Models for Pattern Dependencies: Capturing Effects in Oxide, STI, and Copper CMP

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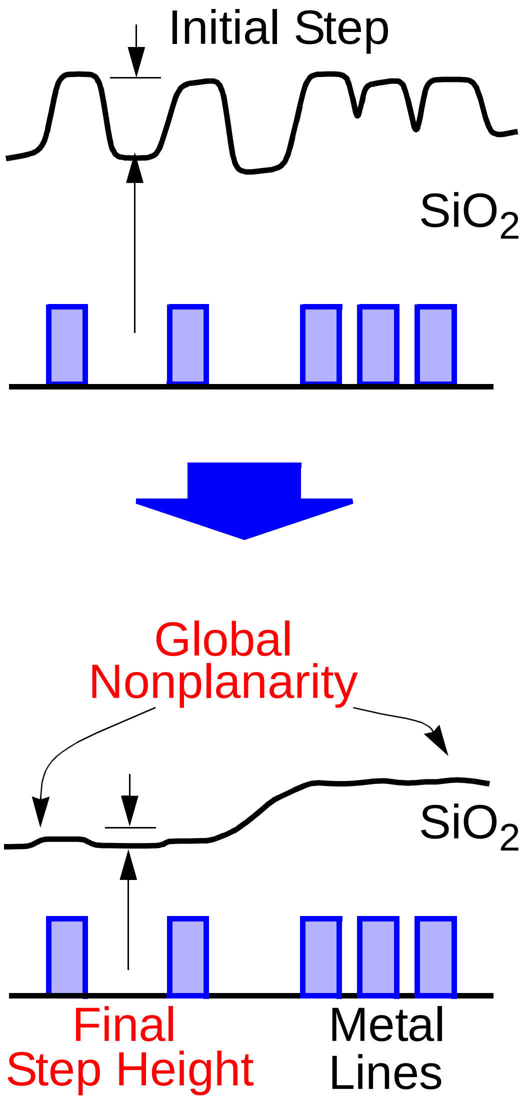
Outline

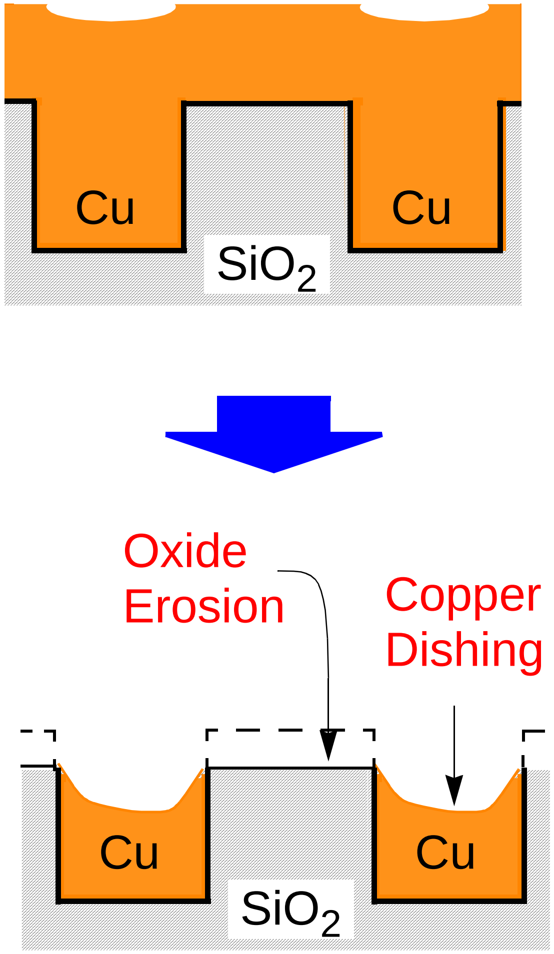
- Motivation: Pattern Dependencies in Oxide, STI, and Metal Polishing
- Pattern Effects and Models
  1. Pattern density: planarization length and density averaging
  2. Deposition profile: lateral bias of layout for conformal/HDP deposition
  3. Step height: local feature contact height and rate vs. height dependence
  4. Nanotopography: contact wear model for film thinning
  5. Dual material selectivity: extensions to density/step-height model
  6. Initial plating topography: integrated contact wear & density/step-height
  7. Multilevel copper polish: integrated contact wear & density/step-height
  8. Alternative consumables - fixed abrasives: non *K*/ρ density dependence
- Current and Future Challenges

Pattern-Dependent CMP Concerns

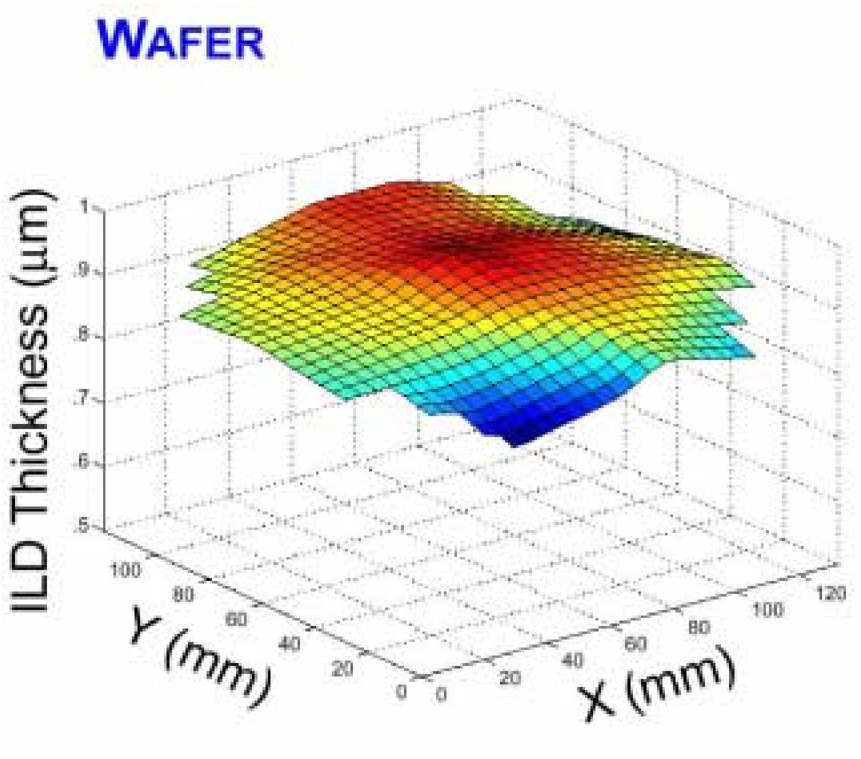
Oxide CMP:

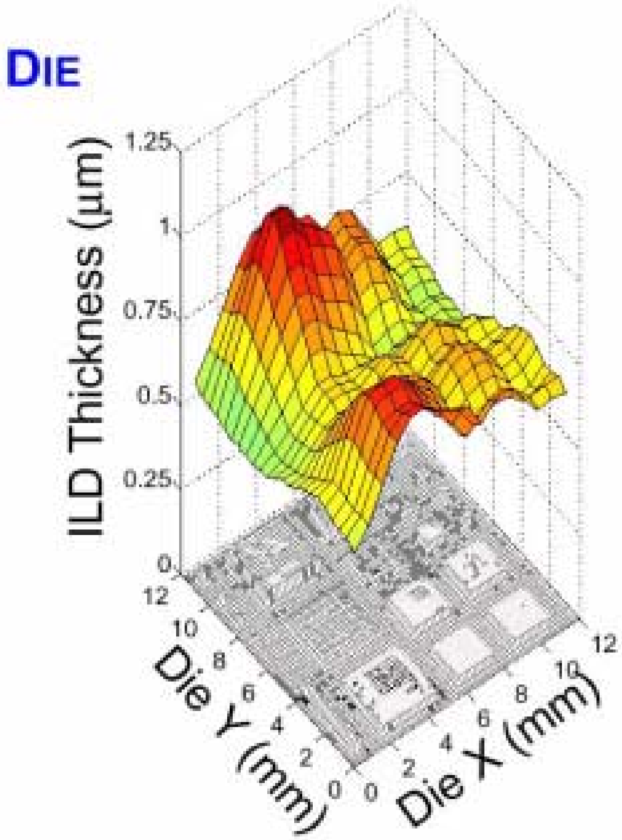


Copper CMP:



Wafer-Level vs. Die-Level CMP Modeling



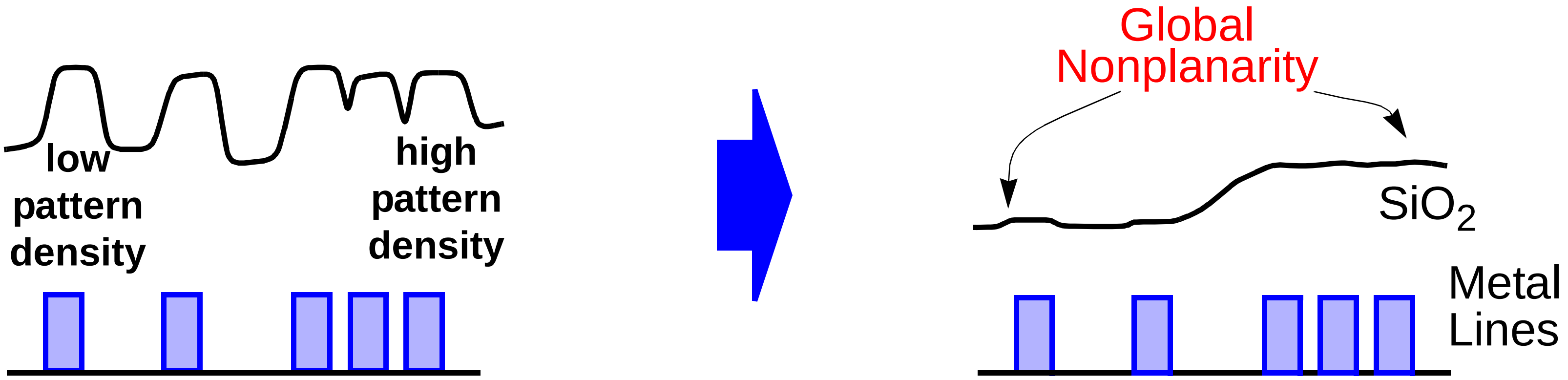


- **Across wafer uniformity** depends on process parameters, tool design, consumable wear
- Mechanics & fluids models

- **Within die uniformity** depends on layout pattern, pad/slurry, process parameters
- Chip and feature-scale models

1. Pattern Density Effects

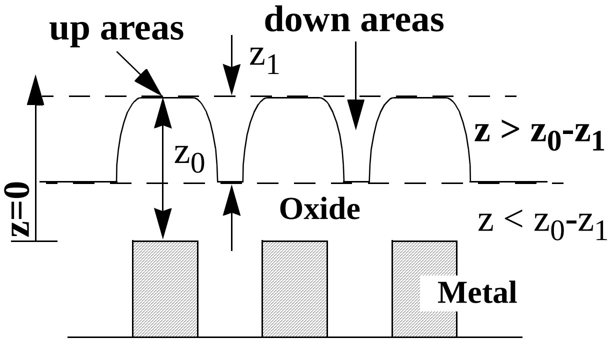
- Basic Idea: up area removal depends on area fraction (pattern density):



1. Polish rate at each location on the die is inversely proportional to the effective pattern density
2. Effective pattern density at each point depends on the nearby topography and layout density
3. The effective pattern density can be determined by averaging over a planarization length (or planarization window)
4. The planarization length must be characterized or extracted for a given CMP consumable set and process

Stine et al., CMPMIC ‘97

Oxide CMP Pattern Dependent Model (Stine et al. ‘97)



- Removal rate inversely proportional to density

$$\frac{dz}{dt} = -k_p p v = -\frac{K}{\rho(x, y)}$$

- Density assumed constant (equal to pattern) until local step has been removed:

$$\rho(x, y, z) = \begin{cases} \rho_0(x, y) & z > z_0 - z_1 \\ 1 & z < z_0 - z_1 \end{cases}$$

- Final oxide thickness related to effective density:

$$z = \begin{cases} z_0 - \left(\frac{Kt}{\rho_0(x, y)}\right) & Kt < \rho_0 z_1 \\ z_0 - z_1 - Kt + \rho_0(x, y) z_1 & Kt > \rho_0 z_1 \end{cases}$$

z = final oxide thickness over metal features

K = blanket oxide removal rate for a die of interest

t = polish time

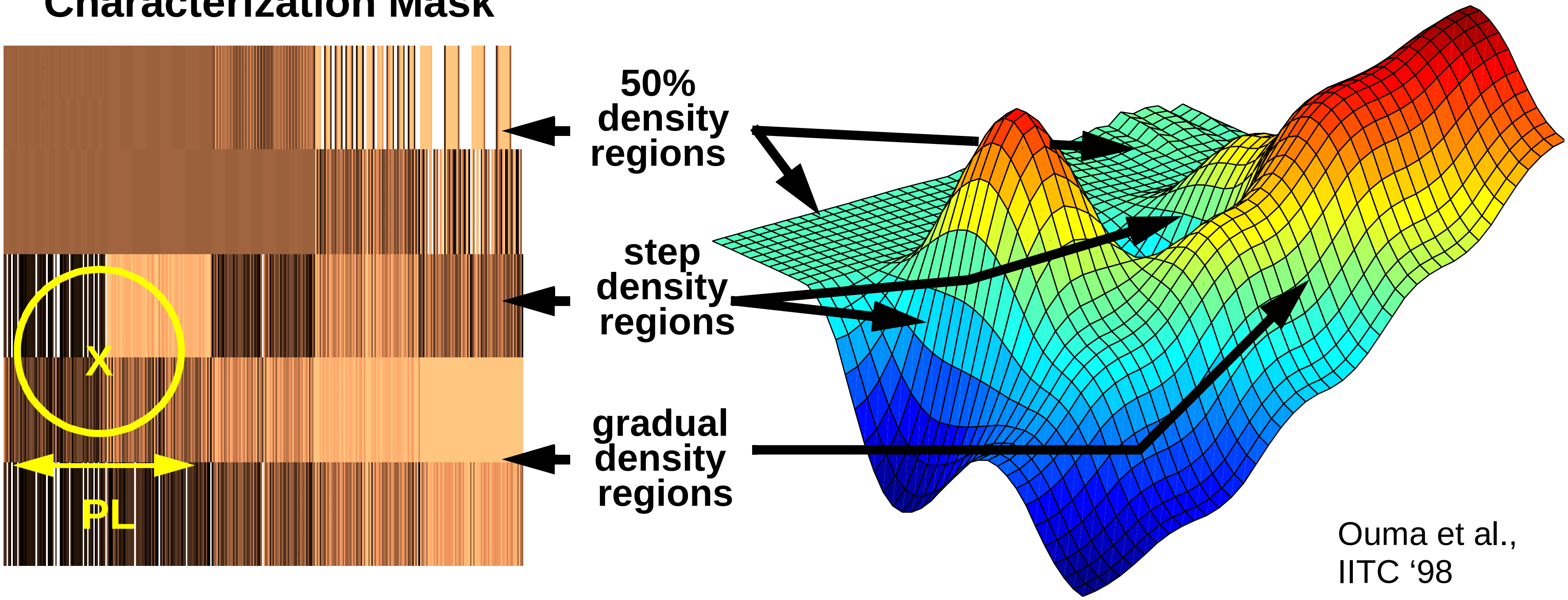
ρ_0 = local pattern density

- Evaluation of pattern density $\rho_0(x, y)$ is key to model development

Effective Density Calculation and Planarization Length Extraction

MIT Integrated Dielectric Characterization Mask

Post-CMP Oxide Thickness (Up Areas)



