2.830J / 6.780J / ESD.63J Control of Manufacturing Processes (SMA 6303)
Spring 2008

2.830/6.780J Control of Manufacturing Processes

"An Industrial Example of Oxide Etch Process Control and Optimization"

Spring 2007

Jing Yao
Kai Meng
Yi Qian

Agenda

- Plasma Etch Process physics
- Industrial Practices
  - SPC Practice
  - A Process Improvement Experiment
- Proposed DOE and RSM methods
- Process control improvements and recommendations

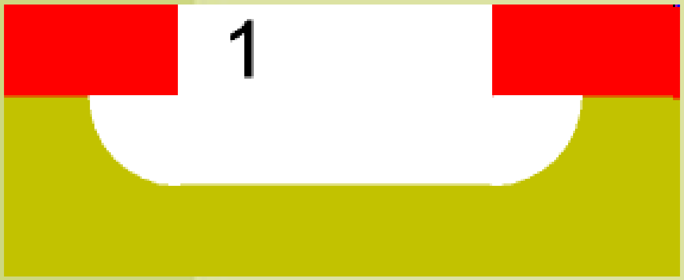
Layered Wafer Manufacturing Process

- 3 basic operations:
  - Film Deposition
  - Photolithography
  - Etch
- This cycle is repeated to build up various layers in the devices.

Image removed due to copyright restrictions. Please see http://dot.che.gatech.edu/henderson/Introductions/Image55.gif

Types of Etching

- Etch techniques
  - Wet etch (Isotropic)
  - Dry etch / Plasma etch (Anisotropic)



Anisotropy is critical in submicron feature fabrication!

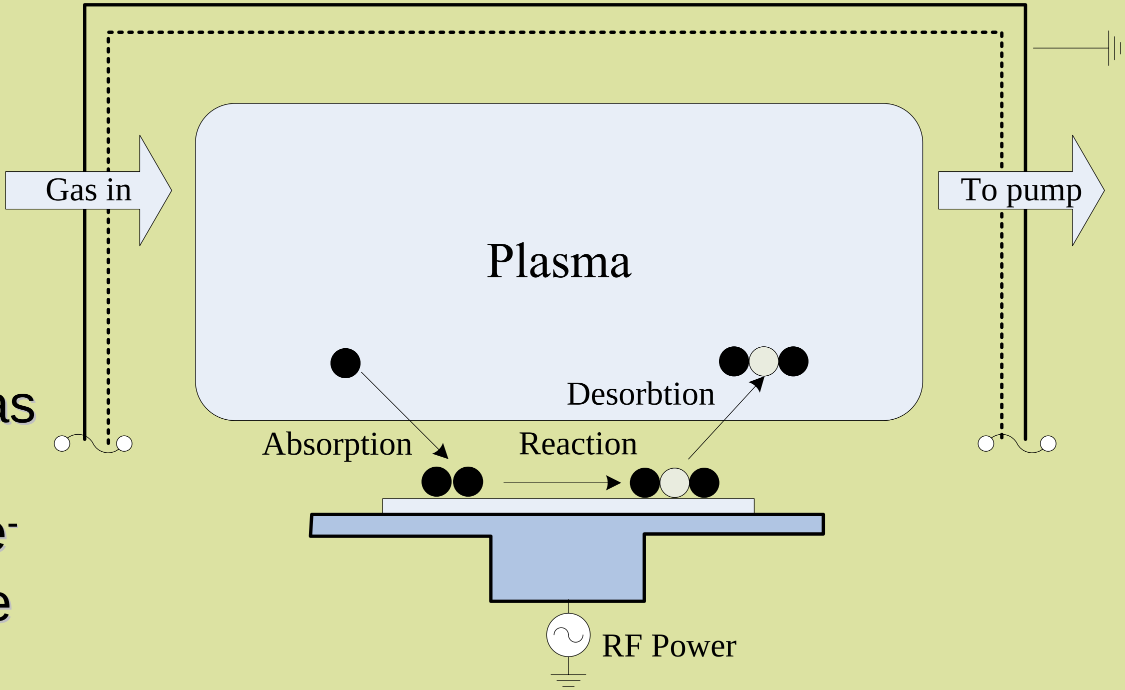
Manufacturing

Plasma Etching Steps

- Plasma etching uses RF power to drive material removal by chemical reaction
- Steps:
  - Formation of active gas species, e.g.

    $CF_4 + e^- \rightarrow CF_3^+ + F + 2e^-$
  - Transport of the active species to the wafer surface
  - Reaction at the surface

    $SiO_2 + 4F \rightarrow SiF_4 + O_2$
  - Pump away volatile products



Physical vs Chemical Etching

	Physical Method	Chemical Method
Mechanism	Ion Bombardment	Chemical Reaction
Etch Rate	Low	High
Selectivity	Low	High
Bombardment-induced damage	High	Low
Anisotropy	High	Low

- Industry often uses hybrid technique: physical method to enhance chemical etching
- This gives anisotropic etch profile, reasonably good selectivity, and moderate bombardment-induced damage.

