CMP Fluid Dynamics and Tribology

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December 2000
Particle Settling & Pad Geometry

• **Slurry:**
  – How do abrasive particles flow during CMP?
  – Which types of abrasives tend to settle during flow?
  – Is abrasive settling a good thing or a bad thing?
  – How does abrasive flow pattern depend on process, slurry type and pad properties?
  – What is the critical abrasive size for determining defectivity?

• **Pad:**
  – How do grooves affect the overall fluid dynamics of the CMP process?
  – Is there an optimum groove design?
  – How do grooves and abrasive particles interact?
  – Can grooves act as particle gettering devices?
Scaled Schematic No. 1 (Macro-Scale)

wafer warp & bow ~ 5 micron across 200 mm

see next foil for expanded diagram
Scaled Schematic No. 2 (Macro-Scale)

wafer nano-topography ~ 50 nm across 2 mm

see next foil for expanded diagram

2000 micron

500 micron
Scaled Schematic No. 3 (Feature-Scale)

see next foil for expanded diagram

50 micron

20 micron

500 micron

500 micron
Scaled Schematic No. 4 (Micro-Scale)
Stokes Number
Response time of particle relative to response time of fluid

\[ St = \frac{\rho_p D^2 u}{\mu L} \]

St < 0.1 particles do not have inertia and they follow the flow field

St > 0.1 particles have inertia and they most likely do not follow the flow field

\[ \rho_p \] density of abrasive particle

\[ D \] mean aggregate diameter

\[ u \] relative pad-wafer linear velocity

\[ \mu \] slurry viscosity

\[ L \] hydraulic diameter of groove
(cross sectional area ÷ wetted perimeter)

**Assumptions:**

- Creeping flow (i.e. Reynolds Number < 0.1)
- No particle-particle interactions
- No chemistry effects
- No gravitational effects
Stokes Number Calculations

groove W X H = 500 X 300 micron ; u = 0.44 meter per second

Stokes Number (unitless)

Particle Diameter (micron)

- settling regime
- ceria abrasive slurry at 1 Poise
- ceria abrasive slurry at 10 Poise
- silica abrasive slurry at 1 Poise

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General Observations Regarding Stokes Number

• For most slurry systems, particles with diameters of 1 micron or less are predicted to follow the flow field:
  – Chances of coming into contact with the wafer surface is greater
  – 1 micron particles may cause scratches
• Particles larger than 1 micron are more likely to settle down into grooves or away from the wafer surface:
  – They may be less dangerous
• Changes in slurry viscosity (due to non-Newtonian or rheopectic behavior) can dramatically affect abrasive flow characteristics
• For a slurry system, both the Stokes Number and the particle size may need to be considered in order to determine the detrimental effects on surface defectivity
Selected Particle Trajectories
Selected Streamlines For Fully-Developed Flow

Effect of Groove Depth

Groove width = 500 micron
Groove depth = 300 micron

Groove width = 500 micron
Groove depth = 600 micron

Streamline imaginary curve in a mass of flowing fluid so drawn that on the curve the net velocity vector is at every point tangent to the streamline.
Ex: Volume Fraction Computation for a 2-minute Polish

[Image showing a graph with particle volume fraction data and a color scale.]

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Volume Fraction Data Can Be Manipulated to Provide Useful Information on Geometric and Inertial Effects

- Residence time of particle in the groove at steady state

\[ \tau_{\text{groove}} = \frac{V_{\text{groove}}}{Q_{\text{particles}}} \]

- Fraction of time particles spend in the groove

\[ \varphi = \frac{\tau_{\text{groove}}}{\tau_{\text{groove}} + \tau_{\text{gap}}} \]

- Volume of groove
- Volumetric flow rate of particles
- Residence time of particle in the gap between wafer and top surface of pad

\[ \tau_{\text{gap}} = \text{residence time of particle in the gap} \]
Volume Fraction as a Function of Groove Shape

120 second polish; 0.1 micron particles; W X D = 500 X 300 micron

\(\tau_{\text{groove}} = 83 \text{ sec} \)
\(\phi = 0.69\)

\(\tau_{\text{groove}} = 83 \text{ sec} \)
\(\phi = 0.69\)

\(\tau_{\text{groove}} = 90 \text{ sec} \)
\(\phi = 0.75\)

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Volume Fraction as a Function of Particle Size

