

All Wafer Maps Are Wrong: An Adventure in Semiconductor Visualization

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WAFER MAPS: Those colorful representations of a response over an entire substrate. Wafer maps are ubiquitous in most branches of semiconductor manufacturing and research. They are churned out with the click of a button by most industry-specific software. They delight managers and strike fear in the hearts of competitors. The problem is, most of the time, they are wrong... or at least misleading. This presentation will demonstrate how to generate a wafer map in JMP using a Neural Network model. Along the way, it will discuss some of the pitfalls of using wafer maps and explore how JMP can facilitate a more nuanced interpretation of these figures.

Introduction

IN MANY INDUSTRIES, including semiconductor manufacturing, surface behavior measurement is critical. These measurements may include properties like surface roughness, coating and film thicknesses, defect numbers or electrical properties. A common thread in the presentation of these data is the use of a plot with two spatial dimensions, x and y , and a response. In the semiconductor industry, these plots are generally known as *wafer maps*. Depending on the application, wafer maps can either be presented using the patterned surface of the wafer as a spatial reference or as un-patterned wafer maps.

Un-patterned wafer maps can be presented in a number of ways. Contour plots, for example, represent the response variable as a contour map using isolines or colored polygons as in Figure 1. Un-patterned wafer maps can also be presented as rough 3D surfaces with straight lines connecting each measurement as in Figure 2. Furthermore, wafer maps can be presented as smoothed contour plots or surfaces whereby an algorithm is used to interpolate between data points as in Figures 3 and 4. It is these last methods, applied to un-patterned wafer maps, that will be addressed herein.

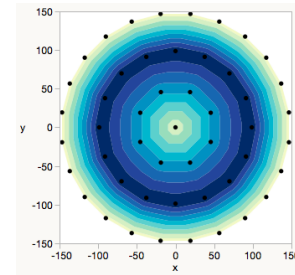


Figure 1: Contour Plot created in JMP13.

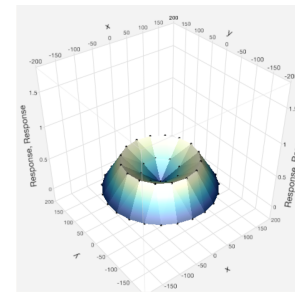


Figure 2: Polygon surface plot created in JMP13.

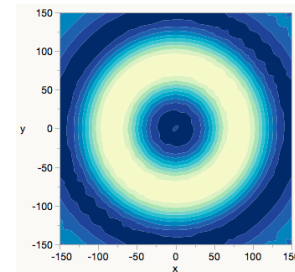


Figure 3: Contour plot generated from a model created in JMP13.

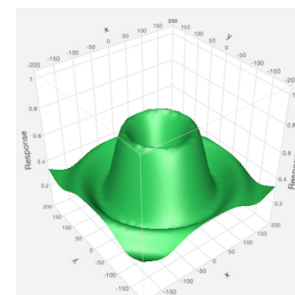


Figure 4: Surface plot of generated from a model created in JMP13.

The Problem

ONE DESCRIBES A TALE BEST BY TELLING THE TALE. You see? The way one describes a story, to oneself or to the world, is by telling the story. It is a balancing act and it is a dream. The more accurate the map, the more it resembles the territory. The most accurate map possible would be the territory, and thus would be perfectly accurate and perfectly useless. The tale is the map that is the territory. You must remember this.

- From the Notebooks of Mr. Ibis, *American Gods*, Neil Gaiman

ENGINEERS HAVE TO FIND a balance between the accuracy of the map they are generating and the practicality of generating that map. Neil Gaiman put it well in his book *American Gods*, "... The most accurate [wafer] map possible would be the [wafer], and thus would be perfectly accurate and perfectly useless." Data collection is expensive, and in some cases destructive. This means that engineering staff are under constant pressure to reduce the number of measurements collected on each part they create. It is in this balance between the accuracy of the map and its efficient generation that the problem with wafer maps ultimately lies.

The surface shown in Figures 3 and 4 is common in semiconductor manufacturing operations. These toroidal surface topologies can result from several different processes, so the specifics of the process itself are unimportant. Assume we are in a manufacturing environment and that we are allowed to measure no more than 17 sites on the wafer, providing an accurate representation of the wafer's topology. Figure 5 shows three common sampling patterns and the resulting contour maps for each sampling pattern. To generate the smooth contour plot generally expected from this analysis, we must construct a model. However, each pattern implies a bias to the model and the resulting map. None gives a perfect reproduction of the true topology of the wafer. Such maps are all more or less wrong - and that's okay - because they should never have been expected to be *perfectly* accurate in the first place.

