Nanometer Scale Patterning and Processing

Spring 2016

Lecture 49

Planarization, Part 2

CMP Oxide Mechanism

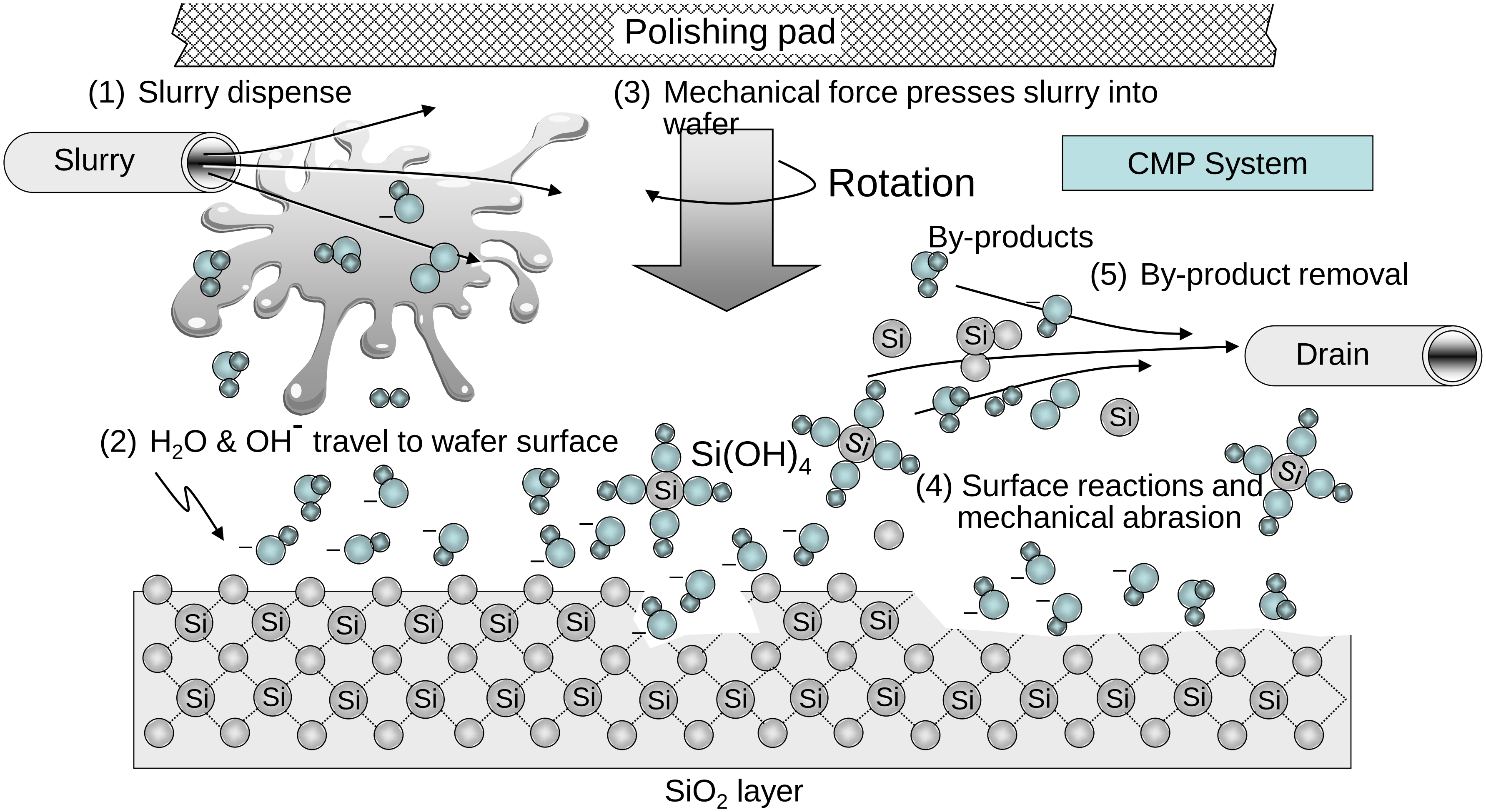


Fig. 18.10 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Solution Complexation

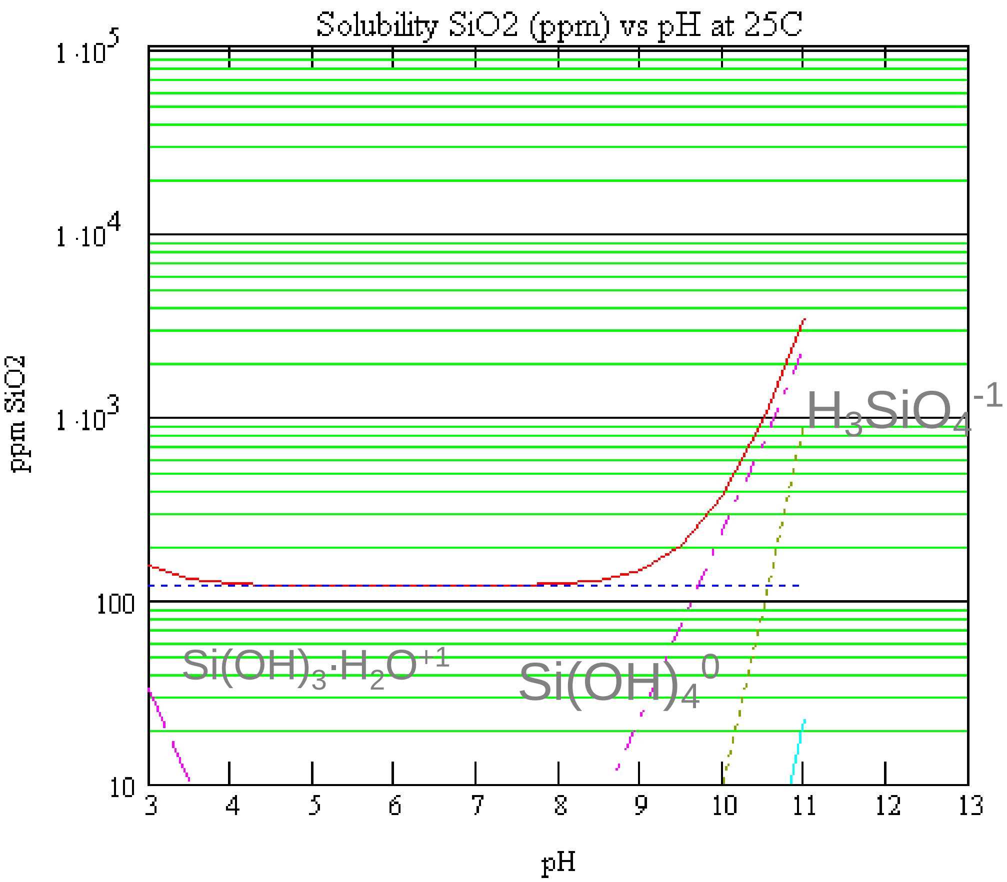
- Solutions are Not Simple but Complex
- Complexation Equilibria
  - $i\ M^{+m} + j\ A^{-a} \Leftrightarrow [M_i\ A_j]^{(im-ja)}$
    - $K_{ij} = \{[M_i\ A_j]^{(im-ja)}\}/\{M^{+m}\}^i\ \{A^{-a}\}^j$ {}=Activity
  - Multiple Anions - A, e.g. NO_3^-, OH^-
  - Multiple Metals - M, e.g. M^{+m}, NH_4^+, H^+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

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

Solution Complexation



Mechanism for Metal CMP

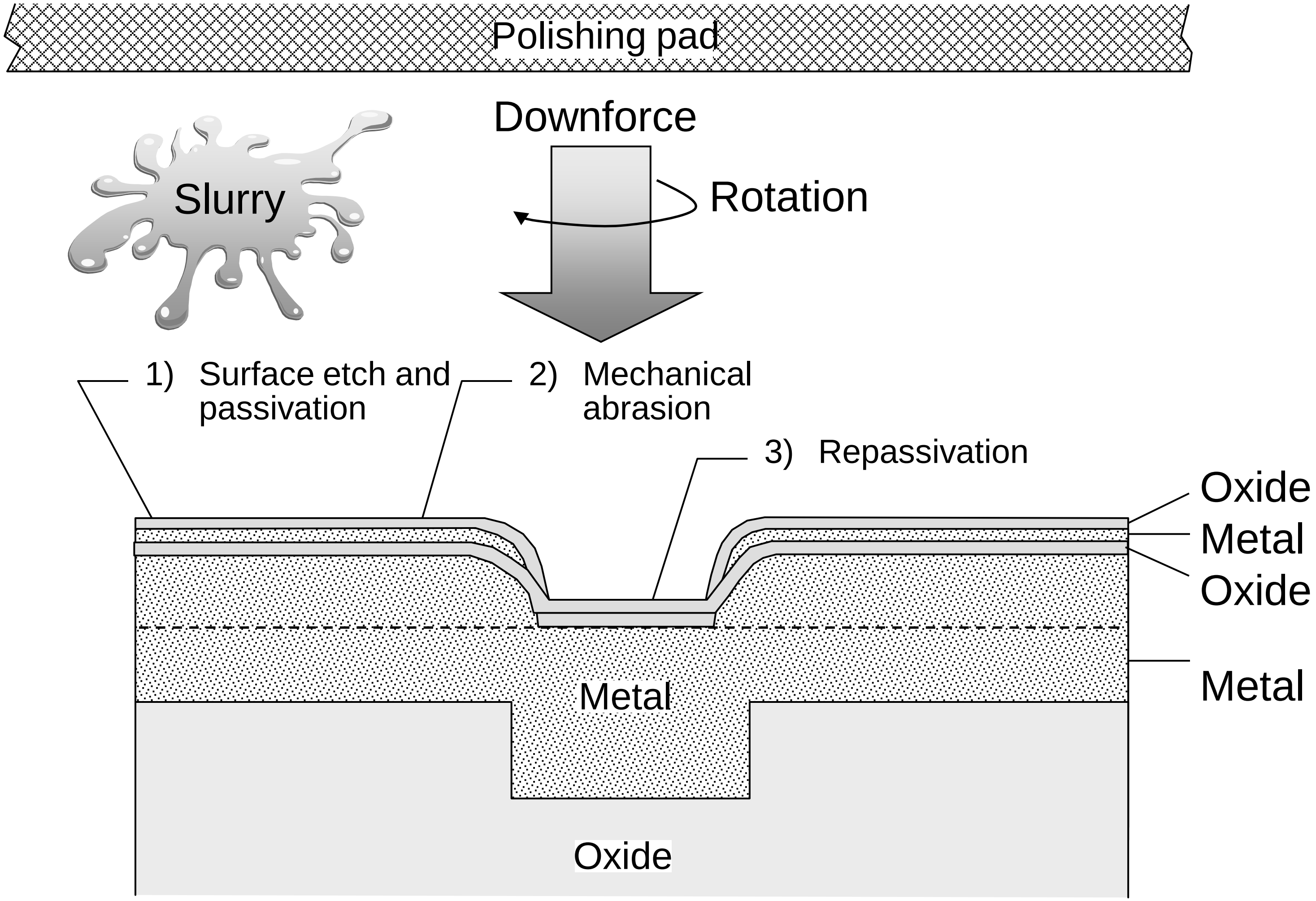
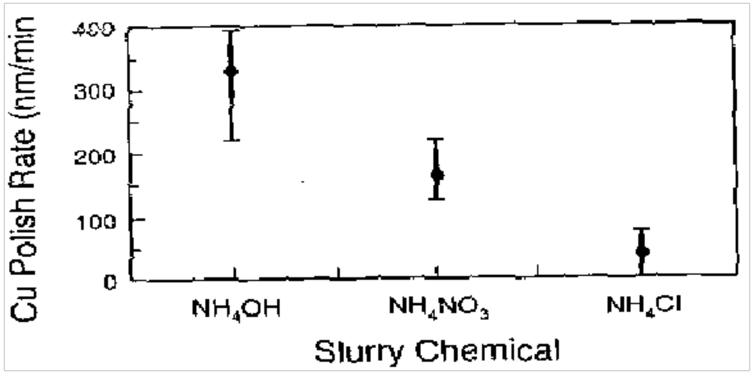
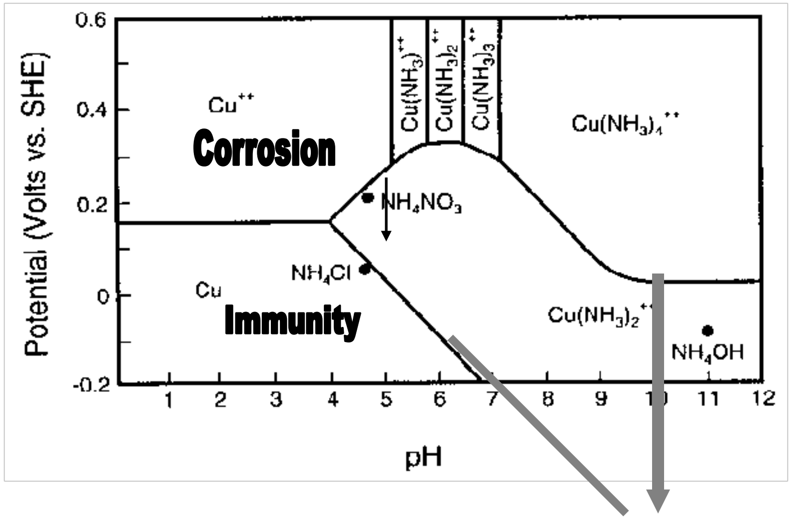


Fig. 18.11 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Copper Dissolution

- Solution Chemistry
  - Must Dissolve Surface Slowly without Pitting
- Supersaturation





Johnson, H.E.and Leja, J., J. Electrochem. Soc. 112,638(1965).

