The Spectral Fingerprints and the Sounds of post-CMP PVA Brush Scrubbing

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Mechanism of Particle Removal Through Scrubbing

- PVA is compressed when it contacts a particle adsorbed on the surface of the wafer
- Pores and asperities on the surface of the brush:
  - Engulf the particle
  - Cause the exposed surface of the particle to adsorb on the surface of the brush (either mechanically, chemically or by capillary suction)
- Torque created by the rotation of the brush dislodges the particle from the surface
- Fluid present on wafer surface, & being pumped in and out of brush pores (during compression & elastic recovery of the brush), carries the particle away from the wafer
Motivation

- For PVA scrubbers with **simple kinematics**, Strubeck curves have been used to determine the lubrication mechanism of the scrubbing process and can help predict brush life, however:
  - Experimentally intensive
  - Inherent uncertainty in estimating the constituents of the Sommerfeld number
    - Fluid film thickness in the brush-wafer interface
      - Nodules
      - Mechanical properties of the polymer
    - Localized brush pressure as a function of brush deformation
      - Completely misleading when **complex kinematics** are involved

\[
So = \frac{(u) \times (\mu)}{(P_{\text{applied}}) \times (h_{\text{eff}})}
\]

- Effective fluid film thickness in the brush-wafer interface ...
  - Dependent on applied pressure
Pressure Mapping Apparatus

- X-wires
- Y-wires
- Pressure resistive sheet
- Protective laminate film

~ 200 microns
Relationship Between Brush Pressure & Contact Area

Rippey brush is 10% less compliant

Total range of pressures

Speedfam-IPEC brush

Brush Pressure (PSI)

Brush-Wafer Contact Area (square inches)
3-D Deformation Characteristics of Rippey Brush
Effective Fluid Film Thickness Approximation in the Brush-Wafer Interface

\[ h_{\text{eff}} \sim (1 - \alpha) \times h_{\text{nodule}} \times \frac{A_{\text{ref-pressure}}}{A_{\text{pressure}}} \]

‘\(\alpha\)’ represents the area of the top of nodules to the area of the outer core of the brush.

\[ \alpha_{\text{Rippey}} = 0.24 \]
\[ \alpha_{\text{Speedfam-IPEC}} = 0.39 \]

Low Pressure

High Pressure

\[ n_{\text{Rippey}} = 8 \]
\[ n_{\text{Speedfam-IPEC}} = 9 \]
Goals

• Determine whether spectral analysis based on raw frictional data obtained during PVA brush scrubbing:
  
  – Can shed light on the tribology of the process as a function of:
    • Brush rotational velocity and oscillation frequency
    • Wafer velocity
    • Solution pH
    • Brush pressure
  
  – Can help ‘fingerprint’ the process and help in:
    • New endpoint detection methods
    • Process, consumables and equipment diagnostics
    • Elucidation of fundamental physical and chemical phenomena taking place during scrubbing

  – Can be extended to allow for its characteristic resonance to be set to music!
    • Technical benefits of the latter are yet to be determined
    • The possibility of reproducing the ‘sound’ of post-CMP scrubbing is, in and of itself, a curious endeavor
Apparatus

\[ COF_{avg} = \frac{F_{Shear}}{F_{Normal}} \]
Experimental Conditions

• Constants:
  - Applied Pressure = 0.35 PSI
    in some cases, other pressures
    have also been investigated
  - Cleaning solution flow rate = 120 cc/min
  - Rippey Symmetry™ PVA-33 brush
  - Frictional force acquisition frequency = 1,000 Hz
  - Wafer type = 5,000 Angstrom ILD
  - Scrubbing time = 2 minutes

• Variables:
  - Brush rotational velocity
    • 10
    • 20
    • 30
    • 40
    • 50
    • 60 RPM
  - Brush oscillation frequency
    • 0 and 20 per minute
  - Wafer rotational velocity
    • 0 and 40 RPM
  - Cleaning solution pH
    • 1.1, 7.0 and 10.7
Striebeck Curves Corresponding to Simple Tool Kinematics (i.e. Brush Rotation Only)

