Statistical Design of Experiments Part IV
A CASE Study
A Polysilicon Deposition System Experiment

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Case Study Outline

- The Problem
- The Experimental Design
- Results
- Analysis
  - ANOVA
- Verification

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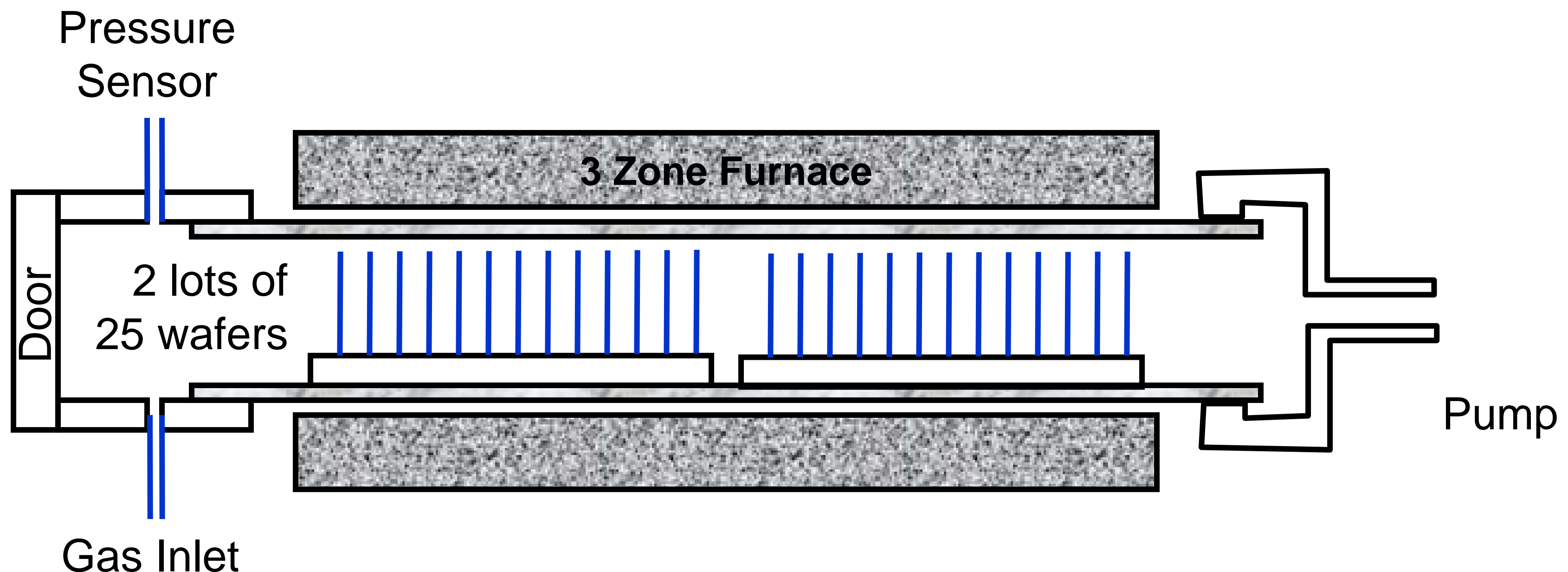
Reference

- **Case Study is from:**
  - **Quality Engineering using Robust Design**
  - **Madhav S. Phadke**
  - **Prentice Hall, 1989**

- **Case study is in Chapter 4.**

The Problem

- **Multi-wafer Reduce Pressure Polysilicon Deposition System**
  1. **Number of Polysilicon defects too large and random:**
     - **Varies from 50 to 5000 defects/cm^2.**
     - **No model for defect generation.**
     - **Need to reduce number of defects.**
  2. **Variation in the thickness of the polysilicon deposited on wafers.**



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The Experiment

- Test three wafers along with 47 dummy wafers for each experiment.
  - Wafers 3, 23 and 48.
  - 47 wafers provided a dummy full load on the system.
- Each test wafer tested at top, middle, and bottom of wafer.
- Tests:
  - Defect density (counted under a microscope)
  - Polysilicon thickness.
    - The run-time was adjusted via engineering judgment to limit the range of the thickness.
    - The thickness divided by the time gave the deposition rate.

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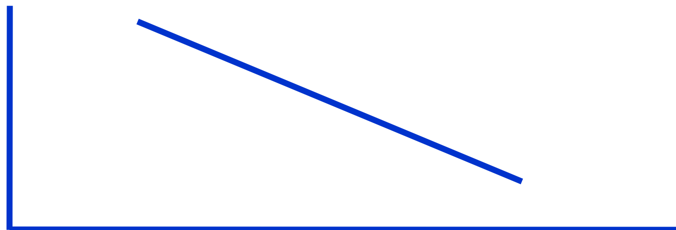
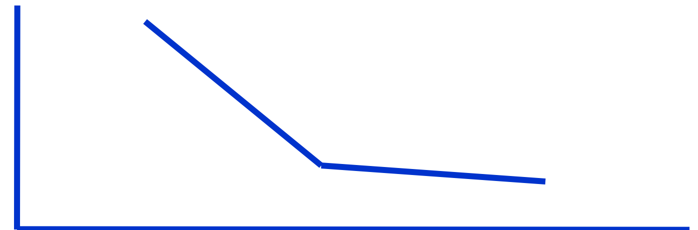
Experimental Parameters

- Continuous Parameters
  - Deposition Temperature
  - Deposition Pressure
  - Nitrogen Flow Rate
  - Silane flow Rate
  - Settling time after placement in System
- Discrete parameter.
  - Cleaning Method
    - Baseline has no cleaning.
- How many level of each?



Two Levels – no nonlinearities



Three Levels shows nonlinearities

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Experimental Parameters with 3 Levels

- Deposition Temperature
  - +/- 25 C from baseline Temperature
- Deposition Pressure
  - +/- 200 mtorr from baseline Pressure
- Nitrogen Flow Rate
  - -75 and -150 from baseline Flow Rate
- Silane flow Rate
  - -50 and -100 from baseline Flow Rate
- Settling time after placement in System
  - +8 and +16 min from baseline settling time.
- Cleaning Method
  - Baseline did not use any cleaning.
  - Try two other cleaning methods, CM_2 and CM_3

		Temperature	Pressure	Nitrogen	Silane	Settling Time	Cleaning
Level	1	T0 - 25	P0 - 200	N0	S0 - 100	t0	None
	2	T0	P0	N0 - 150	S0 - 50	t0 + 8	CM2
	3	T0 + 25	P0 + 200	N0 - 75	S0	t0 + 16	CM3
		C	mtorr	sccm	sccm	min	

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Taguchi L_{18} Array

- **Fractional Factorial Experiment**
  - Advantage
    - Fewer runs
  - Disadvantage
    - Not enough runs to show interactions between parameters.

- **18 Experimental Runs**
- **Up to 8 Parameters**
  - Note that one parameter has only two levels.
- **Use columns marks as A, B, C, D, E, and F for the experiment.**
  - Except for the first column, the choice is arbitrary.

Exp No	e	A	B	C	D	E	e	F
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

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The Experiments

- It took 9 days to conduct the 18 experiments.
- Using DoE requires patience but the rewards can be worth it!

