Modeling the Effect of Non-Prestonian Pressure on Pattern Dependencies in CMP

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Outline - Modeling Non-Prestonian Effects

- Review: Prestonian Removal Rate Dependence on Pressure
- Alternative Slurries: Non-Prestonian Pressure Dependence
  - ☐ Abrasive Free Polishing (AFP)
  - ☐ Threshold Pressure (Ceria/Surfactant)
  - ☐ Abrasive Free Polishing, Part 2
- Issue: How model pattern dependence of these non-Prestonian slurries?
- Existing Pattern Dependent Model
  - ☐ Removal Rate Diagrams: Rate vs. Step Height and Pattern Density
- Model Extension:
  - ☐ Pressure vs. Step Height and Pattern Density
  - ☐ Removal Rate vs. Pressure Dependence
- Application in Contact Wear Models
- Conclusions

Preston’s Equation - Basic Model

- Removal Rate: Preston’s Equation

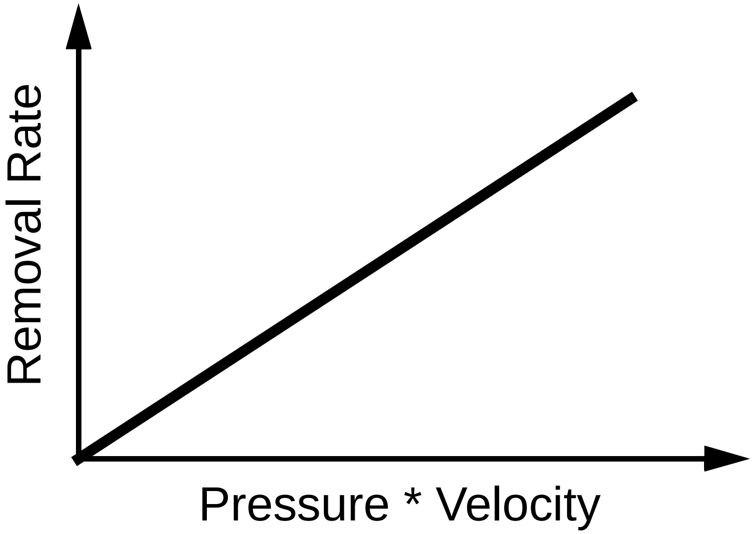
$$\frac{dz}{dt} = K \cdot \frac{N}{A} \cdot \frac{ds}{dt}$$

where z is wafer thickness, t is time, N/A is the pressure due to normal force N on the area A, and s is the distance some point on the wafer travels in contact with pad.

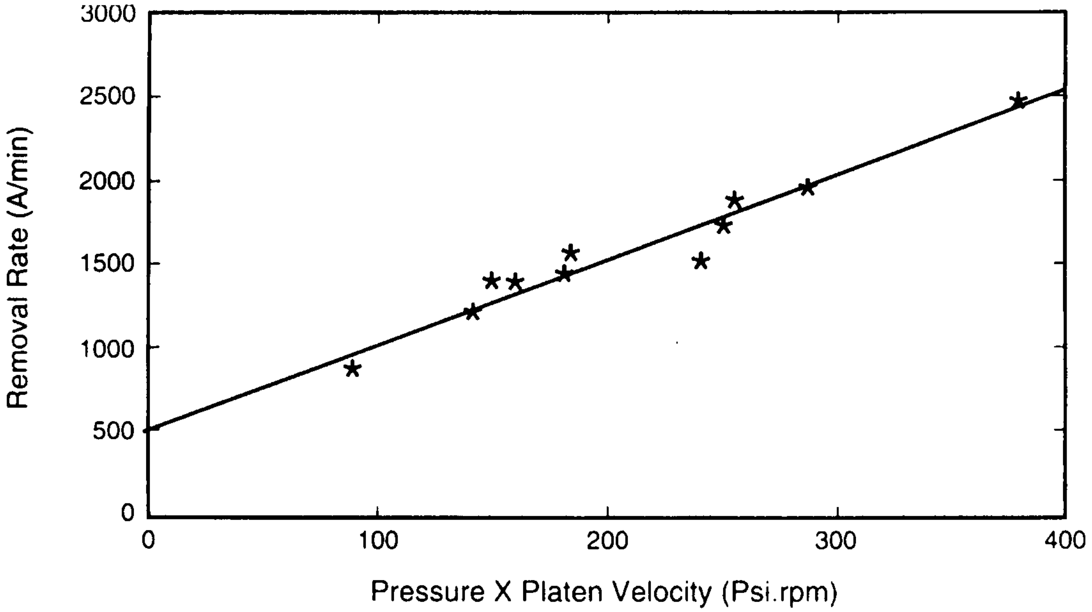
- *K* is “Preston’s Coefficient” -- proportionality constant.
- Also appears as

$$R = K \cdot P \cdot V$$

where R = removal rate, P = pressure, and V = velocity



Conventional Polishing - “Prestonian” Behavior



Sivaram et al., SRC TRC on CMP, 1992. (In Steigerwald, Murarka, and Gutman).

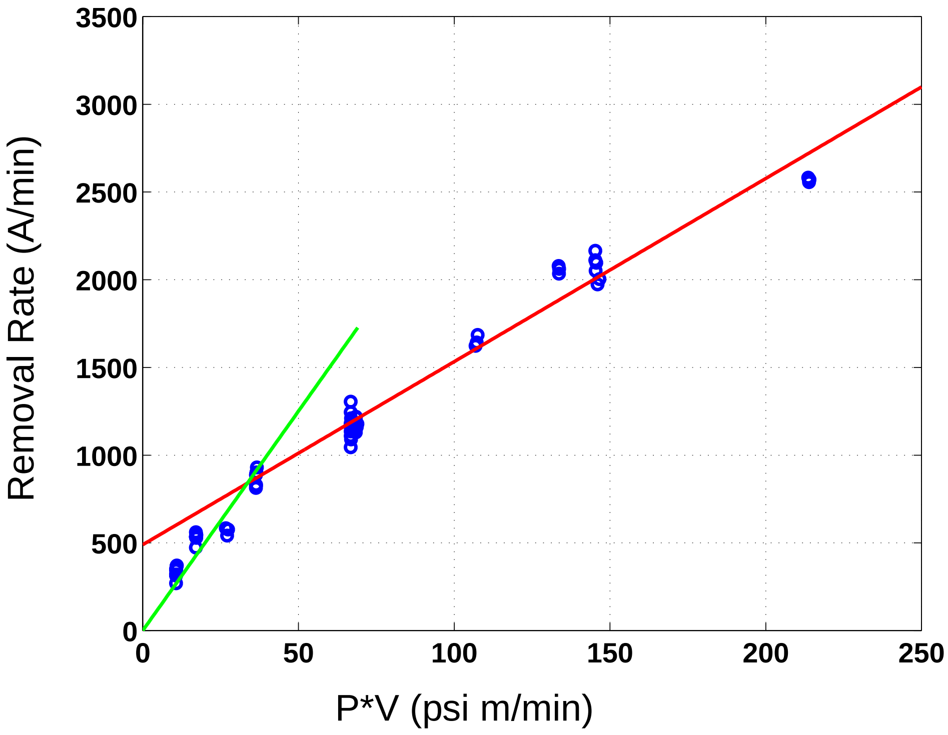
Oxide polish rate vs. pressure×velocity. The polish rate is linear with the pressure×velocity product as predicted by Preston.

- Linear behavior generally seen for practical pressures
- Extrapolation back to non-zero removal rate at zero P*V