120 second polish; W X D = 500 X 600 micron

0.1 μm

1 μm

10 μm

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Volume Fraction as a Function of Groove Depth

120 second polish; 0.1 micron particles;
Groove Width = 500 micron

Groove Depth = 300 micron

- $\tau_{\text{groove}} = 83 \text{ sec}$
- $\varphi = 0.69$

Groove Depth = 600 micron

- $\tau_{\text{groove}} = 92 \text{ sec}$
- $\varphi = 0.76$
General Observations Re: Numerical Analysis

- Most differences observed at the bottom of the groove and not near the wafer-pad gap region
- V-groove results in the most even particle distribution
- U-groove results in the least even particle distribution
- Smaller aspect ratios result in more even particle distribution
- Fluid dynamics differences between 0.1 and 1 micron particles are very minor and can be ignored
- Fluid dynamics differences between 1 and 10 micron particles are major
  - Results are in qualitative agreement with the Stokes analogy presented earlier
The CMP System

Wafer (flat or patterned)

Slurry or chemical or water

Pad (conventional or fixed abrasive)

- C: Slurry (or chemical or water) concentration
- D: Apparent distance between wafer and pad
- FF: Frictional force resulting from interactions between rotating pad, rotating wafer and entrained fluid
- P: Local pressure
Dual-Emission Laser-Induced Fluorescence (DELIF)
Flow Visualization using DELIF
Concentration ($C$)

- How does fresh fluid (i.e. slurry, chemical or water) mix with old fluid?

- Does the CMP system behave like a CSTR (Continuously Stirred Tank Reactor), a PFR (Plug Flow Reactor), or a Dispersed Vessel?

- What is the mean residence time of fluid in the wafer-pad gap and on the pad surface? How much of the slurry actually enters the wafer-pad gap?

- How do process parameters such as down-force, platen speed, carrier speed, flow rate and type of wafer being polished affect ‘$C’? 

- How do polisher parameters such as conditioning methods, fluid injection schemes and the location of the carrier and platen affect ‘$C’? 

- How do consumable parameters such as slurry type, solids content, pH, pad type, groove pitch-depth-width-shape affect ‘$C’?
Design of Experiment (43 Runs)

Variables:
- Pad Manufacturer (Cabot, Rodel & Freudenberg)
- Pad Groove Depth (0 - 40 mils)
- Wafer Pressure (2 - 6 psi)
- Platen Speed (30 - 90 rpm)
- Slurry Flow Rate (20 - 50 ml/min)

Constants:
- Groove Style (X-Y Grooving, 0.025” width)
- Head Speed (60 rpm)
- Head Position (3/4” wafer to platen edge)
- Injection Location (pad center)
- Conditioning (163 Micron diamond grit)

Response:
- Fresh (i.e. entering) slurry concentration vs. time
Repeatability

**Manufacturer:** Cabot  
Slurry Flow Rate: **35 cc/min**  
Wafer Pressure: **4 psi**  
Platen Speed: **60 rpm**  
X-Y Groove Depth: **20 mils**
Slurry Flow Rate

Manufacturer: Rodel
Slurry Flow Rate: 20 & 50 cc/min
Wafer Pressure: 4 psi
Platen Speed: 60 rpm
X-Y Groove Depth: 20 mils
Manufacturer: Freudenberg
Slurry Flow Rate: 35 cc/min
Wafer Pressure: 4 psi
Platen Speed: 30 & 90 rpm
X-Y Groove Depth: 20 mils
Measuring the Slurry Age

- Mean Residence Time

\[ t = \frac{\int C \cdot t \cdot dt}{\int C \cdot dt} \]

- Variance

\[ \sigma^2 = \frac{\int C \cdot (t - \bar{t})^2 \cdot dt}{\int C \cdot dt} \]
# Data Analysis

## Mean Residence Time Significant Factors

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<tr>
<th>Factor</th>
<th>In Situ Coefficient</th>
<th>Ex Situ Coefficient</th>
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<tr>
<td>Constant</td>
<td>22.63</td>
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<td>-12.69</td>
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<td>Pad Manufacturer</td>
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<td>Platen Speed-Platen Speed Interaction</td>
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Correlation Coefficient

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<td></td>
<td>0.80</td>
<td>0.82</td>
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Mean Residence Time Contour Plots

20 mil Groove Depth

30 rpm Platen Speed

Platen Speed (rpm)  Flow Rate (cc/min)

Groove Depth (mils)
How Much of the Fresh Slurry Supplied to the Pad Enters the Wafer-Pad Gap?

