Nanometer Scale Patterning and Processing

Spring 2016

Lecture 48

Planarization, Part 1

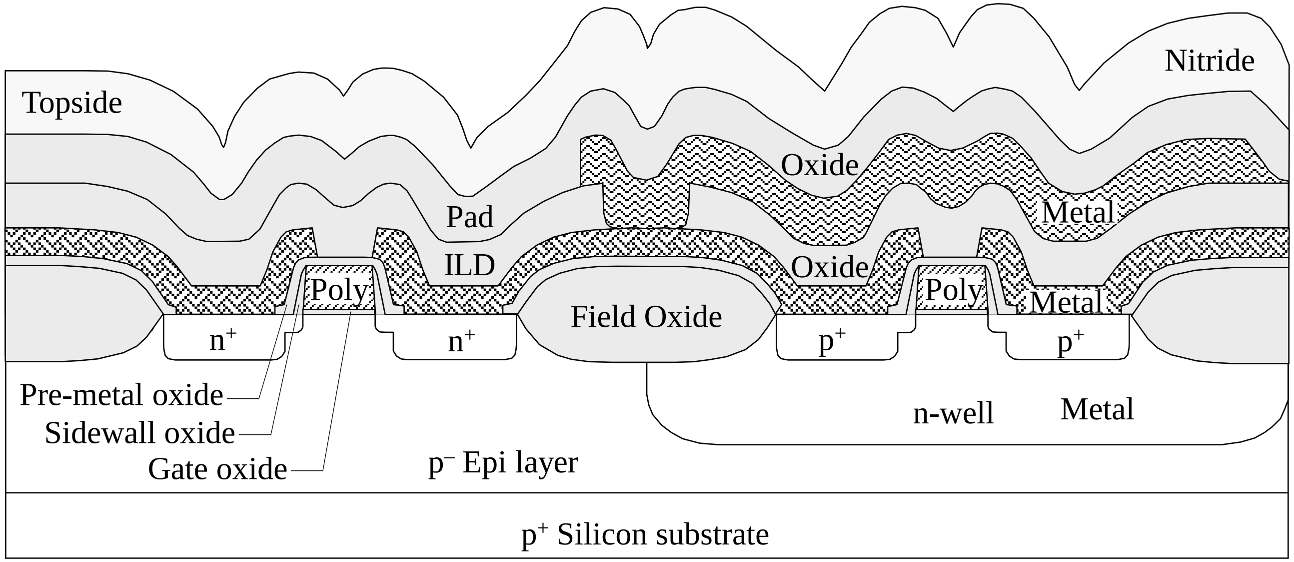
PLANARIZATION

ECE 695, Spring 2016

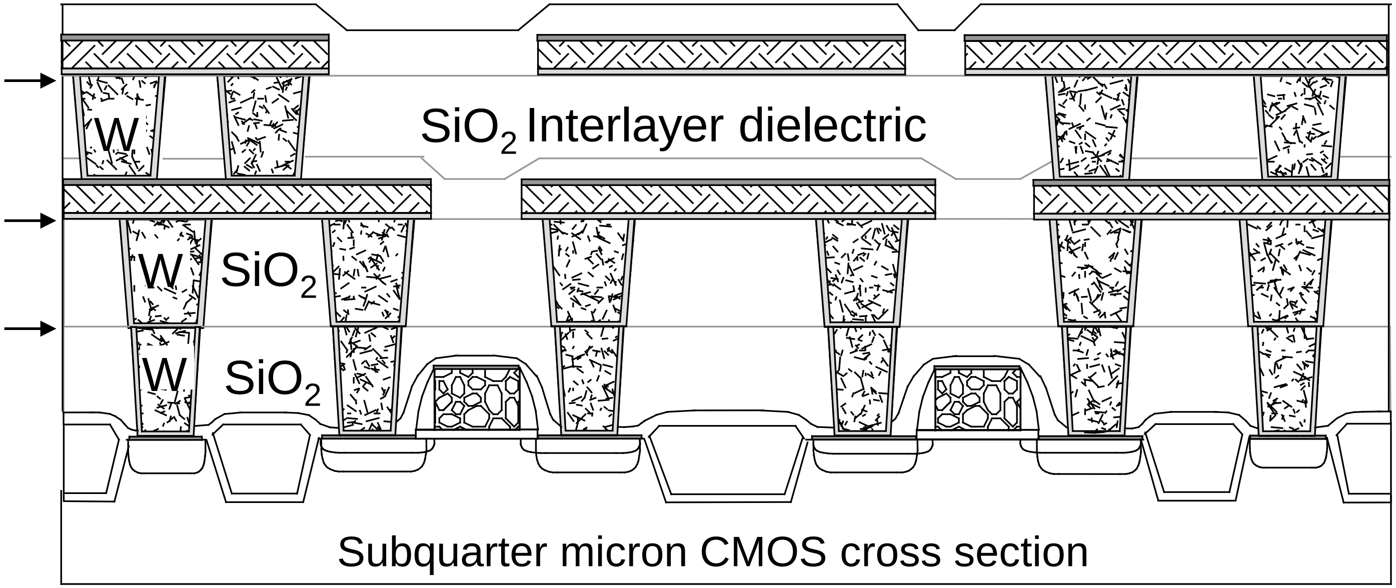
Minghao Qi

Why We Need Planarization?

Early integrated circuits have few metal interconnect layers



Planarized layers of oxide and tungsten

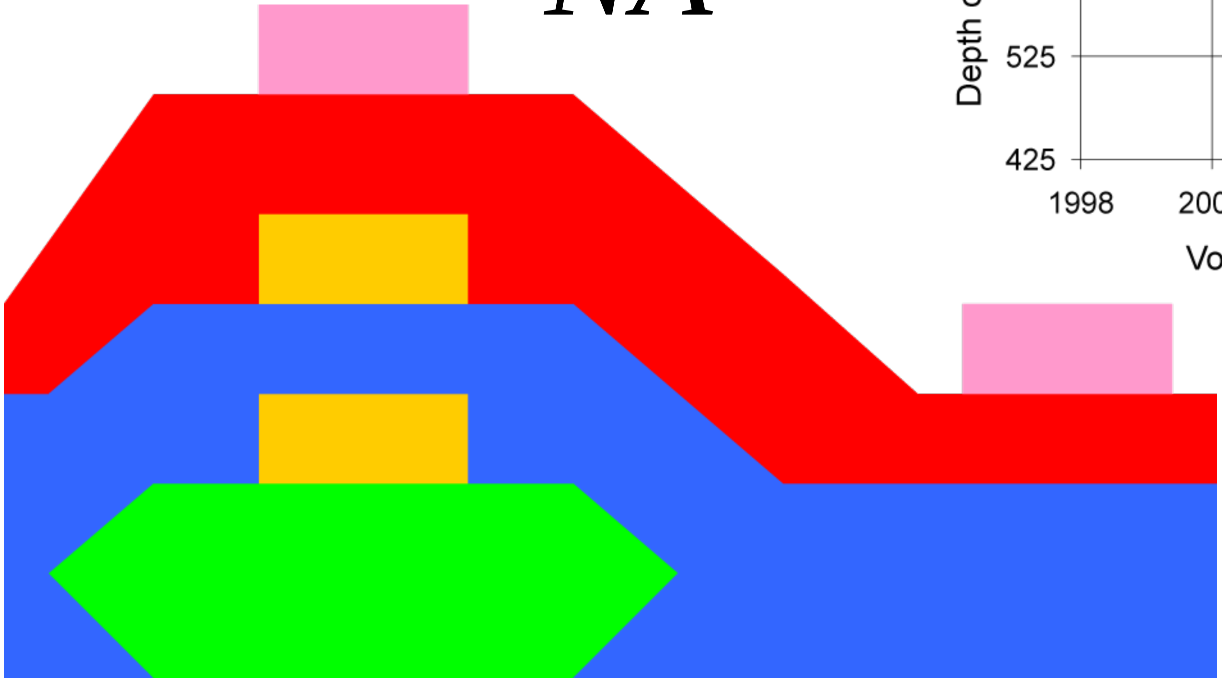


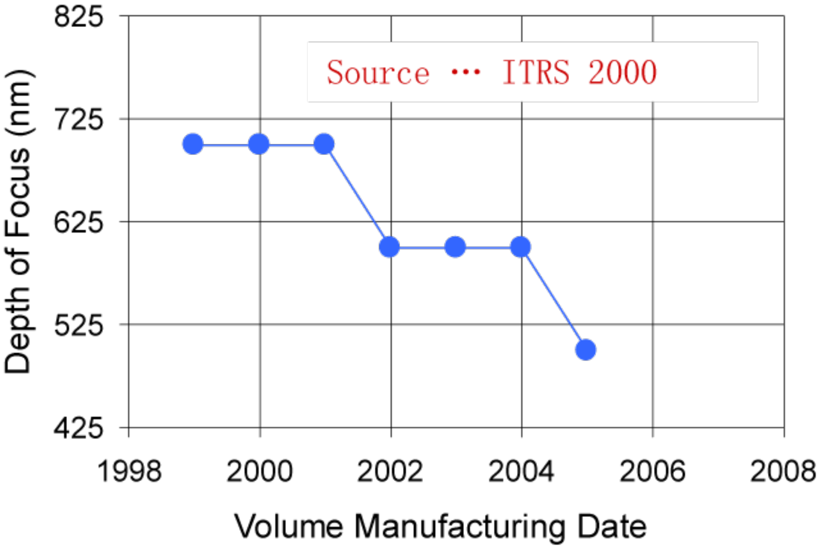
Subquarter micron CMOS cross section

Fig. 18.3 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

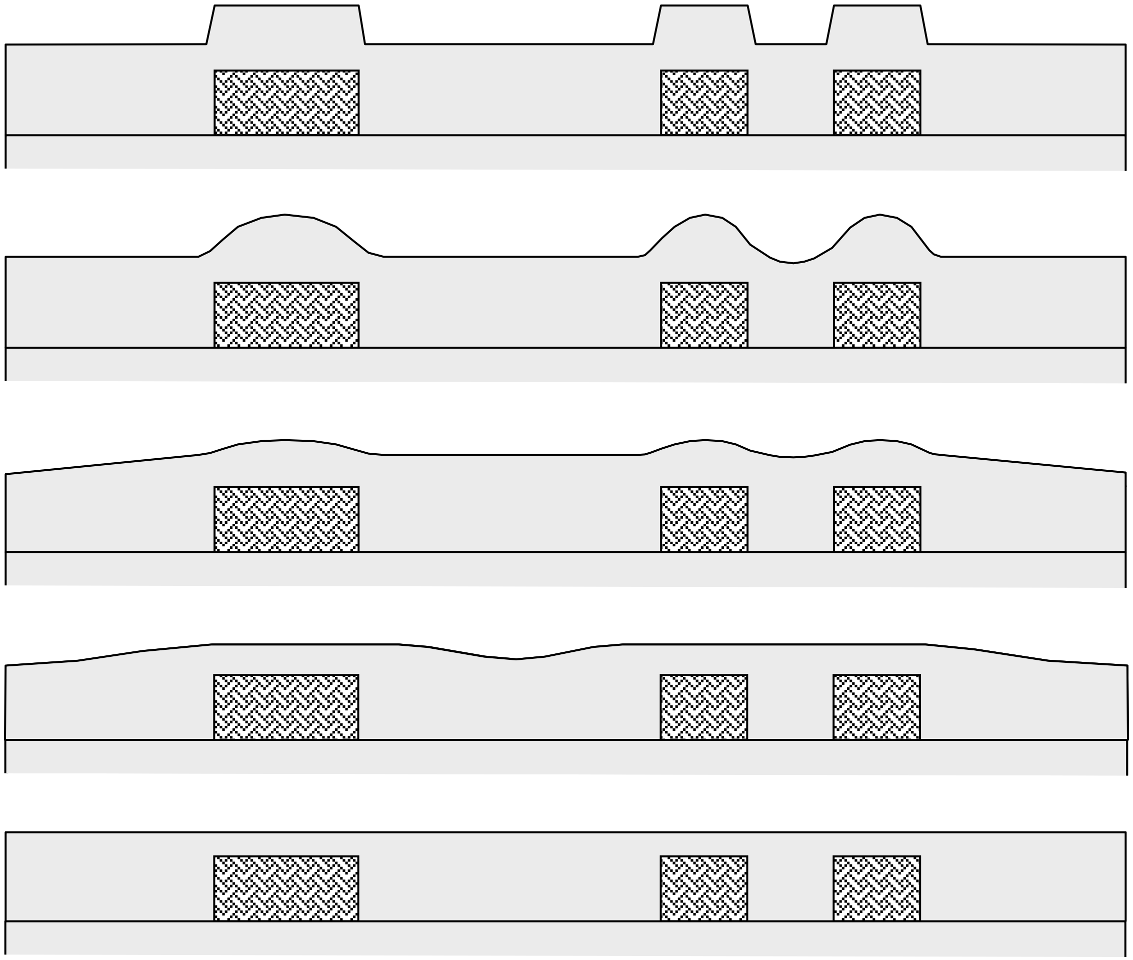
Depth of Focus (DOF) in Optical Lithography