Plasma Etch Parameters

- Gas chemistry
  - Fluorocarbon gases (C_4F_6, CF_4, C_4F_8,etc)

    Atomic F is active etchant for SiO_2

    $SiO_2 + 4F \rightarrow SiF_4 + O_2$

    Carbon reacts with oxygen to form passivation layer on Si → provides selectivity
  - O_2: Under certain level, O_2 scavenge C in Fluorocarbon, results in higher F concentration → Higher etch rate
  - Ar: Ar^+ ion beam enhances chemical reaction

Plasma Etch Parameters

- Pressure
  - Low pressure reduces ion-neutral collision on sidewalls (lateral etch), enhances anisotropic etching
- Bias Power
  - Increase bias power enhances physical bombardment of ions
- Etch Time
- Temperature

Critical Issues

- Anisotropy
- Selectivity
- Microscopic Uniformity
- Etch Depth
- Critical Dimension (CD)

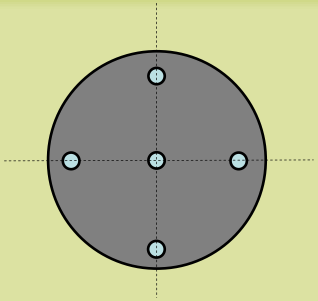
Image removed due to copyright restrictions. Please see http://www.mems-exchange.org/catalog/P3431/file/f38826bf4266f95d6e054553/thumbnail?600

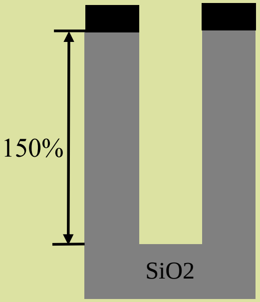
Background

- Industry Practices in a DRAM wafer fabrication plant in Singapore
- Current Technology:
  - 95nm 1GB DRAM on 200mm wafers
  - 78nm 1GB DRAM on 300mm wafers
- Information source
  - Interview with process engineer
  - Scaled data based on experiments data (actual data unknown)

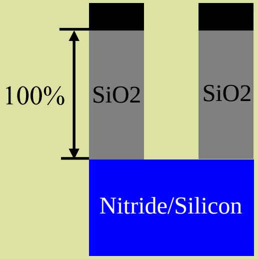
Focused Output

- Etch Depth
  - Measuring Method
    - Test wafer ONLY!
      - Over-etch on test wafer
      - Cost
    - 5 sites measurement
  - Percentage over-etch on test wafer
    - 20%-60% over-etch on test wafer
    - Selectivity





Test Wafer



Production Wafer

- Critical Dimension
  - Measuring Method
    - Test or production wafer
    - 5 sites measurement

Image removed due to copyright restrictions. Please see http://www.mems-exchange.org/catalog/P3431/file/f38826bf4266f95d6e054553/thumbnail?600

SPC Practice

- SPC analysis tools are installed in all production machines
  - X-bar chart and R chart
- Different test methods for different outputs
  - Etch Depth
    - Insert test wafer into production lots
    - Infrequent: ~200 hours
    - Increase frequency when special attention needed
  - Critical Dimension
    - Test 1 wafer per lot (25 wafers)
    - 5 sites average

SPC Practice

- Rules: similar to Western Electrical Handbook rules
- UCL/LCL are set by process engineer
  - Based on USL/LSL
  - UCL/LCL are little bit tighter than USL/LSL
  - Tighten UCL/LCL based on experience
  - UCL/LCL are not based on standard deviation!
- Process pass SPC most of the time
- Stop a machine when a measurement is outside UCL/LCL, other rules mostly ignored
- Slow response

SPC Improvement

- Set UCL/LCL based on sample standard deviation
- Use more effective control chart, like CUSUM or EWMA chart, to improve response time
- Use multivariate process control

A Process Improvement Experiment

- Problem
  - Under-etch
  - Discovered by quality assurance from finished products
  - Process improvement is necessary because no issues found on the machine
- Approach
  1. Focus on two inputs (C_4F_6 Flow Rate, Bias Power)
  2. Vary inputs one step away from current value
  3. Test with all inputs combinations
  4. Change third input (Time)
  5. Repeat 1 to 3
  6. Find the best result

A Process Improvement Experiment

- 1 wafer, no replicates
- 5 sites average

- Goal:
  - CD: 100 ± 5 nm
  - Etch Depth: 1.4 um with 60%~70% over etch on test wafer [2.25um, 2.4 um]

Etch Depth (um)		C4F6 (sccm)		
		14.5	15	15.5
Bias Power (W)	1300	1.72	1.68	1.56
	1400	2.08	2.01	1.91
	1500	2.56	2.45	2.41

