Data Analysis

Integrated Model-Based Run-to-Run Uniformity Control for Epitaxial Silicon Deposition - A. Gower-Hall

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6.780 Semiconductor Manufacturing

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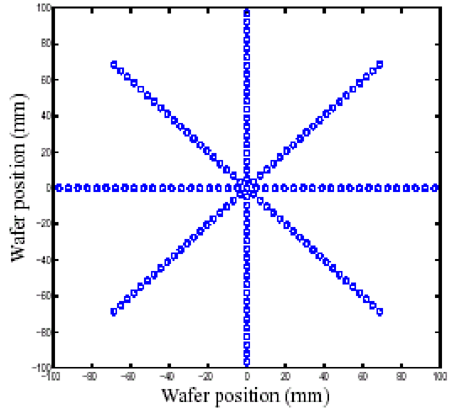
Agenda

- Overview of Thesis DOE
- Thesis Findings
- First Stage - Verification of Findings
- Individual Position Model
- Absolute Radial Position Model

Overview of Thesis

- Data Taken by Aaron Gower-Hall for PhD Thesis
- Run-to-Run Uniformity Control of Thickness and Resistivity for Epitaxial Silicon Deposition

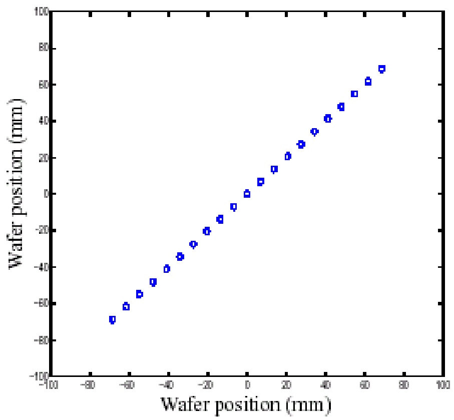
Figure 7-1: DOE thickness measurement map



Design of Experiment

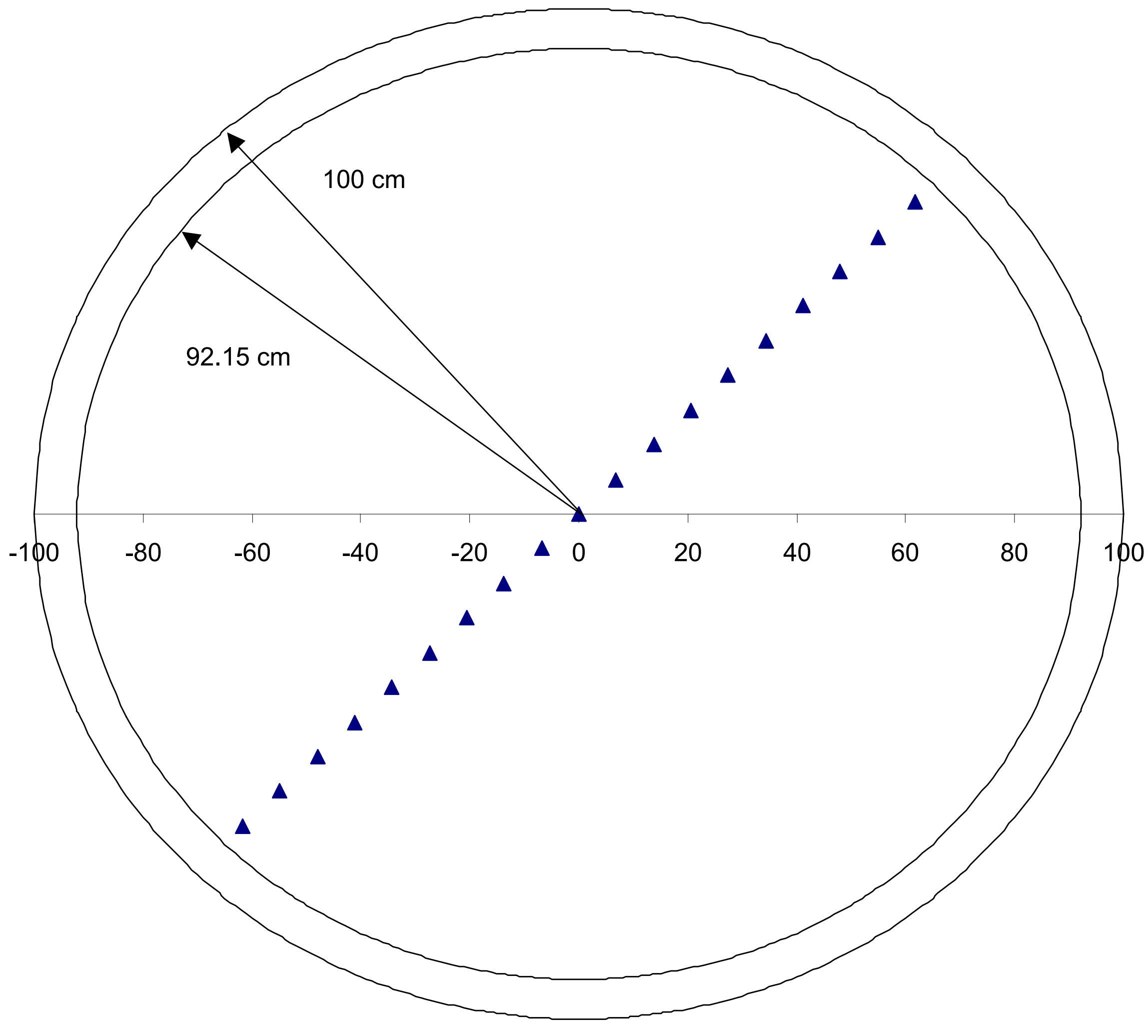
- Multi Variable Fractional Factorial Design
- 9 changing variables (inputs)
- 19 measurement posits (-87.3 to +87.3 cm)
- 112 Experimental Trials
- Total of 2128 data points (19*112)