Copper CMP Chemistry

- $K_3Fe(CN)_6 + NH_4OH$
  - – Cu^{+2} Complexes
    - OH^- - i:j= 1:1, 1:2, 1:3, 1:4, 2:2, 3:4
    - NO_3^- -weak
    - NH_3 - i:j= 1:1, 1:2, 1:3, 1:4, 2:2, 2:4
    - $Fe(CN)_6^{-3}$ - i:j=1:1(weak)
    - $Fe(CN)_6^{-4}$ - i:j=1:1(weak)
  - – Cu^{+1} Complexes

Copper Electro-Chemistry

- Reaction (oxidation)
- -Sainio, C.A., Duquette, D.J., Steigerwald, J.M., Murarka, J. Electron. Mater., 25,1593(1996).

$$Cu + Fe(CN)_6^{3-} + 2\ NH_3 \xleftrightarrow{K_{EQ}} Cu(NH_3)_2^{+} + Fe(CN)_6^{4-}$$

- Activity Based Reaction Rate-Gutman, E.M., "Mechanochemistry at Solid Surfaces," World Scientific Publishing, Singapore, 1994.

$$J(Flux) = k_1'' \prod_{j=reactants} a_j^{\nu_j} - k_2'' \prod_{j=products} a_j^{\nu_j} = k_2'' \prod_j a_j^{\nu_j} \exp\left(\frac{\tilde{A}}{R_g T} - 1\right)$$

  - k"=reaction rate constant 1=forward,2=reverse
  - a_j=activity, υ_j=stociometry, μ_j =chemical potential
  - $\tilde{A} = \Sigma \nu_j \mu_j$ =Overall Reaction Affinity

Chemical Potential

- Mineral Dissolution

$$\mu_i = \mu_{io} + R_g T \ln a_i = \mu_{io} + R_g T \ln \gamma_i \; c_i$$

- Metal Dissolution

$$\mu_i = \mu_{io} + R_g T \ln a_i + z_i \Im \phi = \mu_{io} + R_g T \ln \gamma_i \; c_i + z_i \Im \phi$$

- ø=Electrode Potential
- $\Im$=Faraday’s Constant

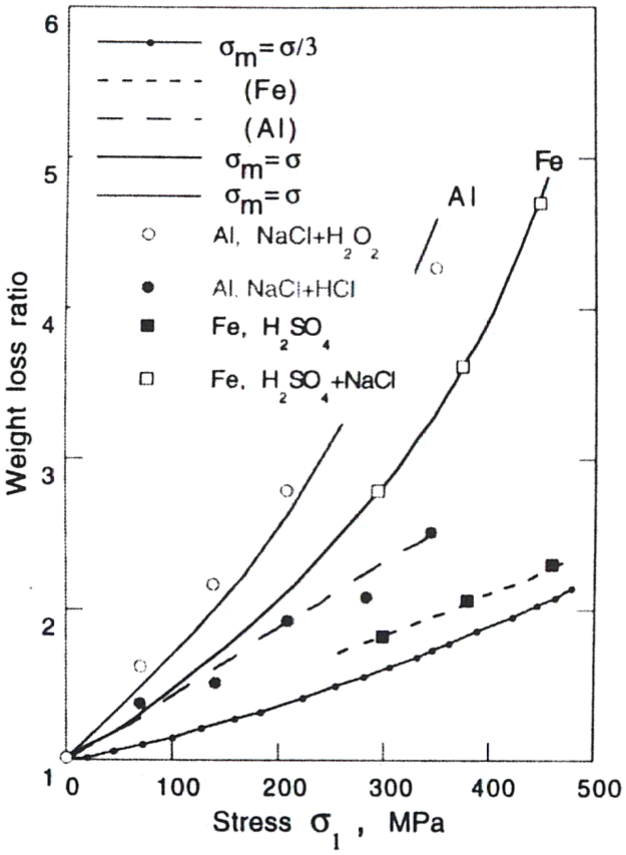
Mechano-Chemical Effect

  - Effect on Chemical Potential of solid
  - Effect of Activity of Solid
- As a result, Dissolution Rate of Metal and Mineral are Enhanced by Stress.

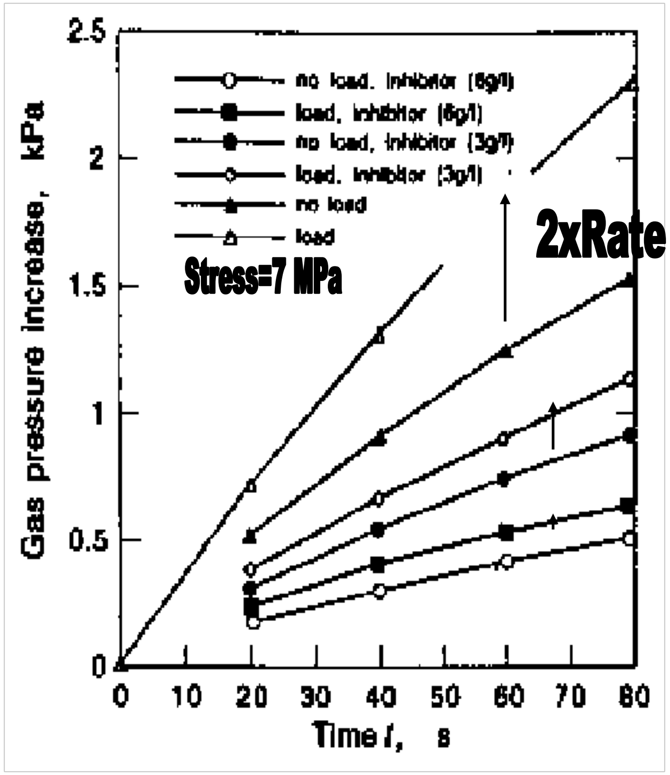
Effect of Stress on Dissolution

Metals

Mineral-$CaCO_3$



Slope of Curve=Rate

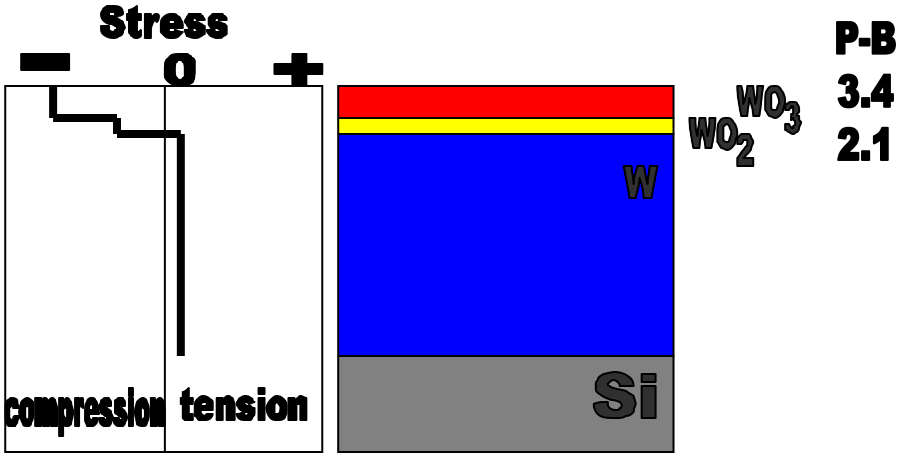


Inhibitor=Caprylic Acid $C_7H_{15}COOH$

Reaction in 3% HCl

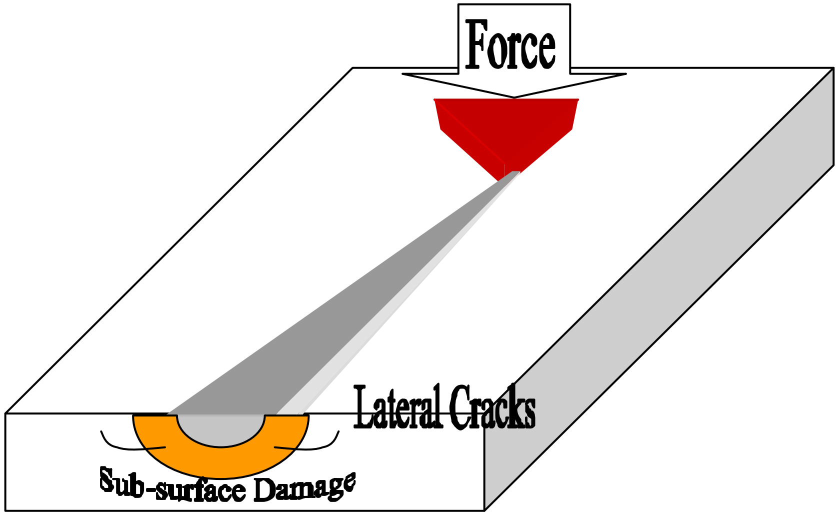
Oxidation of Metal Causes Stress

- Stress, $\sigma_i = E_i (P\text{-}B_i - 1)/(1 - \nu_i)$
    - $P\text{-}B_i$ is the Pilling-Bedworth ratio for the oxide