- Brush rotation = 10 to 60 RPM
- Brush oscillation = 0 per minute
- Wafer Rotation = 0 RPM
- \( P = 0.25 \text{ PSI} \)

- Brush rotation = 10 to 60 RPM
- Brush oscillation = 0 per minute
- Wafer Rotation = 0 RPM
- \( P = 0.35 \text{ PSI} \)

- Brush rotation = 10 to 60 RPM
- Brush oscillation = 0 per minute
- Wafer Rotation = 0 RPM
- \( P = 0.55 \text{ PSI} \)
Brush rotation = 10 to 60 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

Brush rotation = 10 to 60 RPM
Brush oscillation = 20 per minute
Wafer Rotation = 0 RPM

Brush rotation = 10 to 60 RPM
Brush oscillation = 20 per minute
Wafer Rotation = 40 RPM

Strubeck Curves Corresponding to Complex Tool Kinematics

pH = 1.1
pH = 7.0
pH = 10.7
Simplified Schematics of Brush Macro-Deformation During Scrubbing

down pressure

down pressure and rotation

down pressure, rotation & oscillation (+)

down pressure, rotation & oscillation (-)

all of the above & wafer rotation (top view)
Likely Components of Total Friction Caused by the Sliding Action of an Elastomer on a Rigid Body in Wet Conditions

- **Adhesion**
  - **Surface phenomenon** occurring at points of ‘real’ contact
  - Induced by elastomeric structure of flexible chains which are in constant state of thermal motion
    - Formation of bonds between elastomeric chains & molecules on the surface
    - Stretching, rupturing and relaxation of bonds due to relative motion of the two bodies
    - Repetition of the above

- **Deformation (a.k.a. hysteresis)**
  - **Bulk phenomenon** occurring due to delayed recovery of the elastomer after indentation
  - Depends on the elastic or visco-elastic properties of the material

- **Electrostatic forces**
  - **Surface phenomenon** occurring due to presence of EDL
  - Depends on solution pH as well as the zeta potential of the rigid body and the elastomer

- **Capillary forces**
  - **Bulk phenomenon** occurring due to presence of voids and nature of surrounding fluids
Analyzing Raw Frictional Data

- **Typical Scrubbing Process:**
  - 2-minute
  - 1000 frictional force measurements per second
  - 120,000 data points per run

\[
\gamma = \text{Interfacial Interaction Index} \\
\gamma = \text{Area under the curve} \\
\gamma = \text{Total amount of mechanical energy caused by stick-slip}
\]

\[
F_{shear}(t) = F_{shear} + f(t)
\]

\[
\text{COF}_{\text{avg}} = \frac{\overline{F}_{\text{Shear}}}{F_{\text{Normal}}}
\]

Fast Fourier Transform
Contribution of Tool Vibration & Resonance to the Force Spectra

- brush nodule (macro-deformation) effects?
- brush nodule (micro-deformation) effects?

\[ \gamma = \text{Area under the curve} \]
\[ \gamma = \text{Total amount of mechanical energy caused by stick-slip} \]
\[ \gamma = \text{... proportional to variance of frictional force} \]
Stribeck Curves Corresponding to Simple Tool Kinematics

Brush rotation = 10 to 60 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

\[ P = 0.25 \text{ PSI} \]

\[ pH = 1.1 \]
\[ pH = 7.0 \]
\[ pH = 10.7 \]

Brush rotation = 10 to 60 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

\[ P = 0.35 \text{ PSI} \]

Brush rotation = 10 to 60 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

\[ P = 0.55 \text{ PSI} \]
Gamma Curves Corresponding to Simple Tool Kinematics

Brush rotation = 10 to 60 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

P = 0.25 PSI

Brush rotation = 10 to 60 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

P = 0.35 PSI

Brush rotation = 10 to 60 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

P = 0.55 PSI
‘Gamma Criterion’ for Determining the Likely Lubrication Regime

Gamma > 0.001 … Boundary Lubrication

0.0001 > Gamma > 0.001 … Partial Lubrication

Gamma < 0.0001 … Hydrodynamic Lubrication
Time Domain & Frequency Domain Spectra
(pH = 1.1 and Pressure 0.35 PSI)