$$DOF \propto \frac{\lambda}{NA^2}$$





Qualitative Definitions of Planarization



a) No planarization

b) Smoothing

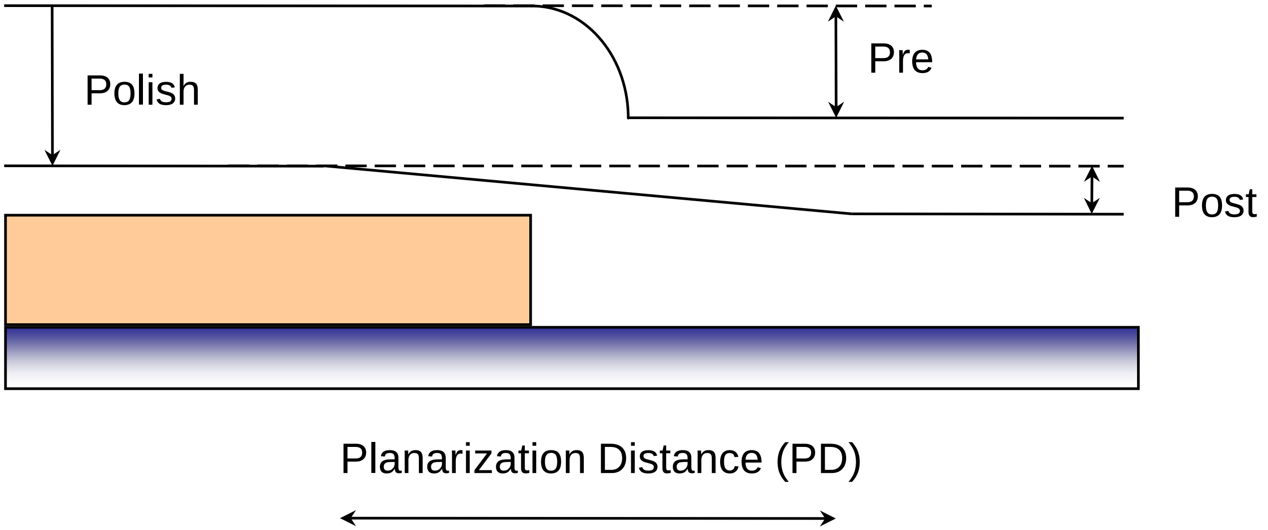
c) Partial planarization

d) Local planarization

e) Global planarization

Fig. 18.2 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Polishing and Planarity



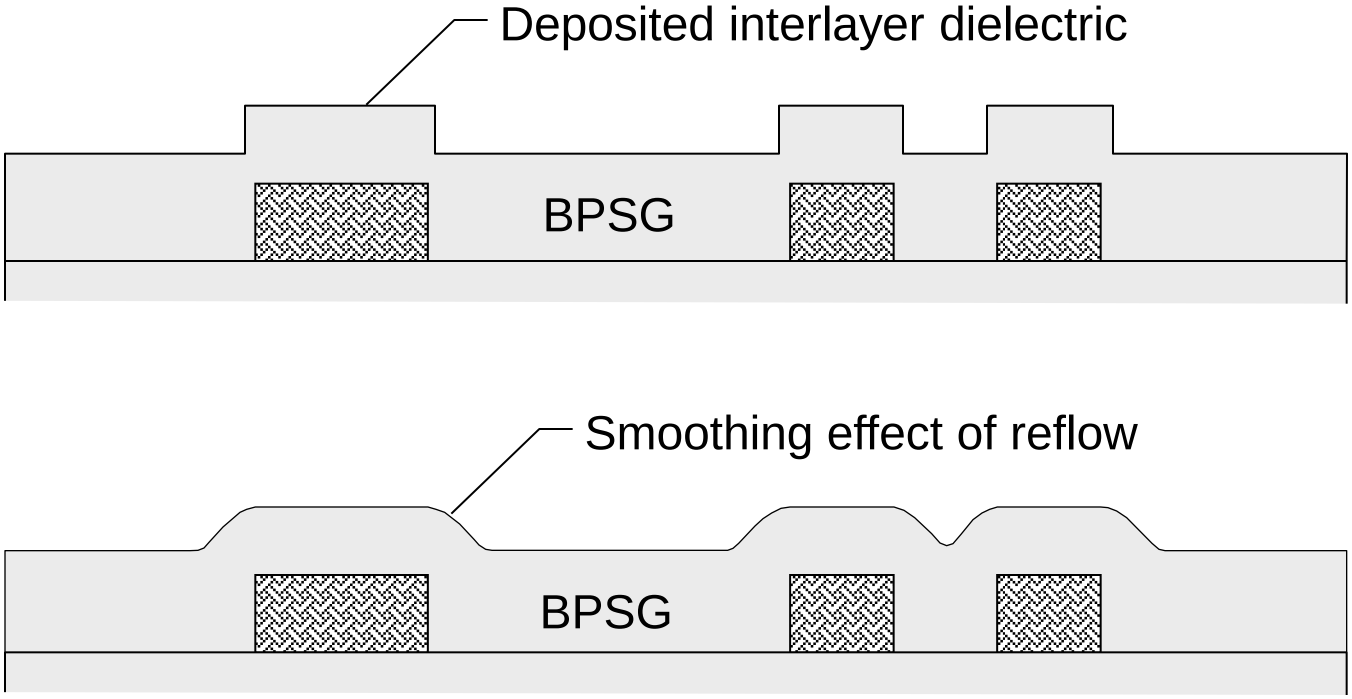
- Step Height Ratio (SHR) = Post Step Height / Pre Step Height.
- The goal is to minimize SHR and maximize Planarization Distance (PD).

Traditional Planarization Approaches

- Glass Reflow
- Spin-on-films
- Etchback after reflow or spin-on

- Uses available tools and processes
- Can not achieve “perfect and global flatness”
- Open loop and difficult to control

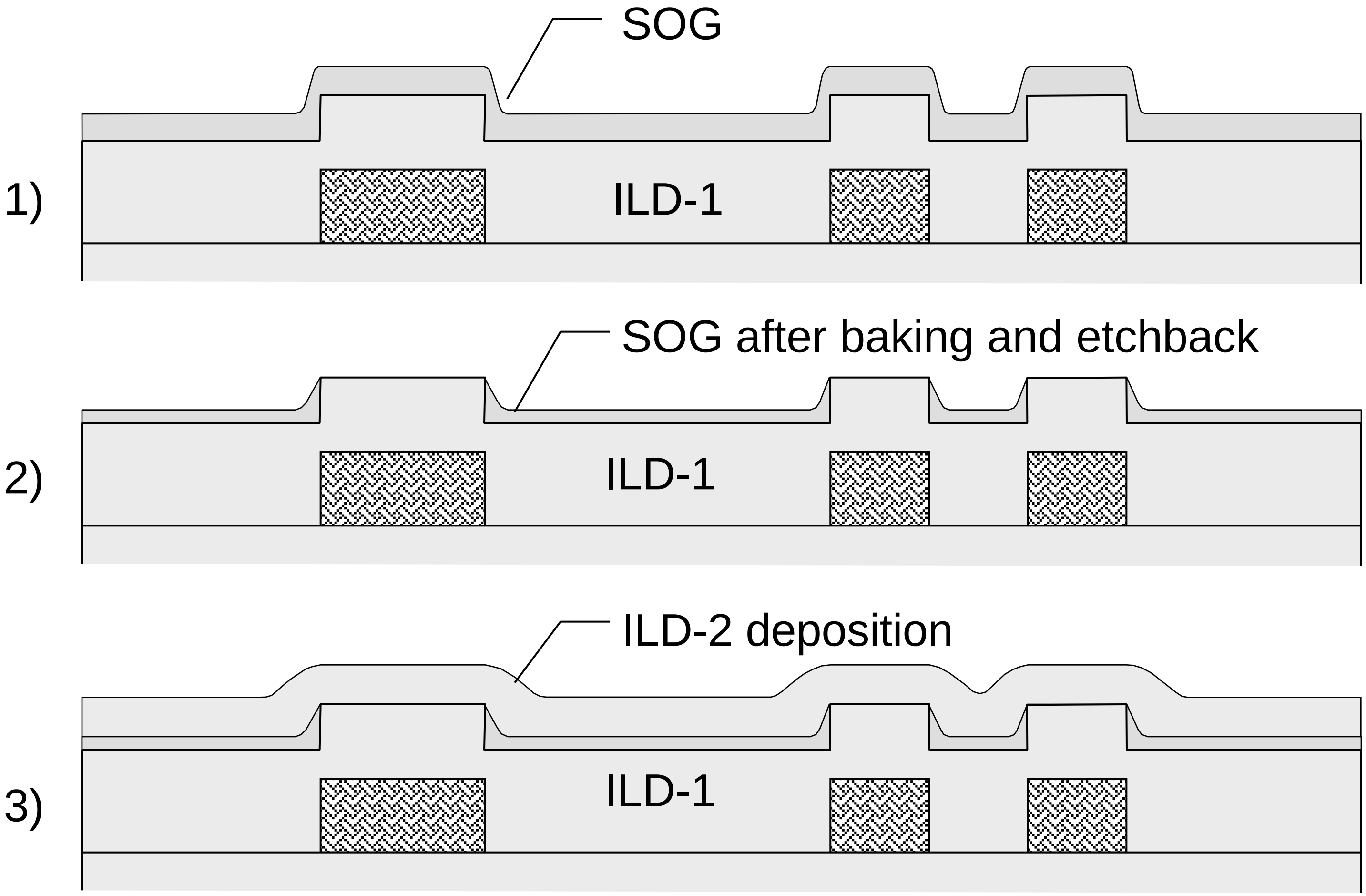
Reflow for Planarization



- BoroPhosphoSilicate Glass (BPSG) reflow
  - – BPSG has lower reflow temperature due to the doping of Boron and Phosphate

