for quantifying the Critical Shape Difference between the designer's intent, OPC application, mask preparation, resist exposure and pattern etch has been developed. This work focuses on overlaying features from the various process stages and using CSD to quantify the regions of overlap in order to assess OPC performance. Specific examples will demonstrate the gap in current 1-D analysis techniques.

Keywords: SEM image analysis, CD SEM, OPC, image analysis, lithography, CSD

1. Introduction

One dimensional feature characterization is inadequate for determining process windows for low-k1 lithography. Effects such as line-end pullback further reduce process windows characterized by width alone. Line-end pullback leads to decreased contact area which increases the contact resistance, ultimately causing increased timing delays and compromising device yield, as illustrated in Figure 1. Although the width of the printed lines is within the specification limits, the line-end pullback makes this an unacceptable two dimensional pattern.

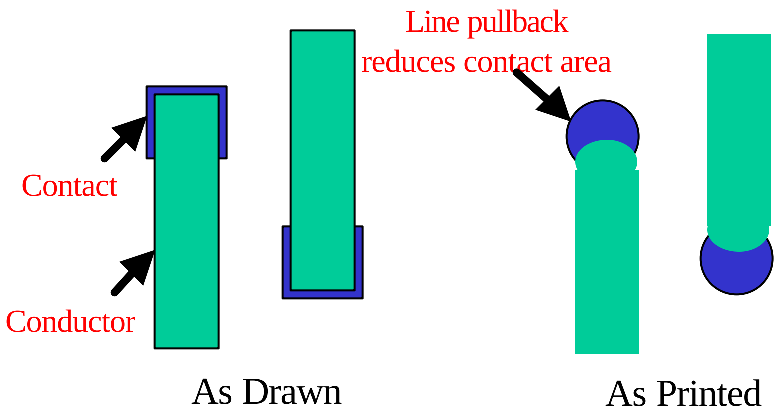


Figure 1. Example of line-end pullback.

Figure 2 illustrates line-end pullback as a function of k1 (defocus). The data is based on simulation results presented in previous work. As can be seen, the pullback increases steadily with lower k_1 values, and the situation becomes even worse when defocus is considered.

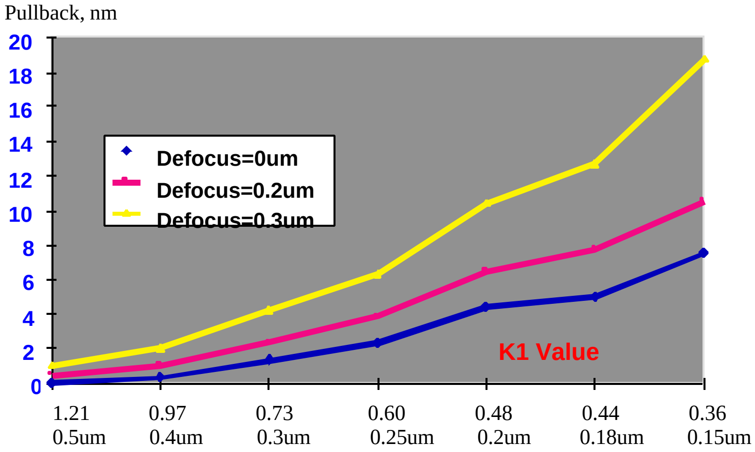


Figure 2. Pullback versus k1 and defocus

Line-end pullback can be corrected using two-dimensional OPC as illustrated in Figure 3. The uncorrected reticle design (solid black line) results in severe line-end pullback at the resist level (light gray). Adding OPC features, such as serifs at the reticle level, can improve the resist image (dark gray), but care must be taken to avoid design rule violations. In this example, we require that the OPC structures do not intrude into the adjacent circuit regions, indicated schematically as the "Do Not Touch" area".