Figure 7-2: Resistivity measurement map



Data Analysis focuses on Resistivity Measurements

Resistivity Map



Resistivity as function of Radial Displacement?

Input Parameters (9)

Center Gas Flow Valve	A	115-155 (Accusett inner)
Outer Gas Flow Valve	B	60-100 (Accusett outer)
Deposition Temperature	B	1090-1150 (deg C)
Dopant Mix Ratio (%)	D	20-80 (%)
Dopant Main Flow	E	40-260 (sccm)
% Lower Power	F	45-55 (%)
% Inner Power	G	40-60 (%)
Dilutant H2 Flow (slm)	H	30-60 (slm)
Trichlorosilane (TSC) flow	I	10-14 (slm)

Large DOE with several input parameters

Visualization of Experimental Design and Results

	Inputs (Changing Variables)										Outputs (Position (cm))				
Exp	A	B	C	D	E	F	G	H	I		-87.3	-77.6	…	87.3	Avg
1	0	0	0	0	0	0	0	0	0		2.5314	2.5892	…	2.5199	2.6490
2	0	0	0	0	0	0	0	0	1.667		3.1463	3.1400	…	3.1407	3.2000
3	0	0	0	0	-1.571	0	0	0	0		2.6352	2.6454	…	2.6357	2.7020
4	0	0	0	0	1.571	0	0	0	0		2.6825	2.6715	…	2.6910	2.7391
5	0	0	0	0	0	0	0	1.5	0		2.4573	2.4644	…	2.4428	2.5052
…	…	…	…	…	…	…	…	…	…		…	…	…	…	…
112	1	1	1	1	-1	-1	-1	1	-1		4.9896	4.9734	…	0.9224	0.9485
										Avg	3.2327	3.2616	…	4.9698	

Dataset required some manipulation

Approach

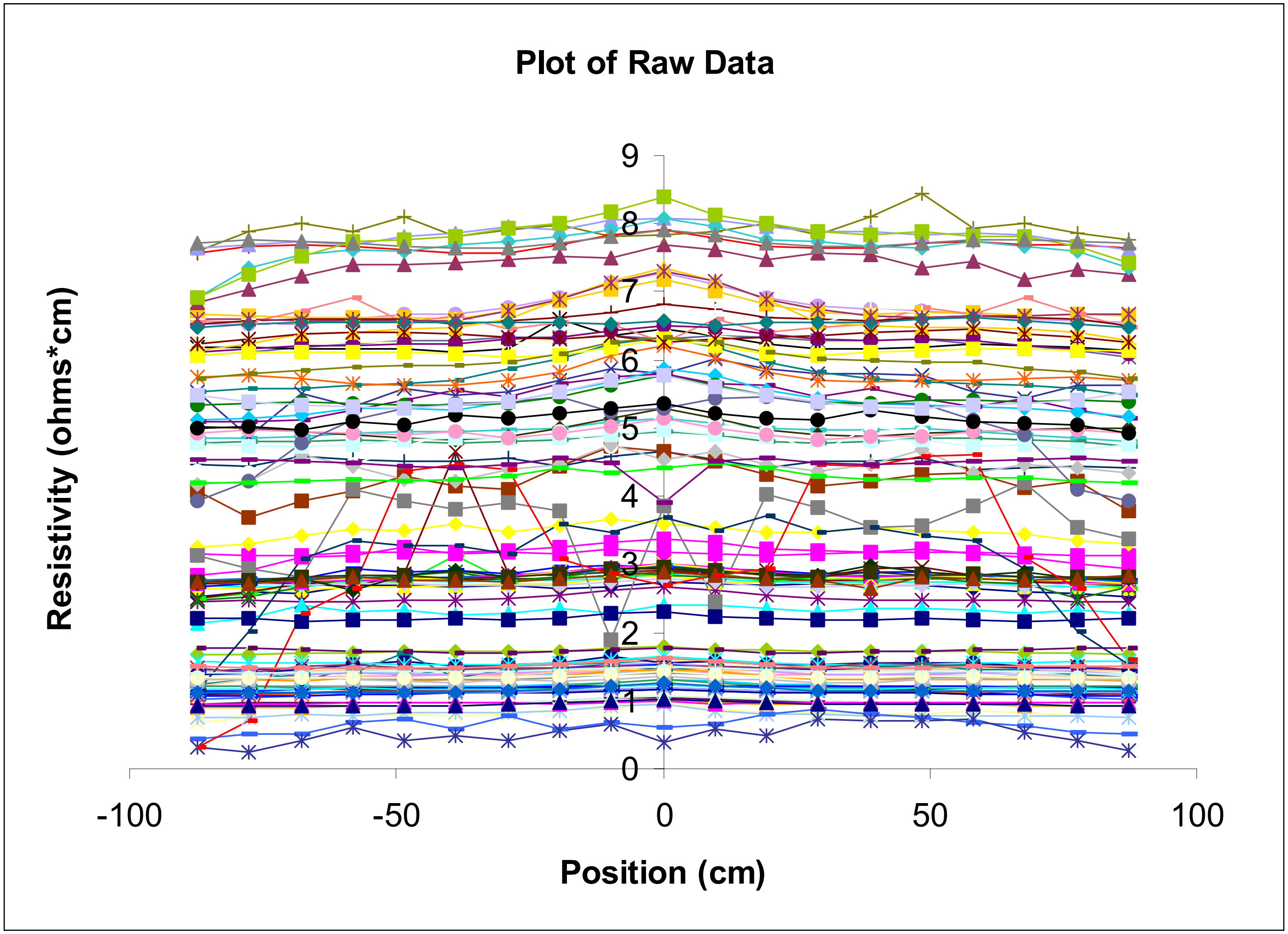
- Looked at Plots of Raw Data
- Looked at Raw Data Averages
- Verified Gower-Hall's Findings
- Built Explicit Models for Each of 19 points
- Included Position as an Explicit Variable