Exp No	e	A	B	C	D	E	e	F	Temperature	Pressure	Nitrogen	Silane	Settling Time	Cleaning
1	1	1	1	1	1	1	1	1	T0 - 25	P0 - 200	N0	S0 - 100	t0	None
2	1	1	2	2	2	2	2	2	T0 - 25	P0	N0 - 150	S0 - 50	t0 + 8	CM2
3	1	1	3	3	3	3	3	3	T0 - 25	P0 + 200	N0 - 75	S0	t0 + 16	CM3
4	1	2	1	1	2	2	3	3	T0	P0 - 200	N0	S0 - 50	t0 + 8	CM3
5	1	2	2	2	3	3	1	1	T0	P0	N0 - 150	S0	t0 + 16	None
6	1	2	3	3	1	1	2	2	T0	P0 + 200	N0 - 75	S0 - 100	t0	CM2
7	1	3	1	2	1	3	2	3	T0 + 25	P0 - 200	N0 - 150	S0 - 100	t0 + 16	CM3
8	1	3	2	3	2	1	3	1	T0 + 25	P0	N0 - 75	S0 - 50	t0	None
9	1	3	3	1	3	2	1	2	T0 + 25	P0 + 200	N0	S0	t0 + 8	CM2
10	2	1	1	3	3	2	2	1	T0 - 25	P0 - 200	N0 - 75	S0	t0 + 8	None
11	2	1	2	1	1	3	3	2	T0 - 25	P0	N0	S0 - 100	t0 + 16	CM2
12	2	1	3	2	2	1	1	3	T0 - 25	P0 + 200	N0 - 150	S0 - 50	t0	CM3
13	2	2	1	2	3	1	3	2	T0	P0 - 200	N0 - 150	S0	t0	CM2
14	2	2	2	3	1	2	1	3	T0	P0	N0 - 75	S0 - 100	t0 + 8	CM3
15	2	2	3	1	2	3	2	1	T0	P0 + 200	N0	S0 - 50	t0 + 16	None
16	2	3	1	3	2	3	1	2	T0 + 25	P0 - 200	N0 - 75	S0 - 50	t0 + 16	CM2
17	2	3	2	1	3	1	2	3	T0 + 25	P0	N0	S0	t0	CM3
18	2	3	3	2	1	2	3	1	T0 + 25	P0 + 200	N0 - 150	S0 - 100	t0 + 8	None

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Measures

- Defect Density
  - Primary goal – too many defects causes wafer rejects
  - Wide range of values from 0 to thousands of defects per cm^2.
- Polysilicon Thickness Uniformity
  - Range of thicknesses in runs
  - Need to measure how uniform the thicknesses are
    - On a wafer
    - Wafer to Wafer
  - Can use time to adjust actual thickness once process is under control.
- Polysilicon Deposition Rate
  - Improving the defectivity but significantly lengthening the process time would trade one cost for another.

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Defects Results

	Wafer 1			Wafer 2			Wafer 3			
Exp No	Top	Center	Bottom	Top	Center	Bottom	Top	Center	Bottom	Exp No
1	1	0	1	2	0	0	1	1	0	1
2	1	2	8	180	5	0	126	3	1	2
3	3	35	106	360	38	135	315	50	180	3
4	6	15	6	17	20	16	15	40	18	4
5	1720	1980	2000	487	810	400	2020	360	13	5
6	135	360	1620	2430	207	2	2500	270	35	6
7	360	810	1215	1620	117	30	1800	720	315	7
8	270	2730	5000	360	1	2	9999	225	1	8
9	5000	1000	1000	3000	1000	1000	3000	2800	2000	9
10	3	0	0	3	0	0	1	0	1	10
11	1	0	1	5	0	0	1	0	1	11
12	3	1620	90	216	5	4	270	8	3	12
13	1	25	270	810	16	1	225	3	0	13
14	3	21	162	90	6	1	63	15	39	14
15	450	1200	1800	2530	2080	2080	1890	180	25	15
16	5	6	40	54	0	8	14	1	1	16
17	1200	3500	3500	1000	3	1	9999	600	8	17
18	8000	2500	3500	5000	1000	1000	5000	2000	2000	18

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Defect results

- 9 results for each experiment.
- Measure: log of mean square surface defects.
  - −10 log(sum(defects²)/9)
- Note: positive is good!

Exp No	Mean surface Defects	mean square surface defects	log mean square surface defects
			$\eta 0$
1	1	1	0.51
2	36	5,376	-37.30
3	136	32,874	-45.17
4	17	377	-25.76
5	1,088	1,793,582	-62.54
6	840	1,671,567	-62.23
7	776	973,171	-59.88
8	2,065	14,742,892	-71.69
9	2,200	6,537,778	-68.15
10	1	2	-3.47
11	1	3	-5.08
12	247	305,798	-54.85
13	150	86,724	-49.38
14	44	4,505	-36.54
15	1,359	2,615,703	-64.18
16	14	538	-27.31
17	2,201	14,142,231	-71.51
18	3,333	15,833,333	-72.00

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Thickness Results

	Wafer 1			Wafer 2			Wafer 3		
Exp No	Top	Center	Bottom	Top	Center	Bottom	Top	Center	Bottom
1	2029	1975	1961	1975	1934	1907	1952	1941	1949
2	5375	5191	5242	5201	5254	5309	5323	5307	5091
3	5989	5894	5874	6152	5910	5886	6077	5943	5962
4	2118	2109	2099	2140	2125	2108	2149	2130	2111
5	4102	4152	4174	4556	4504	4560	5031	5040	5032
6	3022	2932	2913	2833	2837	2828	2934	2875	2841
7	3030	3042	3028	3486	3333	3389	3709	3671	3687
8	4707	4472	4336	4407	4156	4094	5073	4898	4599
9	3859	3822	3850	3871	3922	3904	4110	4067	4110
10	3227	3205	3242	3468	3450	3420	3599	3591	3535
11	2521	2499	2499	2576	2537	2512	2551	2552	2570
12	5921	5766	5844	5780	5695	5814	5691	5777	5743
13	2792	2752	2716	2684	2635	2606	2765	2786	2773
14	2863	2835	2859	2829	2864	2839	2891	2844	2841
15	3218	3149	3124	3261	3205	3223	3241	3189	3197
16	3020	3008	3016	3072	3151	3139	3235	3162	3140
17	4277	4150	3992	3888	3681	3572	4593	4298	4219
18	3125	3119	3127	3567	3563	3520	4120	4088	4138

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Thickness Results

- **Thickness Measure: Ratio of sample mean squared to sample variance**
  - **10 log (m^2/s^2)**
- **Rate Measure:**
  - **10 log(Dep Rate)**

Exp No	average	variance	m2/s2	$\eta 1$	Time	Dep Rate	$\eta 2$
1	1958	1151	3330	35.22	135.0	14.5	23.23
2	5255	7340	3762	35.75	143.6	36.6	31.27
3	5965	8896	4000	36.02	144.1	41.4	32.34
4	2121	269	16755	42.24	58.8	36.1	31.15
5	4572	150254	139	21.43	62.6	73.0	37.27
6	2891	4272	1956	32.91	58.4	49.5	33.89
7	3375	82640	138	21.39	44.1	76.6	37.68
8	4527	106547	192	22.84	42.9	105.4	40.46
9	3946	13570	1148	30.60	34.3	115.0	41.21
10	3415	24083	484	26.85	137.7	24.8	27.89
11	2535	846	7593	38.80	126.8	20.0	26.02
12	5781	5230	6391	38.06	148.2	39.0	31.82
13	2723	4605	1611	32.07	51.3	53.1	34.50
14	2852	376	21642	43.35	62.4	45.7	33.20
15	3201	1848	5545	37.44	58.4	54.8	34.78
16	3105	6286	1533	31.86	40.4	76.8	37.71
17	4074	104415	159	22.01	38.7	105.3	40.45
18	3596	185930	70	18.42	39.3	91.4	39.22