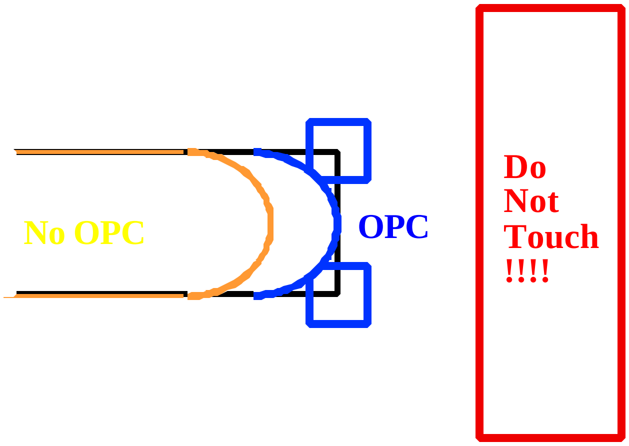


Figure 3. Application of two dimensional OPC to correct line-end pullback

The effectiveness of the OPC through the printing process needs to be evaluated as shown in Figure 4. Key comparisons to be made include design to resist pattern to etch pattern and mask layout to actual mask pattern. The particular dimensions of the OPC feature must be optimized to obtain the correct feature length after etch.

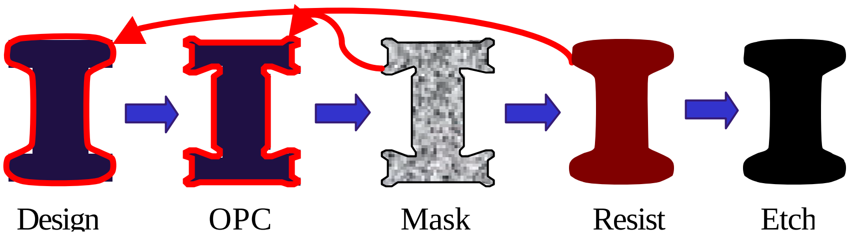
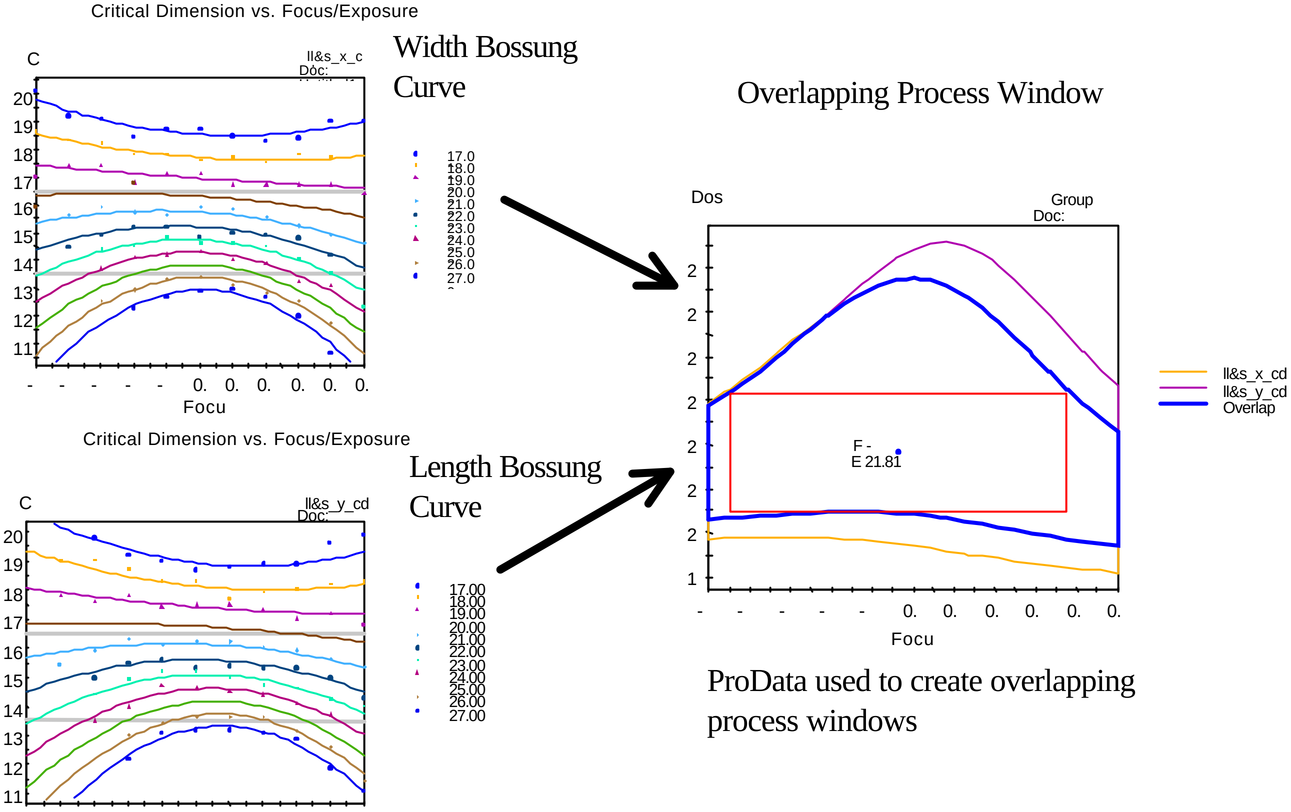


