CASE 39

Optimization of Photoresist Profile Using Simulation

Abstract: In this optimization case, our objective was to shorten the product development cycle drastically and reduce the operating cost by optimizing stability of a photoresist shape through simulation, confirming the shape with an actual pattern. In this optimization especially, we optimized a process dealing with relatively thick (2.2 μm) photoresist on a metal film that greatly affects the shape of photoresist when etched.

1. Introduction

Micromachining used in semiconductor manufacturing is conducted through a repeated process of photomasking, photomask patterning, and etching (Figure 1). In the photomask patterning process (photo process), it is essential to control not only dimensions but also cross-sectional photoresist shapes for stabilizing etching shapes. This is considered a key technology in semiconductor manufacturing that introduces advanced micromachining technologies year after year. Figure 1 shows a case of positive photoresist in which photosensitive parts are removed in alkaline solution.

To optimize conditions for stabilizing dimensions of photoresist and controlling its design shape, we made the most of a simulation technology. As simulation software, we used Prolith/2, supplied by Finle Technologies, Inc. For exposure computation, this software utilizes a theoretical calculation method based on an optical and physical model, and for development computation, a method using actual measurements of the developer dissolution rate. Therefore, we could more realistically analyze the after-development photoresist shape with respect to its dimensions and also perform nonlinear analyses. Although to create and measure a photoresist shape requires a considerable amount of skill, the simulation enabled us to confirm a shape and dimensions at each position instantaneously.

2. Simulation

In the photomask patterning process using exposure, a pattern of light (the width of a light shield) generated by a mask (light shield) is transferred onto photoresist. In the case of the positive photoresist used for this research, photoresist in the area that does not receive any light remains after development. In this case, the ideal situation is that a 1-μm-wide pattern in design is transferred as 1 μm and a 0.5-μm-wide pattern as 0.5 μm.

Therefore, in this study, we regarded it as a generic function that a dimension of the pattern transferred is proportional to that of a mask. As the ideal input/output relationship, we considered the proportionality between a dimension of a mask, M, and the counterpart of a pattern, y ($y = \beta M$) (Figure 2).

A dimension of a mask pattern was chosen as a signal factor, M, that has three different values, 0.6, 0.8, and 1.0 μm. We defined as an ideal condition that the photoresist shape becomes rectangular and does not change at any position in the direction of the photoresist's thickness. Then, as a noise factor, we selected a dimension of photoresist, setting the dimension of a boundary between the photoresist and the metal film below to L_{bot}, the dimension of photoresist at the top to L_{top}, and that in the middle to L_{mid} (Figure 3). When the shape is to be controlled separately, it was analyzed as an indicative factor. Eight factors that affect dimension and shape

 Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

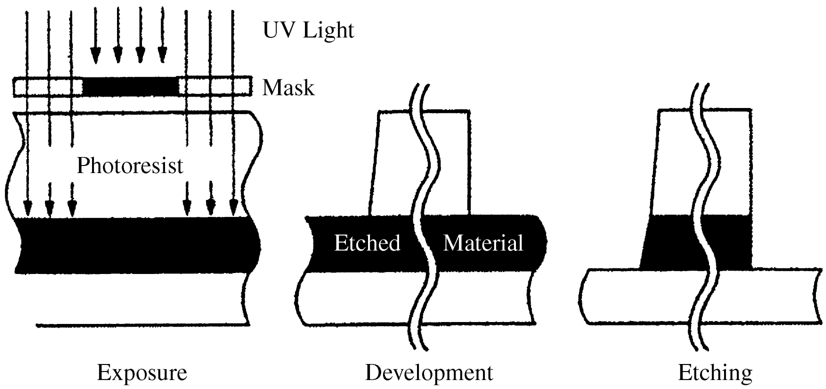

Figure 1
Photoresist and etched shapes

in the process were listed as control factors (Table 1).

For the amount of light (F), we used a sliding-level technique for each experiment. We calculated beforehand the amount of light needed to form a 0.6-μm pattern for a mask of the same size and selected the quantity as the optimal amount of light (EOP) for each experiment. Then we defined factor levels for the amount of light (F) as ±10% of the optimal amount.