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Results Summary

							Defects	Thickness Variation	Deposition Rate
Exp No	T	P	N	S	ST	CM	η0	η1	η2
1	1	1	1	1	1	1	0.51	35.22	23.23
2	1	2	2	2	2	2	-37.30	35.75	31.27
3	1	3	3	3	3	3	-45.17	36.02	32.34
4	2	1	1	2	2	3	-25.76	42.24	31.15
5	2	2	2	3	3	1	-62.54	21.43	37.27
6	2	3	3	1	1	2	-62.23	32.91	33.89
7	3	1	2	1	3	3	-59.88	21.39	37.68
8	3	2	3	2	1	1	-71.69	22.84	40.46
9	3	3	1	3	2	2	-68.15	30.60	41.21
10	1	1	3	3	2	1	-3.47	26.85	27.89
11	1	2	1	1	3	2	-5.08	38.80	26.02
12	1	3	2	2	1	3	-54.85	38.06	31.82
13	2	1	2	3	1	2	-49.38	32.07	34.50
14	2	2	3	1	2	3	-36.54	43.35	33.20
15	2	3	1	2	3	1	-64.18	37.44	34.78
16	3	1	3	2	3	2	-27.31	31.86	37.71
17	3	2	1	3	1	3	-71.51	22.01	40.45
18	3	3	2	1	2	1	-72.00	18.42	39.22

		Temperature	Pressure	Nitrogen	Silane	Settling Time	Cleaning
Level	1	T0 - 25	P0 - 200	N0	S0 - 100	t0	None
	2	T0	P0	N0 - 150	S0 - 50	t0 + 8	CM2
	3	T0 + 25	P0 + 200	N0 - 75	S0	t0 + 16	CM3
		C	mtorr	sccm	sccm	min	

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Results Summary (Reordered Notation)

							Defects	Thickness Variation	Deposition Rate
Exp No	T	P	N	S	ST	CM	$\eta 0$	$\eta 1$	$\eta 2$
1	1	1	3	1	1	1	0.51	35.22	23.23
2	1	2	1	2	2	2	-37.30	35.75	31.27
3	1	3	2	3	3	3	-45.17	36.02	32.34
4	2	1	3	2	2	3	-25.76	42.24	31.15
5	2	2	1	3	3	1	-62.54	21.43	37.27
6	2	3	2	1	1	2	-62.23	32.91	33.89
7	3	1	1	1	3	3	-59.88	21.39	37.68
8	3	2	2	2	1	1	-71.69	22.84	40.46
9	3	3	3	3	2	2	-68.15	30.60	41.21
10	1	1	2	3	2	1	-3.47	26.85	27.89
11	1	2	3	1	3	2	-5.08	38.80	26.02
12	1	3	1	2	1	3	-54.85	38.06	31.82
13	2	1	1	3	1	2	-49.38	32.07	34.50
14	2	2	2	1	2	3	-36.54	43.35	33.20
15	2	3	3	2	3	1	-64.18	37.44	34.78
16	3	1	2	2	3	2	-27.31	31.86	37.71
17	3	2	3	3	1	3	-71.51	22.01	40.45
18	3	3	1	1	2	1	-72.00	18.42	39.22

		Temperature	Pressure	Nitrogen	Silane	Settling Time	Cleaning
Level	1	T0 - 25	P0 - 200	N0 - 150	S0 - 100	t0	None
	2	T0	P0	N0 - 75	S0 - 50	t0 + 8	CM2
	3	T0 + 25	P0 + 200	N0	S0	t0 + 16	CM3
		C	mtorr	sccm	sccm	min	

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Defect Responses to Parameters

- Averaging for 6 experiments for each level.
- For T = Level 1 = T_0 – 25 average experiments 1, 2, 3, 10, 11, 12.

Defects	T	P	N	S	ST	CM
1	-24.2	-27.5	-56.0	-39.2	-51.5	-45.6
2	-50.1	-47.4	-41.1	-46.8	-40.5	-41.6
3	-61.8	-61.1	-39.0	-50.0	-44.0	-49.0

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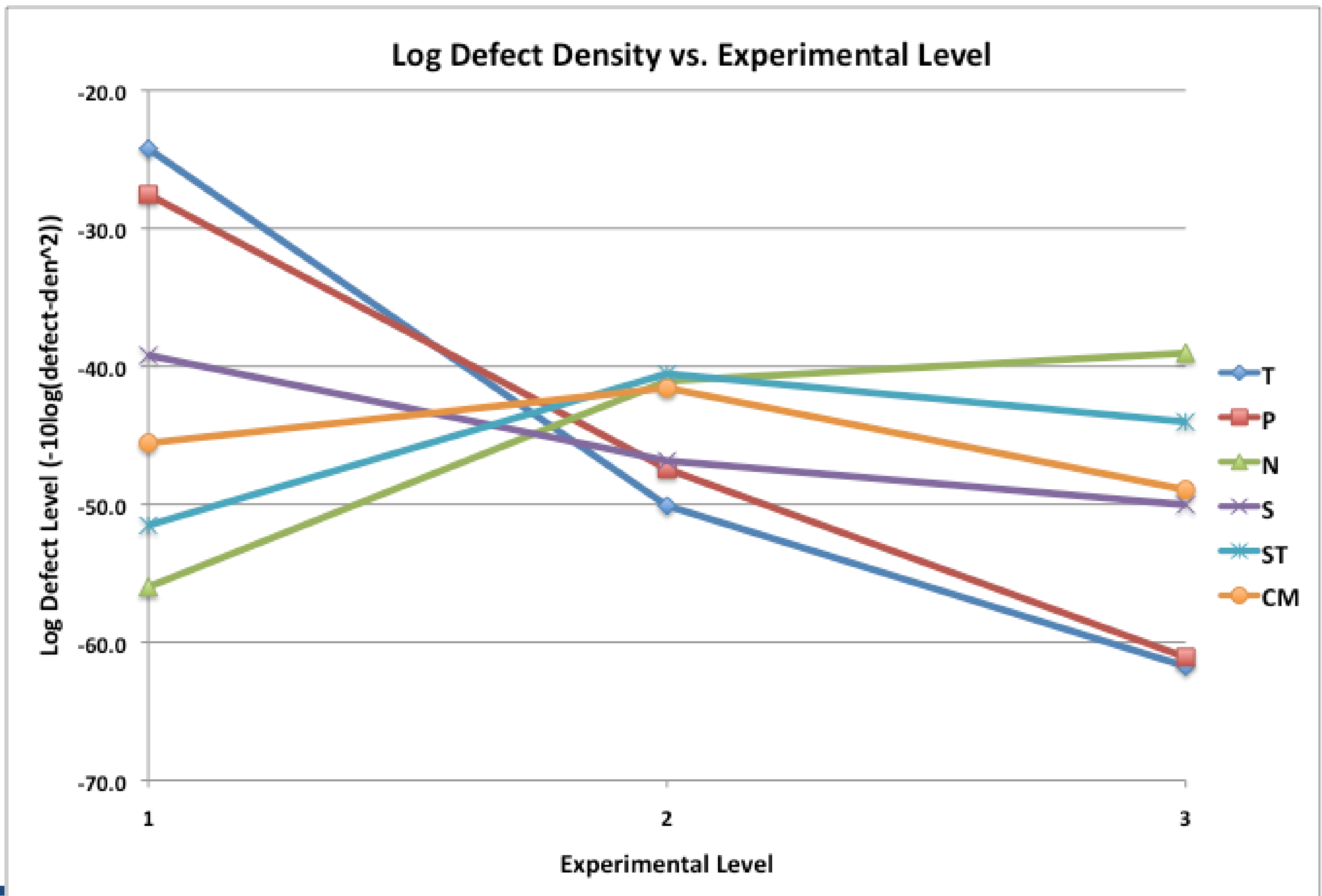
Log Defect Density vs. Parameter Level



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Thickness Variation response to Parameters

Thickness Variation	T	P	N	S	ST	CM
1	35.1	31.6	27.9	31.7	30.5	27.0
2	34.9	30.7	32.3	34.7	32.9	33.7
3	24.5	32.2	34.4	28.2	31.2	33.8

