METHODS FOR EFFICIENT SLURRY UTILIZATION AND
TRIBOLOGICAL STABILITY ANALYSIS IN
CHEMICAL MECHANICAL PLANARIZATION

by
Matthew Bahr

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Dedicated to My Beautiful Adri
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NOMENCLATURE

\( COF \) = Coefficient of friction
\( COF_i \) = Coefficient of friction at time \( i \)
\( \delta \) = Effective slurry film thickness
\( Down \; Force_i \) = Down force at time \( i \)
\( \mu \) = Viscosity
\( P \) = Applied pressure
\( Shear \; Force_i \) = Shear force at time \( i \)
\( So \) = Sommerfeld number
\( T \) = Pad surface temperature
\( v \) = Linear sliding velocity
ABSTRACT

This thesis presents a series of studies pertaining to tribological, thermal, kinetic and slurry utilization aspects of chemical mechanical planarization processes. The purpose of this work is to both develop a better method of characterizing the tribological mechanisms during polishing, as well as propose methods by which slurry utilization efficiency can be increased in order to minimize environmental hazards and operational costs associated with polishing without compromising the desired polish outcomes.

The first study was conducted using a modified version of the generic Strubeck curve using real-time shear and down force data collection at 1,000 Hz. This investigation served to provide a better understanding of the tribological and thermal mechanisms associated with polishing copper and tungsten blanket wafers on an industrially relevant soft pad. A multitude of gradual yet continuous changes in sliding velocity and polishing pressure were applied during polishing. Results indicated that polishing on the soft pad produced stable coefficient of friction (COF) values entirely within the “boundary lubrication” regime, while copper polishing on a hard pads produced a tremendous spread of data and resulted in both “boundary lubrication” and “mixed lubrication” regimes. In addition, the average pad surface temperature showed a linear relationship with the product of the COF, sliding velocity, and downward pressure for all copper and tungsten polishes on both soft and hard pads.

Another study in this thesis investigated slurry availability and the extent of slurry mixing for three different slurry injection schemes. An ultraviolet enhanced fluorescence
technique was employed to qualitatively measure slurry film thicknesses atop the pad surface during polishing. This study investigated standard pad-center point slurry dispensing and a slurry injection system (SIS) that covered only the outer half of the wafer track. Results indicated that the radial position of slurry injection and fluid interactions with the SIS greatly influenced slurry mixing and availability atop the pad. Silicon dioxide removal rates were also found to increase as slurry availability increased. Using a combination of standard pad-center slurry dispensing and a half-wafer track SIS resulted in similar silicon dioxide removal rates as standard pad-center slurry dispensing but at a 40% lower slurry flowrate.

The final study in this thesis investigated the effects of ultrapure (UPW) water dilution of a ceria-based slurry on silicon dioxide removal rates. Results showed that pre-mixing the slurry and UPW increased the removal rate with dilution up to a slurry to UPW ratio of 1:7.5 due to the increasing presence of Ce$^{3+}$ via the reduction of Ce$^{4+}$ by UPW. Further dilution yielded a plateau in the removal rate trend as additional UPW reduced the coefficient of friction (COF) and the temperature during polishing, causing the benefits of increased ceria-silica binding to be offset by mechanical limitations. Mixing the slurry directly at point-of-use at the dispense nozzle resulted in a removal rate trend that was highly similar to pre-mixing, however, removal rates were higher at every dilution ratio. A novel slurry injection system (SIS) was employed at various rotation angles as measured from the leading edge. The SIS angles produced different retaining ring bow wave thicknesses, which led to varying extents of dilution and, by extension, removal rates. The SIS at -8° produced the highest removal rates of all angles. A third dilution ratio test was performed using point-of-use mixing through the SIS at the optimum angle of -8°, which
resulted in a similar removal rate trend as pre-mixing and pad-center dispense point-of-use mixing, but with dramatically higher removal rates at each dilution ratio. The ability to attain higher removal rates could potentially allow integrated circuit (IC) manufacturers to either reduce polishing times or reduce slurry consumption, subsequently reducing slurry waste and creating a more environmentally benign semiconductor manufacturing process.
CHAPTER 1
INTRODUCTION

1.1 Chemical Mechanical Planarization: An Overview

Chemical Mechanical Planarization (CMP) is an enabling step in the fabrication of integrated circuit (IC) technologies. This process aims to achieve both local (micrometer scale) and global (millimeter scale) surface planarity through both chemical and mechanical means. The CMP process follows a natural evolution of two particular processes found in the glass industry: grinding and lapping. In glass processing, much of the bulk material is removed through grinding in order to shape the final product, while lapping serves the purpose of finely smoothing and polishing the final surface. In the exact same manner as glass processing, CMP serves the purpose of removing bulk deposited material and leaving a highly planar surface.

During the mid-1980s, faced with the challenges of rapidly decreasing feature sizes and increasing transistor densities, International Business Machines (IBM) developed the modern CMP technique to gain greater control over the achievable level of planarity in IC manufacturing (Wolf 2004). In the IC manufacturing process, an initial layer consisting of transistors and other electronic devices are created on the wafer surface. In order to connect the individual devices together, multiple layers of metal and interlayer dielectrics (ILDs) are sequentially constructed atop each previous layer. Further, each of these layers consists of a multitude of steps such as masking, photolithography, and barrier layer application. In total, a finished multi-layer IC consists of hundreds of sequential steps, all of which depend on precision planarity. Figure 1.1 shows an example of a multi-layer IC with and without
interim CMP processes. Referencing this figure, it is clear that a lack of planarity in a multi-layer IC manufacturing process would result in uncontrolled etching, non-uniform photoresist application, unreliable metallization thicknesses, etc. In short, planarization is critical to the fabrication of high-yield IC devices.

Figure 1.1: SEM images of (a) a non-planarized and (b) planarized Multi-layer Metallization structure (Rhoades 2011).

Figure 1.2 illustrates the ideal principle of CMP, in this case the back-end-of-line (BEOL) planarization of ILD and copper (Cu) in the metallization layers. In both ILD (left) and Cu (right) planarization, a particular pattern is etched into the initial material to create space for the secondary material to be deposited (i.e. Cu deposition into ILD structures, or ILD deposition into Cu structures). Deposition leaves an overburden layer, or layer of excess material, to ensure the created trenches are completely filled. CMP serves the purpose of removing this overburden layer (akin to the bulk removal of glass grinding), and leaving a perfectly planar surface (akin to the smoothing finish of glass lapping). As each layer is built on top of the last, any non-uniformities in surface topography will
translate to amplified defects in proceeding layers, yielding a non-functional device. Therefore, precision CMP processes must be employed to meet the topographical and structural needs of increasingly dense IC devices.

A general schematic of a single-platen CMP process, such as the one used throughout this thesis, is depicted in Figure 1.3. Typically, a wafer is held by a wafer carrier featuring a retaining ring that prevents the wafer from slipping away during the dynamic polishing process. The wafer is held under a particular down force with the polished side facing downwards against the top surface of the polishing pad. The pad is adhered to a platen which rotates counterclockwise during the polishing process. Meanwhile, the wafer carrier also rotates in the same counterclockwise manner, resulting in the wafer
experiencing a linear sliding velocity. A slurry containing abrasive nanoparticles, oxidizers, surfactants, pH buffers, and other chemicals is injected onto the pad surface. This slurry is distributed across the pad surface via centrifugal forces while the pad grooves and asperities facilitates transport to the pad wafer interface. The interaction of the slurry, abrasives, pad asperities, and wafer surface are enabled by the down force and sliding velocity to promote chemical etching and mechanical shearing, which describes the primary mechanism of material removal in CMP (Hu et al. 1995). In addition, pad asperities can become flattened under applied pressure during the CMP process or become clogged with spent slurry and other polishing debris. A diamond disk pad conditioner sweeps across the pad under a certain pressure in order to regenerate these asperities and enable continual material removal.

