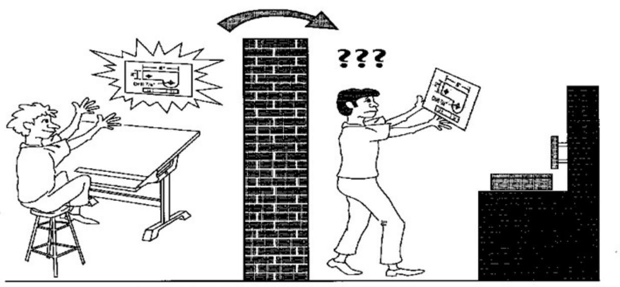
Engineering Design and Manufacturing/Production

- Traditional engineering design
  - functional needs
  - technological availability
  - prototype testing
- Little consideration given to manufacturing processes



"Over the Wall" Design and Manufacturing
Figure 1.4 Traditional (Over-the-Wall) Approach to Design and Manufacturing

Product Design among Quality Activities

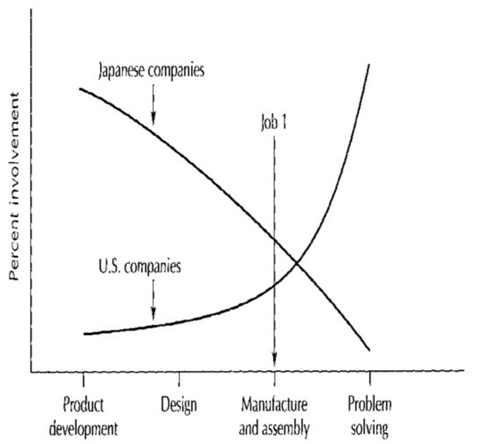


Figure 1.1 Quality Effort by Activity (Adapted from L. P. Sullivan, "The Seven Stages of Company-Wide Quality Control," Quality Progress, May 1986.)

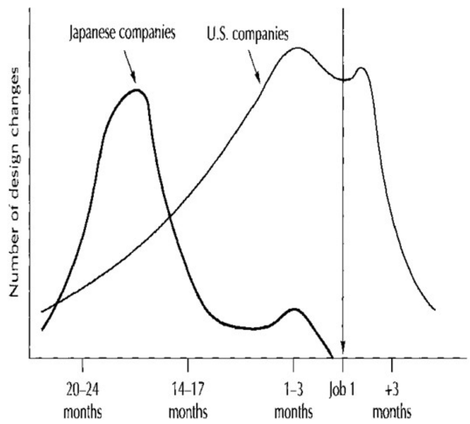
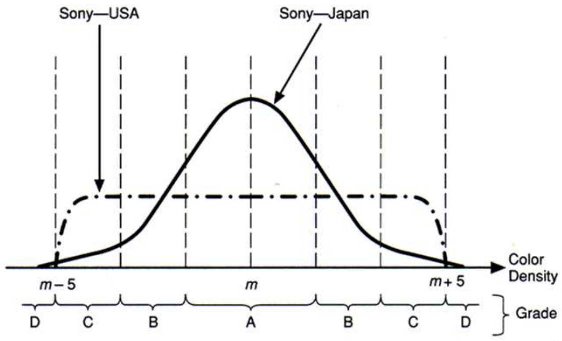


Figure 1.5 Comparison of Japanese and U.S. Product Design Life Cycles (Adapted from L. P. Sullivan, "Quality Function Deployment," Quality Progress, June 1986.)

Different Philosophies of Quality Control

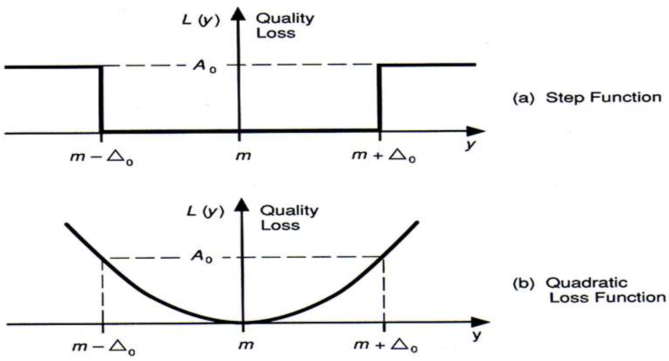
- Example: Sony-USA vs. Sony-Japan



Distribution of color density in television sets. (Source: *The Asahi*, April 17, 1979).

