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

Control of Manufacturing Processes

Subject 2.830/6.780/ESD.63

Spring 2008

Lecture #19

Case Study: Tungsten CVD DOE/RSM

April 29, 2008

Case Study Reading

- Thomas E. Clark, Mei Chang, and Cissy Leung, "Response surface modeling of high pressure chemical vapor deposited blanket tungsten," *J. Vac. Sci. Technol. B,* vol. 9, no. 3, pp. 1478-1486, May/June 1991.

Agenda

- Background: Tungsten CVD
- Preliminary Work (not shown in paper)
- Experimental Design: Central Composite
- Data
- RSM Analysis
  - Paper vs. In-Class
- Exploratory Analyses: JMP
  - Stepwise regressions
  - Optimization
- Other Ideas?

Tungsten Plugs

- W is a conductor used for:
  - *contacts* (to silicon or poly)
  - *plugs* (between aluminum metal layers)
  - W plugs remain important in copper interconnect (contacts)
- Highly conformal: able to fill small holes
- Originally used with plasma *etchback* (as shown)
  - Now CMP is used for plug formation with a polish-back step

Image removed due to copyright restrictions. Please see Fig. 1 in Clark, Thomas E., et al. "Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten." *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

Inputs:

- Gap space
- Temperature
- H_2 pressure
- WF_6 pressure

Tungsten CVD Outputs

1. Deposition rate
   – desire a high rate, e.g. 500 nm/min
2. Resistivity ρ
   – desired value depends on application; usually desire low resistivity
3. R_s uniformity
   – need good wafer-level uniformity (<3%) to avoid recessed plugs in etchback
4. Film stress
   – avoid high stress to prevent delamination
5. Step coverage
   – desire 100% fill (flat fill) of trench or hole
6. WF_6 conversion
   – want efficient usage of this expensive gas
7. Reflectance
   – desire highly reflective surface, indicating smooth surface morphology
8. Reproducibility
   – need good run to run repeatability of process

Step Coverage & Surface Roughness

Experimental Design Goals

- Build response surface models for the seven outputs
  - reproducibility is judged based on the repeated center point designs, under assumption that reproducibility is comparable within the entire process space
- Explore the trade-offs implied by the models
- Use RSM to suggest optimal operating points

Prior Work (not shown in paper)

- Screening experiments
  - used to identify the four input parameters that are the subject of this study
- Prior growth rate characterization
  - all films are grown to ~1.0 μm thickness in DOE
    - mimic target application
    - for fair comparison of sheet resistance, etc.
  - thus, required prior estimation/characterization of growth rates at all design combinations so the appropriate growth time could be used to achieve near target thickness
    - suggests that there may have been a whole additional run of the DOE prior to that shown in the paper!

Experimental Design

- Central composite
  - five levels
  - replicated center points

Response Models to be Fit

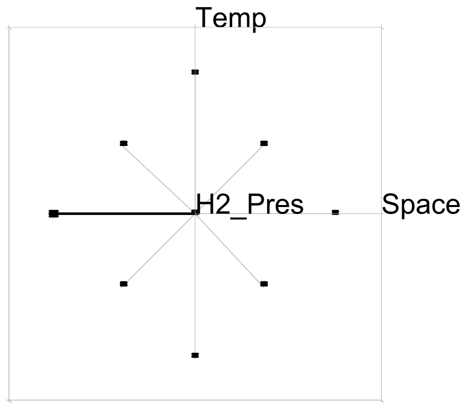
- Second order polynomial models
  - models built using coded variables
  - no transformations of output variables attempted
    - log, inverse, etc.

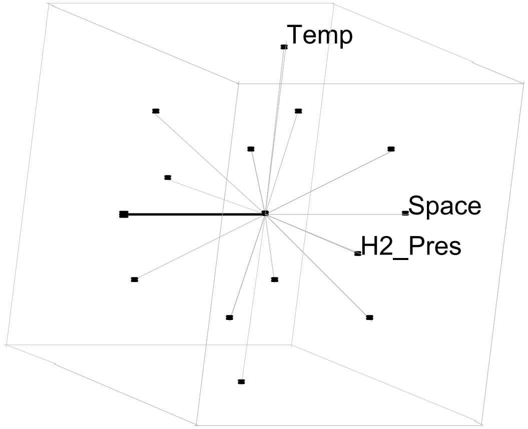
$$Y = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{j=i+1}^{n} \sum_{i=1}^{n} b_{ij} X_i X_j + \sum_{i=1}^{n} b_{ii} X_i^2, \qquad (1)$$

- Questions:
  - enough data/levels to fit these models?
  - able to evaluate lack of fit?

