

LETTERS

Comments on "Off-Line Quality Control in Integrated Circuit Fabrication Using Experimental Design," by M. S. Phadke, R. N. Kackar, D. V. Speeney, and M. J. Grieco*

I have recently read with extreme interest the article "Off-Line Quality Control in Integrated Circuit Fabrication Using Experimental Design," by M. S. Phadke et al. (hereafter denoted as Phadke).

The authors acknowledge the contributions of Professor Genichi Taguchi in this report. I believe my understanding of the Taguchi method is sufficient to raise the issues below. It is believed that the issues are sufficient so as to challenge the usefulness of the Taguchi Method if Phadke is used as a primer. If this should happen it is believed that a new and useful tool might be lost to the engineer.

The introduction to Phadke gives a concise presentation of the Taguchi Method. The problem arises when Phadke has to establish a signal-to-noise ratio (s/n) for analysis and selection of the optimal process by maximizing s/n . One must first understand the meaning of the 5 (experiments 5, 15, and 18) or 10 data points in Table III of Phadke. It is abundantly clear from the table headings (and the text) that these multiple measurements at each experimental condition fit into two categories:

1. They are the result of multiple measurements at different spots on a given wafer, and
2. They are the result of measurements on a second wafer processed at the same time as the first.

Phadke processes these 5 or 10 measurements to establish the mean pre-etch line width and the respective standard deviation listed in Table IV. It is at this point Phadke breaches the teachings of Taguchi. The standard deviation listed in Table IV is *not* the variance (square of the standard deviation) of which Taguchi speaks. The standard deviation values in Table IV are in fact due to at least four possible factors:

1. Experimental measurement error (treated only cursorily on page 1281).
2. Variations from wafer to wafer (undoubtedly small for adjacent wafers cut from a large boule). No information is given about the source of the wafers, except that they were scarce.
3. Variations at the five locations due to the effects of the mask variations, or other asymmetries in the wafer processing (e.g., the means of all 33 measurements of the pre-etch line width data—Table

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III—show that the “bottom” line width is distinctly different from the other four, i.e., its average value is 2.81 μm versus 2.62 to 2.69 for the other four; in fact, one is about 90-percent confident that the “bottom” data are different from the “left” data).

4. Variations in location due to the experimental process (i.e., experiment 2 versus experiment 9, etc.).

It is extremely clear that the signal-to-noise ($\eta = \log \bar{x}/s$) data in Table IV (page 1286) are not even remotely related to s/n that Taguchi teaches since the standard deviation is composed primarily of the effects of repeat measurements for one experiment. That is, the s/n in Table IV is simply another response, just as line width (\bar{x}) is a response. On the other hand, Taguchi’s noise (variance) is due to repeat experiments at the same or nearly the same experimental conditions (see the Wheatstone Bridge example in Ref. 3 of Phadke).

It is in the reduction to practicality where Phadke seemingly slips. The average s/n (η) in Table V is simply the appropriate average of the $s/n = \log \bar{x}/s$ in Table IV. For example, the average s/n for factor A level 1 is $(1.4803 + 1.3512 + \dots + 1.2709)/9 = 1.28568$ with a standard deviation of 0.13749. If one were interested in calculating the s/n ratio for Table V using the s/n of Table IV as a response variable, then the values would be those shown below for two of the 24 values that can be calculated (more will be said about the log transformation later).

Table V—Pre-etch line width for average s/n

Factor	Average s/n		
	Level 1	Level 2	Level 3
A Mask Dimension	1.2857	1.5166	
BD Viscosity Bake Temperature	(B_1D_1) 1.3754	(B_2D_1) 1.3838	(B_1D_2) 1.4442
B Viscosity	1.4098	1.3838	
D Bake Temperature	1.3796	1.4442	
C Spin Speed	1.3663	1.3503	1.4868
E Bake Time	1.4328	1.4625	1.3082
F Aperture	1.5368	1.4011	1.2654
G Exposure Time	1.3737	1.3461	1.4836
H Developing Time	1.3881	1.4042	1.4111

Overall average s/n = 1.4011.

THIS VALUE SHOULD BE

$$\frac{1.2857}{0.1375} = 9.3510$$

BEFORE ANY TRANSFORMATION

$$\frac{1.51657}{0.23747} =$$

6.3864

In the case of the correct data in Table V (as per Jugle) the noise is due to fluctuations in the other eight process variables. *This* is the noise of which Taguchi speaks. However, the object (first paragraph of Section I in Phadke) of this experiment was to determine a process for which the line width was under control and its variance was minimal (i.e., the line width s/n ratio was a maximum). If this is the case, the data in Table V would look like Table Va below (note that only three values have been calculated and no transformation has been applied to the \bar{x}/s values).