![Figure 1.3: Generalized schematic of a rotary CMP tool (Liao 2014).](image)

### 1.2 Applications of CMP in Semiconductor Manufacturing

As described in the previous section, CMP is an enabling step in the semiconductor manufacturing process. Currently, CMP technology has been adopted primarily for polishing and planarizing:
• Interlayer Dielectric (ILD)
• Cu/Barrier layer
• Shallow Trench Isolation (STI)
• Tungsten (W) plug

1.2.1 ILD CMP

Planarization of ILD trenches and films is critical in IC device fabrication, especially in the construction of BEOL metallization layers. Referring back to Figure 1.2, an ILD material such as silicon dioxide (SiO$_2$) is deposited between the etched metal structures of the current layer. This material serves the purpose of insulating the metal interconnects to ensure proper device functionality. Because deposition creates a film that builds on top of the peak-and-valley topography of the etched metal layer, the resultant film is non-planar. CMP is used to planarize the ILD film, creating a surface in which the following optical lithography step can efficiently and properly etch the following layer.

1.2.2 STI CMP

Unlike the ILD planarization process, STI is a front-end-of-line (FEOL) process that is used to separate active devices in the initial substrate-level layer of an IC. Earlier processes utilized local oxidation of silicon (LOCOS) techniques to create the necessary isolations, however, issues such as bird’s beak encroachment created oxidation areas that were larger than intended resulting in less available area for devices (Li 2008). To circumvent this issue, STI was used to selectively place and control isolation layers. The
STI process consists of depositing a nitride layer on the silicon surface. Next, a trench is etched into the silicon and subsequently filled with a dielectric material. CMP is then employed to continually remove the excess dielectric until the nitride layer is exposed. At this point, the nitride layer will act as a stopping layer, as CMP in STI applications use slurries with high oxide-to-nitride removal rate selectivity, effectively stopping CMP material removal.

1.2.3 Cu/Barrier Layer CMP

Current IC fabrication uses copper as the metal of choice for creating the interconnects, as this metal offers a lower electrical resistivity than the previous choice of aluminum (Babu 2016). The formation of interconnects utilizes the Cu damascene process, with the addition of a barrier layer to address adhesion and diffusion issues. A schematic of this process is depicted in the left image of Figure 1.4. To create the interconnects, a trench is created in the ILD layer using photolithographic and etching techniques. Next, a thin barrier layer such as Ta/TaN is then deposited on the walls of the trench. This barrier layer prevents the copper from diffusing into the ILD layer over the life of the device, and provides better adhesion to the Cu interconnects than the ILD itself. Following barrier layer deposition, Cu is sufficiently deposited such that the trench is filled, and an overburden copper layer is formed. For this step in the IC fabrication process, two stages of CMP are used to clear the excess. Initially, a CMP process is employed to remove the bulk Cu in the overburden layer which stops at the underlying barrier layer deposited on the upper surface of the ILD. Subsequently, a secondary finishing CMP process serves to remove the thin barrier layer on the ILD surface.
1.2.4 W CMP

As mentioned in the previous subsection, Cu diffuses into silicon structures, rendering this metal as a poor choice to interface with the devices in the substrate layer. For this reason, W is used in the IC manufacturing process to connect the devices to the interconnect layers above (Luo 2013). The W plug formation process, depicted as the rightmost image in Figure 1.4, is highly similar to the Cu damascene process. The similarities of the processes translate to the same need for a two stage CMP process that performs bulk metal removal, subsequently followed by barrier layer removal.
1.3 COO and Environmental Considerations: The SIS

CMP is one of the most expensive processes employed in IC manufacturing. The Cost of Ownership (COO) includes consumables such as the pad, slurry, and conditioner, as well as other factors such as equipment, labor, and other operational costs. Figure 1.5 shows a graphical representation of the consumable cost factors of CMP.

![Pie chart showing consumable cost factors of CMP](image)

Figure 1.5: Factors contributing to the total consumable cost of the CMP module (Roberts 2014).

As shown in the figure above, slurry accounts for nearly half of the entire consumables cost of the CMP module. Further, CMP slurries are comprised of ultra-fine abrasive particles and other additives such as organic and inorganic acids and bases, anticoagulating agents, surfactants, oxidizing agents, corrosion inhibitors, chelating and complexing agents, buffers, bactericides, and fungicides. These small particles and additives present many environmental, health, and safety (EHS) hazards, rendering excessive slurry use (and the resulting waste) as a critical EHS issue. Table 1.1 lists a few of the main components associated with commercial slurries.
Table 1.1: Main properties of the different slurries for different CMP applications (Wei 2010).

<table>
<thead>
<tr>
<th>Slurry Type</th>
<th>ILD</th>
<th>STI</th>
<th>Tungsten</th>
<th>Copper &amp; Tantalum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle material</td>
<td>Silica</td>
<td>Silica &amp; Ceria</td>
<td>Silica &amp; Alumina</td>
<td>Silica &amp; Alumina</td>
</tr>
<tr>
<td>Slurry solution</td>
<td>Inorganic base</td>
<td>Inorganic base</td>
<td>Organic acid</td>
<td>Organic acid with corrosive inhibitor</td>
</tr>
<tr>
<td>Particle concentration (wt%)</td>
<td>10-30%</td>
<td>0.5-30%</td>
<td>5-10%</td>
<td>1-10%</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>None</td>
<td>None</td>
<td>Hydrogen peroxide, Ferric nitrate &amp; Potassium ferricyanide</td>
<td>Hydrogen peroxide &amp; Ammonium persulfate</td>
</tr>
</tbody>
</table>

In current CMP processes, slurry is dispensed onto the pad center and is allowed to freely flow over the pad surface. The slurry is subjected to centrifugal forces of the rotating platen, and is oftentimes drawn directly to the waste stream without ever entering the pad-wafer interface. Due to this action, slurry utilization efficiency is minimized, generally ranging from only 2 to 22 percent (Philipossian et al. 2003). Many IC manufacturers achieve optimal removal rates by increasing slurry flowrates in order to provide adequate slurry availability to the pad-wafer interface, however, the amount of wasted slurry...
increases proportionally with the flowrate. In turn, both the cost and EHS hazards associated with the particular CMP process grow tremendously.

Because of the exorbitant cost and critical EHS issues associated with excessive slurry use, slurry reduction and efficient slurry utilization techniques are paramount. One such apparatus that achieves both efficient slurry utilization and reduces slurry consumption is the Araca, Inc. slurry injection system (SIS). The SIS is a small, weighted passive apparatus that sits on the polishing pad, and is comprised of an injector body featuring slurry injection ports as well as an injector mount. This innovative system injects slurry onto the wafer track immediately upstream of the wafer, allowing more slurry to reach the pad-wafer interface than standard pad-center slurry dispensing techniques. Further, the injector body serves to direct spent slurry, pad debris, polishing by-products, and excess ultrapure water (UPW) to the waste stream. This removal of residual fluid prevents dilution of the slurry at the pad-wafer interface, increasing removal rates. This reduces the need for greater slurry flowrates, and decreases COO and EHS concerns by a considerable margin. In general, these SIS features can reduce slurry consumption by 40% compared to standard slurry application methods (http://aracainc.com/equipment/slurry-injection-systems/).
CHAPTER 2
EXPERIMENTAL APPARATI

All studies in this thesis utilize a single-platen R&D APD-800 polisher and tribometer, which is described in Section 2.1. The analytical instrumentation used in these studies are as follows:

- Reflectometer
- Ultraviolet enhanced fluorescence (UVEF) system

The configurations and working principles of the above tools are described in Section 2.2

2.1 The Araca, Inc. APD-800 Polisher and Tribometer

The APD-800 is a single-platen research and development polisher and tribometer designed for CMP and polishing of substrates measuring up to 300 mm in diameter. The tool is manufactured by Fujikoshi Machinery Corporation and is equipped with signal acquisition hardware such as direction-dependent load cells, as well as Araca Inc.’s FSX-800 signal analysis software. This feature provides the unique ability to acquire accurate real-time shear force and down force measurements during the CMP process. Figure 2.1 highlights the main hardware components of the APD-800. A brief description of their functions are listed in Table 2.1 while some components will be described in further detail in subsequent sections.
Figure 2.1: The Araca, Inc. APD-800 polisher and tribometer with its major components emphasized.
Table 2.1: Main parts of the APD-800; with brief descriptions.