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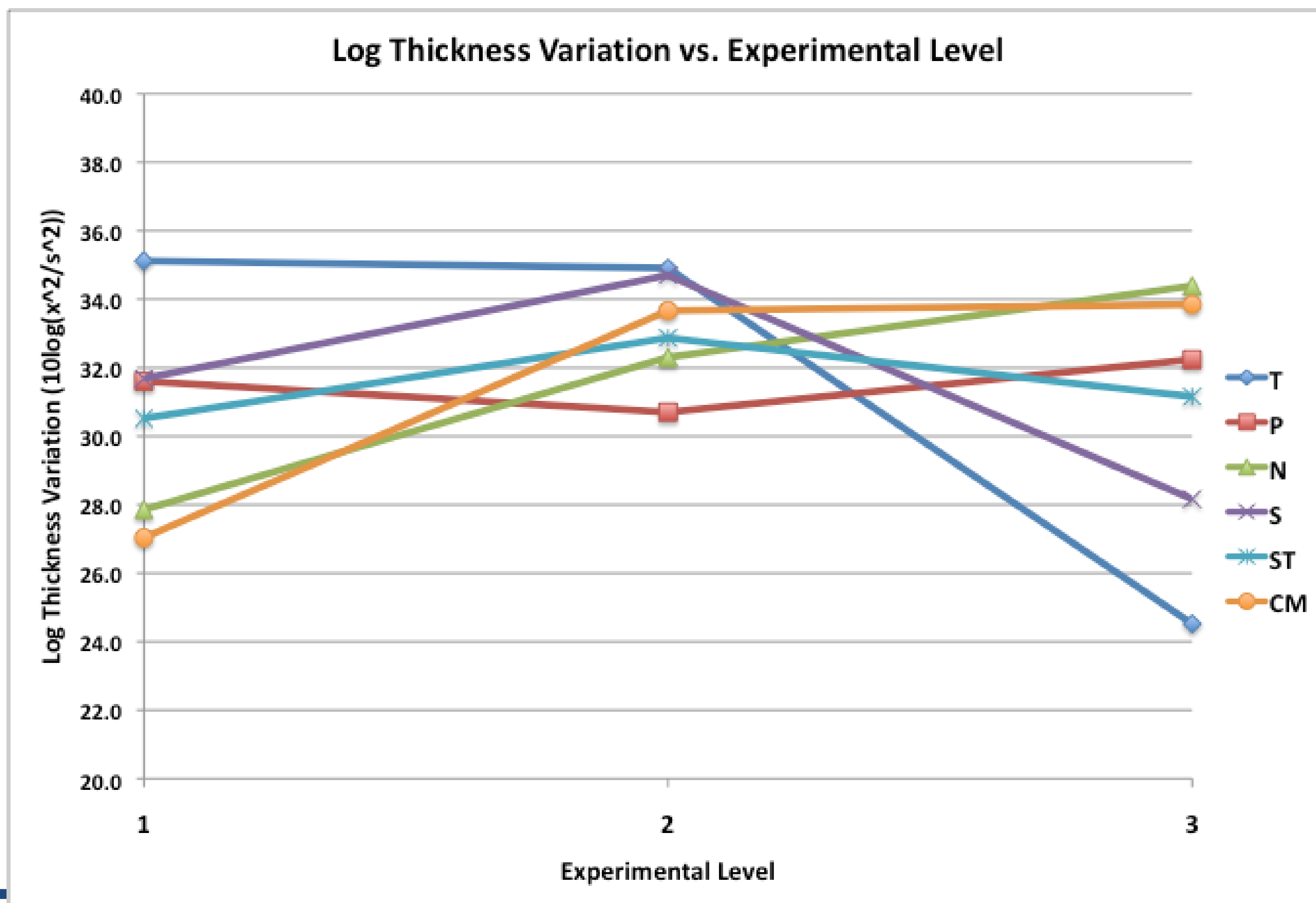
Log Thickness Variation vs. Parameter Level



Deposition Rate response to Parameters

Deposition Rate	T	P	N	S	ST	CM
1	28.8	32.0	35.3	32.2	34.1	33.8
2	34.1	34.8	34.2	34.5	34.0	34.1
3	39.5	35.5	32.8	35.6	34.3	34.4

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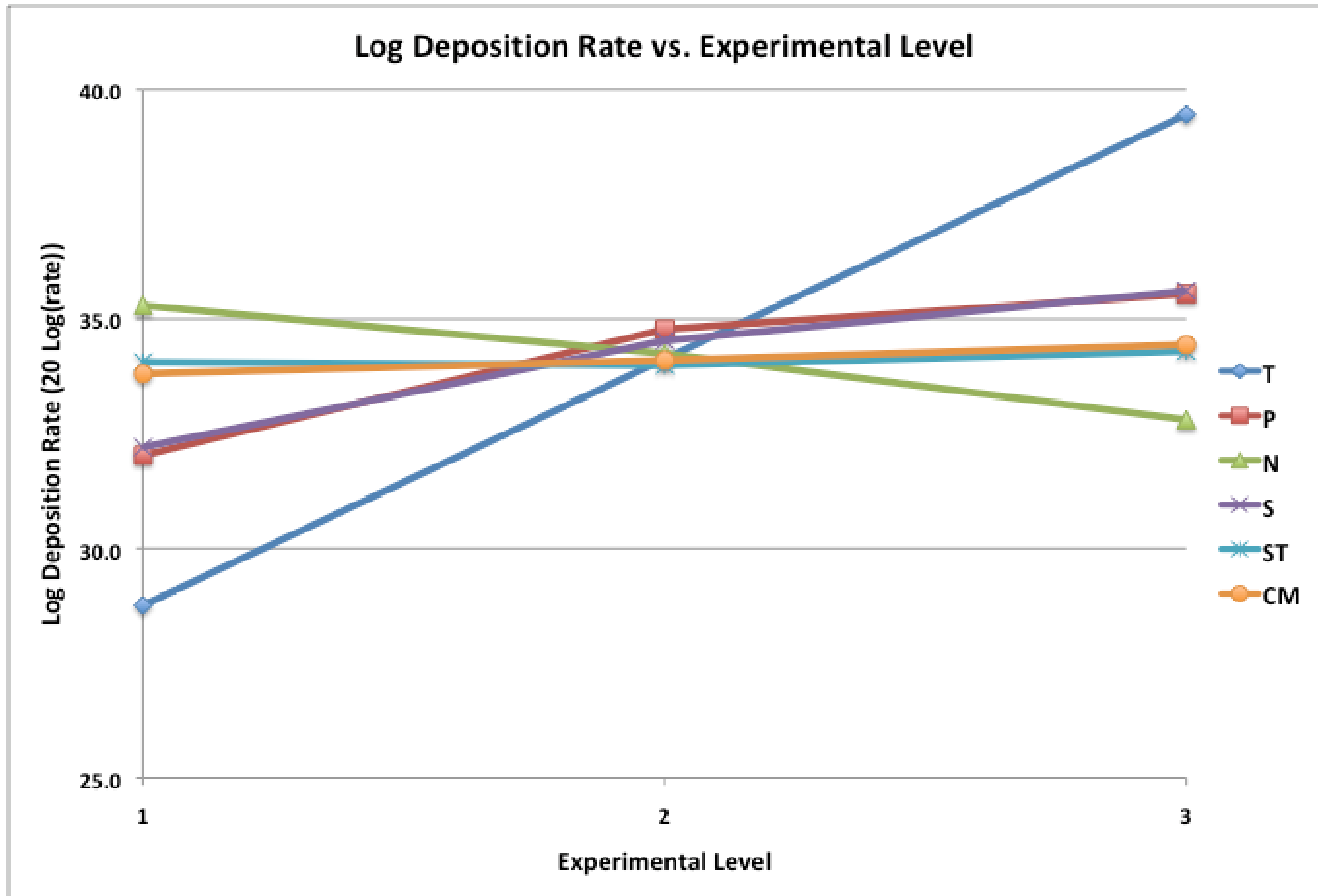
Log Deposition Rate vs. Parameter Level