3. Parameter Design with Position in Thickness Direction as Noise Factor

When using a position in the direction of thickness (vertical direction) as the noise factor (Table 2), the SN ratio is calculated as follows.

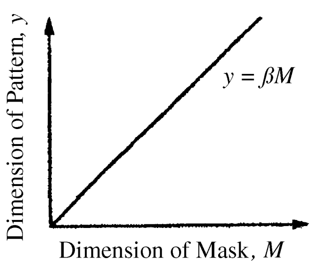

Figure 2
Generic function

Total variation:

$$S_T = 0.325^2 + 0.568^2 + 0.783^2 + \cdots + 1.041^2 = 4.670 \qquad (f = 9) \tag{1}$$

Effective divider:

$$r = 0.6^2 + 0.8^2 + 1.0^2 = 2.0 \tag{2}$$

Linear equations:

$$L_1 = (0.6)(0.325) + (0.8)(0.568) + (1.0)(0.783) = 1.432 \tag{3}$$

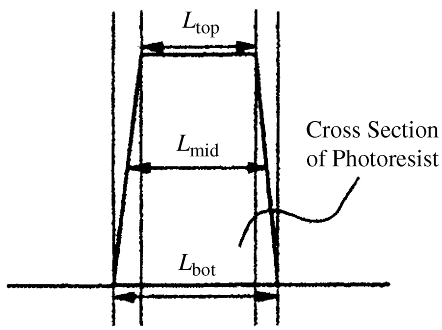

Figure 3
Dimensions checked

Table 1
Control factors and levels

Control Factor	Level 1	Level 2	Level 3
A: photoresist type	Current	New	—
B: prebaking temperature (°C)	80	90	100
C: mask bias (μm)	−0.05	0	+0.05
D: numerical aperture	0.50	0.54	0.57
E: focus (μm)	−0.3	0	+0.3
F: exposure time (ms)	−10%	EOP	+10%
G: baking temperature (°C)	100	110	120
H: development time	60	90	120

$$L_2 = 1.636$$

$$L_3 = 2.135 \qquad (4)$$

Variation of proportional term:

$$S_\beta = \frac{(1.432 + 1.636 + 2.135)^2}{(3)(2.0)} = \frac{27.07}{6} = 4.513 \qquad (f = 1) \qquad (5)$$

Variation of differences between proportional terms:

$$S_{N\beta} = \frac{1.432^2 + 1.636^2 + 2.135^2}{2.0} - 4.513 = 0.131 \qquad (f = 2) \qquad (6)$$

Error variation:

$$S_e = 4.670 - 4.513 - 0.131 = 0.026 \qquad (f = 6) \qquad (7)$$

Error variance:

$$V_e = \frac{0.026}{6} = 0.00438 \qquad (8)$$

Total error variance:

$$V_N = \frac{4.670 - 4.513}{8} = 0.0196 \qquad (9)$$

SN ratio:

$$\eta = \frac{[1/(3)(2.0)](4.513 - 0.00438)}{0.0196} = 38.30 \ (15.83 \text{ dB}) \qquad (10)$$

Sensitivity:

$$S = \frac{1}{(3)(2.0)}(4.513 - 0.00438) = 0.751 \ (-1.241 \text{ dB}) \qquad (11)$$

Figure 4 shows the response graphs when using a position in the direction of thickness as a noise factor. Considering that only the amount of light is used as an adjusting factor under the optimal configuration and the SN ratio should be prioritized, we selected $A_2B_1C_3D_3E_2F^*G_3H_1$ as the optimal configuration. In the response graphs, O and Δ indicate the optimal and current levels, respectively. Since

Table 2
Data for one run in an L_{18} orthogonal array

Noise	Signal 0.6 μm	Signal 0.8 μm	Signal 1.0 μm	Linear Equation
N_1	0.325	0.568	0.783	L_1
N_2	0.422	0.645	0.867	L_2
N_3	0.694	0.8477	1.041	L_3