Fig. 18.6 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

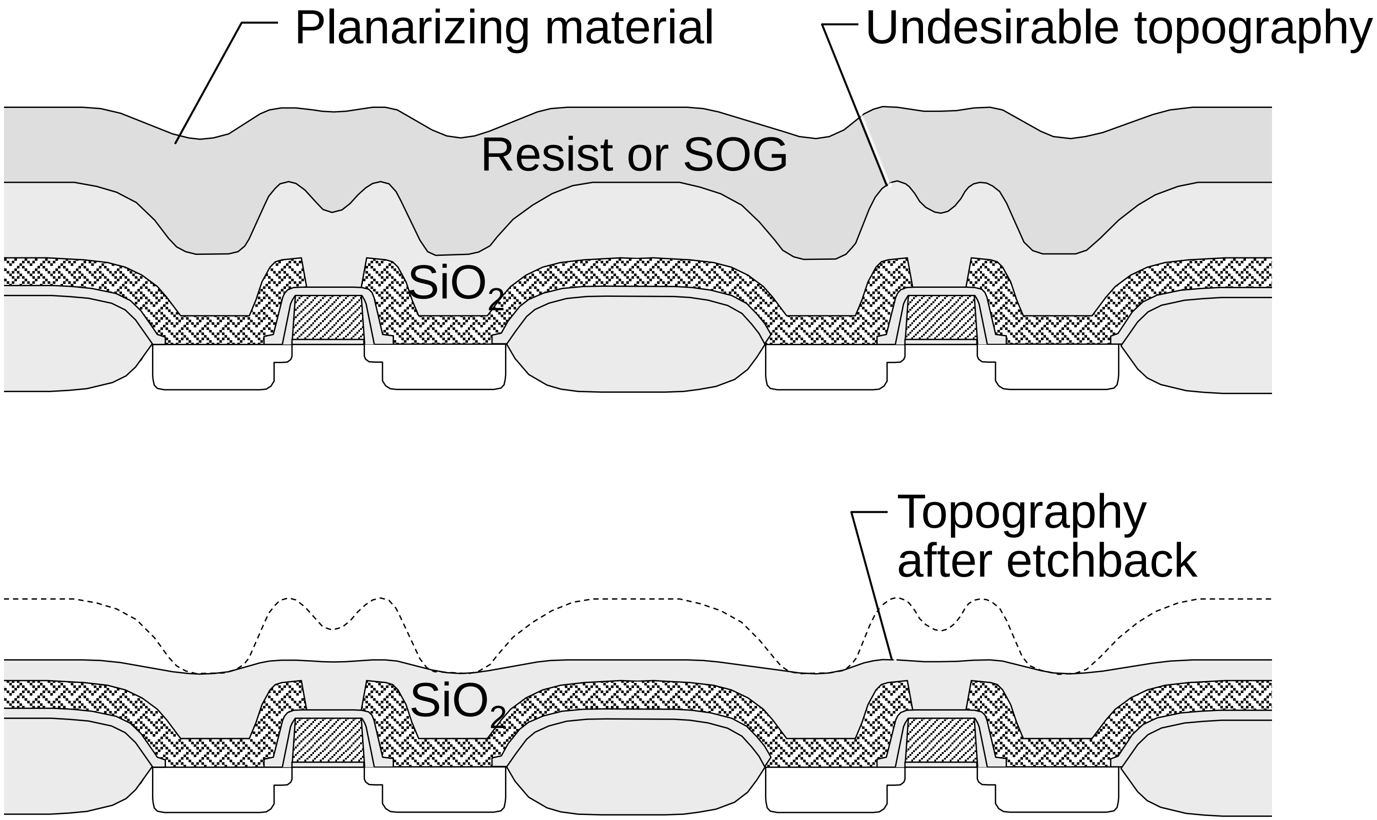
Spin-On Glass or Dielectrics



- Spin-on glass (SOG)
- Spin-on Dielectrics (SOD)
  - Hydrogensilsesquioxane (HSQ)

Fig. 18.7 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

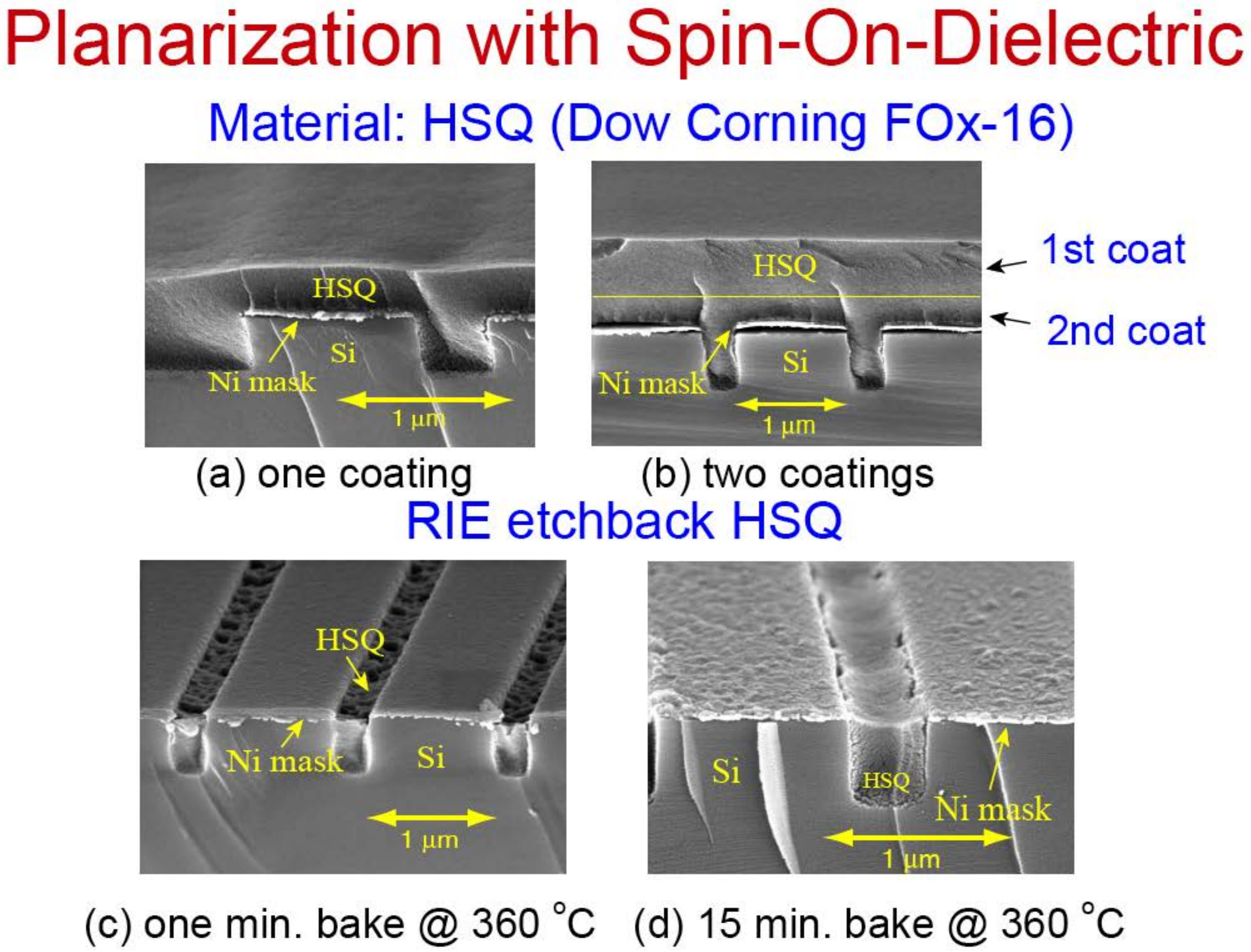
Etchback



- Difficult to control (open loop)

Fig. 18.5 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

SOG + Etchback: a Simple Alternative



Planarization with Spin-On-Dielectric

Material: HSQ (Dow Corning FOx-16)

(a) one coating (b) two coatings

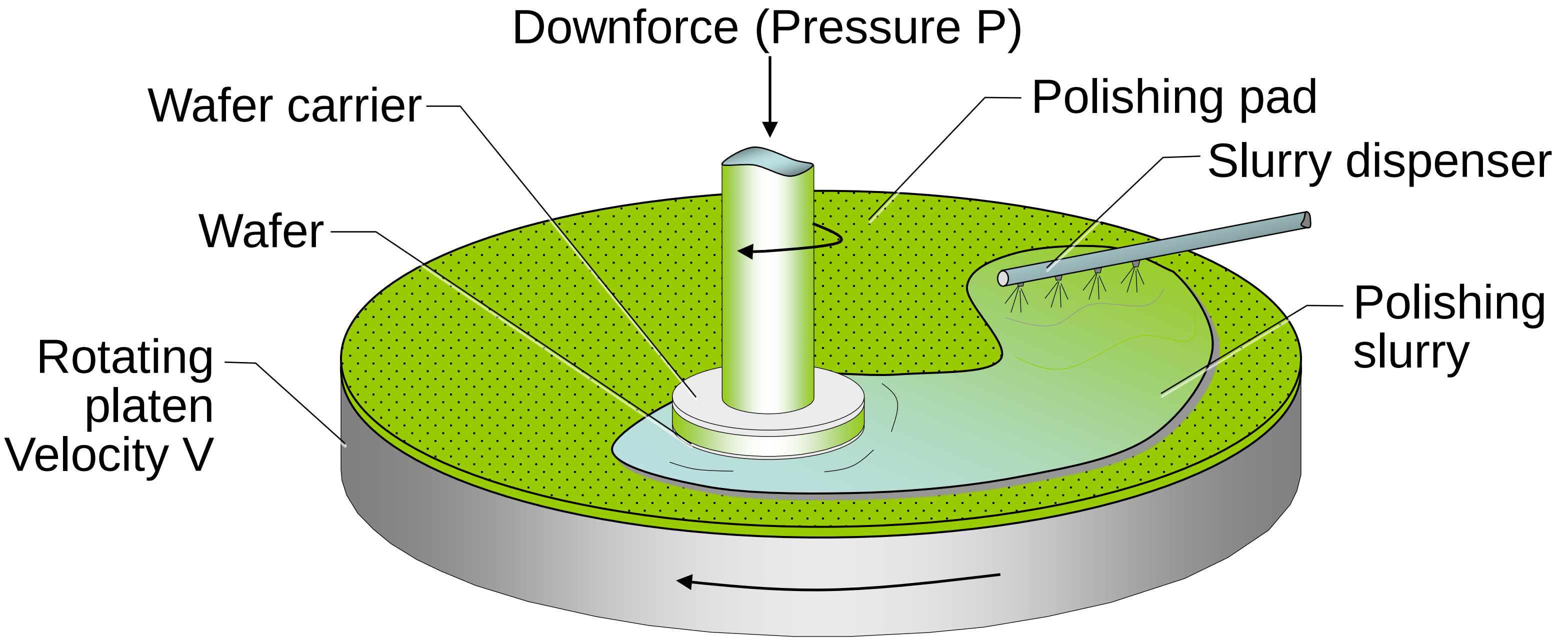
RIE etchback HSQ

(c) one min. bake @ 360 °C (d) 15 min. bake @ 360 °C

Chemical Mechanical Planarization (CMP)

- What is CMP?
  - CMP is a physical-chemical process used to make wafer surfaces locally (micrometer scale) and globally (millimeter scale) flat.
  - Chemical action
    - hydroxyl ions attack SiO_2 in oxide CMP, causing surface softening and chemical dissolution
    - oxidants enhance metal dissolution and control passivation in metal CMP
  - Mechanical action
    - polisher rotation and pressure

Chemical Mechanical Planarization (CMP)