Conventional Polishing - “Prestonian” Behavior

- Experiments at low pressure and velocities indicate:
    - ❑ Possible “low PV” regime with a different dependence
    - ❑ Intersects origin as expected
- For practical modeling, linear dependence in operating regime is satisfactory:
    - ❑ Extrapolation back to non-zero removal rate at zero P*V

$$RR = R_0 + K \cdot P \cdot V$$

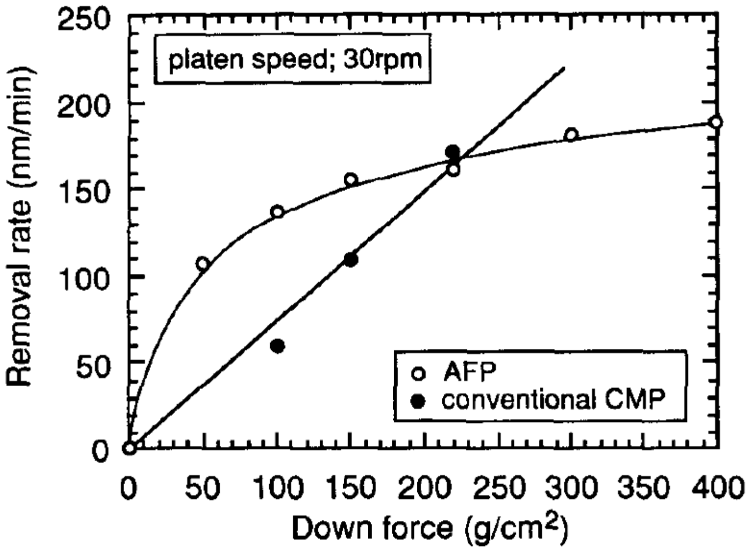


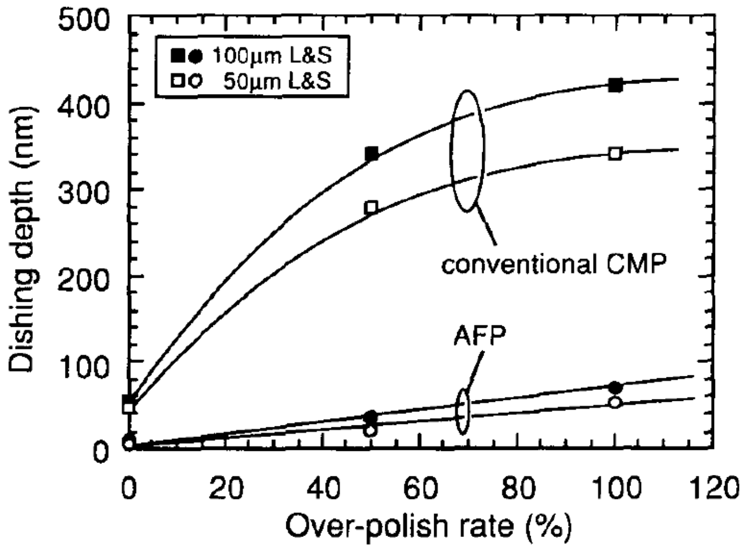
D. Ouma, PhD Thesis, MIT, 1998.

- Several alternative “non-Prestonian” models available having different P, V power law dependencies with incremental improvements in data fit

Abrasive-Free Polishing (AFP) - Hitachi

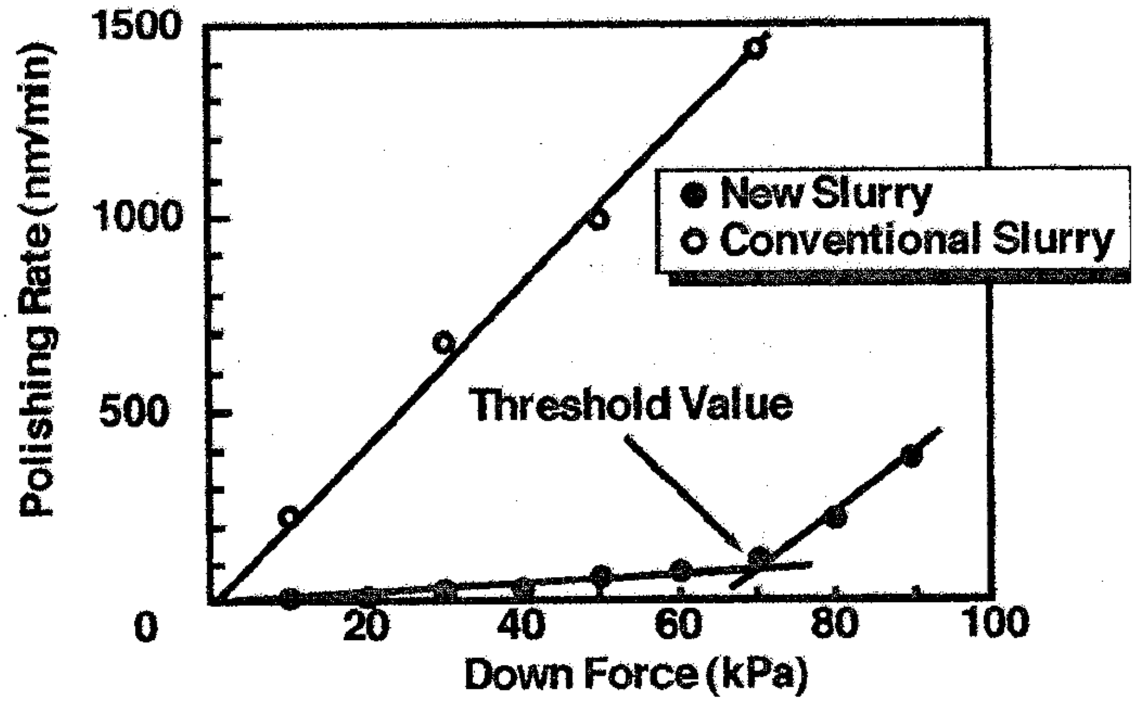
- Abrasive-Free Polishing (AFP):
  - chemical slurry without abrasive particles
  - novel “Non-Prestonian” rate vs. pressure dependence
    - removal rate drops off rapidly with moderate down force
- Benefits:
  - substantially improved dishing and erosion performance
  - reduced solid content in effluent
  - reduced scratching during CMP
- Challenges:
  - may be difficult to completely clear the copper off field regions





Kondo et al. (Hitachi), *IITC 2000.*

Threshold Pressure (Ceria/Surfactant)

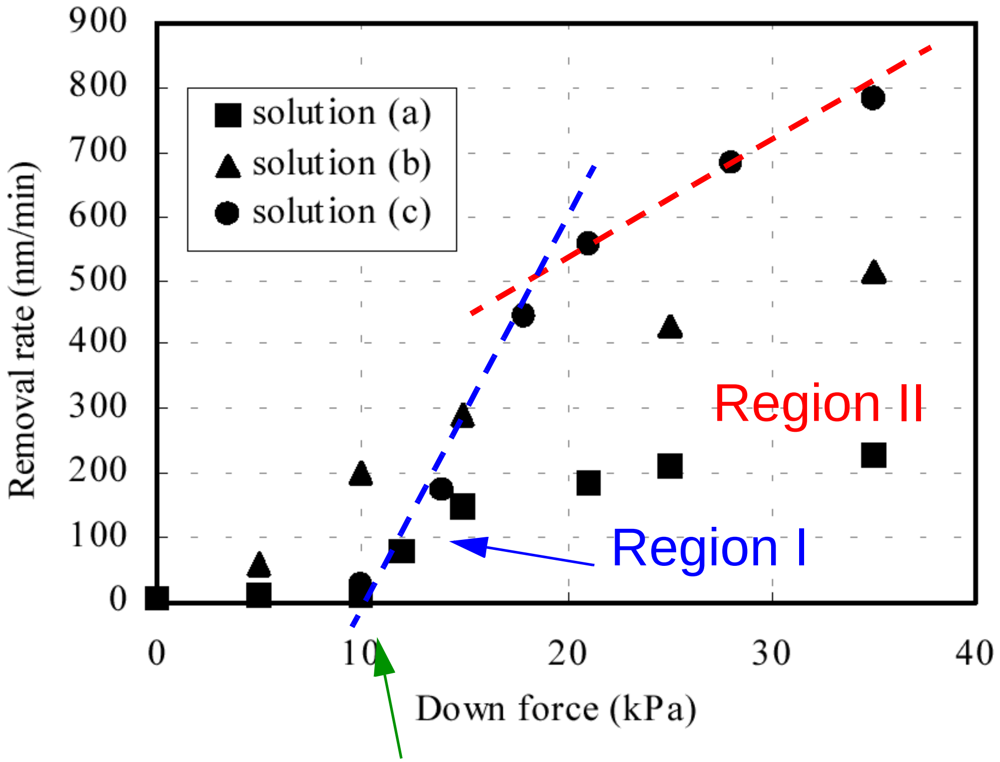


Nojo,
Kodera, and
Nakata,
IEDM 1996.