Trying to understand Resistivity relation with position

Visualization of Experimental Design and Results

	Inputs										Outputs				
	Changing Variables										Position (cm)				
Exp	A	B	C	D	E	F	G	H	I		-87.3	-77.6	…	87.3	Avg
1	0	0	0	0	0	0	0	0	0		2.5314	2.5892	…	2.5199	2.6490
2	0	0	0	0	0	0	0	0	1.667		3.1463	3.1400	…	3.1407	3.2000
3	0	0	0	0	-1.571	0	0	0	0		2.6352	2.6454	…	2.6357	2.7020
4	0	0	0	0	1.571	0	0	0	0		2.6825	2.6715	…	2.6910	2.7391
5	0	0	0	0	0	0	0	1.5	0		2.4573	2.4644	…	2.4428	2.5052
…	…	…	…	…	…	…	…	…	…		…	…	…	…	…
112	1	1	1	1	-1	-1	-1	1	-1		4.9896	4.9734	…	0.9224	0.9485
										Avg	3.2327	3.2616	…	4.9698	

Raw Data

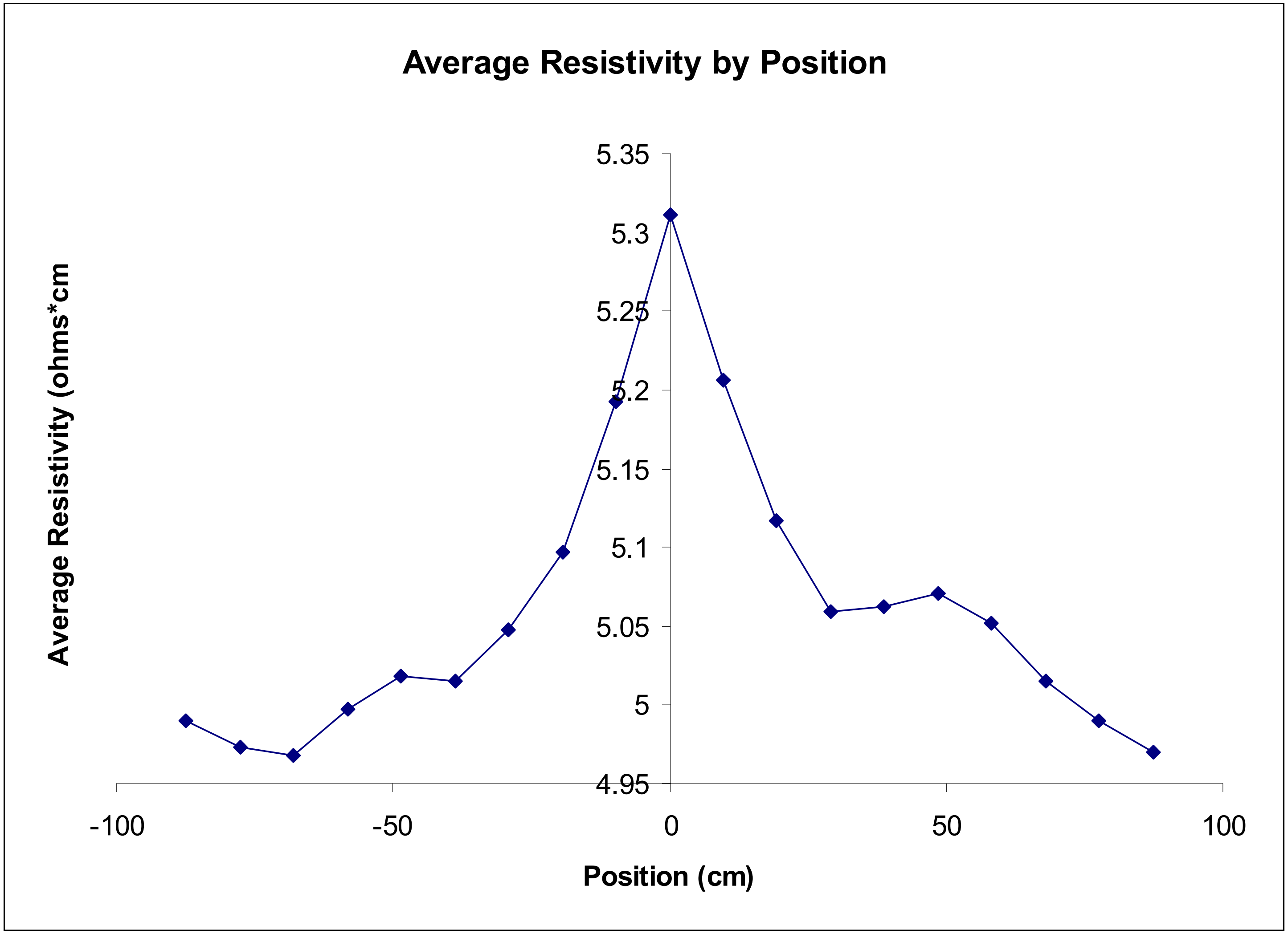


Plot of Raw Data
Resistivity (ohms*cm)
0
1
2
3
4
5
6
7
8
9
Position (cm)
-100
-50
0
50
100

Visualization of Experimental Design and Results

	Inputs										**Outputs**				
	Changing Variables										Position (cm)				
Exp	A	B	C	D	E	F	G	H	I		-87.3	-77.6	…	87.3	Avg
1	0	0	0	0	0	0	0	0	0		2.5314	2.5892	…	2.5199	2.6490
2	0	0	0	0	0	0	0	0	1.667		3.1463	3.1400	…	3.1407	3.2000
3	0	0	0	0	-1.571	0	0	0	0		2.6352	2.6454	…	2.6357	2.7020
4	0	0	0	0	1.571	0	0	0	0		2.6825	2.6715	…	2.6910	2.7391
5	0	0	0	0	0	0	0	1.5	0		2.4573	2.4644	…	2.4428	2.5052
…	…	…	…	…	…	…	…	…	…		…	…	…	…	…
112	1	1	1	1	-1	-1	-1	1	-1		4.9896	4.9734	…	0.9224	0.9485
										Avg	3.2327	3.2616	…	4.9698	

Average Resistivity across wafer



MRS Experimental Design and Results

	Inputs										Outputs				