Quadratic Quality Loss

- Notion of quadratic quality loss

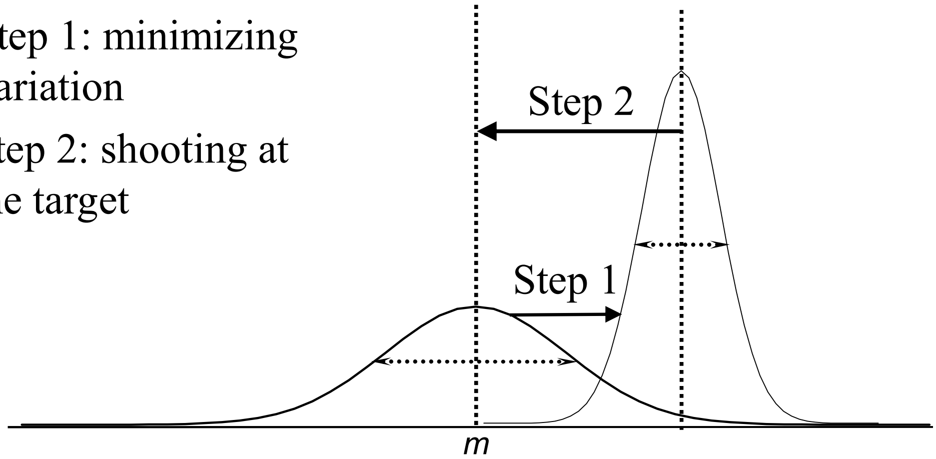


Quality loss function.

Two-Step Optimization Strategy

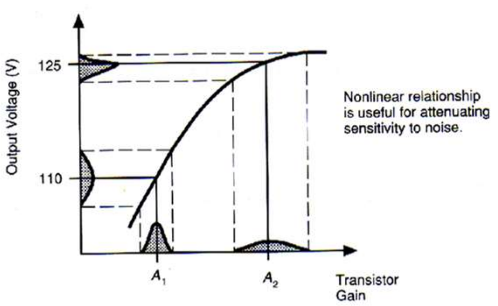
Step 1: minimizing variation

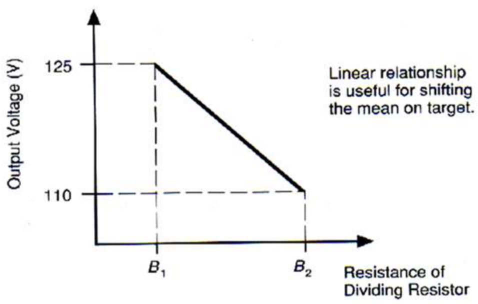
Step 2: shooting at the target



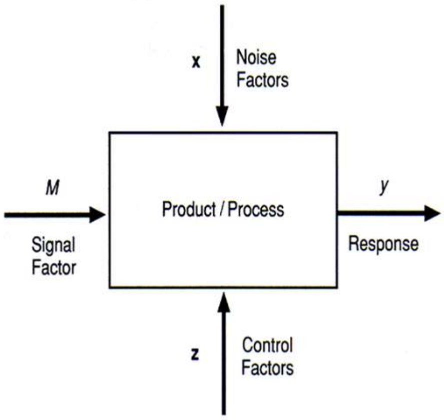
Exploiting Nonlinearity

- Step 1: use the nonlinearity to minimize the effect on variations
- Step 2: use the linearity to adjust the process mean to the target





Classifying Affecting Factors



Control factor (Z)
- parameters that affect the variability of the performance response (Y)

Signal (scaling) factor (M)
- parameters that affect only the mean level of response Y

Noise factor (X)
- parameters that can't be controlled during production

Ideas of Robust Design

- Minimize variations at the design stage
  - admitting the existence of variation: noise factor
  - minimizing the effect of the causes of variation without eliminating the causes
- How? 2-step optimization: exploiting nonlinearity/linearity
  - nonlinearity: control factor
  - linearity: signal factor
- Statistics instead of Physics

Tools of Robust Design

- Measuring performance response and its variation
  - defining an effective performance measure
  - listing possible affecting factors
- Understanding the process and its factors
  - Black box approach: design and analysis of experiments to classify the factors and construct an input-output model
- Two-step optimization
  - Step 1: minimizing variation
  - Step 2: shooting at the target

Defining Performance Measure

- To minimize variations
  - *why do we work in terms of the SN ratio rather than the standard deviation (SD)? Frequently, as the mean decreases the SD decreases and vice versa. In such cases, if we work in terms of the SD, the optimization cannot be done in two steps; i.e., we cannot minimize the SD first and then bring the mean on target. (Phadke, 1982)*
- Example: traffic

Performance Measure: Signal-to-Noise (SN) Ratio

- Nominal-the-best: as close as possible to a nominal target

$$SN_T = \underbrace{10\log_{10}}_{2}\underbrace{\left(\frac{\overline{X}^2}{s^2}\right)}_{1}$$