200 sec

CD (nm)		C4F6 (sccm)		
		14.5	15	15.5
Bias Power (W)	1300	100	95	88
	1400	110	103	96
	1500	118	110	104

Etch Depth (um)		C4F6 (sccm)		
		14.5	15	15.5
Bias Power (W)	1300	1.63	1.60	1.50
	1400	2.00	1.95	1.87
	1500	2.50	2.37	2.28

190 sec

CD (nm)		C4F6 (sccm)		
		14.5	15	15.5
Bias Power (W)	1300	98	93	85
	1400	106	100	94
	1500	114	106	100

sccm : **Standard Cubic Centimeters per Minute**

A Process Improvement Experiment

- A combination of DOE and OFAT
  - Rely on theoretical study and experience
- Find an optimal based on tested input combinations
- No Response Surface analysis
- No replicates or center points
  - Hard to prove model accuracy
- No variance study
- Confidence Level unknown!

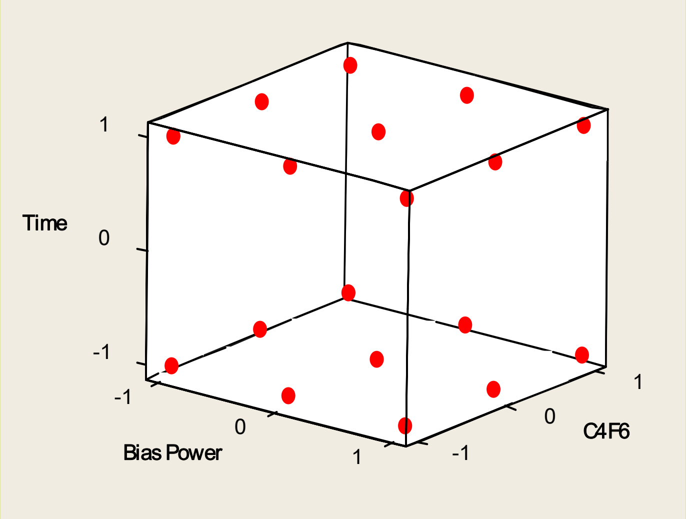
Experimental Design

- Bias Power and C_4F_6
  - – Central composite design
  - – 3 levels
- Etching Time
  - – 2 levels

Factor	Actual test levels (coded test level)			
	(-1)	(0)	(1)	
X1-Bias Power	1300	1400	1500	W
X2-C4F6	14.5	15.0	15.5	sccm
X3-Etching Time	190		200	sec

Run Data

Trial	Bias Power	C4F6	Time	Etch Depth (um)	Critical Dimension (nm)
1	-1	-1	1	1.72	100
2	0	-1	1	2.08	110
3	1	-1	1	2.56	118
4	-1	0	1	1.68	95
5	0	0	1	2.01	103
6	1	0	1	2.45	110
7	-1	1	1	1.56	88
8	0	1	1	1.91	96
9	1	1	1	2.41	104
10	-1	-1	-1	1.63	98
11	0	-1	-1	2.00	106
12	1	-1	-1	2.50	114
13	-1	0	-1	1.60	93
14	0	0	-1	1.95	100
15	1	0	-1	2.37	106
16	-1	1	-1	1.50	85
17	0	1	-1	1.87	94
18	1	1	-1	2.28	100



Note: each run data is the mean of 5 sites average on 1 wafer

Response Models

- Second order polynomial models
  - models built using coded variables
  - no transformations of output variables attempted

$$Y = b_0 + \sum_{i=1}^{3} b_i X_i + \sum_{j=i+1}^{3} \sum_{i=1}^{3} b_{ij} X_i X_j + \sum_{i=1}^{3} b_{ii} X_i^2$$