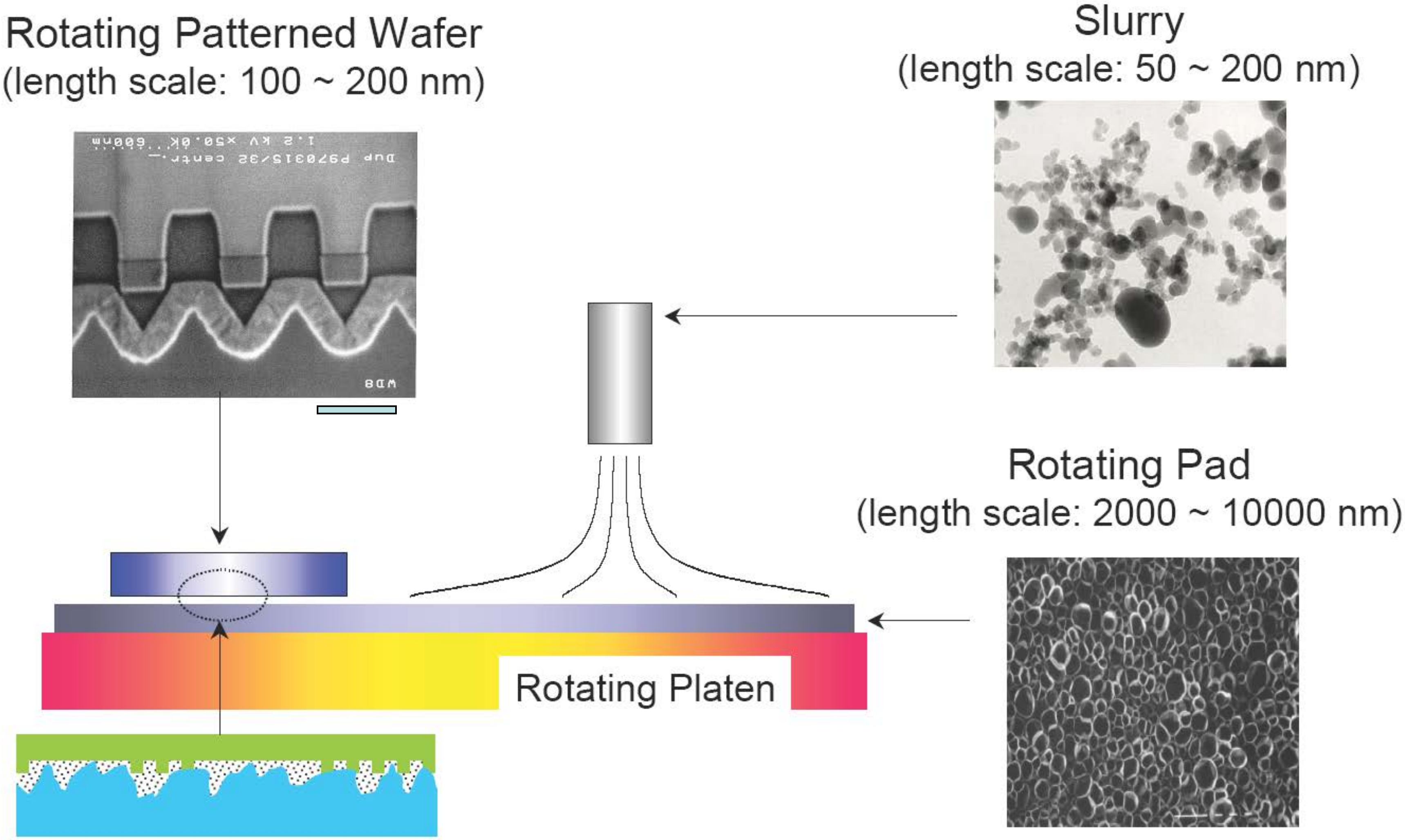
Preston Equation (Preston, F., J. Soc. Glass Technol., 11,247,(1927)).

Removal Rate = K_p*S*P

S =Relative Velocity, P = pressure and K_p is the proportionality constant.

Fig. 18.8 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Major CMP components



Rotating Patterned Wafer
(length scale: 100 ~ 200 nm)

Slurry
(length scale: 50 ~ 200 nm)

Rotating Pad
(length scale: 2000 ~ 10000 nm)

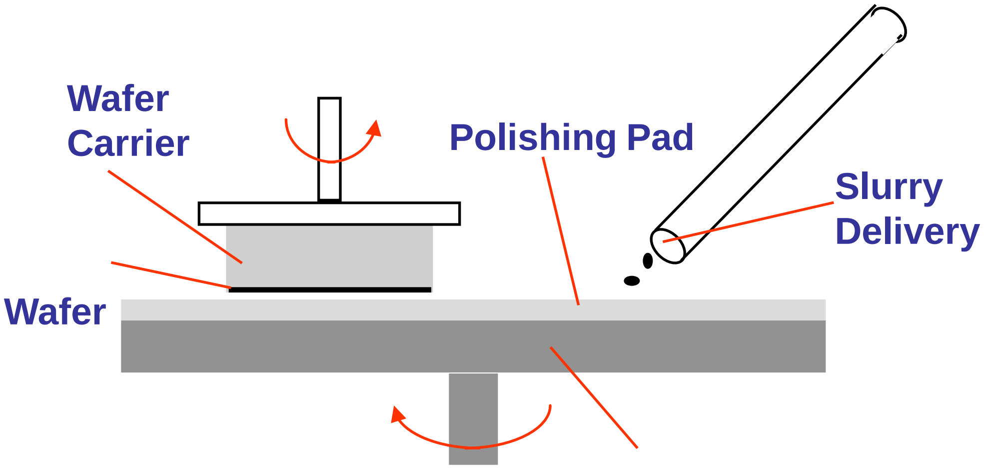
Rotating Platen

CMP Systems and Parameters

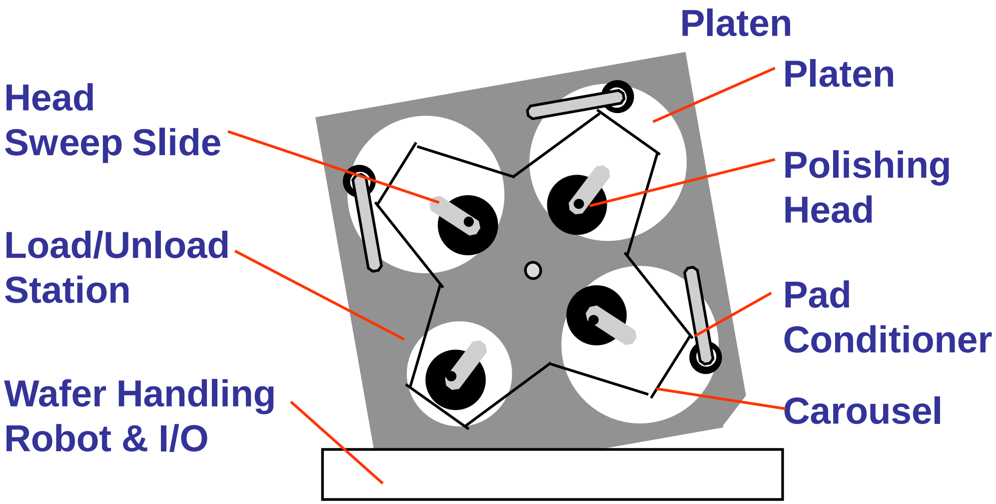
Backing (Carrier) Film
  Polyurethane
Pad
  Polyurethane
Pad Conditioner
  Abrasive

CMP (Oxide)
  Silica Slurry
  KOH *
  NH_4OH *
  H_2O
CMP (Metal)
  Alumina *
  $FeNO_3$

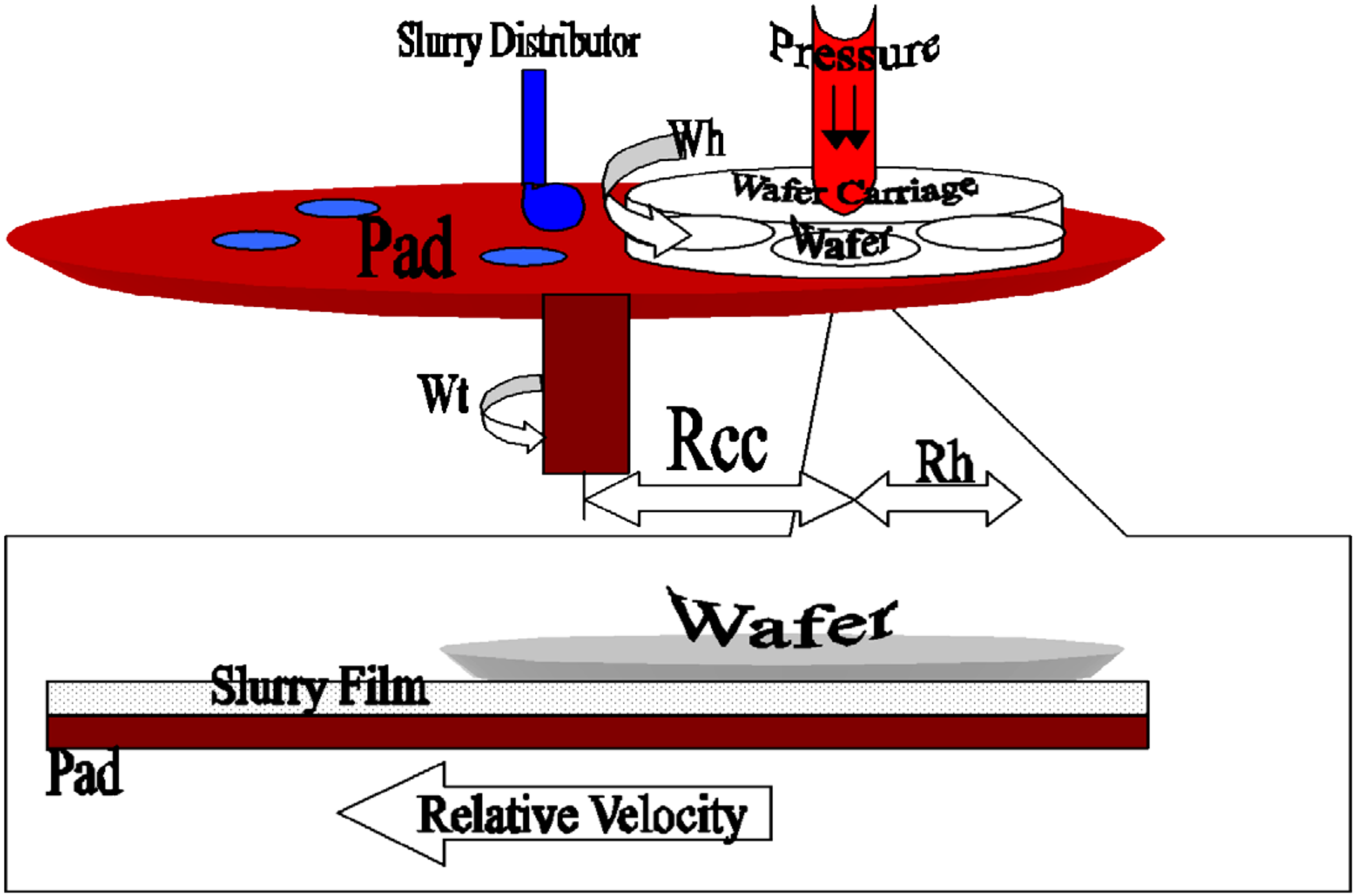
* High proportion of the total product use.