X: quality observations
X-bar: sample mean (signal)
s: sample standard deviation (noise)

1. Assuming that the mean is proportional to the standard deviation
2. Stabilizing the measure for a linear model

Classification of Factors

- Goal : maximize SN Ratio (η).
- Factors that have a significant effect on η
  - control factors to minimize the variability, i.e., to maximize η
- Factors that have a significant effect on μ but practically no effect on η
  - signal (scaling) factor to adjust mean
- Factors that have no effect on μ and η
  - choose levels that are cost effective, easy to use

Other Types of SN Ratios

- Smaller-the-better: as small as possible

$$SN_S = 10\log_{10}\frac{1}{\frac{1}{n}\sum_{i=1}^{n}(X_i - 0)^2} = -10\log_{10}[\frac{1}{n}\sum_{i=1}^{n}X_i^2]$$

- Larger-the-best: as large as possible

$$SN_L = -10\log_{10}[\frac{1}{n}\sum_{i=1}^{n}(\frac{1}{X_i})^2]$$

Problems of Experimental Design

- Problem: suppose you have 5 factors to be investigated and each factor has 3 change levels. How many experiment runs are required? 3^5=243 runs → not efficient
- Ideas of Orthogonal Arrays (OAs): Capture main effects and important interactions.
- Example: L_9 (3^4)

Orthogonal Arrays (OA) - Experimental Design

- The values of several parameters are changed simultaneously and their effects are estimated efficiently based on statistical theory.
- It is different from and more efficient than the traditional one-factor-at-a-time approach.
- Orthogonality is interpreted in the combinatorial sense. For any pair of columns, all combinations of factor levels occur equal times.

Design of Experiment

Factor

Factor	Levels*		
	1	2	3
A. Temperature (°C)	T_0-25	$\underline{T_0}$	T_0+25
B. Pressure (mtorr)	P_0-200	$\underline{P_0}$	P_0+200
C. Settling time (min)	$\underline{t_0}$	t_0+8	t_0+16
D. Cleaning method	<u>None</u>	CM_2	CM_3

* The starting level for each factor is identified by an underscore.

Matrix

Expt. No.	Column Number and Factor Assigned				Observation* η (dB)
	1 Temperature (A)	2 Pressure (B)	3 Settling Time (C)	4 Cleaning Method (D)	
1	1	1	1	1	$\eta_1 = -20$
2	1	2	2	2	$\eta_2 = -10$
3	1	3	3	3	$\eta_3 = -30$
4	2	1	2	3	$\eta_4 = -25$
5	2	2	3	1	$\eta_5 = -45$
6	2	3	1	2	$\eta_6 = -65$
7	3	1	3	2	$\eta_7 = -45$
8	3	2	1	3	$\eta_8 = -65$
9	3	3	2	1	$\eta_9 = -70$

* $\eta = -10 \log_{10}$ (mean square surface defect count).

Analysis of Experimental Results

- Effect Plots:
  - Intuition to interpret experiment results through graphical representations.
- Analysis of Variance (ANOVA):
  - Statistical tool to distinguish effects of factors.

Effects Estimation

Expt. No.	Column Number and Factor Assigned				Observation* η (dB)
	1 Temperature (A)	2 Pressure (B)	3 Settling Time (C)	4 Cleaning Method (D)	
1	1	1	1	1	$\eta_1 = -20$
2	1	2	2	2	$\eta_2 = -10$
3	1	3	3	3	$\eta_3 = -30$
4	2	1	2	3	$\eta_4 = -25$
5	2	2	3	1	$\eta_5 = -45$
6	2	3	1	2	$\eta_6 = -65$
7	3	1	3	2	$\eta_7 = -45$
8	3	2	1	3	$\eta_8 = -65$
9	3	3	2	1	$\eta_9 = -70$

* $\eta = -10 \log_{10}$ (mean square surface defect count).

$$\overline{A}_1 = \frac{1}{3}(\eta_1 + \eta_2 + \eta_3) = -20$$

$$\overline{A}_2 = \frac{1}{3}(\eta_4 + \eta_5 + \eta_6) = -45$$

$$\overline{A}_3 = \frac{1}{3}(\eta_7 + \eta_8 + \eta_9) = -60$$

Effects Estimation

Expt. No.	1 Temperature (A)	2 Pressure (B)	3 Settling Time (C)	4 Cleaning Method (D)	Observation* η (dB)
1	1	1	1	1	$\eta_1 = -20$
2	1	2	2	2	$\eta_2 = -10$
3	1	3	3	3	$\eta_3 = -30$
4	2	1	2	3	$\eta_4 = -25$
5	2	2	3	1	$\eta_5 = -45$
6	2	3	1	2	$\eta_6 = -65$
7	3	1	3	2	$\eta_7 = -45$
8	3	2	1	3	$\eta_8 = -65$
9	3	3	2	1	$\eta_9 = -70$