<table>
<thead>
<tr>
<th>Part</th>
<th>Part Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Wafer carrier motor</td>
<td>Operate rotation and pressure application of carrier head</td>
</tr>
<tr>
<td>B</td>
<td>Shear force load cell</td>
<td>Measures real-time shear force</td>
</tr>
<tr>
<td>C</td>
<td>Conditioner carrier motor</td>
<td>Operate rotation and oscillation of conditioner</td>
</tr>
<tr>
<td>D</td>
<td>Control panel</td>
<td>Control hardware operation</td>
</tr>
<tr>
<td>E</td>
<td>On/Off switch</td>
<td>Turn on/off the APD-800</td>
</tr>
<tr>
<td>F</td>
<td>Emergency stop switch</td>
<td>Turn off APD-800 immediately in case of emergency</td>
</tr>
<tr>
<td>G</td>
<td>Automatic run switches</td>
<td>Run polishing with automatic set up</td>
</tr>
<tr>
<td>H</td>
<td>Manual switches</td>
<td>Attach/release wafer and raise/lower carrier head (see Figure 2.4)</td>
</tr>
<tr>
<td>I</td>
<td>Signal conditioners and amplifiers</td>
<td>Reset, amplify and calibrate force signal from load cells</td>
</tr>
<tr>
<td>J</td>
<td>Platen, wafer and conditioner carriers</td>
<td>See more details in subsequent sections</td>
</tr>
<tr>
<td>K</td>
<td>Down force load cells</td>
<td>Measures real-time down force. Two more load cells exist on the rear side (not shown)</td>
</tr>
<tr>
<td>L</td>
<td>Tank and slurry delivery system</td>
<td>Deliver slurry or water to the system</td>
</tr>
</tbody>
</table>

2.1.1 APD-800 Controls

The APD-800 has numerous switches and controls with a majority located on the front panel. The front panel is shown in greater detail in Figure 2.2, and a further description of the components functions are found in Table 2.2. Among these components, the critical touch screen control panel allows user input for tank selection, slurry flow rate, polishing pressure, carrier and platen rotation rate, and polishing time for up to 5 polishing steps. A sample polishing recipe is shown in Figure 2.3.
Figure 2.2: The front panel of the APD-800.
Table 2.2: Main parts and functions of the APD-800 front panel.

<table>
<thead>
<tr>
<th>Part</th>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Control panel</td>
<td>Control hardware operation</td>
</tr>
<tr>
<td>B</td>
<td>Secondary ON switch</td>
<td>Turn on APD-800 after the primary “ON/OFF” switch is turned on</td>
</tr>
<tr>
<td>C</td>
<td>Secondary OFF switch</td>
<td>Turn off APD-800 before the primary “ON/OFF” switch is turned off</td>
</tr>
<tr>
<td>D</td>
<td>Emergency stop switch</td>
<td>Stop polisher operations immediately in case of emergency</td>
</tr>
<tr>
<td>E</td>
<td>Auto run STOP switch</td>
<td>Stop polishing sequence for automatic run set-up; reset tool after alarm deactivation</td>
</tr>
<tr>
<td>F</td>
<td>Auto run START switch</td>
<td>Start polishing sequence for automatic run set-up</td>
</tr>
<tr>
<td>G</td>
<td>Manual/auto run switch</td>
<td>Switch run mode between manual and auto</td>
</tr>
<tr>
<td>H</td>
<td>USB connector</td>
<td>Connect APD-800 to the PC</td>
</tr>
<tr>
<td>I</td>
<td>Shear force conditioner and amplifier</td>
<td>Reset and amplify shear force signal from load cell</td>
</tr>
<tr>
<td>J</td>
<td>Down force conditioner and amplifier</td>
<td>Reset and amplify down force signal from load cell</td>
</tr>
</tbody>
</table>

Figure 2.3: A sample polishing recipe defined by user input.
In addition to the touch screen control panel, the APD-800 features switches allowing manual control over the vertical position of the carrier head and attaching or releasing the wafer from the carrier head in between polishing processes. These switches operate independently of the touch screen control panel. Figure 2.4 shows this panel in greater detail. A list of the switches functions are given in Table 2.3.

![Figure 2.4: Manual switches on the front side of the APD-800.](image)

**Table 2.3: APD-800 front side manual switches and their functions.**

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier UP</td>
<td>Raise wafer carrier head</td>
</tr>
<tr>
<td>Carrier DOWN</td>
<td>Lower wafer carrier head</td>
</tr>
<tr>
<td>Wafer VAC</td>
<td>Attach wafer to carrier head</td>
</tr>
<tr>
<td>Wafer BLOW</td>
<td>Release wafer from carrier head</td>
</tr>
</tbody>
</table>
2.1.2 Platen and Z-axis Load Cells

Figure 2.5 depicts the platen, platen motor, and two of the Z-axis load cells of the APD-800. The 800-mm platen is made out of a ceramic material to avoid possible corrosion or degradation by slurries used during CMP. Various polishing pads are fixed directly to this ceramic surface using an adhesive interlayer. The platen is driven by the platen motor which features a variable rotation rate within the range of 20 to 180 RPM. The Z-axis (down force) load cells are located under the platform supporting the platen and platen motor. Figure 2.6 shows the full schematic highlighting all four Z-axis load cells.

Figure 2.5: The APD-800 polishing platen system and two down force load cells (circled).
The load cells function by outputting a voltage signal that is linearly correlated with the pressure or down force exerted on the cell. This signal is transferred through the force amplifiers listed in Section 2.1.1 before being sent, via a USB connection, to a dedicated computer running Araca Inc.’s proprietary LabVIEW® program to visualize the down force readings. Due to the asymmetric placement of the four Z-axis load cells, the down force output is displayed as four separate readings within the LabVIEW® program. Figure 2.7 provides an example of these individual down force measurements.

Figure 2.7: Example of the down force measurements for each Z-axis load cell during polishing (Jiao 2012).
During polishing, the four individual down force measurements are resolved by summation into a single down force measurement, as shown in Figure 2.8.

![Figure 2.8: Overall actual down force measurement during polishing (Jiao 2012).](image)

**2.1.3 Wafer Carrier System and Y-axis Load Cell**

Figure 2.9 shows the entirety of the wafer carrier system. The portion of the system encased in the plexiglass consists of a motor, a carrier up/down motor, two separate vacuum pressure lines, and the Y-axis load cell.

![Figure 2.9: The APD-800 wafer carrier system.](image)
The motor provides the rotation of the carrier head within the range of 15 to 120 RPM, which compliments the rotation of the platen producing a relative linear sliding velocity of the wafer. The piston controls the vertical position of the carrier head. Figure 2.10 shows the carrier head, which consists of a ceramic wafer attachment plate and an internal pressure chamber. This ceramic carrier head is manufactured with an array of small holes such that one of the vacuum lines can hold the polycarbonate wafer template (shown in Figure 2.11) to the carrier head during the polishing process. The second pressure line increases the pressure within the internal chamber which applies the required down force.

Figure 2.10: The carrier head and ceramic plate.

Figure 2.11: The water-filled polycarbonate template: (a) front, with backing film and (b) back, which attaches to the ceramic plate.
Figure 2.11 shows the water-filled polycarbonate template designed for 300-mm CMP processes. The front of the template consists of a backing film and retaining ring (made by PR Hoffman®) which holds the wafer in place during polishing. The black backing film, when slightly wet, holds the wafer securely to the template via capillary forces to prevent slipping. The retaining ring (the green outer ring shown in Figure 2.11(a)) creates a small pocket in which the wafer sits during polishing. This ring acts as a secondary method for preventing the wafer from slipping out from underneath the carrier head during polishing. It is critical that the pocket depth of the retaining ring is smaller than the thickness of the substrate to eliminate contact between the retaining ring and the pad while processing. The water-filled internal chamber of the template serves the purpose of uniformly distributing the applied pressure to the wafer surface. The back of the template features a recessed surface that is machined to the diameter and protrusion depth of the ceramic carrier head plate. The template holding the wafer is manually installed onto the ceramic plate and is held in place by vacuum conditions existing in the carrier head.

