Analysis of Variation Sources in Ring Oscillator Layouts (May 2003)

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Abstract—**this document elaborates on work done by Gonzalez-Valentin to extract and determine variation sources that are due to layout differences. We will be creating models and performing multivariate analysis when relevant data exists. In particular, we will examine in more detail the effect of polysilicon density, vertical structures, greater spacing between lines and a single finger structure. Finally, we will do some comparisons of single chips to the grand average of all chips in the study.**

***Index Terms*—ring oscillators, analysis of variance, polysilicon density (effects of), vertical layout, finger spacing, single finger layout, semiconductor manufacturing**

I. INTRODUCTION

ANALYSIS of the variation caused by layout decisions is an important task that can enable better design decisions through understanding the effects of certain structures.

Our work is an extension of original research performed by Karen M. Gonzalez-Valentin in her Master's Thesis titled "Extraction of Variation Sources due to Layout Practices". In her work, Mrs. Gonzalez-Valentin developed a test chip consisting of several specifically designed ring oscillator (RO) test structures, which exercised common layout parameters that many design engineers manipulate today. An abbreviated list of her design modifications are below:

TABLE I
RING OSCILLATOR TYPES AND QUANTITIES

Ring Oscillator Types	Number per Chip
Single Finger	*126*
Small Single Finger	18
Canonical FEOL	*225*
2 Fingers, 1.5x Minimum Length	54
4 Fingers, Minimum Length	54
2 Fingers, 2x Minimum Length	54
Single Finger, 4x Minimum Length	54
1.5x Spacing Between Poly Lines	81
2x Spacing Between Poly Lines	81
3x Spacing Between Poly Lines	*81*
1.2x Spacing Between Poly Lines	81
Vertical Canonical FEOL	*36*
Vertical, 3x Spacing Between Poly Lines	*36*
Vertical Single Finger	*36*
0% Polysilicon Density	*6*
12% Polysilicon Density	*6*
25% Polysilicon Density	*6*
50% Polysilicon Density	*8*
Canonical At End Of Density Structures	4

Gonzalez-Valentin's test chip consisted of over 2000 ring oscillator positions that were tested for frequency using a scan chain. Of particular interest to us in our analysis, however, are the ring oscillator types shown in italics. We will discuss each of these in more detail later in this section. Additionally, the experiment consisted of 36 identical chips distributed throughout the top half of a wafer. A spatial mapping of her chip placements can be seen in Figure 1.

Gonzalez-Valentin initiated some work to understand whether each of the Front-End-of-Line (FEOL) device structures and Back-End-of-Line (BEOL) structures were significant. Of particular interest was her ANOVA execution, which demonstrated that many of the structure did have a significant effect on the output (frequency). She also suggests that spacing between polysilicon fingers can shift ring oscillator frequency by 4.4%, and polysilicon density can alter frequency by 2.1%.

Much of Gonzalez-Valentin's analysis was done on a 'superchip' level, meaning that she aggregated the responses of multiple chips to obtain her results. Though this analysis is valid and increases the number of results used in the analysis, this approach also leaves some significant areas in which to explore further.

We have chosen to pursue some analysis on an individual chip level, comparing the analyses achieved by Gonzalez-Valentin to the results on a per chip basis. Furthermore, we will perform some multivariate analysis as appropriate on different oscillator properties. Specifically, we will look at the following issues:

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- Model fit for the effect of polysilicon density on ring oscillator performance
- Multivariate analysis of effect of vertical and of 3x spacing
- Multivariate analysis of effect of vertical and of single finger
- Comparison of ‘superchip’ versus individual chips for polysilicon density model

We will discuss each of these analyses and their significance briefly below:

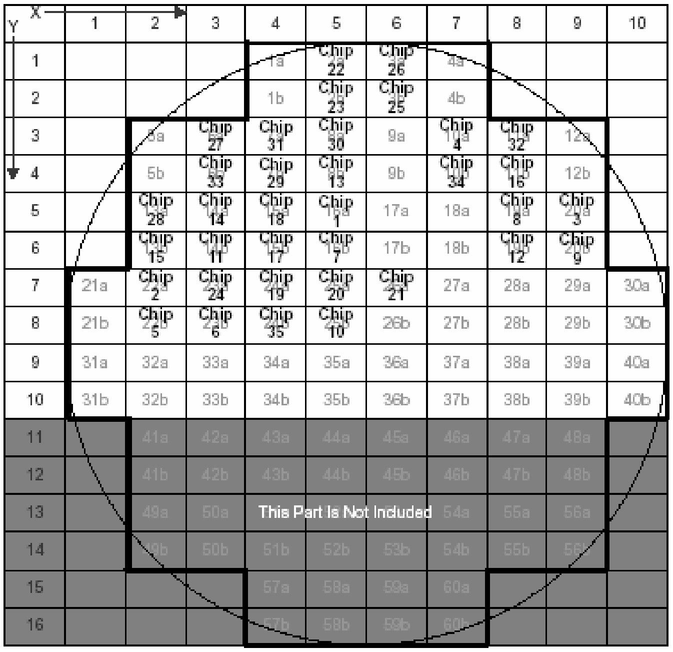

Fig. 1. Spatial positioning of the test chips on the top half of the wafer.

A. Fit Model for Polysilicon Density Effects

Gonzalez-Valentin discovered that global density around a ring oscillator did have a significant effect on frequency of 2.1%. The hypothesis is that the presence of more conductive material around the oscillator will create a capacitive load, reducing the frequency of the structure.

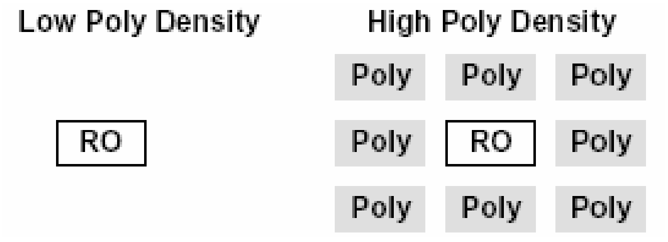

Fig. 2. Polysilicon Density around the ring oscillator was varied from 0% to 50%.

We will try multiple models and find the best fit to correctly predict the effects of polysilicon on the oscillation frequency.

B. Correlation of Vertical RO’s and 3x spacing

C. Correlation of Vertical RO’s and single finger RO’s

Many of the experiments placed on the chip only tested one specific attribute and are ill-suited to look for correlation between multiple parameters. However, a few select designs were set up to allow for a two-way multivariate analysis using a design of experiments (DOE) format. Both of these instances include the effect of vertical ring oscillators.

Gonzalez-Valentin recognized a significant difference in the speed of vertically placed (rotated 90 degrees) FEOL ring oscillators. In general, these oscillators were slower than their horizontal brethren. The difference was attributed to variation in ion implantation, mask scan, or perhaps other direction dependent manufacturing processes.

Some structures on the chip were not only were placed in vertical orientation, they also designed with another property. In this case, we can perform a multivariate analysis to see what the main effects are and whether cross or second order effects are significant. We pursue this experiment with the FEOL ring oscillators with minimum and 3x minimum spacing AND with FEOL ring oscillators with a single gate (finger) that is 3 times the minimum gate length.

D. Polysilicon Density Differences between chips and grand average

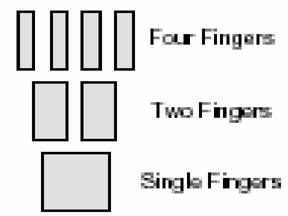

Fig. 3. The single finger has the same effective gate length as the canonical FEOL. Theoretically, the single finger should output a frequency that is nominally identical to the canonical structure.

The polysilicon density effects given in the thesis were for the ‘superchip’. Therefore, some analysis can be done on whether the results of the superchip actually hold for the individual chips. We will take a sampling of individual chips and see if the same trends (intercept, slope) exist and to what extent.

II. Materials and Methods

A. Polysilicon Density Effects

We examined several aspects of polysilicon density. In particular, we looked at creating a fit model that suggests the relationship between the density of polysilicon and the effect on frequency. Figure 4 shows the mean and the 95% confidence intervals for the four values of polysilicon density. This graph clearly shows a decrease in frequency as the density increases. We will fit a model to this ‘superchip’ data that is a combination of all individual chips superimposed into one chip. We expect the model to predict this trend with a high level of confidence.