- Added 2-5 wt% surfactant to CeO_2 slurry
- Observed a “threshold pressure” below which removal rate is very low
- Application: “self-stopping dishing-free SiO_2 polish”

Abrasive-Free Polishing (AFP) - Part 2

- More recent version of AFP (Hitachi):
  - ❑ Threshold pressure
  - ❑ Approximately linear pressure region I
  - ❑ Approximately linear pressure region II
- Complete clearing of copper in field regions difficult
  - ❑ Reported solution based on “optimized total process design” for 0.13 µm (e.g. addressing plating overfill)
  - ❑ Applied Materials reports abrasive free copper polish approach with variable pressure process to achieve clearing (Li et al., IITC2001)



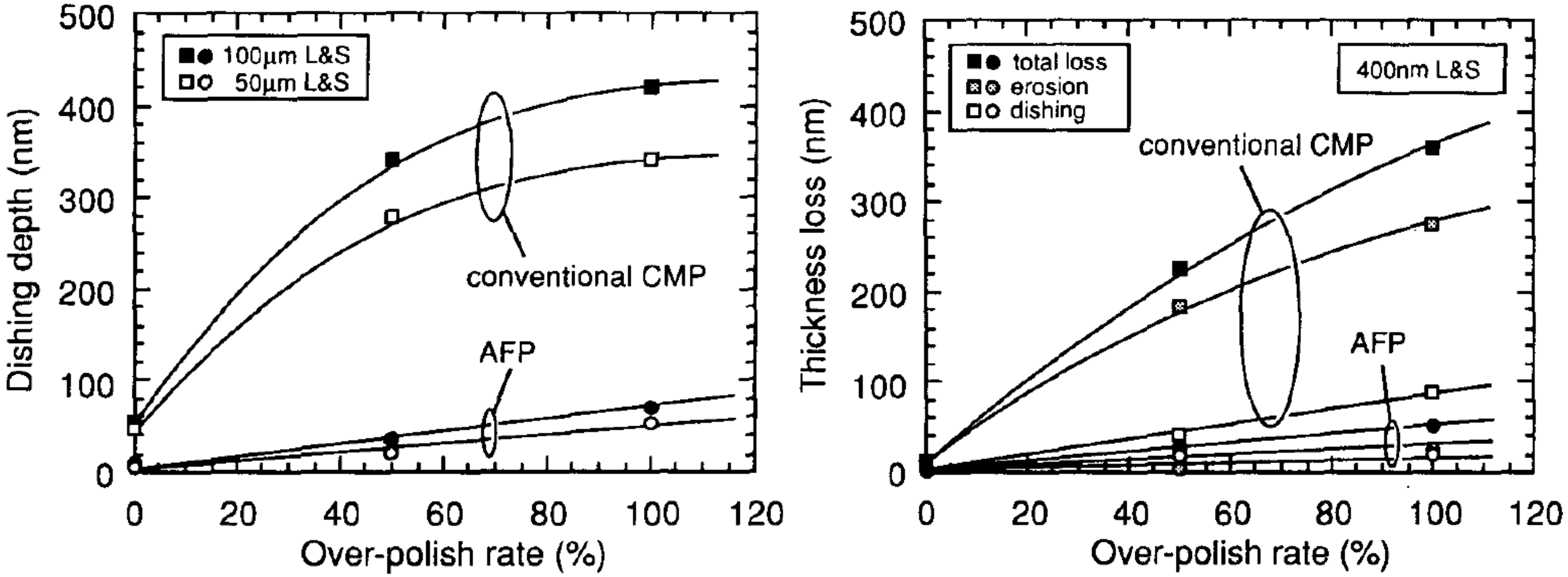
Region II

Region I

Threshold Pressure

Ohashi et al.
(Hitachi), *IITC 2001.*

Goal: Modeling Pattern Dependencies with Alternative Consumables



Kondo et al. (Hitachi), *IITC 2000.*

- Dishing and erosion substantially reduced but still present: ~500 Å
  - Pattern dependencies (density, feature size) remain
- Interactions with high density regions (e.g. plating overfill and topography) also need to be modeled

Outline

- Review: Prestonian Removal Rate Dependence on Pressure
- Alternative Slurries: Non-Prestonian Pressure Dependence

- **Issue: How model pattern dependence of non-Prestonian slurries?**
- **Review Existing Pattern Dependent Model**
  - **Removal Rate Diagrams: Rate vs. Step Height and Pattern Density**
- **Model Extension:**
  - **Pressure vs. Step Height and Pattern Density**
  - **Removal Rate vs. Pressure Dependence**

- Application in Contact Wear Models
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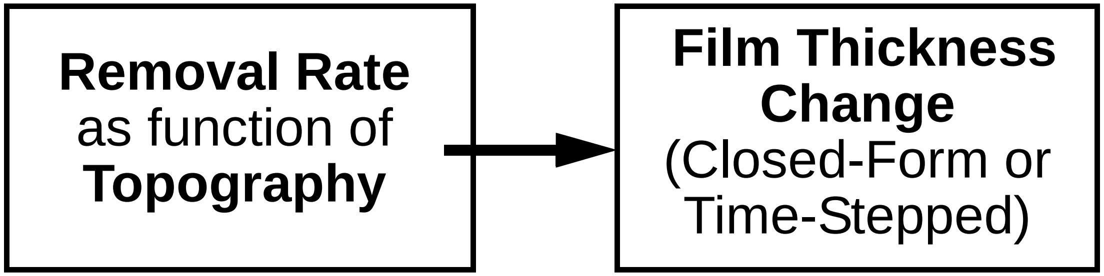
Pattern Dependent Modeling - Effects and Approach

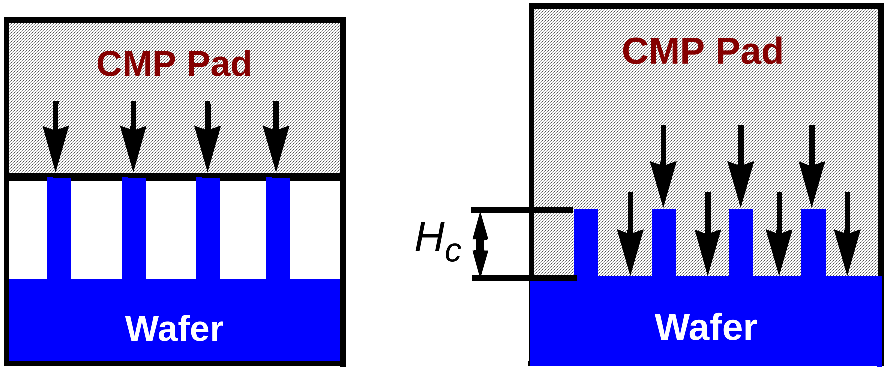


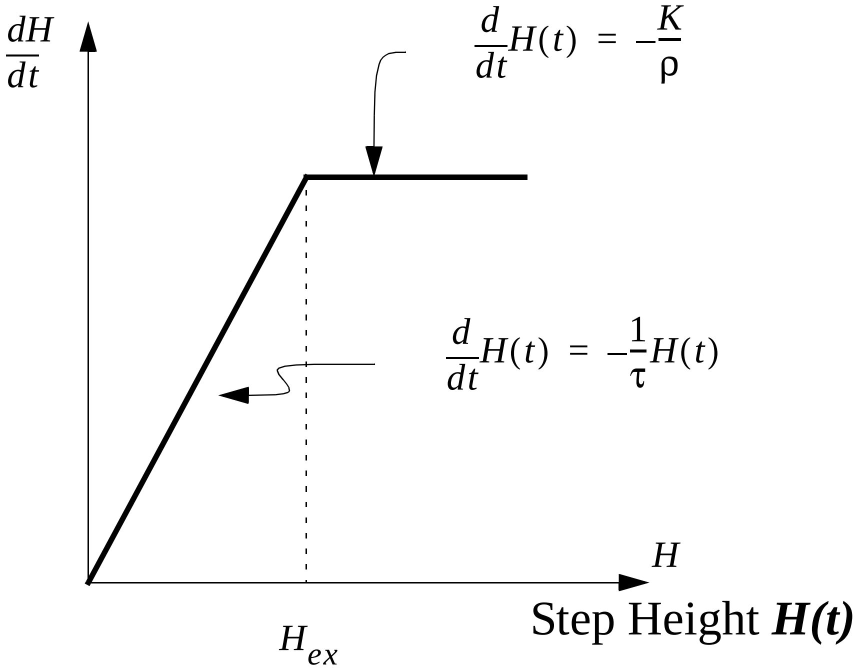
Removal Rate
as function of
Topography

Film Thickness Change
(Closed-Form or Time-Stepped)

- Pattern density effects
  - Topography differences from deposition over/into patterned features
  - Die-level variation due to volumetric removal rate differences
- Step height effects
  - Accurate modeling of step height reduction needed for improved down area prediction
  - Critical for in-laid processes to model dishing into features

Step Height Dependence





- For large step heights:
  - step height reduction goes as 1/pattern-density
  - height decays linearly with time:

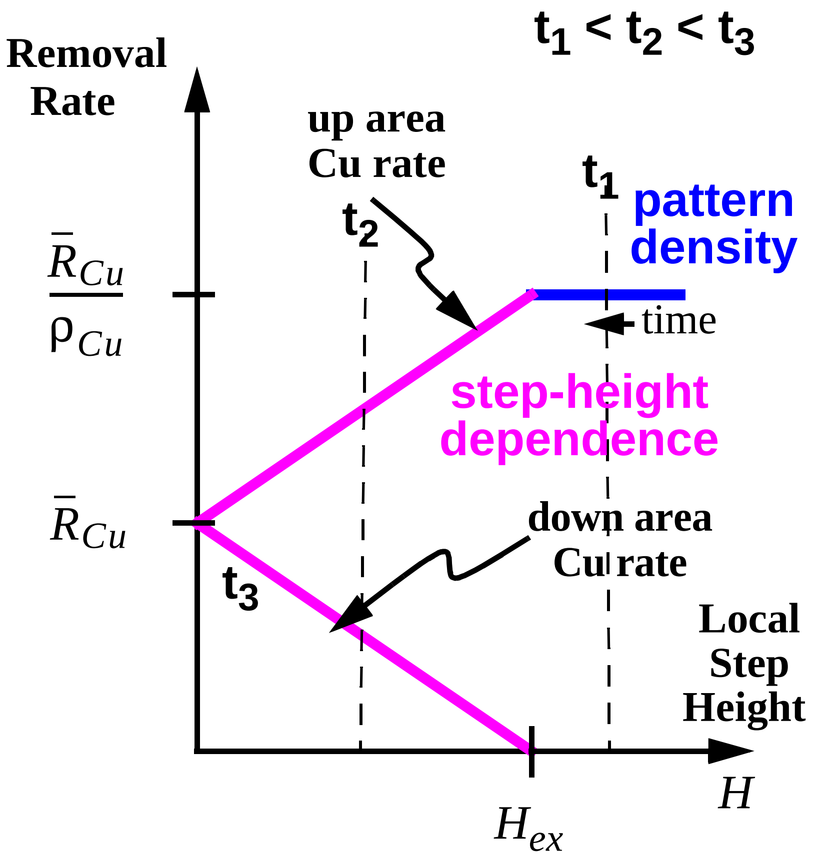
$$H(t) = H_0 - \frac{K}{\rho}t$$

- For small step heights (less than the "contact height"):
  - height reduction rate is proportional to height
  - height decays with time constant τ:

$$H(t) = H_{ex}e^{-(t-t_c)/\tau}$$

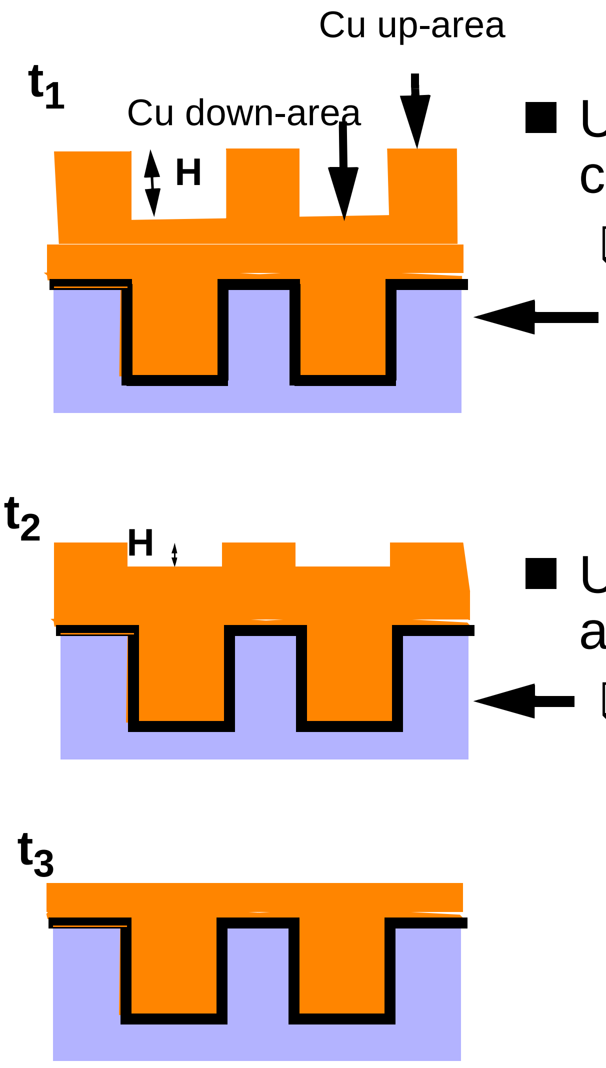
Grillaert et al., *CMP-MIC '98,*
Ouma et al., *IITC '98*;
Smith et al., *CMPMIC '99*

Removal Rate Diagrams - Planarization



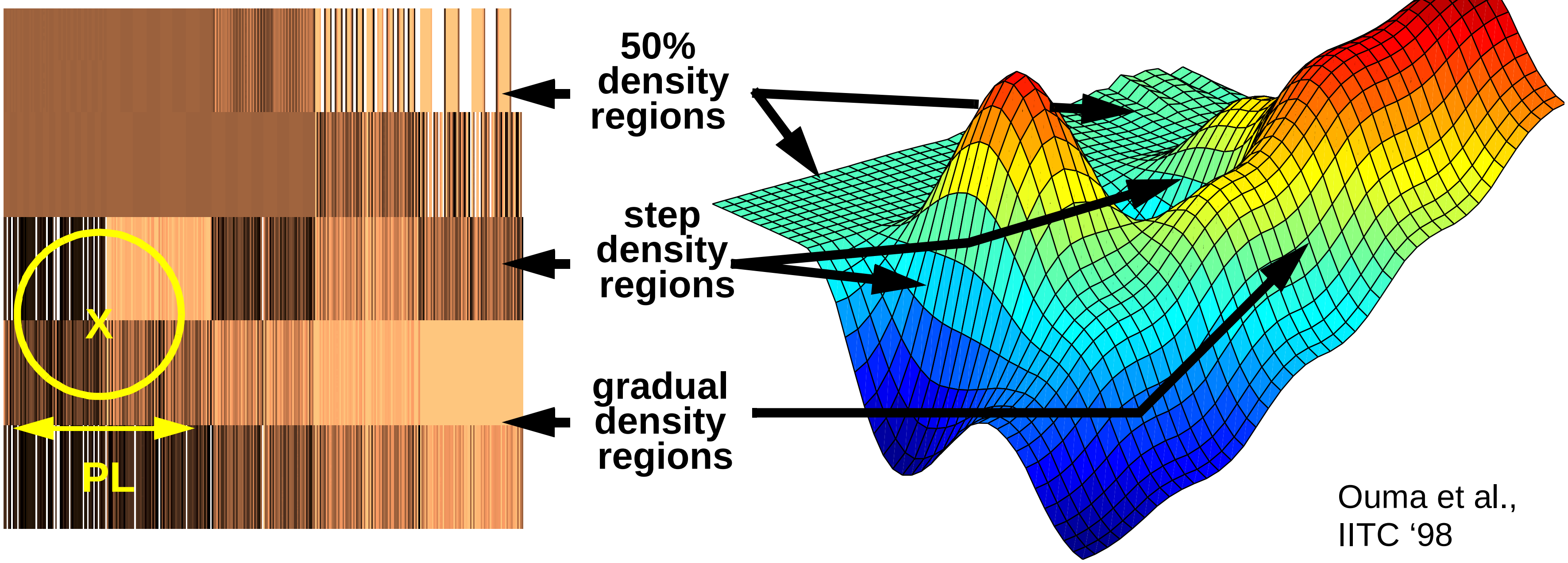
- Generates observed step height reduction:

$$-\frac{dH}{dt} = RR_{up} - RR_{down}$$



- Up area contact only:
  - Rate depends on pattern density
- Up and down area contact:
  - Rates depend on step height

Effective Density Calculation



MIT Integrated Dielectric Characterization Mask

Post-CMP Oxide Thickness (Up Areas)

50% density regions

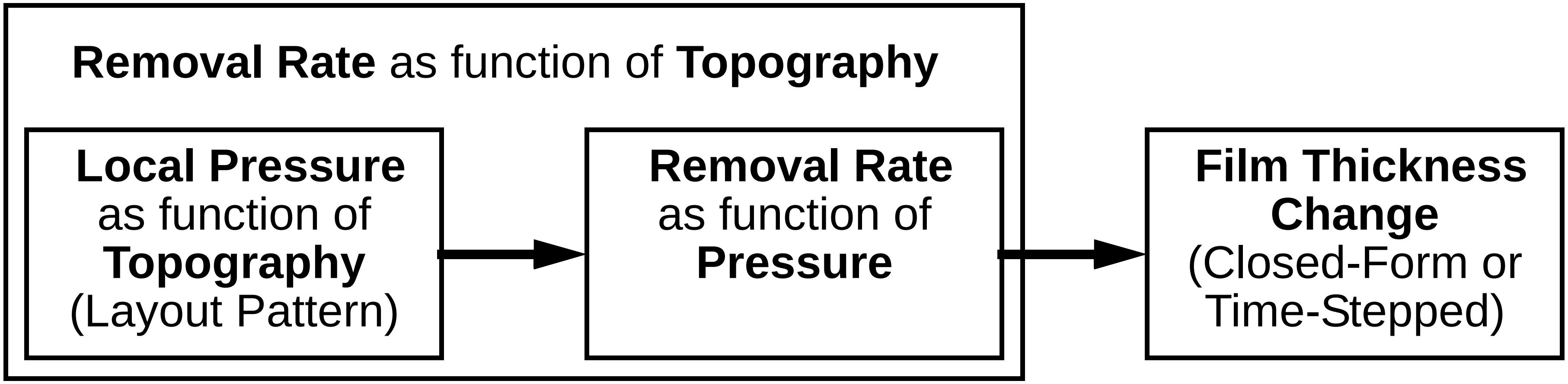
step density regions

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: $RR = \dfrac{K}{\rho(x, y, PL)}$