Model Evaluation

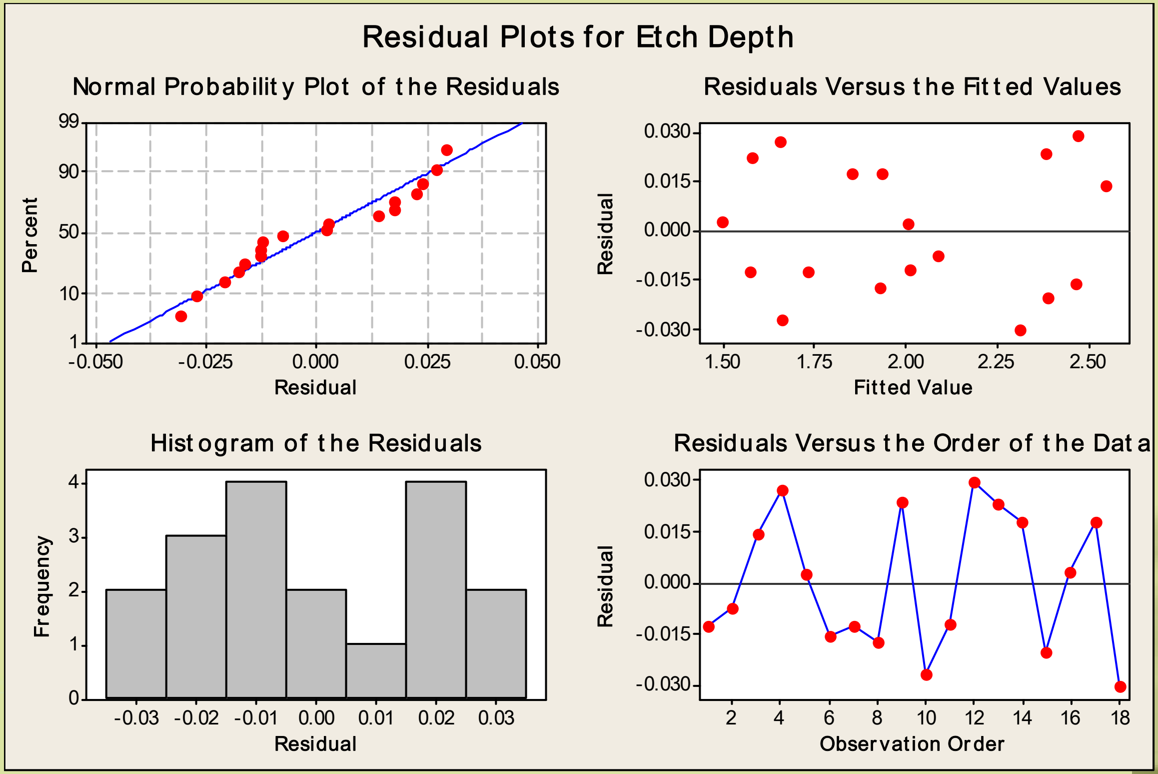
- RSM fitting
  - ANOVA performed
  - Each output model claimed significant at >99.8% confidence level or higher
- Regression coefficients shown for significant terms

Etch Depth

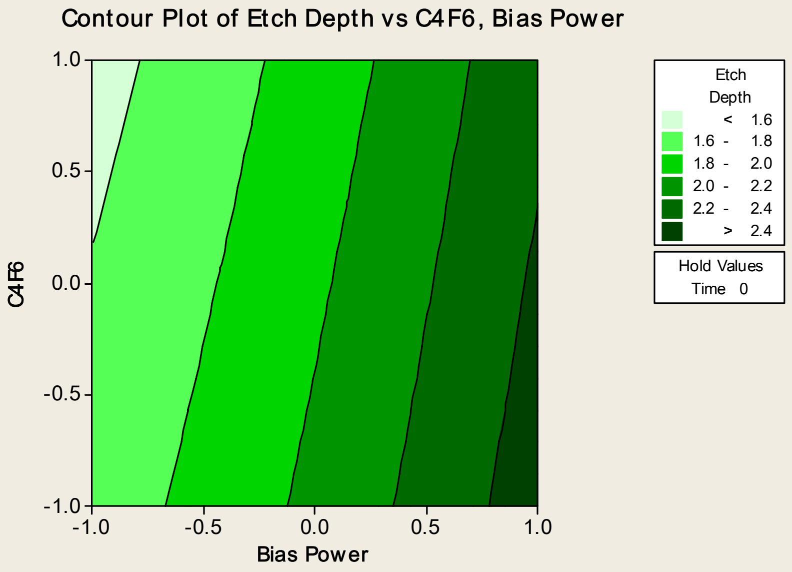
- Response Surface model

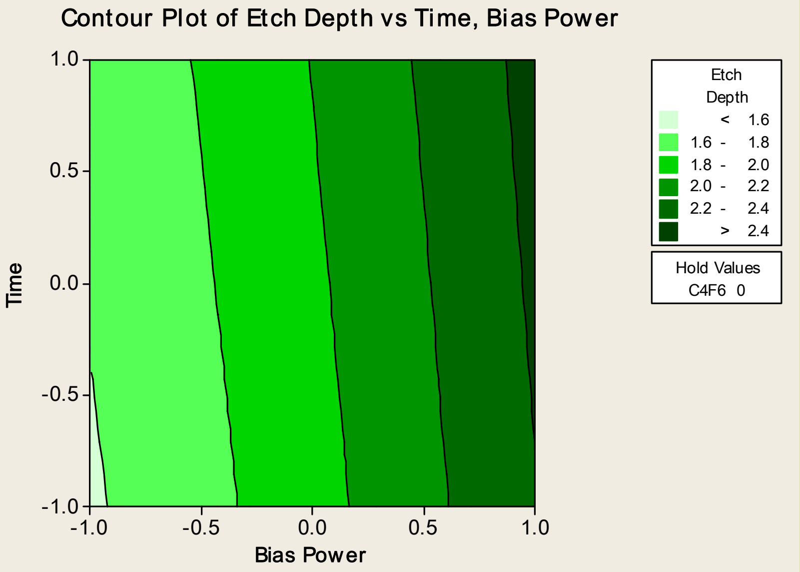
$$ED = 1.970 + 0.407x_1 - 0.080x_2 + 0.038x_3 + 0.052x_1^2$$

