# Solving process issues at an ASIC fab using design of experiments

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*A series of case studies at an ASIC fab demonstrates the power of DOEs to uncover the source of frog-spot defects and etch-rate issues, reducing process costs dramatically.*

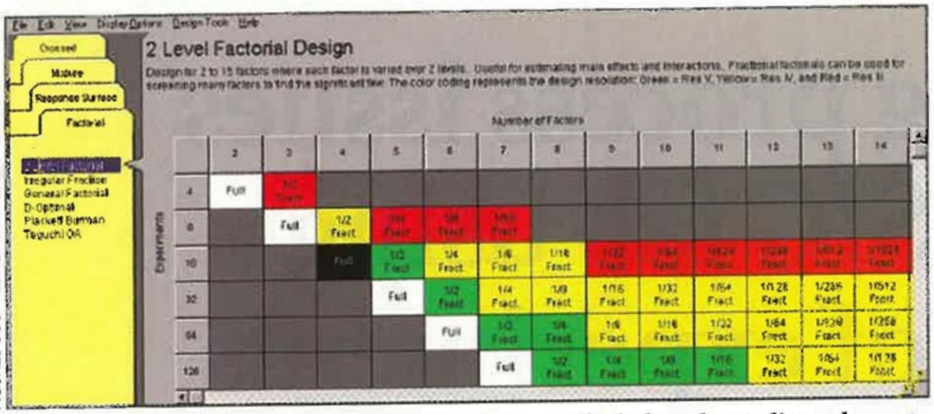
*When engineers talk about* frog spots, recipes, and wafers, chances are that many people will not know that they are using application-specific integrated circuit (ASIC) fabrication lingo. At AMI Semiconductor (AMIS) in Pocatello, ID, manufacturing conversations involving these words led engineers to solve two perplexing wafer production mysteries. They used design of experiments (DOEs) to investigate the problems and developed solutions that have saved the company $180,000 a year.

## Case Study 1: Frog Spots at Fab Nine

A stable process at Fab Nine inexplicably began to produce sporadic wafer imperfections known as frog spots, a surface discoloration that often caused the fab's 5-in. wafers to end up as underetched scrap. Curiously, although two matched metal etchers from Plasmatherm (currently Unaxis, Pfäffikon, Switzerland) fabricated identical wafers for automotive and medical device applications, only one of the etchers produced the defect. It was not known why the two etchers were performing differently.

The metal-etch process at Fab Nine has three main sequences, with more than 10 controllable factors at each step. Following a series of brainstorming sessions that focused on product knowledge, wafer recipe comparisons, and a review of historical data, 19 possible causes of the frog spots were identified, five of which were:

- *RF Power.* If RF power was too high, wafers were more susceptible to frog spots.
- *Chloroform Temperature/Flow.* Variations in flow rate, line condensation, and line temperature seemed to influence the onset of frog spots.




FIGURES COURTESY OF STAT-EASE

**Figure 1: DOE two-level factorial design using a traffic light color-coding scheme to indicate aliasing patterns: red = stop and think, yellow = proceed with caution, and green = go.**

- *Main Pressure.* Etch-chamber pressure variations during the main etch step, which are normally in the 200-mmHg range, were thought to contribute to the defects.
- *Chuck Cleanliness.* A dirty chuck may have generated contaminants that caused wafer lifting, leading to underetch, overetch, or frog spots.
- *Metal-Etch Level.* Defects occurred predominantly at metal 2 etch, but not at metal 1 etch.

The 19 variables had to be reduced to a more specific and manageable set of factors. DOE screening experiments identify those factors that have a significant impact on responses. Although screening does not reveal extensive information about interactions (such as synergisms or antagonisms), it does make the significant few positive and negative factors stand out from the trivial many. It reduces a large list of potential suspects to a few likely candidates through a small, efficient number of experimental runs.