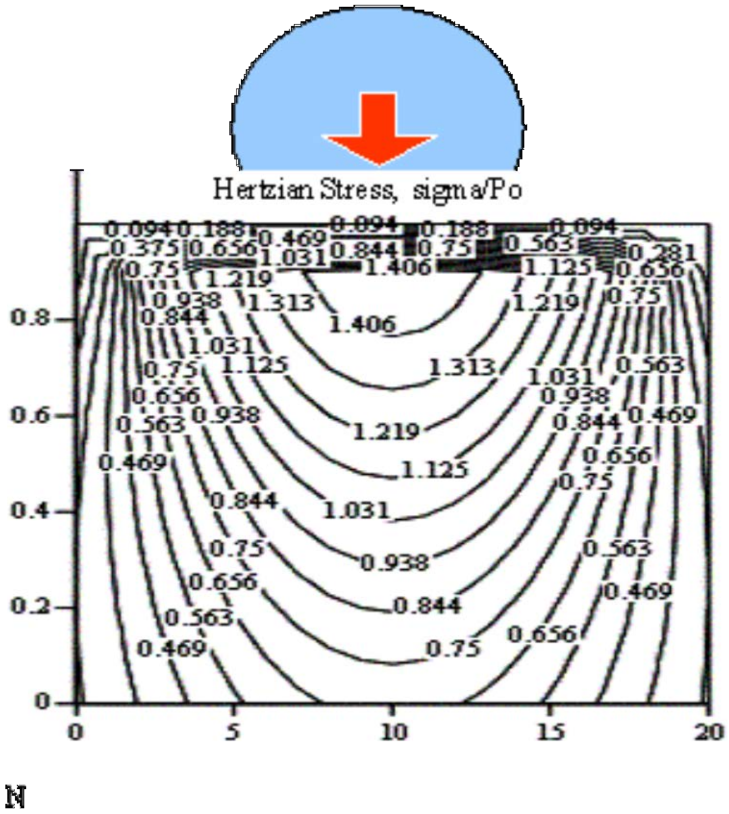


Mechanical Properties

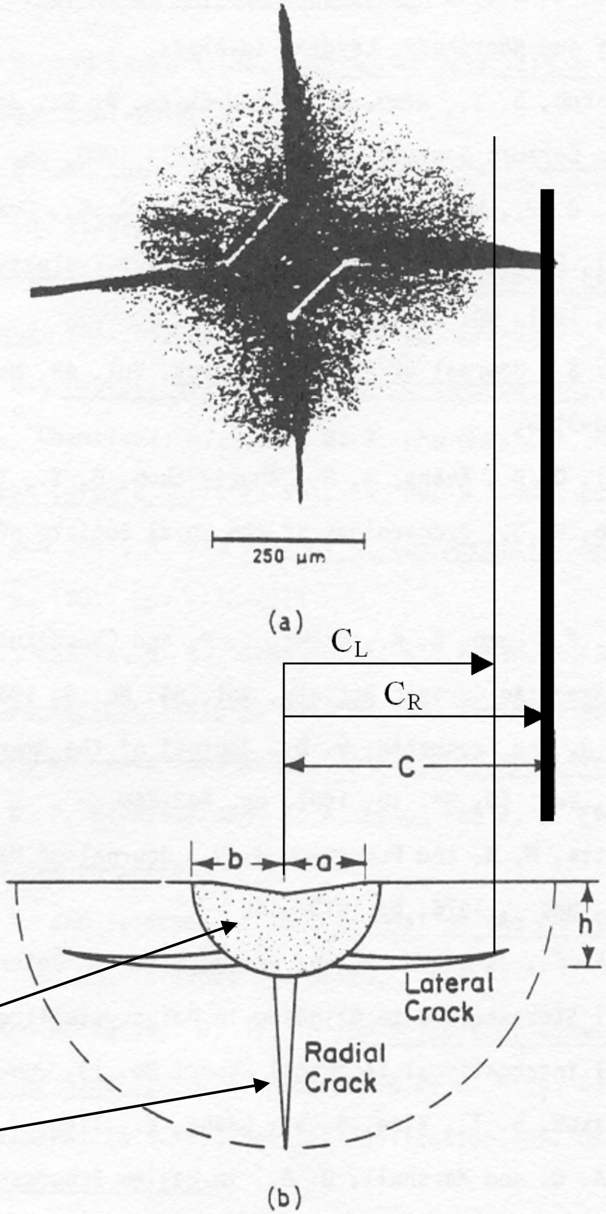
- Elastic Deformation
- Plastic Damage
- Plastic Deformation
  - Scratching



Indentation



Elastic Behavior



Plastic Damage

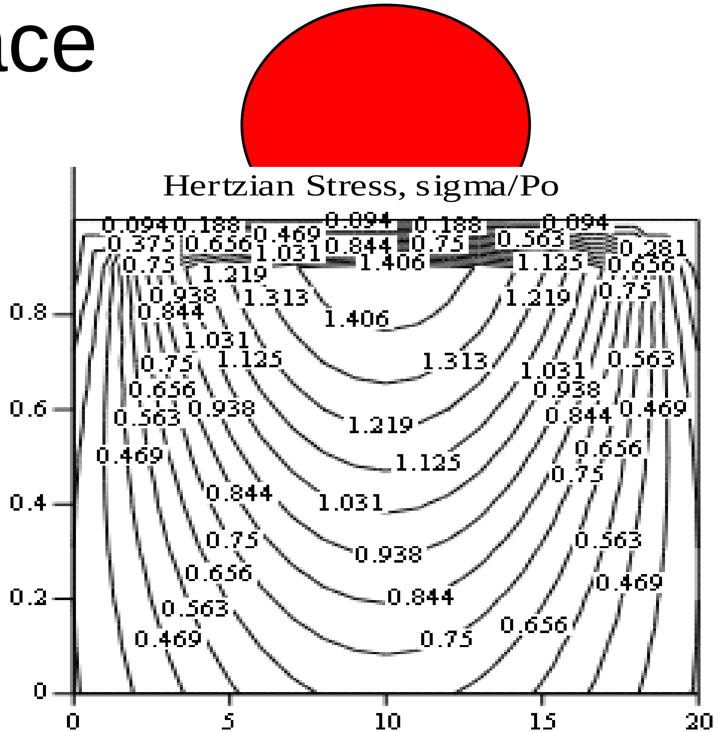
Brittle Damage

(a) Vickers indentation in ZnS.

(b) Schematic cross section of indentation, showing deformation zone and fractures.

Abrasive Particles Cause Surface Stress

- Collisions with Wafer Surface Cause Hertzian Stress
- Collision Rate ?

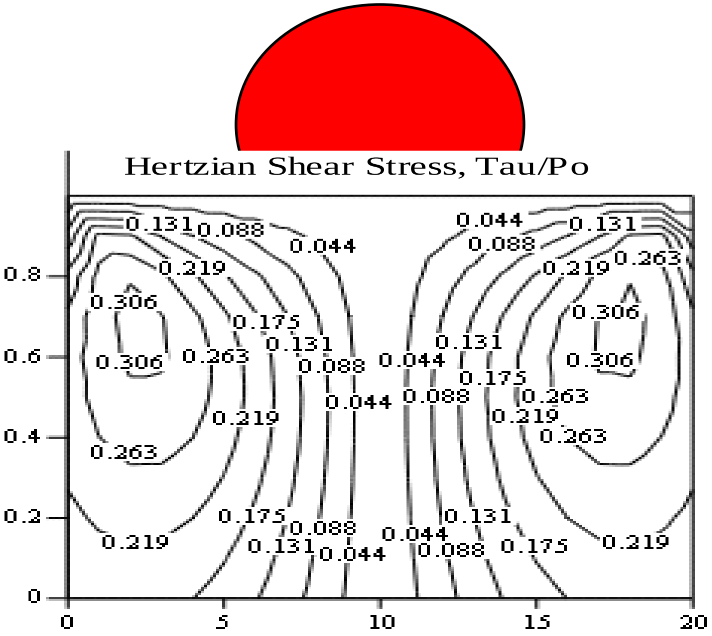


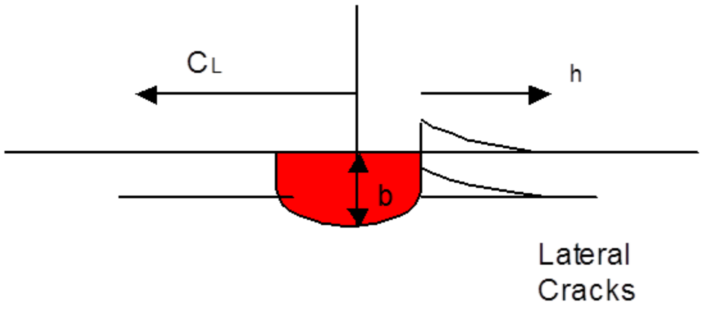
- Stress Due To Collision
- P[=(H tan^2 Ψ)$^{1/3}$ $U_k^{2/3}$] is the peak load (N) due to the incident kinetic energy of the particles, U_k,The load is spread over the contact area

A. Evans "Mechanical Abrasion"

Hertzian Shear Stress

- Delatches the Oxide Layer
- Weak Interface Bond





- $C_L=0.096\ (E/H)^{2/5}\ K_c^{-1/2}\ H^{-1/8}\ [\ 1-\ (P_o/P)^{1/4}]^{1/2}\ P^{5/8}$
  - A. Evans, UC Berkeley.

Slurry

- Aqueous Chemical Mixture
  - Material to be removed is soluble in liquid
  - Material to be removed reacts to form an oxide layer which is abraded by abrasive
- Abrasive
  - 5-20% wgt of ~200±50nm particles
    - Narrow particle size distribution (PSD), high purity(<100ppm)
    - Fumed particle = fractal aggregates of spherical primary particles (15-30nm)

Abrasive in 2D Flow Model

- In the 2-D approach the effect of the slurry and specifically the particles in the slurry is reduced to that of an unknown constant, α, determined by experimental measurements

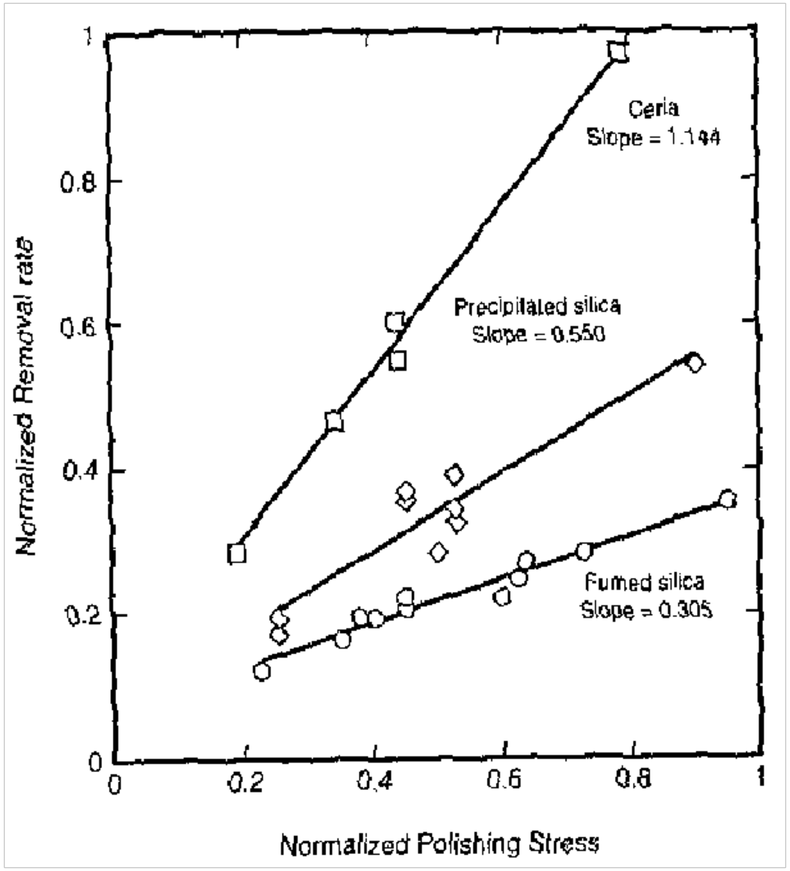
$$\frac{Polishing\ Rate\ with\ Abrasive}{Polishing\ Rate\ without\ Abrasive} \equiv 1 + \alpha\, \tau_w\, C_A$$

- where τ_w is the shear stress at the wafer surface and C_A is the concentration of abrasive.
  - τ_w : product of
    - Viscosity at wall shear stress
    - Velocity Gradient at wall

Sundararajan, Thakurta, Schwendeman, Mararka and Gill,
J. Electro Chemical Soc. 146(2),761-766(1999).