One can now follow the Taguchi Method and ANOVA on the data shown in Table VII and Table Va to establish a process condition under which the appropriate process control variable can shift the mean pre-etch line width with little, or no, change in the variance and select the other process variable settings so as to minimize the variance (maximize the s/n). If one uses the data in Table V (as per Jugle) and the data in Table IV, one can determine a process variable, which controls the mean s/n across the wafer, and a set of process variables, which minimizes variance in this s/n value. The two conditions may, or may not, be the same, so the appropriate trade-off would have to be made.

There are two other comments which must be made. First, the log transformation of \bar{x}/s is of concern and it should be used only discriminately. Taguchi (as well as Phadke et al.) are products of the communications industry where \bar{x} is generally very large (10^3 through 10^{15}) and s is comparatively small (10^0 through 10^3). In this case the log transformation not only makes sense, but it is mandatory. However, in the Phadke experiment, and in many other experiments, $0.02\bar{x} \leq s \leq 0.20\bar{x}$. In this case the compression of larger values by the log transformation may deemphasize larger effects and might have contributed to the second comment below. Second, on page 1303 Phadke talks about "implementation and the benefits of optimum levels." It

Table Va—Pre-etch line width s/n

Factor	Level 1	Level 2	Level 3
A	5.448	6.804	—
BD	8.587	•	•
•	•	•	•
•	•	•	•
•	•	•	•

$$A_1 \quad \bar{x} = \frac{2.500 + 2.684 + \dots + 2.829}{9} = 2.487$$

$$s^2 = \frac{1}{n-1} \sum_{i=1}^9 (x_i - \bar{x})^2 = 0.4565$$

$$s/n = 2.487/.4565 = 5.448$$

is somewhat disturbing that after optimization by their analysis they had to change the control variable (Taguchi's signal factor) called exposure setting from a nominal position (90) to beyond the experimental range (140 versus 108, assuming a fixed aperture of 2). This would suggest that there exists either a major uncontrolled variable in the experiment or a strong unrecognized interaction controlling the results, and that the positive outcome (in terms of implementation and benefits) is largely fortuitous.

Finally, in the calculation for Table Va the mean value for the pre-etch width calculated by this author does not agree with the value published in Phadke in Table VII (i.e., 2.487 versus 2.39). The data in Table IV are self-consistent (x, s, η); hence one would expect that the x values are correct. This may be a transcription error. However, there are enough small errors in the calculated data I have checked (i.e., only about 5 percent of the calculations) to suggest some further review is necessary.

I would like to thank T. Barker and L. Smith (both of Xerox Corporation) for helpful discussions.

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Reply to Letter by D. B. Jugle

Designing a process or a product that is robust against all noises is the key objective of off-line quality control. However, not only do we usually not know all noise factors, but even if we knew them it is inefficient and unnecessary to include all of them in an off-line quality control experiment. It is generally adequate to consider a few important noises in the experiment, with an anticipation that a design robust against the chosen noises will be robust against all noises. The confirmation experiment, then, verifies the robustness of the optimum design.

Signal-to-noise ratio (s/n) is a measure of process variation, which in turn is a measure of robustness. Depending on the problem, a different method is used to compute s/n . In the article by M. S. Phadke et al.* the s/n was calculated from the variation of the line width between wafers and within wafers. This s/n takes into consideration

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the line width variation resulting from material variation between wafers, the nonflatness of a wafer, nonuniformity of projection printing across a wafer and from one exposure to another, etc. But, this s/n does not include the effect of normal variation in the process factors around their nominal values. Another way to compute s/n is to consider the data from all experiments at a particular level of a factor. For example, to calculate the s/n for level 1 of factor A we would use all observations on pre-etch line width corresponding to experiments 1 through 9. This s/n would then include the effect of variation in the other eight process parameters. However, the variation in the process parameters among experiments 1 through 9 is too wide compared to their normal variation. So, this s/n is also not perfect. The s/n used in our paper was selected on the basis of engineering judgment.

In his letter to the editor, Mr. Jugle has suggested in Table V (as per Jugle) that the s/n for various factor levels should be computed from the s/n for individual experiments. This should never be done because we are not interested in the variation of s/n . Also, the s/n suggested in Table Va (as per Jugle) is not appropriate because it ignores the linewidth variation within wafers and between wafers.

The main reason for taking the log of \bar{x}/s is that the factorial effects have better additivity in the log domain. For example, without the log transformation it is possible for the prediction of \bar{x}/s to be negative. This unrealistic prediction is avoided by the log transformation.

After publication of the article,* the authors realized that there were some typographical errors in the data. However, these errors have little impact on the final results. The presence of these errors is regretted.

The confirmation experiment reported in the article referenced showed without doubt that there was a four-fold reduction in the process variance and a three-fold reduction in the cases of unopened window. Also note that the off-line quality control method has been applied successfully in improving numerous processes in AT&T and elsewhere.

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