The Y-axis load cell is responsible for collecting real-time shear force data during CMP. The wafer carrier system is mounted to a friction table featuring three parallel stainless steel plates. The lower plate is fixed directly to the APD-800 frame, while the upper plate is free to move along sliders fixed to the middle plate in conjunction with the movement of the carrier head. During polishing, the movement of the top plate relative to the fixed middle plate provides a Y-axis force exerted on the load cell. The signal is processed in the same manner as the down force measurements discussed previously. An example of the shear force output is shown in Figure 2.12.
2.1.4 Pad Conditioning System

Pad conditioning is a crucial feature of polishing primarily due to the need for pad asperity regeneration as well as being a secondary method of removal of used slurry and pad debris. The pad conditioning system for the APD-800 is shown in Figure 2.13.

Figure 2.12: An example of a shear force measurement during polishing.

Figure 2.13: Pad conditioning system of the APD-800.
Much like the carrier system, the conditioner system consists of a vacuum line, a hydraulic piston, and a rotational motor. However, the conditioner system also features a rail and stepper motor to allow the conditioner head to sweep radially across the pad surface. The rotational motor controls the rotation of the conditioner head, and the hydraulic piston controls the vertical position of the head. Again, much like the carrier system, the conditioner system features a pressure chamber in which the vacuum pressure line applies a pressure, resulting in a conditioner down force on the pad surface. The conditioner down force, rotation speed, sweep rate, and radial range are all defined by user input through the touch screen control panel mentioned in Section 2.1.1.

2.1.5 Slurry Distribution and Temperature Measurement Systems

The APD-800 has three independent computer-controlled 5-gallon stirred tanks with dedicated peristaltic pumps. These tanks and pumps are shown in Figure 2.14. Slurry or DI water is placed inside the tanks as needed and continuously stirred. A flexible rubber tube is inserted in the fluid volume through a small port in the lid, and is extracted during polishing by the peristaltic pumps. The pumps are calibrated and wired to the APD-800 control panel such that the user can define the desired tanks and flow rate to run autonomously during polishing. Figure 2.15 shows the slurry outlet tubes above the platen.

Figure 2.15 also shows the single-point infrared (IR) temperature sensor used for measuring real-time temperature data during polishing. The sensor tube is attached to an arc rail near the leading edge of the carrier head. This allows the user to collect temperature data at a single point anywhere within the wafer track during polishing. The real time
temperature data is collected and displayed through the LabVIEW® program much like the shear and down force measurements. An example of the temperature output is shown in Figure 2.16.

![Figure 2.14: APD-800 tanks and peristaltic pumps.](image)

![Figure 2.15: Slurry/DI water outlet tubes and temperature sensor.](image)
2.1.6 Data Acquisition Program

The APD-800 is equipped with data collection and analysis software integrated by Araca, Inc. The data acquisition program is written in LabVIEW® 8.0 and features the ability to display and manipulate data via a USB connected computer. The data analysis program is capable of collecting the following data:

- Temperature (°C)
- Shear force (lb f)
- Down force (lb f)
- Flow rate (ml/min)
- Pad velocity (RPM)
- Wafer velocity (RPM)
- Conditioner velocity (RPM), position (mm) and oscillation (count/min)
- Conditioner motor current (A)
- Platen motor current (A)
- Carrier motor current (A)
2.1.7 APD-800 Specifications

The APD-800 polisher and tribometer general specifications and hardware information is listed in Table 2.4.

Table 2.4: APD-800 tool specifications (APD-800 operations manual).

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Fujikoshi Machinery Corporation and Araca Incorporated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer Size</td>
<td>300-mm (or smaller)</td>
</tr>
<tr>
<td>Wafer Carrier</td>
<td>Down force control = Pneumatic</td>
</tr>
<tr>
<td></td>
<td>Pressure = 0.6 to 8.0 PSI (1.4 to 8.0 PSI for 200-mm)</td>
</tr>
<tr>
<td></td>
<td>Rotation rate = 15 to 200 RPM</td>
</tr>
<tr>
<td>Platen</td>
<td>Ø = 800 mm</td>
</tr>
<tr>
<td></td>
<td>Rotation rate = 20 to 180 RPM</td>
</tr>
<tr>
<td></td>
<td>Material = SUS410</td>
</tr>
<tr>
<td></td>
<td>Built-in heat exchanger (requires external coolant)</td>
</tr>
<tr>
<td>Conditioner</td>
<td>Ø = 108 mm</td>
</tr>
<tr>
<td></td>
<td>Rotation rate = 12 to 120 RPM</td>
</tr>
<tr>
<td></td>
<td>Stroke length = 320 mm</td>
</tr>
<tr>
<td></td>
<td>Sweep velocity = 0 to 500 mm/sec through 10 independently controlled zones</td>
</tr>
<tr>
<td></td>
<td>Down force = 3.3 to 13.2 lb</td>
</tr>
<tr>
<td></td>
<td>Scheme = ex-situ or in-situ</td>
</tr>
<tr>
<td>Chemical Delivery</td>
<td>Three computer-controlled, 20-liter, chemical-resistant,</td>
</tr>
<tr>
<td>Systems</td>
<td>removable tanks with impeller mixers, roller pumps and level sensors. Flow rate = 10 to 450 cc/min.</td>
</tr>
<tr>
<td>Pad Water Rinse</td>
<td>Dedicated high flow rate water rinse injector</td>
</tr>
<tr>
<td>Force Sensors</td>
<td>Shear force (1 sensor) and down force (4 multiplexed sensors)</td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>Adjustable single-point pad surface IR detector</td>
</tr>
<tr>
<td>Data Capture vs.</td>
<td>Platen rotational velocity</td>
</tr>
<tr>
<td>Time (capture</td>
<td>Carrier rotational velocity</td>
</tr>
<tr>
<td>frequency up to</td>
<td>Conditioner rotational velocity, position, oscillation speed and motor current</td>
</tr>
<tr>
<td>2,300 Hz; display</td>
<td>Tanks 1, 2 and 3 chemical flow rates</td>
</tr>
<tr>
<td>frequency = 1 Hz)</td>
<td>Shear force and down force</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Friction (COF)</td>
</tr>
<tr>
<td></td>
<td>Pad surface temperature</td>
</tr>
<tr>
<td>Basic Data Analysis</td>
<td>Average and variance for the entire (or a subset of the) polishing period for all parameters being captured</td>
</tr>
<tr>
<td>Advanced Data Analysis</td>
<td>Shear force and down force Fast Fourier Transform (FFT)</td>
</tr>
<tr>
<td>and Correlation</td>
<td>COF vs. Sommerfeld number</td>
</tr>
<tr>
<td></td>
<td>COF vs. pad temperature</td>
</tr>
<tr>
<td>Control, Monitoring</td>
<td>Programmable touch-screen controller for polisher</td>
</tr>
<tr>
<td>and Analysis</td>
<td>operation Notebook computer for process monitoring and data analysis</td>
</tr>
<tr>
<td>W × L × H</td>
<td>100 × 140 × 203 cm (polisher)</td>
</tr>
<tr>
<td></td>
<td>80 × 38 × 190 cm (electrical cabinet)</td>
</tr>
<tr>
<td></td>
<td>50 × 150 × 81 cm (three chemical delivery systems)</td>
</tr>
<tr>
<td>CDA</td>
<td>Minimum pressure = 72 PSI (500,000 Pa)</td>
</tr>
<tr>
<td></td>
<td>Flow rate = 550 liters per minute</td>
</tr>
<tr>
<td>Platen Coolant Water</td>
<td>Maximum pressure = 43 PSI (300,000 Pa)</td>
</tr>
<tr>
<td></td>
<td>Flow rate = 15 liters per minute</td>
</tr>
</tbody>
</table>
2.2 Analytical Tools

2.2.1 Reflectometer

In this thesis, ILD removal rate studies using SiO$_2$ blanket wafers were investigated. Silicon dioxide film thicknesses were measured both before and after CMP in order to quantify the removal rate in each study. The film thicknesses were measured using a SENTECH Film Thickness Probe (FTP) reflectometer, shown in Figure 2.17. The basic principle of operation is as follows: the aperture of the reflectometer emits a light beam of a particular wavelength at a target point on the wafer surface. The light beam interacts with the film and is reflected back with a characteristic reflectance spectra. The reflectance spectra is determined by the properties of the target point on the film, such as the film thickness, refractive index, absorption coefficient, and other pertinent optical properties. The reflected light beam is then collected and analyzed by the FTP software which compares the data to theoretical models using the optical properties of the thin film. The matching of real data to theoretical models yields the film thickness, allowing calculation of the ILD removal rate.