ALL Models Are Wrong

IT WOULD BE WONDERFUL if the problem with models were new, but the problems inherent in constructing models with real data are well-documented fact. Over 30 years ago, George Box made his now famous declaration: "All models are wrong, but some are useful." One particularly apt form of this axiom is found in his paper, "Robustness In The Strategy of Scientific Model Building," from the

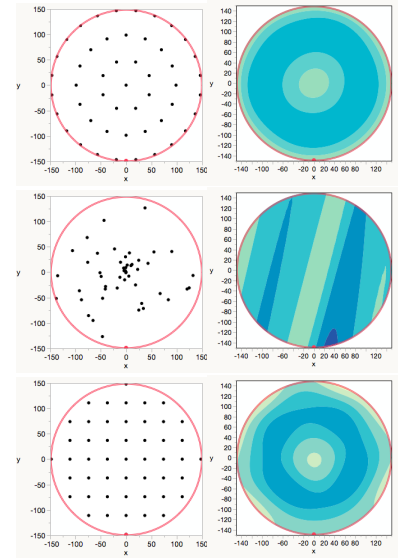


Figure 5: Three common 49 site sampling plans and modeled contour plots generated using the same surface.

anthology *Robustness in Statistics* from 1979.

NOW IT WOULD BE VERY REMARKABLE if any system existing in the real world could be exactly represented by any simple model. However, cunningly chosen parsimonious models often do provide remarkably useful approximations. For example, the law $PV = RT$ relating pressure P , volume V and temperature T of an "ideal" gas via a constant R is not exactly true for any real gas, but it frequently provides a useful approximation and furthermore its structure is informative since it springs from a physical view of the behavior of gas molecules.

For such a model there is no need to ask the question "Is the model true?". If "truth" is to be the "whole truth" the answer must be "No". The only question of interest is "Is the model illuminating and useful?".

- G. E. P. Box, *Robustness In The Strategy of Scientific Model Building*, 1979

IN OTHER WORDS, it is okay that the results shown in Figure 5 are wrong because they're *models*, and *all models are wrong*. A better question might be "Are these models useful?" The Ideal Gas Law mentioned by Dr. Box has been subjected to rigorous experimental tests, and the conditions under which it is useful are well documented. But what about when the situation is not so clear? How do we know a colleague's or software package's contour plot is useful? With contour maps we can't generally answer these questions. Most of the time the things we need to gauge the quality of the model are hidden or withheld. Herein lies the problem - unless we were to build our own contour maps from scratch of course. And that is where JMP comes in.

The Road Less Traveled

CONSTRUCTING A BASIC WAFER MAP IN JMP is relatively easy and can be accomplished using a single platform and a few mouse clicks. Generating publication quality wafer maps requires a few additional steps beyond the basic procedure. The upside of doing map generation manually is significant. JMP provides statistics about the fit quality and can provide both the prediction equation and variance information. In addition, we are given tools for visually interacting with the model in a number of different formats. This combination of proper statistics and compelling visualizations provides a more accurate picture of what can and can't be said regarding a contour map.

Some may argue that making these maps manually is too time consuming. This is an interesting argument. With a little arithmetic, using the semiconductor industry as an example, we can test this theory. Assume that an un-patterned 350 mm silicon wafer costs \$150

and that 10 wafers are allocated to run the experiment. Further assume that this experiment will take approximately 12 hours to run, inclusive of process and measurement time, at a total cost of \$400/hr. Assume that, conservatively, the technician or engineer running the experiment costs the company approximately \$50/hr in salary and overhead. The running of the experiment alone will cost the company \$6,900. Also assume that the analysis is done by the same engineer that ran the experiment and took 2 hours inclusive of cleaning the data, generating the results and wafer maps, and preparing the results for presentation. The total cost of the analysis represents approximately 1.5% of the total experiment cost. Since the analysis is the least expensive, but most critical, part of the experiment, we can reasonably assume that the engineer's supervisors are going to expect the analysis - including the wafer maps and the conclusions drawn from them - to be correct.

Building a Basic Wafer Map

Building the basic wafer map is possible in a number of platforms in JMP. This paper will focus on using the Neural Network Platform, but the basic work flow could be followed with the Fit Model Platform or the Gaussian Process Platform as well. The minimum requirements for model generation are the spatial coordinates of each measurement site, the response at that site, and possibly the unique identification number for the wafers in the data set. The inclusion of process conditions - i.e., gas flow rates, temperatures, etc. - can also be included, but were omitted here for simplicity. The results of the procedure are shown in Figure 6.