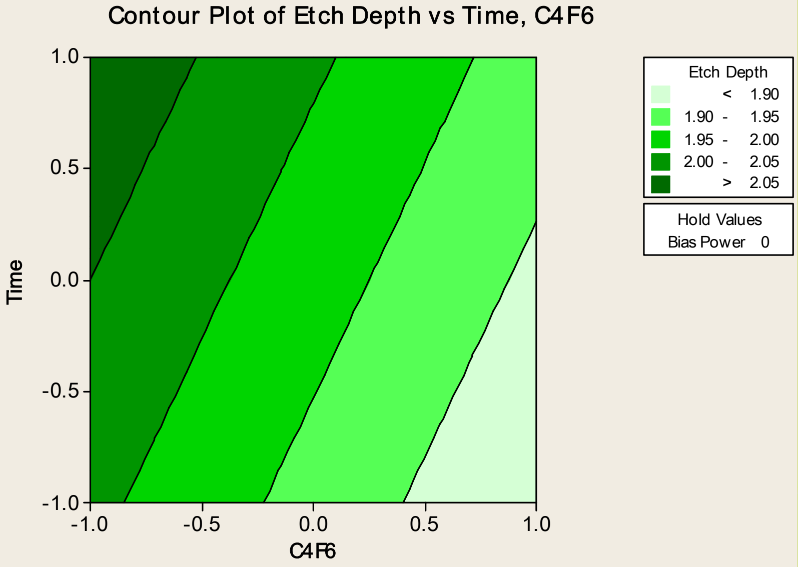
- Residual



Etch Depth – Contour Plot


Contour Plot of Etch Depth vs C4F6, Bias Power


Contour Plot of Etch Depth vs Time, Bias Power


Contour Plot of Etch Depth vs Time, C4F6

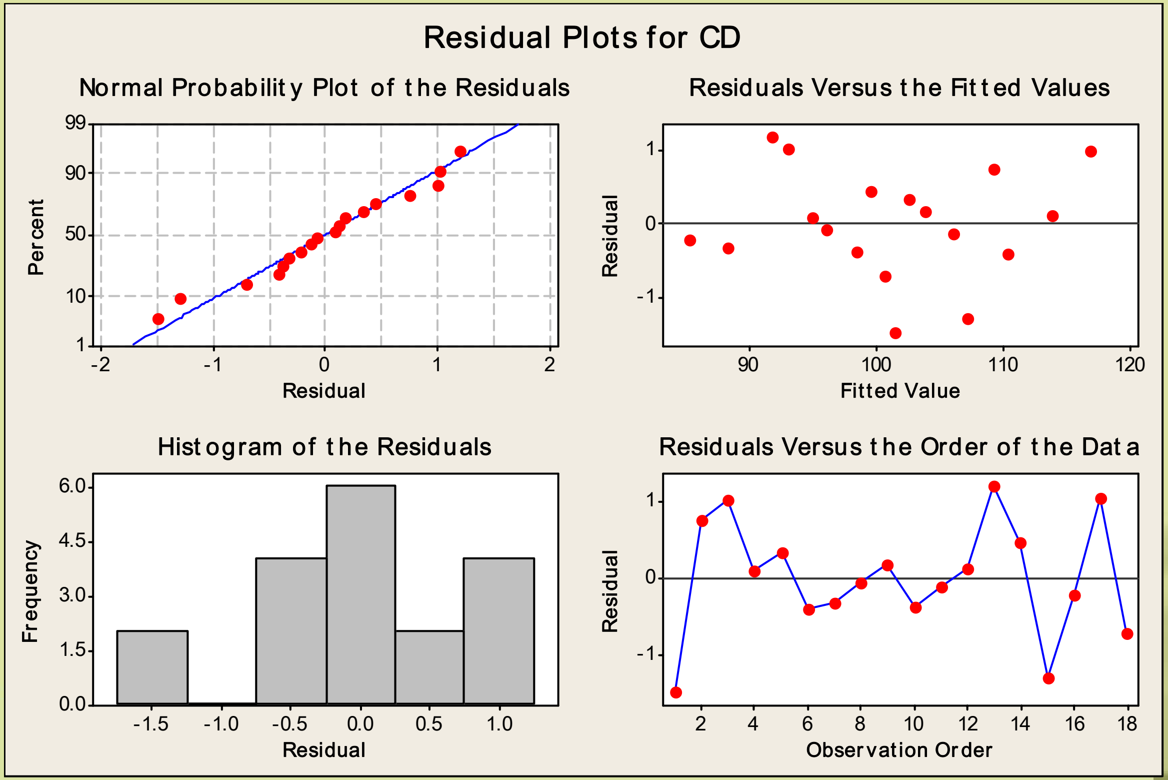
- Etch Depth most sensitive to Bias Power
- Bias Power ↑, or Time ↑, or C_4F_6 ↓ ⟶ Etch Depth ↑