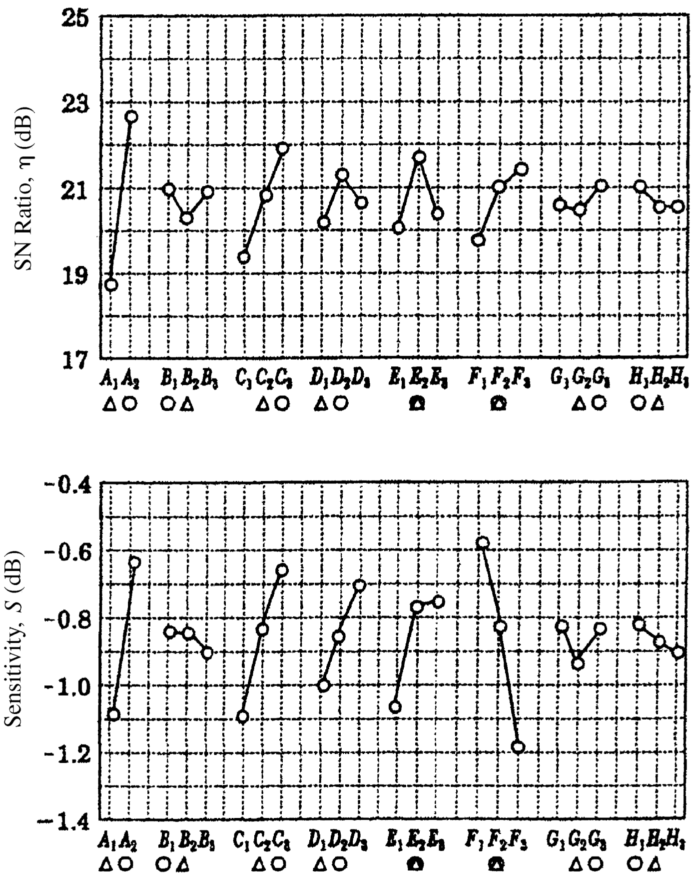

Figure 4
Response graphs using position in thickness direction as a noise factor

the SN ratio depends greatly on the type of photoresist, we can improve the SN ratio by overexposing photoresist to light under the conditions of a positive mask bias.

4. Parameter Design with Position in Thickness Direction as Indicative Factor

To control the shape (taper angle), we also performed an analysis using each measurement point as an indicative factor. Since the variation in the differences between proportional terms $S_{N\beta}$ in the preceding section is dealt with as an indicative factor, we did not use it for calculating the SN ratio. In this case, as adjusting sensitivities, we computed sensitivities S_1 to S_3, corresponding to the dimension at each measurement point.

SN ratio:

$$\eta^* = \frac{(1/3r)(S_\beta - V_e)}{V_e}$$

$$= \frac{[1/(3)(2.0)](4.513 - 0.00438)}{0.00438}$$

$$= 171.5 \quad (22.34 \text{ dB}) \qquad (12)$$

Variation of proportional term for each indicative factor, N_1, N_2, and N_3:

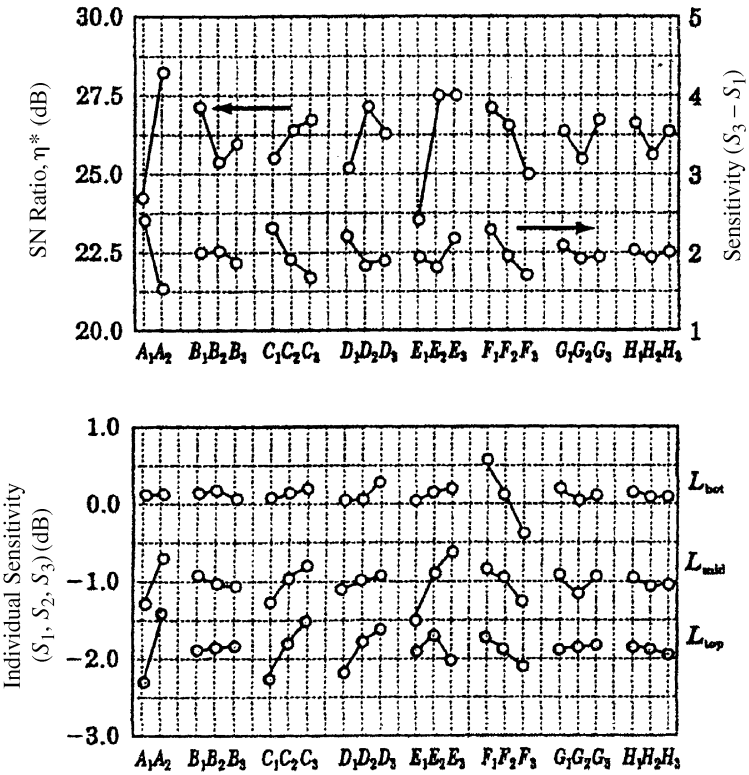

Figure 5
Response graphs using position in thickness direction as indicative factor

$$S_{\beta 1} = \frac{L_1^2}{r} = \frac{1.432^2}{2.0} = 1.026$$

$$S_{\beta 2} = \frac{L_2^2}{r} = 1.338$$

$$S_{\beta 3} = \frac{L_3^2}{r} = 2.279 \qquad (13)$$

Sensitivity:

$$S_1 = \frac{1}{r}(S_{\beta 1} - V_e) = 0.511 \ (-2.92 \text{ dB})$$

$$S_2 = 0.667 \ (-1.76 \text{ dB})$$

$$S_3 = 1.137 \ (0.056 \text{ dB}) \qquad (14)$$

Now, to make the analysis of the taper shape more understandable, we calculated $S_3 - S_1$ as the sensitivity:

$$S_3 - S_1 = 0.056 - (-2.92) = 3.48 \qquad (15)$$

Figure 5 shows the response graphs when using a measurement point in the direction of thickness as an indicative factor.

A smaller sensitivity, $S_3 - S_1$, used to control the taper angle, indicates a more vertical shape. Shape improvement was confirmed from both the SN ratio and sensitivity, $S_3 - S_1$. $S_3 - S_1$ can be used to tune the shape. The change in the amount of light, F, gives the opposite tendency in SN ratio and sensitivity, $S_3 - S_1$, thus improving both the SN ratio and the shape. To control taper shape, we can solve the orthogonal polynomial equation for sensitivity at each position and make adjustments.

Table 3
Confirmation of SN ratio and sensitivity (dB)

	SN Ratio		Sensitivity	
Configuration	**Estimation**	**Confirmation**	**Estimation**	**Confirmation**
Optimal	26.63	26.73	−0.19	−0.27
Current	18.76	19.37	−1.13	−1.10
Gain	7.87	7.36	0.94	0.83

5. Confirmatory Calculation and Comparison with Actual Pattern for Photoresist

Estimating the SN ratios and sensitivities under the optimal and current configurations, we confirmed the reproducibility in gain based on the results obtained from our resimulation (Table 3).

Optimal configuration: $A_2B_1C_3D_2E_2F_2G_3H_1$

Current configuration: $A_1B_2C_2D_1E_2F_2G_2H_2$

As a result, we confirmed high reproducibility in gain: 93.8% for SN ratio and 88.8% for sensitivity.

Figure 6 illustrates the relationships between the dimension of a mask and the dimension at each position of the actual photoresist. According to these charts, we can see that under the current configuration, there is a large variability in the direction of thickness, and that the smaller the dimensions of a mask become, the more the bottom dimension is enlarged and the top, diminished. In contrast, under the optimal configuration, this tendency is improved significantly. This result implies improvement in the phenomenon whereby the pattern of photoresist crashes as the dimension of a pattern becomes smaller.

The cross-sectional shapes under the optimal and current configurations when using simulation and in actual patterns are compared in Figure 7. For both cases we used a 0.6-μm-wide pattern. Using a scanning electron microscope we measured the actual pattern. The shapes confirmed by simulation under the optimal and current configurations were sufficiently consistent with those of actual patterns. When using each measurement as an error, the reproducibility in gain of the nominal-the-best SN ratio is also consistent (Table 4).