50% density regions

step density regions

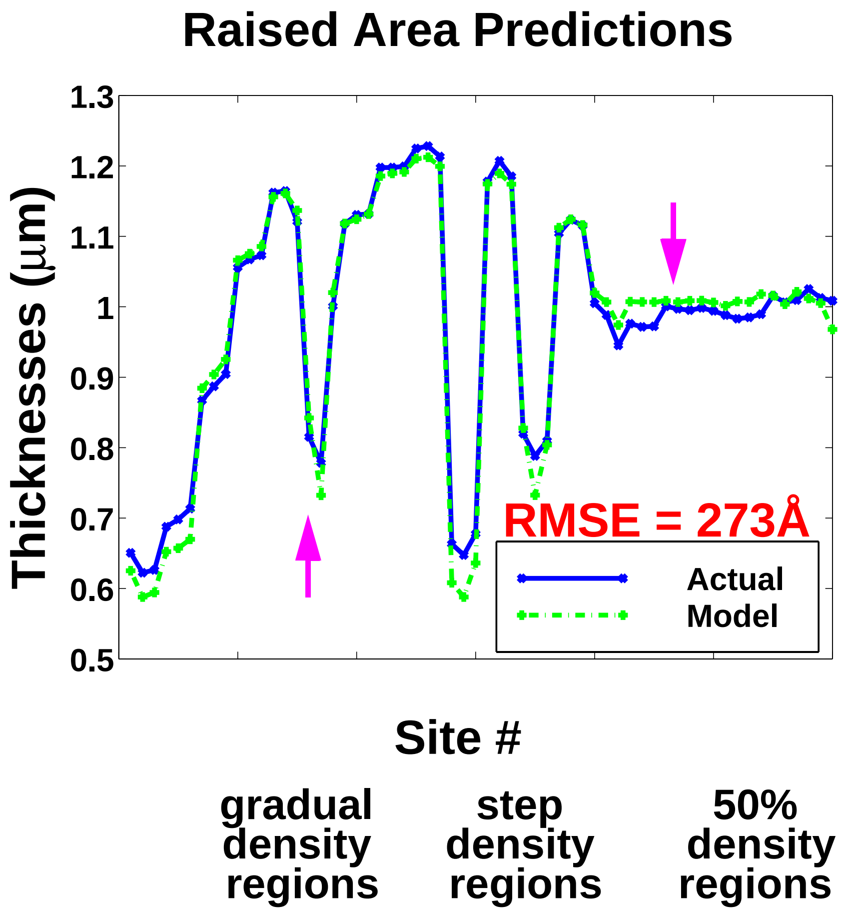
gradual density regions

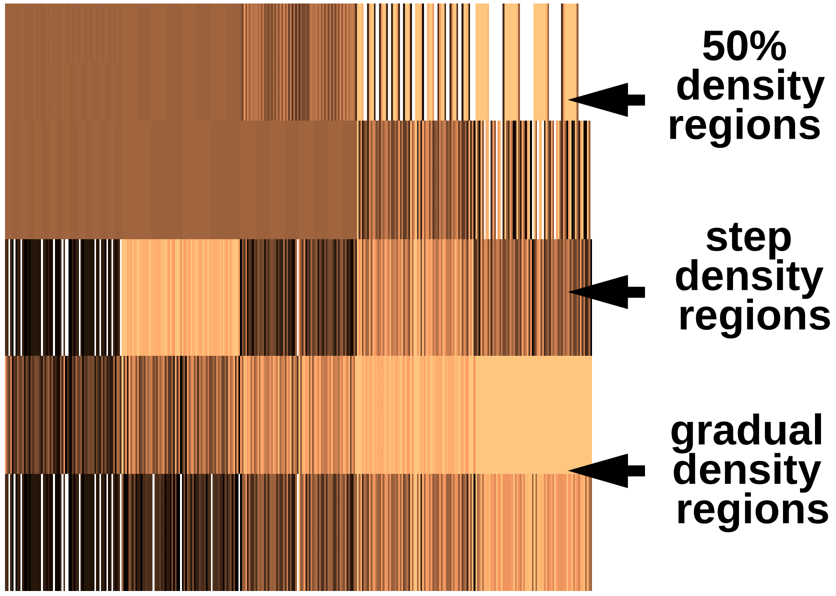
Ouma et al., IITC ‘98

- Use circular weighted window (based on deformation of an elastic material) to calculate average or effective density ρ for each point on die
- Effective density determines polish rate: $RR = \dfrac{K}{\rho(x, y, PL)}$

Example: Post-Oxide Polish Thickness Prediction

- Density dependent model applied to “up” (over metal) oxide thickness resulting from oxide CMP:

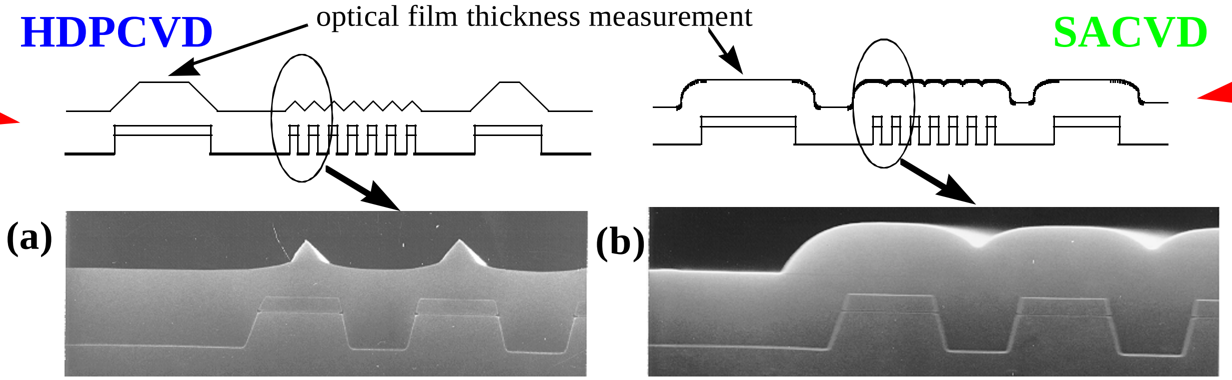




Smith et al.,
CMP-MIC ‘99

2. Deposition Profile Effects

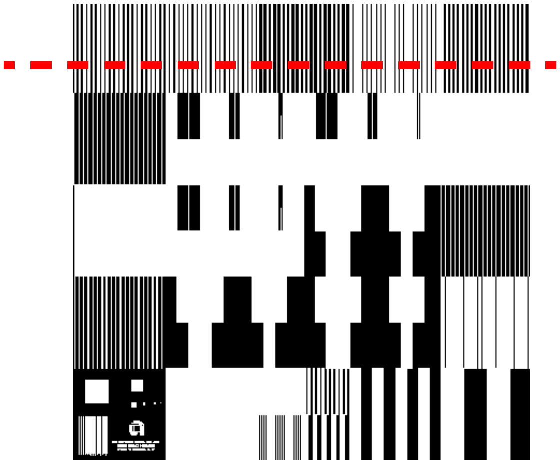
- Oxide topography is critical (especially for STI CMP)

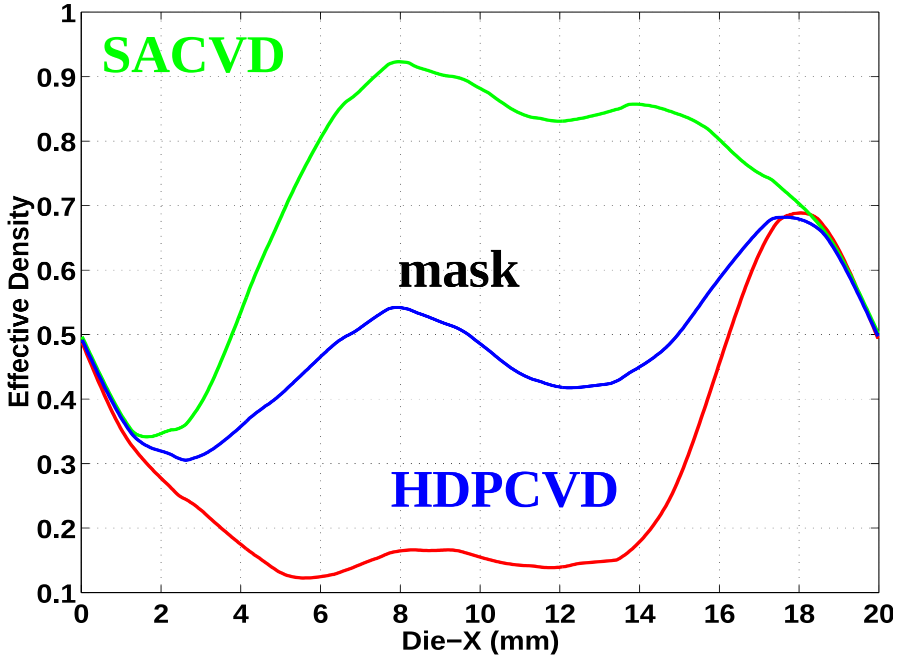


Negative Lateral Bias

Positive Lateral Bias

- Effective density model for oxide polish

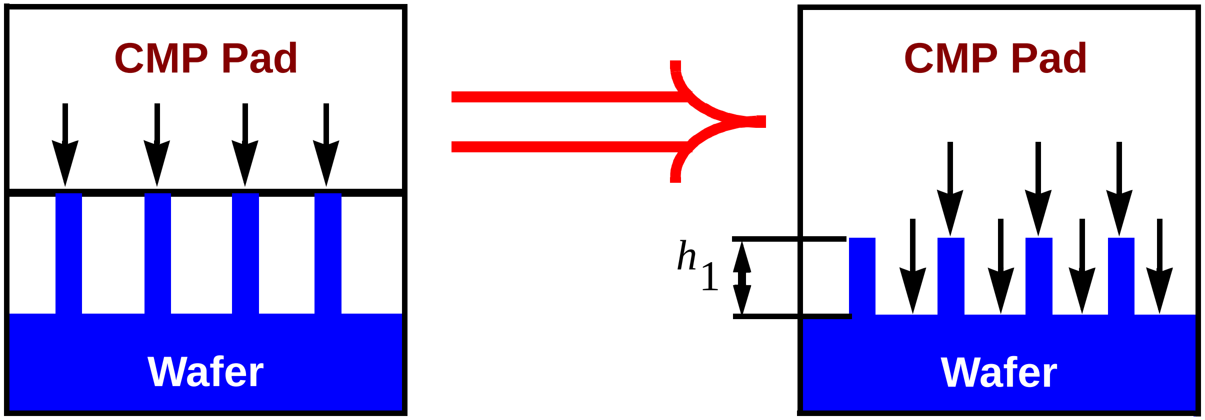




T. Pan et al., VMIC ‘98

3. Step Height Dependent Effects

- Incompressible Pad Model:
  - ❑ Up area removal rate scaled by density (e.g. MIT density model)
- Compressible Pad Model:
  - ❑ Up area removal rate proportional to step height (Burke, Tseng, others)
- Transition from incompressible to compressible pad model (Grillaert et al. - IMEC)
  - ❑ Occurs at contact height h_c or contact time t_c where $h_c = h_0 - \left(t_c \cdot \frac{K}{\rho}\right)$