Wafer Carrier
Polishing Pad
Slurry Delivery
Wafer

Process Conditions (Oxide)
  Flow: 250 to 1000 ml/min
  Particle Size: 100 to 250 nm
  Concentration: 10 to 15%, 10.5 to 11.3 pH
Process Conditions (Metal)
  Flow: 50 to 100 ml/min
  Particle Size: 180 to 280 nm
  Concentration: 3 to 7%, 4.1 - 4.4 pH


Platen
Head Sweep Slide
Platen
Polishing Head
Load/Unload Station
Pad Conditioner
Wafer Handling Robot & I/O
Carousel

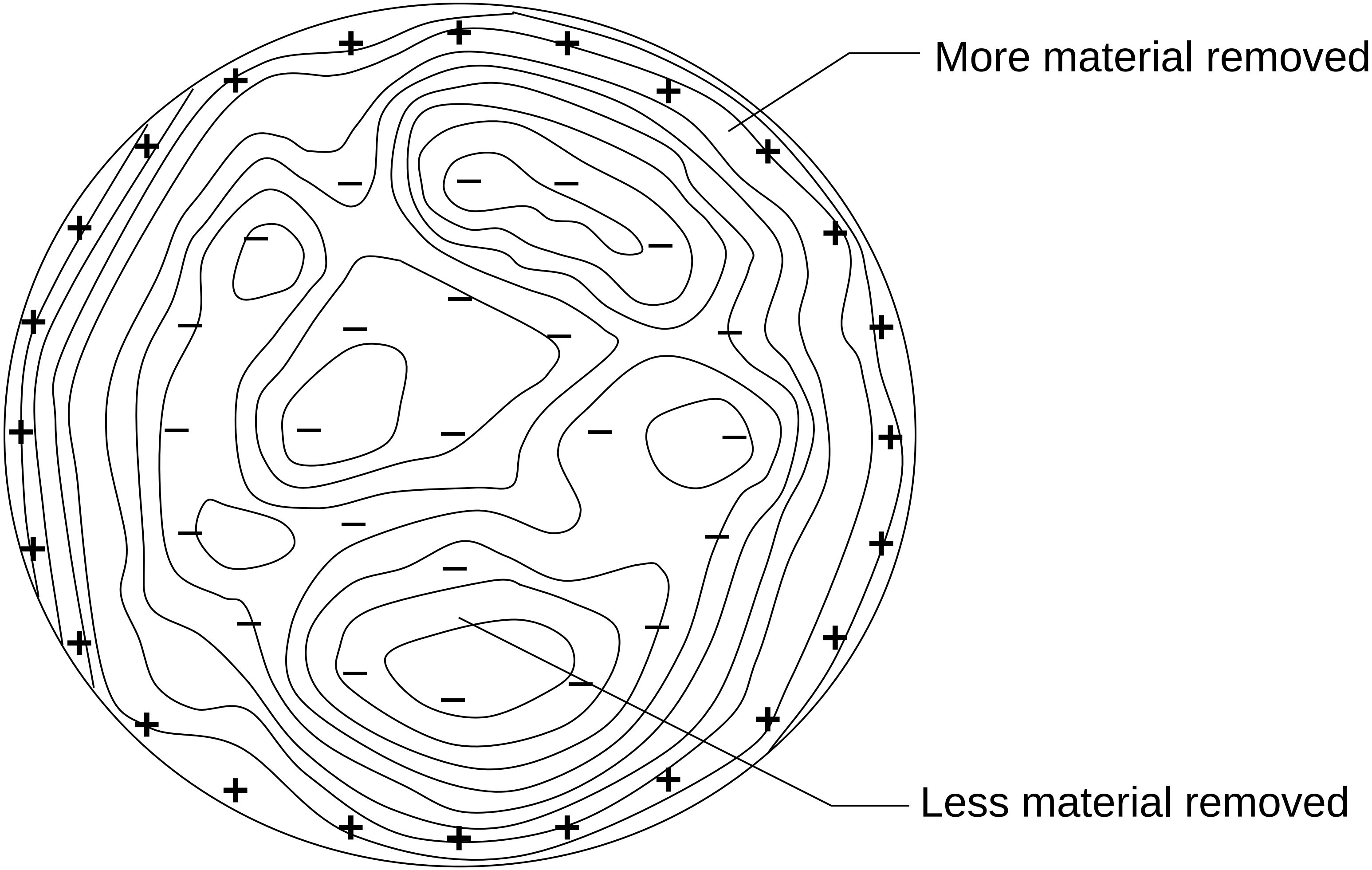
Relative Velocity, S



- Rotating Multi-head Wafer Carriage and Rotating Pad
- Wafer rotates on Film of Slurry

- Relative Velocity: $S = (Wt \times Rcc) - [Rh \times (Wh - Wt)]$
  - when Wh=Wt Velocity = const.

CMP Contour Plot for Center Slowness

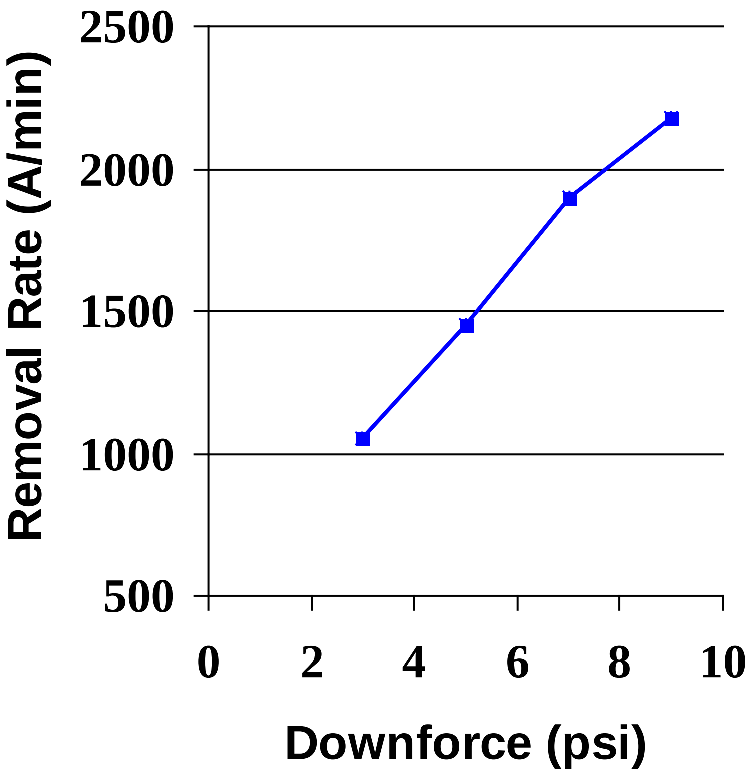


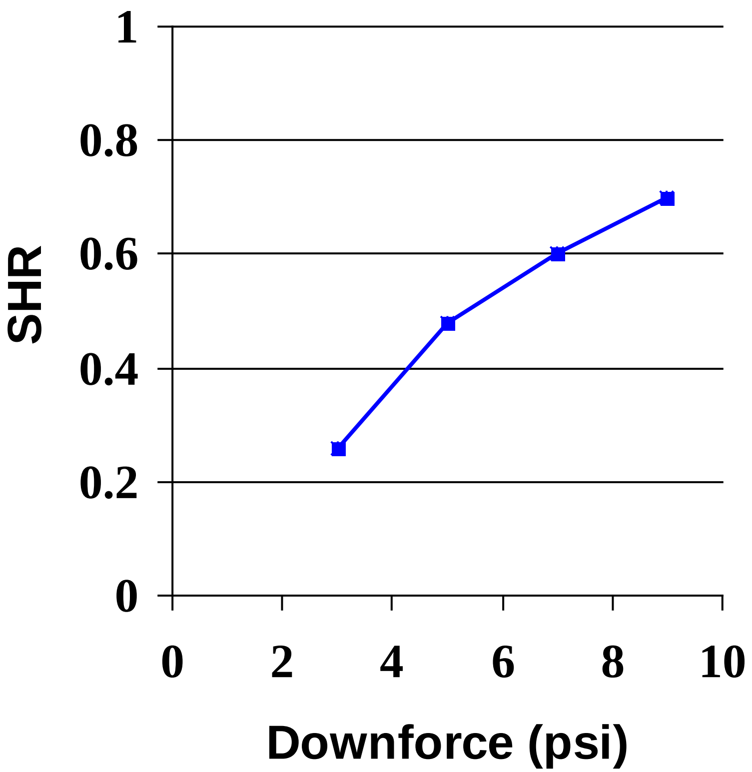
More material removed

Less material removed

Figure 18.16

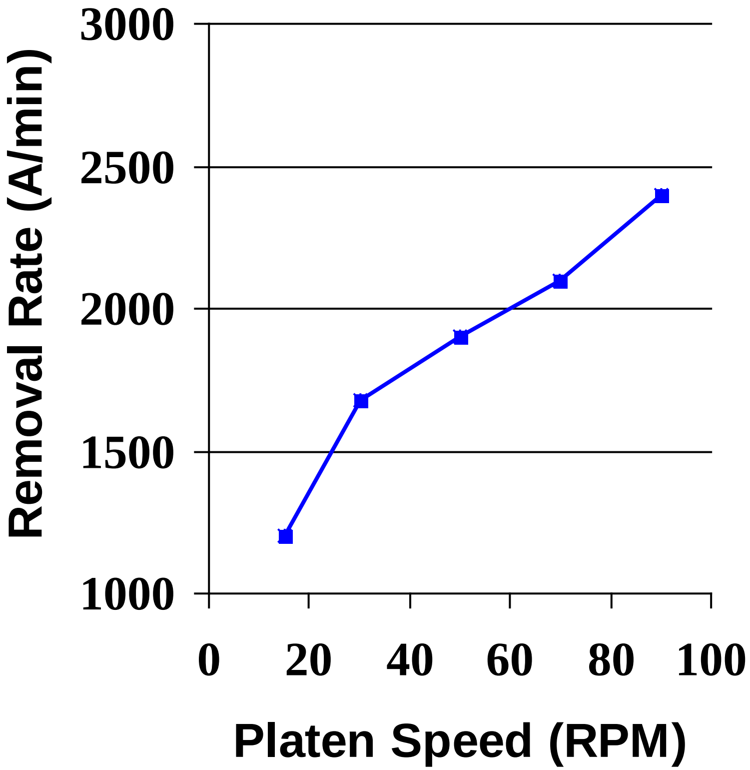
Effect of Downforce on Removal Rate & Planarity

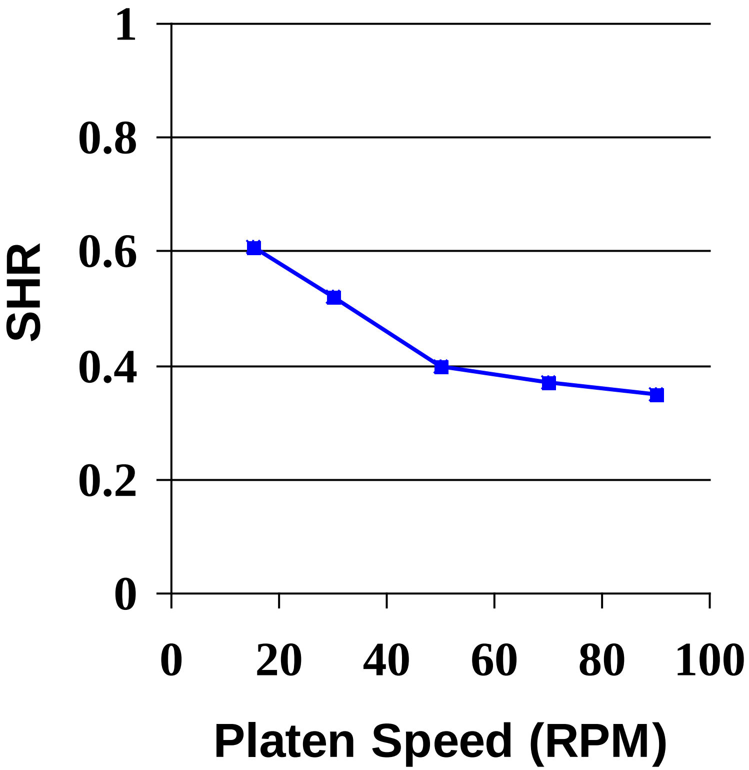




- Increase in downforce (wafer pressure applied to the polishing pad) results in a linear increase in removal rate (i.e. Preston’s Equation)
- Increase in downforce degrades planarity due to pad deformation and subsequent increase in local pressure at the ‘valley’ regions (i.e. Hook’s Law)