Figure 4. Pattern transfer process, showing the transformation from design level to final etched features. Intermediate steps (OPC layout and mask pattern) may be significantly different than the starting or ending patterns. Key comparisons are design to resist to final etched pattern and layout (with OPC) to mask patterns.

Two dimensional feature characterization is required to determine the effectiveness of OPC for reducing line-end pullback. Overlapping process window analysis is common for accessing the lithography process window for isolated and dense features. This paper will demonstrate how the same technique can be extended to the evaluation of OPC performance.


Width Bossung Curve

Overlapping Process Window

Length Bossung Curve

ProData used to create overlapping process windows

Figure 5. Schematic illustration of the overlapping process window technique.

2. Experimental

This work focuses on the characterization of OPC required to print a 0.18 µm wide by 0.75 µm long trench. In the baseline case, the feature at the reticle level is simply four times larger (4x) than the desired wafer level pattern. In this case, the baseline reticle pattern is a rectangle 0.72 µm wide by 3.0 µm long. Four OPC features were compared to a baseline, uncorrected case. The four test cases are summarized in Figure 6. For the OPC cases, the trench was altered from the original layout by biasing the length of the line, and by adding a hammerhead assist feature to the line ends. The hammerheads were 50 nm wider than the line width with a variable overlap dimension. The experimental design tested assist features with overlaps from near zero to almost 1 micron long, and line end extensions from 0.1 to 0.5 microns in length at the reticle level. The four features studied in detail tested very short (0.1 µm) to fairly long (0.5 µm) line end extensions, and hammerheads of two different lengths (0.40 and 0.55 µm).

	Test Case				
	None	A	B	C	D
Length	3	3	3.3	3.1	3.5
Overlap	0	0.4	0.4	0.55	0.55

* Dimensions are in microns, as drawn on mask (4X)

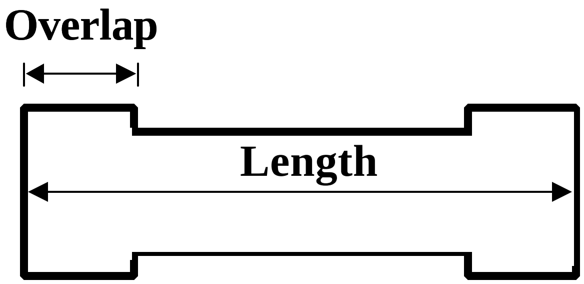


Figure 6. Four OPC test cases compared to baseline (no OPC) case for 0.18 x 0.75 micron trench structure.

A test reticle was fabricated using this layout, and measured extensively using a KLA-Tencor 8100R CD-SEM to determine how accurately the mask making process replicated the intent of the OPC design. The SEM showed that case A – no added length and short hammerhead overlap – was practically indistinguishable from the baseline case, and it was dropped from further study. Focus-exposure wafers were shot on a 0.7 NA DUV stepper with annular illumination using Shipley UV210 photoresist and a film stack of Si rich nitride over polysilicon on thin oxide. The two dimensional process windows were also simulated using Prolith 6 to minimize the number of 2D wafer measurements required. The simulations were not specifically tuned to match the process or lens parameters. Actual reticle images were used in the simulations to capture the realities of the OPC mask making process.