(Column Number and Factor Assigned)

* $\eta = -10 \log_{10}$ (mean square surface defect count).

$$\overline{B}_1 = \frac{1}{3}(\eta_1 + \eta_4 + \eta_7) = \text{-}30$$

$$\overline{B}_2 = \frac{1}{3}(\eta_2 + \eta_5 + \eta_8) = \text{-}40$$

$$\overline{B}_3 = \frac{1}{3}(\eta_3 + \eta_6 + \eta_9) = \text{-}55$$

Effects Estimation

Expt. No.	1 Temperature (A)	2 Pressure (B)	3 Settling Time (C)	4 Cleaning Method (D)	Observation* η (dB)
1	1	1	1	1	$\eta_1 = -20$
2	1	2	2	2	$\eta_2 = -10$
3	1	3	3	3	$\eta_3 = -30$
4	2	1	2	3	$\eta_4 = -25$
5	2	2	3	1	$\eta_5 = -45$
6	2	3	1	2	$\eta_6 = -65$
7	3	1	3	2	$\eta_7 = -45$
8	3	2	1	3	$\eta_8 = -65$
9	3	3	2	1	$\eta_9 = -70$

(Column Number and Factor Assigned)

* $\eta = -10 \log_{10}$ (mean square surface defect count).

$$\overline{C}_1 = \frac{1}{3}(\eta_1 + \eta_6 + \eta_8) = \text{-}50$$

$$\overline{C}_2 = \frac{1}{3}(\eta_2 + \eta_4 + \eta_9) = \text{-}35$$

$$\overline{C}_3 = \frac{1}{3}(\eta_3 + \eta_5 + \eta_7) = \text{-}40$$

Effects Estimation

Expt. No.	Column Number and Factor Assigned				Observation* η (dB)
	1 Temperature (A)	2 Pressure (B)	3 Settling Time (C)	4 Cleaning Method (D)	
1	1	1	1	1	$\eta_1 = -20$
2	1	2	2	2	$\eta_2 = -10$
3	1	3	3	3	$\eta_3 = -30$
4	2	1	2	3	$\eta_4 = -25$
5	2	2	3	1	$\eta_5 = -45$
6	2	3	1	2	$\eta_6 = -65$
7	3	1	3	2	$\eta_7 = -45$
8	3	2	1	3	$\eta_8 = -65$
9	3	3	2	1	$\eta_9 = -70$

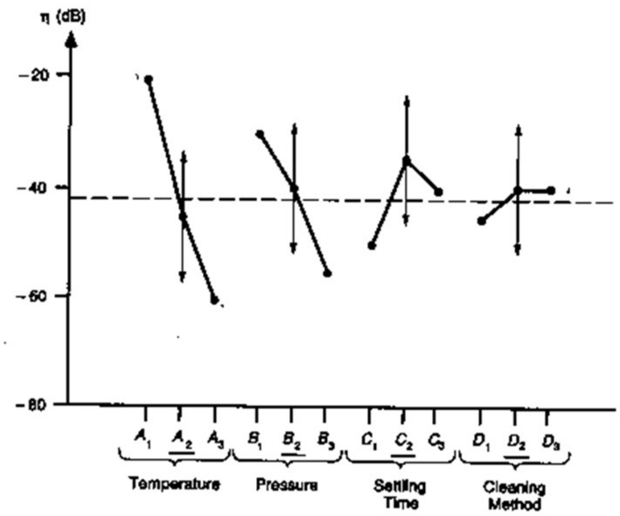
* $\eta = -10 \log_{10}$ (mean square surface defect count).

$$\bar{D}_1 = \frac{1}{3}(\eta_1 + \eta_5 + \eta_9) = \text{-45}$$

$$\bar{D}_2 = \frac{1}{3}(\eta_2 + \eta_6 + \eta_7) = \text{-40}$$

$$\bar{D}_3 = \frac{1}{3}(\eta_3 + \eta_4 + \eta_8) = \text{-40}$$

Factor Effects



ANOVA (to be explained in later classes)

Total sum of squares = sum of the sum of squares due to various factors + sum of squares due to error

Factor/Source	Degrees of Freedom	Sum of Squares	Mean Square	F
A. Temperature	2	2450	1225	12.25
B. Pressure	2	950	475	4.75
C. Settling time	2	350*	175	
D. Cleaning method	2	50*	25	
Error	0	0	–	
Total	8	3800		
(Error)	(4)	(400)	(100)	

* Indicates sum of squares added together to estimate the pooled error sum of squares indicated by parentheses. F ratio is calculated by using the pooled error mean square.

