Practical and Theoretical Considerations for Cu e-CMP*

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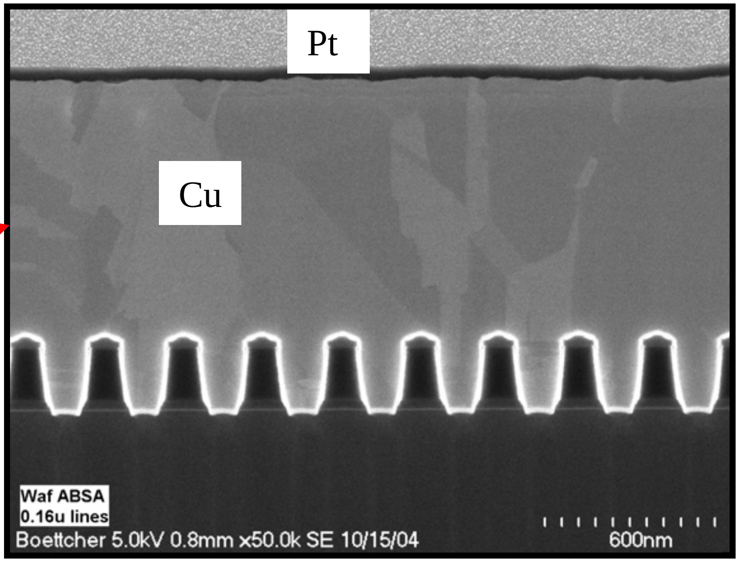
Why e-CMP?

low down-force replacement of or complement to CMP

Goals:

- remove partially or completely overburden
- planarize
- fewer defects than CMP
- achieve high throughput

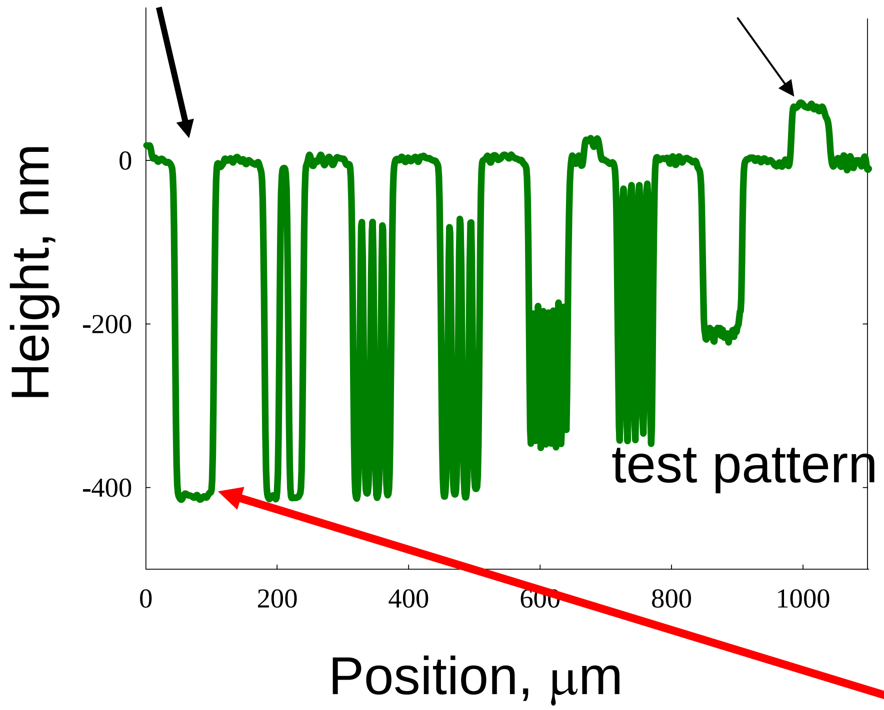


overburden

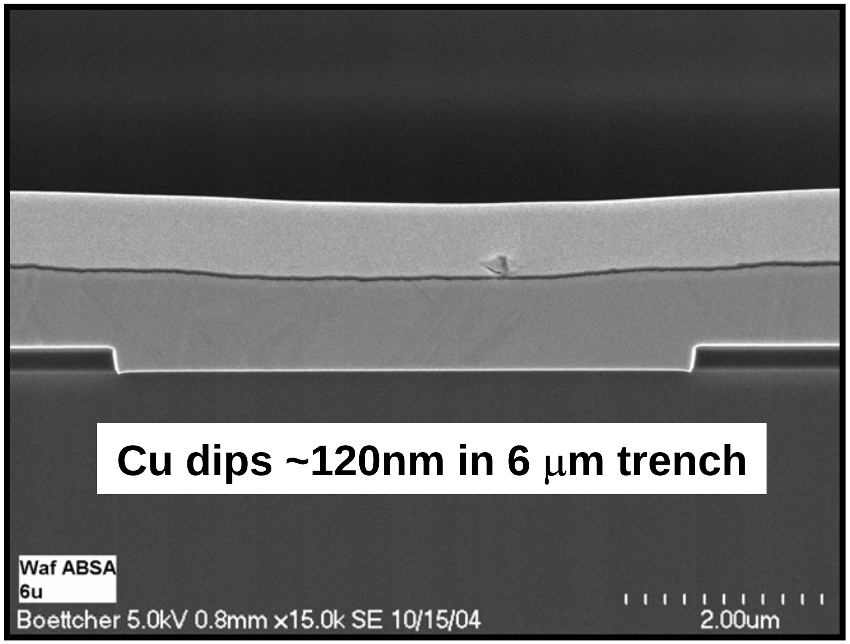
The Challenge:
As-Deposited Overburden Topography