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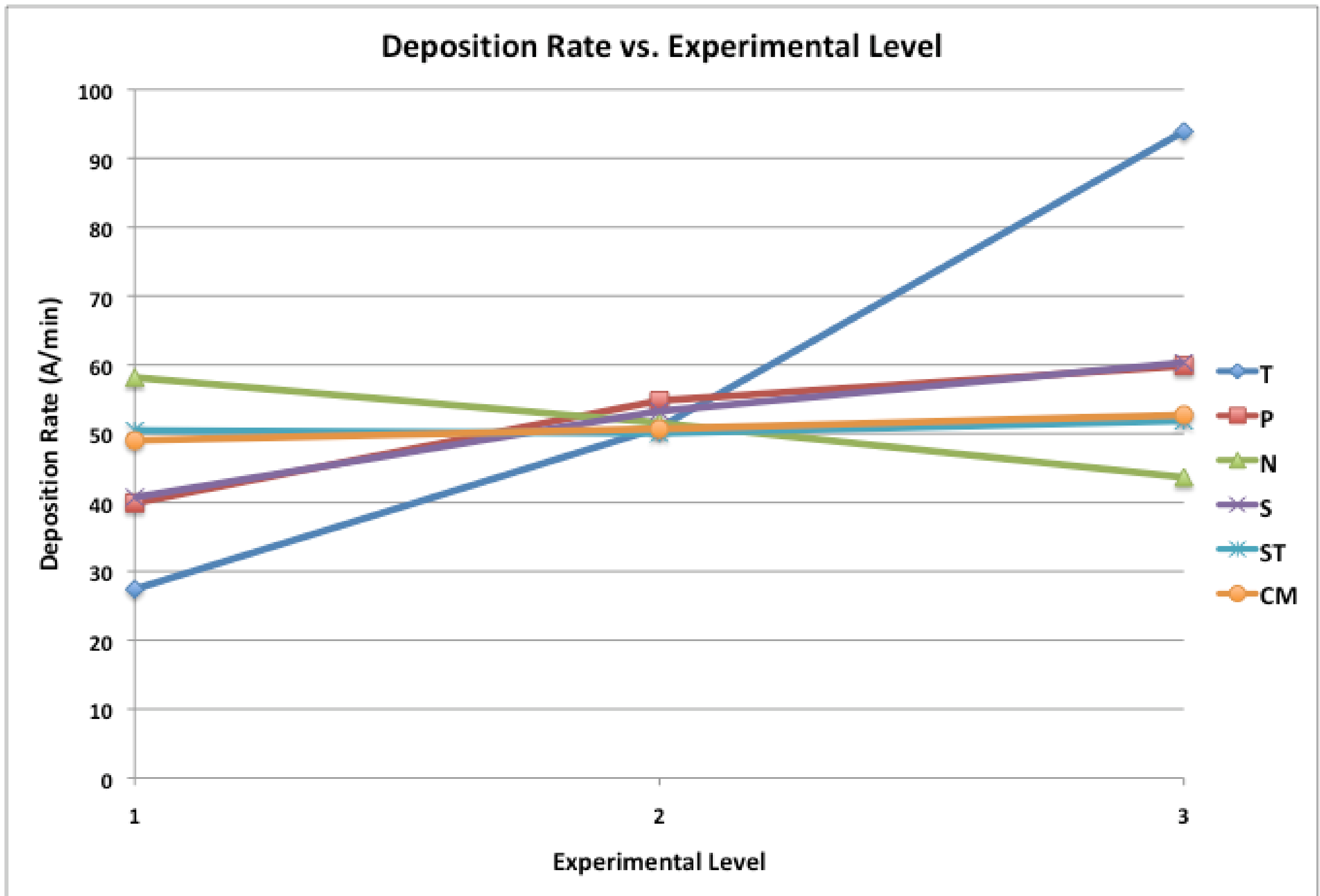
Deposition Rate vs. Parameter Level



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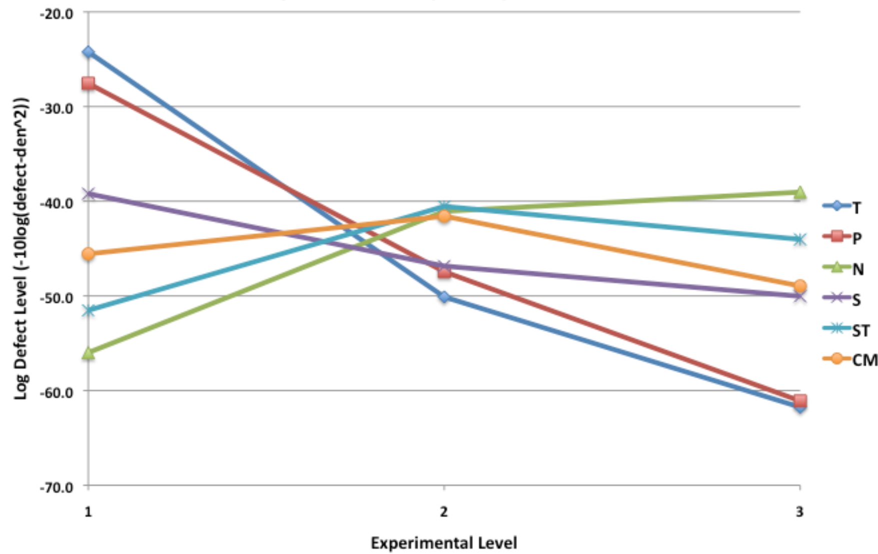
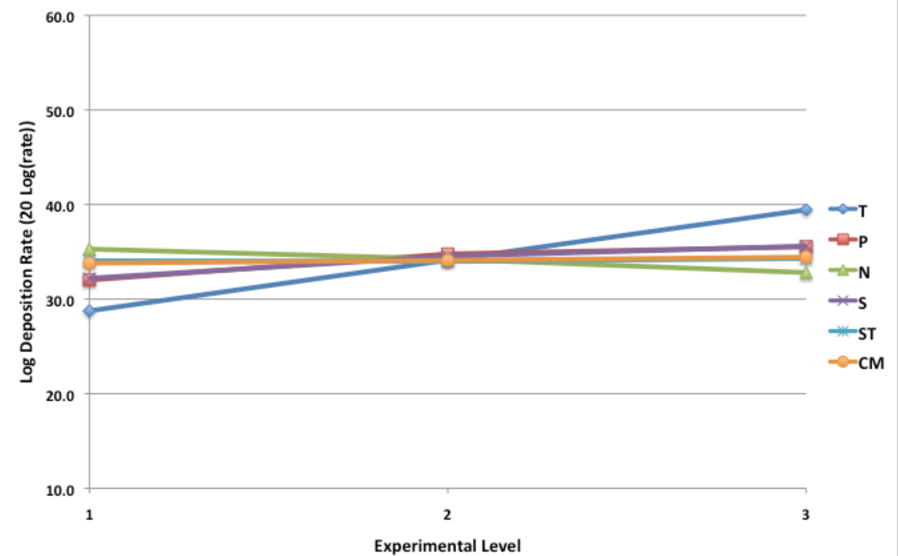
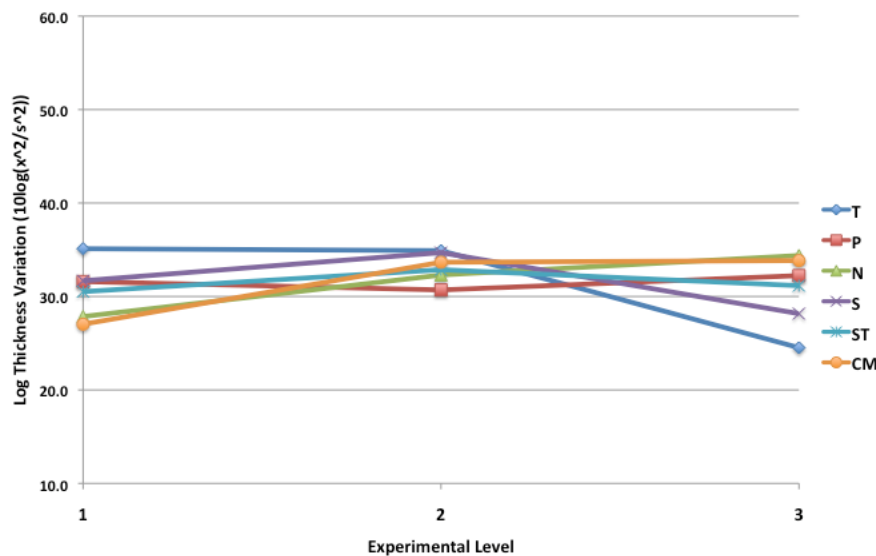
Conclusions (So far)