Critical Dimension

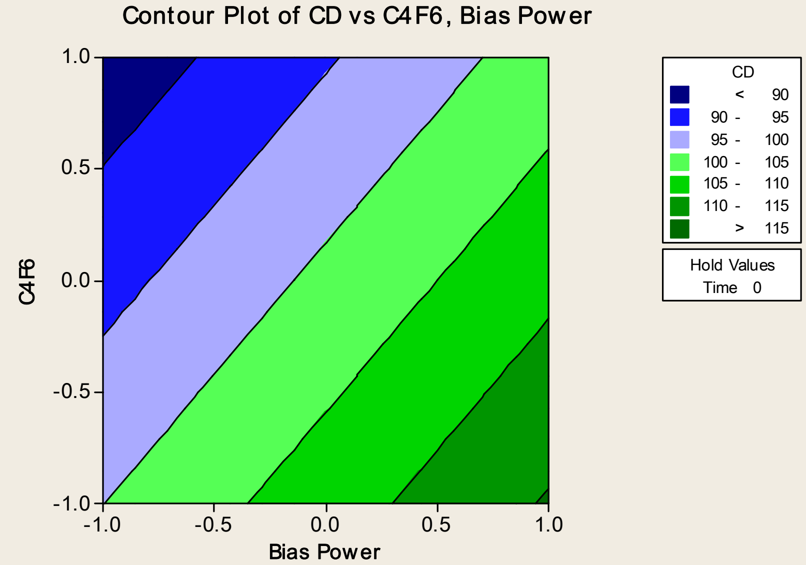
- Response Surface model

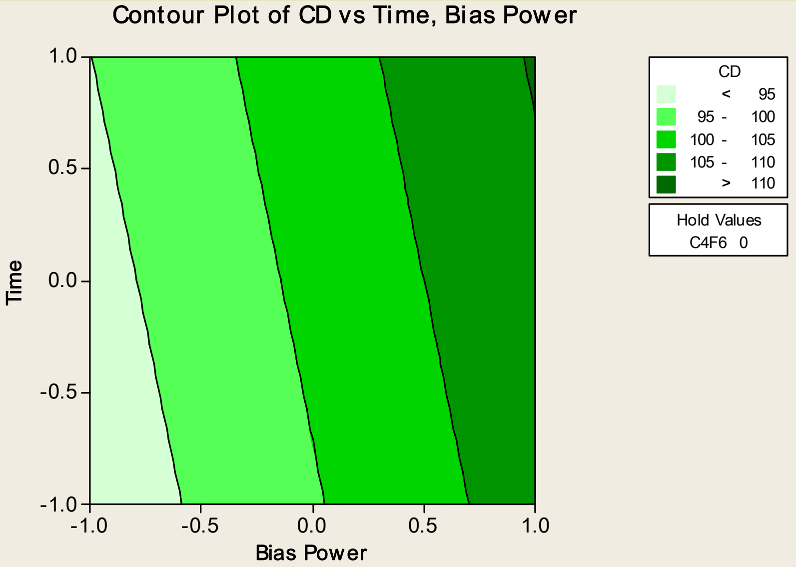
$$CD = 101.111 + 7.750x_1 - 6.583x_2 + 1.556x_3$$

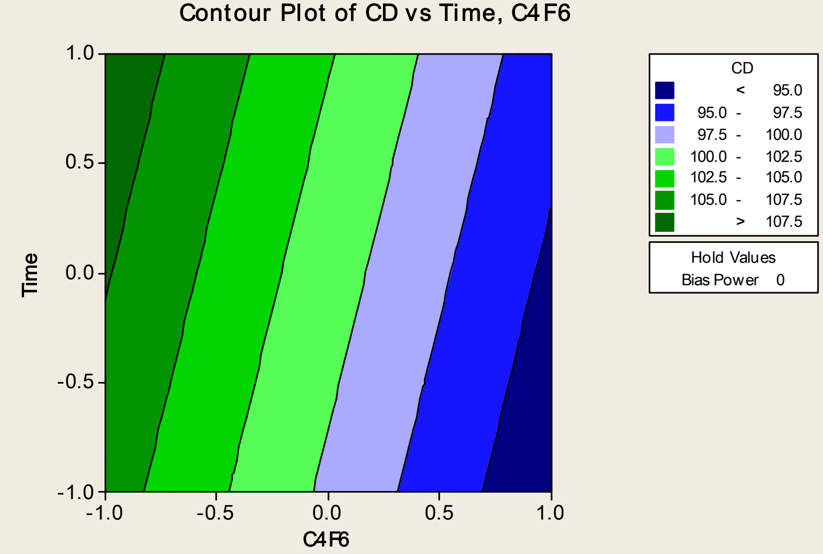
- Residual



Critical Dimension – Contour Plot


Contour Plot of CD vs C4F6, Bias Power


Contour Plot of CD vs Time, Bias Power


Contour Plot of CD vs Time, C4F6

- CD most sensitive to Bias Power & C_4F_6
- Bias Power ↑, or Time ↑, or C_4F_6 ↓ ⟶ CD ↑