Dishing above large features

Mounds above clusters of small features



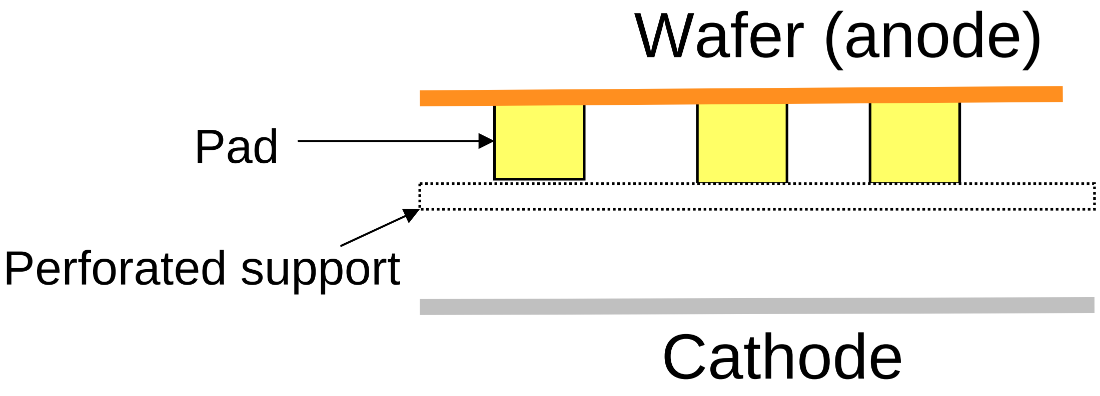
test pattern



Cu dips ~120nm in 6 μm trench

$$s_o / w_f = 0.008$$

What is e-CMP?



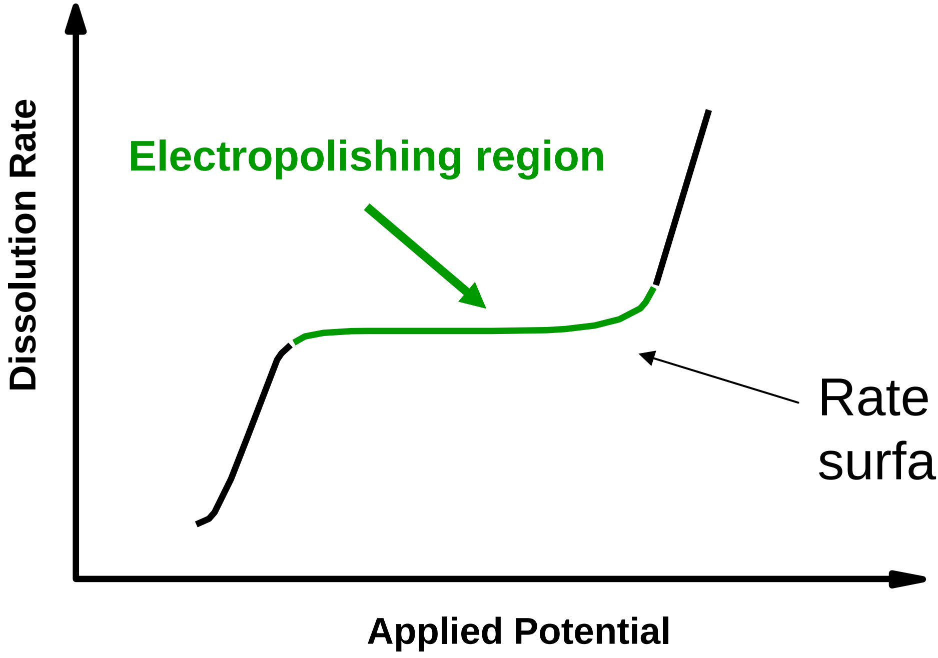
- Couples electrochemical oxidation of Cu with polishing pad
- Electrons supplied by external circuit to oxidize Cu

  In CMP, oxidizing agent is in the electrolyte

Electropolishing Electrolytes as Starting Point for e-CMP?