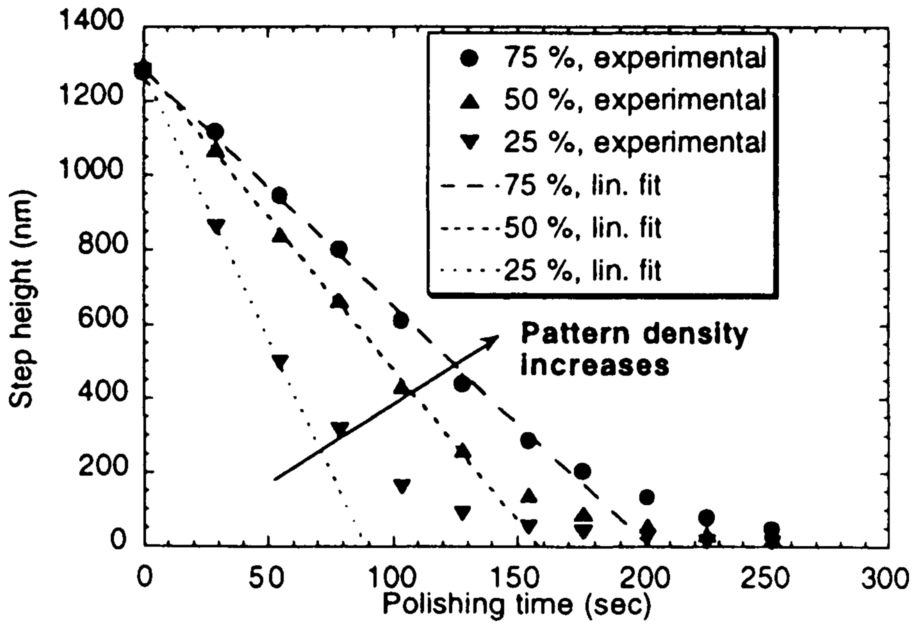


Incompressible Pad Model

Compressible Pad Model

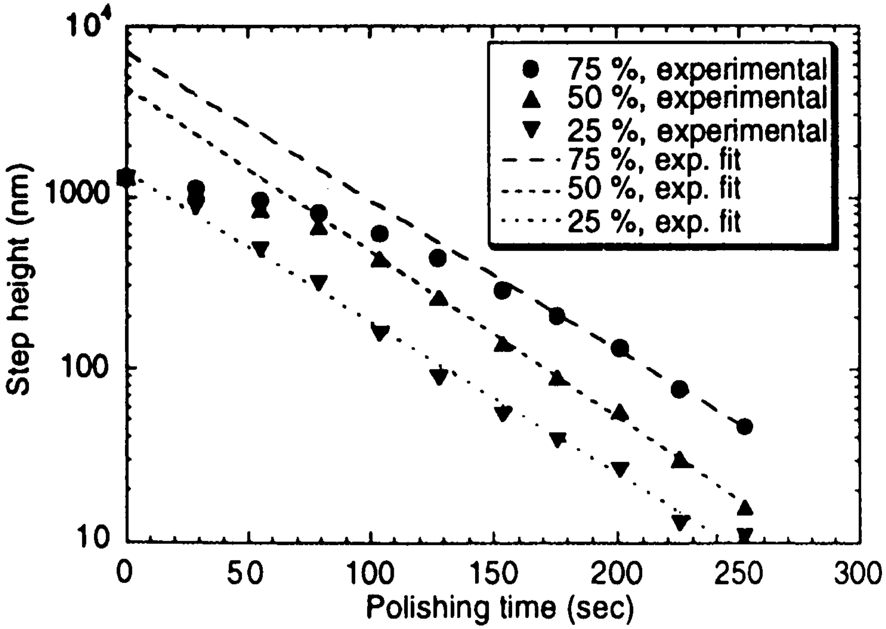
Step Height Reduction

- Large Step Heights



  - Density effect dominates
  - Step height reduction linear in time

- Small Step Heights

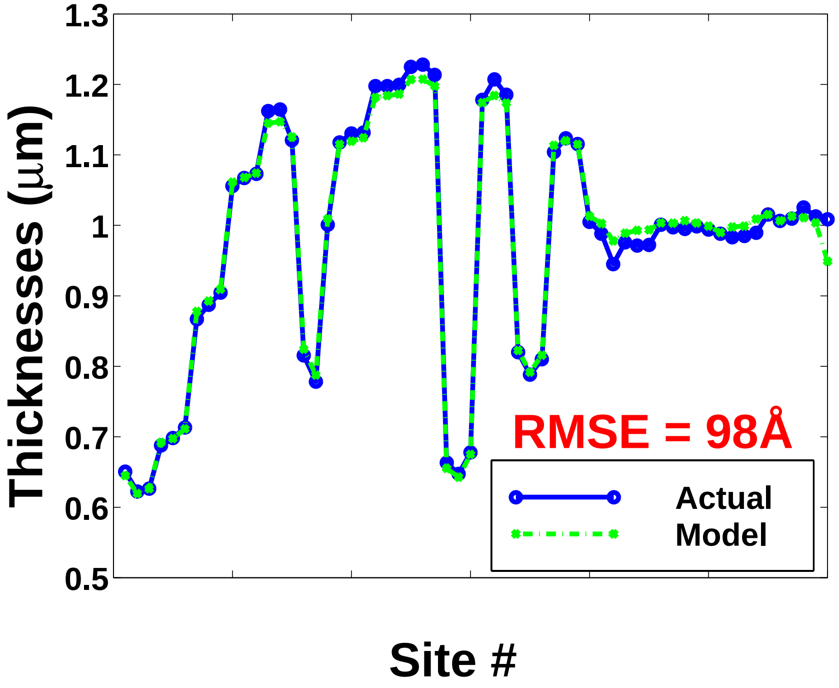


  - Up/down area pressure difference
  - Step height reduction exponential in time

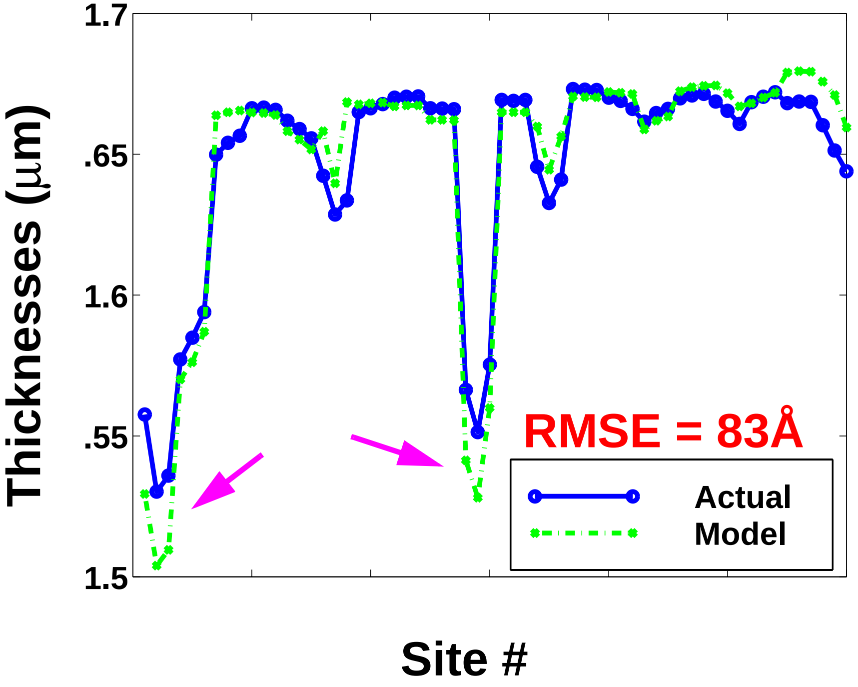
Grillaert et al., CMP-MIC '98

Results: Integrated Density/ Step Height Model

Raised Area Predictions



Down Area Predictions



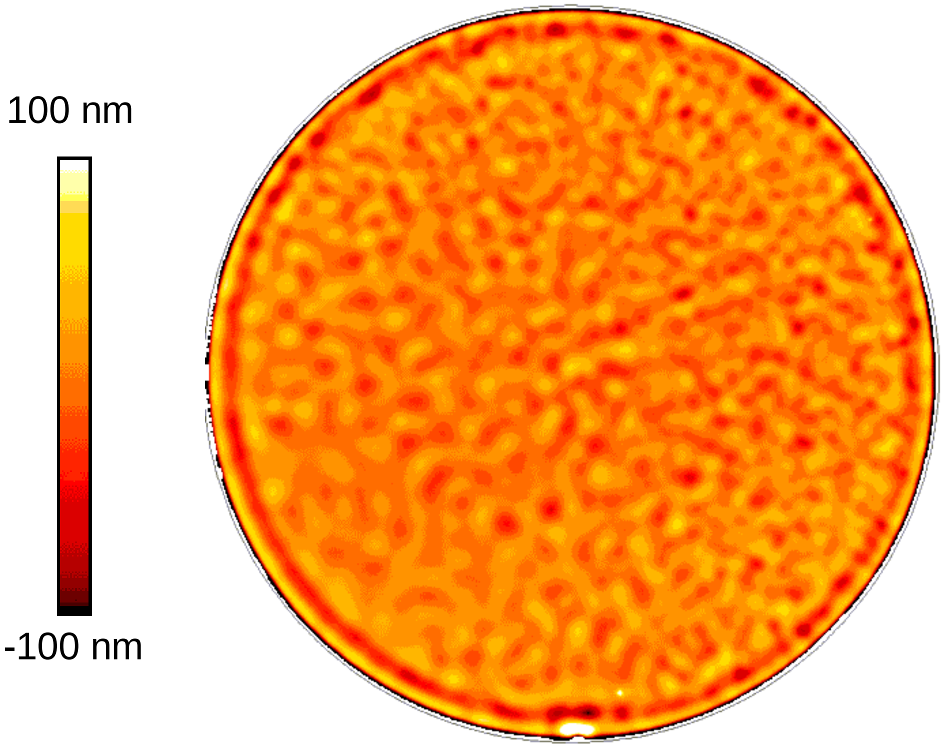
Smith et al.,
CMP-MIC '99

- Dramatically reduced errors:
  - ☐ 273 Å rms (density model) --> 98 Å RMSE (integrated model)
- Challenge:
  - ☐ Over-predicts down polish at low density: macro bending limit?

4. Wafer Nanotopography Effects

“Nanotopography” refers to wafer surface variations with:

1. Lateral length scales from 0.2 mm to 20 mm
2. Height variations ~ 10 to 100 nm

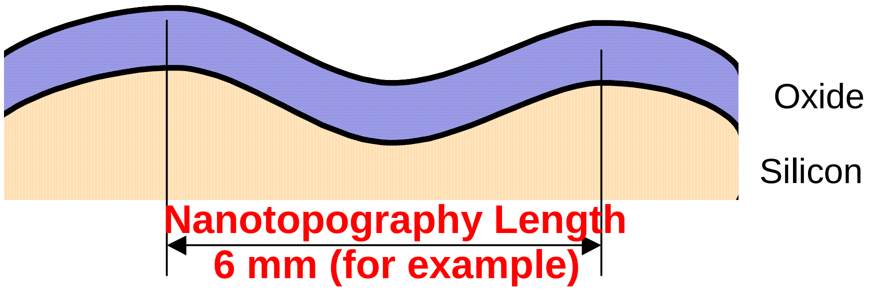


**Nanotopography Map:
8” SSP Silicon Epi Wafer**

Filtered data measured using a NanoMapper™ production nanotopography tool at ADE Phase Shift in Tucson, AZ

Nanotopography vs. Planarization Length

Given nanotopography variations on some length scale...

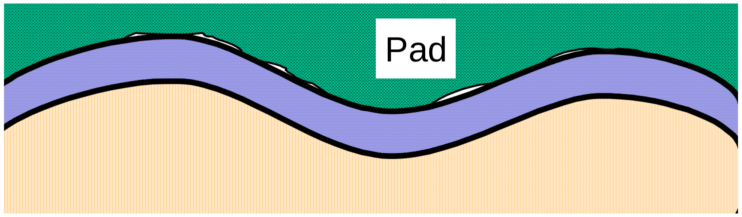


What happens during CMP?

CMP

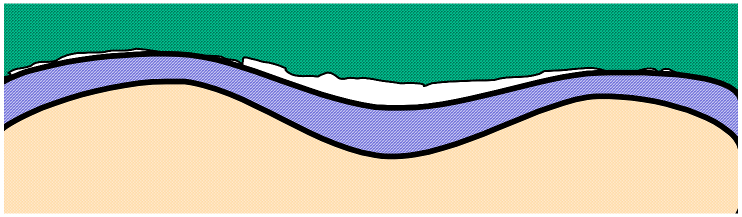
"Soft" Pad CMP Process

Planarization Length ~ 3-4mm



"Stiff" ("Hard") Pad CMP Process

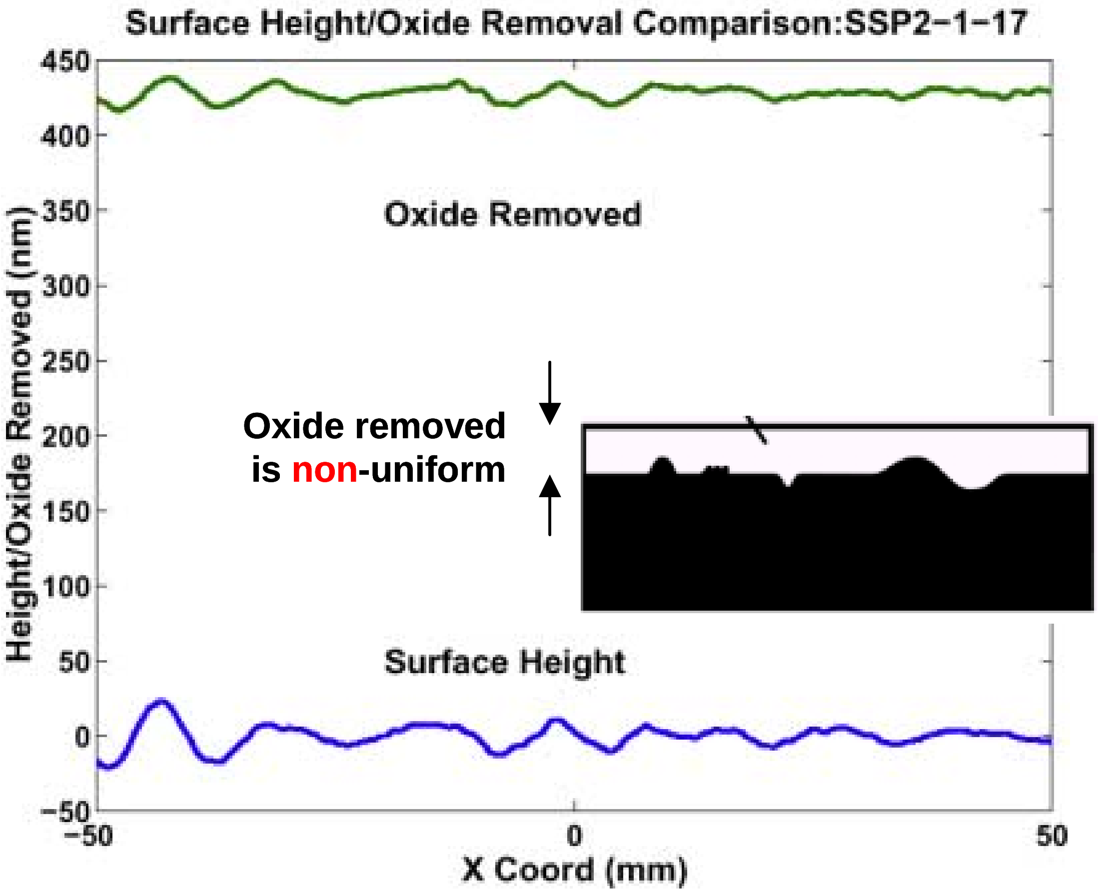
Planarization Length ~ 7-10 mm



- pad conforms around nanotopography variations and polishes uniformly

- pad "bridges" across nanotopography down areas and preferentially thins surface films in raised nanotopography areas

Example: Short NL and Long PL (Stiff Pad)



Oxide removed is non-uniform

Split Details

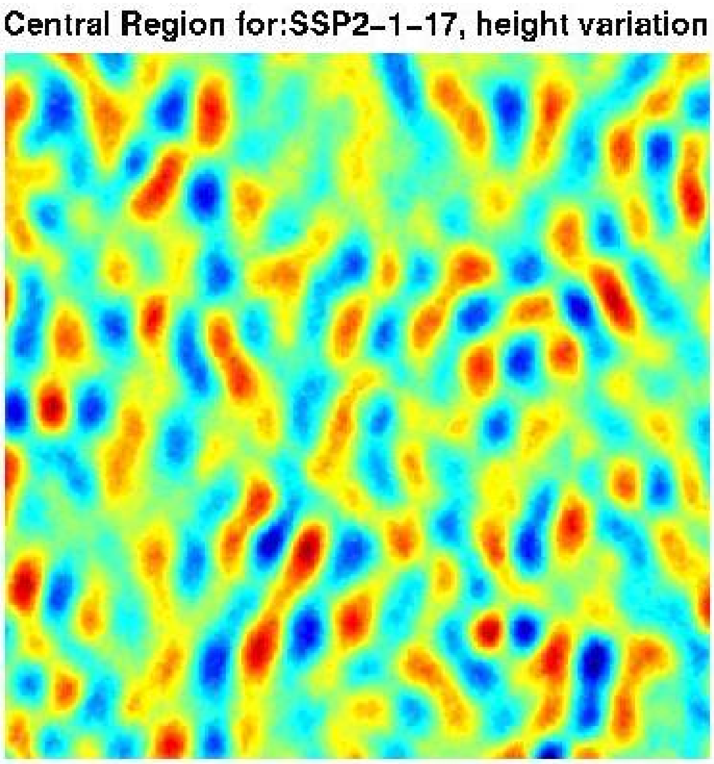
- IC1000 solo pad (8.5mm planarization length)
- SSP2 wafer (short-range nanotopography)