	Changing Variables										Position (cm)				
Exp	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**		**-87.3**	**-77.6**	**…**	**87.3**	**Avg**
1	0	0	0	0	0	0	0	0	0		2.5314	2.5892	…	2.5199	2.6490
2	0	0	0	0	0	0	0	0	1.667		3.1463	3.1400	…	3.1407	3.2000
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…	…	…	…	…	…	…	…	…	…		…	…	…	…	…
112	1	1	1	1	-1	-1	-1	1	-1		4.9896	4.9734	…	0.9224	0.9485
										Avg	3.2327	3.2616	…	4.9698	

What factors influence the output with 95% or better significance?

Assn: Only main effects, one-way interactions, and 2nd-degree polynomial terms are significant.

Significant Effects and Interactions

Deposition Temperature	B	x1
Dopant Mix Ratio (%)	D	x2
Dilutant H2 Flow (slm)	H	x3
Trichlorosilane (TSC) flow	I	x4

3 Significant One-Way Interactions

Dop Mix*TCS	x2*x4
Dep Temp*Dopant Mix	x1*x2
Dopant Mix * Dil H2	x2*x3

Results

Parameter Estimates

Term		Estimate	Std Error	t Ratio	Prob>|t|
Intercept		3.3448562	0.044178	75.71	<.0001
Dep Temp	x_1	-0.445737	0.048131	-9.26	<.0001
Dop Mix	x_2	-2.235974	0.048926	-45.7	<.0001
Dil H2	x_3	-0.291859	0.048298	-6.04	<.0001
TSC	x_4	0.3759196	0.04782	7.86	<.0001
Dep Temp * Dop Mix	x_1*x_2	0.3205027	0.049333	6.5	<.0001
Dop Mix * Dil H2	x_2*x_3	0.19822	0.049519	4	0.0001
Dop Mix * TCS	x_2*x_4	-0.270065	0.049299	-5.48	<.0001

$$y = 3.345 - 0.446x_1 - 2.236x_2 - 0.292x_3 + 0.376x_4$$
$$- 0.270x_2 x_4 + 0.321x_1 x_2 + 0.198x_2 x_3$$