Pattern Dependent Modeling - Generic Approach



Removal Rate as function of **Topography**

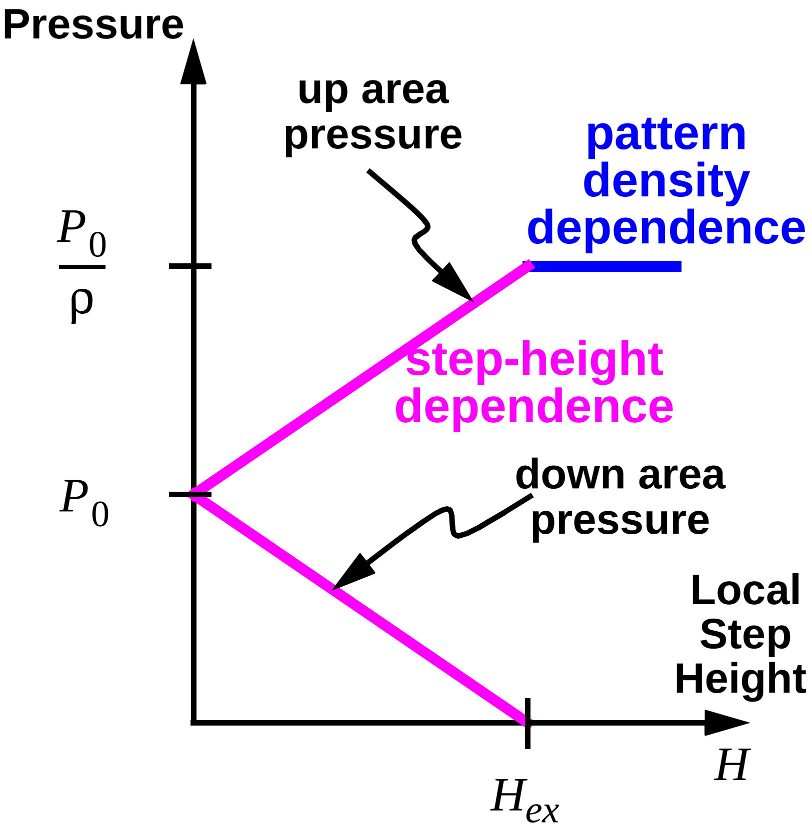
Local Pressure as function of **Topography** (Layout Pattern)

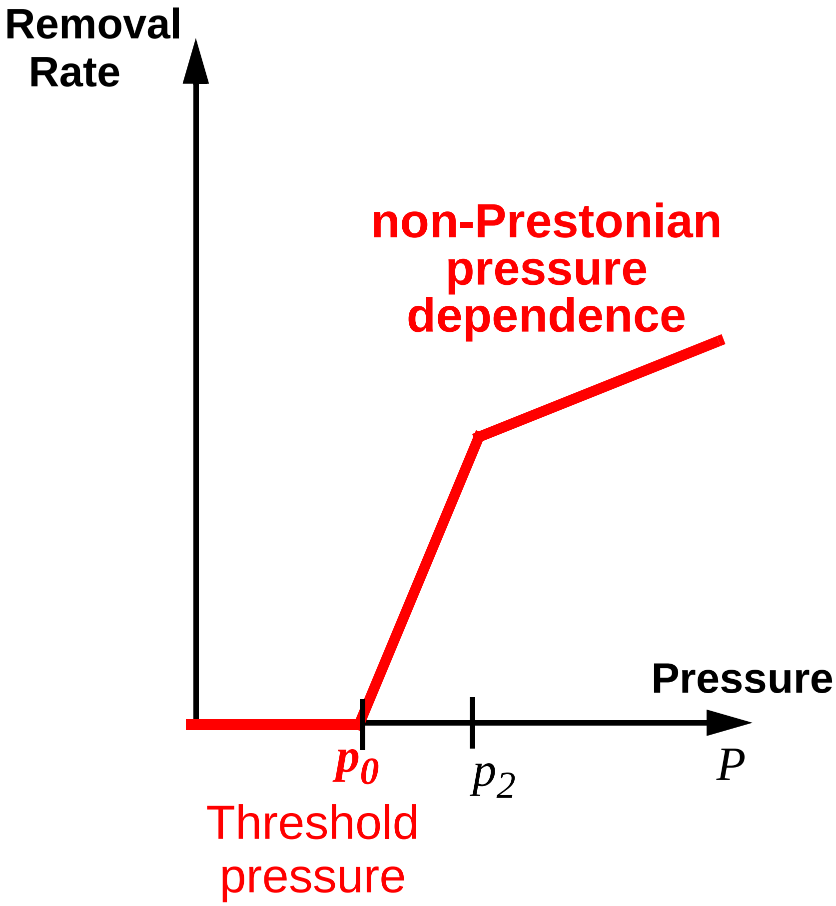
Removal Rate as function of **Pressure**

Film Thickness Change (Closed-Form or Time-Stepped)

- Pressure Calculation Options:
  - Pattern Density and Step Height Model
  - Contact Mechanics Model
- Possible Removal Rate vs. Pressure Dependencies:
  - Linear (conventional or Prestonian)
  - Non-Linear (non-Prestonian)