Result

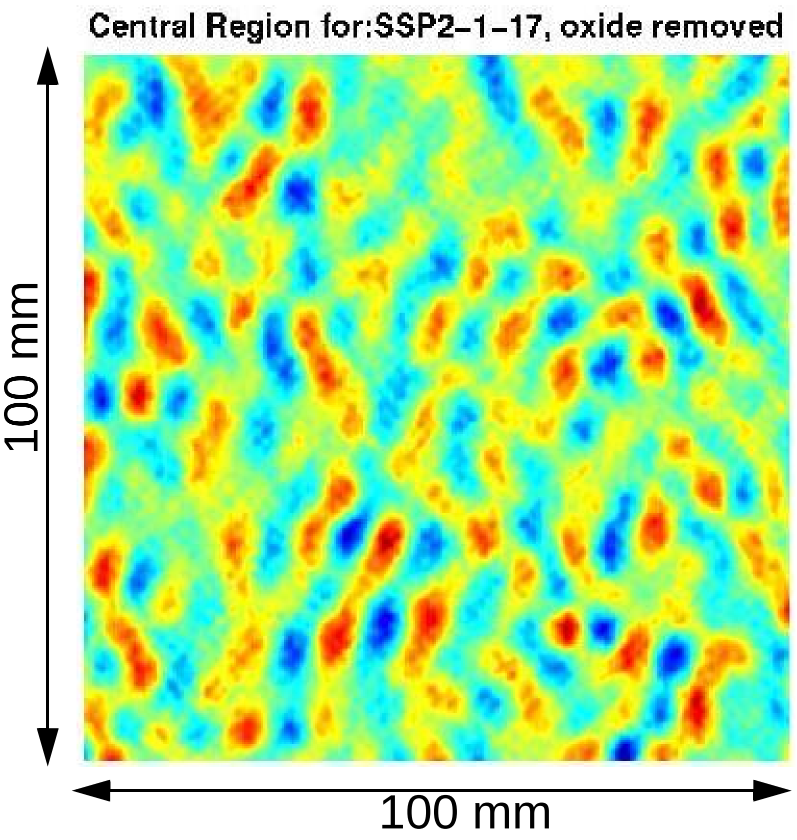
- Nanotopography *propagates* strongly into oxide film
- Filtered data used (removes wafer scale polish non-uniformity)

Short NL and Long PL (Stiff Pad) - cont’d

- SSP2 wafer; IC1000 solo pad, process has PL = 8.5 mm
- Variation for central 100mm portion of wafer
  - Deviation in each normalized: full range variation around each mean shown



Central Region for:SSP2-1-17, height variation



Central Region for:SSP2-1-17, oxide removed

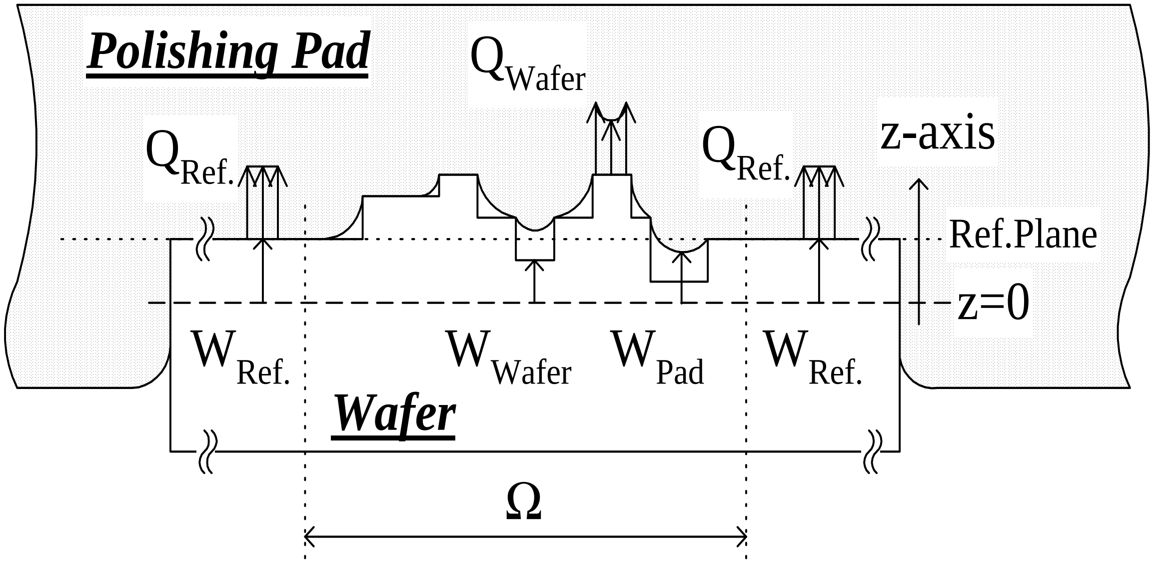
Nanotopography Modeling

- Density/Step-Height Model Difficulties:
  - ☐ Pattern Density
    - generally refers to area fraction of equal height patterned features
    - no clear definition in case of nanotopography
  - ☐ Step Height
    - in density/step-height model, the step height is a local parameter (i.e. applying to micron-scale features)
    - in nanotopography, structures with gentle (long range) step height variations

- Alternative Modeling Approach: Contact Wear
  - ☐ Goal: account for the specific configuration of nanotopography features on CMP:
    - compute effect of height differences on long-range pad pressure distributions
    - explicitly account for pad bending and pressure apportionment

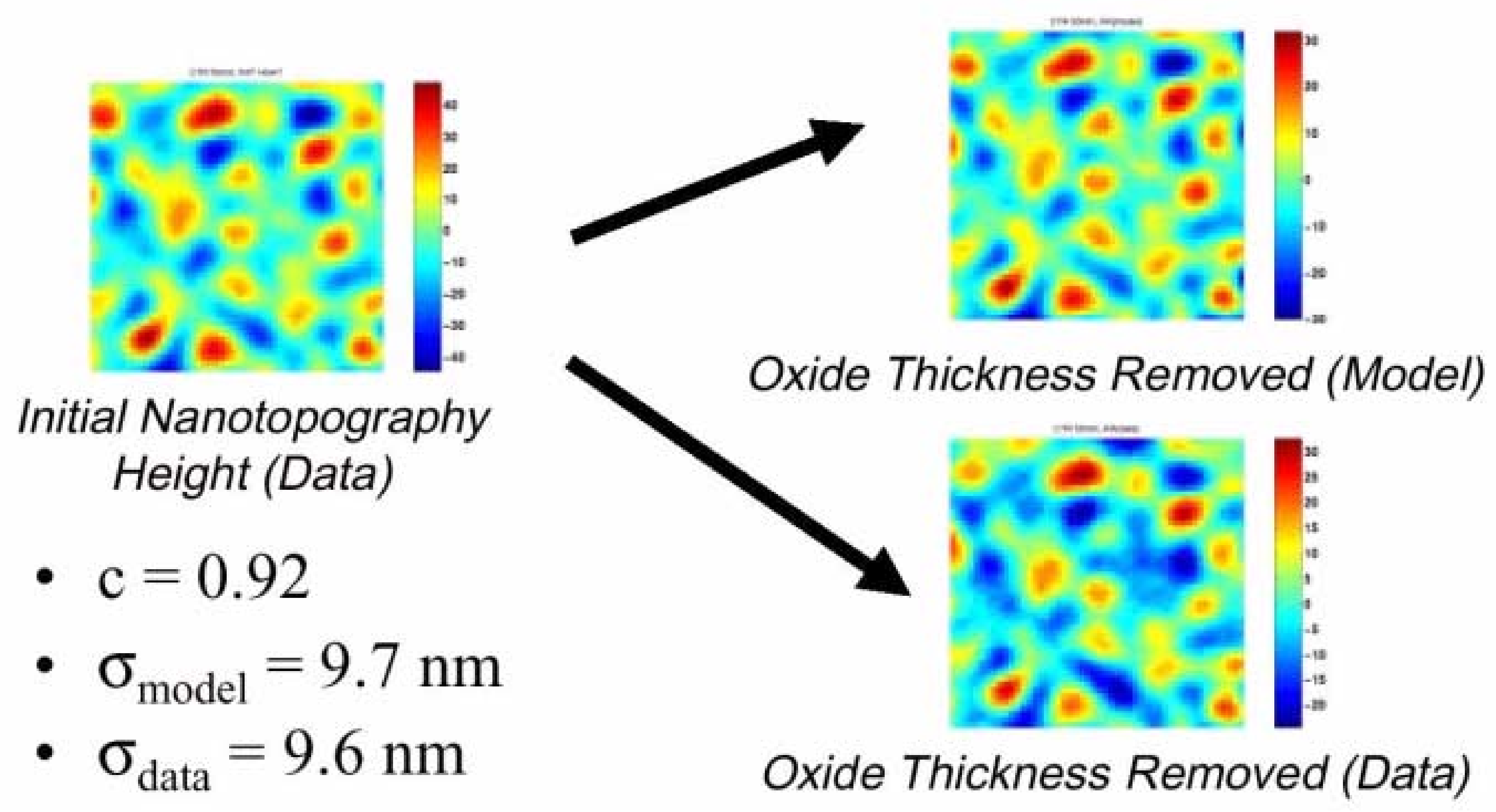
Contact Wear Model

- Treat the polishing pad as an elastic body: displacement function of load
- Discretized boundary elements are considered with boundary conditions:
  - w - localized heights/displacements
    - when pad contact wafer, q unknown, $w_{i,\,known} = W_{Ref} - W_{i,\,wafer}$
  - q - localized pressures
    - when pad not in contact, w unknown, $q_{i,\,known} = Q_{Ref}$
- Solve for pressures and displacements at each point in time, gives removal rate and advancement of the boundary element



T. Yoshida, *ECS PV 99-37*, 1999.

Results: Contact Wear Nanotopography/CMP Model



Initial Nanotopography Height (Data)

Oxide Thickness Removed (Model)

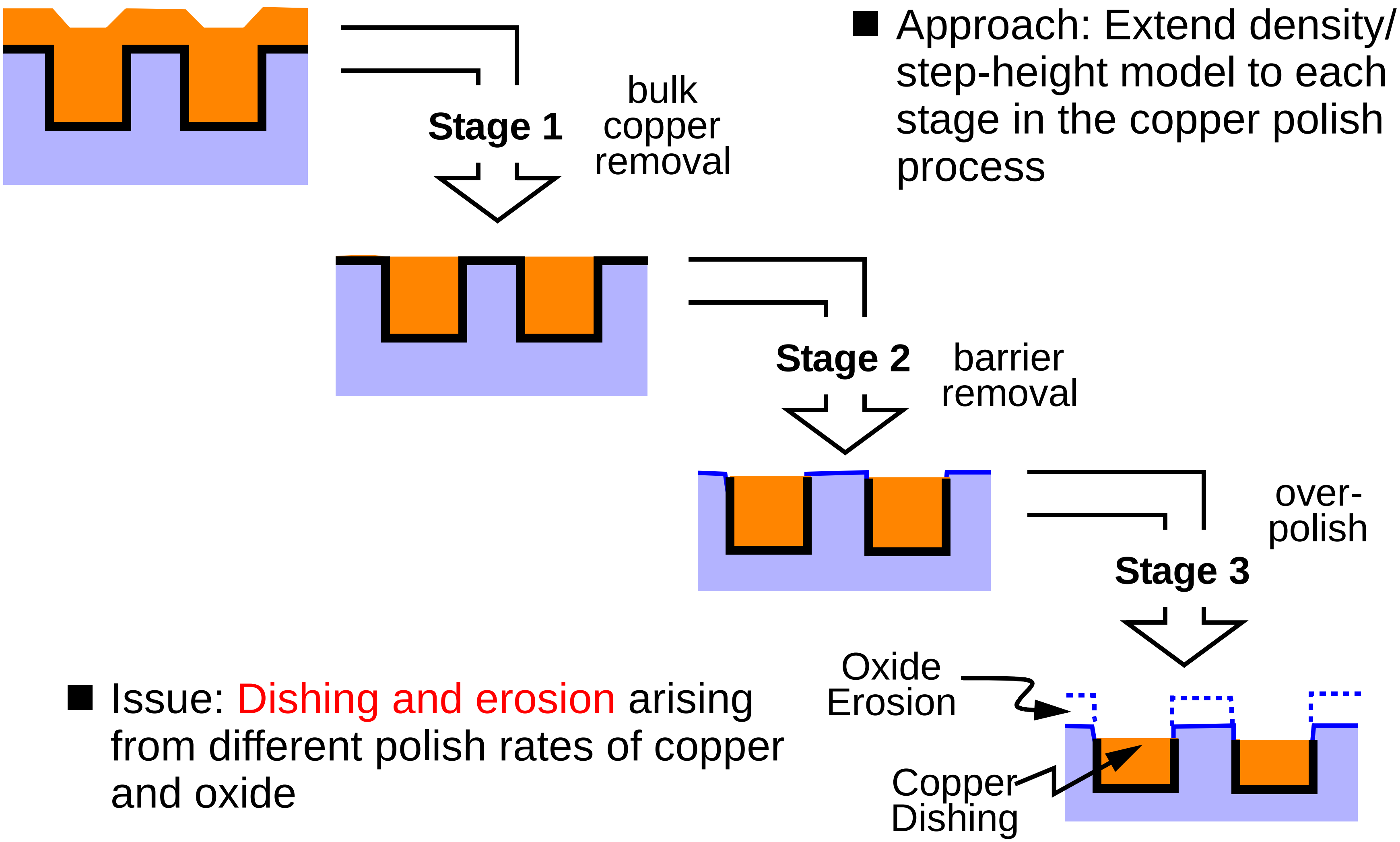
Oxide Thickness Removed (Data)

- $c = 0.92$
- $\sigma_{model} = 9.7$ nm
- $\sigma_{data} = 9.6$ nm

Lee et al., MRS 2001.