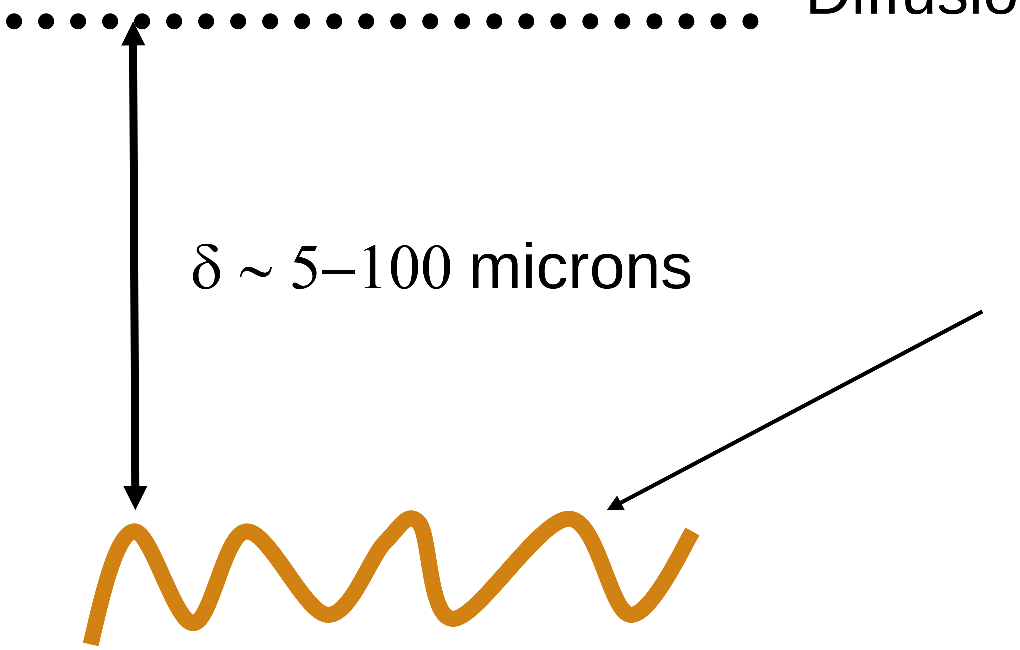
- Assumed to be in most early work

  Reviewed in: Alan C. West, Panos Andricacos, and Lili Deligianni, “Electrochemical Polishing of Metallization,” *IBM J. Res. Devel.*, **49**, 37 (2005).



Rate is limited by diffusion from surface to bulk electrolyte

Electropolishing Requires Transport Control



Diffusion layer

$\delta \sim 5\text{–}100$ microns

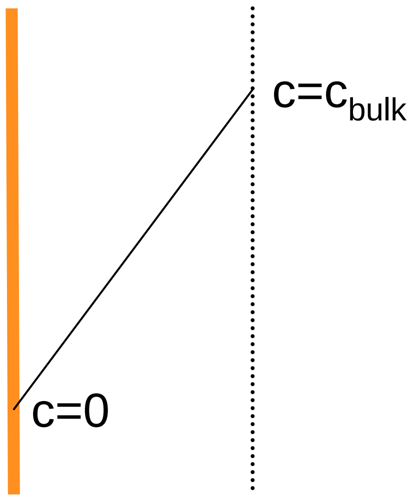
Under diffusion control:
Peaks dissolve more quickly than valleys

Roughness on anode

What is source of Diffusion Control?

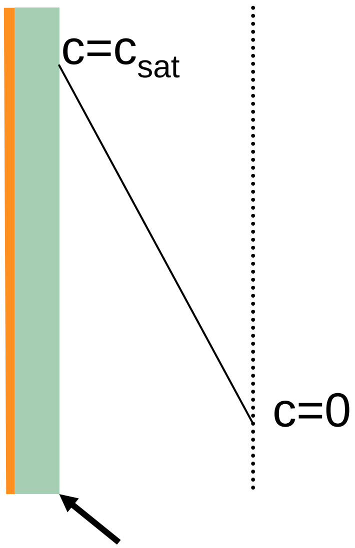
- Diffusion-limited rates only achievable in select electrolytes
- Two primary mechanisms have been identified

Acceptor Mechanism



$$\mathrm{Cu} + \mathrm{nA} \rightarrow \mathrm{CuA}_{\mathrm{n}}^{2+} + 2e^{-}$$

Salt-Film Mechanism



Cu-Salt film

Mechanism for Cu

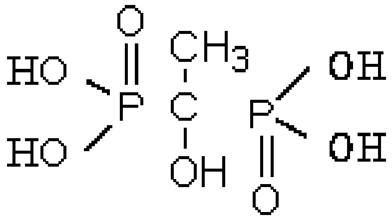
- Phosphoric acid: acceptor mechanism

Roberto Vidal and Alan C. West, *J. Electrochem. Soc*., **142**, 2689 (1995) and *J. Electrochem. Soc*., **142**, 2682 (1995).