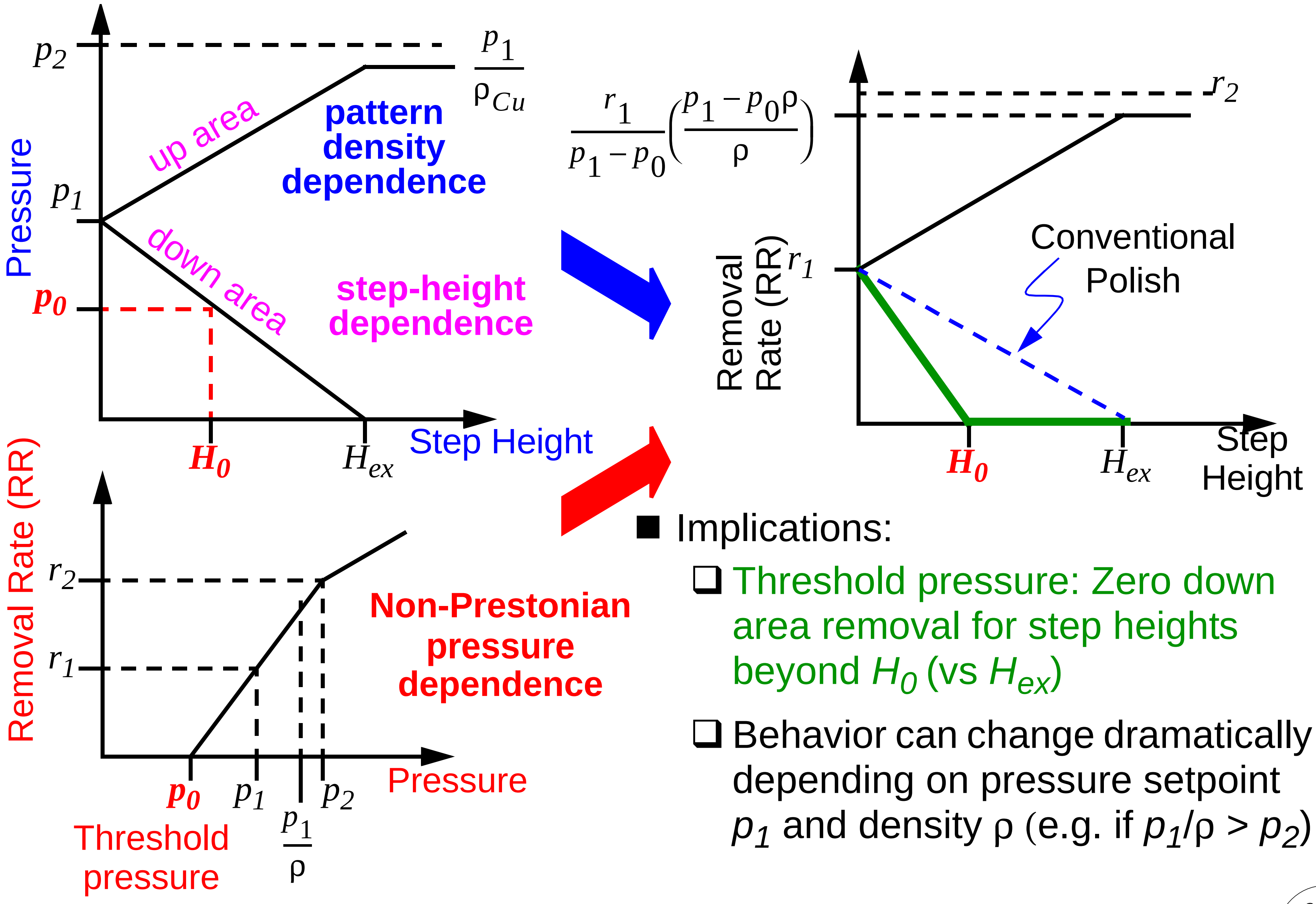
Splitting Removal Rate Diagrams





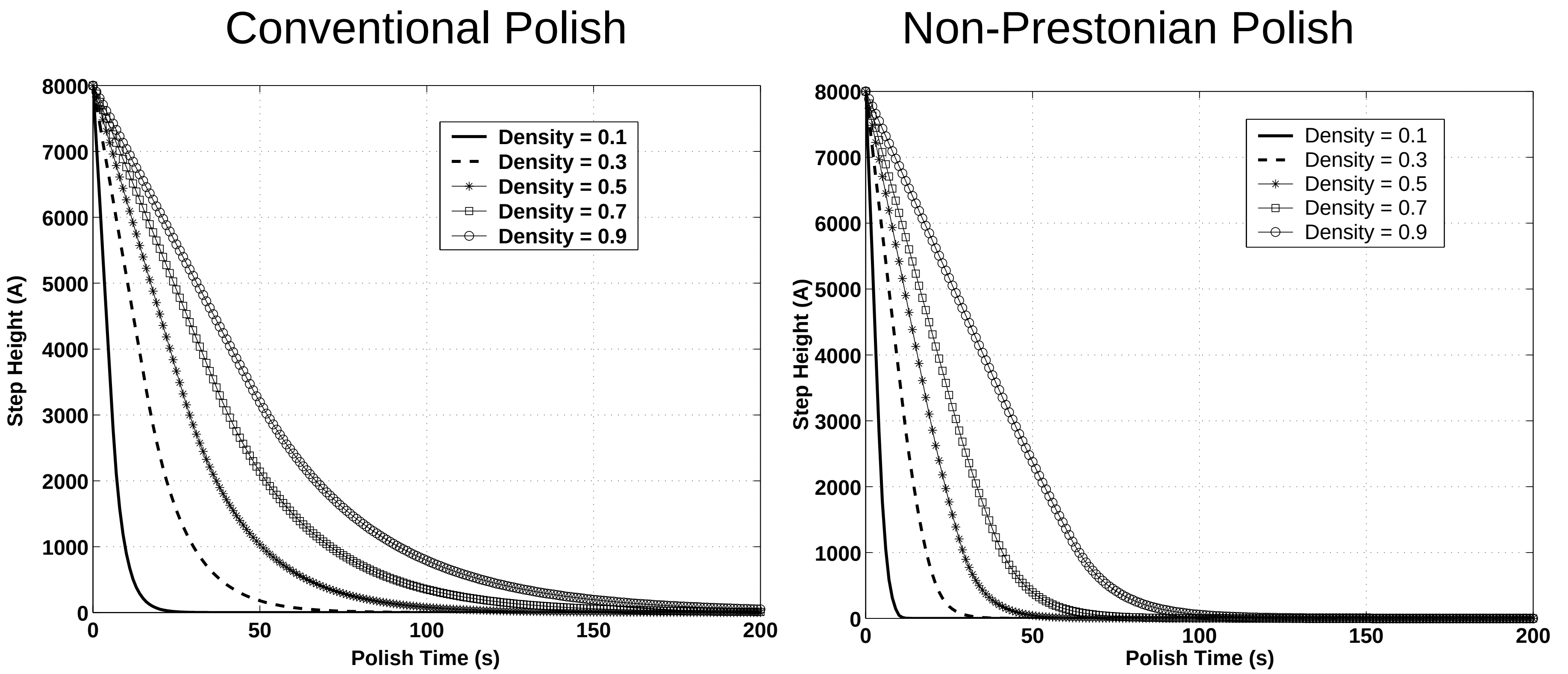
- Model key effects:
  - ☐ pattern density effect on up area pressure
  - ☐ step height effect on up/down area pressure
  - ☐ removal rate dependence on removal rate

Result: Extended Removal Rate Diagrams



- Implications:
  - ❑ Threshold pressure: Zero down area removal for step heights beyond H_0 (vs H_{ex})
  - ❑ Behavior can change dramatically depending on pressure setpoint p_1 and density ρ (e.g. if $p_1/\rho > p_2$)

Simulation: Density/Step Height Model

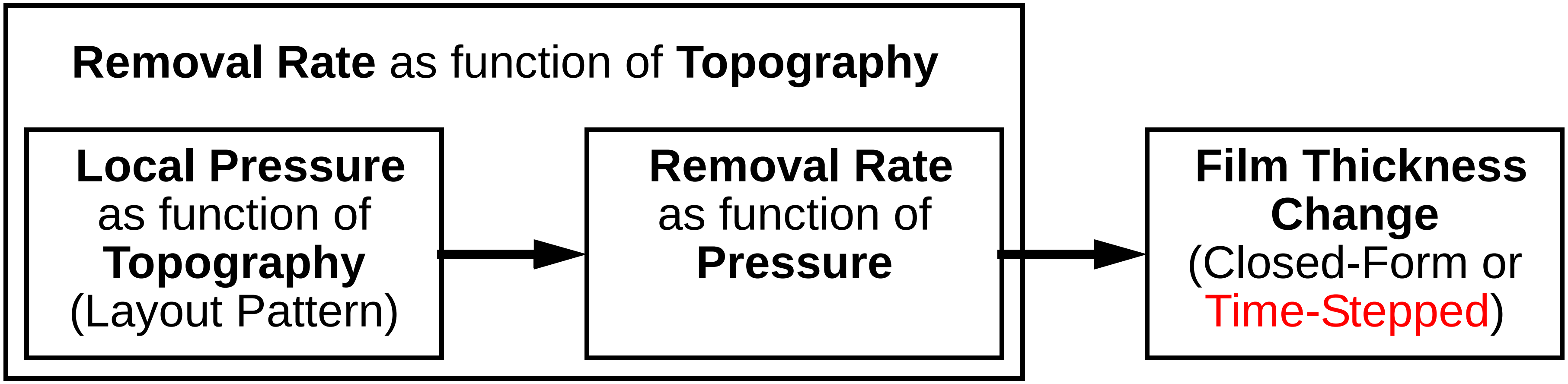


Conventional Polish

Non-Prestonian Polish

- Assumed non-Prestonian removal rate vs. pressure dependence:
  - ❑ p_0 = 3 psi, p_1 = 4.7 psi, p_2 = 6.5 psi; H_{ex} = 3500 Å
  - ❑ blanket removal rate r_1 (at nominal pressure p_1) = 5200 Å/min
- At these conditions -- improved (steeper) step height reduction

Pattern Dependent Modeling - Generic Approach



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Removal Rate as function of **Pressure**

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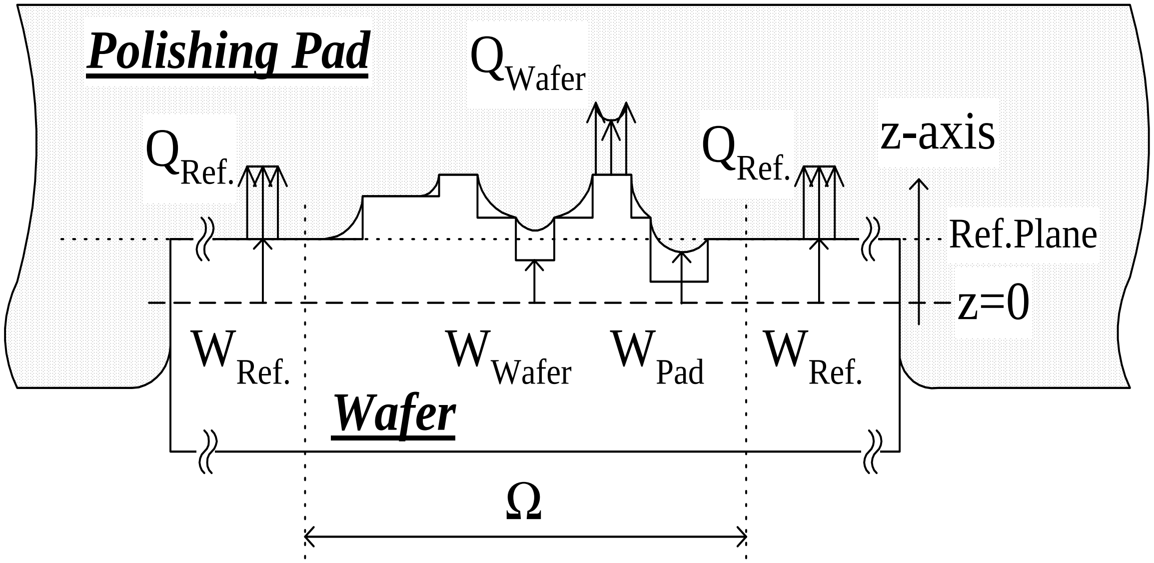
  - ☐ Pattern Density and Step Height Model
  - ☐ **Contact Mechanics Model**
- Possible Removal Rate vs. Pressure Dependencies:
  - ☐ Linear (conventional or Prestonian)
  - ☐ Non-Linear (non-Prestonian)