5. Copper CMP: Dual Material Polish Effects

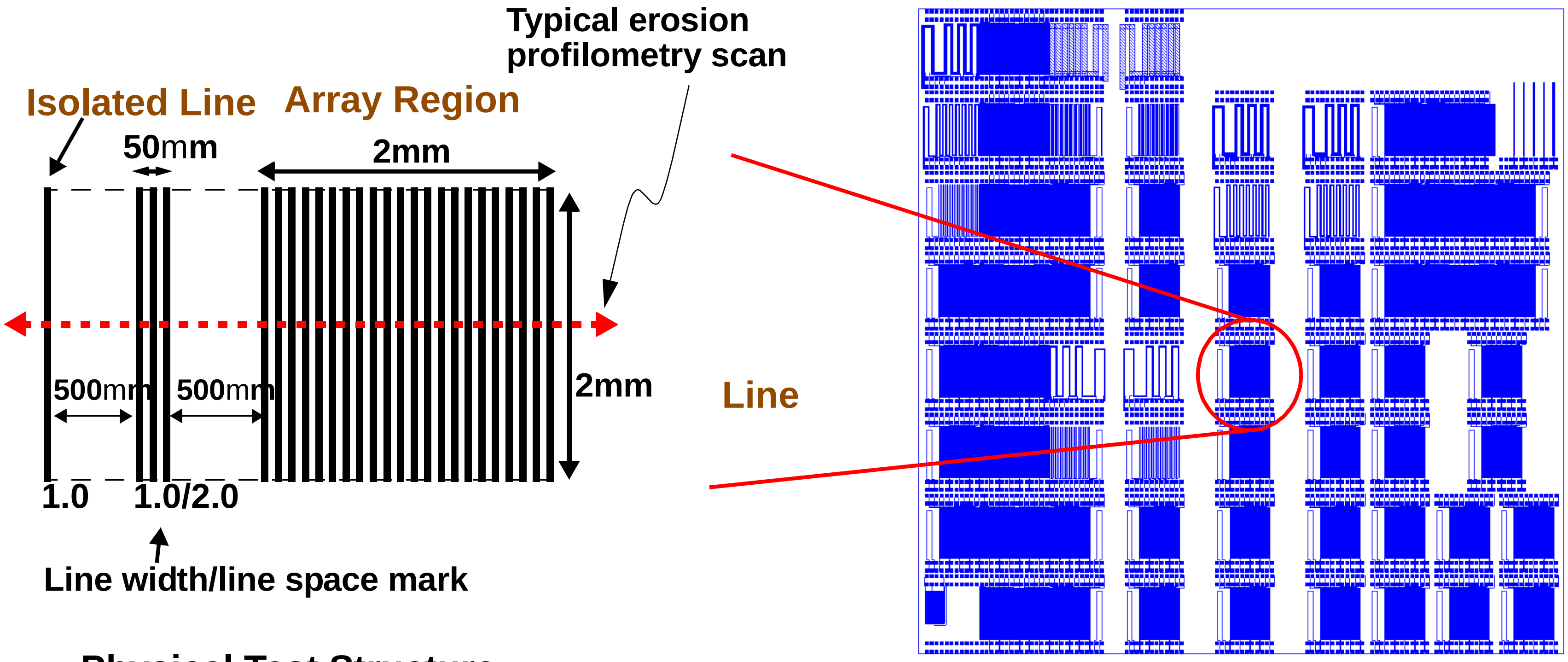
- Approach: Extend density/ step-height model to each stage in the copper polish process



- Issue: Dishing and erosion arising from different polish rates of copper and oxide

Test Structures and Test Masks: Dishing and Erosion Characterization

Metal 1

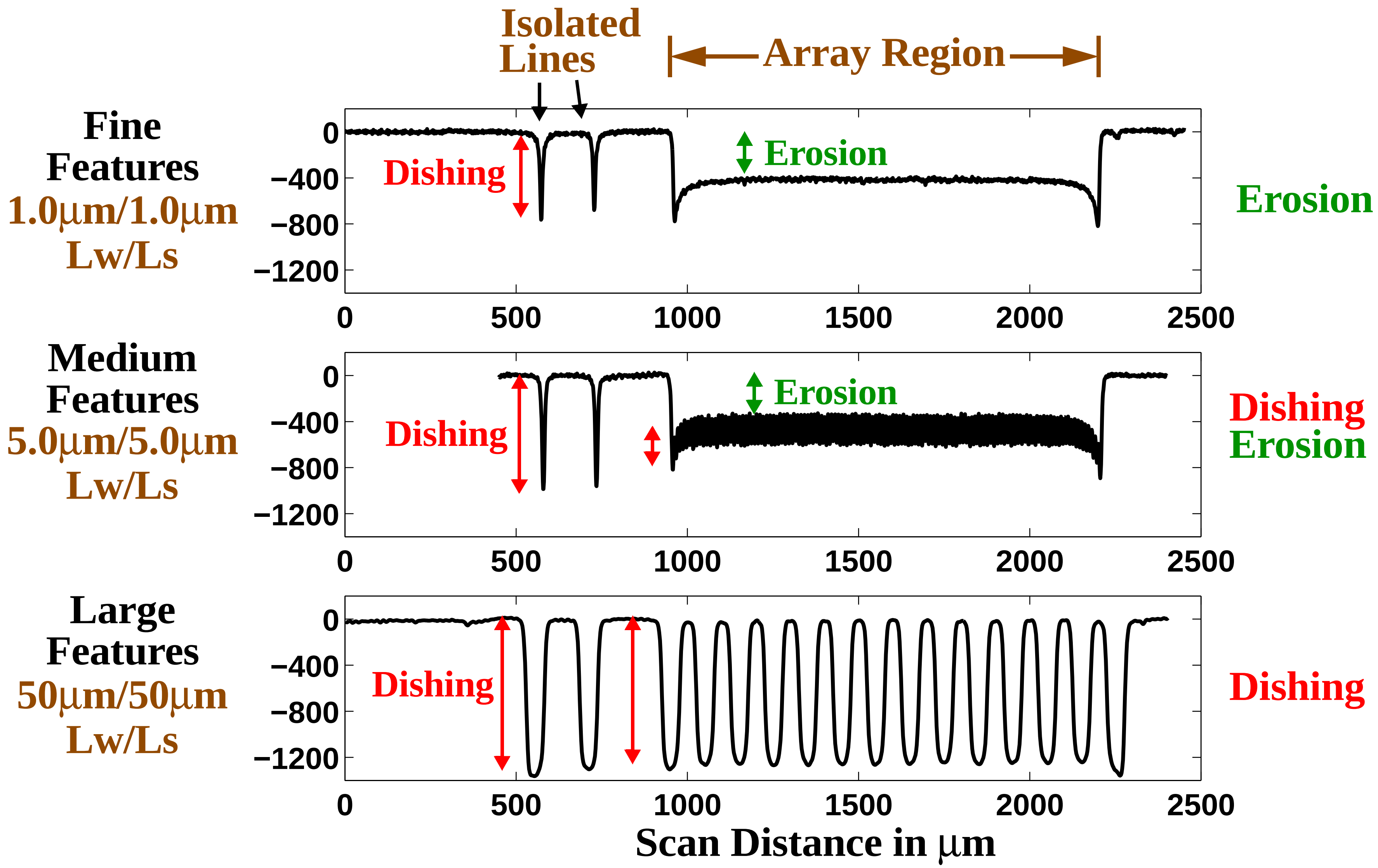


Physical Test Structure

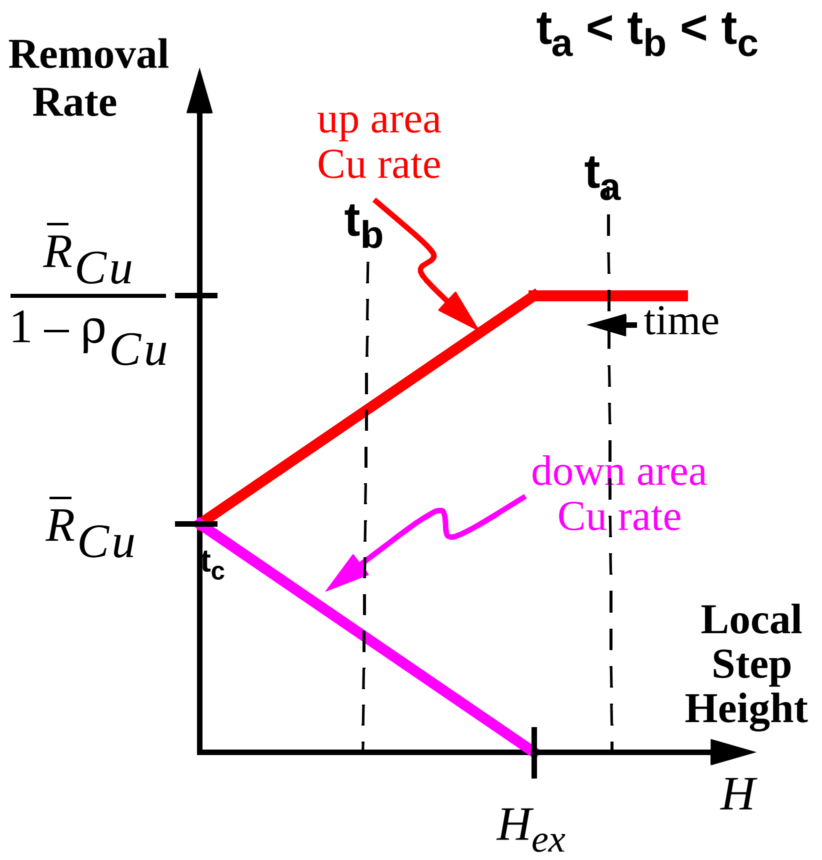
- Single level effects: Layout factors on M1 to study creation of topography
  - ❑ density
  - ❑ line width & line space combinations

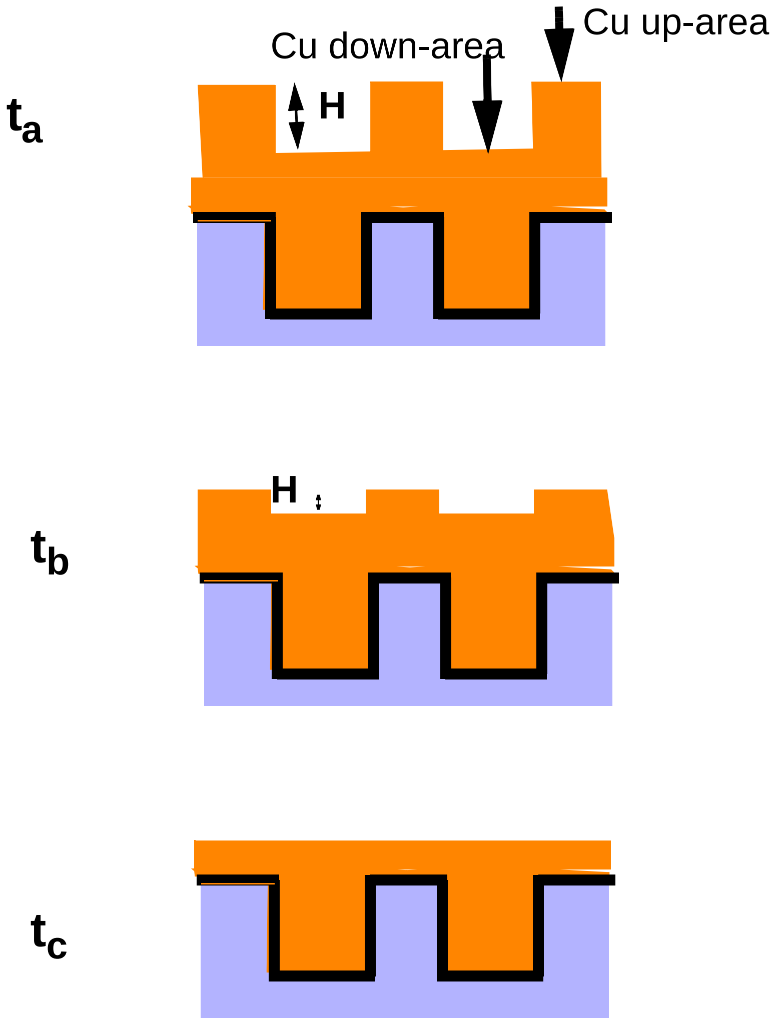
Copper Dishing and Erosion Trends

Surface Profiles (in Å)



Cu CMP Modeling --
Stage 1: Removal of Overburden Cu

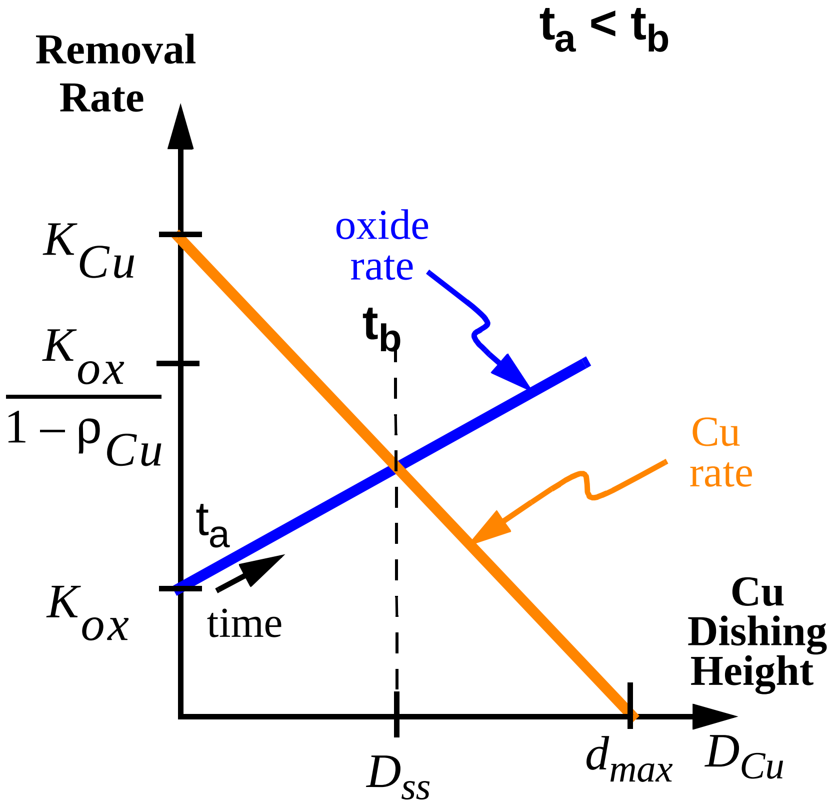


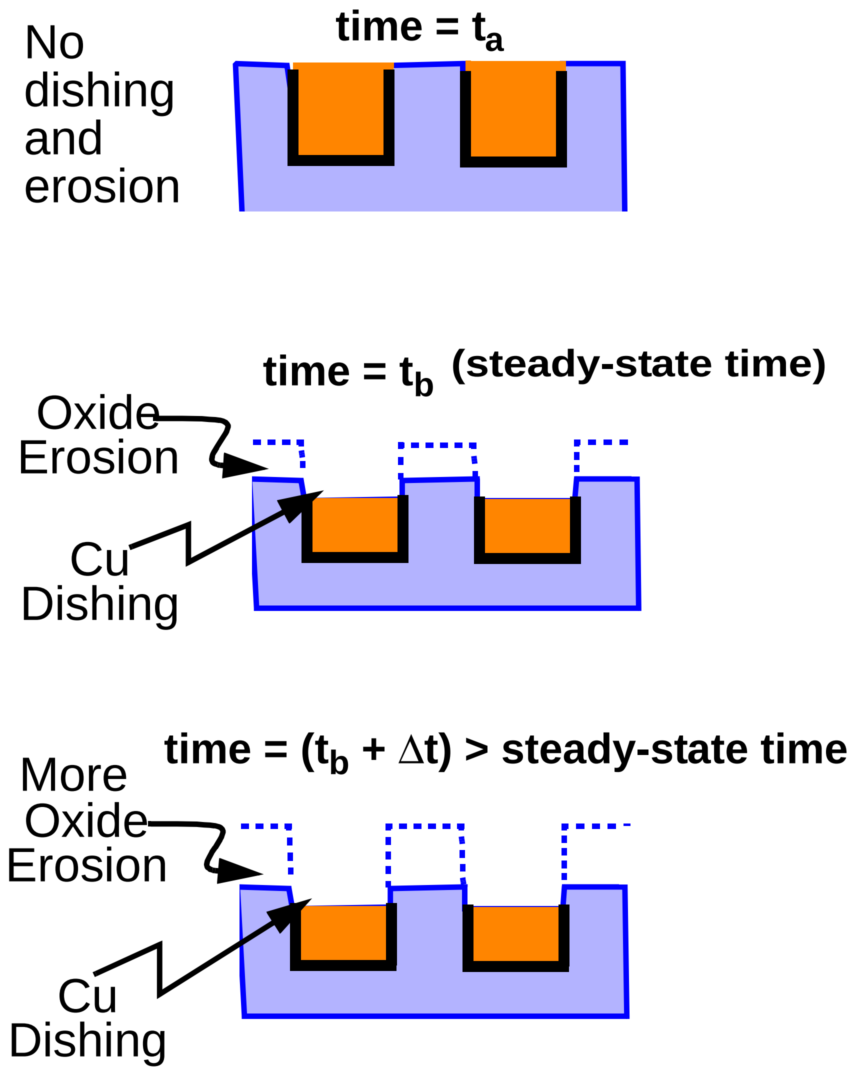


- ***H_{ex}***: Local step height above which the pad does not contact the down area.