Steps in Robust Design

•**Planning the experiment**

1) Identify the main function, side effects, and failure modes.
2) Identify noise factors and the testing conditions for evaluating the quality loss.
3) Identify the quality characteristic to be observed and the objective function to be optimized.
4) Identify the controllable factors and their alternate levels.
5) Design the matrix experiment (OAs) and define the data analysis procedure.

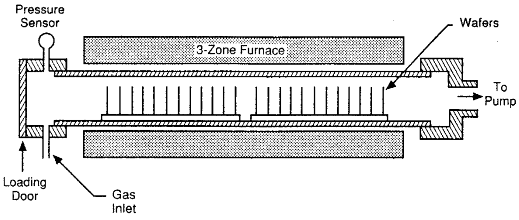
•**Performing the experiment**

6) Conduct the matrix experiment.

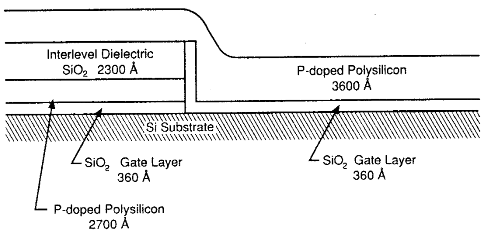
•**Analyzing and verifying the experiment results**

7) Analyze the data, determine optimum levels for the control factors, and predict performance under these levels.
8) Conduct the verification (also called confirmation) experiment and plan future actions.

LPCVD Experiment



Schematic diagram of a reduced pressure reactor.



Cross section of a wafer showing polysilicon layer.

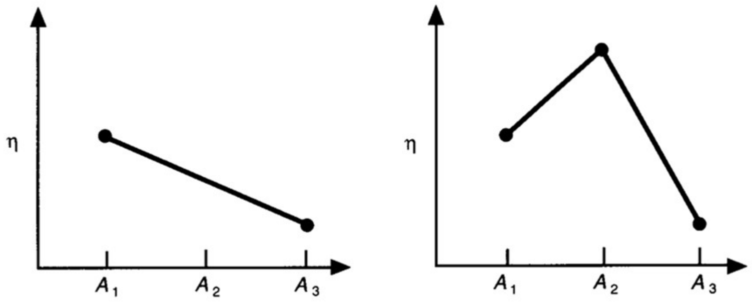
Quality Characteristics:

1. Surface defect
2. Thickness
3. Deposition rate

LPCVD Experiment - Goals

- Reduce defect
  - maximize $\eta = -10\ log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right]$
- Minimize wafer-to-wafer thickness non-uniformity and adjust mean thickness to target value
  - maximize $\eta' = 10\ log_{10}\ (\mu^2 / \sigma^2)$
  - use "deposition time" as the scaling factor
- Maximize deposition rate
  - maximize $\eta'' = -10\ log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right] = 10\ log_{10} y_i^2 \quad (n=1)$

Determining Level Number



(a) With two points we can only fit a straight line.

(b) With three points we can identify curvature effects and, hence, peaks.

Identifying Factors

Factor	Levels*		
	1	2	3
A. Deposition temperature (°C)	$T_0 - 25$	$\underline{T_0}$	$T_0 + 25$
B. Deposition pressure (mtorr)	$P_0 - 200$	$\underline{P_0}$	$P_0 + 200$
C. Nitrogen flow (sccm)	$\underline{N_0}$	$N_0 - 150$	$N_0 - 75$
D. Silane flow (sccm)	$S_0 - 100$	$S_0 - 50$	$\underline{S_0}$
E. Settling time (min)	$\underline{t_0}$	$t_0 + 8$	$t_0 + 16$
F. Cleaning method	$\underline{None}$	CM_2	CM_3

* Starting levels are identified by underscore.

L_{18} Orthogonal Array and Factor Assignment

Expt. No.	Column Numbers and Factor Assignment*							
	1 e	2 A	3 B	4 C	5 D	6 E	7 e	8 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

* Empty columns are identified by e.