Manufacturing

Process Optimization

- Optimization criteria for Oxide etch and the best values attainable within the resulting optimized factor space

Factor	Optimization Criteria	Best Values
Etch Depth	$2.25\mu m \le CD \le 2.40\mu m$	$2.25\mu m$
Critical Dimention	$100 \pm 5nm$	$100nm$

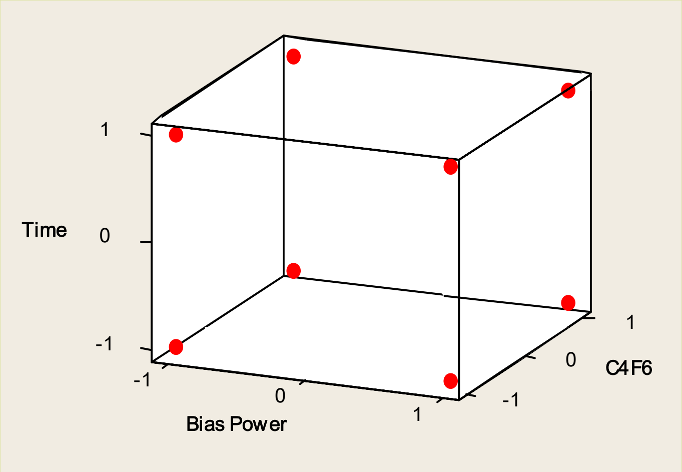
- Optimal Input

	X1-Bias Power	X2-C4F6	X3-Etching Time
Model	1487 W	15.48 sccm	190 sec
Actual	1500 W	15.5 sccm	190 sec

2^3 Full Factorial Design

- Only consider linear relationships
- Drop other 10 test points

(possible test points for lack-of-fit)



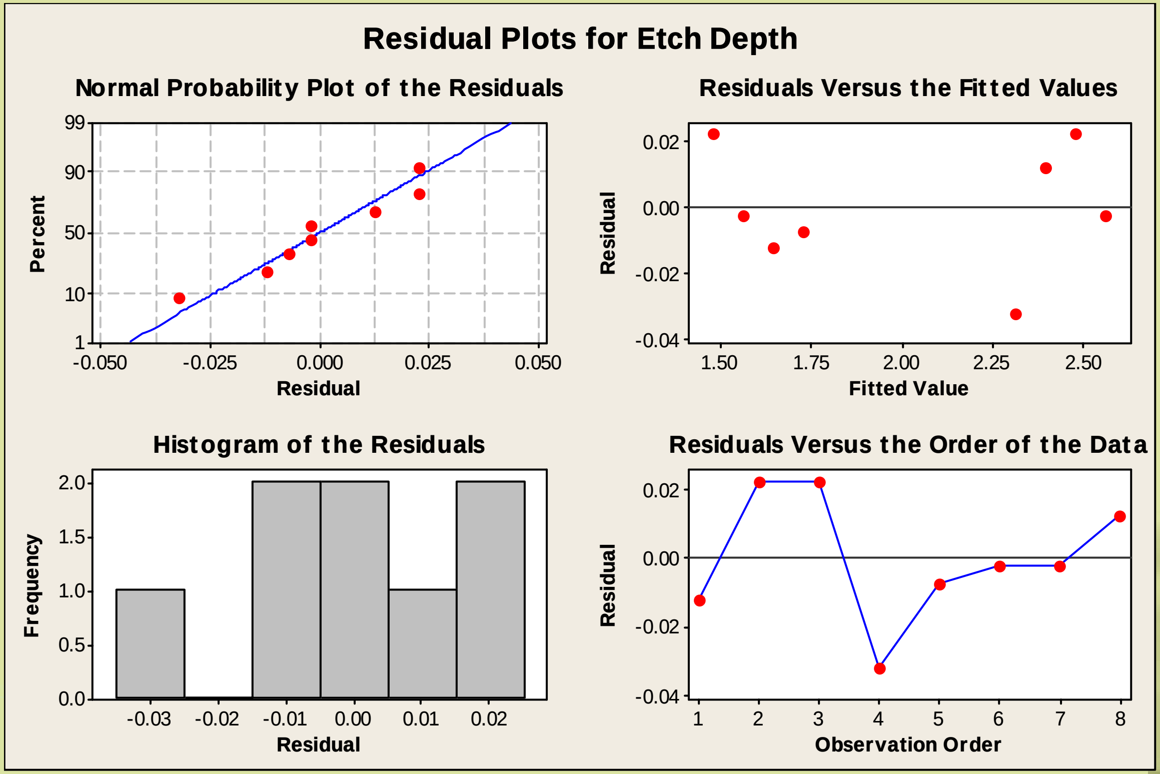
Trial	Bias Power	C4F6	Time	Etch Depth (um)	Critical Dimension (nm)
1	-1	-1	1	1.72	100
2	1	-1	1	2.56	118
3	-1	1	1	1.56	88
4	1	1	1	2.41	104
5	-1	-1	-1	1.63	98
6	1	-1	-1	2.50	114
7	-1	1	-1	1.50	85
8	1	1	-1	2.28	100