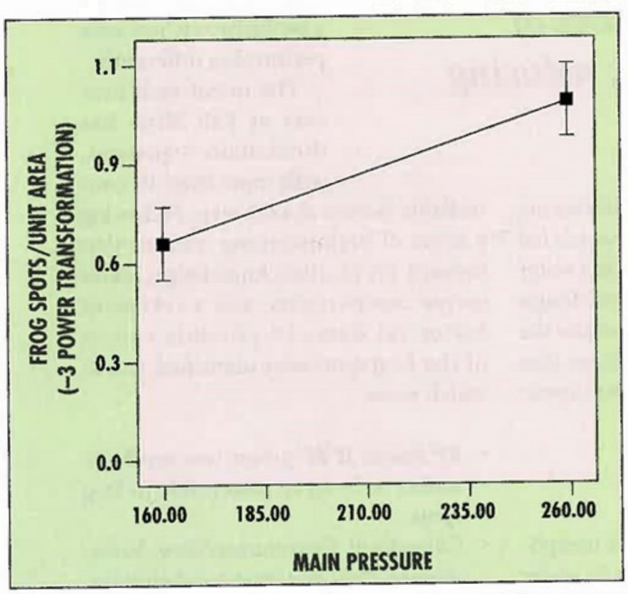



**Figure 2: Plot showing that the occurrence of frog spots decreased when main pressure was lowered.**

To keep runs to a minimum, only two levels (high and low) are designated for each factor (represented as $k$). Even with this restriction, however, the number of combinations (mathematically expressed as $2^k$) can still be excessive. For example, if $k = 5$, 32 experimental runs are required for a full two-level factorial design. To get by with fewer runs, some experimenters opt for a fractional-factorial design that identifies only the important main effects and two-way interactions. When $k = 5$, this approach, called a resolution V design, requires only 16 runs — a half fraction. While this method enables experimenters to perform fewer runs than does a full two-level factorial design, its ability to estimate interaction effects is reduced.

Sometimes, experimenters must resort to using lower-resolution designs out of necessity. Two examples are resolution IV, which estimates main effects but not some two-way interactions, and resolution III, where even main effects become difficult to resolve. Experimenters must be cautious when using fractional-factorial designs because of aliasing, in which effects and interactions become confounded among themselves.

Analyzing fractional-factorial resolution patterns can be simplified by using DOE software. Statistical analysis of the frog spots was accomplished using Design-Expert from Stat-Ease (Minneapolis), a dedicated, PC-based DOE program that employs a traffic-light metaphor, allowing users to see color-coded resolution relationships, as presented in Figure 1:

- *Red—Stop and Think.* A resolution III design indicates that main effects may be confused (aliased) with two-factor interactions. Resolution III designs can be misleading when significant two-factor interactions affect the response.
- *Yellow—Proceed with Caution.* A resolution IV design indicates that main effects may be aliased with three-factor interactions. Two-factor interactions may be aliased with other two-factor interactions. Resolution IV designs are a good choice for a screening design because the main effects will be clear of two-factor interactions.
- *Green—Go Ahead.* Resolution V (or higher) designs are almost as good as a full-factorial design and require far fewer runs. Assuming that no three-factor and higher interactions occur (very unlikely), all of the main effects and two-factor interactions can be estimated.

Only by implementing DOE screening techniques were the investigators able to single out one factor from the long list of candidates thought to be causing the frog spots: main pressure. As illustrated in Figure 2, after