Summary Statistics

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	528.59914	75.5142	347.5453
Error	104	22.59698	0.2173	Prob > F
C. Total	111	551.19612		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	15	9.957507	0.663834	4.6743
Pure Error	89	12.639468	0.142016	Prob > F
Total Error	104	22.596975		<.0001
				Max RSq
				0.9771

R-sq (Adj) = 96.5244

Experimental Design and Results

	Inputs										Outputs				
	Changing Variables										Position (cm)				
Exp	A	B	C	D	E	F	G	H	I		-87.3	-77.6	…	87.3	Avg
1	0	0	0	0	0	0	0	0	0		2.5314	2.5892	…	2.5199	2.6490
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5	0	0	0	0	0	0	0	1.5	0		2.4573	2.4644	…	2.4428	2.5052
…	…	…	…	…	…	…	…	…	…		…	…	…	…	…
112	1	1	1	1	-1	-1	-1	1	-1		4.9896	4.9734	…	0.9224	0.9485
										Avg	3.2327	3.2616	…	4.9698	

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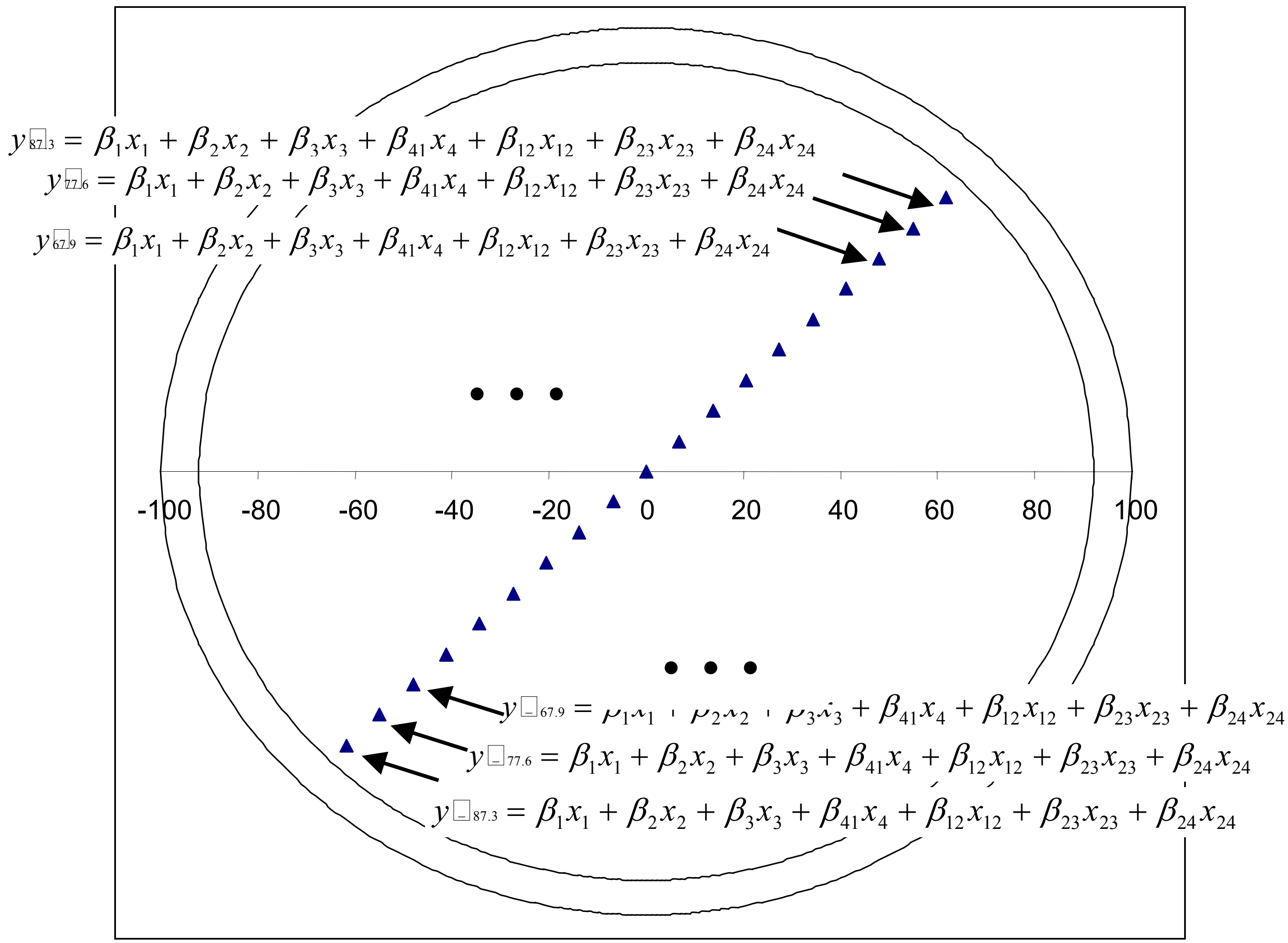
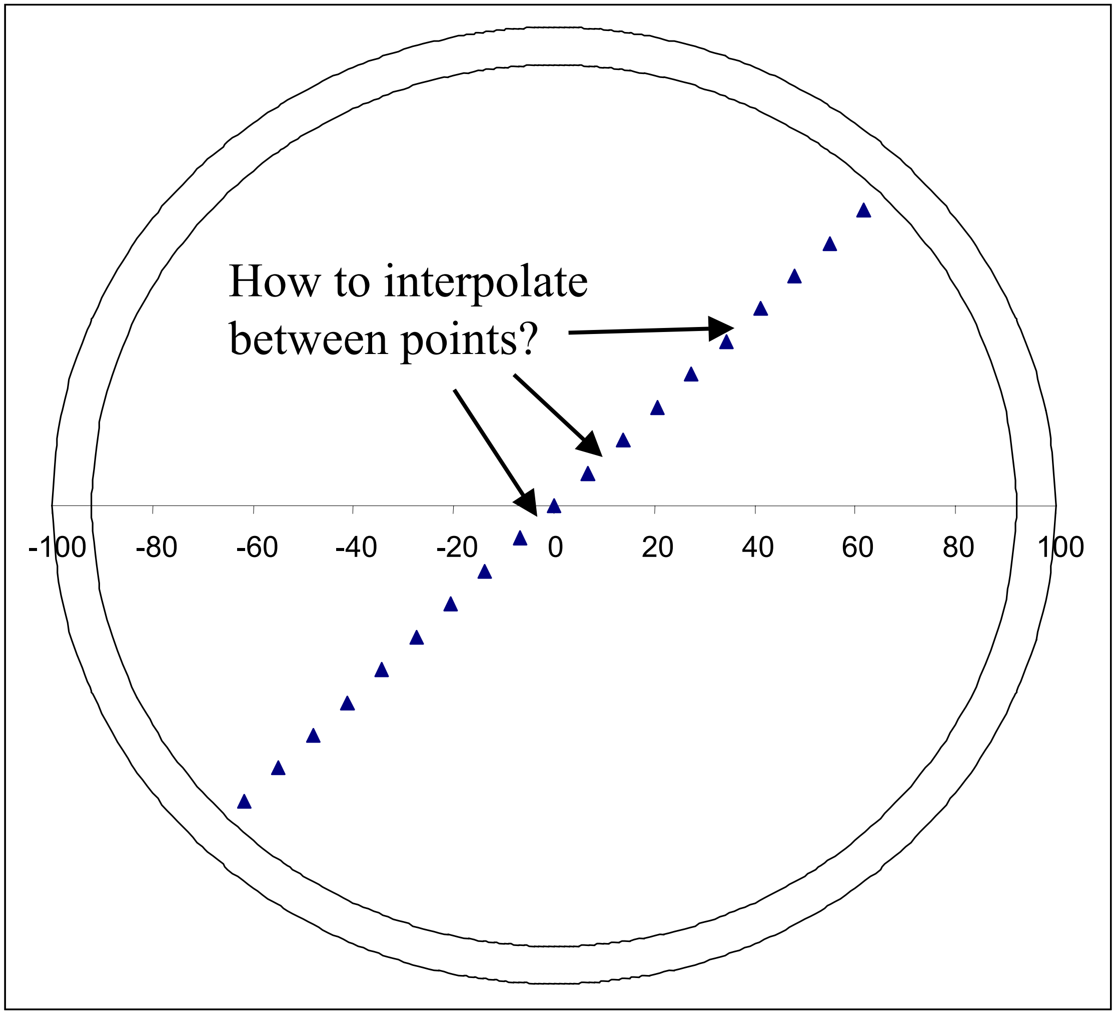
Assn: Only main effects, one-way interactions, and 2nd-degree polynomial terms are significant.


$y_{87.3} = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{41} x_4 + \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{24} x_{24}$
$y_{77.6} = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{41} x_4 + \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{24} x_{24}$
$y_{67.9} = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{41} x_4 + \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{24} x_{24}$
-100
-80
-60
-40
-20
0
20
40
60
80
100
$y_{67.9} = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{41} x_4 + \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{24} x_{24}$
$y_{77.6} = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{41} x_4 + \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{24} x_{24}$
$y_{87.3} = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{41} x_4 + \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{24} x_{24}$

$$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{41} x_4 + \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{24} x_{14}$$