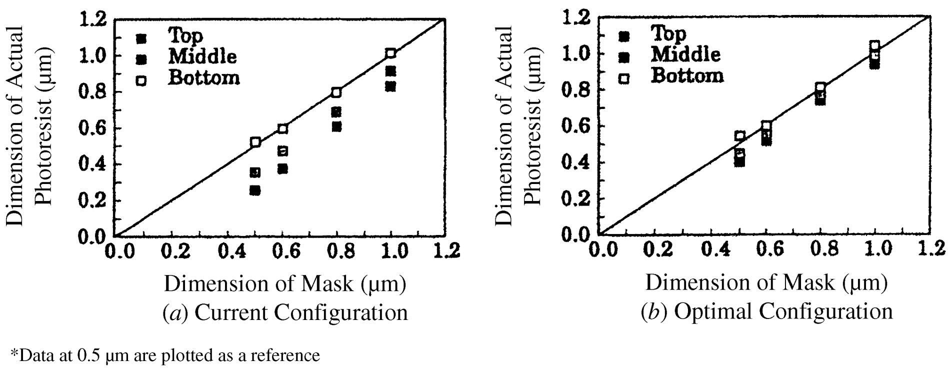

Figure 6
Comparison of dimensions before and after optimization

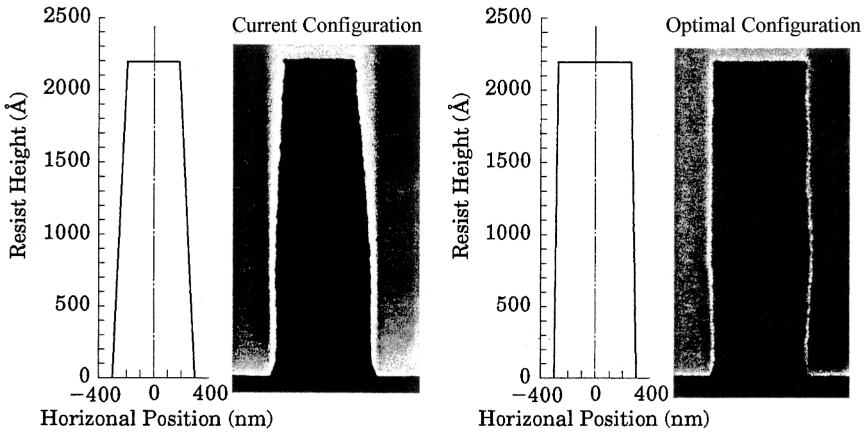

Figure 7
Comparison of shapes of photoresist before and after optimization

Table 4
Reproducibility of shapes (dB)

	Reproducibility: SN Ratio		
	Optimal	**Current**	**Gain**
Actual cross-sectional shape	29.59	16.80	12.79
Simulation	27.55	15.59	11.96

Since the simulation technique in this research used as developer model parameters, parameters calculated from data for dissolution rates of photoresist in actual development, our analysis based on dynamic characteristics reflected the actual situation.

Through simulation, our research successfully visualizes and optimizes the cross-sectional dimension of photoresist, which has been considered difficult to measure in an actual experiment. The fact that both the shape obtained by simulation and the actual pattern shape are fairly consistent demonstrates that our analysis process can contribute much to optimizing the photoresist shape and variability in dimensions. In addition, our new method takes only two days, whereas a conventional method required a few months. Consequently, we can shorten the analytical cycle time dramatically.

On the other hand, by selecting the dimension in the direction of thickness as an indicative factor in our analysis, we can obtain parameters for adjusting the taper shape, which is regarded as one of the important indices for optimization. Although it is believed that the analysis of shapes and dimensions will become increasingly difficult in more microscopic pattern forming, our new method is expected to contribute to shorter-term optimization.

Reference

Isamu Namose and Fumiaki Ushiyama, 2000. Optimization of photoresist profile using simulation. *Proceedings of the 8th Quality Engineering Symposium,* pp. 302–305.

This case study is contributed by Isamu Namose.