Brush rotation = 30 RPM
Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

Brush rotation = 30 RPM
Brush oscillation = 20 per minute
Wafer Rotation = 0 RPM

Brush rotation = 30 RPM
Brush oscillation = 20 per minute
Wafer Rotation = 40 RPM
Gamma Curves Corresponding to Complex Tool Kinematics

- **Brush rotation = 10 to 60 RPM**
  - Brush oscillation = 0 per minute
  - Wafer Rotation = 0 RPM

- **Brush rotation = 10 to 60 RPM**
  - Brush oscillation = 20 per minute
  - Wafer Rotation = 0 RPM

- **Brush rotation = 10 to 60 RPM**
  - Brush oscillation = 20 per minute
  - Wafer Rotation = 40 RPM
PVA Brush Scrubbing and The Violin

[Diagram of a violin with labeled parts: Chin rest, Tailpiece, Fine tuners, Bridge, Belly, F-holes, Tuning pegs, Scroll, Strings, Fingerboard, Neck, Back plate.]

[Graphs showing Bow Speed vs Time and String Speed vs Time, with waveforms indicating string speed changes over time.]
Waveforms in Time and Frequency Domains

$pH = 1.1; BV = 20$ RPM
$P = 0.25$ PSI

$pH = 1.1; BV = 20$ RPM
$P = 0.55$ PSI
Examples of PVA Brush Scrubbing Force Spectra

In all 3 Cases ... pH = 7.0 ; Brush Velocity = 30 RPM ; Brush Pressure = 0.35 PSI

Brush oscillation = 0 per minute
Wafer Rotation = 0 RPM

Brush oscillation = 20 per minute
Wafer Rotation = 0 RPM

Brush oscillation = 20 per minute
Wafer Rotation = 40 RPM

pH = 1.1 ; BV = 60 RPM
P = 0.55 PSI

pH = 7.0 ; BV = 60 RPM
P = 0.55 PSI
Summary

- **New tool & new methods** developed to precisely quantify the extent of wafer-brush frictional forces
- **Stribeck curves:**
  - Useful in determining the lubrication mechanism for simple kinematics
  - Misleading when complex kinematics are involved
- **New spectral technique developed for determining the tribological mechanism of a given process in terms of stick-slip phenomena:**
  - Based on FFT spectral analysis of raw frictional waveforms in time domain
  - Subsequent integration of the resulting spectrum in frequency domain
- **New parameter (Gamma) obtained at multiple pressures, kinematics and pH values:**
  - Gamma > 0.001 (BL)
  - 0.0001 > Gamma > 0.001 (PL)
  - Gamma < 0.0001 (HL)
- **Above method may potentially eliminate the need for Stribeck curves:**
  - Experimentally efficient
  - No need to compute the Sommerfeld Number
  - Does not require any prior knowledge of the particulars of the process
- **Significant differences in the ‘Spectral Fingerprint’ among various processing conditions:**
  - May pave the way towards design of novel brushes and processes
- ‘Spectral Fingerprint’ allows the unique ‘sounds’ of post-CMP PVA brush scrubbing to be synthesized for various processes
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Solubility & Gellation Characteristics of Silica (ILD) in the SiO2-Water System

pH = 1.1 ... High values of COF due to strong localized gelling in the brush-wafer interface
Polymerization of silicic acid monomers to form high MW ‘particles’
Collision and aggregation of above ‘particles’ to form 3-dimensional networks (gels)

pH = 7.0 ... Moderate values of COF due to increased stability of the system
Little or no tendency to gel
Increase in hydroxyl groups causing breakage of network-forming siloxane bonds
Partial hydration of ILD surface with network-terminating Si-OH groups

pH = 10.7 ... Low values of COF due to complete dissolution of silica
ILD surface is continually dissolving and rejuvenating
Complete elimination of silanol groups from the surface