	Int	β1	β2	β3	β4	$\beta_1\beta_2$	$\beta_2\beta_3$	$\beta_2\beta_4$	**R^2-adj**	**Prob LOF**
-87.3	3.184	-0.414	-2.117	-0.317	0.388	0.298	0.232	-0.283	0.897	<0.0001
-77.6	3.212	-0.435	-2.138	-0.321	0.383	0.319	0.230	-0.279	0.909	<0.0001
-67.9	3.276	-0.432	-2.192	-0.313	0.369	0.315	0.213	-0.265	0.940	<0.0001
-58.2	3.319	-0.429	-2.216	-0.320	0.357	0.300	0.223	-0.250	0.954	<0.0001
-48.5	3.346	-0.449	-2.244	-0.304	0.348	0.321	0.196	-0.256	0.969	<0.0001
-38.8	3.364	-0.456	-2.249	-0.286	0.348	0.328	0.192	-0.244	0.967	<0.0001
-29.1	3.360	-0.456	-2.256	-0.285	0.355	0.334	0.188	-0.252	0.967	<0.0001
-19.4	3.401	-0.440	-2.282	-0.280	0.389	0.309	0.189	-0.280	0.959	<0.0001
-9.7	3.440	-0.470	-2.280	-0.242	0.424	0.330	0.156	-0.313	0.942	0.0005
0	3.493	-0.450	-2.327	-0.258	0.425	0.327	0.173	-0.311	0.953	<0.0001
9.7	3.441	-0.462	-2.296	-0.252	0.418	0.331	0.166	-0.307	0.948	<0.0001
19.4	3.392	-0.430	-2.276	-0.285	0.380	0.308	0.192	-0.277	0.958	<0.0001
29.1	3.369	-0.448	-2.258	-0.283	0.359	0.325	0.190	-0.256	0.968	<0.0001
38.8	3.374	-0.454	-2.264	-0.281	0.362	0.326	0.182	-0.259	0.968	<0.0001
48.5	3.385	-0.458	-2.269	-0.290	0.358	0.329	0.190	-0.251	0.967	<0.0001
58.2	3.361	-0.455	-2.250	-0.295	0.360	0.328	0.200	-0.247	0.967	<0.0001
67.9	3.329	-0.441	-2.230	-0.312	0.361	0.315	0.214	-0.250	0.956	<0.0001
77.6	3.280	-0.450	-2.190	-0.307	0.378	0.326	0.214	-0.271	0.941	0.0003
87.3	3.227	-0.441	-2.149	-0.316	0.382	0.323	0.226	-0.278	0.924	0.0221
max	3.493	-0.414	-2.117	-0.242	0.425	0.334	0.232	-0.244	**0.969**	**0.0221**
min	3.184	-0.470	-2.327	-0.321	0.348	0.298	0.156	-0.313	**0.897**	**0.0003**
% diff	**9.70%**	**13.37%**	**9.89%**	**32.89%**	**22.22%**	**12.13%**	**48.67%**	**28.09%**		


How to interpolate
between points?
-100
-80
-60
-40
-20
0
20
40
60
80
100

Solution: Make Position an Explicit Parameter

	Inputs Changing Variables										Outputs Position (cm)				
Exp	A	B	C	D	E	F	G	H	I		-87.3	-77.6	…	87.3	Avg
1	0	0	0	0	0	0	0	0	0		2.5314	2.5892	…	2.5199	2.6490
2	0	0	0	0	0	0	0	0	1.667		3.1463	3.1400	…	3.1407	3.2000
3	0	0	0	0	-1.571	0	0	0	0		2.6352	2.6454	…	2.6357	2.7020
4	0	0	0	0	1.571	0	0	0	0		2.6825	2.6715	…	2.6910	2.7391
5	0	0	0	0	0	0	0	1.5	0		2.4573	2.4644	…	2.4428	2.5052
…	…	…	…	…	…	…	…	…	…		…	…	…	…	…
112	1	1	1	1	-1	-1	-1	1	-1		4.9896	4.9734	…	0.9224	0.9485
										Avg	3.2327	3.2616	…	4.9698	

Inputs

Changing Variables

Exp	A	B	C	D	E	F	G	H	I	Posit (cm)	Output
1	0	0	0	0	0	0	0	0	0	-87.3	2.5314
	0	0	0	0	0	0	0	0	0	-77.6	2.5892
					...					...	...
	0	0	0	0	0	0	0	0	0	87.3	2.5199
2	0	0	0	0	0	0	0	0	1.667	-87.3	3.1463
	0	0	0	0	0	0	0	0	1.667	-77.6	3.1400
					...					...	...
	0	0	0	0	0	0	0	0	1.667	87.3	3.1407
		...			...			...			...
112	1	1	1	1	-1	-1	-1	1	-1	-87.3	4.9896
	1	1	1	1	-1	-1	-1	1	-1	-77.6	4.9734
					...					...	...
	1	1	1	1	-1	-1	-1	1	-1	87.3	0.9224

