Precision Substrate Cleaning
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Motivation

- The size of the features in the solid state industry is shrinking, pushing down the size of the contaminating particles that need to be removed (current particle threshold limit ~ 22 nm).
- Disk drive OEMs face increasingly stringent cleaning requirements driven by (current measurement limitation ~ 60 nm):
  - Areal density growth
  - Flying height reduction
- Failure to meet those requirements results in severe problems with drive yield and reliability.
- Ultrasonic/Megasonic cleaning (USC/MSC) meets the future cleaning requirements for cleaning substrates and disks.
  - Great particle removal efficiency (PRE) can be achieved for particles as small as 34 nm [1].
- The underlying physics of particle removal mechanism is not still well understood [2].
Introduction

- A USC/MSC system uses transducers to generate acoustic waves in a tank that is filled with a liquid solution (DI Water and/or a diluted amount of some chemicals).

- The type and concentration of the chemical substance varies from one application to another and can be tuned to achieve the target PRE.

- The frequency of the acoustic waves is typically between 150 kHz and 600 kHz for the USC systems and > 600 kHz for the MSC systems.
• The major role of a chemical substance in the solution is to loosen particle adhesion to the substrate surface while enhancing cavitation and boosting ionic double layer force.

• However, to minimize the negative effects of chemicals (such as substrate scrap) and to reduce the cost of chemicals, a very low concentration (< 1 %) of chemicals is used.

• In the present study, we focus on spherical particles that have a diameter of < 400 nm and we investigate the following cases:
  – Glass particles on glass substrate
  – Alumina particles on alumina substrate (surface of aluminum substrate is usually oxidized when it is exposed to air)

• The detachment of such particles subject to the acoustic waves generated by a piezoelectric transducer is investigated herein.

• The model proposed herein can be expanded to analyze adhesion and detachment of similar/dissimilar of various materials.
• The figure below summarizes the adhesion and detachment forces that are discussed in this presentation:
A particle attached to a substrate may be dislodged through one of the following methods [3]:

- Rolling Dislodgement (particle rolls off and is detached from the substrate)
  \[ F_{Det} \left( \frac{d}{2} - b \right) \geq F_{Adh} \]
  Minimum detachment force is required when \( \theta = 0 \) →

- Sliding Dislodgement (particle slides off and is detached from the substrate)
  \[ F_{Det} \geq F_{Adh} \mu \]
  Minimum detachment force is required when \( \theta = 0 \) →

- Lift-off Dislodgement (particle is pulled off and is detached from the substrate)
  Minimum detachment force is required when \( \theta = 90 \text{ deg} \) →
  \[ F_{Det} \geq F_{Adh} \]

Rolling dislodgement is the most likely mechanism of dislodgment.
Adhesion of Particles to Substrate: Summary

- For the cases of glass-on-glass and alumina-on-alumina, the dominant adhesion force is the Van der Waals force.
- Other forces not discussed here:
  - Coulombic Image Force
  - Electric Double Layer Force
  - Capillary Force
  - Chemical Bonding

<table>
<thead>
<tr>
<th>Force</th>
<th>Adhesive</th>
<th>Repulsive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van der Waals Force</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Ionic Double Layer Force</td>
<td>IF particle and substrate have zeta potentials of opposite sign</td>
<td>YES IF particle and substrate have zeta potentials of similar sign</td>
</tr>
<tr>
<td>Hydrophobic Interaction Force</td>
<td>IF the interface is hydrophobic ($\theta_{avg} &gt; 90$ deg)</td>
<td>YES IF the interface is hydrophilic ($\theta_{avg} &lt; 45$ deg)</td>
</tr>
</tbody>
</table>
Van der Waals (VDW) force is a short-range adhesion force between a particle and substrate [4]:

\[ F = \frac{A_{132}d}{12z_0^2} \]

- According to the JKR theory [5], the increment in the VDW force due to such deformation is predicted to be:
  - < 8% for the case of alumina-on-alumina in water medium (d < 400 nm)
  - < 1% for the case of glass-on-glass in water medium (d < 400 nm)
Adhesion of Particles to Substrate: \textit{Van der Waals Force} …

- VDW force is much less in water than in air. Hence, the particle removal is easier in water than in air.
- VDW force for alumina-on-alumina is larger than that for glass-on-glass.
Adhesion of Particles to Substrate: Ionic Double Layer Force

- Ionic double layer (IDL) is a structure that appears near the outer surface of an object when it is immersed in a liquid.
- It consists of two parallel layers of ions. The first layer is the surface charge (either positive or negative) and the other layer is in the fluid, and electrically screens the first layer.
Zeta Potential is the characteristic for the IDL force and is measured at the slipping plane which is located at Debye Length away from the surface.

The Zeta potential is a function of solution PH and the chemical and the composition of the substrate/particle.