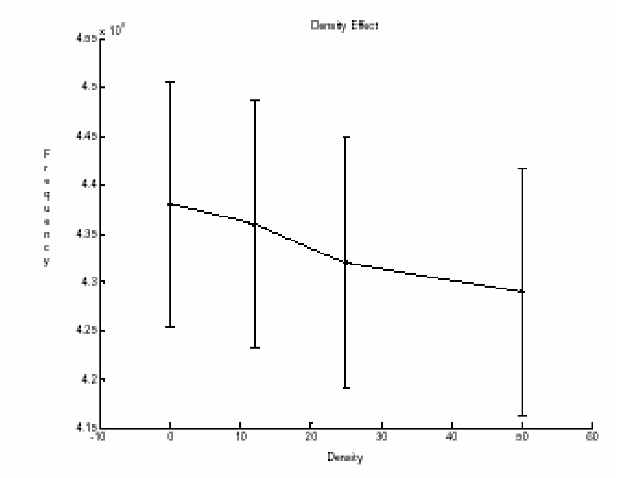

Fig. 4. Global Polysilicon Density effect with standard deviations.

B. Correlation of Vertical RO's and 3x spacing

For this experiment, we began by taking data from sample chips located in different sections of the wafer and isolated the following structure types:

- Canonical FEOL – The standard ring oscillator style.
- Vertical Canonical FEOL – This is just the standard ring oscillator constructed at a 90 degree rotation from the Canonical FEOL.
- 3x Spacing between Poly lines – Three times the minimum spacing between the polysilicon gates that form the transistors.
- Vertical, 3x Spacing between Poly Lines – Same as above, but with a vertically constructed structure.

Each chip had many instances of each structure. Therefore the results could be analyzed with a high degree of confidence.

The design of the experiment was a full factorial 2^2 design with multiple replicates for each. The purpose of the analysis was to look at the main effects and any potential two-factor interactions that are present. The factors were normalized in the following manner:

Canonical FEOL (-1) to Vertical Canonical FEOL (+1)
3x Spacing between poly (-1) to Vertical, 3x Spacing (+1)

JMP-IN was used in a stepwise fashion to determine significant effects (first-order, second-order and two way). In addition, parameter estimates were recorded to understand magnitude of effect, and the R^2 was calculated to ascertain model fit.

We compared the different model parameters and R^2 values for several chips, including Chips #5, #12, #20, and #26, representing the left, right, top and middle of the wafer. We also looked at the 'superchip' to see how it compares with the results of individual chips.

C. Correlation of Vertical RO's and single finger RO's

Very similar to the methods described in section B above, we will be performing a multivariate analysis to look for correlations between vertical ring oscillators and the finger size. Our data consisted of:

- Canonical FEOL – The standard ring oscillator style.
- Vertical Canonical FEOL – This is just the standard ring oscillator constructed at a 90 degree rotation from the Canonical FEOL.
- Single Finger – The canonical FEOL has three fingers of equal width. In this case, these three fingers are replaced with a single finger with three times the width. The nominal frequency of the single finger should be similar to that of canonical FEOL, though the total variation on gate length may decrease.
- Vertical, Single Finger – Same as above, but with a vertically constructed structure.

Again, we compared the fit model and magnitudes of several individual chips with each other and the 'superchip'. The factors were normalized in the following manner:

Canonical FEOL (-1) to Vertical Canonical FEOL (+1)
Single Finger (-1) to Vertical, Single Finger (+1)

D. Polysilicon Density Differences – individual versus aggregate

After fitting the linear model to the aggregate data from all of the chips, we further explored some of the differences between individual chips and the 'superchip.' We wanted to determine if the 'superchip' model for slope and intercept agrees with the actual individual chips. This was accomplished by looking at 17 out of the 34 individual chips and comparing them to the aggregate. The 17 chips were selected to sample the largest variety of sights possible with the given data.