Design Points

Image removed due to copyright restrictions. Please see Table I in Clark, Thomas E., et al. "Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten." *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.





Data

- Single replicates at design points
  - use to assess pure error (‘noise’) as percentage of the response: generally in 1.5-5% (1σ) range
- Randomized run order
  - should have reported this, so reader could check/verify lack of trends (esp. in replicates)
- Outlier analysis performed
  - not discussed, but noted in data
- Available as “tungsten.xls”
  - outliers included

Image removed due to copyright restrictions. Please see Table III in Clark, Thomas E., et al. "Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten." *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

Reported RSM Fitting

- ANOVA performed (but not shown)
- Each output model claimed significant at >99.9% confidence level
- R^2:
  - moderately high for ρ: 0.79
  - very high for other models: 0.88 to 0.97
- Lack of fit:
  - some evidence of LOF for R_s uniformity and reflectance
    - conjectures due to small pure error term
    - could try X or Y variable transformations
- Regression coefficients shown, for significant terms
  - criteria for inclusion not stated

RSM Model Coefficients

Image removed due to copyright restrictions. Please see Table IV in Clark, Thomas E., et al. “Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten.” *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

Growth Rate & WF6 Conversion

Image removed due to copyright restrictions. Please see Fig. 2 in Clark, Thomas E., et al. “Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten.” *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

- Rate most sensitive to temperature and H_2 & WF_6 pressures
  - slight dependence on showerhead to wafer spacing

Resistivity and Reflectance

Image removed due to copyright restrictions. Please see Fig. 3 in Clark, Thomas E., et al. "Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten." *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

- ρ of 8-20 $\mu\Omega\cdot$cm acceptable for 0.75 μm contacts
- observe 7.7 to 10.5 $\mu\Omega\cdot$cm
  - temperature has greatest effect; changes in morphology believed

R_S Uniformity

Image removed due to copyright restrictions. Please see Fig. 4 in Clark, Thomas E., et al. “Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten.” *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

- R_s uniformity a complex function of the process variables

Tensile Stress

Image removed due to copyright restrictions. Please see Fig. 5 in Clark, Thomas E., et al. "Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten." *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

- Stress most sensitive to temperature
- Observations of delamination set a limit for 1 μm thick films of 17 x 10^9 dyn/cm^2

Step Coverage

Image removed due to copyright restrictions. Please see Fig. 6 in Clark, Thomas E., et al. "Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten." *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

- Depends on all four factors

Process Optimization

Image removed due to copyright restrictions. Please see Table V in Clark, Thomas E., et al. “Response Surface Modeling of High Pressure Chemical Vapor Deposited Blanket Tungsten.” *Journal of Vacuum Science and Technology B* 9 (May/June 1991): 1478-1486.

Process Optimization, cont'd

- Constraints for deposition rate, resistivity, stress, WF_6 conversion, and reflectance do not greatly reduce factor space
- Criteria for R_S uniformity and for step coverage *do* constrain the space
  - step >95% implies WF_6 pressure to >1.5 Torr, H_2 pressure to <18 Torr, and spacing to <400 mils
  - R_S < 3% further restricts showhead spacing to between 300 and 400 mils
- Paper does not disclose process conditions at stated "optimum"

Exploratory Analysis

- Become knowledgeable with at least one statistics package
  - Excel: weak
  - Matlab: statistics/doe package pretty good
    - integrates well with additional modeling and optimization tools
  - JMP: good interactive analysis tool
  - Splus: extremely powerful, but harder to learn

Additional Ideas/Suggestions?

- What additional analyses or uses of this data might you suggest?