The results presented below will compare the relative predictions from the simulations vs. the actual measured data. Both simulated and measured data were ported to the Klarity ProData process window analysis software with the SEM Image Analysis Module (SIAM) to compute and display the overlapping process windows for both feature length and width. The process window tolerances were set at ± 10% for the resist linewidth (± 18 nm). The definition of the process window for the length is subject to more flexibility. For this study, we set the length tolerance to be very close to the absolute value of the width tolerance, or ± 20 nm at the wafer level; this is considerably smaller than ± 10% of the feature length. Since line-edge pullback is known to vary more as a function of focus and exposure than line width, we expect that this will be a very demanding specification.

3. Results and Discussion

The baseline and test cases B through D are illustrated in Figure 7. Test case A was not included since it was virtually the same as the baseline. As can be seen in Fig. 7a, the baseline case has no overlapping process window for both length and width. At the best exposure for the line width, the trench length is much too short due to line-end pullback. Only by severely overexposing the feature does the length meet the target dimension, resulting in zero overlap between the length and width process windows. As OPC is added in case B, the two windows move closer together, but still fail to overlap. Case C, with longer hammerheads but less length extension, moves the two windows still closer together, resulting in a very small overlapping process window. Finally, case D- with both longer hammerheads and more length extension- shows that we actually overshot the target; the correct exposure dose for the line width now makes the trench too long. The optimum OPC for this case would clearly be between cases C and D.