III. STUDY RESULTS

A. Polysilicon Density Effects

The polysilicon density data was limited to only four discrete increments of increasing poly density. With only four data points the best model to predict the data is a simple line.

$$\mathit{frequency} = 4.477 - 0.213 * \mathit{density}$$

With additional data points there is the possibility of a more complex equation to model this effect. This equation represents the best fit for this 'superchip' with the detailed ANOVA analysis is show in Table II:

TABLE II
FIT MODEL FOR POLYSILICON SUPERCHIP

RSquare	0.212123
RSquare Adj	0.211255
Root Mean Square Error	79410.49
Mean of Response	4426185
Observations (or Sum Wgts)	910

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4477505.7	4207.551	1064.2	0.0000

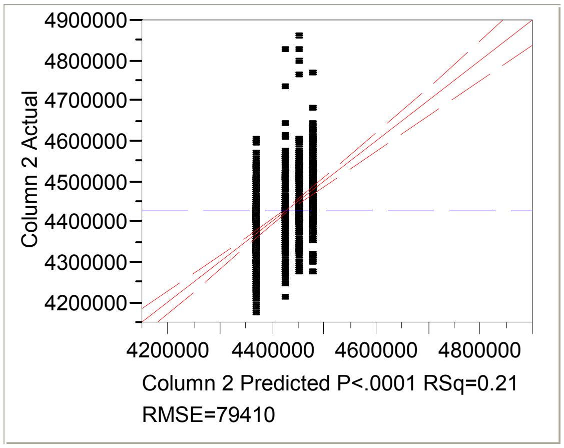

Fig. 5. Actual versus predicted for the ‘superchip’ model fit.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Density	-213493.7	13654.55	-15.64	<.0001

The R^2 value for the proposed model is only 0.21, so the model does not explain all of the data. However the model coefficients have high t-Ratios, so we are highly confident that the model is predicting a trend that is dependent upon the percentage of polysilicon surrounding the ring oscillators.

This is best observed in figure 5 which shows the results that the model predicts plotted against the actual data points. There is a definite trend of decreasing frequency with increased polysilicon density.

It is clear that there is a wide amount of variation within the aggregate sample set. It is not obvious where this variation comes from, but some deviation may be due to spatial variation that was not considered in this study. In section D, we investigate the variation of the intercept and slope of the single chips and how they compare with the ‘superchip’.

B. Correlation of Vertical RO’s and 3x spacing

In our assessment, we determined that the effects of second order terms and cross terms are not significant. Consider the example of the ‘superchip’:

TABLE III
FIT MODEL FOR SUPERCHIP FOR VERTICAL VS. 3X SPACING

RSquare	0.686508
RSquare Adj	0.686447
Root Mean Square Error	97104.33

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	4314655.4	943.9751	4570.7	0.0000
vertical	-31345.26	847.9452	-36.97	<.0001
3x spacing	-159322.7	885.1775	-180	0.0000
(vertical+0.38776)*(3x spacing+0.46939)	-880.4651	959.4333	-0.92	0.3588

The effect of vertical ring oscillators and the triple spacing are both very visible. However, there does not seem to be any real interaction between the two main effects.

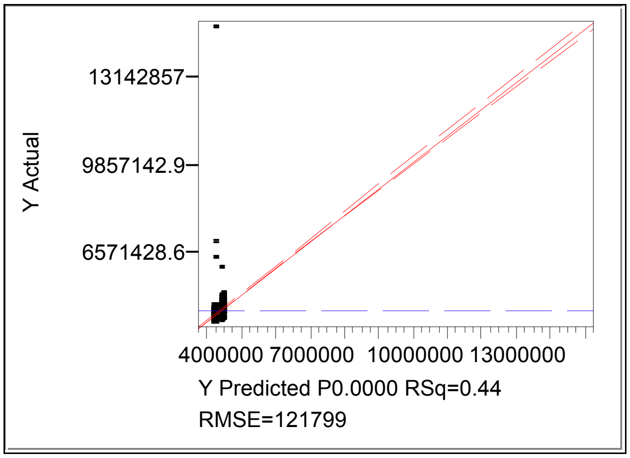

Fig. 6. Actual by Predicted Plot for the ‘superchip’ based on a two-way model for vertical and single finger. Notice the four points that are significant outliers.