- Temperature
  - Reduction of 25 C results in:
    - 26 dB (-50.1 to -26.2) (20X) reduction in root mean square surface defect count. (good)
    - 5.3 dB (34.1 to 28.8) (2X) reduction in deposition rate. (bad)
    - The effect on thickness uniformity (0.2 dB) is small.
- Pressure
  - Reduction of 200 ntorr results in:
    - 20 dB (-47.4 to -27.5) (10X) reduction in root mean square surface defect count. (good)
    - 2.8 dB (34.8 to 32.0) (37%) reduction in deposition rate. (bad)
    - The effect on thickness uniformity (0.9 dB improvement) is small.

Results on Same Scale







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Conclusions (so far) (cont.)

- **Nitrogen Flow Rate**
  - Small improvement opportunity.
- **Silane Flow Rate**
  - Small improvement opportunity.
- **Settling Time**
  - Increase by 8 min. results in:
    - 11 dB (-51.5 to -40.5) (3.5X) improvement in root mean square surface defect count.
- **Cleaning Method**
  - Adding Cleaning (either method) results in:
    - 6.7 dB (27.0 to 33.7) (2X) improvement in thickness uniformity.
    - CM2 could be performed in the reactor so is easier.

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Analysis of Variance (ANOVA)

- A formalized statistical method for determining the significance of parameters in the variation of a response.
- One Factor ANOVA: Are the results of multiple experiments on one factor equivalent?
- Multi-factor ANOVA: what is the influence of the various factors on the variation in the response?
- References in NIST ESH
  - 1.3.5.4
  - 1.3.5.5
  - 7.4.3 and subsections 1-8

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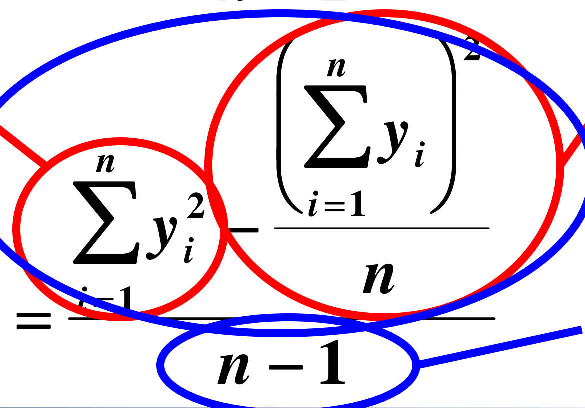
Expansion of Variance Calculation

$$s^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}$$

$$= \frac{\sum_{i=1}^{n}\left(y_i - \frac{\sum_{j=1}^{n} y_j}{n}\right)^2}{n-1}$$



$$= \frac{\sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}}{n-1}$$

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Sums of Squares for Analysis of Variance

- **Grand Sum of Squares**
  - Analogous to Total Power
- **Sum of Squares due to Mean**
  - Analogous to DC Power
- **Total Sum of Squares**
  - Analogous to AC Power

	Def Den	Tk Var	Dep Rate
Mean	-45.4	31.5	34.1
Grand Sum of Squares	47230	18883	21392
Sum of Squares due to Mean	37039	17879	20950
Total Sum of Squares	10191	1004	442

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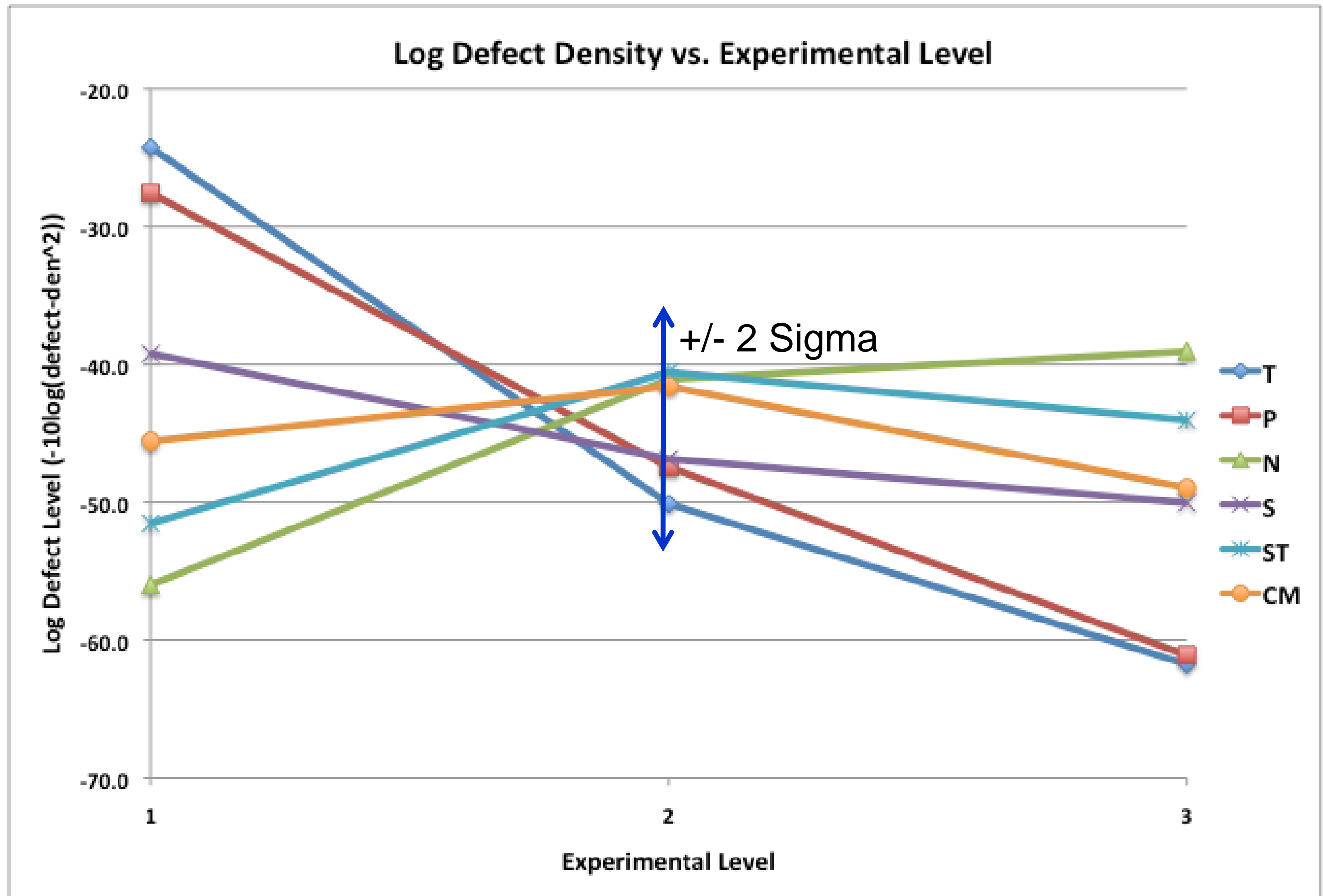
Defect Density ANOVA