Procedure

1. Open the dataset in JMP
2. Select *Analyze > Predictive Modeling > Neural* in JMP.
3. Place the column names that contain the spatial coordinates and any additions factors of interest into the **X, Factor** area of the dialog.
4. Place the response column name in the **Y, Response** area of the dialog.
5. If the wafer identification numbers are present they can be placed in the **By** area.
6. Click **OK**.
7. Select the KFold validation method from the drop down menu.

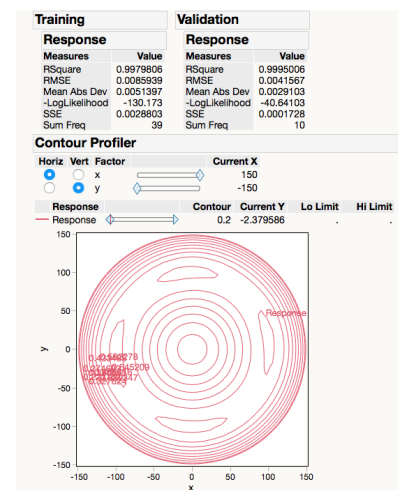


Figure 6: Contour Profiler showing Neural Network model for a 49 site radial sampling pattern.

8. Build the model
 - (a) JMP: Enter the desired number of nodes in the available dialog box.
 - (b) JMP Pro: Build the model using the various nodes available (see the JMP Documentation for details on each).
9. Run the model. If there are multiple wafers holding down the CTRL (Cmd in OS X) key while clicking **Go** will start the modeling for all the wafers at once.
10. The contour map can be generated by selecting **Contour Profiler** from under the Red Triangle menu for any of the models and turning on **Contour Grid** from the contour map Red Triangle.

Analytic Transparency

THE MODELING OUTPUT from the Neural Network includes elements missing from most other wafer mapping tools. Most importantly are statistics for the quality of fit and the ability to export an equation to predict values not directly measured. Looking at the fitting statistics in Figures 7 and 8, it is easy to see that there is a great deal of variation in the ability of sampling patterns to describe a wafer's topology. This variation is particularly evident in cases wherein the production sampling pattern has the lower and least consistent RSquare statistic of the pair. In cases wherein the model demonstrates sufficient reliability, it is then possible to use a profiler like that in Figure 6 to predict the response for a particular set of input parameters.

Compelling Visualization

WHILE THE USE OF THE CONTOUR PROFILER in the Neural Network Platform is sufficient to assess the quality of the model, many engineers desire something more in line with what they receive from other software packages. These contour maps, along the lines of those found in the first figures of this paper, can be generated using the Neural Network model output, the Contour Plot Platform in JMP with a few customizations.

Normally, a contour plot generates figures like the one shown in Figure 9. It is possible to generate space filling contour plots using a formula column, like a saved model, and a specified grid of data points as shown in 10. The procedure first requires that a model be saved to the data table. This is accomplished in the Neural Network

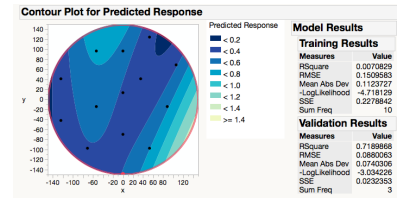


Figure 7: Wafer contour map with low RSquare using a 13 site sampling pattern for in line production measurements.

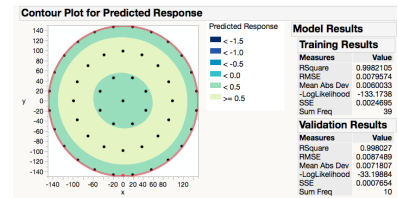


Figure 8: Wafer contour map with high RSquare using a common 49 site radial sampling pattern.

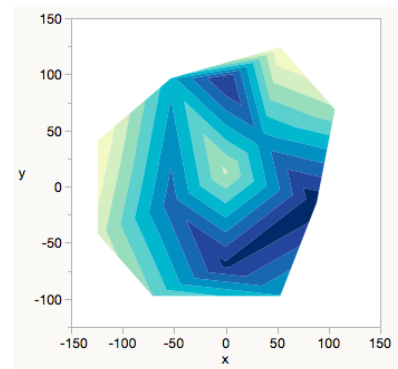


Figure 9: Contour plot of an exported model using the original 13 measurement sites.

Platform by selecting **Save Fast Formulas** from under the the Red Triangle next to the model. If multiple wafers were modeled, i.e., using the unique wafer identification number as a By variable, holding down CTRL (CMD for OS X) will export formulae for all the wafers into a single column.