Also notice that the fit as noted by the R^2 term is fairly low. If we look more closely at the some of the individual chips, we see that the fit is much better. For example, Chip 12 (right side of wafer) had a tighter model:

TABLE IV
FIT MODEL FOR CHIP 12 FOR VERTICAL VS. 3X SPACING

RSquare	0.924248
RSquare Adj	0.923728
Root Mean Square Error	39560.94

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4327950.2	2312.474	1871.6	0.0000
vertical	-23797.62	2312.474	-10.29	<.0001
3x spacing	-154705.7	2312.474	-66.90	<.0001
vertical*3x spacing	-2104.802	2312.474	-0.91	0.3632

This result, along with several other analyses of individual chips, seems to indicate that the ‘superchip’ model is not a particularly good description of the effects of vertical RO’s or triple spacing. However, all of the individual chips sampled demonstrated that there were no significant cross effects.

C. Correlation of Vertical RO’s and single finger RO’s

Correlating the effect of vertical ring oscillators and single fingers turned out to have a surprising effect. There appears to be a significant cross effect between these two attributes, though the overall impact of the effect is minor relative to the large effect the two main effects have.

First, we looked at the ‘superchip’ results:

TABLE V
FIT MODEL FOR SUPERCHIP FOR VERTICAL VS. SINGLE FINGER

RSquare	0.442632
RSquare Adj	0.442533
Root Mean Square Error	121798.8

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4363792.7	1153.876	3781.9	0.0000
vertical	-22979.12	1153.876	-19.91	<.0001
single finger	-110366.5	1153.876	-95.65	0.0000

Term	Estimate	Std Error	t Ratio	Prob>|t|
vertical*single finger	7898.9525	1153.876	6.85	<.0001

It is immediately apparent that the vertical FEOL, the single finger and the cross effect between them are ALL significant factors. However, it is equally as important to note that magnitude of the cross effect is very small in comparison to the other effects. Pulling out the term from the model fit only affects the R^2 metric minimally. In fact, if you pull out the cross term, the R^2 becomes 0.441096.

Again, the fit as measured by R^2 for the 'superchip' is very low. Some of this lack of fit may be attributed to some very abnormal measurements that ranged from 6 MHz to over 15 MHz (See Figure 5).

These outliers come from two chips, namely Chip #1 and Chip #4. Unfortunately, these chips are not close together, so we cannot make an immediate link regarding the reason for the strange measurements.

We observed that the individual chips had much better fits for their separate models. A good example is chip #5 (far left hand side):

TABLE VI
FIT MODEL FOR CHIP 5 FOR VERTICAL VS. SINGLE FINGER

RSquare	0.928747
RSquare Adj	0.928303
Root Mean Square Error	35882.55

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4454921.1	2011.099	2215.2	0.0000
Vertical	-12433.88	2011.099	-6.18	<.0001
single finger	-133722.7	2011.099	-66.49	<.0001
vertical*single finger	6887.2237	2011.099	3.42	0.0007

All of the effects still appear to be very significant.

We also looked at the slopes of the lines to see if any of the magnitude of the effects of the individual chips were dramatically different than those of the 'superchip'. From our analysis of six different chips, we saw many slopes that were over two standard errors away from the 'superchip' slope.

D. Polysilicon Density Differences – individual versus aggregate

We first looked at the confidence interval for the slope and then compared it to the confidence intervals from 17 of the individual chips as shown in figure 7. The 95% confidence interval for the 'superchip' contained the entire confidence interval for 16 out of the 17 individual chips. This was a little bit surprising since there was so much variation in the individual points. We conclude from this that the 'superchip' provides a good representation of the slope confidence interval for the individual chips.