Experimenter's Log

Expt. No.	Temperature	Pressure	Nitrogen	Silane	Settling Time	Cleaning Method
1	T_0-25	P_0-200	N_0	S_0-100	t_0	*None*
2	T_0-25	P_0	N_0-150	S_0-50	t_0+8	CM_2
3	T_0-25	P_0+200	N_0-75	S_0	t_0+16	CM_3
4	T_0	P_0-200	N_0	S_0-50	t_0+8	CM_3
5	T_0	P_0	N_0-150	S_0	t_0+16	*None*
6	T_0	P_0+200	N_0-75	S_0-100	t_0	CM_2
7	T_0+25	P_0-200	N_0-150	S_0-100	t_0+16	CM_3
8	T_0+25	P_0	N_0-75	S_0-50	t_0	*None*
9	T_0+25	P_0+200	N_0	S_0	t_0+8	CM_2
10	T_0-25	P_0-200	N_0-75	S_0	t_0+8	*None*
11	T_0-25	P_0	N_0	S_0-100	t_0+16	CM_2
12	T_0-25	P_0+200	N_0-150	S_0-50	t_0	CM_3
13	T_0	P_0-200	N_0-150	S_0	t_0	CM_2
14	T_0	P_0	N_0-75	S_0-100	t_0+8	CM_3
15	T_0	P_0+200	N_0	S_0-50	t_0+16	*None*
16	T_0+25	P_0-200	N_0-75	S_0-50	t_0+16	CM_2
17	T_0+25	P_0	N_0	S_0	t_0	CM_3
18	T_0+25	P_0+200	N_0-150	S_0-100	t_0+8	*None*

Surface Defect Data (Defects / Unit Area)

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

Thickness and Deposition Rate Data

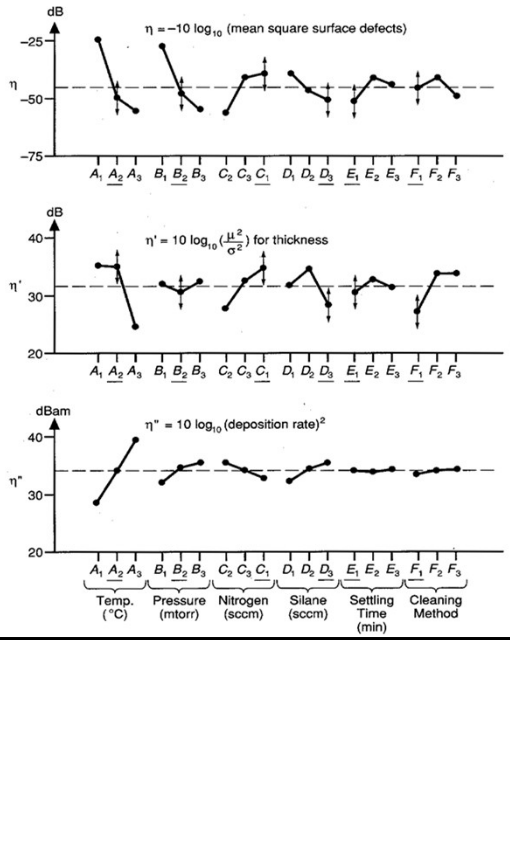
Expt. No.	Thickness (Å)									Deposition Rate (Å/min)
	Test Wafer 1			Test Wafer 2			Test Wafer 3			
	Top	Center	Bottom	Top	Center	Bottom	Top	Center	Bottom	
1	2029	1975	1961	1975	1934	1907	1952	1941	1949	14.5
2	5375	5191	5242	5201	5254	5309	5323	5307	5091	36.6
3	5989	5894	5874	6152	5910	5886	6077	5943	5962	41.4
4	2118	2109	2099	2140	2125	2108	2149	2130	2111	36.1
5	4102	4152	4174	4556	4504	4560	5031	5040	5032	73.0
6	3022	2932	2913	2833	2837	2828	2934	2875	2841	49.5
7	3030	3042	3028	3486	3333	3389	3709	3671	3687	76.6
8	4707	4472	4336	4407	4156	4094	5073	4898	4599	105.4
9	3859	3822	3850	3871	3922	3904	4110	4067	4110	115.0
10	3227	3205	3242	3468	3450	3420	3599	3591	3535	24.8
11	2521	2499	2499	2576	2537	2512	2551	2552	2570	20.0
12	5921	5766	5844	5780	5695	5814	5691	5777	5743	39.0
13	2792	2752	2716	2684	2635	2606	2765	2786	2773	53.1
14	2863	2835	2859	2829	2864	2839	2891	2844	2841	45.7
15	3218	3149	3124	3261	3205	3223	3241	3189	3197	54.8
16	3020	3008	3016	3072	3151	3139	3235	3162	3140	76.8
17	4277	4150	3992	3888	3681	3572	4593	4298	4219	105.3
18	3125	3119	3127	3567	3563	3520	4120	4088	4138	91.4