Parameter	1	2	3	Degrees of Freedom	Sum of Squares	Mean Square	F	Fref	F*	F*ref	Error STD*
A Temperature	-24.2	-50.1	-61.8	2	4427	2214	27.3	5.8	18.5	4.0	4.5
B Pressure	-27.5	-47.4	-61.1	2	3416	1708	21.1	5.8	14.2	4.0	4.5
C Nitrogen	-56.0	-41.1	-39.0	2	1030	515	6.4	5.8	4.3	4.0	4.5
D Silane	-39.2	-46.8	-50.0	2	372	186	2.3	5.8			
E Settling Time	-51.5	-40.5	-44.0	2	378	189	2.3	5.8			
F Cleaning Method*	-45.6	-41.6	-49.0	2	164	82	1.0	5.8			
Error				5	405	81					
Total					10191						
Error*				11	1319	120					

* indicates parameters “in the noise” added to the error.

- Mean Square = Sum of Squares / Degrees of Freedom = Variance
- F = Mean Square / Error Mean Square = Variance Ratio
  - Compare to F(α , Df Parameter, Df Error)
- Estimate of the Error STD= Sqrt(Mean Square Error/Values at level)

Log Defect Density vs. Parameter Level



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Thickness Variation ANOVA

Parameter	1	2	3	Degrees of Freedom	Sum of Squares	Mean Square	F	Fref	F*	F*ref	Error STD*
A Temperature	35.1	34.9	24.5	2	440	220	11.5	3.6	16.4	4.3	1.5
B Pressure*	31.6	30.7	32.2	2	7	4	0.2	3.6			
C Nitrogen	27.9	32.3	34.4	2	134	67	3.5	3.6	5.0	4.3	1.5
D Silane	31.7	34.7	28.2	2	128	64	3.3	3.6	4.8	4.3	1.5
E Settling Time*	30.5	32.9	31.2	2	18	9	0.5	3.6			
F Cleaning Method	27.0	33.7	33.8	2	181	90	4.7	3.6	6.7	4.3	1.5
Error				5	96	19					
Total					1004						
Error*				9	121	13					

* indicates parameters “in the noise” added to the error.

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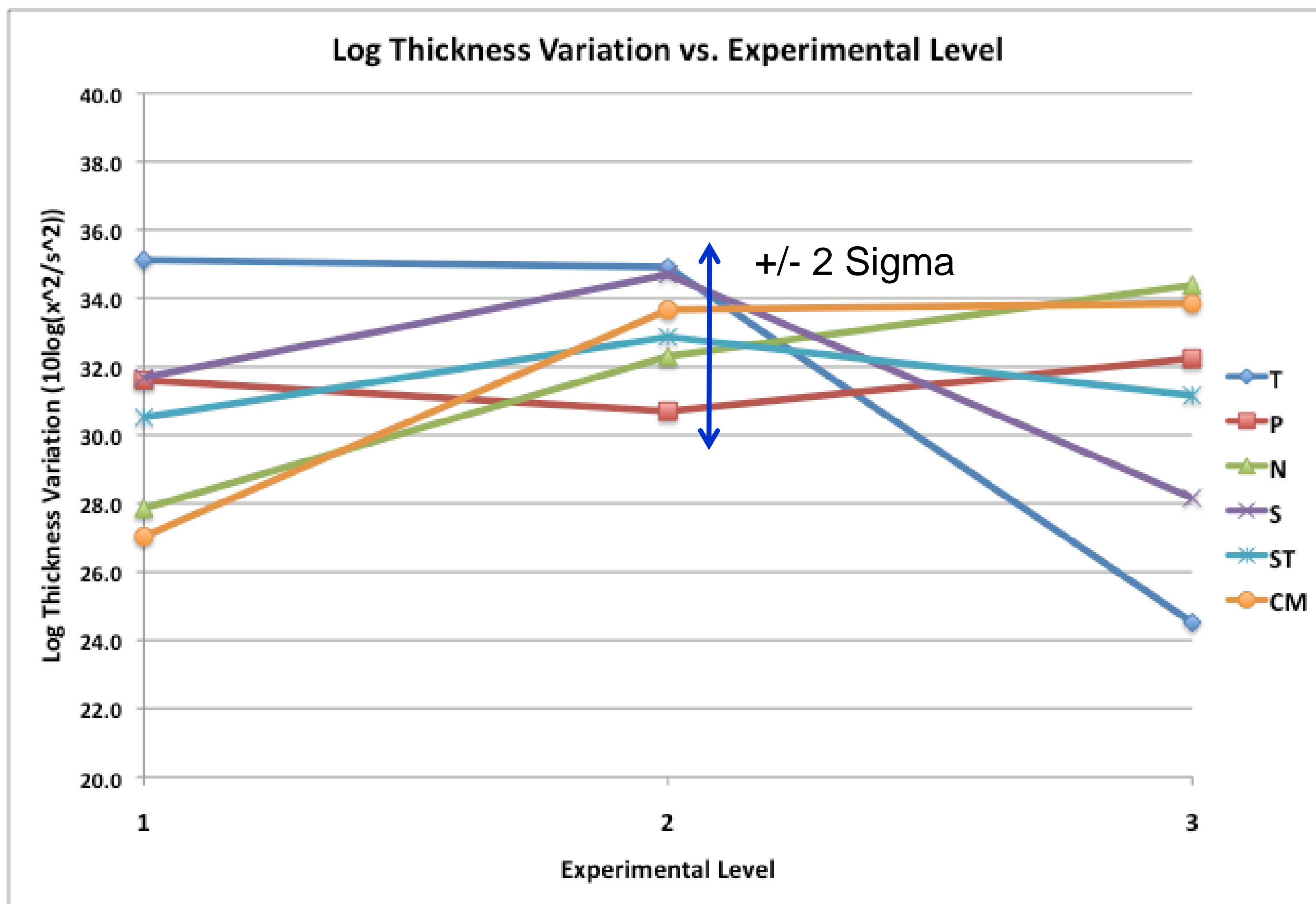
Log Thickness Variation vs. Parameter Level



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Deposition Rate ANOVA

Parameter	1	2	3	Degrees of Freedom	Sum of Squares	Mean Square	F	Fref	F*	F*ref	Error STD*
A Temperature	28.8	34.1	39.5	2	343	172	131.0	3.6	544	4.3	0.2
B Pressure	32.0	34.8	35.5	2	41	21	15.7	3.6	65	4.3	0.2
C Nitrogen	35.3	34.2	32.8	2	19	9	7.2	3.6	30	4.3	0.2
D Silane	32.2	34.5	35.6	2	36	18	13.9	3.6	58	4.3	0.2
E Settling Time*	34.1	34.0	34.3	2	0	0	0.1	3.6			
F Cleaning Method*	33.8	34.1	34.4	2	1.2	1	0.5	3.6			
Error				5	1.3	0.3					
Total					442						
Error*				9	2.8	0.3					

* indicates parameters “in the noise” added to the error.