Effect of Particles on CMP is Unknown

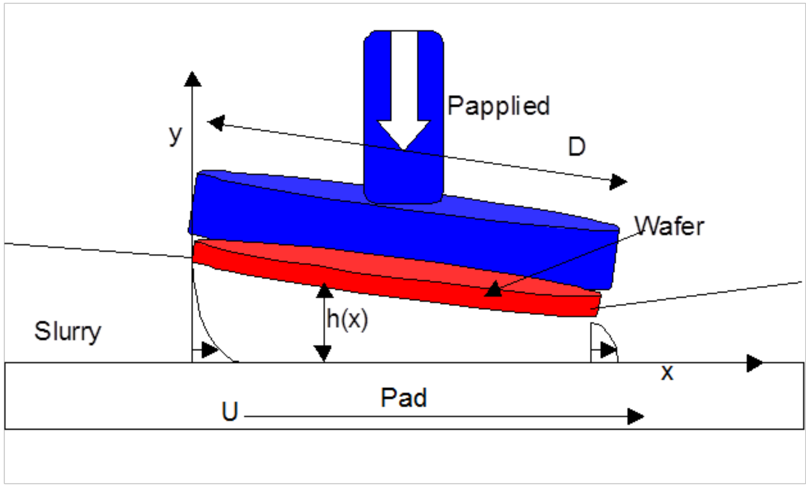
- Effect of Particles on CMP
  - Particle Density
  - Particle Shape & Morphology
  - Crystal Phase
  - Particle Hardness & Mechanical Properties
  - Particle Size Distribution
  - Particle Concentration
  - Colloid Stability



P*V

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

Fluid Flow: Momentum Balance

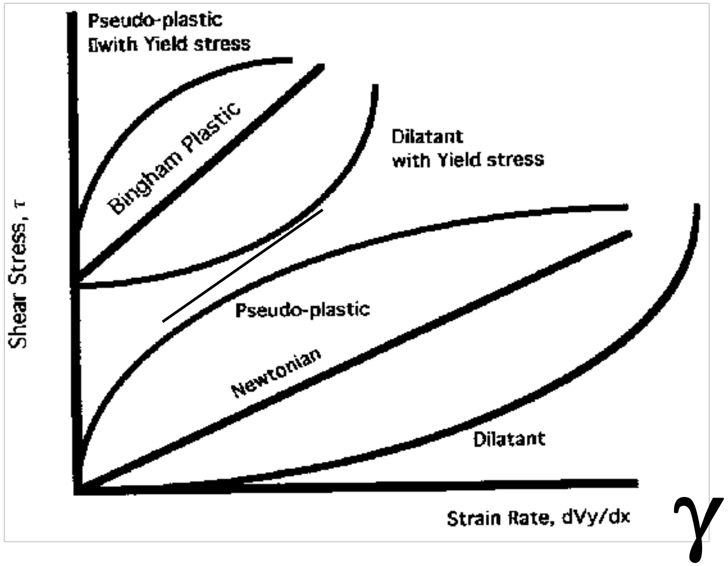


- Newtonian Lubrication Theory

$$0 = -\nabla P - \eta \nabla^2 u(x,y)$$

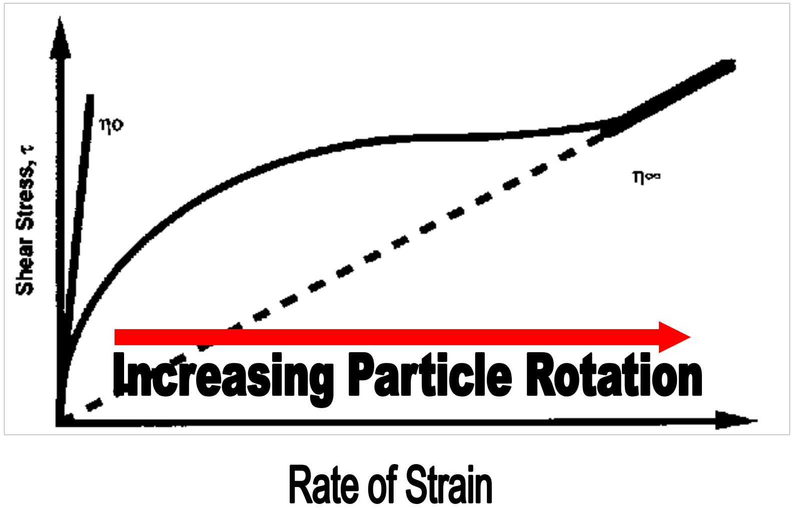
- Non-Newtonian Fluids

$$0 = -\nabla P - \nabla^2 \eta(\dot{\gamma}) u(x,y)$$

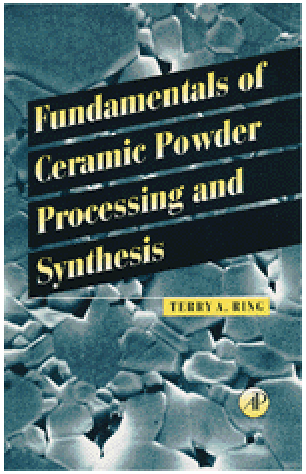


Slurries are Non-Newtonian Fluids

- Crossian Fluid- Shear Thinning



Increasing Particle Rotation



Fundamentals of Ceramic Powder Processing and Synthesis

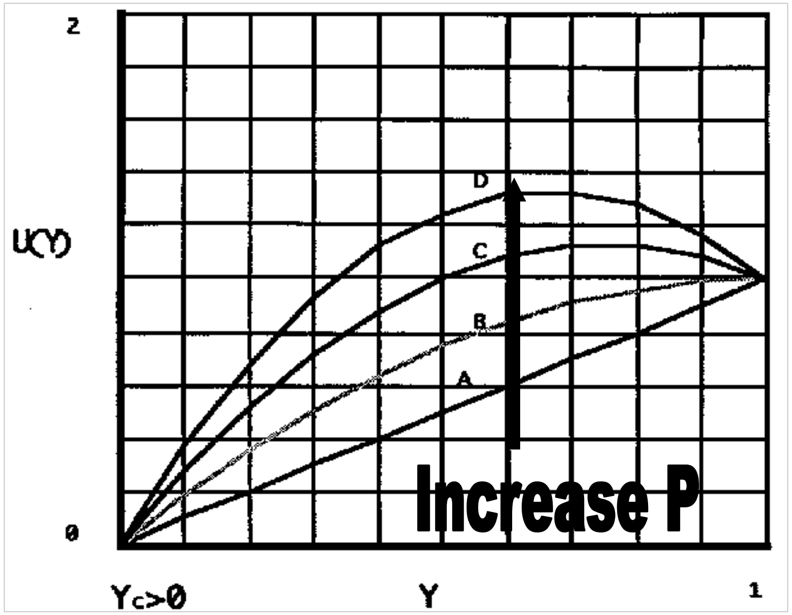
TERRY A. RING

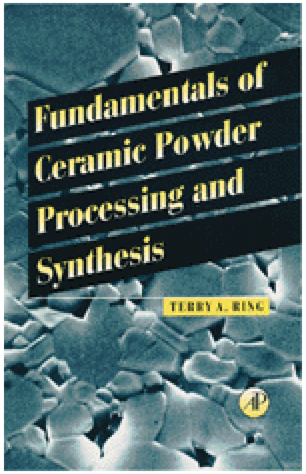
Diffusion altered rotation

CMP Flow Analogous to Tape Casting

-RING T.A., Advances in Ceramics vol. 26", M.F. Yan, K. Niwa, H.M. O'Bryan and W. S. Young, editors ,p. 269-576, (1988).

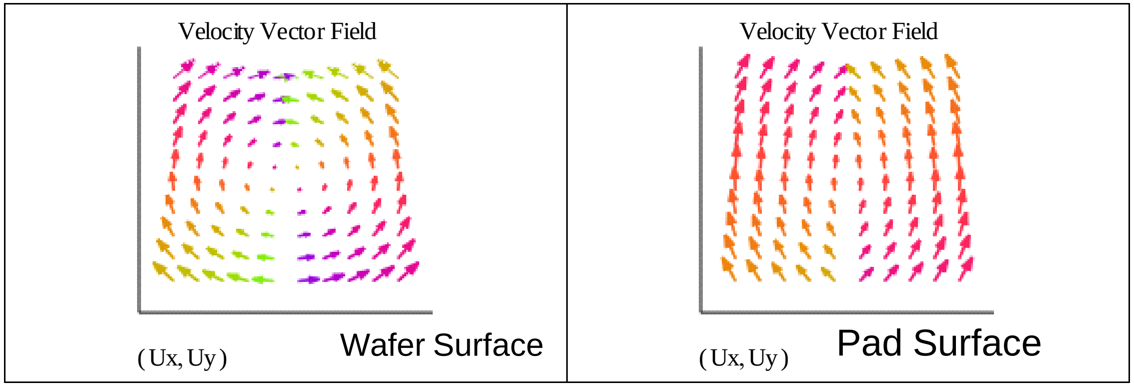
- Newtonian $Y_c=0$,
  - – Flow Profile depends upon Pressure
- Bingham Plastic, $Y_c \neq 0$



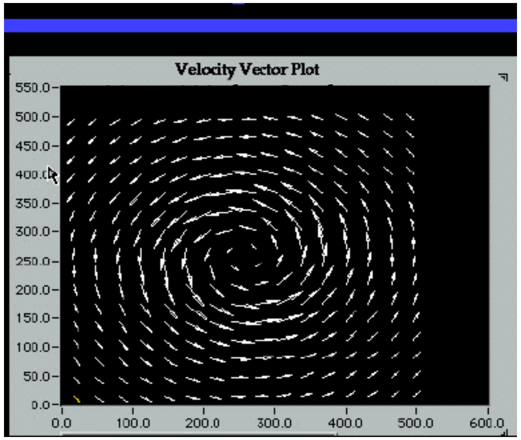


Macro Fluid Flow

- Continuity Equation
- Navier Stokes Equation (Newtonian Fluid)
  - Rotation of Wafer (flat)
  - Rotation of Pad (flat)
    - Sohn, I.-S., Moudgil, B., Singh, R. and Park, C.-W., Mat. Res. Soc. Symp. Proc. v 566, p.181-86(2000)



$$\gamma = \frac{R_w\Omega_w}{\delta}\left[\left(\frac{r}{R_w} - \frac{\Omega_p}{\Omega_w}\left(\frac{r}{R_w}+\frac{L}{R_w}\cos\theta\right)\right)^2 + \left(\frac{\Omega_p}{\Omega_w}\frac{L}{R_w}\sin\theta\right)^2\right]^{1/2}$$



Tufts University
Expt. Results

Mass Transfer

- Driving Force for dissolution,
  - $C-C_{eq}=C_{eq}(1-S)$
  - $S=C/C_{eq}$
- Different Rate Determining Steps
  - Diffusion - J(Flux) = $k_c C_{eq}\ (1-S)$
  - Surface Nucleation
    - Mono - $J \alpha \exp(1-S)$
    - Poly - $J \alpha (1-S)^{2/3} \exp(1-S)$
  - Spiral(Screw Dislocation) - $J \alpha (1-S)^2$

Bohner, M. Lemaitre, J. and Ring, T.A., "Kinetics of Dissolution of β-tricalcium phosphate," J. Colloid Interface Sci. 190,37-48(1997).

Advantages of CMP

Benefits	Remarks
1. Planarization	Achieves global planarization.
2. Planarize different materials	Wide range of wafer surfaces can be planarized.
3. Planarize multi-material surfaces	Useful for planarizing multiple materials during the same polish step.
4. Reduce severe topography	Reduces topography to allow for fabrication with tighter design rules and additional interconnection levels.
5. Alternative method of metal patterning	Provides an alternate means of patterning metal (e.g., Damascene process), eliminating the need of the plasma etching for difficult-to-etch metals and alloys.
6. Improved metal step coverage	Improves metal step coverage due to reduction in topography.
7. Increased IC reliability	Contributes to increasing IC reliability, speed and yield (lower defect density) of sub-0.5µm devices and circuits.
8. Reduce defects	CMP is a subtractive process and can remove surface defects.
9. No hazardous gases	Does not use hazardous gases common in dry etch process.

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

Disadvantages of CMP

Disadvantages	Remarks
1. New technology	CMP is a new technology for wafer planarization. There is relatively poor control over the process variables with a narrow process latitude.
2. New defects	New types of defects from CMP can affect die yield. These defects become more critical for sub-0.25 µm feature sizes.
3. Need for additional process development	CMP requires additional process development for process control and metrology. An example is the endpoint of CMP is difficult to control for a desired thickness.
4. Cost of ownership is high	CMP is expensive to operate because of costly equipment and consumables. CMP process materials require high maintenance and frequent replacement of chemicals and parts.