Figure 2.17: SENTECH® FTP reflectometer.
2.2.2 Ultraviolet (UV) Enhanced Fluorescence

Owing to the dynamic nature of CMP, the thin, continually changing fluid flow fields on the pad surface present a large challenge for slurry film thickness measurement. The simplest and most non-intrusive method of film measurement is the UV-Enhanced Fluorescence (UVEF) technique. In the case of CMP, and in this thesis, UVEF uses an external UV-light source to illuminate a slurry mixed with fluorescent dye. A high-powered camera is set to focus on a specific portion of the pad during polishing, and is adjusted such that high contrast between the illuminated slurry and dark background can be achieved. The camera records a high-contrast video of the slurry flow throughout the CMP process. Once polishing is complete, the video files are analyzed using an in-house image analyzer written in LabVIEW®.

Figure 2.18 shows the virtual interface of the LabVIEW® image analyzer after analyzing a video. A user first selects regions of the cameras viewing angle to be analyzed. The video is then segmented into individual image frames based upon the framerate of the video, and each image is subsequently cropped to the user defined region. The user can also define the segments of time desired for the analysis. The program then analyzes the image for average brightness values based upon the light intensity of the slurry. This particular UVEF technique yields comparative slurry film thickness measurements (i.e. not exact film thickness measurement) for each region per documented CMP process.
Figure 2.18: LabVIEW® image analyzer interface and sample brightness analysis data
CHAPTER 3
GENERAL THEORY

This chapter describes the general theory of tribology and its application to CMP. A brief theory on the ceria-silica removal mechanism is also presented in Section 3.2. Specific theoretical approaches and study-based extensions of the general theories will be discussed in each chapter separately.

3.1 Tribology in CMP

Tribology is generally stated as the investigation of interacting surfaces in relative motion. During CMP, a wafer attached to a rotating carrier head is pressed against the surface of a rotating polymeric pad in the presence of an abrasive slurry at some predetermined values of pressure and RPM. The interplay of these parameters yield varying degrees of frictional forces and lubrication mechanisms which govern material removal.

3.1.1 Two-Body Contact Striebeck Curve

Early tribological studies were performed on journal bearings, as depicted in Figure 3.1. In such an experimental set-up, a journal (shaft) was rotated under load within a bearing that was lubricated with oil. The shear force generated by the contact of the shaft and bearing was recorded and divided by the down force (pressure) applied by the suspended load to attain the coefficient of friction (COF). Hersey number, defined in Eq.

3.1, lumps the lubricant viscosity ($\mu$), linear velocity ($v$), and applied pressure ($P$) into a quantity usable for determining the lubrication mechanism. It is important to note that the Hersey number is in units of length.

$$\text{Hersey Number} = \frac{\mu v}{P} \quad \text{Eq. 3.1}$$

Figure 3.1: Schematic of a journal bearing-shaft system.

When Hersey number is plotted against the COF in a log-log plot, the Stribeck curve for a two-body contact system is generated as depicted in Figure 3.2. As pictured in this figure, there are three distinct lubrication regimes seen in the relationship of Hersey number to COF. The first region (I) is referred to as boundary lubrication where the two bodies (i.e. the shaft and bearing) are in intimate contact. Within this regime, the COF remains relatively constant over a range of Hersey numbers. The next region (II) is referred to as partial lubrication characterized by a large drop over a small range of Hersey numbers. This region is characterized by a partial separation of the shaft and bearing resulting from an increase in velocity and decrease in pressure. The final region (III) is referred to as hydrodynamic lubrication where the bearing and shaft are completely separated by the lubricant (Ludema 1996).
3.1.2 Three-body Contact Stribeck Curve

During CMP, 3-body contact occurs between the pad, wafer, and slurry abrasive particles. Although this 3-body contact appears more complex than the two-body contact mechanisms described above, a simple change of parameters can yield a Stribeck curve for the 3-body contact as experienced in CMP. The Sommerfeld number ($S_0$) is a CMP-relevant re-definition of the Hersey number, using the parameters of slurry viscosity ($\mu$), pad-wafer sliding velocity ($v$), applied wafer pressure ($P$), and the effective slurry film thickness ($\delta$). The equation for $S_0$ is shown in Eq. 3.2 as:

$$S_0 = \frac{\mu v}{P \delta}$$  
\text{Eq. 3.2}
A popular CMP-relevant form of the Striebeck curve is the log-log plot of the COF vs. the Sommerfeld number. In such a curve, COF is averaged over the entire polish time for each polish event. Knowing the shape of the Striebeck curve over a wide range of the Sommerfeld numbers can be highly beneficial in CMP because it gives direct evidence regarding the extent of 3-body contact between the wafer, the pad, and the slurry abrasive particles. Based on a generic, 3-body contact Striebeck curve (Figure 3.3) and Ludema’s definition (Ludema 1996), 3 major types of contact can be depicted: the first type of contact is referred to as “boundary lubrication” where all solid bodies are assumed to be in intimate contact with one another. This regime generally occurs at low values of Sommerfeld number with the curve taking on a relatively flat shape. Because of close three-body contact events, values of COF are relatively high. If material removal is assumed to be predominantly due to mechanical contact, then the COF values will likely affect material removal rates in this regime. The second type of contact occurs at intermediate values of the Sommerfeld number. This regime is typically referred to as “partial lubrication” where the wafer and the pad are not in intimate contact with one another. The slurry film layer, with the same thickness as the pad surface roughness, develops and partially separates the wafer from the pad. As the lubrication mechanism transitions from “boundary lubrication” to “partial lubrication”, the slope of the Striebeck curve changes from roughly zero to a large negative value. Given the log-log nature of the plot, a negative slope represents sizeable drops in COF which eventually reaches a minimum as the wafer and the pad completely separate from one another by the slurry film. Finally, the “elasto-hydrodynamic lubrication” regime emerges at higher values of Sommerfeld number, where smaller values of removal rate and COF are typically observed. Here, the pad and wafer become further
separated as the slurry film is relatively thick and continues to grow. At very high values of Sommerfeld number, the slope of the Striebeck curve tends to become zero, or slightly positive or even slightly negative depending on the size and concentration of abrasive particles in the slurry, the nature of the chemical reactions on the wafer surface and other complications that may result from film turbulence.