2X increase in flow rate (i.e. from 22 to 44 cc/min) does not reduce Mean Residence Time by 2X!

It reduces MRT from 21 sec to only 16 sec!

Therefore only ~ 45% of fresh slurry supplied to the pad enters the wafer-pad gap region!

~ 55% gets totally wasted!
In-Situ Conditioning

Mean Residence Time = 20 vs 11 sec

(there is tremendous potential to decrease flow rate during in-situ conditioning)
### Data Analysis

#### Variance Significant Factors

<table>
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<th>Factor</th>
<th>In Situ Conditioning</th>
<th>Ex Situ Conditioning</th>
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<td>Correlation Coefficient</td>
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Depth (D)

- Does CMP occur via hydrodynamic lubrication, asperity contact or a combination of both?

- How do process parameters such as down-force, platen speed, carrier speed, flow rate and type of wafer or film being polished affect ‘D’?

- How do polisher parameters such as conditioning methods and carrier designs affect ‘D’?

- Can $\frac{d(D)}{dt}$ act as a predictor of pad life?

- How do consumable parameters such as slurry type, solids content, pH, pad type, groove pitch-depth-width-shape affect ‘D’?

- How do pads bend locally & globally during the CMP process?
Effect of Platen Speed & Pressure on ‘D’ (fluid = water)
Local & Global Pad Bending
Thickness Profile Underneath Wafer and Microscope Slide Cover
Friction Force (FF)

- What is the magnitude of frictional forces acting on the pad-wafer system?
- How do process parameters such as down-force, platen speed, carrier speed, flow rate and type of wafer or film being polished affect ‘FF’?
- How do polisher parameters such as wafer cooling and conditioning methods affect ‘FF’?
- Can d(FF)/d(t) act as a predictor of pad life?
- How do consumable parameters such as slurry type, solids content, pH and pad type affect ‘FF’?
- How much ‘FF’ can organic VLK, ELK or ULK materials tolerate without getting de-laminated during CMP?
Measuring Coefficient of Friction

- Rotating Wafer
- Applied Wafer Pressure
- Slurry
- Diamond Grit Plate with Rotation & Translation
- Measured Lateral Force
- Rotating Platen
- Polisher Base
- Sliding Friction Table
- Strain Gauge
- Floor

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Effect of Platen Speed on ‘D’ & ‘FF’

(Fluid = H2O)
Effect of Wafer Pressure on ‘D’ and ‘FF’

(Fluid = H2O)
‘FF’ for Various Wafer Pressures

Platen Speeds & pH values

(Fluid = H2O with In-Situ Conditioning)
Lubrication in Journal Bearings … Striebeck Curve


Asperity contact
Partial contact (mixed lubrication)
Hydrodynamic lubrication

Coefficient of Friction (unitless)

(Shaft Velocity, rpm) x
(Oil Viscosity, cPoise) /
(Bearing Pressure, psi)
Wafer Shape Effects

In both cases, the amplitude is \( \sim 5 \text{ micron} \)
Coefficient of Friction and the Stribeck Curve

Determination of the Tribological Mechanism

Convex wafer … mixed lubrication mechanism

Hersey Number = 
\[ \frac{\text{RPM} \times \text{cP}}{\text{PSI}} \]

Concave wafer … mechanism unknown

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Possible Asperity Contact Models

**MODEL - I**
3-body asperity contact model

**MODEL - II**
2-body asperity contact model
Partial Contact (Mixed Lubrication) Model
Coefficient of Friction vs. Wafer Down Pressure

Convex Wafer

Concave Wafer

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Pressure Measurement Apparatus & Location of Pressure Taps on the Wafer

- Glass Wafer
- Pressure Tap
- Plug
- Sliding Contact
- Pick-up Arm
- Pressure Transducer
- Rotating Platform
- Tygon Tubing
- Pad
- Platen
Pressure Measurement Apparatus
Average Fluid Pressure vs. Wafer Radius
Platen Speed = 60 RPM; Wafer Pressure = 3 PSI

Convex Wafer

Concave Wafer

Measured Data
Calculated From Overall Force Balance

Measured Data
Calculated From Overall Force Balance
Varieties of Fumed Silica Slurry

Courtesy of Degussa-Huls AG