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

CMP for Oxide Fill of Shallow Trench Isolation (STI)

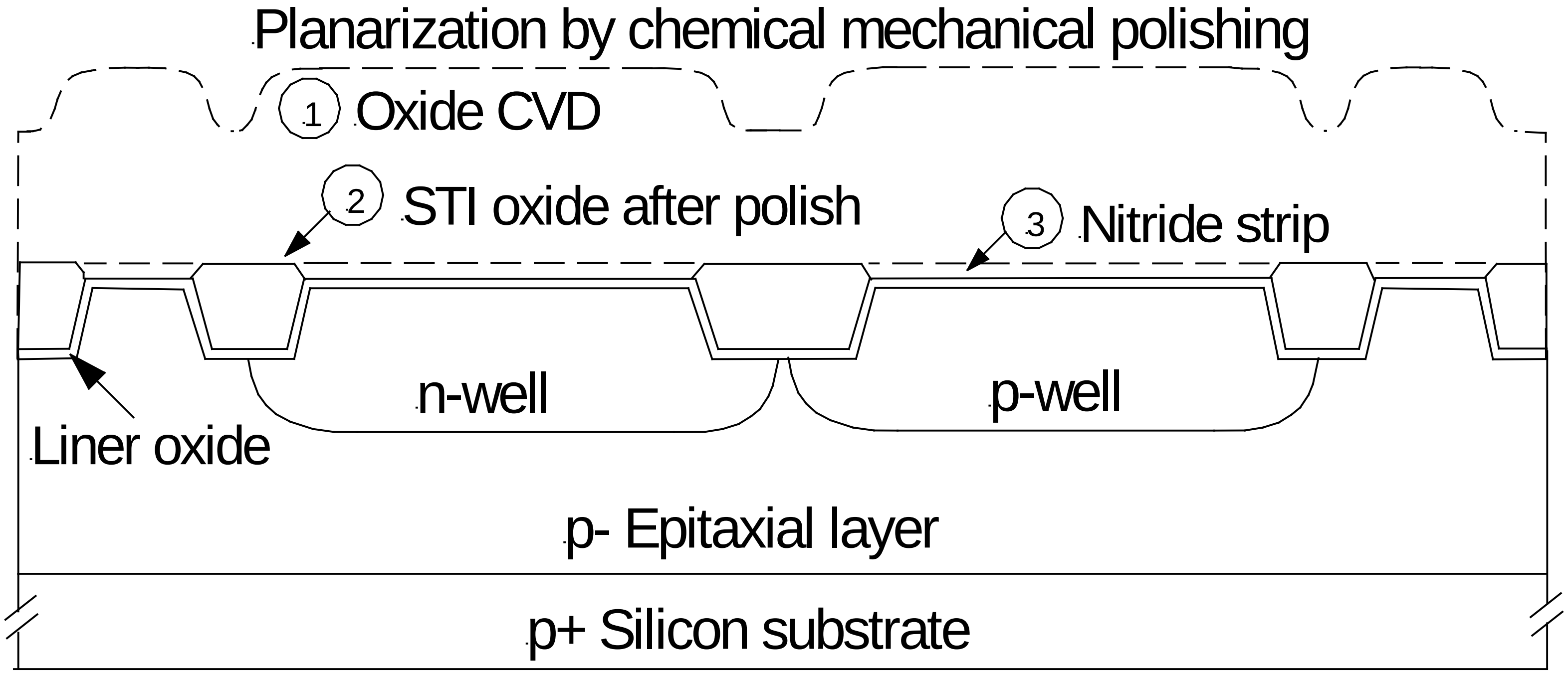


Fig. 18.23 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Layer 1 Oxide before and after CMP

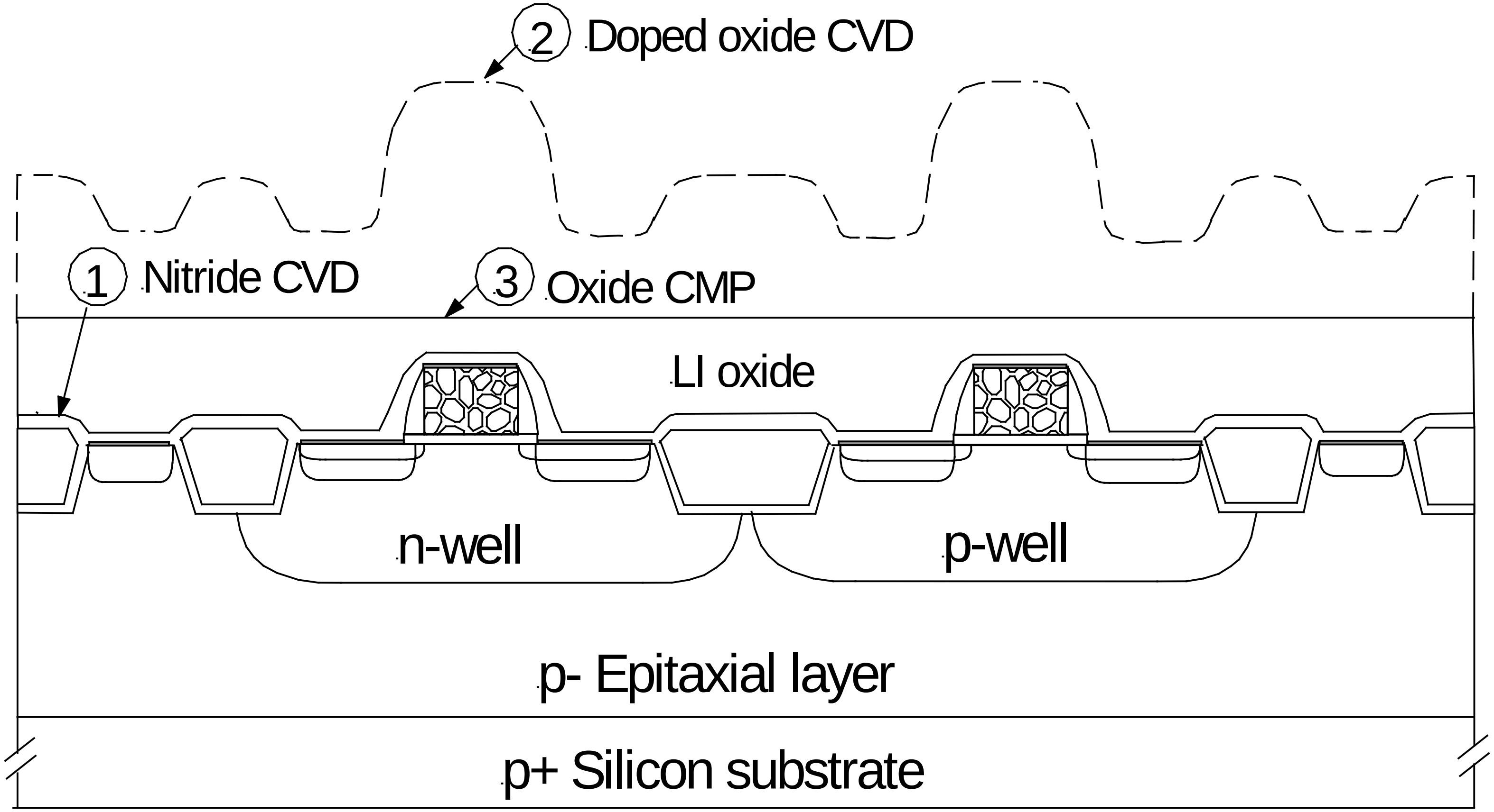


Fig. 18.24 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Inter Layer Dielectric (ILD) Oxide Polish

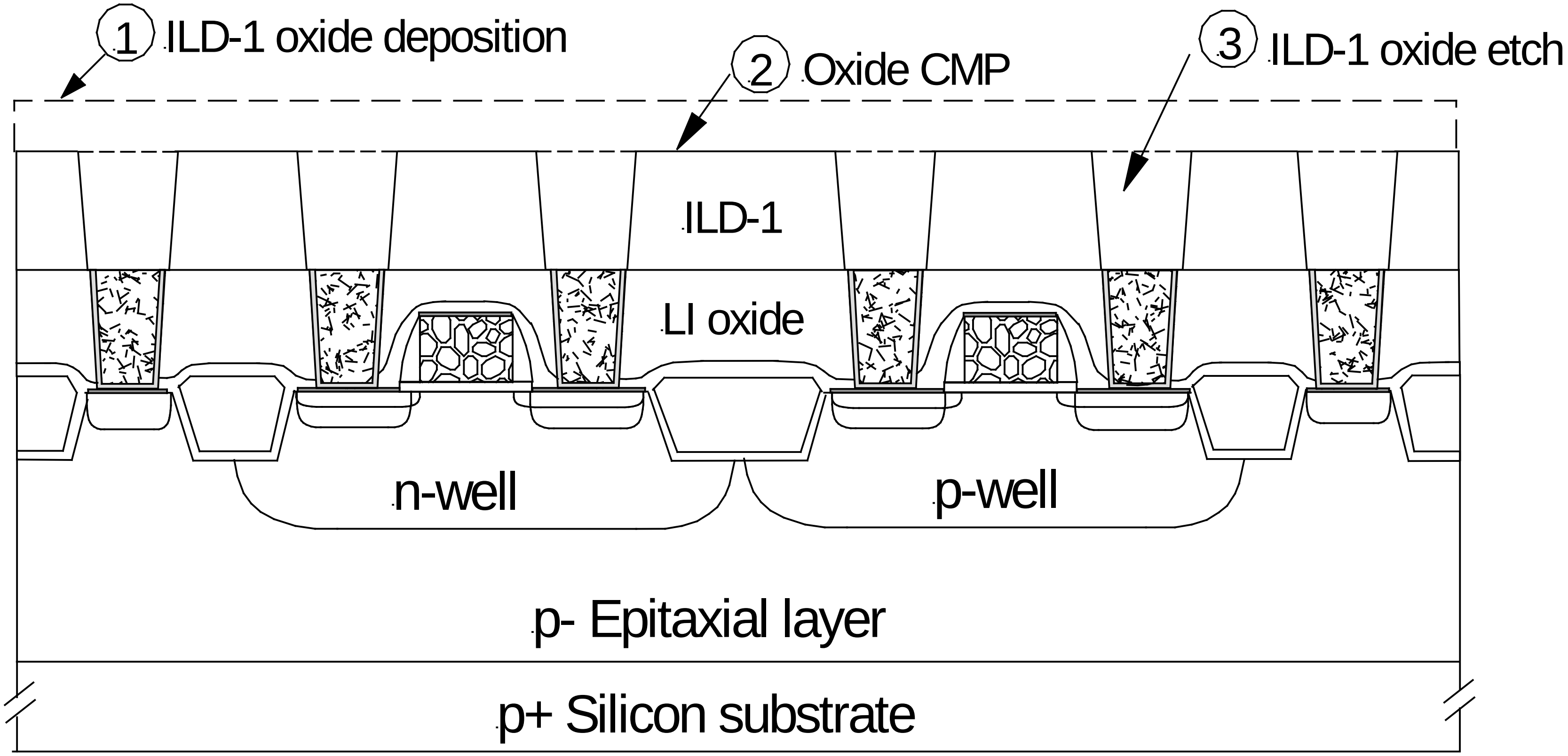
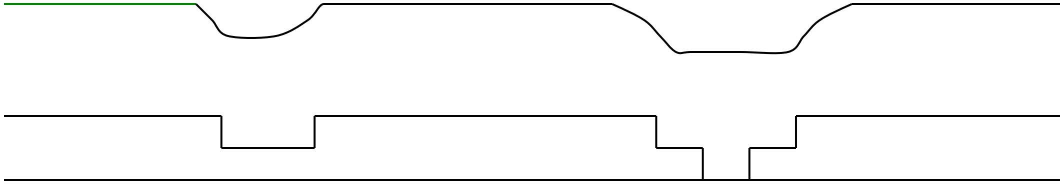


Fig. 18.25 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

CMP for Metals (Damascene Process)

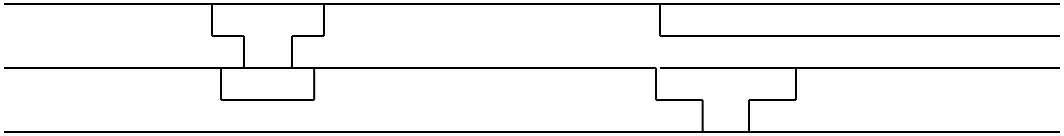
- Trenches/vias etched into ILD (interlayer dielectric)