Figure 3.3: Generic representation of a Striebeck curve based on the Sommerfeld number.
3.2 The General Ceria-Silica Removal Mechanism

In CMP, several studies have focused on the interactions between ceria-based abrasives (as CeO₂) with silica surfaces (Srinivasan et al. 2015; Abiade et al. 2006; Abiade 2004; Wang et al. 2007). These investigations often cite two widely accepted mechanisms by Hoshino et al. and Cook, both of which claim that silica removal with ceria abrasives is predominantly a chemical process in which ceria binds to the silica surface, thus facilitating its removal by enhanced frictional tearing or chemical dissolution (Cook 1990; Hoshino et al. 2001). Further studies have shown that it is the presence of Ce³⁺ ionic species that causes this chemical reaction (Abiade 2004; Wang et al. 2007). Although the stoichiometry of CeO₂ suggests that Ce⁴⁺ ions get generated, studies have shown that CeO₂ also yields an appreciable amount of Ce³⁺ which may differ in its abundance depending on the ionic strength of the slurry, method of manufacture of the ceria nano-particle and the presence of proprietary additives. Dutta et al. has shown that CeO₂ particles often have oxygen vacancies on their surface nano-structure, leading to a localization of an electron which occupies the 4f orbit of the Ce⁴⁺ species, thereby yielding some Ce³⁺ on the surface (Dutta et al. 2006). Furthermore, Ce⁴⁺ has been shown to reduce to Ce³⁺ in the presence of ultrapure water (UPW) (Koslova et al. 2009), thus verifying Abiade’s assertion that, during CMP, the ceria abrasive surface should consist of predominantly Ce³⁺ (Abiade 2004).
CHAPTER 4

IMPROVEMENTS IN STRIEBECK CURVES FOR COPPER AND TUNGSTEN
CHEMICAL MECHANICAL PLANARIZATION ON SOFT PADS

This chapter aims to understand the tribology of polishing processes using an improved Striebeck curve (i.e. referred as Striebeck+ curve) and elucidates the essential factors governing the mechanical aspects of chemical mechanical planarization. This study investigated tribological and thermal aspects of copper and tungsten blanket wafer polishing on the Politex soft pad with a multitude of gradual yet continuous changes in polishing pressure and sliding velocity. This work also attempted to understand the frictional and thermal transients associated with such dynamic processes. Results showed that polishing with the Politex pad produced stable COF values that indicated a “boundary lubrication” regime throughout. In contrast, copper polishing on hard pads produced tremendous spread of data clusters having a trend in COF that started with “boundary lubrication” and then transitioned to the “mixed lubrication” mode. Regarding temperature effects, the plots between average pad surface temperature and the product of COF, velocity and downward pressure showed a linear relationship between the two parameters for all copper and tungsten polishing used in conjunction with Politex and hard pads.

4.1 Introduction

For several decades, chemical mechanical planarization (CMP) has proved to be an essential step in high-volume manufacturing of integrated circuit (IC) devices by achieving precision dimensions of local and global planarity. These critical factors enable high-yield
production of multi-level IC devices by meeting stringent depth-of-focus and critical feature size requirements. During CMP, a slurry containing abrasive nanoparticles and metal-softening chemicals is distributed across the rotating pad surface, producing a thin film. A patterned wafer of non-planar topography is then pressed against the pad via a rotating carrier head at a pre-determined pressure. As polishing proceeds, a combination of the pad asperities and slurry components remove the “up-features” on the wafer surface through chemical and mechanical action, yielding a wafer of desired local and global planarity.

Given the critical nature of CMP as described in the brief overview above, it is paramount to understand the mechanism of action in greater detail. Understanding the tribology of the process gives unprecedented insight into essential factors governing the mechanical aspects of CMP. Historically, “Stribeck curves” have been used as the primary investigative method for CMP tribology (Li et al. 2005; Philipossian and Olsen 2003). These curves plot the coefficient of friction (COF) versus the Sommerfeld number (a collection of CMP-relevant parameters such as relative pad-wafer velocity, wafer pressure, slurry viscosity, and slurry film thickness) on a log-log scale (Hersey 1938; Hersey 1966). These classic Stribeck curves, however, assume a constant downforce (and subsequent applied wafer pressure) during each polishing run, and fail to account for variations in those parameters. Moreover, to construct one such curve at least 9 individual wafers need to be polished and the resulting shear forces need to be analyzed one by one; a costly and time-consuming undertaking.

Recently, Han et al. proposed the use of “Stribeck+ curves” that employ instantaneous shear and downforce data collection at a high frequency (i.e. 1,000 Hz) along
with polishing only 1 wafer during which all conditions (i.e. multitude of pressures and velocities) are changed dynamically during a continuous 75-sec run (Han et al. 2017). Such curves capture particular transient behaviors of the polishing process, such as instability, vibrations, and lubrication regime fluctuations, that would not normally be seen using the traditional approach.

Han et al. proved the efficacy of Strubeck+ curves in the type of information that they provide on hard pads using copper slurries (Han et al. 2017). However, many CMP processes may require a greater focus on achieving low defect levels attainable only through the use of soft pads (Li 2008). Furthermore, as IC designs reach 8 nm and smaller feature sizes, many polishing methods are being designed strictly around the use of soft pads (https://www.cabotcmp.com/wp-content/uploads/CMC_Ruthenium_CMP_Integration.pdf). This investigation serves to prove that Strubeck+ curves can also be applied to soft pads and achieve results that mirror those found on hard pads. The focus of this work is mainly on the tribological and thermal aspects of the polishing process along with attempting to understand the frictional and thermal transients associated with such dynamic measurements using blanket tungsten and copper wafers along with a variety of pads and slurries.

4.2 Improving the Strubeck Curve

In CMP, Strubeck curves have historically relied solely on the calculation of the COF by dividing the average measured shear force by the downforce. The latter has always assumed to be constant and essentially calculated from the pressure set-point programmed in the polisher’s micro-controller. Similarly, Strubeck curves provide no information on the
relative standard deviation of COF which at times can be more important than their mean values. Meanwhile, since the Sommerfeld number lumps sliding velocity and polishing pressure together, it is often unclear as to which of these two parameters contribute most to the tribological behavior. A full description of the Stribeck curve in CMP is described in Section 3.1.2.

As mentioned earlier, the Stribeck+ method proposed by Han et al. shows a better picture of what may be going on, tribologically, in the pad-slurry-wafer interface. The method, which involves a multitude of gradual changes (e.g. continuous time-dependent ramp-ups and ramp-downs) in the polishing pressure and sliding velocity within a given polishing run, does not assume downforce to be constant throughout the polishing process. Instead, it involves the instantaneous measurement of downforce along with shear force causing the COF to be instantaneously calculated and recorded. The equation for the instantaneous COF calculation is given in Eq. 4.1.

\[
COF_i = \frac{Shear \ Force_i}{Down \ Force_i}
\]  

Eq. 4.1

Using this equation, the COF is calculated at the same rate by which the shear and force data is collected, at 1,000 Hz.

4.3 Experimental Apparatus and Procedure

All tests were performed on an Araca APD-800 polisher and tribometer which is equipped with proprietary force transducers suitable for acquiring real-time shear force and downforce at high frequencies (http://aracainc.com/wp-content/uploads/2015/10/APD800-brochure.pdf). Attached to the carrier head is an interface template with a retaining ring
and backing film assembly. The retaining ring prevents the wafer from slipping out while the wetted backing film assembly is used to securely hold the wafer via capillary forces. The back-side of the interface template is fitted onto the carrier head using the existing vacuum conditions in the head. All input and output parameters associated with the polishing process are automated, controlled and monitored via a dedicated computer running on a proprietary LabVIEW® software developed specifically for these purposes. The computer also synchronizes the friction table to the polishing process so that the real-time shear force, downforce, polishing kinematics and pad surface temperature data can be obtained at 1,000 Hz acquisition frequency. The exact point of temperature measurement was at the wafer center track near the leading edge of the carrier head.

The soft pad used in this study for both copper and tungsten polishing was an embossed 31-in Politex REG (by Dow Electronics Materials). The copper slurries employed included PL-7103 (by Fujimi) and C8902 (by Cabot Microelectronics). For tungsten, SS-W2000 and SS-W7000 slurries (both by Cabot Microelectronics) were used. A constant slurry flowrate of 300 ml per min was used in all cases.