Results

- Position Transformed to Absolute Radial Distance

Results – “Pared Down” Model

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.3448562	0.010676	313.31	0
Dep Temp	-0.445737	0.011631	-38.32	<.0001
Dop Mix Ratio	-2.235974	0.011823	-189.1	0
Dil H2 Flow (slm)	-0.291859	0.011672	-25.01	<.0001
TCS flow (slm)	0.3759196	0.011556	32.53	<.0001
(Dep Temp-0.02679)*(Dop Mix Ratio+0.00893)	0.3205027	0.011921	26.88	<.0001
(Dop Mix Ratio+0.00893)*(Dil H2 Flow (slm)+0.04464)	0.19822	0.011967	16.56	<.0001
(Dop Mix Ratio+0.00893)*(TCS flow (slm)-0.02679)	-0.270065	0.011913	-22.67	<.0001

Summary of Fit

RSquare	0.951576
RSquare Adj	0.951416
Root Mean Square Error	0.491
Mean of Response	3.392218
Observations (or Sum Wgts)	2128

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	15	189.19264	12.6128	82.49052
Pure Error	2105	321.89971	0.1529	**Prob > F**
Total Error	2120	511.09235		<0.0001

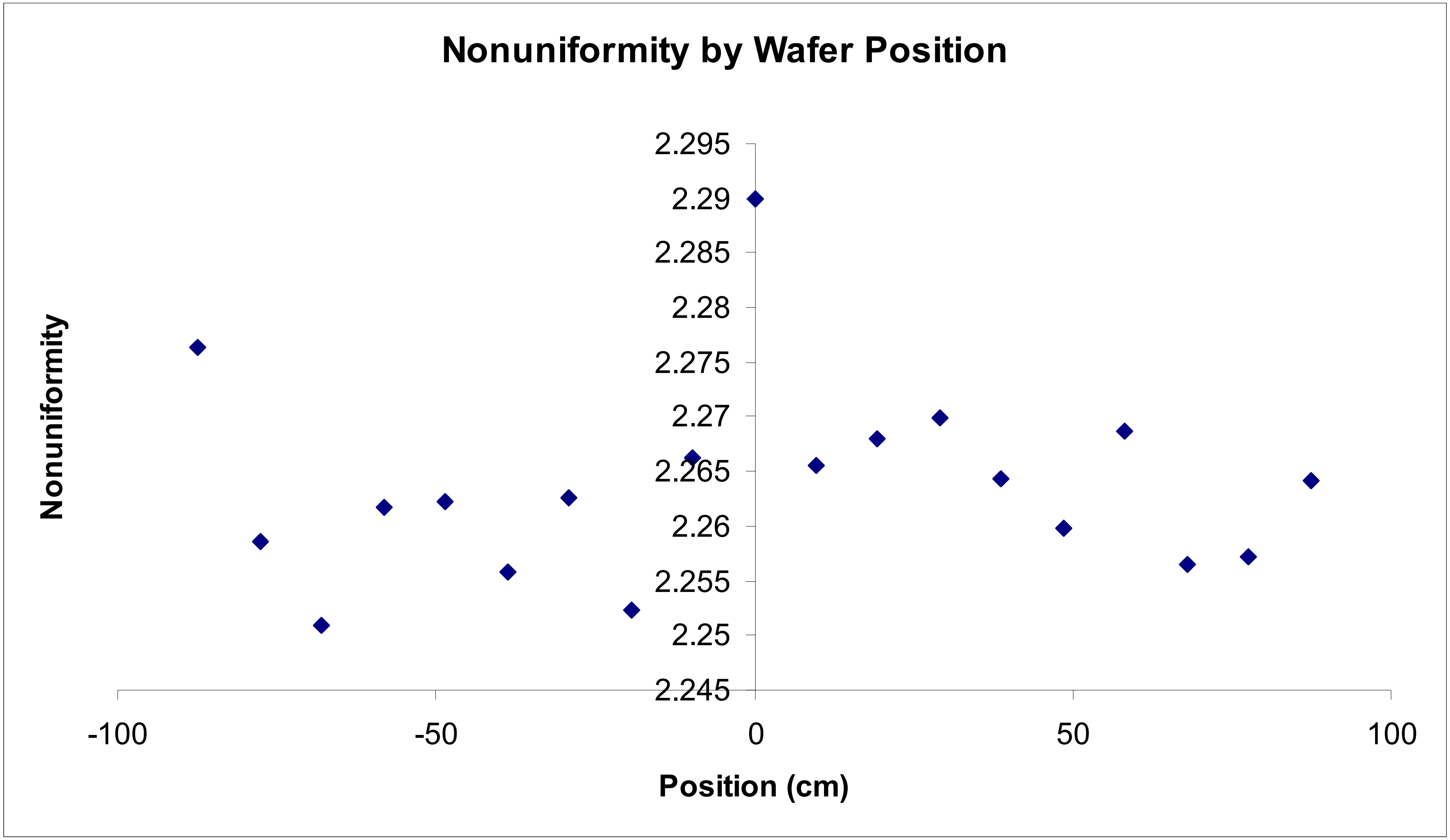
Conclusions

- Verified and Quantified Gower-Hall’s Findings
- Confirmed that Radial Position does have an effect on Resisitivity
- The way that you “cut” data effects significance of results and analysis

Thank You

QUESTIONS?

Uniformity Analysis



No Evidence of large non-uniformity