Effect of Platen Speed on Removal Rate & Planarity



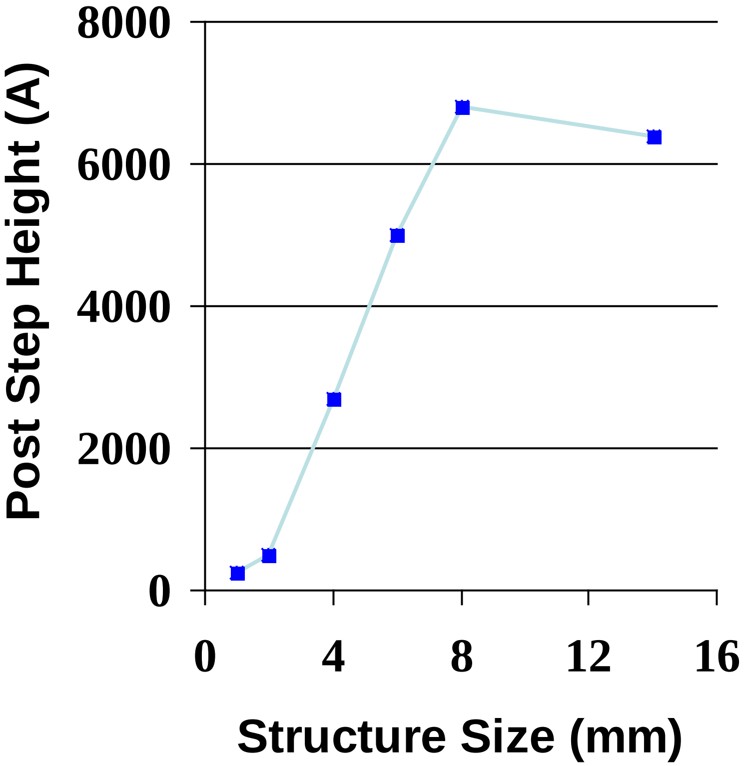


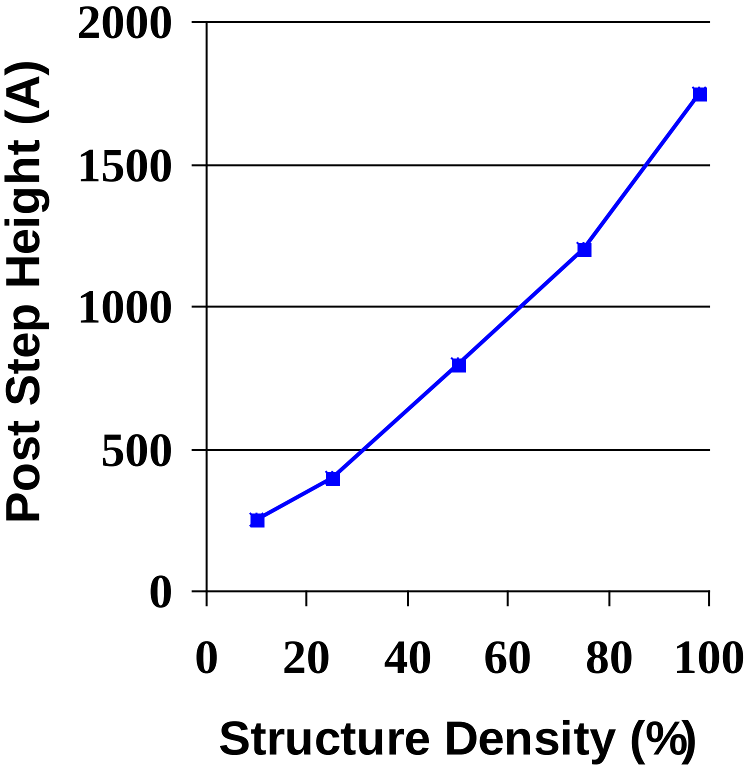
- Increase in platen speed increases removal rate linearly
- Increase in platen speed improves planarity
- At higher speeds the pad contacts mainly the ‘hill’ regions since it does not have sufficient time to conform to the ‘valley’ regions

Preston's Equation

- Simplest (and probably the only) CMP model
- Expresses polishing rate in terms of applied pressure and relative velocity between polishing pad and wafer
  - – $RR = K_p \bullet P \bullet S$
    - K_p = Preston coefficient (inversely proportional to elastic modulus of material being polished)
    - P = down pressure
    - S = pad-wafer relative speed
  - – can predict general trends
  - – observed RR usually proportional to P and S
  - – cannot predict within wafer non-uniformity, feature effects, or variations due to pattern density effects

Effect of Structure Size & Density on Post Step Height



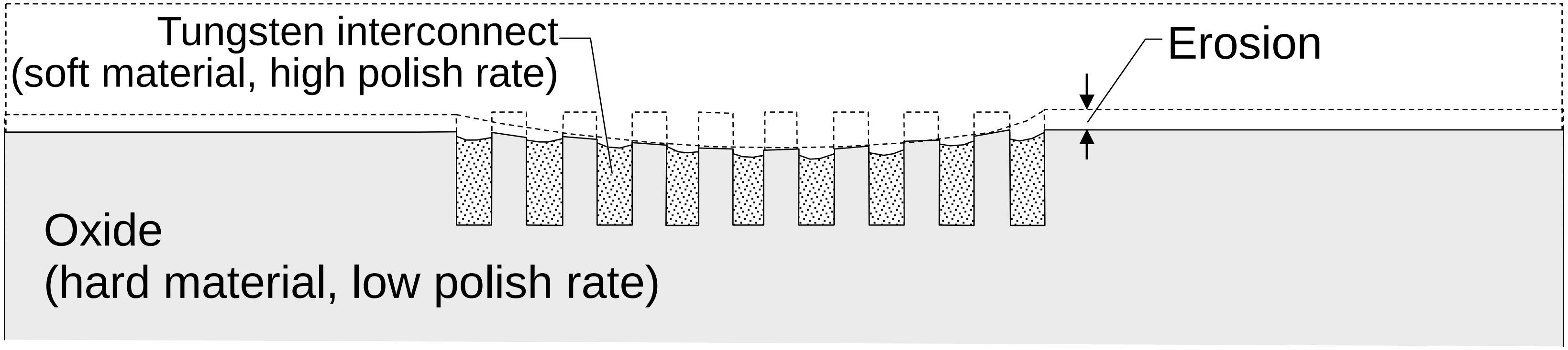


- SHR is greater on metal pads compared to isolated narrow lines
- Areas with lower circuit density polish faster than areas with dense underlying topography
- Each circuit design will have a different WIDNU due to variations in size and density of interconnects

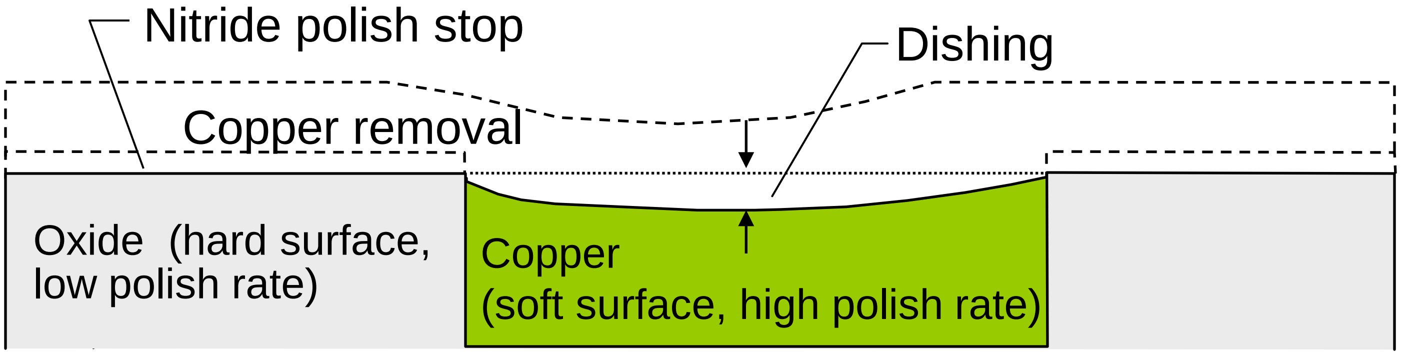
Dummy structures can mitigate this problem