- Metal deposition or plating



- Metal CMP

- Repeat for multiple levels of metal



CMP for Dual Damascene Copper Metallurgy

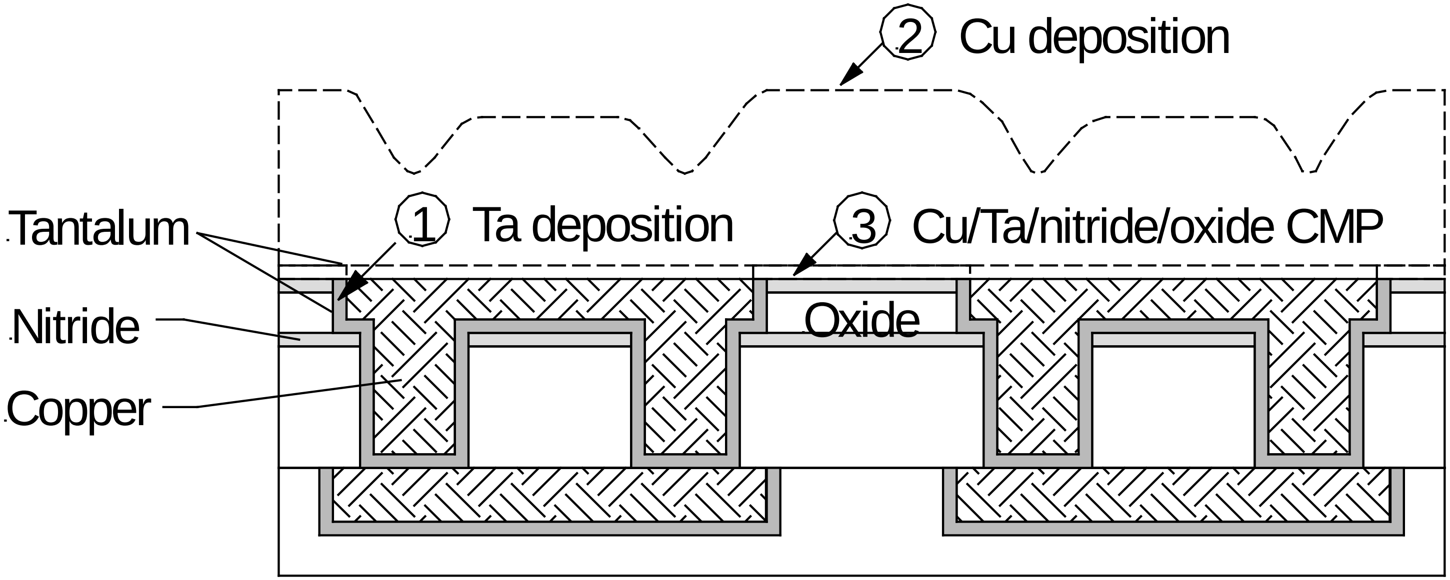
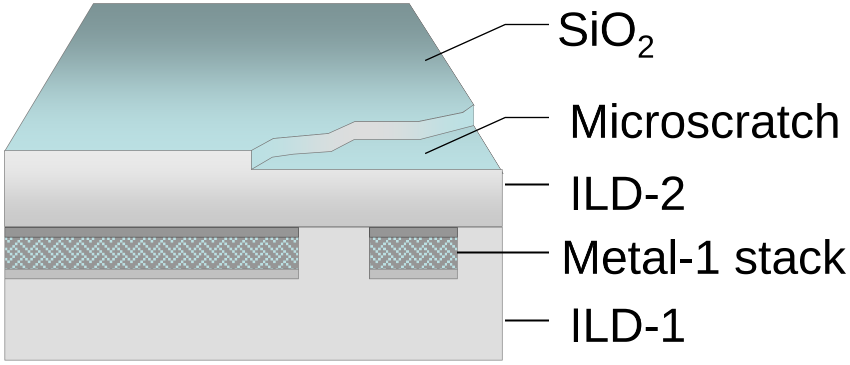
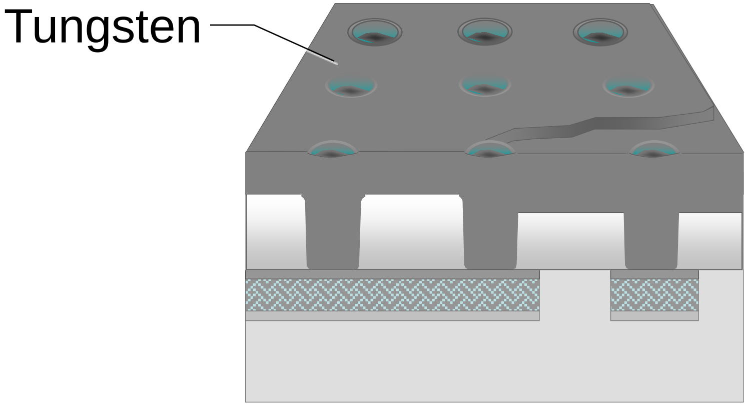


Fig. 18.26 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

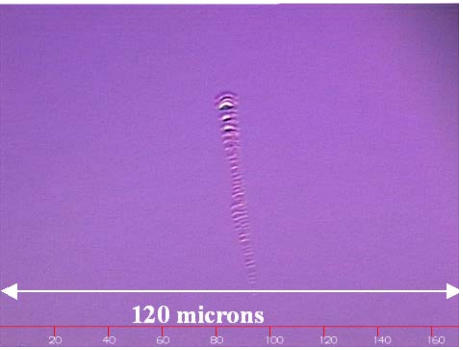
Consequences of CMP Micro-Scratch

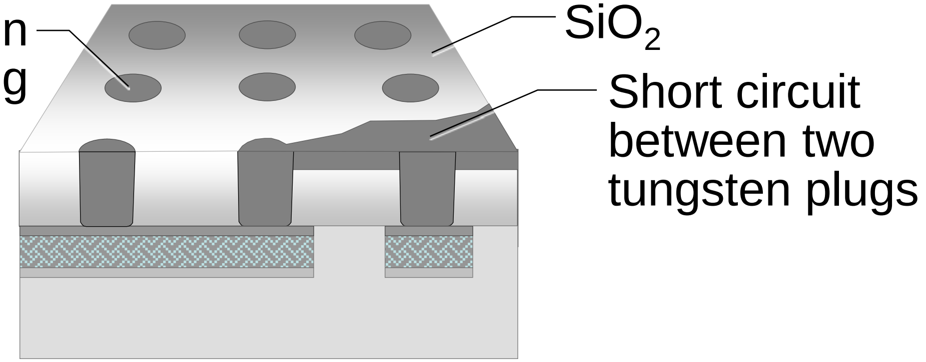


1) SiO_2 deposition followed by CMP



2) Via etch followed by tungsten via fill





3) Tungsten CMP

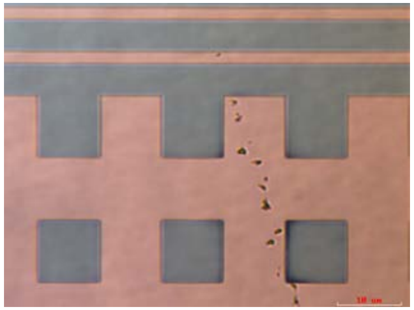


Fig. 18.27 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

Industrial CMP Requirements

- Stable, predictable, reproducible process
- High removal rates (>1700 Å/min for SiO_2 and >2500 Å/min for W)
- Independent of device/circuit design, substrate
- Good selectivity between metal and dielectric and similar polishing rates for metals and liners
- Few defects (scratches, peeling, particles)
- Low Non-uniformity
  - less than 5% variation in film thickness across wafer
- 3-6 mm edge exclusion

Characteristics of CMP

- CMP is widely used in IC manufacturing
  - Shallow trench isolation
  - Inter-metal Layer Dielectrics (ILD)
  - Copper metalization
- CMP is an art rather than science
  - Much more empirical data and rules than basic understanding of the process
  - Process parameters can be qualitatively understood but cannot be quantitatively modeled and predicted
- CMP is a dirty process (requires post-cleaning)

Process Issues

- Planarity:
  - Pad type
  - Circuit density & structure size
  - Extent of ILD removed
  - Downforce, platen speed & carrier speeds
  - The goal is to minimize SHR and maximize PD thereby minimizing Within-Die Non-Uniformity (WIDNU)

- Defect density:
  - Pad & slurry type
  - Use of secondary platen
  - Post-CMP cleaning method

- Removal rate:
  - Carrier film, pad & slurry type
  - Downforce
  - Platen & carrier speeds

- Within-Wafer Non-Uniformity (WIWNU):
  - Wafer flatness
  - Carrier film, pad & slurry type
  - Carrier design
  - Pad conditioning method
  - Platen & carrier speeds
  - Retaining ring design (i.e. extent of pressure discontinuity between wafer edge and retaining ring)
  - Slurry injection scheme

CMP Parameters

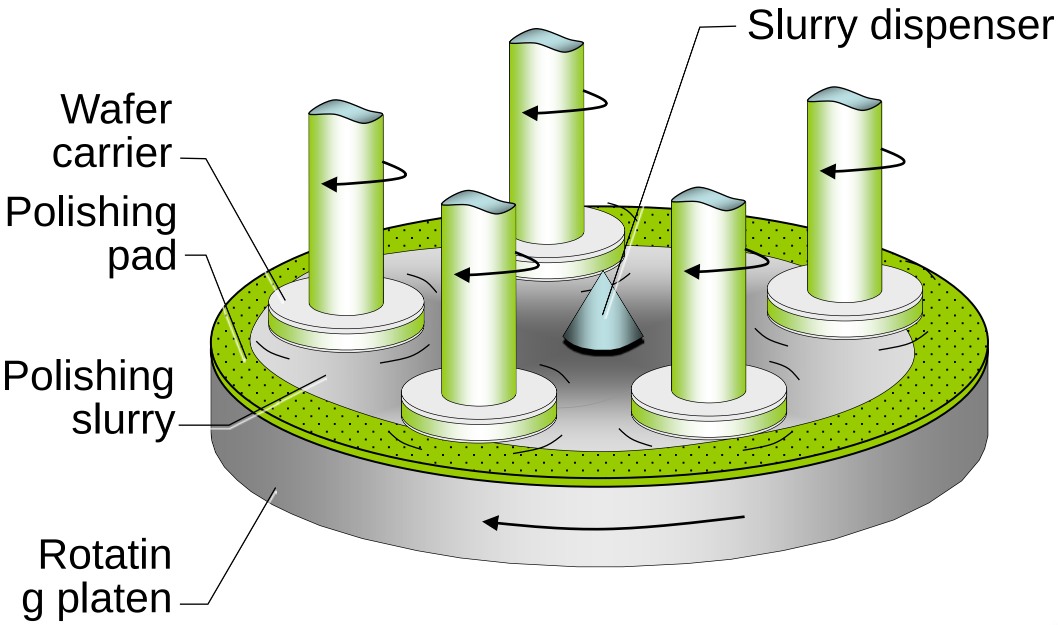
Parameter	Planarization Results on Wafer
Polish time	• Amount of material removed • Planarity
Pressure on wafer carrier (downforce)	• Removal rate • Planarization and non-uniformity
Platen speed	• Removal rate • Non-uniformity
Carrier speed	• Non-uniformity
Slurry chemistry	• Material selectivity • Removal rate
Slurry flow rate	• Affects how much slurry is on the pad and the lubrication properties of the system
Pad conditioning	• Removal rate • Non-uniformity • Stability of CMP process
Wafer/slurry temperature	• Removal rate
Wafer back pressure	• Center slowness/non-uniformity • Wafer breakage