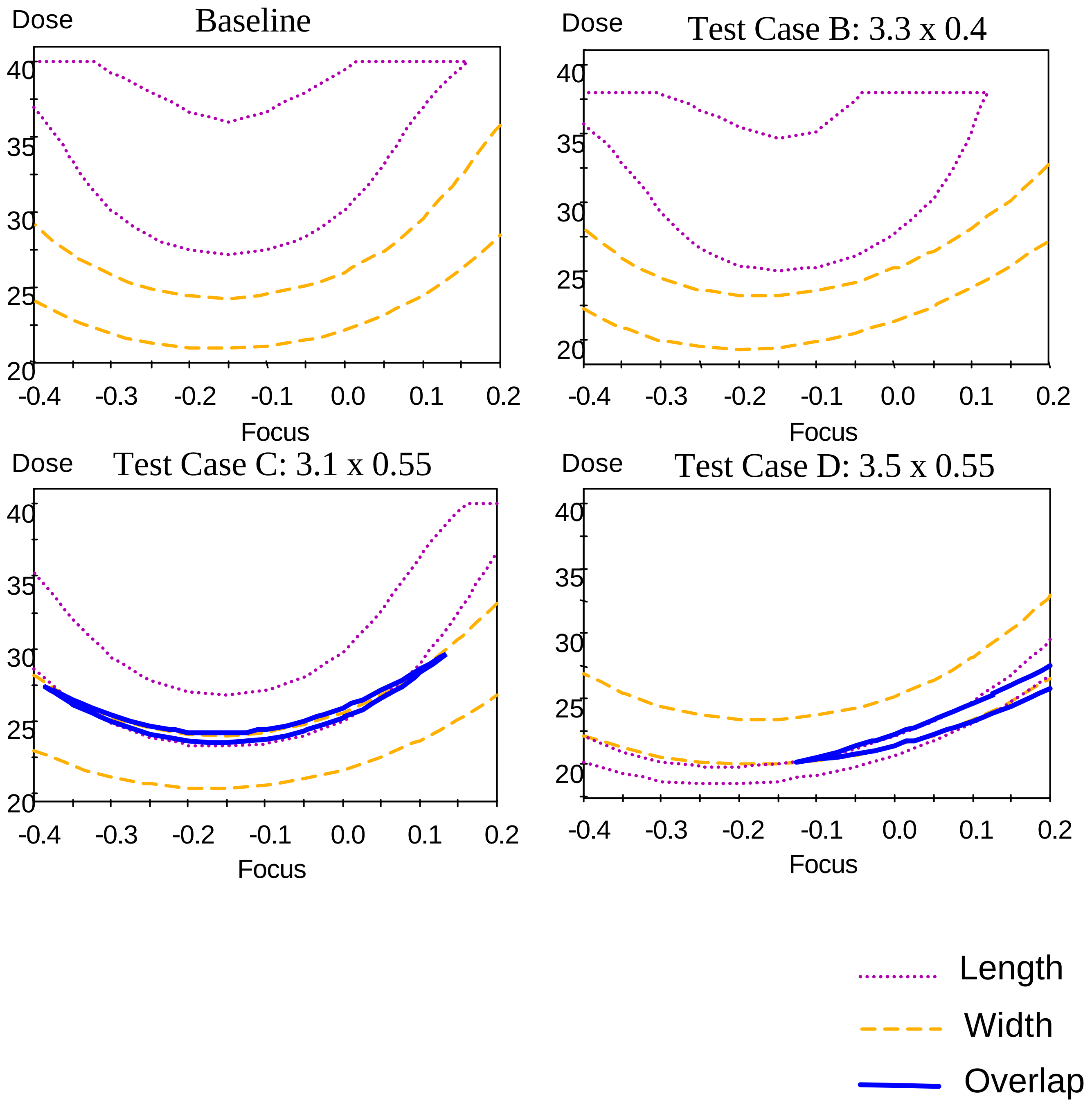


Figure 7. Baseline and test cases B to D.

In viewing the trends of Figs. 7a-d, we see that as OPC is added more aggressively, not only does the process window for feature length move closer to the same optimum dose as the window for feature width, but the size and shape of the length window change as well. The baseline case, where the trench must be drastically overexposed to meet the target length, actually has the largest process window for feature length, in line with previous studies which show that line-end pullback for trench structures is less variable in the overexposed condition. As the OPC becomes more effective at moving the two windows together, the optimum dose for both length and width converges to a single value as desired, but with the undesired side effect that that the size of the process window for the trench length is significantly reduced.

Fig. 8 shows experimental data for the process window overlap for an improved design with OPC corrections midway between designs C and D. The process window overlap is improved, but due to the reduced size of the window for trench length and difference in the curvature of the two windows, it still leaves inadequate margin for exposure variation under production conditions. The overlap is greatly improved if we loosen the tolerance on the length to allow more than ± 20 nm variation; the exact value required in production must be determined by the specific design rules.

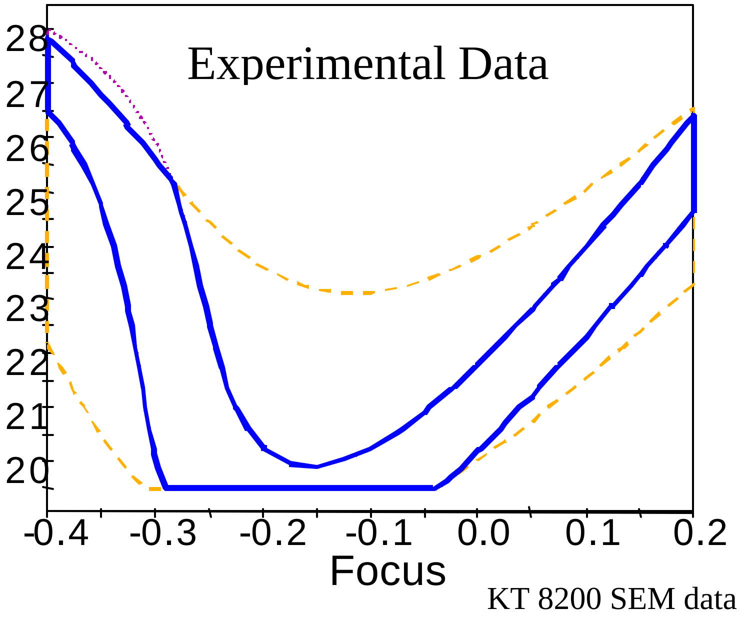


Figure 8. Overlapping process windows for length and width of an optimized trench structure. The process window for line width is the darker dashed line; for trench length, the lighter dashed line. The overlap is shown as a solid line, which mainly follows the limits of the length window.

These observations highlight one of the basic difficulties of implementing any form of reticle enhancement technology; the benefit is never obtained without paying a price, and the number of degrees of freedom that must be optimized expands quickly. In this case, we chose the NA and annular illumination conditions to maximize the process window for the line width, then added OPC to match the process window for trench length to the width window. It is quite possible that different combinations of NA, illumination, and OPC might produce better overlap. Exploring the entire parameter space experimentally would be prohibitive; this is where simulation can be especially valuable in guiding the minimum number of experiments.