Pattern Erosion and Large Feature Dishing

- Dense SRAM Array

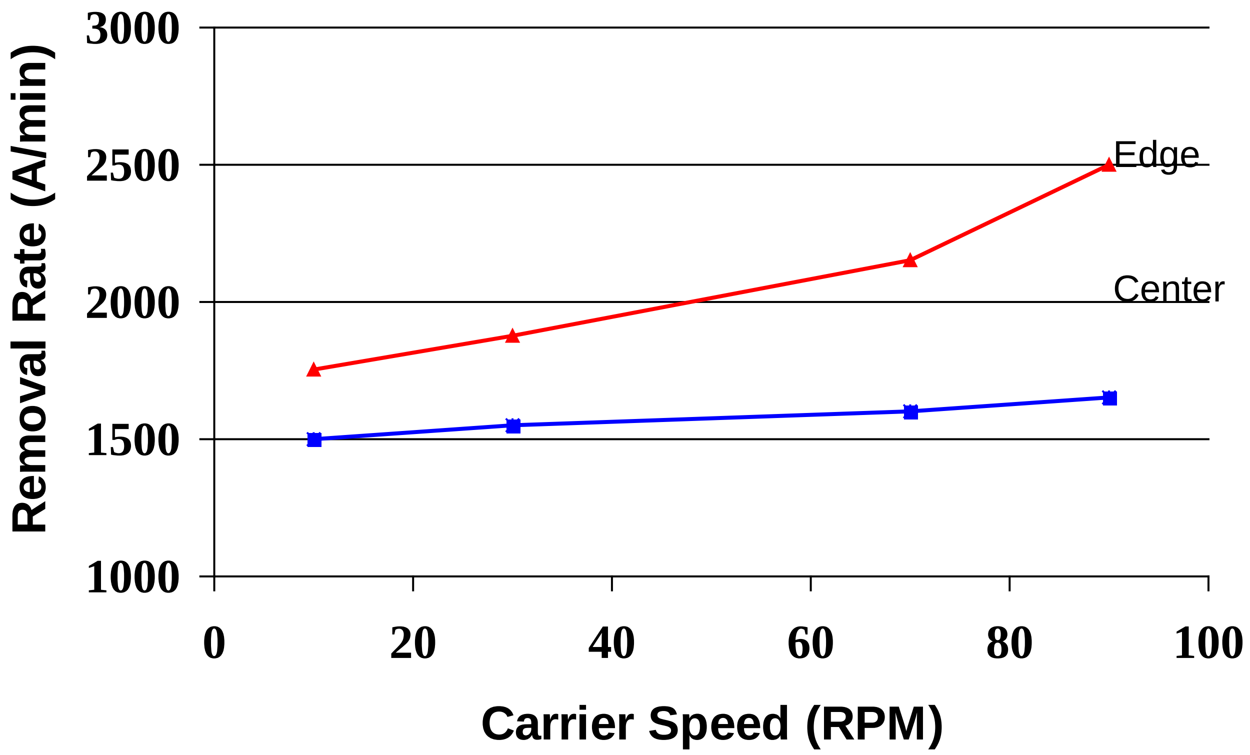


- Dishing



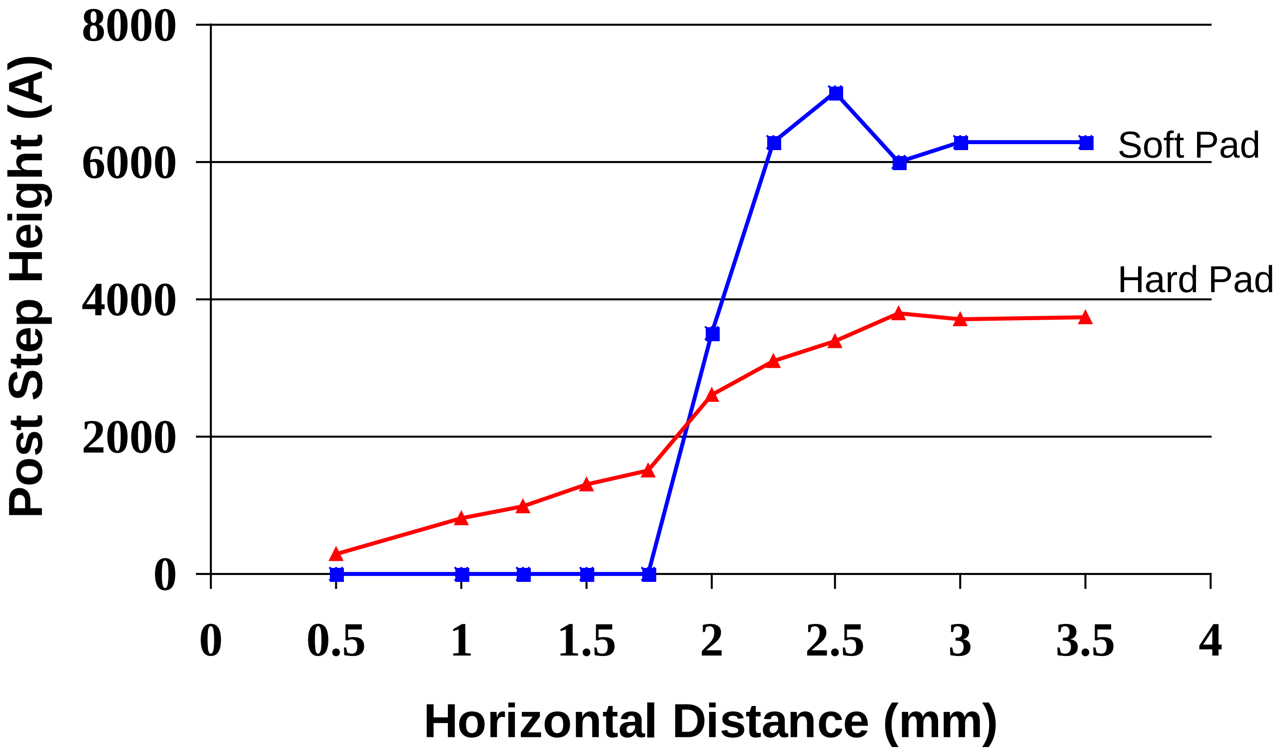
  - Erosion is the thinning of oxide and metal in a patterned area, while dishing is a reduction in the thickness of a large tungsten feature toward the center of that feature.

Effect of Carrier Speed on Wafer Center & Edge Removal Rates



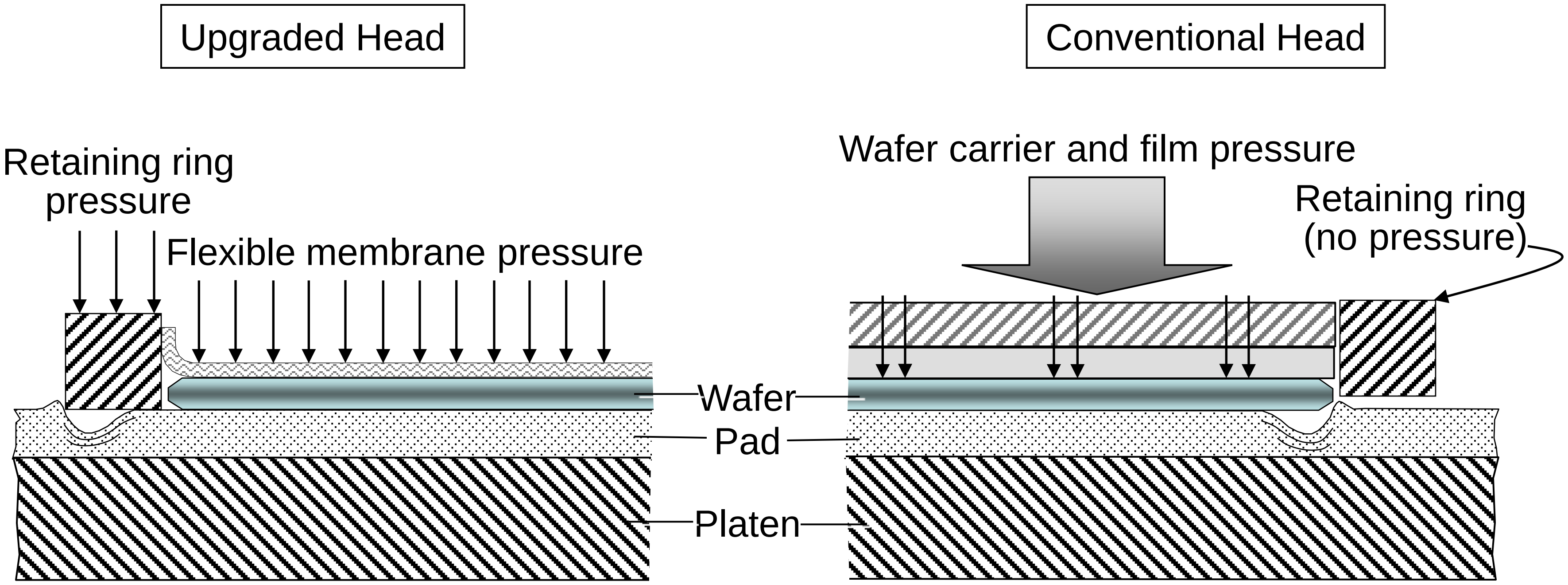
- Platen speed is maintained at 70 RPM
- Center-to-edge removal rate difference increases with increasing carrier speed
- Carrier diameter << platen diameter & at low carrier speeds, the linear velocity vector created by the carrier is much smaller than that created by the platen
- As carrier speeds approach & exceed platen speed, the linear velocity vector created by the carrier becomes significant

Effect of Pad Hardness on Post Step Height and Planarization Distance



- Harder pads deform less under pressure thus leading to:
  - Lower SHR, higher PD, and improved within die non-uniformity (WIDNU, i.e in mm range)
- Harder pads also result in higher removal rates and higher defect densities

CMP Head Carrier Design and Wafer Edge Nonuniformity

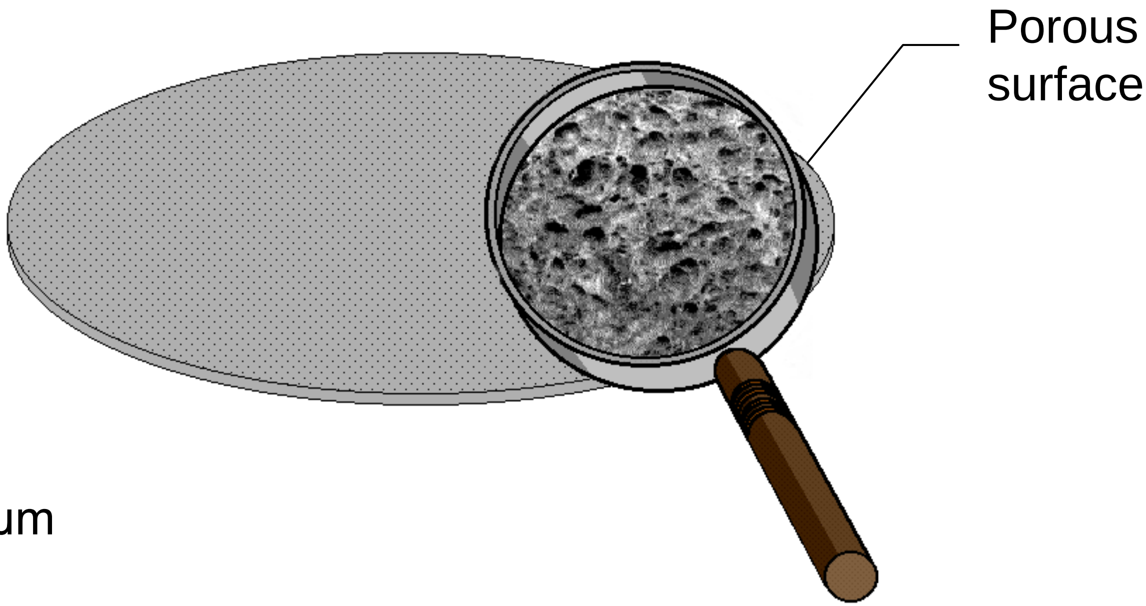


Redrawn from K. Wijekoon, R. Lin, B. Fishkin, S. Yang, F. Redeker, G. Amico, and S. Nanjanqud, “Tungsten CMP Process Developed,” *Solid State Technology*, (April, 1998), p. 55

Figure 18.20

CMP Polishing Pad

Polyurethane
- tough polymer
  - Hardness = 55
- Fiber Pile
  - Specific Gravity = 0.3
  - Compressibility=16%
  - rms Roughness = 30µm
- Conditioned



- Pad Mechanical Model - Planar Pad
  - Warnock,J.,J. Electrochemical Soc. 138(8) 2398-402(1991).
- Does not account for Pad Microstructure

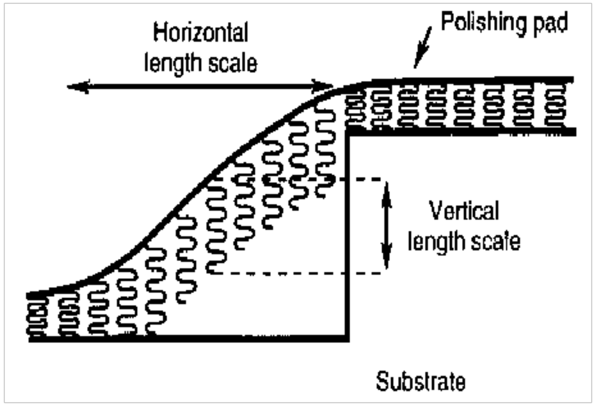
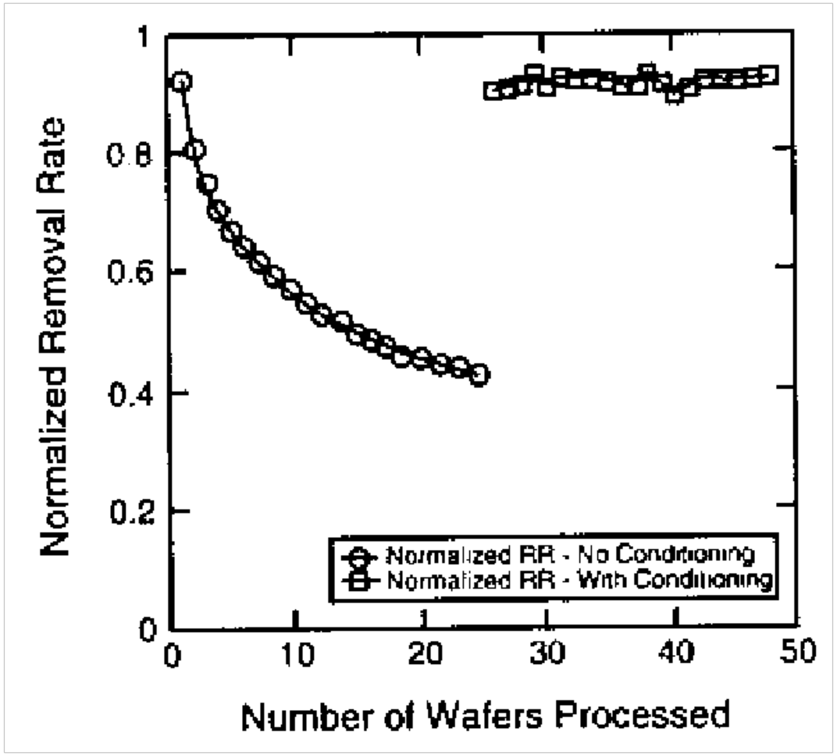


Fig. 18.15 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Pad Conditioning

- Effect of Pad on CMP
    - Roughness increases Polishing Rate
  - – Effect of Pad Hardness &Mechanical Properties
  - – Effect of Conditioning
  - – Reason for Wear-out Rate



Jairath, R., Desai, M., Stell, M., Toles, R. and Scherver-Brewer, D., Mat. Res. Soc. Symp. Proc. 337,121(1994).