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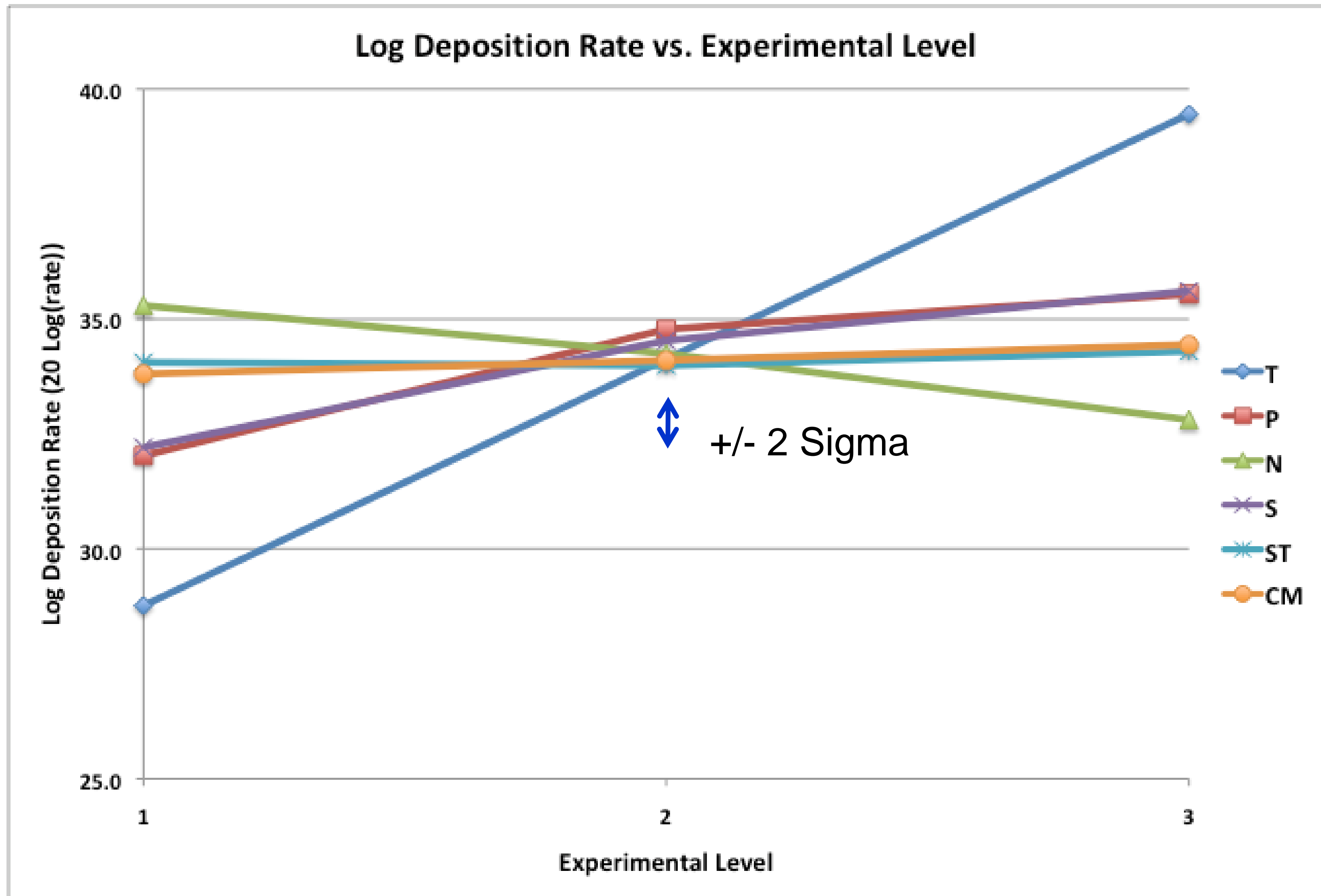
Log Deposition Rate vs. Parameter Level



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Case Study Outline

- The Problem
- The Experimental Design
- Results
- Analysis
  - Building a Model
- Verification

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The Defect Density Model

Parameter	1	2	3		1	2	3
A Temperature	-24.2	-50.1	-61.8	a	21.1	-4.7	-16.4
B Pressure	-27.5	-47.4	-61.1	b	17.8	-2.1	-15.7
C Nitrogen	-56.0	-41.1	-39.0	c	-10.6	4.3	6.3
D Silane	-39.2	-46.8	-50.0	d	6.2	-1.5	-4.7
E Settling Time	-51.5	-40.5	-44.0	e	-6.2	4.8	1.3
F Cleaning Method	-45.6	-41.6	-49.0	f	-0.2	3.8	-3.6

$$\eta(A_i, B_j, C_k, D_l, E_m, F_n) = \mu + a_i + b_j + c_k + d_l + e_m + f_n + \varepsilon$$

- **Model Parameters**
  - **$a_i = A_i - \mu$**
  - **$b_i = B_i - \mu$**
  - **etc.**
- **μ = - 45.4**

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Thickness Variation Model Parameters

Parameter	1	2	3		1	2	3
A Temperature	35.1	34.9	24.5	a	3.6	3.4	-7.0
B Pressure*	31.6	30.7	32.2	b	0.1	-0.8	0.7
C Nitrogen	27.9	32.3	34.4	c	-3.7	0.8	2.9
D Silane	31.7	34.7	28.2	d	0.2	3.2	-3.4
E Settling Time*	30.5	32.9	31.2	e	-1.0	1.4	-0.4
F Cleaning Method	27.0	33.7	33.8	f	-4.5	2.1	2.3

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Growth Rate Model Parameters

Parameter	1	2	3		1	2	3
A Temperature	28.8	34.1	39.5	a	-5.4	0.0	5.3
B Pressure	32.0	34.8	35.5	b	-2.1	0.7	1.4
C Nitrogen	35.3	34.2	32.8	c	1.2	0.1	-1.3
D Silane	32.2	34.5	35.6	d	-1.9	0.4	1.5
E Settling Time*	34.1	34.0	34.3	e	-0.1	-0.1	0.2
F Cleaning Method*	33.8	34.1	34.4	f	-0.3	0.0	0.3

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Case Study Outline

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The Decision

- Temperature
  - Decrease Temperature 25 C to setting 1
- Pressure
  - Hold Pressure at setting 2
- Nitrogen Flow
  - Hold Flow at setting 3
- Silane Flow
  - Hold Flow at setting 3
- Settling Time
  - Increase settling time by 8 min, setting 2.
- Cleaning Method
  - Add internal system cleaning method, setting 2.

- Engineering decision to decrease defects as cost of process time.

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Results of Old and New Setting Predictions

Parameter	Original Setting	Defect	Th Var	Dep Rt	New Settings	Defect	Th Var	Dep Rt
A Temperature	2	-4.7	3.4	0.0	1	21.1	3.6	-5.4
B Pressure	2	-2.1	-0.8	0.7	2	-2.1	-0.8	0.7
C Nitrogen	3	6.3	2.9	-1.3	3	6.3	2.9	-1.3
D Silane	3	-4.7	-3.4	1.5	3	-4.7	-3.4	1.5
E Settling Time	1	-6.2	-1.0	-0.1	2	4.8	1.4	-0.1
F Cleaning Method	1	-0.2	-4.5	-0.3	2	3.8	2.1	0.0
Mean		-45.4	31.5	34.1		-45.4	31.5	34.1
Total		-56.9	28.1	34.6		-16.0	37.3	29.5

- **Defect Improvement**
  - **39.1 dB (~ 90X)**
- **Thickness Variation Improvement**
  - **9.2 dB (~3X)**
- **Deposition Rate**
  - **- 5.1 dB reduction (1.8 X slower)**

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Actual Results

- Defect Improvement
  - $600/cm^2$ to $7/cm^2$.
  - 39.1 dB (~ 90X) Prediction
  - 38.7 dB Actual
- Thickness Variation Improvement
  - 0.028 to 0.013 sigma/mean.
  - 9.2 dB (~3X) Prediction
  - 6.6 dB Actual
- Deposition Rate
  - 60 A/min to 35 A/min.
  - - 5.1 dB reduction (1.8 X slower)
  - - 4.7 dB Actual

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