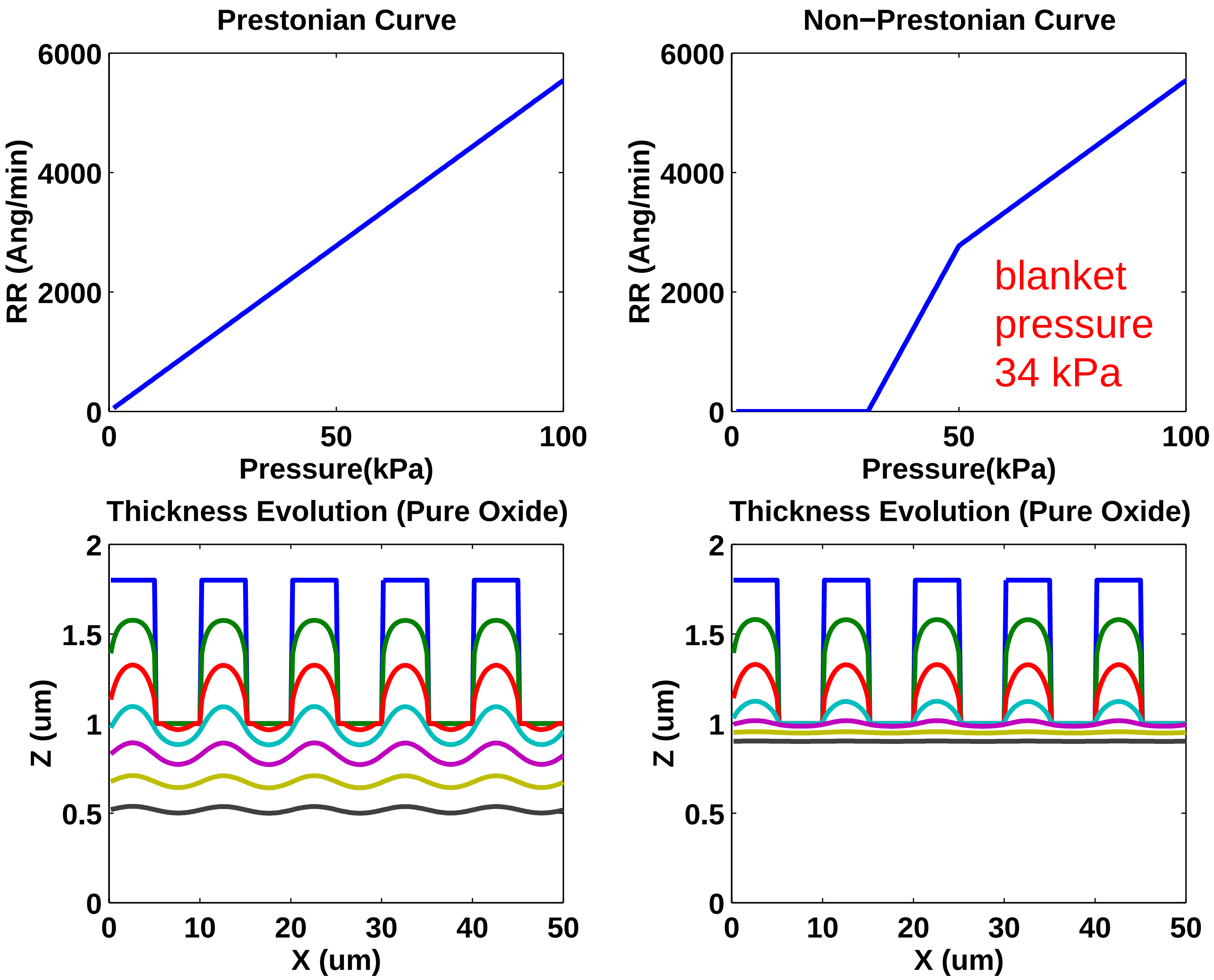
Contact Wear Model

- 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.