Comparison of experimental and simulated results shows good qualitative agreement, although the quantitative values for dose differ significantly (Fig. 9). This is not surprising since we did not have model parameters for the specific chemically amplified resist used in the experiments. We were forced to use resist parameters from an older generation resist, and no effort was made to tune the model to achieve better agreement. Despite this, Fig. 9 shows good agreement for both the shape and relative spacing of the two process windows, as well as the two-dimensional top-down patterns, shown here at best focus.

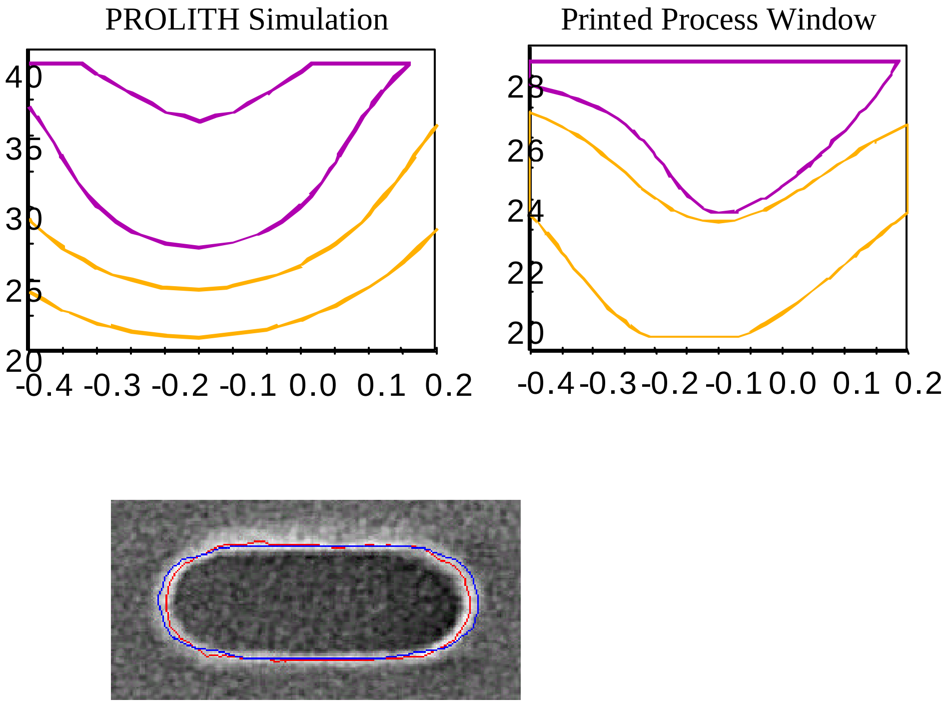


Figure 9. Comparison of simulated vs. experimental results for the baseline case (no OPC), showing good qualitative agreement between the shape and relative spacing of the process windows, as well as 2-dimensional top down profiles.

4. Conclusions

Both experimental and simulated results show that OPC can be effective in creating overlapping process windows for multiple metrics of pattern quality, but the task of optimizing the reticle and illumination conditions to achieve the best results for these metrics is much more difficult than for one-dimensional CD control of a single feature type.

The combination of simulation and experiments can help study multiple combinations of reticle and exposure parameters in a reasonable amount of time, as well as studying other effects which may not be experimentally accessible, such as sensitivity to reticle CD errors (Mask Error Factor).

Automating the analysis and display of overlapping process windows greatly expedites the experimental procedure, and provides the means to incorporate other metrics of OPC pattern quality as well, such as corner rounding, critical shape error, or other metrics currently being defined by industry groups.

The actual reticle pattern is a critical element to understanding the pattern transfer process. Especially in the case of small OPC corrections, what the CAD software intends to put on the reticle is not necessarily the same as the structure that actually emerges from the mask making process. Reticle SEM measurements are critical for characterizing the pattern transfer process and determining the optimum OPC models to apply to product layouts.

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