Data Summary by Experiment

Expt. No.	Experiment Condition Matrix* e A B C D E e F	Surface Defects η (dB)	Thickness μ (Å)	Thickness η′ (dB)	Deposition Rate η″ (dBam)
1	1 1 1 1 1 1 1 1	0.51	1958	35.22	23.23
2	1 1 2 2 2 2 2 2	−37.30	5255	35.76	31.27
3	1 1 3 3 3 3 3 3	−45.17	5965	36.02	32.34
4	1 2 1 1 2 2 3 3	−25.76	2121	42.25	31.15
5	1 2 2 2 3 3 1 1	−62.54	4572	21.43	37.27
6	1 2 3 3 1 1 2 2	−62.23	2891	32.91	33.89
7	1 3 1 2 1 3 2 3	−59.88	3375	21.39	37.68
8	1 3 2 3 2 1 3 1	−71.69	4527	22.84	40.46
9	1 3 3 1 3 2 1 2	−68.15	3946	30.60	41.21
10	2 1 1 3 3 2 2 1	−3.47	3415	26.85	27.89
11	2 1 2 1 1 3 3 2	−5.08	2535	38.80	26.02
12	2 1 3 2 2 1 1 3	−54.85	5781	38.06	31.82
13	2 2 1 2 3 1 3 2	−49.38	2723	32.07	34.50
14	2 2 2 3 1 2 1 3	−36.54	2852	43.34	33.20
15	2 2 3 1 2 3 2 1	−64.18	3201	37.44	34.76
16	2 3 1 3 2 3 1 2	−27.31	3105	31.86	37.71
17	2 3 2 1 3 1 2 3	−71.51	4074	22.01	40.45
18	2 3 3 2 1 2 3 1	−72.00	3596	18.42	39.22

* Empty column is denoted by e.

Plots of Factor Effects



Summary of Factor Effects

Factor	Level	Surface Defects η (dB)	Surface Defects F	Thickness η' (dB)	Thickness F	Deposition Rate η'' (dBam)	Deposition Rate F
A. Temperature (°C)	A_1: T_0-25	−24.23		35.12		28.76	
	$\underline{A_2: T_0}$	−50.10	27	34.91	16	34.13	553
	A_3: T_0+25	−61.76		24.52		39.46	
B. Pressure (mtorr)	B_1: P_0-200	−27.55		31.61		32.03	
	$\underline{B_2: P_0}$	−47.44	21	30.70	–	34.78	66
	B_3: P_0+200	−61.10		32.24		35.54	
C. Nitrogen (sccm)	$\underline{C_1: N_0}$	−39.03		34.39		32.81	
	C_2: N_0-150	−55.99	6.4	27.86	5.0	35.29	30
	C_3: N_0-75	−41.07		32.30		34.25	
D. Silane (sccm)	D_1: S_0-100	−39.20		31.68		32.21	
	D_2: S_0-50	−46.85	2.3	34.70	4.8	34.53	58
	$\underline{D_3: S_0}$	−50.04		28.17		35.61	
E. Settling time (min)	$\underline{E_1: t_0}$	−51.52		30.52		34.06	
	E_2: t_0+8	−40.54	2.3	32.87	–	33.99	–
	E_3: t_0+16	−44.03		31.16		34.30	
F. Cleaning method	F_1: *None*	−45.56		27.04		33.81	
	$\underline{F_2: CM_2}$	−41.58	–	33.67	6.8	34.10	–
	F_3: CM_3	−48.95		33.85		34.44	
Overall mean		−45.36		31.52		34.12	

Determination of Optimal Levels

- Temperature A_1 can significantly reduce the number of surface defects but also reduce the deposition rate. Since reducing surface defects is our major goal we choose A_1.
- E_2 and F_2 are the optimal levels for settling time and cleaning method to improve the surface defects and thickness uniformity.
- In order to keep a high deposition rate, keep the pressure (B), Nitrogen flow rate (C), and Silane flow rate (D) unchanged

Predictive Additive Model

$$\hat{\eta} = \boldsymbol{Overallmean} + \sum_{factor} (\overline{\boldsymbol{factor}}_{level} - \boldsymbol{Overallmean})$$

Example: optimal levels for surface defects

$$\hat{\eta}(\text{Surface Defects}) = \boldsymbol{Overallmean} + (\overline{\boldsymbol{A}}_2 - \boldsymbol{Overallmean}) + (\overline{\boldsymbol{B}}_2 - \boldsymbol{Oeverallmean})$$
$$+(\overline{\boldsymbol{C}}_1 - \boldsymbol{Oeverallmean}) + (\overline{\boldsymbol{D}}_3 - \boldsymbol{Oeverallmean}) + (\overline{\boldsymbol{E}}_2 - \boldsymbol{Oeverallmean})$$
$$+(\overline{\boldsymbol{F}}_2 - \boldsymbol{Oeverallmean})$$
$$= \mathbf{-45.36 + [-24.23 - (-45.36)] + [-47.44 - (-45.36)] + [-39.03 - (-45.36)] +}$$
$$\mathbf{[-50.04 - (-45.36)] + [-40.54 - (-45.36)] + [-41.58 - (-45.36)]}$$
$$= \mathbf{-45.36 + 21.13 - 2.08 + 6.33 - 4.68 + 4.82 + 3.78 = -16.06}$$