- HEDP: salt-film mechanism claimed

J. Huo, R. Solanki, and J. McAndrew, *J. Appl. Electrochem.,* in press (2004).

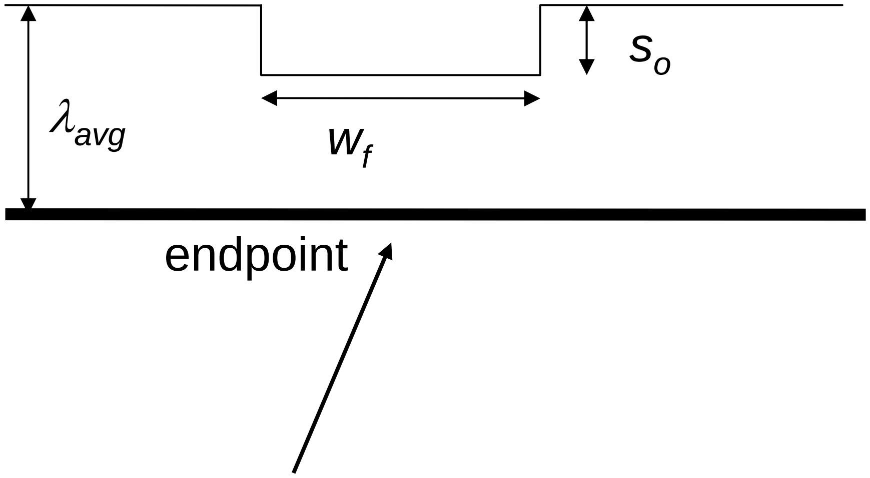
HEDP



Numerical Simulation of Electrochemical Planarization

- Used to evaluate viability of electrochemical polishing

Results normally do not depend on mechanism



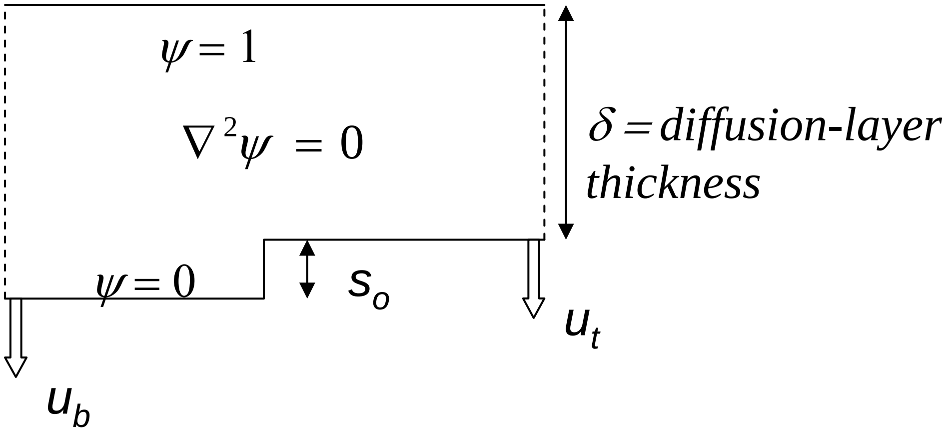
e.g., could be liner

Results shown for reduction in step height as function of material removed

Numerical Simulation of Electrochemical Planarization

Simulation summary:

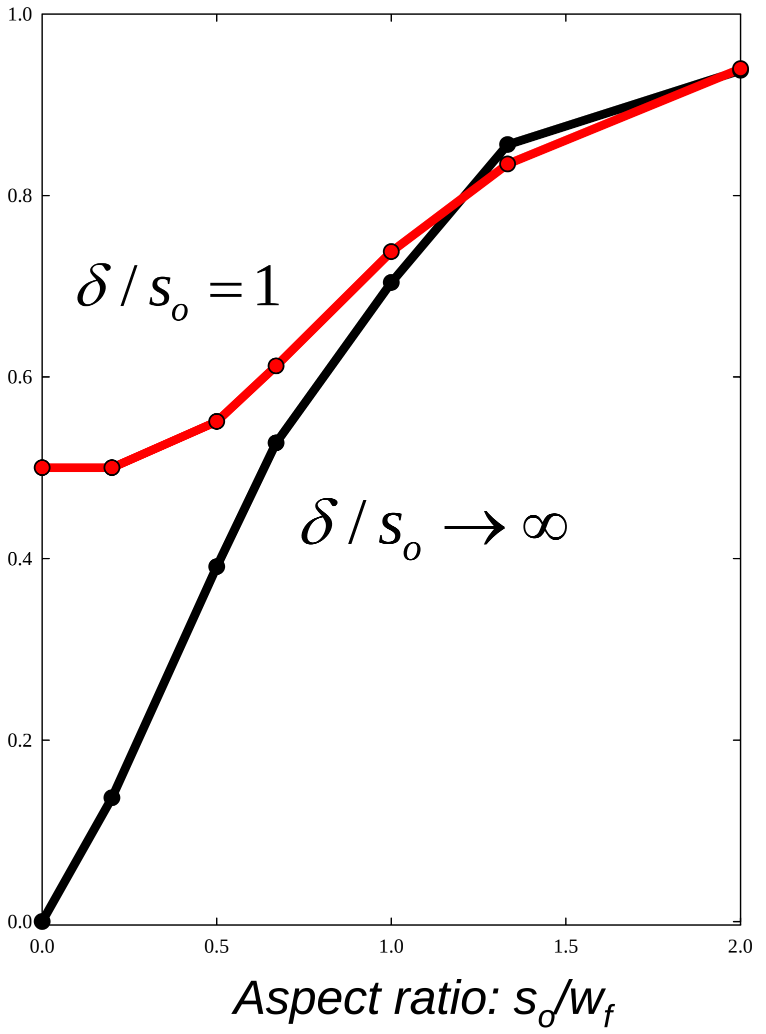
1. assume idealized geometry of single feature with initial step height s_o
2. Calculate normalized concentration ψ, assuming diffusion-controlled dissolution rate
3. Move surface, tracking changes in step height