D. Boning, MIT

Cu CMP Modeling -- Stage 3: Overpolish



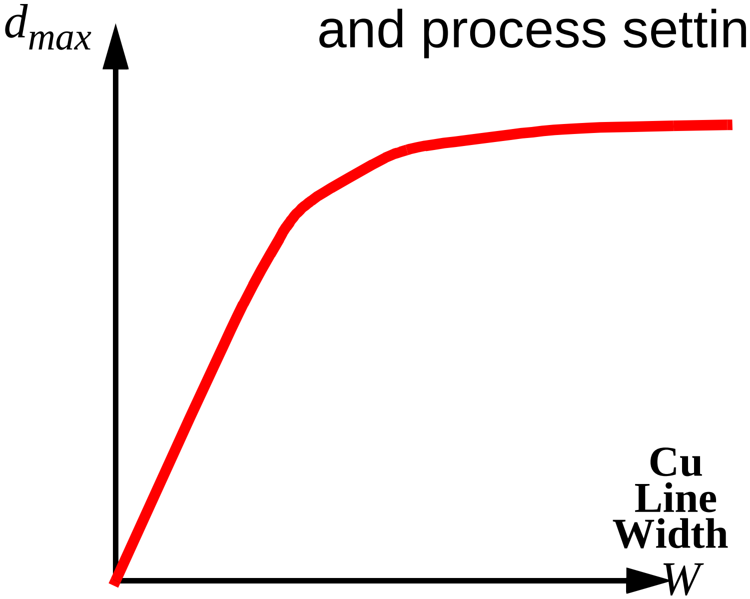


- D_{ss} is steady-state Cu dishing.
- D_{Cu} is Cu dishing.
- d_{max} is maximum Cu dishing.

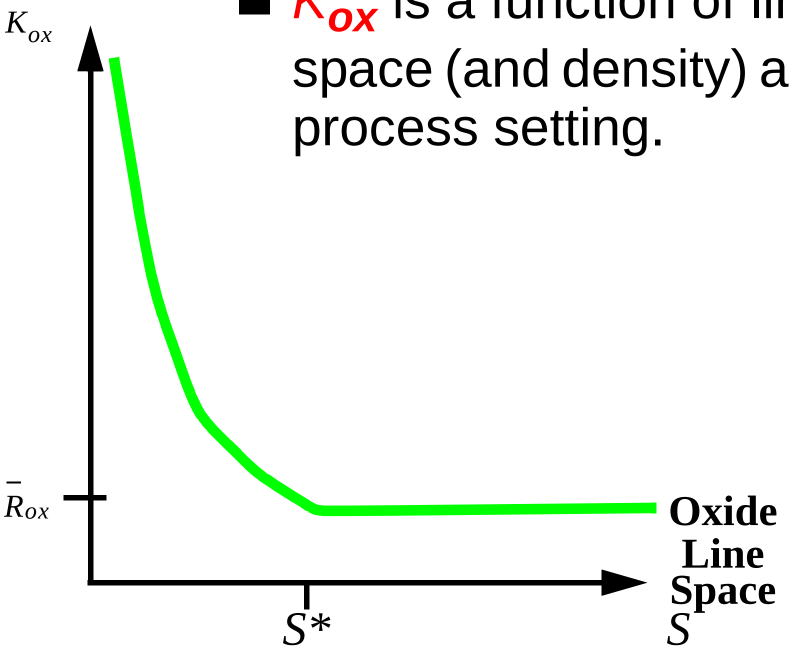
Cu CMP Model Parameters

- The model parameters (unknowns) are K_{ox}, K_{Cu}, K_b, d_{max}, and H_{ex}. These parameters depend on Cu line width or oxide line space, pattern density and process parameters (down force, table speed, slurry, pad elasticity, etc.).
- For a given process, these model parameters can be estimated from time evolution experiments done with specially designed test masks.

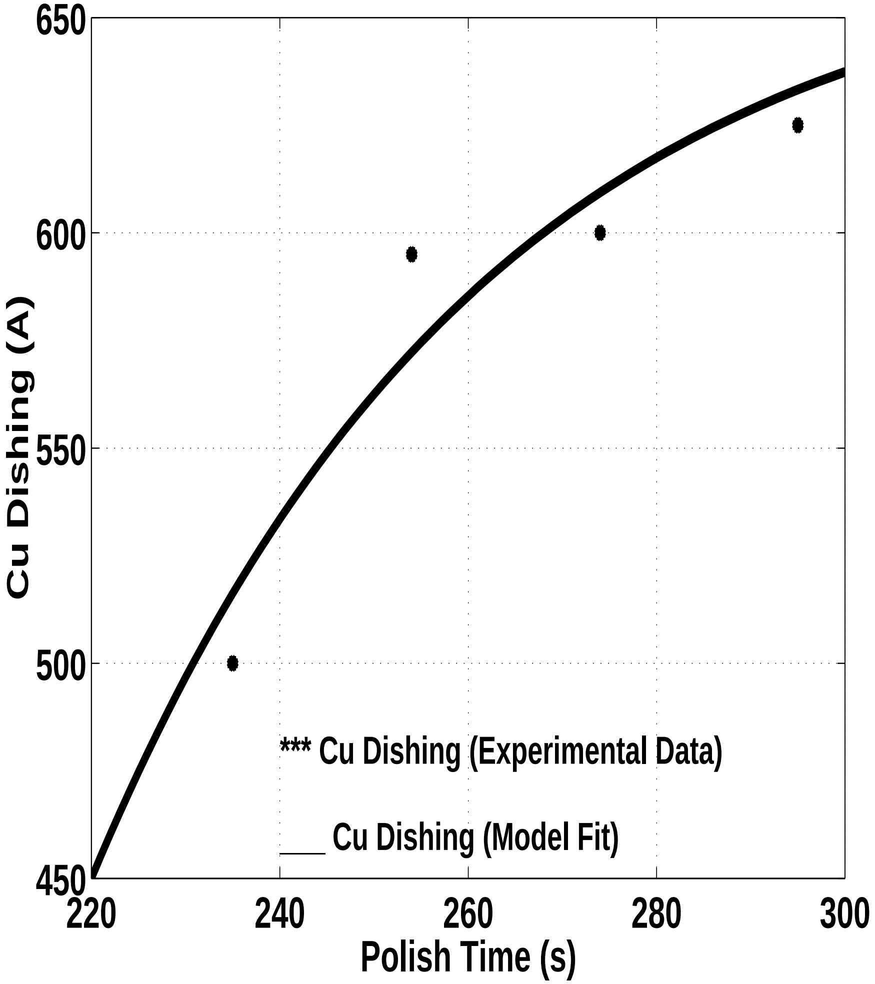
- d_{max} is a function of line width (and density) and process setting.



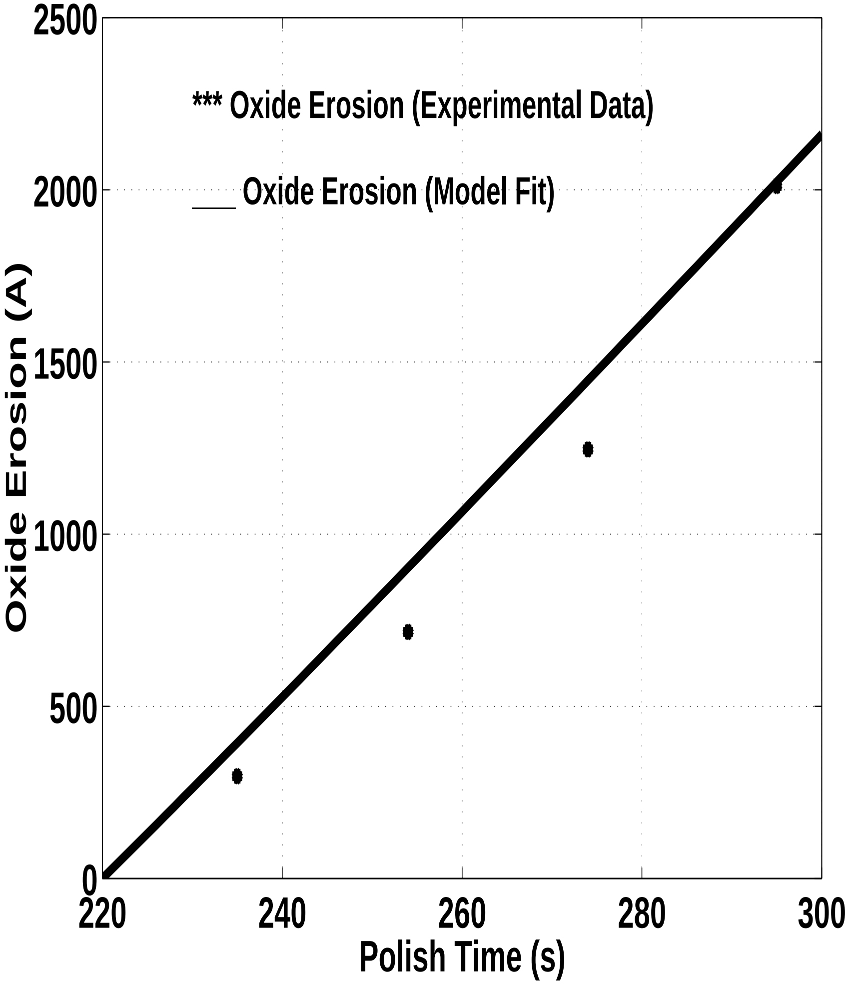
- K_{ox} is a function of line space (and density) and process setting.



Experimental Data versus Model: Cu Dishing/Erosion Time Trend

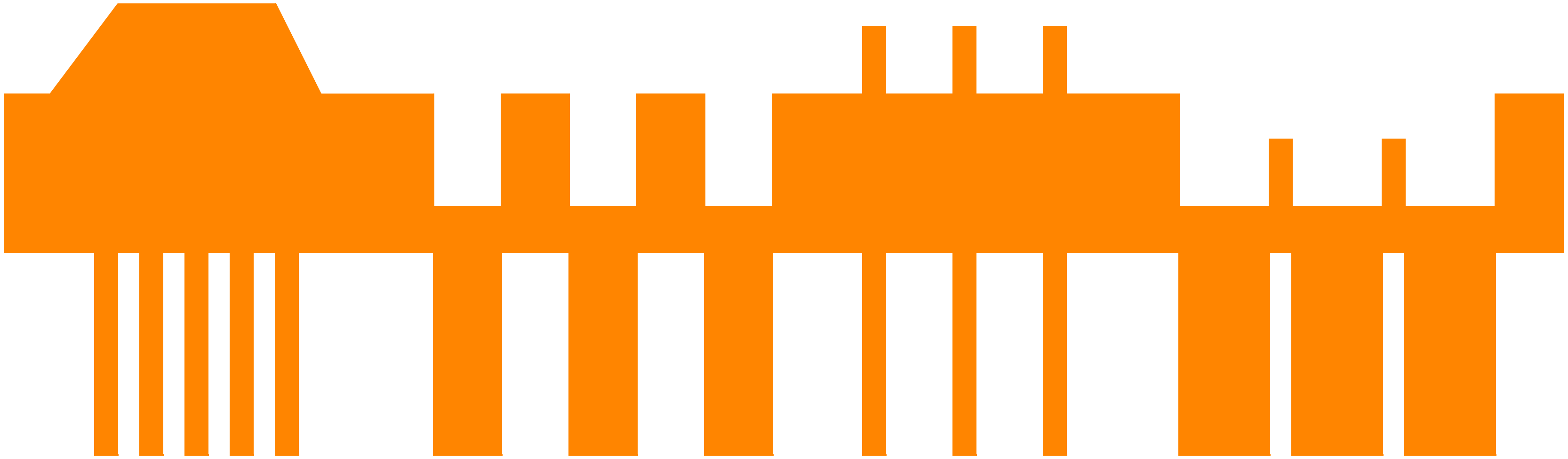


Dishing versus polish time for line width of 10 μm and density of 50%.



Erosion versus polish time for line space of 10μm and density of 50%.

6. Copper Electroplating Topography Effects



Fine features

Large features

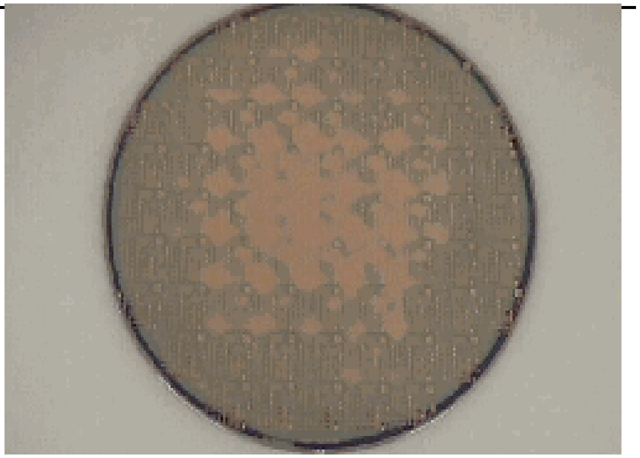
Low density (with fine lines).

High density (with fine spaces)

“BOTTOM-UP” fill plating

- Topography leads to excessive overpolish which causes:
  - Excessive metal loss (dishing plus erosion).
  - Surface non-uniformity

Tugbawa et al., MRS 2001.



Contact Wear vs. Density/Step-Height

- Density/Step-Height Model
    - Excellent for local effect prediction
    - Does not take into account global step-heights

- Contact Wear Model
    - Excellent for long-range pressure apportionment
    - Computationally prohibitive if discretization is down to the feature level

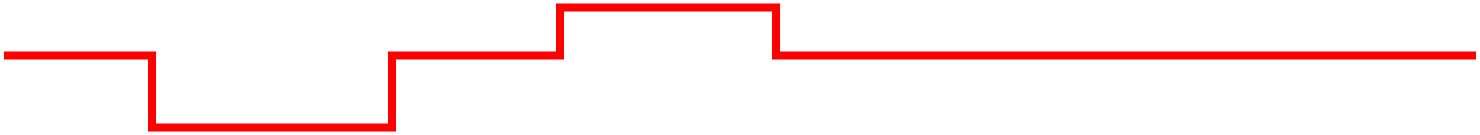
INTEGRATED MODEL

Tugbawa et al., MRS 2001.