If a particle and substrate have the same chemical composition, they have the same zeta potential and consequently the IDL force is repulsive (e.g., glass-on-glass and alumina-on-alumina).
Adhesion of Particles to Substrate: Hydrophobic Interaction Force

- The hydrophobic adhesion force between a particle and substrate depends on the contact angle of the particle and substrate, which in turn depends on the chemical composition and the surface treatment of substrate/particle.

- For glass and alumina, the contact angle is less than 45 degrees. Hence, the hydrophobic interaction will not occur for the cases of glass-on-glass and alumina-on-alumina.
USC/MSC System: Acoustic Streaming

- Propagation of an acoustic wave in a solution causes the formation of an acoustic boundary layer on the substrate [6-7].

\[ \delta = \left( \frac{2 \nu}{2 \pi f} \right)^{1/2} \]

\[ u(y,t) = u_e \cos(2 \pi f t) \left[ 1 - \exp \left( -\frac{v}{\delta} \right) \cos \left( -\frac{y}{\delta} \right) \right] \]

- When a particle that is attached to a flat substrate is exposed to such a boundary layer flow, it would experience an aerodynamic force and moment [4]:

\[ F_D = 1.7 \left( 3 \pi \mu d V \right) \]

\[ M = 0.370 F_D d \]

\( \nu \): Kinematic Viscosity of Solution
\( f \): Transducer Frequency
\( \delta \): Acoustic Boundary Layer Thickness
\( I \): Power Intensity of Transducers
\( C \): Speed of Sound in the Solution (~ 1475 m/sec)
\( \rho \): Density of Solution (~ 1000 kg/m³)
\( \mu \): Dynamic Viscosity of Solution
\( V \): Flow Velocity at the Particle Center
\( d \): Particle Diameter

The acoustic streaming force increases by increasing the transducer frequency due to the reduction in the thickness of acoustic boundary layer.
• Propagation of an acoustic wave in a solution causes high and low pressure in the solution:
  – The low pressure half-cycle can cause expansion of pre-existing bubbles and, potentially, formation of new bubbles
  – The high pressure half-cycle can cause compression or, potentially, the implosion of bubbles

• There are two types of cavitation that can be caused by acoustic field:
  – Transient/inertial cavitation $\rightarrow$ bubbles implode producing shock waves that can cause physical damage to substrate (pitting)
  – Stable/noninertial cavitation $\rightarrow$ bubbles oscillate in size and shape

Detachment of fluorescent spherical PSL particles (0.71 µm to 1 µm) from a flat Si wafer induced by acoustic bubbles. Transducer frequency is set at 950 kHz [2].

$$\begin{array}{|c|c|}
\hline
f & d_B \\
\hline
430 \text{ kHz} & \sim 16 \ \mu\text{m} \\
950 \text{ kHz} & \sim 8 \ \mu\text{m} \\
\hline
\end{array}$$

The diameter of active bubble [8]

Detachment of fluorescent spherical PSL particles (0.71 µm to 1 µm) from a Si channel wafer induced by an acoustic bubble. Transducer frequency is set at 950 kHz [2].
• When a pressure variation wave passes over a particle, the particle experiences a force due to the pressure gradient across the particle [9]:

\[
F_{AP} = 2 \pi f \left( \frac{\pi d^3}{6} \right) \sqrt{\frac{2 \rho I}{C}}
\]

- \( I \) : Power Intensity of Transducers (W/m\(^2\))
- \( C \) : Speed of Sound in the Solution (~ 1475 m/sec)
- \( \rho \) : Density of Solution (~ 1000 kg/m\(^3\))
Particle Dislodgement Inspection

• Figures below compare the adhesion and detachment forces, predicting the possibility of particle dislodgement based on the rolling method:

\[ F_{Det} \geq F_{VDW}^* \]

Dislodgement Condition:

\[ F_{VDW}^* = F_{VDW} \frac{a}{d/2 - b} \]

- VDW: Van der Waals
- AC: Acoustic Cavitation
- AS: Acoustic Streaming
- AP: Acoustic Pressure

- For the case of **alumina-on-alumina**, particles larger than 50 nm can be dislodged
- For the case of **glass-on-glass**, particles larger than 10 nm can be dislodged
- The largest detachment force is:
  - Acoustic cavitation force for particles larger than 35 nm
  - Acoustic streaming force for particles smaller than 35 nm
Conclusions and Summary

• Adhesion forces depend on
  – particle size
  – hardness of particle and substrate
  – chemical composition of particle and substrate
  – the environment in which contaminated substrate is located

• The detachment forces in a USC/MSC system depend on
  – particle size
  – transducer frequency
  – power intensity of transducer
  – the chemical composition and physical properties of the solution

• The acoustic cavitation force is dominant detachment force for particles larger than 35 nm.

• It was also found that:
  – For the case of alumina-on-alumina, particles larger than 50 nm can be dislodged
  – For the case of glass-on-glass, particles larger than 10 nm can be dislodged