$$\text{dissolution rate } u \propto \frac{\partial \psi}{\partial n}$$

Simulated Effect of Aspect Ratio

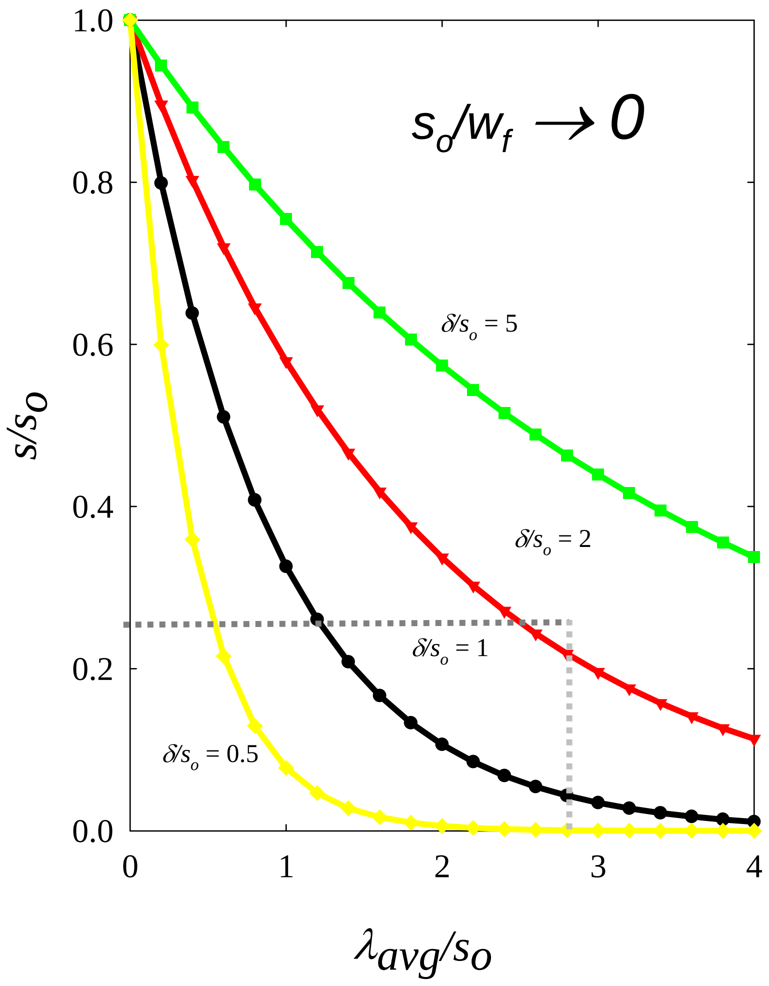
Small aspect ratios are most difficult to planarize



$\Delta s_{\max} / \lambda_{avg}$

Upper limit in step-size reduction over average amount of material removed

Simulated Reduction in Step Size of Small-Aspect Ratio Trench



Assume:

s_o < 250 nm from ECD

And we require from polishing :

λ_{avg} = 700 nm
final step height s = 60 nm

Design requires that:

δ < 500 nm

Conventional electropolishing is infeasible

- For a wafer rotating at 100 rpm, using physical properties of phosphoric acid:

  δ = 27 microns

- Further reductions require dramatic changes in chemistry, flow, design, or concept

e-CMP is one example

Planarization Process*

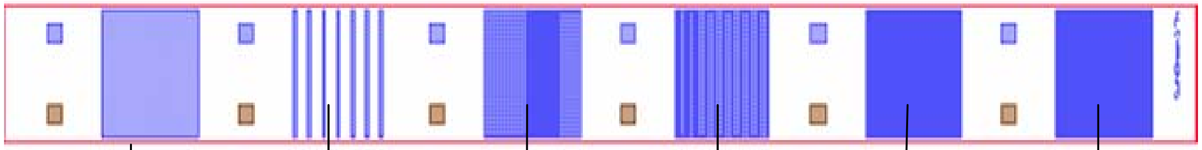
Platen 1: e-CMP down to average overburden thickness of 180 nm

Platen 2 and 3: low down force CMP to remove barrier and Cu

characterized at
this point

*Economikos et al., *IITC Conference Proceedings*, 233 (2004).