The last step in generating a wafer map requires some customizations. Customizations allow for the addition of annotations to a platform's created image. For wafer maps, the customizations used will be 3 circles (the wafer edge, exclusion edge, and the wafer notch) and 4 custom polygons that will be used to mask off areas of the contour map that are outside of the wafer edge. These can be added via JMP's point and click interface, but a script is also provided with this paper to create them programmatically. A general script to generate the 4 polygons is provided here but without the specific data points needed to create masks for the sake of readability. The final result of this procedure is shown in Figure 11.

Procedure

1. Select *Graph > Contour Plot* in JMP.
2. Place the formula column for the modeling the **Y** column.
3. Place the columns containing the x and y coordinates for each measurement site in the **X** column.
4. If a By column was used to generate the model, i.e. multiple wafers, place the same By column into the **By** column.
5. Click **Specify Grid...** in the lower left area of the model dialog.
6. Set the desired density of points (levels), and the area of the model to be mapped. For 300 mm wafers this would be -150 mm to 150 mm or -150000 μm to 150000 μm if the coordinates are in microns.
7. Click **OK**.
8. Right Click on the contour plot and select **customize**.
9. Click the + symbol in the customization window and use the coordinate information from the script to generate the first of the 4 corner masks using this code: `Fill Color("white"); Polygon({x coordinates}, {y coordinates});`
10. Repeat the previous step to generate the remaining 3 corner masks.
11. Click the + symbol in the customize window again and add this code: `Pen Color("red"); Pen Size(1); Circle({0,0} $<$wafer radius$>);`

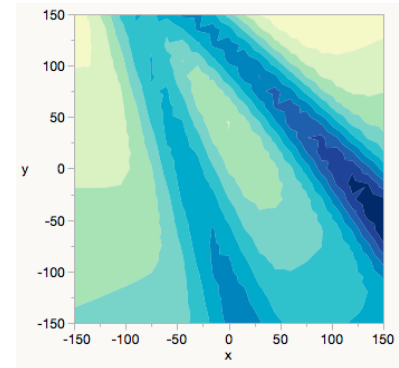


Figure 10: Contour plot of an exported model using a 21 site x 21 site specified grid.

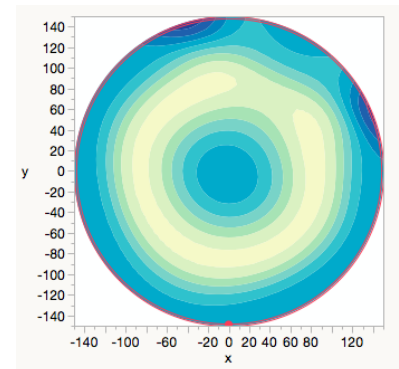


Figure 11: Completed wafer map with annotation scripts.

12. Repeat the previous step to generate the exclusion zone edge using the wafer radius minus the exclusion zone, i.e. if using a 2 mm exclusion zone the radius would be $150 - 2 = 148$.
13. To mark the notch of the wafer a small filled circle is generated using: `Fill Color("red"); Circle({0, - $<$ wafer radius$>$} 2);`

Conclusions

THIS WORK HAD A NUMBER OF GOALS. First, to demonstrate that there are multiple methods by which to generate both a wafer map and the fitting statistics required to evaluate the usefulness of that wafer map in JMP. While a Neural Network model in JMP Pro was used, this process could have been demonstrated using a Gaussian Process, LOESS spline, or any of the other modeling methods in JMP. Second, to demonstrate that different measurement patterns impart a bias to the maps calculated from the data collected using them. This bias was easily seen in the figures shown early on using common industry sampling patterns (see figures 5, 7 and 8). Statistics for those fits demonstrated that one wafer map was suspect and should not be considered useful. Lastly, this work sought to provide the procedures and scripts needed to construct wafer maps in JMP. The latter can be found in the form of a supplemental file accompanying this paper.

THERE ARE ALSO SOME CRITICAL POINTS TO BE MADE regarding wafer maps in general. First, contour based wafer maps as presented in the semiconductor industry are a visual representation of mathematical models - even ones that claim to use a simple smoothing algorithm or interpolation. *All models*, no matter how precise or generic, are approximations and have inherent error. Before we can use a wafer map, we must understand the error in the model used to generate it. We can use the statistics calculated while constructing the model to determine whether it is useful for the desired task. Most industry applications that generate wafer maps do not provide these statistics, leaving such visualizations open to misinterpretation.