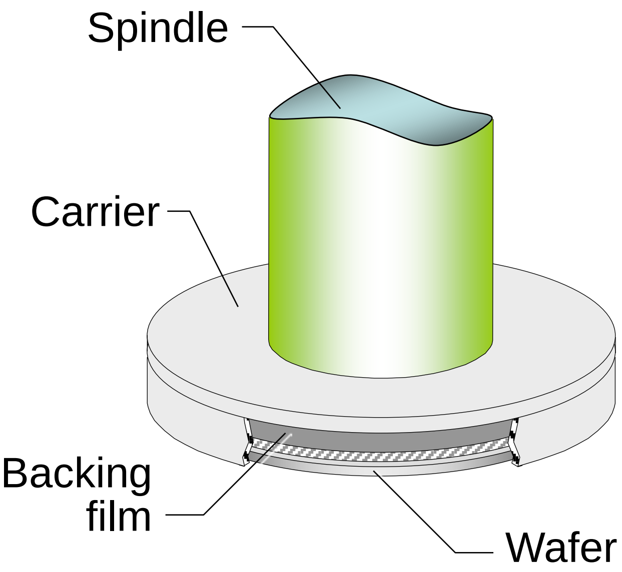
Table 18.4

The CMP Infrastructure

- Polishing:
  - Rotary (single or multiple heads and platens)
  - Linear (multiple heads)
- Cleaning:
  - Mechanical scrubbing (with & without chemistry or megasonics)
  - Wet cleaning (with and without megasonics)
- Measurement and inspection:
  - Removal Rate
  - Thickness uniformity (wafer-to-wafer, within-die, die-to-die)
  - Defect density
  - Dishing
  - Erosion
  - Plug recess
  - Planarity
  - Surface Roughness

CMP Tool with Multiple Wafer Carriers





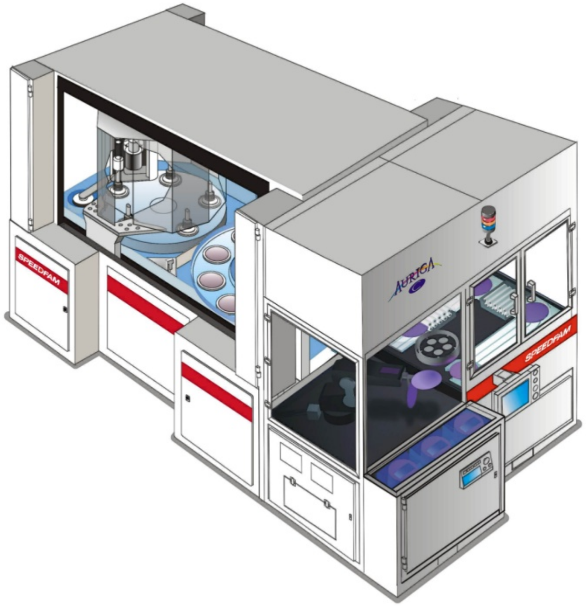
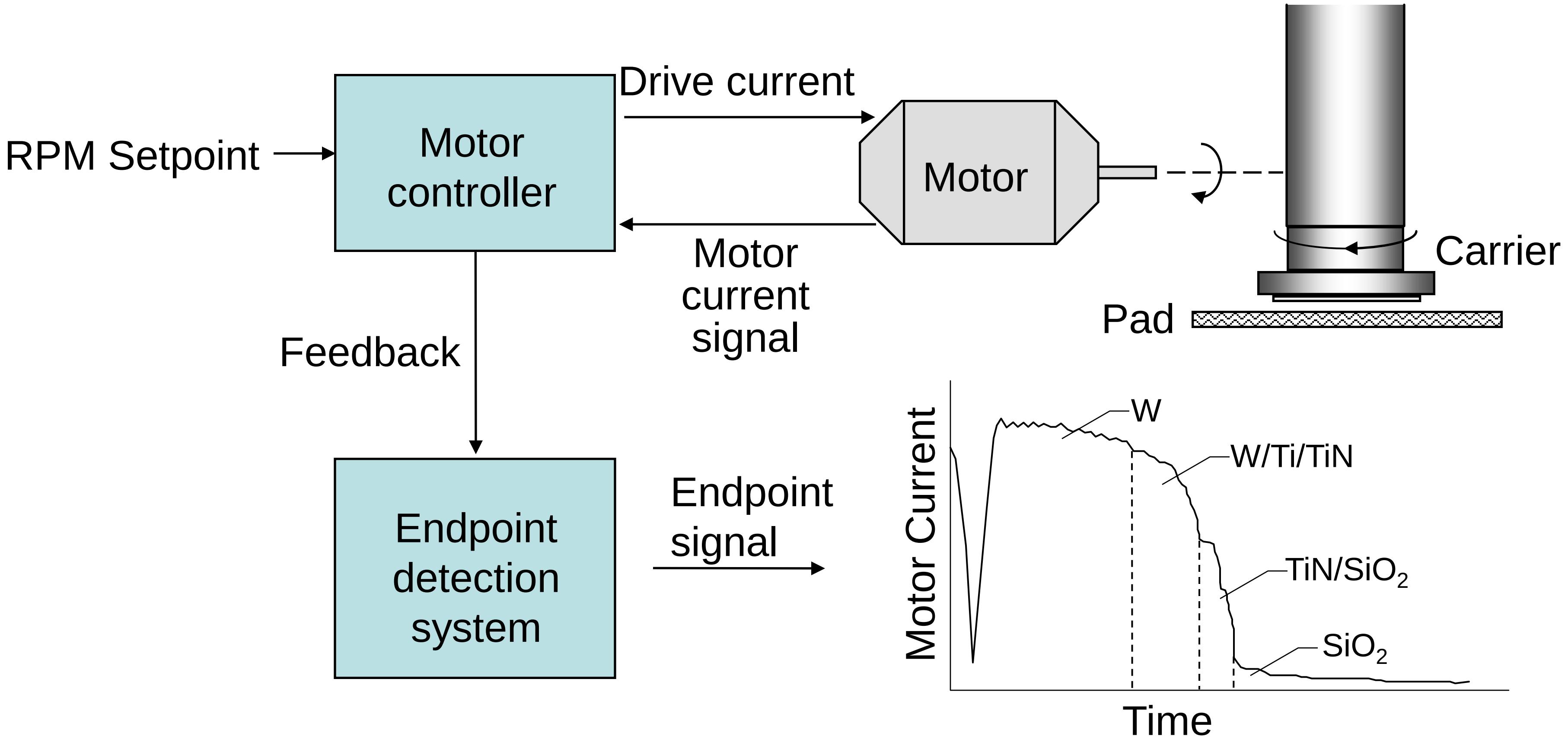


Figure 18.17

Motor Current Endpoint Detection



RPM Setpoint

Motor controller

Drive current

Motor

Motor current signal

Carrier

Pad

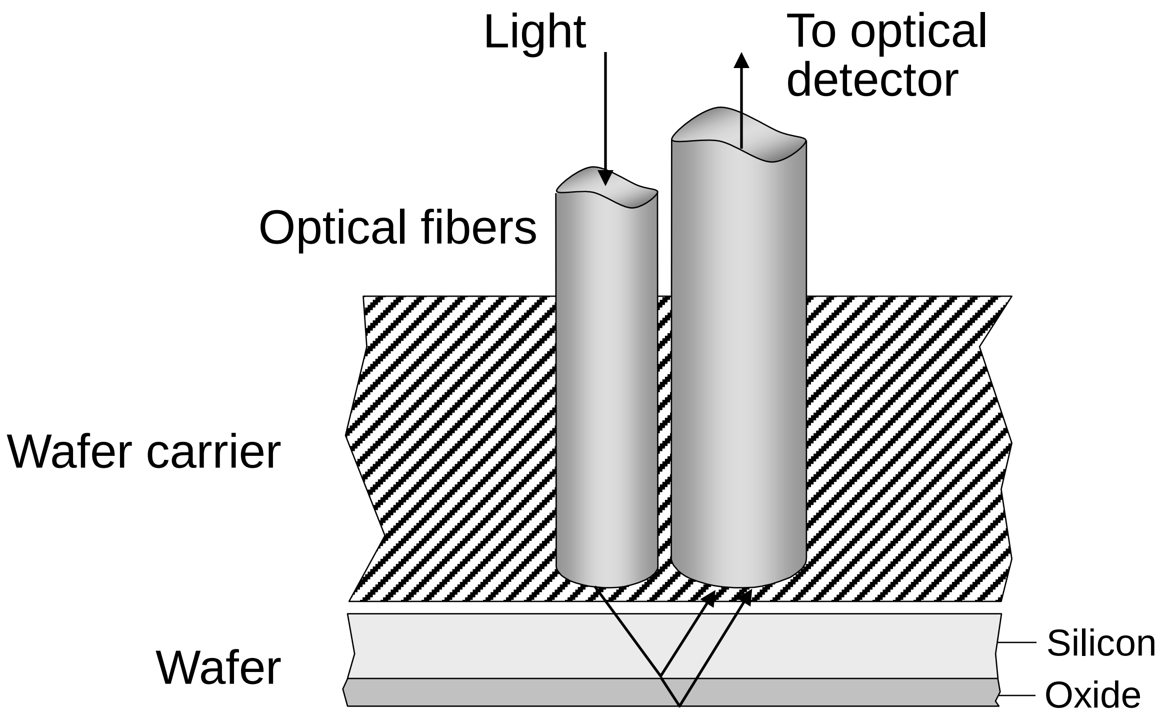
Feedback

Endpoint detection system

Endpoint signal

Figure 18.18

Optical Interferometry for Endpoint Detection

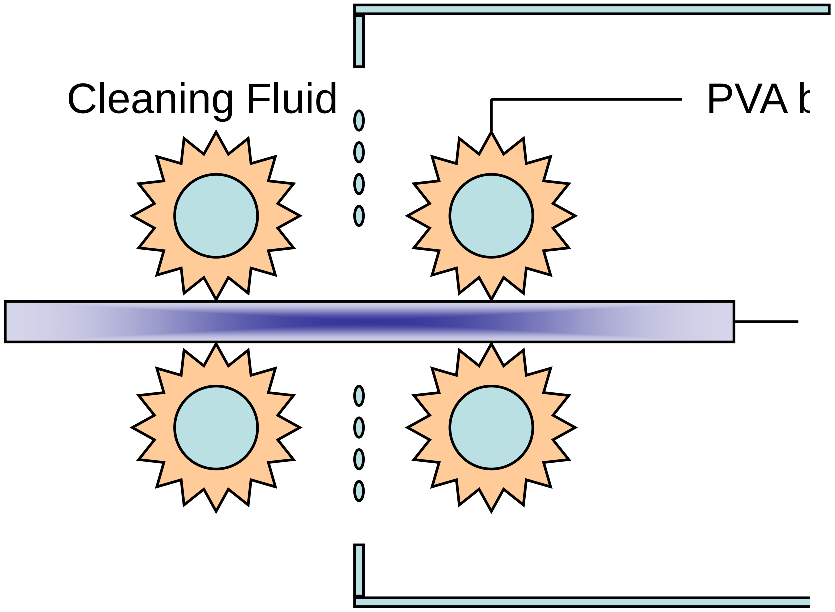


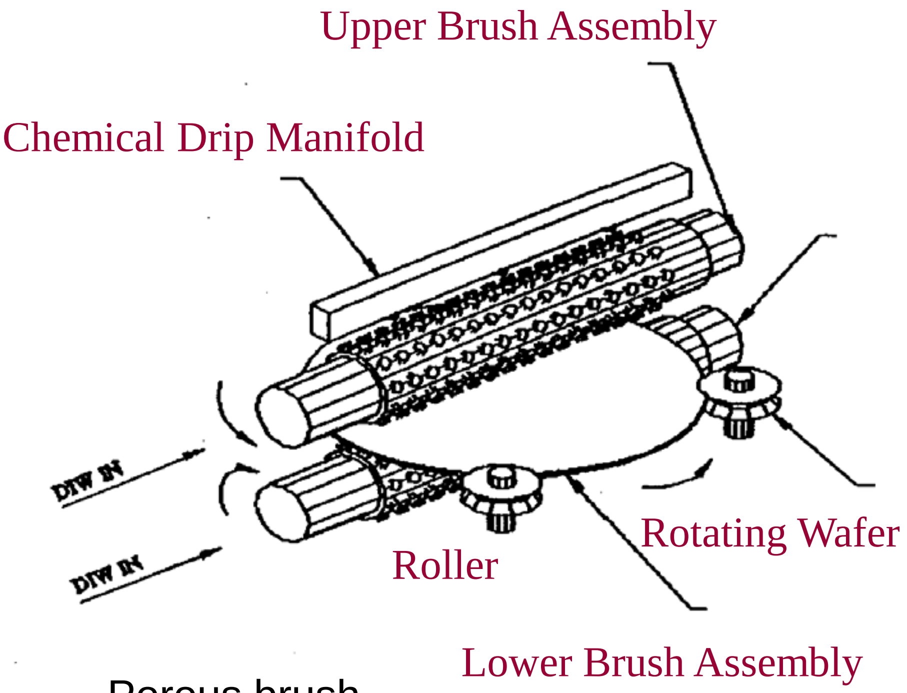
Redrawn from H. Lituak and H. M. Tzeng, “Implementing Real-Time Endpoint Control in CMP,” *Semiconductor International*) July, 1996) p. 262.