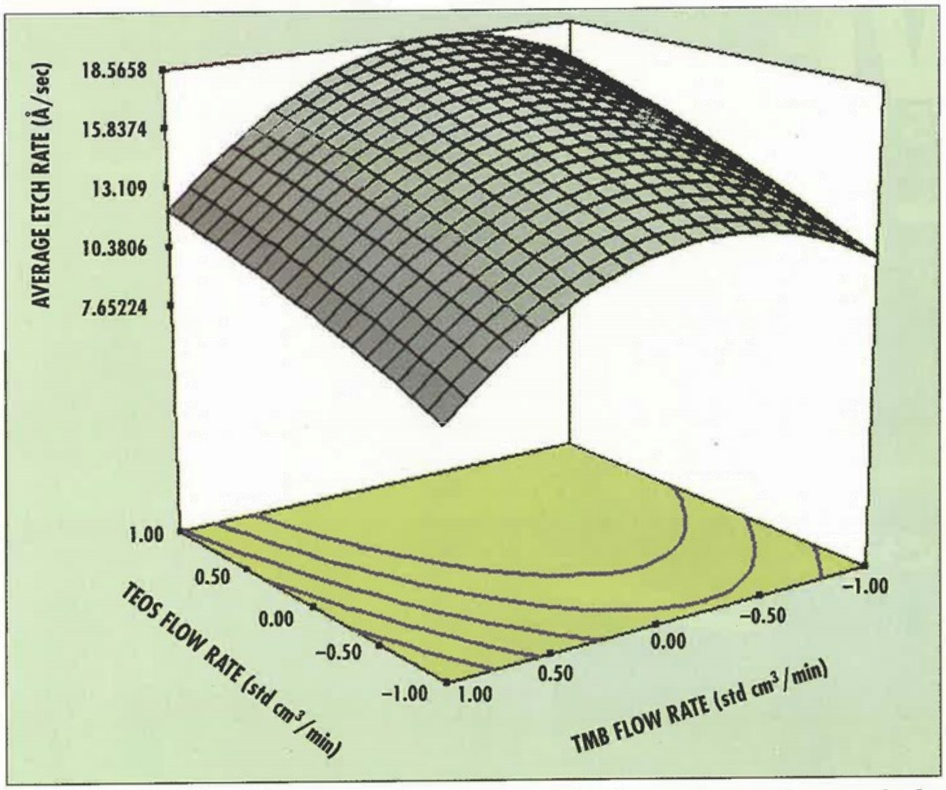



**Figure 3: TEOS and TMB versus etch rate. After discovering that TEOS flow rate had a greater influence on the wet-etch rate than was originally believed, engineers were able to develop a control system to better control the process.**

main pressure was decreased, the number of defects was reduced.

## Case Study 2: The Complaint about the Difficult Deposition

With the mystery of the frog spots solved, the experimenters began to use other DOE techniques to further optimize process settings that are dependent on main pressure.

The second wafer-defect mystery, variations in an insulating film placed between two layers of material (polysilicon and metal), was costing AMIS $150,000 annually. An experimental design was needed to determine the impact of seven insulating-film factors on the contact wet-etch rate.

The contact wet-etch process opens holes in dielectric film to provide contact between metal and polysilicon layers. If the etch rate is too high, holes become blown out and too large, resulting in device failure. If the etch rate is too low, holes remain too small, increasing contact resistance to unacceptable levels. Because the wafer at this point has undergone most value-adding process steps, it is essential that the contact wet-etch process perform well.

Varying amounts of boron, delivered by trimethylborate (TMB) gas, and phosphorus, delivered by trimethylphosphite gas, in the dielectric film were originally the most strongly suspected causes of wet-etch-rate variations. But surprisingly, the DOE revealed that the largest effect was caused by the flow rate of tetraethylorthosilicate (TEOS), a liquid silicon used for dielectric-film deposition. The results of this experiment are illustrated in Figure 3.

TEOS is maintained at a vapor-over-liquid temperature, enabling a carrier gas to move the vapor at a tightly controlled rate into a P5000 metal-etch tool from Applied Materials (Santa Clara, CA). The P5000 uses plasma-enhanced chemical vapor to deposit a thin film onto a substrate surface. The result is an insulating dielectric film between polysilicon and metal layers.

A DOE not unlike that used to uncover the source of the frog spots was conducted on seven factors. The first four—TMB, trimethylphosphite, TEOS, and oxygen—were varied within this process's operational alarm limits. The remaining factors—power, pressure, and x-y spacing—were varied over a much larger range to find optimal gas-flow ranges. (The more that factors can be manipulated at or near their extremes, the bigger the effect will be.) The DOE revealed that the amount of film-thickness variation immediately after deposition could be reduced by decreasing pressure, increasing TEOS flow, and providing more spacing.

## Conclusion

A series of fab case studies demonstrates the power of DOEs to reveal the causes of process excursions, reduce defects, and lower costs. In the first case, a DOE enabled engineers to uncover the source of wafer frog spots, enabling the fab to save $30,000 annually. In the second, a DOE was performed to explain why there were variations in an insulating film placed between polysilicon and metal layers and to determine the impact of film factors on the contact wet-etch rate. That experiment led to improvements that have saved the fab $150,000 annually.

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