e-CMP Test Structure



Pad 1
line width = 200 μm

Pad 2
line width = 6 μm
Spacing = 24 μm

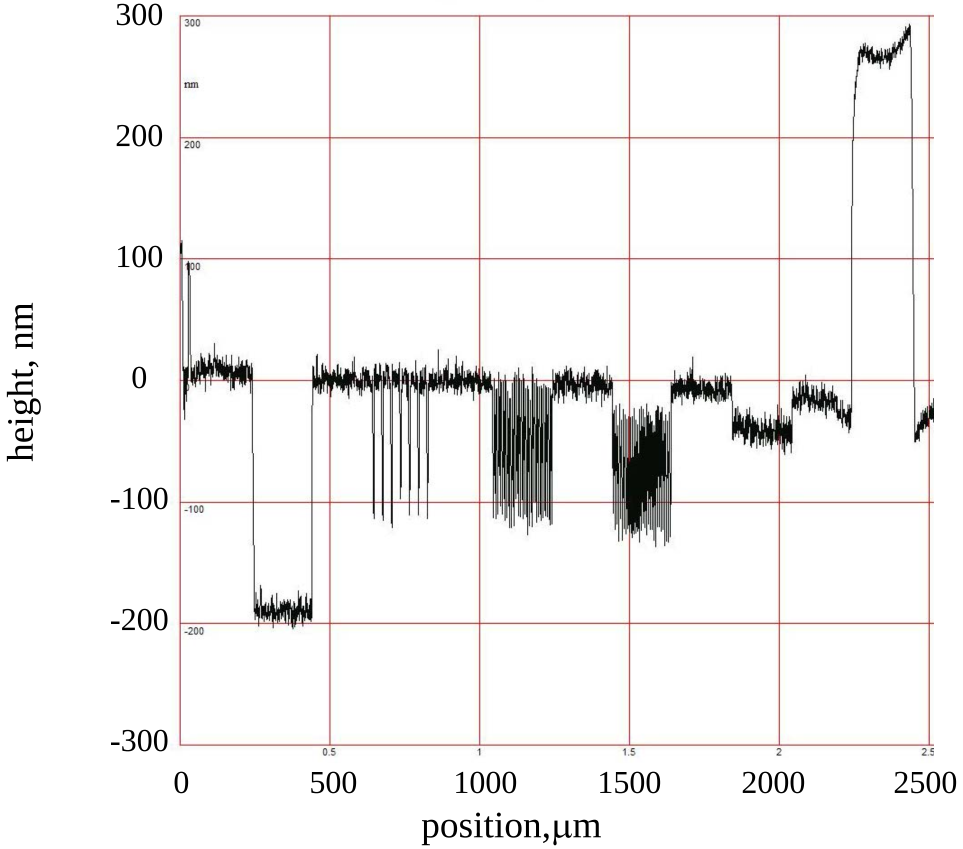
Pad 3
line width = 6 μm
Spacing = 1.5 μm

Pad 4
line width= 6 μm
Spacing = 0.14 μm

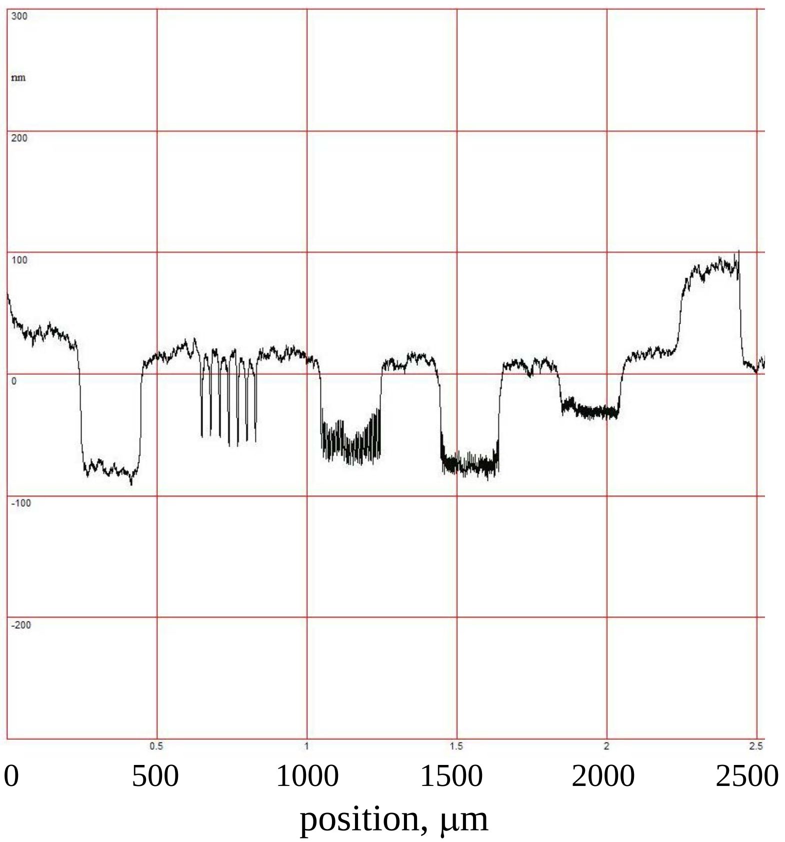
Pad 5
line width = 1.6 μm
Spacing = 0.14 μm

Pad 6
Minimum width
Minimum spacing

As Deposited (350 nm overburden)