Simulation: Non-Prestonian Effects in Contact Wear Model


Prestonian Curve

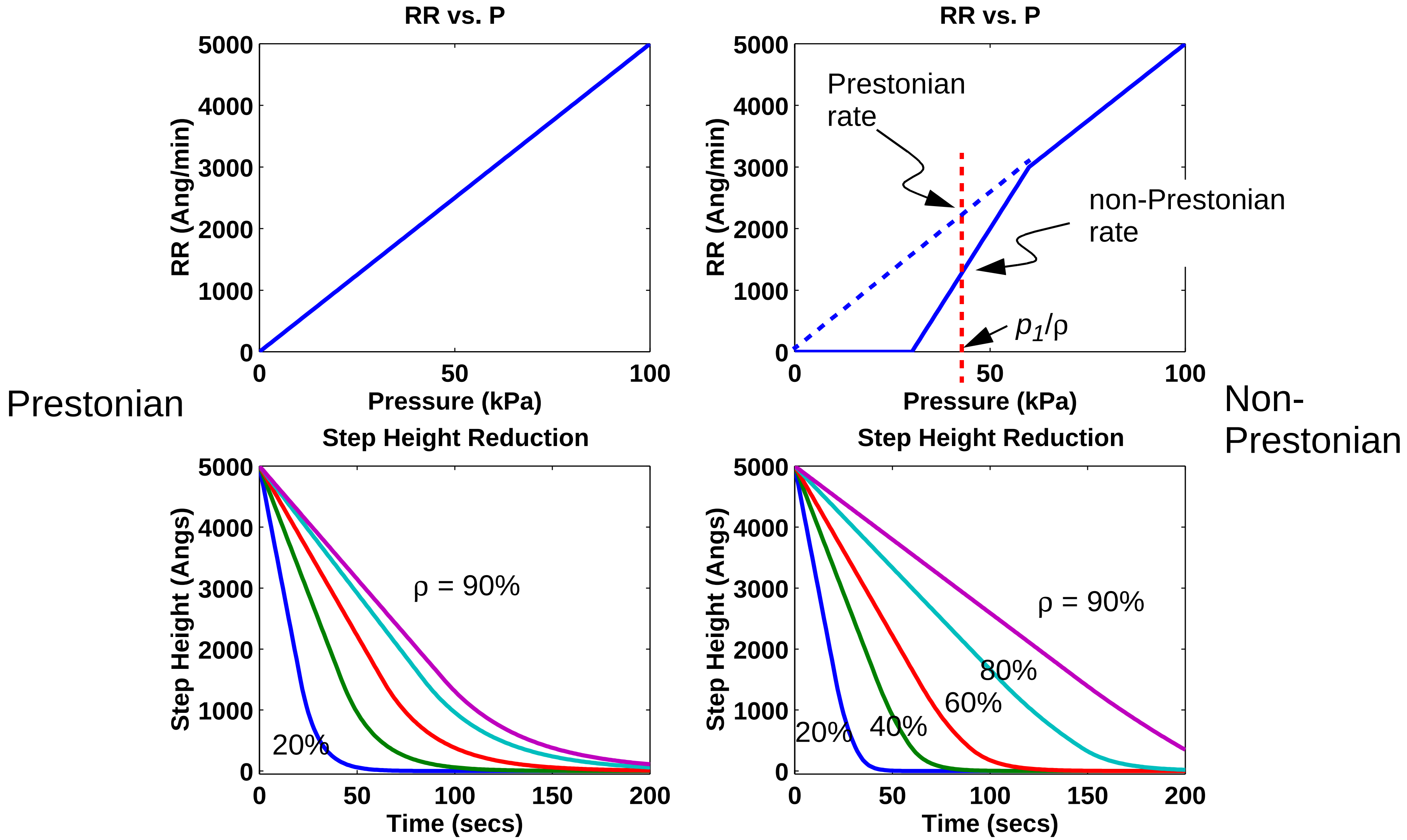
Non−Prestonian Curve

blanket pressure 34 kPa

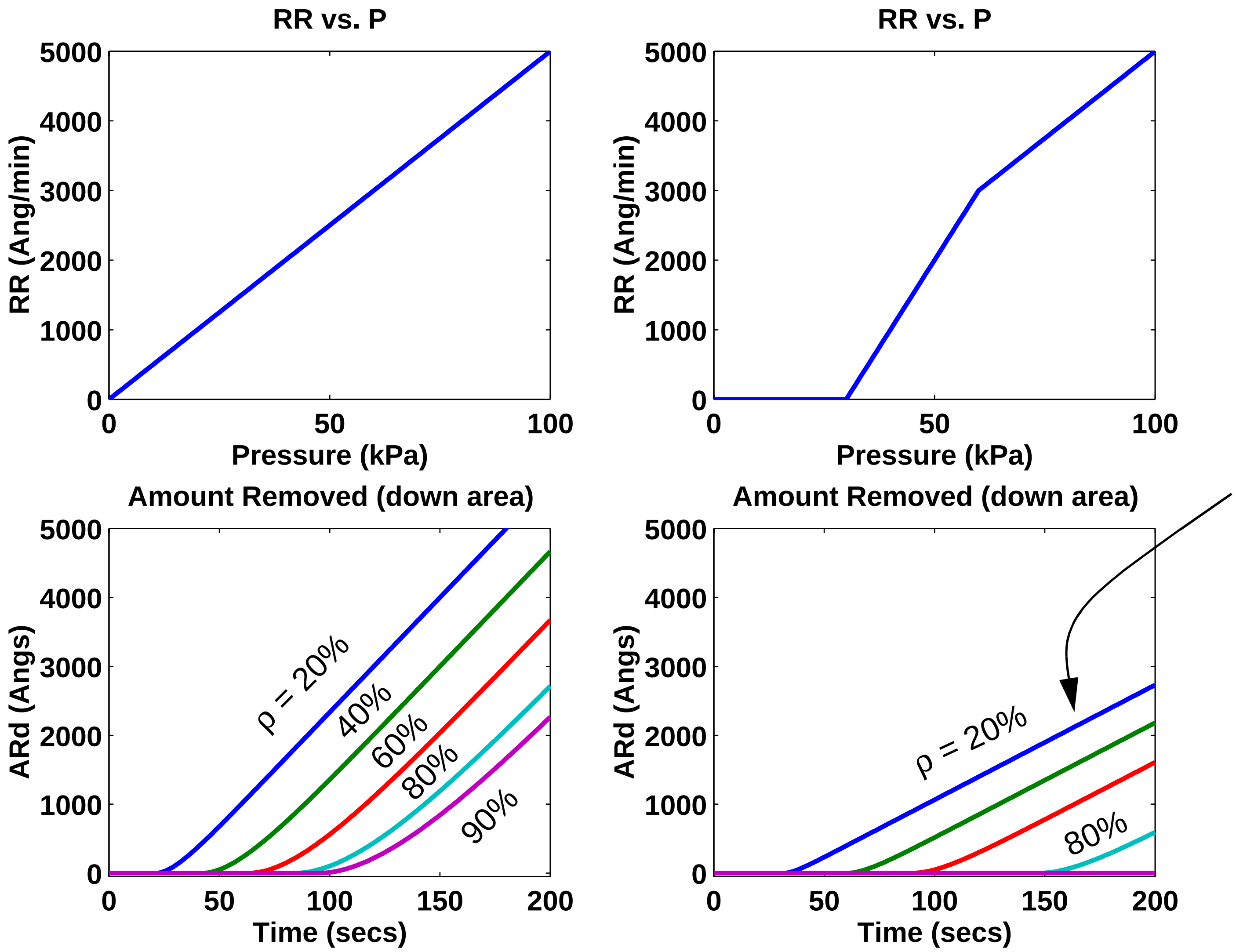
Thickness Evolution (Pure Oxide)

Thickness Evolution (Pure Oxide)

Note: Non-Prestonian Dependence Does Not Always Improve Step Height Reduction

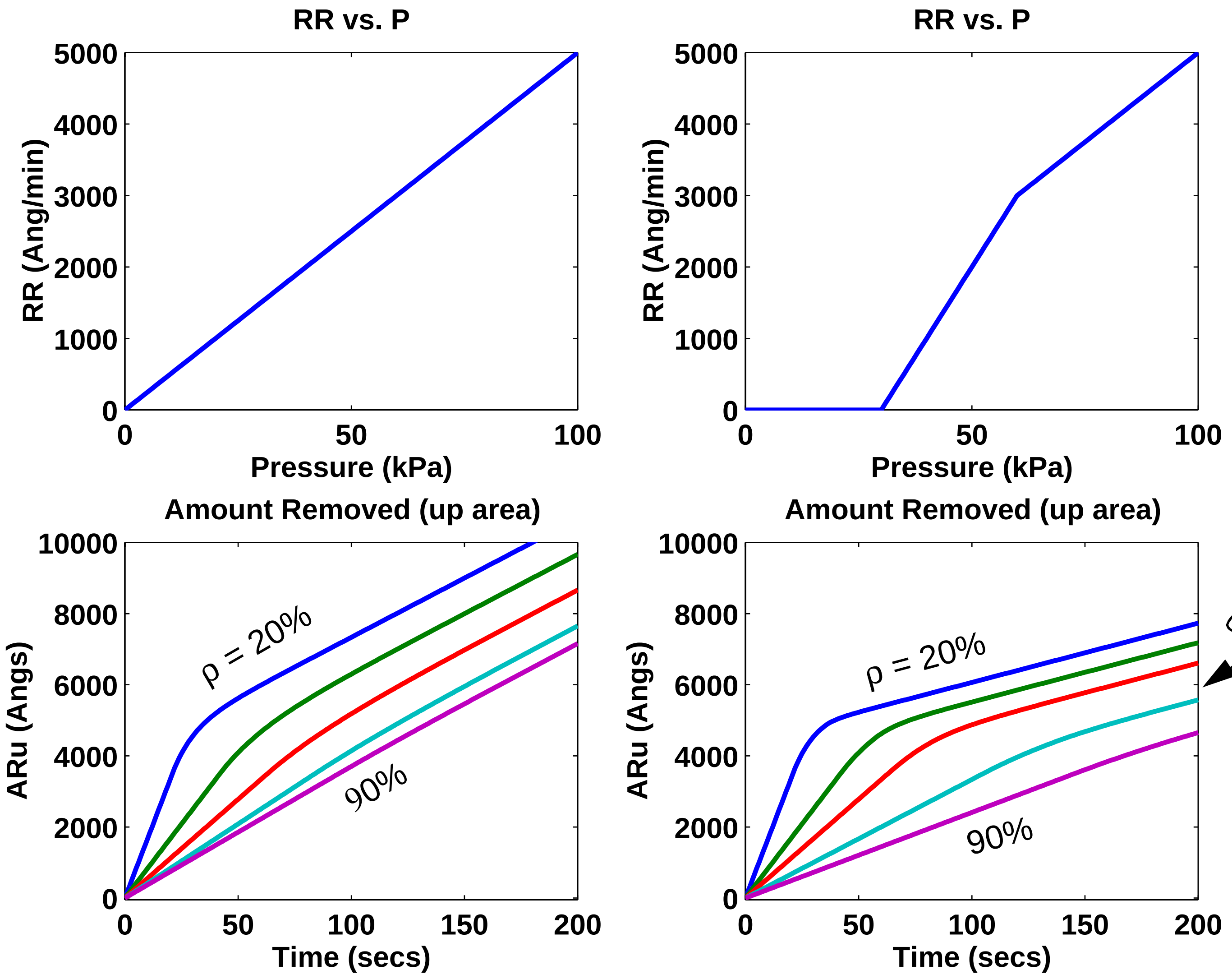


Example, Cont'd: Down Area Amount Removed



Less down area removal compared to Prestonian case (as desired), but ...

Example, Cont'd: Up Area Amount Removed



The up area rate is also lower than in Prestonian case, resulting in the slower step height reduction.

Summary - Modeling Non-Prestonian Effects

- Conventional Polish: Prestonian Removal Rate Dependence on Pressure
- Non-Prestonian Pressure Dependence:
  - Abrasive Free Polishing (AFP)
  - Threshold Pressure (Ceria/Surfactant)

- Modeling Approach
  - Calculations of Pressure for Given Topography
    - Step Height and Pattern Density Model
    - Contact Wear Model
  - Removal Rate vs. Pressure Dependence
    - Accommodate Arbitrary Dependence

- Current Work:
  - Use Model to Study Implications (e.g. good/bad operating points)
  - Apply to Dishing and Erosion Case: Copper Abrasive Free Polish
    - Expect real benefit of non-Prestonian case to be reduced dishing
  - Experimental Extraction and Validation of Extended Model