CMP Polishing Pad

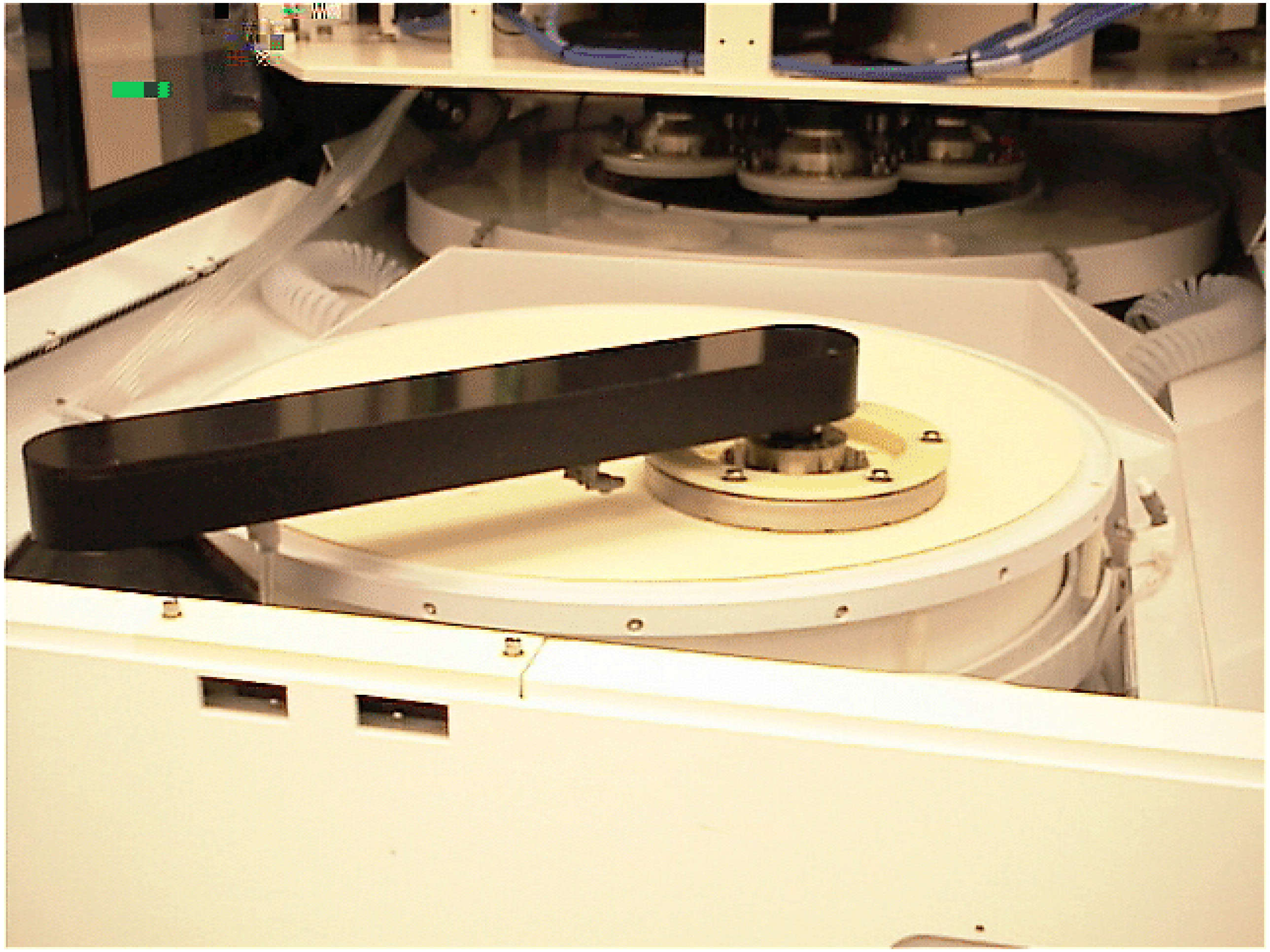


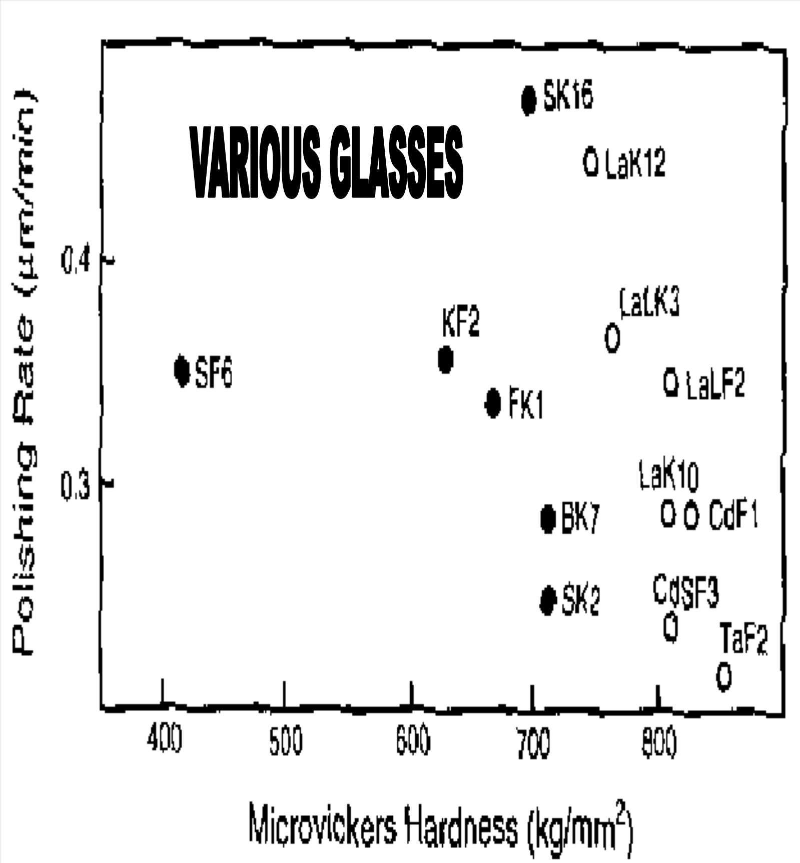
Photo courtesy of Speedfam-IPEC

Photo 18.2

Layer Hardness Effects

- Effect of Mechanical Properties of Materials to be polished

- Relationship of pad, abrasive and slurry chemistry needed for the materials being polished.



Izumitani, T. in Treatis on Materials Science and Techn., Academic Press, 1979, p.115.

CMP Oxide Mechanism

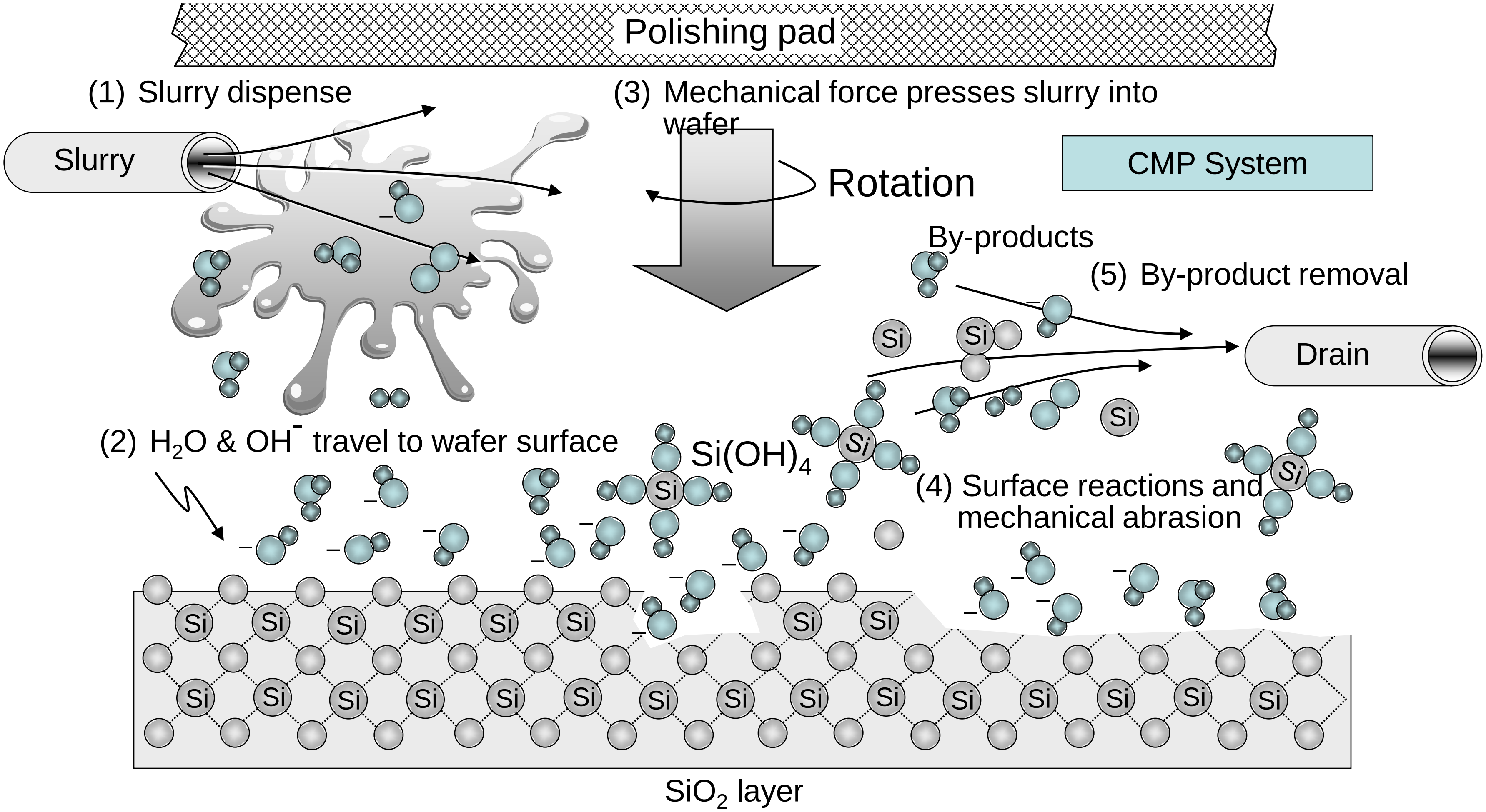


Fig. 18.10 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Solution Complexation

- Solutions are Not Simple but Complex
- Complexation Equilibria
  - $i\ M^{+m} + j\ A^{-a} \Leftrightarrow [M_i\ A_j]^{(im-ja)}$
    - $K_{ij} = \{[M_i\ A_j]^{(im-ja)}\}/\{M^{+m}\}^i\ \{A^{-a}\}^j$ {}=Activity
  - Multiple Anions - A, e.g. NO_3^-, OH^-
  - Multiple Metals - M, e.g. M^{+m}, NH_4^+, H^+
- Complexation Needed to Determine the Equilibrium and Species Activity, $\{\}_i = a_i$

Chen, Y. and Ring, T.A., "Forced Hydrolysis of In(OH)3-Comparison of Model with Experiments" J. Dispersion Sci. Tech., 19,229-247(1998).

Silica Dissolution - Solution Complexation

$SiO_2(c) + H_2O$ <---> $Si(OH)_4$	Amorphous SiO_2 dissolution	
$Si(OH)_4 + H^{+1}$ <---> $Si(OH)_3 \cdot H_2O^{+1}$	pKo= -2.44	ΔHo= -16.9 kJ/mole
$Si(OH)_4 + OH^{-1}$ <---> $H_3SiO_4^{-1} + H_2O$	pK1= -4.2	ΔH1= -5.6 kJ/mole
$Si(OH)_4 + 2\ OH^{-1}$ <---> $H_2SiO_4^{-2} + 2\ H_2O$	pK2= -7.1	ΔH2= -6.3 kJ/mole
$4Si(OH)_4 + 2\ OH^{-1}$ <---> $Si_4O_6(OH)_6^{-2} + 6\ H_2O$	pK3= -12.0	ΔH3= -12 kJ/mole
$4Si(OH)_4 + 4\ OH^{-1}$ <---> $Si_4O_4(OH)_4^{-4} + 8\ H_2O$	pK4=~ -27	