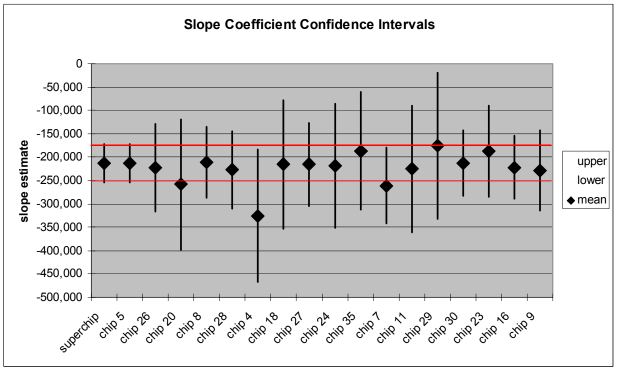

Fig. 7. Polysilicon Density Effects – slope confidence intervals. The slope on the 'superchip' is on the far left. The horizontal bars are the 95% confidence intervals around the slope.

Next we looked at the confidence interval for the 'superchip mean and compared it to the 17 individual chips as shown in figure 8 with significantly different results. The 95% confidence interval for the 'superchip' only overlapped with a small percentage of the individual chips. There is some effect that affects the intercept that is not being captured with this model. It would be interesting to do some type of spatial analysis to determine if the intercept is affected by some combination of wafer location and polysilicon density.

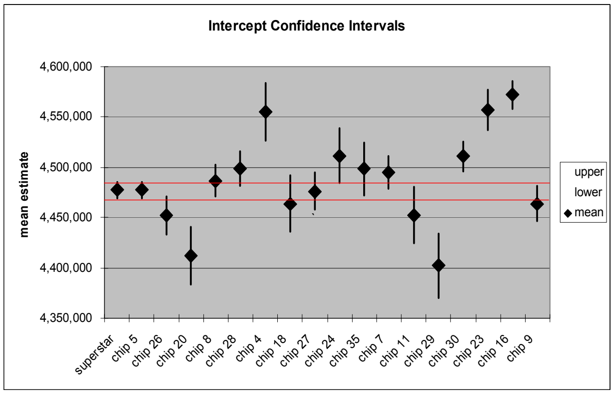

Fig. 8. Polysilicon Density Effects – intercept confidence intervals. The intercept on the 'superchip' is on the far left. The horizontal bars are the 95% confidence intervals around the intercept.

IV. CONCLUSIONS

Our analysis allows us to make three conclusions:

1. All main effects inspected in paper were significant
2. Density has a consistent linear effect over multiple individual chips
3. There is a significant but small interaction between vertical RO's and single finger

The significance of the main effects was first noted by Gonzalez-Valentin, and we were able to affirm her findings through our analysis.

Next, we were able to fit a model for the effect of polysilicon density. The effect of density appears fairly consistent across all of the sample chips, though there is certainly still some variation. What remains unclear is what other factors may be contributing to variation, though accounting for chip location on the wafer may prove to be a significant factor.

Finally, we concluded that there is no interaction between vertical layout ring oscillators and line spacing, but there is some cross effect between vertical layout ring oscillators and the number of fingers used in layout.

For the vertical versus singer finger case, the interaction between them is in the opposite direction of the main effects. More specifically, the effects of a vertical layout and a single finger are both negative on frequency. The interaction, however, has a slight positive effect on frequency. We rationalize this observation by the fact that a single finger is less susceptible to gate length variation than the multiple gates in the canonical FEOL. Any direction dependent manufacturing processes would affect a three-finger structure approximately three times as much as a single finger structure.

For future research into the topic of the effect of layout variation, we envision the following possibilities:

- More ring oscillator structures with multiple effects, enabling the experimenter to quantify effect interactions. For example, identify cross effects between polysilicon density and the number of fingers.
- Fabrication of test chips on multiple wafers, to account for the possibility of systemic problems with the original test wafer.
- Fabrication of test chips on more randomly spaced locations throughout the wafer, reducing the likelihood of spatial effects.
- Studies on whether there is a spatial relationship to the variances in polysilicon density effect slope or intercept.
- Effect of spatial relationships on vertical ring oscillators, spacing differences and the use of fewer/more fingers with equivalent gate lengths.
- Increase the number of different percentages of polysilicon to enable possible higher order models

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[1] K. M. Gonzalez-Valentin, "Extraction of Variation Sources Due to Layout Practices." Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2002.
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