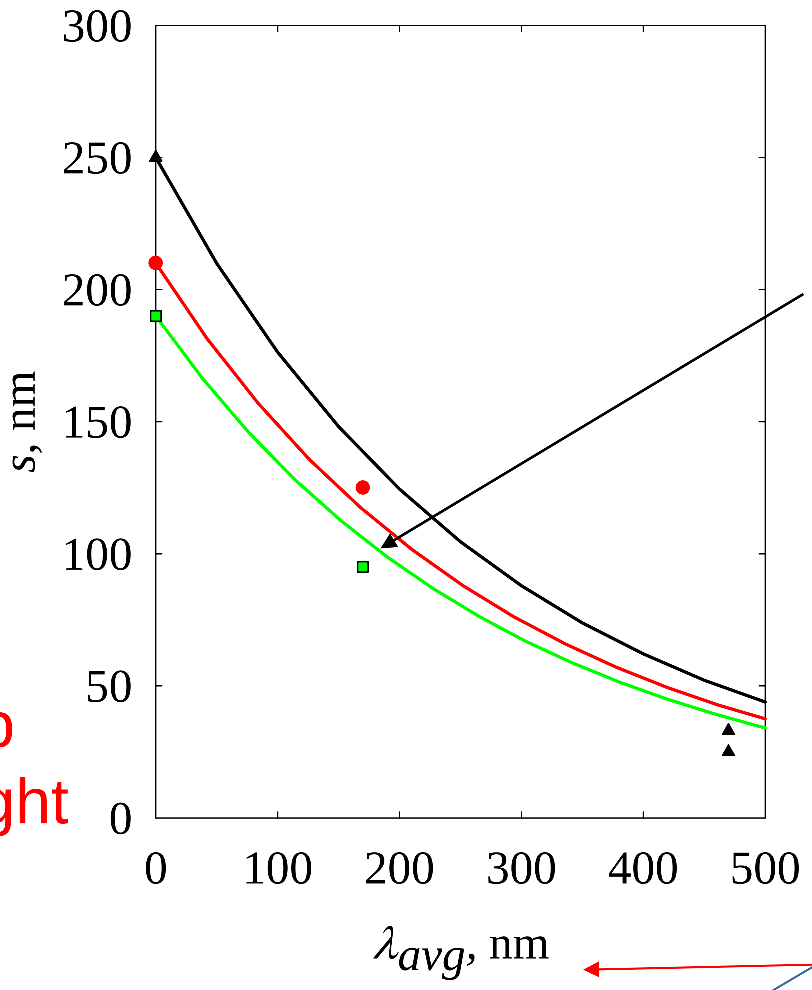


After Platen 1 (180 nm overburden)



- Results obtained for 350 and 650 nm initial overburden thickness
- Also at wafer center and edge

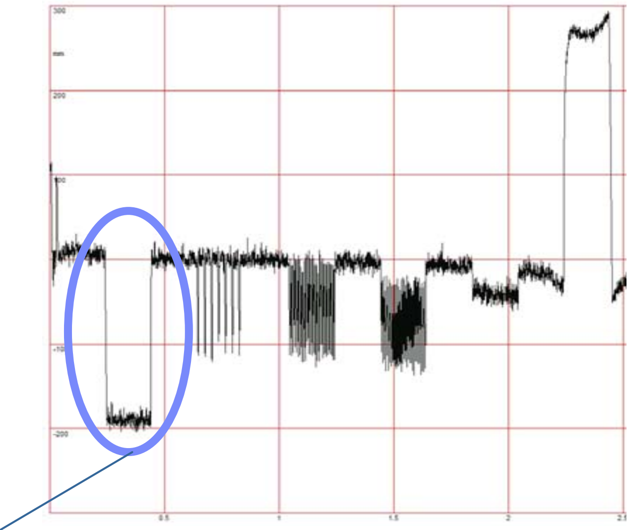
Reduction in Step Height Above Dish



step height

Lines are electropolishing simulations:

- Process is equivalent to δ = 315 nm



Material removed

In theory, essentially same result for $s_o/w_f < 0.1$

Conclusions

- Small-Aspect ratio features are the most difficult to planarize
- Numerical simulations indicate the electropolishing is not likely to be effective
- Models based on Laplace's equation may describe e-CMP results
  - predictive over a limited range
  - Physical basis of length scale?

Acknowledgments

- Silvia Franz
- Wei-Tsu Tseng
- Steve Boettcher

- Panos Andricacos and Lili Deligianni for the opportunity to spend my sabbatical with IBM