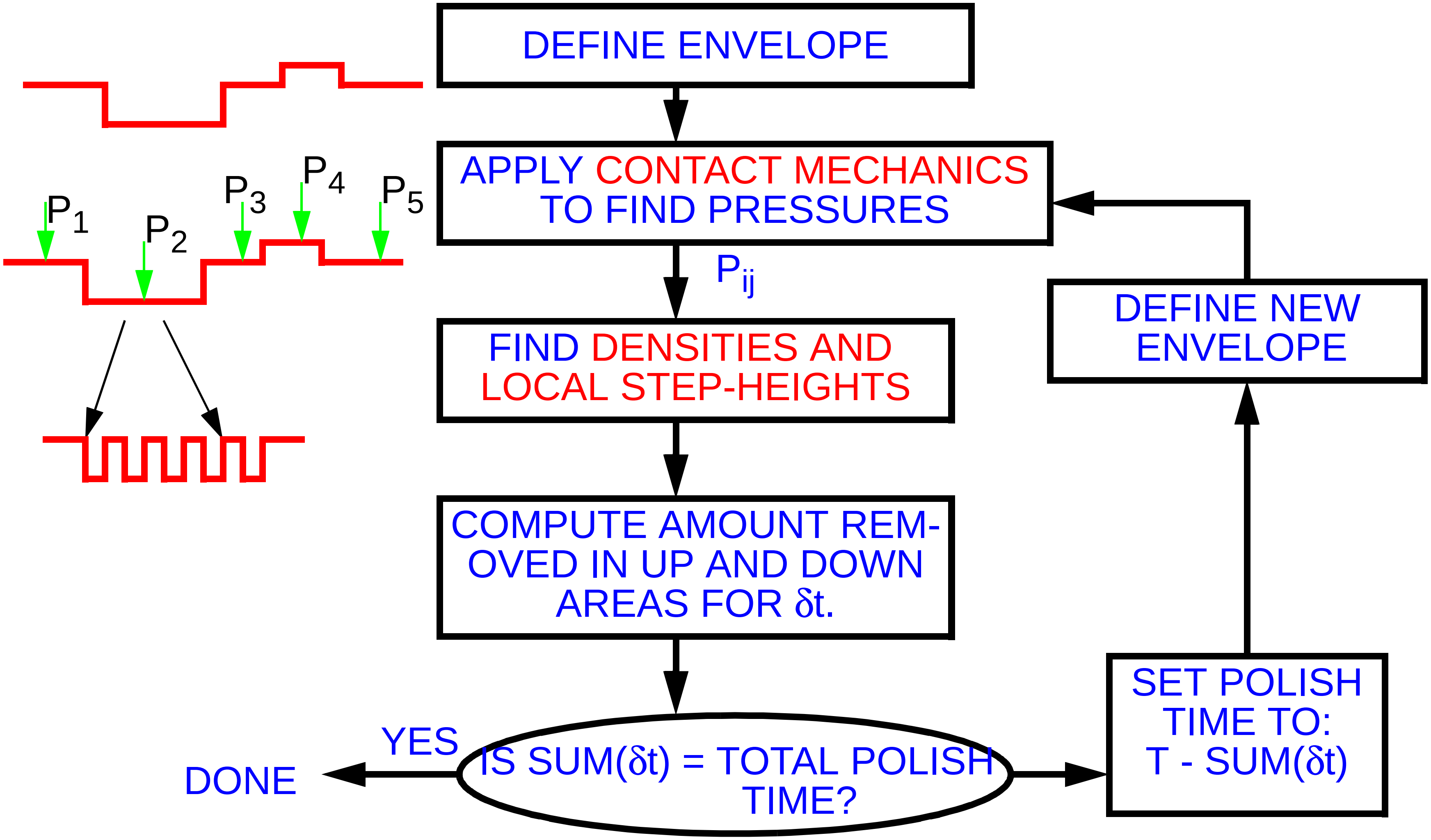
Integrated Contact Mechanics and Density/Step-Height Model

- Consider the following problem in the bulk copper clearing stage:

- Define an “envelope” which gives the relative heights of the local “up-areas” across some large scale (coarsely discretized) region
  - ☐ Use contact wear model to determine pressures *across* each of these large scale regions
  - ☐ Use density/step-height model to determine up/down area removal rate *within* each region



Integrated Contact Mechanics and Density/Step-Height Model, cont'd



DEFINE ENVELOPE

APPLY CONTACT MECHANICS TO FIND PRESSURES

FIND DENSITIES AND LOCAL STEP-HEIGHTS

COMPUTE AMOUNT REMOVED IN UP AND DOWN AREAS FOR δt.

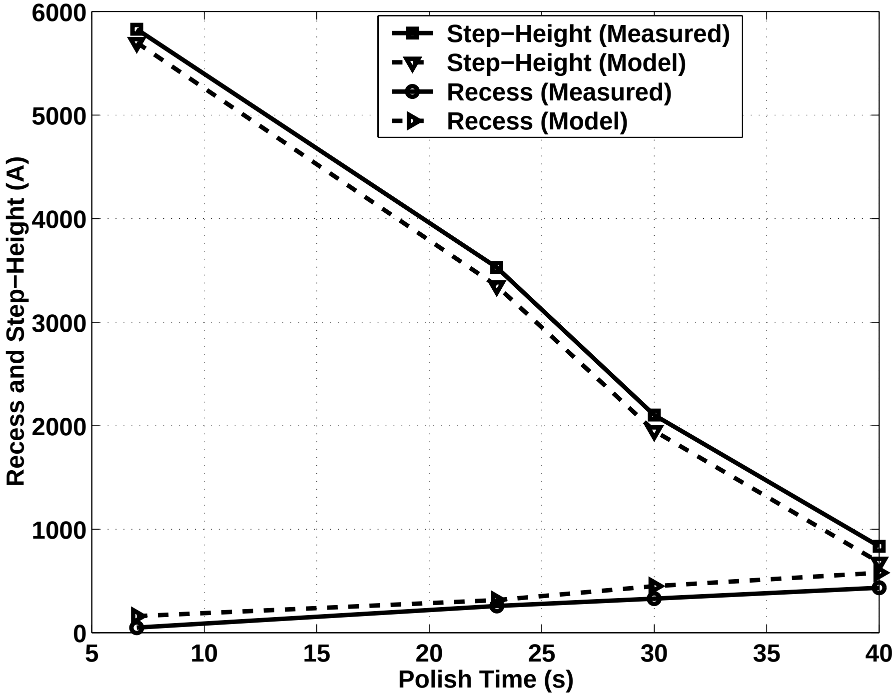
IS SUM(δt) = TOTAL POLISH TIME?

DONE

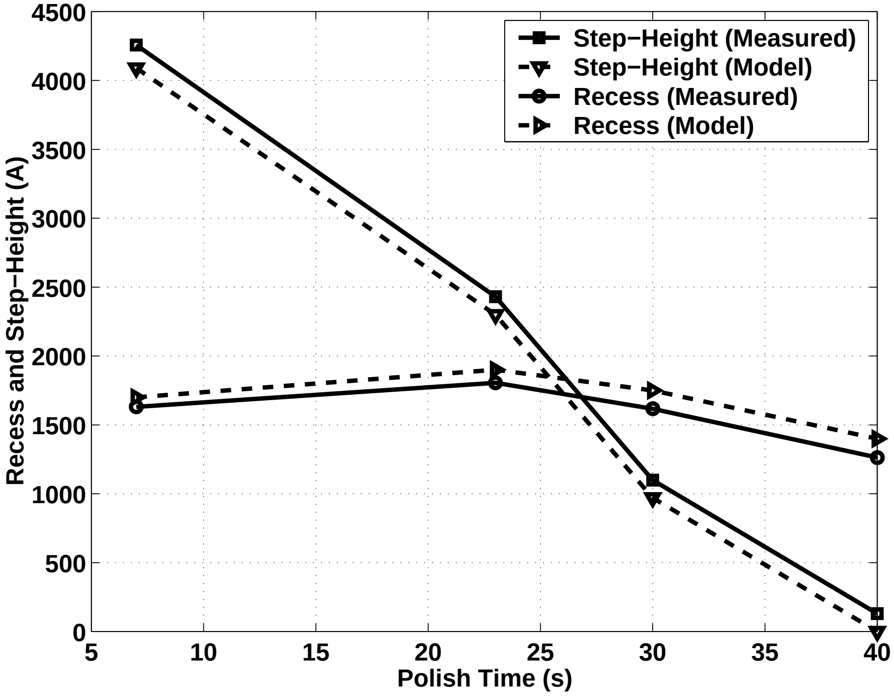
SET POLISH TIME TO: T - SUM(δt)

DEFINE NEW ENVELOPE

Results: Stage 1 (Bulk Copper Polish)



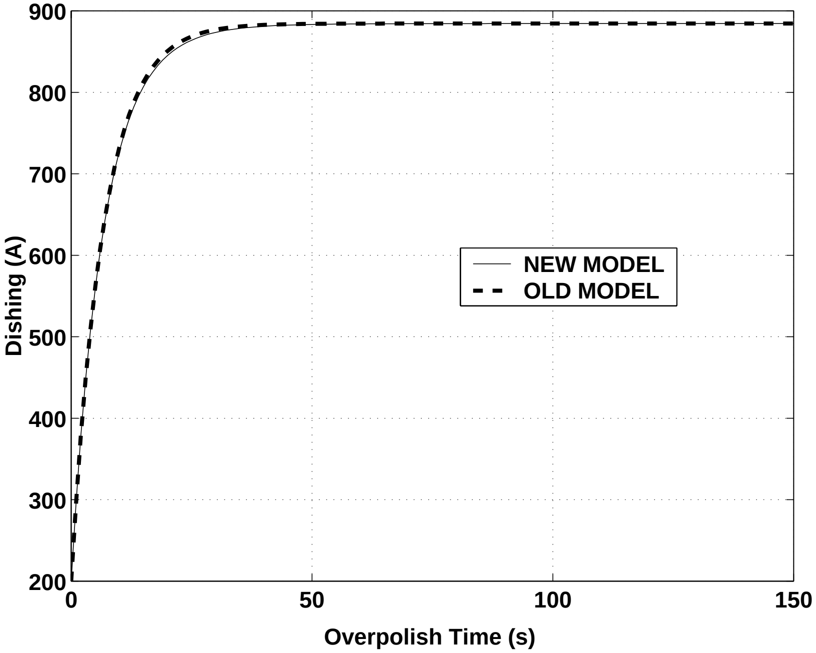
Recess and Step-Height versus time for 50 µm width and space



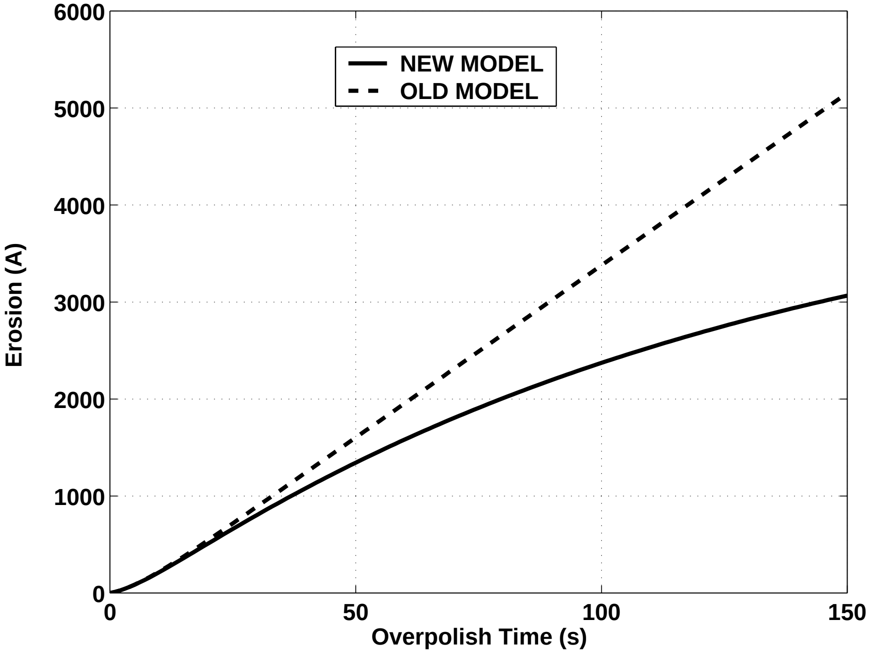
Recess and Step-Height versus time for 9 µm width, and 1 µm space

- The new model captures the recess and step-height trends

Results: Stage 3 (Over-Polish)



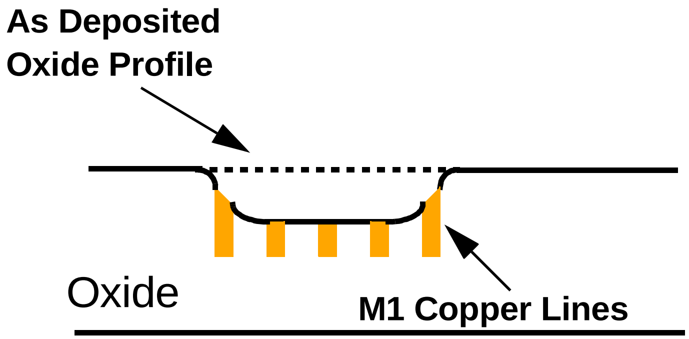
Dishing versus polish time



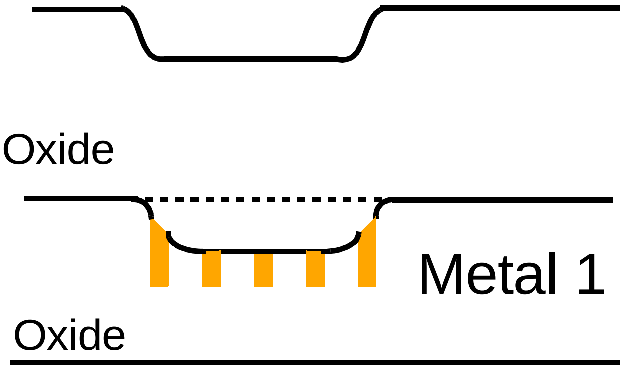
Erosion versus polish time

- Model captures the “reported” saturation of array erosion with excessive overpolish (array structure is surrounded by large field region).