Prediction Using The Additive Model

Factor	Starting Condition				Optimum Condition			
	Setting	Contribution† (dB)			Setting	Contribution† (dB)		
		Surface Defects	Thickness	Deposition Rate		Surface Defects	Thickness	Deposition Rate
A*	A_2	−4.74	3.39	0.01	A_1	21.13	3.60	−5.36
B	B_2	−2.08	0.00	0.66	B_2	−2.08	0.00	0.66
C	C_1	6.33	2.87	−1.31	C_1	6.33	2.87	−1.31
D	D_3	−4.68	−3.35	1.49	D_3	−4.68	−3.35	1.49
E*	E_1	−6.16	0.00	0.00	E_2	4.82	0.00	0.00
F*	F_1	0.00	−4.48	0.00	F_2	3.78	2.15	0.00
Overall Mean		−45.36	31.52	34.12		−45.36	31.52	34.12
Total		−56.69	29.95	34.97		−16.06	36.79	29.60

* Indicates the factors whose levels are changed from the starting to the optimum conditions.
† By *contribution* we mean the deviation from the overall mean caused by the particular factor level.

Results of Verification Experiment

		Starting Condition	Optimum Condition	Improvement
Surface Defects	rms	$600/cm^2$	$7/cm^2$	
	η	−55.6 dB	−16.9 dB	38.7 dB
Thickness	std. dev.*	0.028	0.013	
	η'	31.1 dB	37.7 dB	6.6 dB
Deposition Rate	rate	60 Å /min	35 Å /min	
	η''	35.6 dBam	30.9 dBam	−4.7 dBam

* Standard deviation of thickness is expressed as a fraction of the mean thickness.

Analysis of Surface Defects Data

Factor	Average η by Factor Level (dB) 1	2	3	Degree of Freedom	Sum of Squares	Mean Square	F
A. Temperature	− 24.23	<u>−50.10</u>	− 61.76	2	4427	2214	27
B. Pressure	− 27.55	<u>−47.44</u>	− 61.10	2	3416	1708	21
C. Nitrogen	<u>−39.03</u>	− 55.99	− 41.07	2	1030	515	6.4
D. Silane	− 39.20	− 46.85	<u>−50.04</u>	2	372	186	2.3
E. Settling time	<u>−51.52</u>	− 40.54	− 44.03	2	378	189	2.3
F. Cleaning method	<u>−45.56</u>	− 41.58	− 48.95	2	164†	82	
Error				5	405†	81	
Total				17	10192		
(Error)				(7)	(569)	(81)	

* Overall mean $\eta = -45.36$ dB. Underscore indicates starting level.
† Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.

Analysis of Thickness Data

Factor	Average η′ by Level (dB) 1	2	3	Degree of Freedom	Sum of Squares	Mean Square	F
A. Temperature	35.12	34.91	24.52	2	440	220	16
B. Pressure	31.61	30.70	32.24	2	7†	3.5	
C. Nitrogen	34.39	27.86	32.30	2	134	67	5.0
D. Silane	31.68	34.70	28.17	2	128	64	4.8
E. Settling time	30.52	32.87	31.16	2	18†	9	
F. Cleaning method	27.04	33.67	33.85	2	181	90.5	6.8
Error				5	96†	19.2	
Total				17	1004	59.1	
(Error)				(9)	(121)	(13.4)	

* Overall mean $\eta' = 31.52$ dB. Underscore indicates starting level.
† Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.

Analysis of Deposition Rate Data

Factor	Average η″ by Factor Level (dBam) 1	2	3	Degree of Freedom	Sum of Squares	Mean Square	F
A. Temperature	28.76	34.13	39.46	2	343.1	171.5	553
B. Pressure	32.03	34.78	35.54	2	41.0	20.5	66
C. Nitrogen	32.81	35.29	34.25	2	18.7	9.4	30
D. Silane	32.21	34.53	35.61	2	36.3	18.1	58
E. Settling time	34.06	33.99	34.30	2	0.3†	0.2	
F. Cleaning method	33.81	34.10	34.44	2	1.2†	0.6	
Error				5	1.3†	0.26	
Total				17	441.9	25.9	
(Error)				(9)	(2.8)	(0.31)	

* Overall mean $\eta'' = 34.12$ dBam. Underscore indicates starting level.
† Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.