Prior to polishing and data acquisition, the pad was broken in for 30 minutes with ultra-pure water (UPW). The pad break-in was performed using a 3M PB32A brush subjected to a load of 13.7 N, a rotation rate of 95 RPM, and a sweep frequency of 10 per minute. The break-in process was followed by polishing several dummy wafers to confirm process consistency and to ensure that steady-state conditions had been reached prior to COF data acquisition. The above conditioning recipe was also used for in-situ conditioning during the experiments that follow.
For generating Stribeck+ curves, one 75-sec polishing run (with a single blanket copper or tungsten wafer) with a multitude of gradual yet continuous changes (e.g. time-dependent ramp-ups and ramp-downs) in polishing pressure and sliding velocity was performed (Han \textit{et al}. 2017). During each 75-sec run, downforce and shear force were instantaneously measured at 1,000 Hz and recorded for Stribeck+ curve extraction. Contemporaneously, pad surface temperature was also measured at the wafer center track near the leading edge of the carrier head.

Table 4.1 shows the polishing conditions for each step of the 300-mm blanket copper or tungsten wafer polishing process. Figure 4.1 shows an example of the forces (top) and pad surface temperature (bottom) that were measured and recorded during a copper wafer polishing event. The steps in Table 4.1 are echoed by their respective encircled numbers on the force and temperature charts. Each ramp-up and ramp-down step took approximately 2 seconds to reach the intended polishing conditions, and an additional 13 seconds at the intended polishing conditions. In this study, slurry viscosity and film thickness were assumed to be constant (Han \textit{et al}. 2017; Lu \textit{et al}. 2004; Sun \textit{et al}. 2010). This assumption allowed the Sommerfeld number in the Stribeck curve to be replaced by ratio of the relative sliding velocity to the applied wafer pressure, \(v/P\).

<table>
<thead>
<tr>
<th>CMP Step</th>
<th>Pressure (P, PSI)</th>
<th>Sliding Velocity (v, m/s)</th>
<th>(v/P) (m/(Pa.s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td>1.45E-04</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td>1.09E-04</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1.0</td>
<td>7.25E-05</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>1.0</td>
<td>4.83E-05</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0.6</td>
<td>2.90E-05</td>
</tr>
</tbody>
</table>
Figure 4.1: Down force (green, top), shear force (red, top) and temperature (bottom) data corresponding to copper CMP using the PL-7103 slurry and the Politex pad.

4.4 Results and Discussion

*Copper CMP* – Figure 4.2 shows the Striebeck+ curve obtained from the data shown in Figure 4.1 (top). The curve starts off flat and increases only slightly at higher values of \(v/P\) indicating the presence of a “boundary lubrication” mechanism throughout the polishing steps. From the extent of clustering, it is obvious that the polishing process is tribologically more stable at low values of \(v/P\). The shape of the clusters at high values of \(v/P\) suggest significant scattering in both vertical and horizontal directions. Vertical clusters indicate that the actual \(v/P\) varies in small range in each step. In this case, therefore, the vertical spread on COF (i.e. shear force divided by downforce) clusters are generally proportional to the extent of shear force fluctuation. Horizontal scatters are likely due to...
two factors: First of all, the polishing recipe subjects the same wafer through multiple pressures and velocities with ramp-ups or ramp-downs in between each condition. Since force data is retrieved at 1,000 Hz, and each ramp takes about 2 seconds to reach steady state, there are approximately 2,000 transient data points collected between each condition which cause the curve to stretch horizontally. Second, while sliding velocity is known to be relatively constant during the last 13 seconds of each step, the actual downforce tends to fluctuate in real-time measurement as evidenced by the shape of the green curve of Figure 4.1 (top). Therefore, data clusters in Figure 4.2 tend to stretch out horizontally indicating continual vibrations in polishing pressure.

Figure 4.2. Strieber+ curve based on data presented in Figure 4.1 (top).
It is important to note that the proposed “dynamic polishing” method for obtaining Stribeck+ curves is not simply an exercise in search of the tribological mechanism of a certain process. Current generation CMP processes often times adopt rapid changes in both velocity and pressure during a given polishing step to optimize bulk metal polish, soft-landing on the barrier film, and even barrier film removal. Such dynamic adjustments allow for platen matching (i.e. getting the removal time on each platen to be more or less the same as the neighboring platen), wafer throughput optimization and wafer-level defect reductions. One factor that exponentially affects removal of metal films, and hence polish time and issues that prevent proper platen matching, is temperature. Given the large thermal mass of the pad-platen system, rapid changes in pad surface temperature grossly lag any changes in velocity and/or pressure thus complicating optimization efforts. The proposed Stribeck+ method, when combined with real-time temperature measurement, becomes even more valuable as it helps shed light on the extent of temperature transients and also helps clarify certain misconceptions about the relationship between COF and temperature.

A common misconception that has not been properly dealt with in the literature is the notion that the higher the pad-slurry-wafer COF, the greater the extent of heat dissipation, and therefore the higher the pad surface temperature. After all, there have been many studies in the past that have reported a linear relationship between COF and temperature (Mudhivarthi 2007; Sorooshian et al. 2004; Jiao et al. 2011; Lee et al. 2007). However, when one plots (see Figure 4.3) the COF data shown in Figure 4.2 against the temperature data of Figure 4.1 (bottom), no such correlation is seen.
Figure 4.3: Instantaneous pad surface temperature vs. instantaneous COF based on data presented in Figure 4.1 (bottom) and Figure 4.2.

The reason behind such seemingly anomalous behavior is simple yet subtle. Past reports of a direct correlation between temperature and COF have all involved static conditions at pseudo steady state (that is, constant values of sliding velocity and downforce for polish times or around a minute). In this case, due to the systematic 15-second changes in velocity and downforce, temperature (once given sufficient time for it to stabilize) should not correlate to COF but rather to the power input represented by the product of COF, velocity and downward pressure (i.e. COF × P × v). In this case, when average pad surface temperature, as measured during the 13th through 14th second of the 15-sec polishing process (i.e. once temperature has somewhat stabilized) is plotted against COF × P × v a linear relationship is indeed observed (Figure 4.4).
Figure 4.4: Average pad surface temperature (measured between the 13\textsuperscript{th} and 14\textsuperscript{th} second of a 15-second polishing step) vs. COF × P × v based on data presented in Figure 4.1 (bottom), Figure 4.2 and the process information in Table 4.1.

Somewhat related to this, the systematic changes in velocity and downforce from a given 15-second step to another show the extent of temperature transients that may exist in a typical soft landing process during metal polish. Given the fact that activation energies associated with copper or tungsten polish are quite large (Sorooshian et al. 2004), any significant lags in pad surface temperature can cause material removal to experience a runaway or to slow down unexpectedly depending on the particular values of COF, polishing pressure or sliding velocity.

By way of another example, Figure 4.5 shows the Strubeck+ curve corresponding to copper polishing with an entirely different slurry, C8902, by Cabot Microelectronics coupled with the Politex pad. The relatively flat COF in the Stribeck+ curve indicates that the C8902 operates in “boundary lubrication” as well. In contrast to the PL-7103 system, the C8902 process results in consistently lower COFs at all polishing conditions. In typical copper CMP applications, the PL7103 is used mainly for bulk copper removal, whereas the C8902 is a finishing slurry that focuses more on precise material removal that causes
lower wafer-level defects. The gentler, lower material removal rate formulation of the C8902 slurry corresponds to a lower COF and, more specifically, a lower shear force. Aside from this, both the C8902 and the PL7103 slurries yield similar data clusters that stretch out in both x and y-axis.

![Graph](image)

Figure 4.5: Stribeck+ curve corresponding to copper CMP using the C8902 slurry and the Politex pad.