Current Progress

- New Students

  Kristin Shattuck

  Paula Cojocaru – visiting scholar

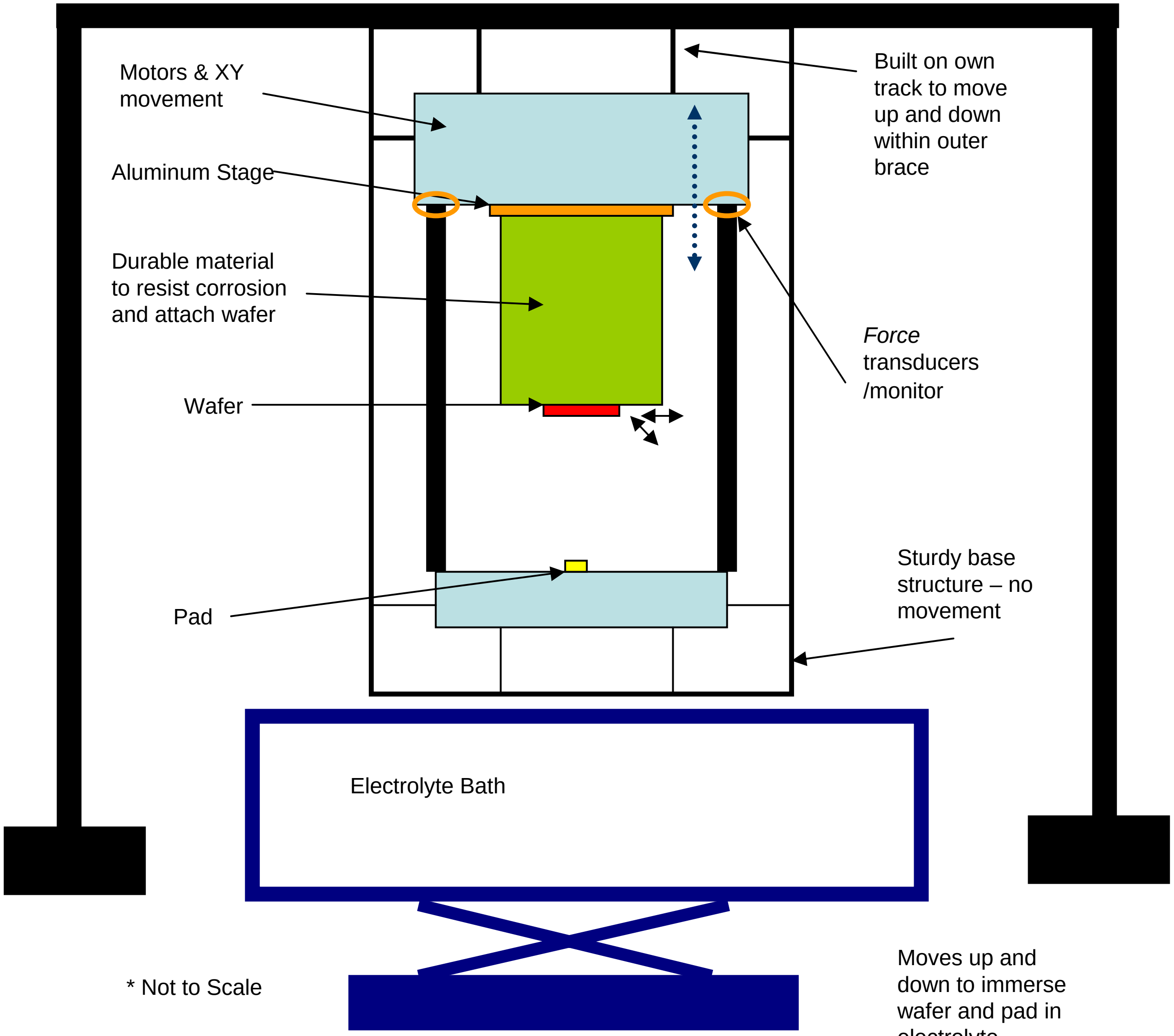
1. Preliminary Design of Benchtop ECMP Device

2. Electrochemical Characterization

   KPO_3 – H_3PO_3 / BTA System

Design of ECMP Apparatus

- Currently working with vendors to optimize specific design features
  - Wafer polishing motion
  - Planarization issues
  - Controlling/ Monitoring force between wafer and pad
  - Wafer contacts



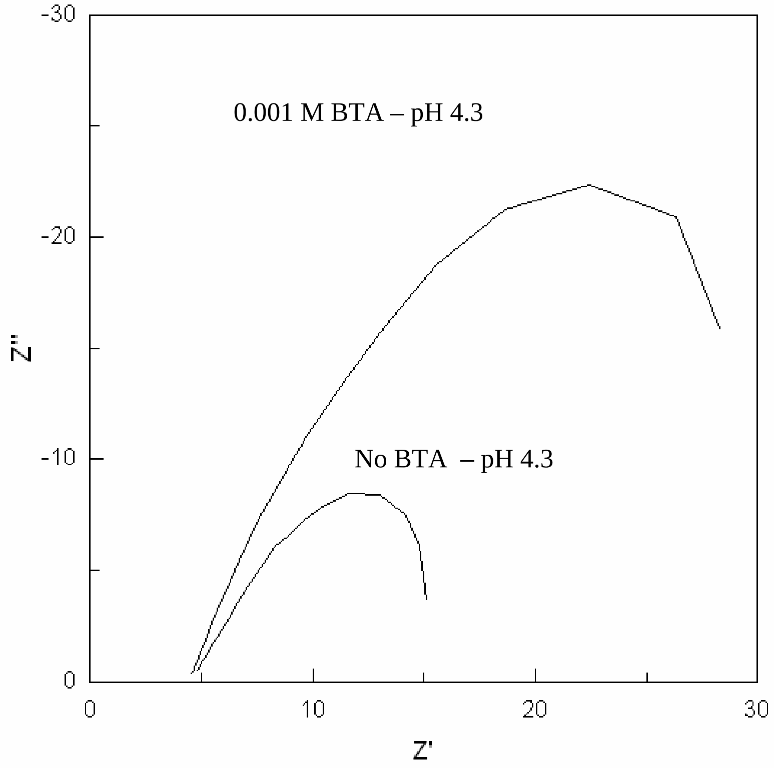
* Not to Scale

Electrochemical Characterization

- Experimental Parameters
  - pH
  - BTA concentration
  - Mass transfer

- Characterization
  - Electrochemical Impedance Spectroscopy (EIS)
  - Linear Sweep Voltametry (LSV)
  - Currently Investigating
    - Profilometry
    - 4 Point Probe

EIS Nyquist Plot – 100 RPM



Planarization Capability

- Where:

  I = current with 0.001 M BTA

  I_{no} = current with No BTA

- Related to dissolution rate with and without a polishing pad