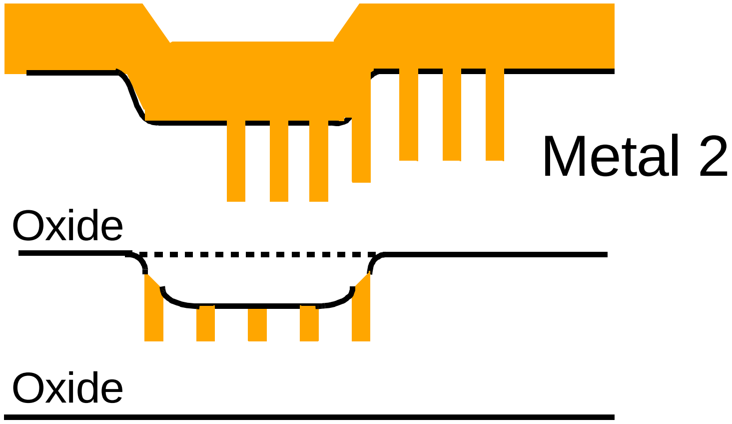
7. Multi-Level Copper Process Sequence



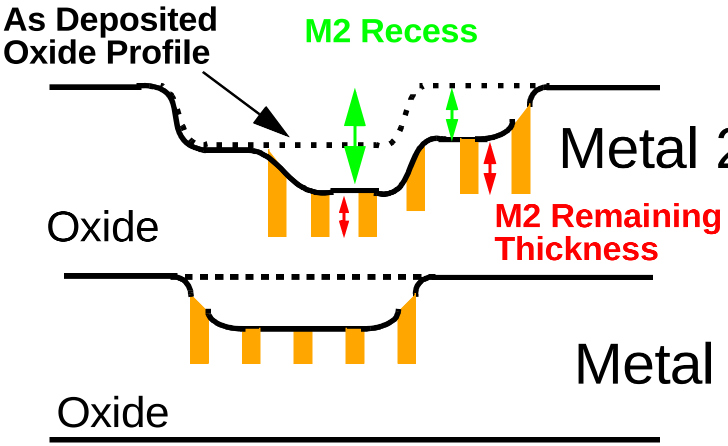
1. M1 Polish



2. M2 Oxide Deposition



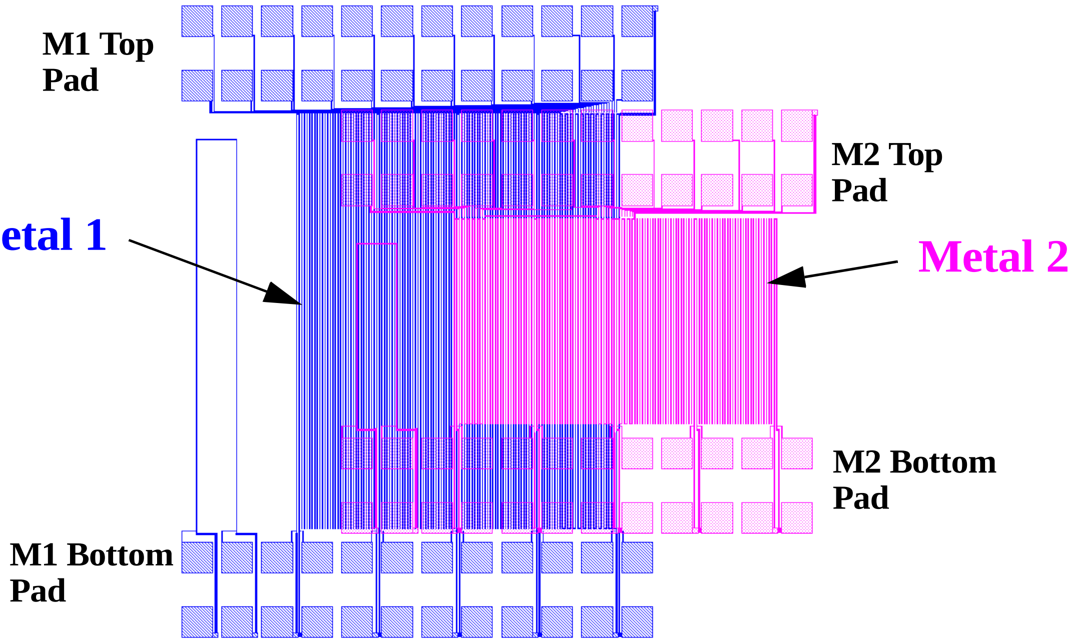
3. M2 Cu Deposition



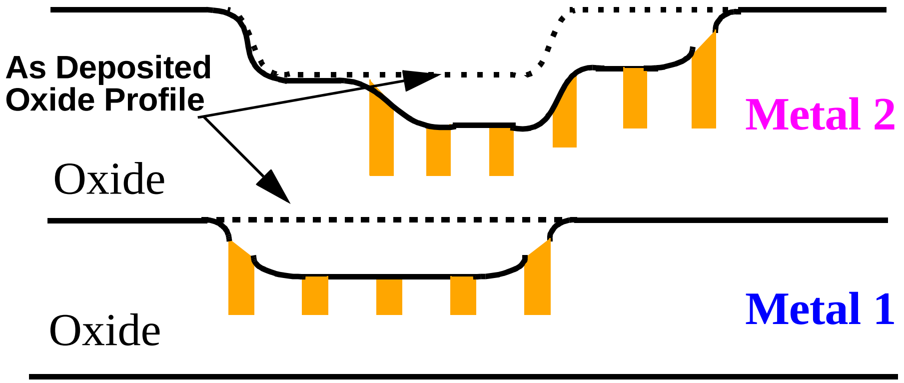
4. M2 Polish

Half Overlap Test Structure

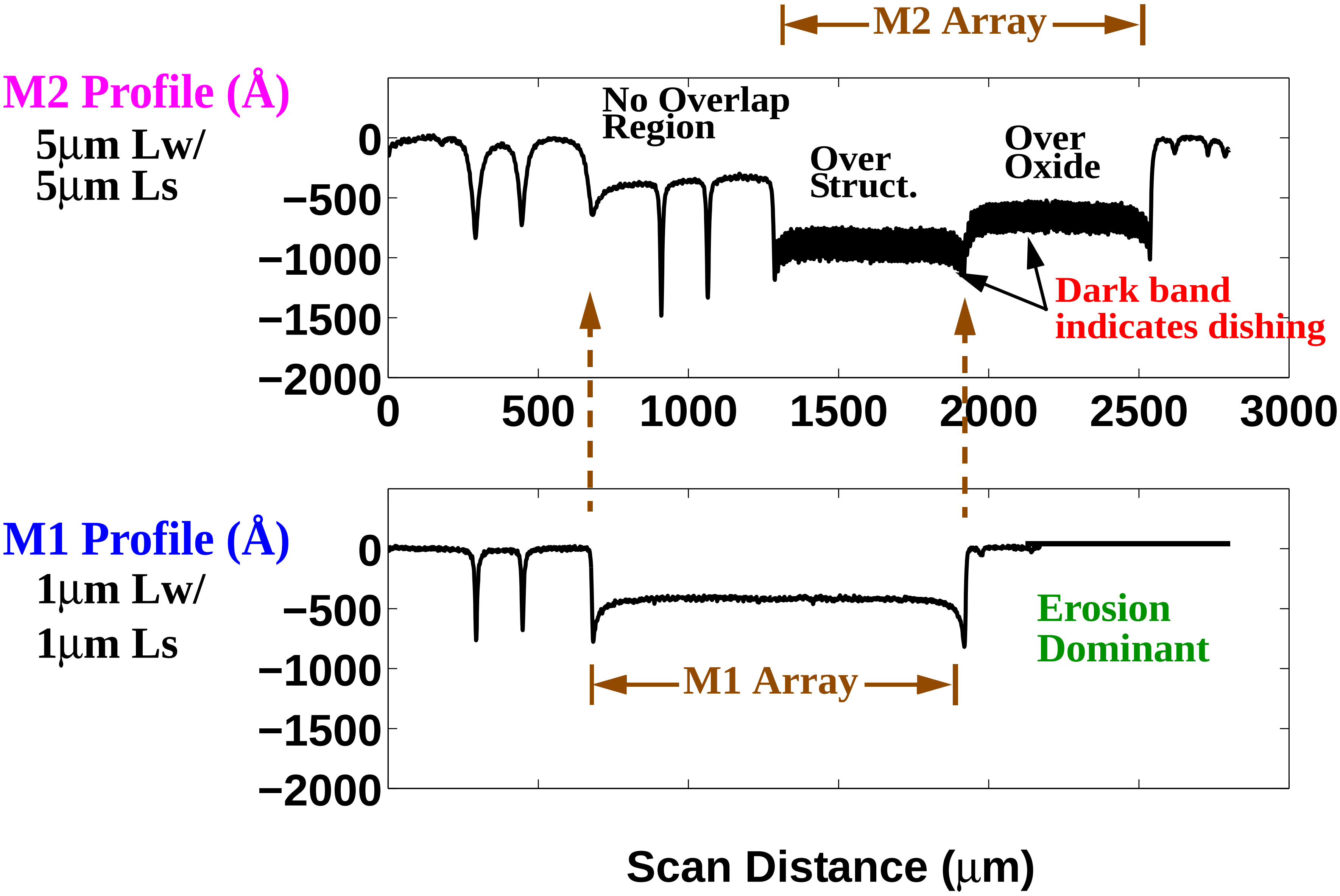
Top Down View



Cross Sectional View



Half Overlap: Erosion to Dishing/Erosion

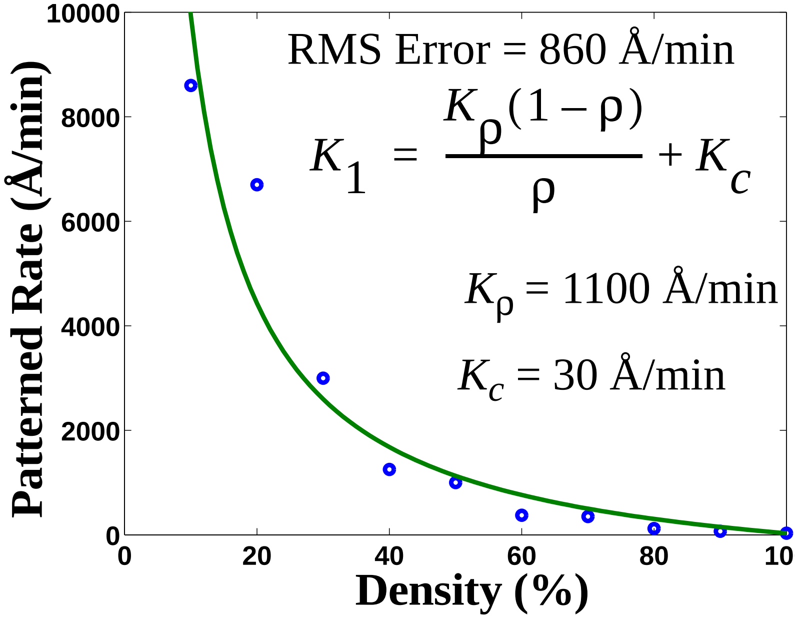


8. Alternative Consumables Models: Fixed Abrasive Pad Effects

- Conventional CMP:
  - ☐ Blanket polish rate: K ~ 1500 A/min
  - ☐ Patterned polish rate: inversely proportional to pattern density ~ K/ρ
- Fixed Abrasive CMP:
  - ☐ Low blanket polish rate: K_c ~ 30 A/min
  - ☐ Patterned polish rate: much larger than K_c/ρ
    - model patterned rate as

$$K_1 = \frac{K_\rho(1-\rho)}{\rho} + K_c$$

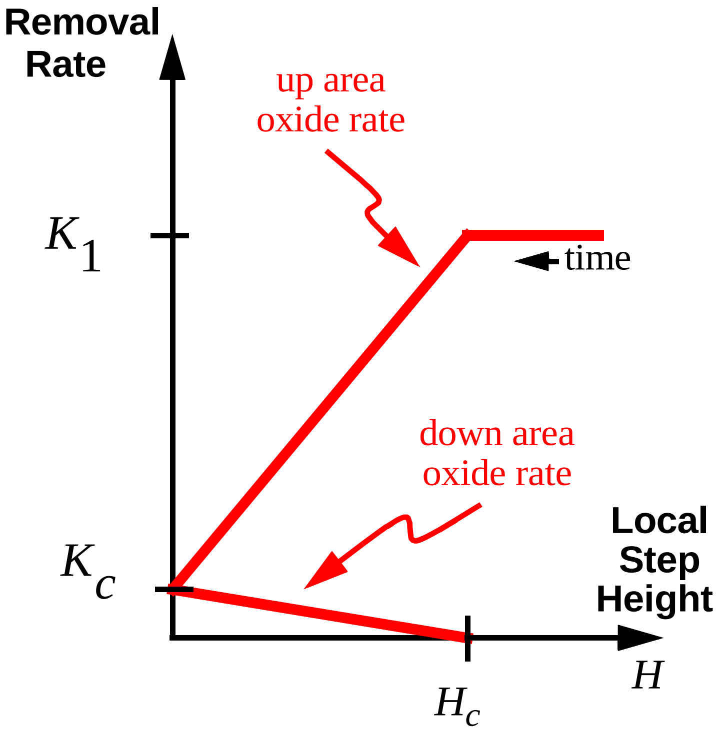
B. Lee et al., *CMPMIC 2001*

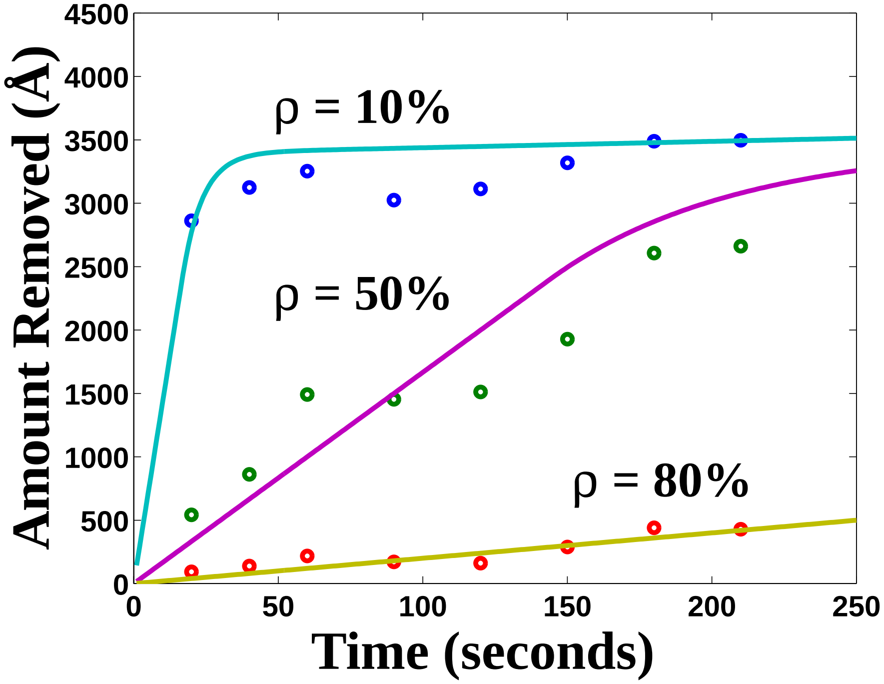


Fixed Abrasive Pad CMP Model

- Decouple patterned rate from blanket rate: $K_1 = \frac{K_\rho(1-\rho)}{\rho} + K_c$
- Apply density/step-height model with assumed linear rate dependence on step height between K_c and K_1

Results:





Status and Future Challenges in CMP Modeling

- Oxide (Interlevel Dielectric CMP)
  - Pattern density models are simple and provide good accuracy
  - Layout biasing for small linewidths accounts for deposition profile
  - Step height model for accurate up and down area predictions
- Shallow Trench Isolation CMP
  - Dual-material density/step-height models give reasonable accuracy for STI polishes with conventional consumables
  - Challenge: Nanotopography effects integrated with chip pattern effects
  - Challenge: Extended models to account for effects seen with new and alternative consumable sets (fixed abrasive pads, abrasive free slurry)
- Copper CMP
  - Challenge: calibration of models in realistic multi-step processes
  - Challenge: develop and integrate electrodeposition profile models
  - Challenge: multilevel CMP effects