Etch Depth

- Predicted Value ($p<0.01$)

$$ED = 2.020 + 0.418x_1 - 0.083x_2 + 0.043x_3$$

- Residual

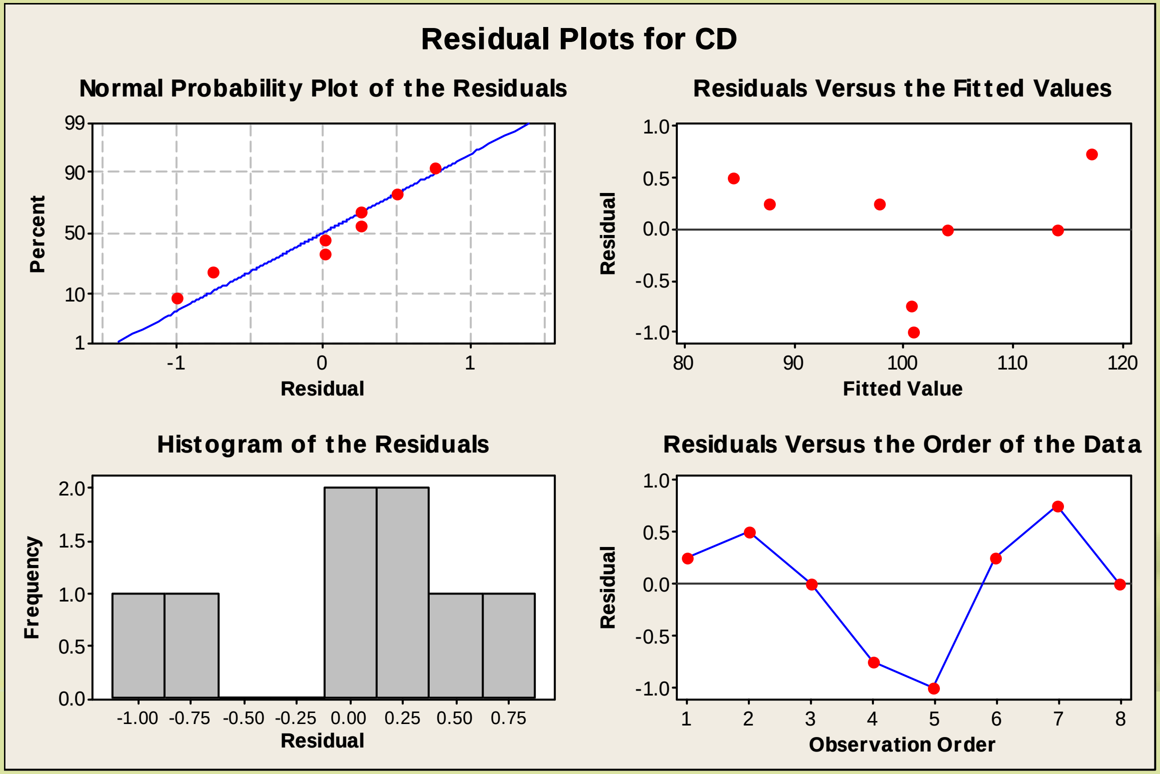


Critical Dimension

- Predicted Value ($p<0.01$)

$$CD = 100.875 + 8.125x_1 - 6.625x_2 + 1.625x_3$$

- Residual



DOE Improvement

- Adding replicates at center points
  - Use to assess pure error ('noise') as percentage of the response
  - Assess lack of fit
- Use Factorial Design

– Current practice	18 trails
– 2^3 with 4 center points	12 trails
– 3^{3-1}_{III} with 6 center points	15 trails

- Analyze Variation
  - consider variation at the desired value
- Randomize run order
  - Esp. in replicates to minimize the trend

Process Control Recommendations

- SPC Analysis
  - Use more effective control chart, like CUSUM or EWMA chart
  - Use multivariate process control
- DOE and RSM optimization
  - Adding replicates at center points
  - Use Factorial Design
  - Analyze Variation
  - Randomize run order

Thank You!