Post CMP Cleaning

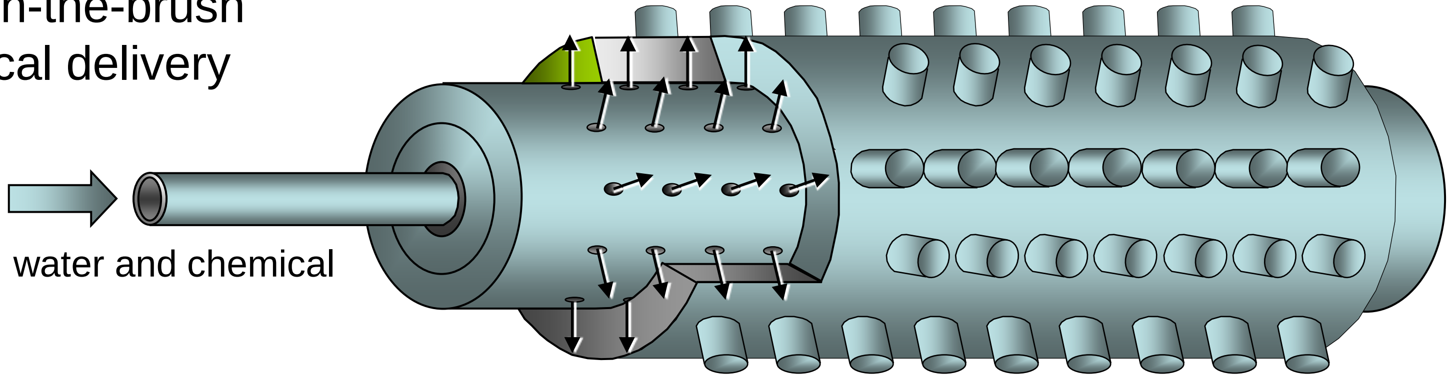
- Remove particles and chemical contamination following polishing
- Involves buff, brush clean, megasonic clean, spin-rinse dry steps
- Buffing
  - after main polish , wafers “polished” using soft pads
  - used following metal CMP
  - oxide slurries, DI water, or NH_4OH used
    - changes pH of system to reduce adhesion of metal particles
    - removes metal particles embedded in wafer
- Brush cleaning
  - brushes made from PVA with 90% porosity
  - NH_4OH (1-2%) added for particle removal (prevents redeposition), citric acid (0.5%) added for metal removal, HF etches oxide to remove subsurface defects
- Megasonic cleaning
  - sound waves add energy to particles, thin boundary layers
  - cleaning chemicals added (TMAH, SC1, etc.)
  - “acoustic streaming” induces flow over particles

Schematic Diagram of Post-CMP Scrubbing





Through-the-brush chemical delivery



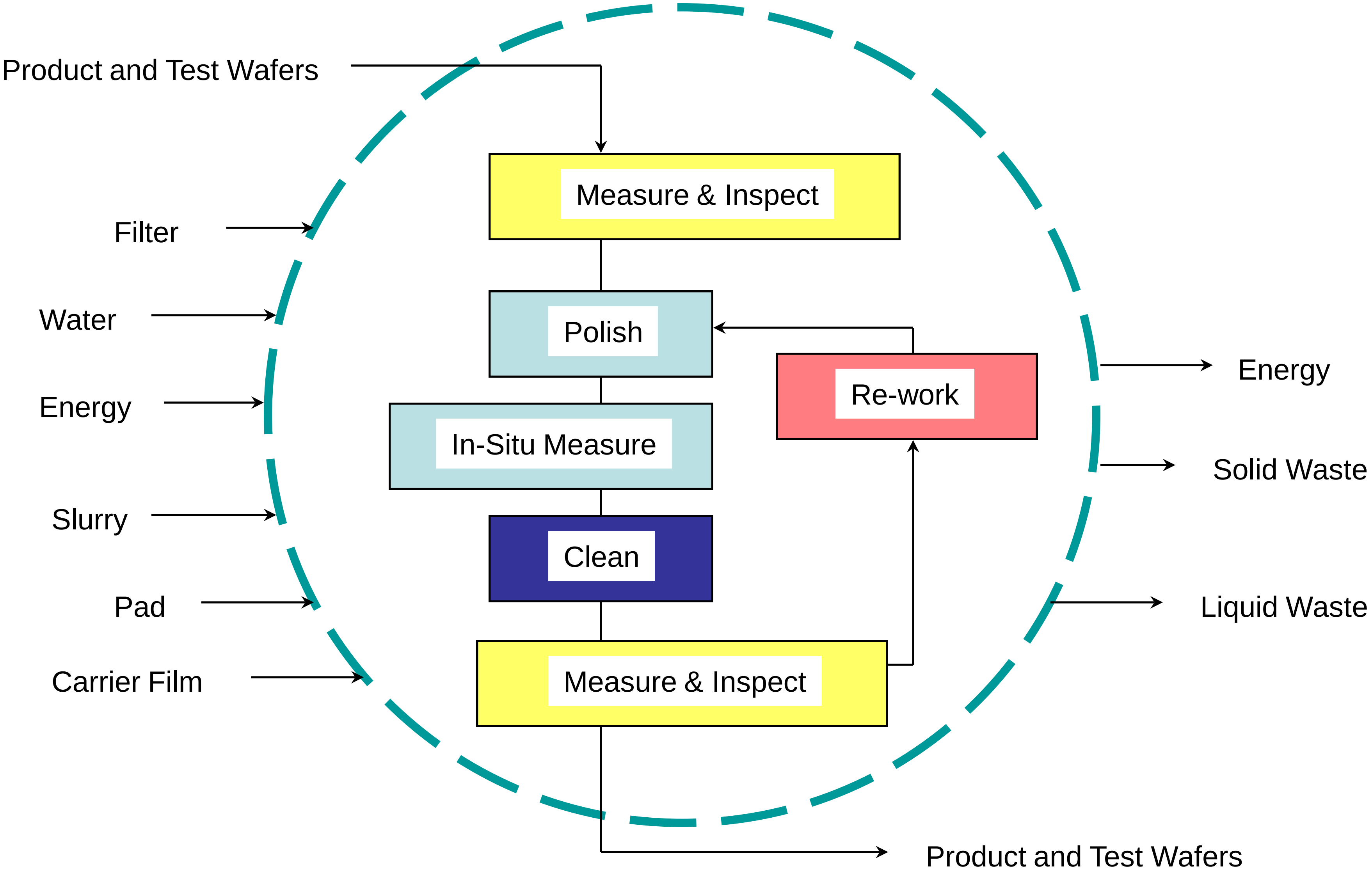
Redrawn from D. Hynes, et al, “Brush Scrubbing Emerges as Future Wafer-Cleaning Technology, *Solid State Technology*, (July 1997): p. 210.

Evolution of Post-CMP Cleaning

	Wet bench with megasonics	Doublesided scrubber + DI water	DSS + NH_4OH	DSS + NH_4OH and HF	DSS + Additional Chemistries
Oxide CMP	√	√	√	√	
Tungsten CMP			√	√	
Copper CMP					√

Fig. 18.21 in *Semiconductor Manufacturing Technology,* by M. Quirk and J. Serda, © *2001 by Prentice Hall*

The CMP Module



Product and Test Wafers

Filter

Water

Energy

Slurry

Pad

Carrier Film

Measure & Inspect

Polish

In-Situ Measure

Clean

Measure & Inspect

Re-work

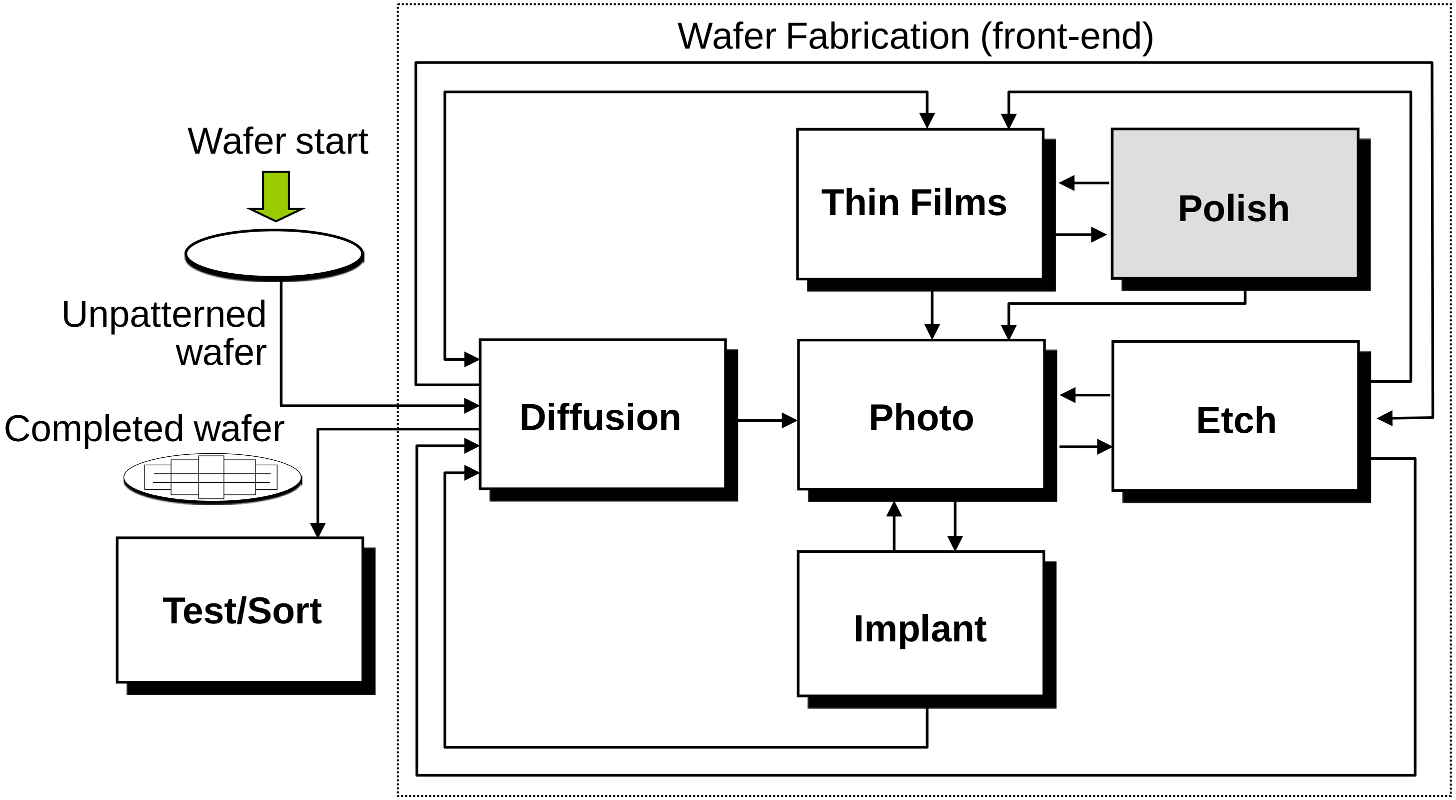
Energy

Solid Waste

Liquid Waste

Product and Test Wafers

Wafer Process Flow with CMP



Courtesy of Advanced Micro Devices