Having demonstrated the utility of the Stribeck+ curve for rapidly determining the tribological mechanism of copper CMP processes on a soft Politex pad, the results are now compared with Stribeck+ curves obtained using hard pads. Figure 4.7 compares 3 copper CMP Stribeck+ curves all using the PL7103 slurry with Politex and 2 hard pads (e.g. the Dow IC1000 K-groove and the CMC D100) as reported by Han et al. (Han et al. 2017). To compare better, the y-axis range is widened, otherwise, the Stribeck+ curve corresponding to the Politex pad is the same as that shown previously in Figure 4.2. In all cases, the sliding velocity and wafer pressure settings are identical.
Figure 4.6: Stribeck+ curves corresponding to copper CMP using the PL7103 slurry with 3 types of pads: Politex (top), D100 (center) and IC1000 (bottom).
When comparing all 3 curves, one can infer as follows:

- Hard pads result in tremendous spread of data clusters in both x- and y- directions. This indicates a greater level of instability and stick-slip in the shear and down forces compared to soft pads.

- The lubrication mechanism shifts when hard pads are used. The IC1000 produces a trend in COF that begins in “boundary lubrication” and then falls rapidly into “mixed lubrication” where pad-wafer contact is significantly reduced (Hersey 1938). For the D100, the Stribeck+ curve starts off in “boundary lubrication” and shifts slightly to “mixed lubrication” half way through where average COF drops to around 0.40. In contrast, polishing with Politex at these conditions produces stable COF values that indicate a “boundary lubrication” regime throughout.

- The above trends indicate that the Politex pad results in a more robust process (tribologically speaking) as compared to both the IC1000 K-groove and the D100 concentrically groove pads. In addition, polishing using the Politex pad at a lower \( v/P \) condition (i.e. combination of lower sliding velocity and higher polishing pressure) indicates a more stable process as indicated by its smaller data cluster.

- Average COF values associated with the soft pad are greater than those obtained by both hard pads.

*Tungsten CMP* – Figures 4.7 and 4.8 show the Stribeck+ curves for tungsten CMP processes (with a Politex pad) using the SS-W2000 slurry (by Cabot Microelectronics) and the SS-W7000 slurry (also by Cabot Microelectronics), respectively. Comparing the two figures, it is evident that changing the slurry does not affect the overall tribology of the
system. The lubrication mechanism for both processes is “boundary lubrication”. Compared to SS-W7000, the SS-W2000 slurry generates higher values of COF throughout which is most likely due to concentration and morphological differences in the respective abrasive particles as well as presence of additives in each formulation. The SS-W2000 contains fumed silica as its primary abrasive particle that generally have a greater micro-structure in all 3 dimensions. In contrast, the SS-W7000 employs colloidal silica particles with a generally smooth and spherical geometry. It is well known that, during polishing, abrasive particles with smoother surfaces and minimal micro-structure tend to generate lower COFs than particles aggregates that have more advanced 3-dimensional micro-structures. Similar to the copper CMP results with Politex, the Stribeck+ curves for tungsten CMP also show a more stable process at lower values of $v/P$ as indicated by the smaller size of the data cluster.

![Figure 4.7: Stribeck+ curve corresponding to tungsten CMP using the SS-W2000 slurry and the Politex pad.](image-url)
Figure 4.8: Strubeck+ curve corresponding to tungsten CMP using the SS-W7000 slurry and the Politex pad.

Regarding temperature effects, similar to Figure 4.4, Figure 4.10 summarizes the relationship between average pad surface temperature, as measured during the 13th through the 14th second of each 15-sec polishing process and the product of COF × P × v for all 4 slurries (copper and tungsten) used in conjunction with the Politex pad. The P × v represents the polishing power. By changing the velocity and/or the pressure, the power input changes accordingly. However, the polishing power alone does not govern temperature changes in polishing pad. During polishing, heat generation occurs due to the frictional forces between the wafer and pad surface. Along this line of reasoning, Borucki et al. stated that the rise in temperature above that of the ambient is proportional to the COF (Borucki et al. 2007). The COF is required as this parameter yields the extent of friction between the pad and the wafer. The COF × P × v product then describes the extent of pad-wafer contact modulated by the amount of polishing power applied to the wafer, and
therefore offers a more logical representation of heat generation and temperature changes. In Figure 4.9, not only is a linear relationship between the two parameters seen, but all data points seem to more or less fall on a universal curve as well. This suggests that average pad surface temperature is not as much a function of what is being polished (e.g. copper or tungsten) or the respective heat of reaction of each process. The latter was always believed to be negligible due to the fact that a very small percentage of the slurry that flows actually participates in the chemical reaction(s). Rather pad surface temperature seems to depend entirely on the resulting COF as well as the velocity and pressure of the process. A similar universal curve is also observed with copper polishing using the PL-7103 slurry and two different hard pads as seen in Figure 4.10. This figure spans a larger temperature range than the data in Figure 4.9, allowing for greater variation and thus shows a larger spread of data. Further, the hard pads are composed of different materials than the soft pad and have different grooving designs, leading to differing heat dissipation rates and differing convective cooling interactions with the slurry.

Figure 4.9: Average COF × P × v vs. average temperature using SS-W2000 (filled black circles), SS-W7000 (open black circles), PL-7103 (filled gray circles), and C8902 (open gray circles) slurries on a Politex pad.
In this study, the tribological behaviors and pad temperatures of 300-mm copper and tungsten blanket wafers polished on the Politex soft pad with a multitude of gradual yet continuous changes in polishing pressure and sliding velocity were investigated. The results with Strubeck+ curves obtained using hard pads as reported previously in the literature were also compared. Using the Politex soft pad, the Strubeck+ curves showed that the polishing mechanism stayed in the “boundary lubrication” regime for both copper and tungsten processes. Polishing at a lower $v/P$ condition showed a more stable process as indicated by its smaller size data cluster. In contrast, copper polishing on hard pads produced tremendous spread of data clusters having a trend in COF that began in “boundary lubrication” and then transitioned to “mixed lubrication” mode. Regarding temperature effects, the plots between average pad surface temperature and the product of COF, velocity and downward pressure showed a linear relationship between the two parameters for all copper and tungsten polishing used in conjunction with Politex and hard pads. In addition, all data points followed a universal curve. Such observation suggested
that average pad surface temperature seemed to depend entirely on the resulting COF as well as the velocity and pressure of the process irrespective of the type of the polished substrates.
CHAPTER 5
SLURRY INJECTION SCHEMES ON THE EXTENT OF SLURRY MIXING AND AVAILABILITY DURING CHEMICAL MECHANICAL PLANARIZATION

In this chapter, slurry availability and the extent of slurry mixing (i.e. among fresh slurry, spent slurry and residual rinse-water) were varied via three different slurry injection/application schemes. An ultraviolet enhanced fluorescence technique was employed to qualitatively measure slurry availability and its flow on the pad during polishing. This study investigated standard pad center area slurry application and a slurry injection system (SIS) that covered only the outer half of the wafer track. Results indicated that the radial position of the slurry injection point and the alteration of fluid mechanics by the SIS played important roles in slurry mixing characteristics and slurry availability atop the pad. Removal rates were found to decrease with a decrease in slurry availability while a higher degree of slurry mixing decreased the fraction of fresh slurry and, consequently, lowered removal rate. By using a hybrid system (i.e. a combination of slurry injection via the SIS and standard pad center slurry application), the polishing process benefited from higher slurry availability and a higher fraction of fresh slurry than the conventional pad center slurry application and the shorter SIS, individually. This work underscored the importance of optimum slurry injection geometry and flow for obtaining a more cost-effective and environmentally benign chemical mechanical planarization process.
5.1 Introduction

Chemical mechanical planarization (CMP) is an enabling step in integrated circuit (IC) manufacturing for achieving local and global surface planarity through combined chemical and mechanical means. In certain CMP processes, slurry cost may represent up to 50% of the total cost of ownership of the CMP module (Holland et al. 2002; Philipossian and Mitchell 2003). Furthermore, slurry consumption has tremendous environmental impacts as spent slurries contain hazardous chemicals with large amounts of abrasive nanoparticles. Although the recovery and reuse of spent slurries have been investigated and adopted by a handful of IC manufacturers (Kettler et al. 2013; Amoroso et al. 2012), the best solution is to optimize the slurry usage by either reducing the slurry flow rate for the same CMP performance (i.e. removal rate and defects) or applying the same slurry flow rate for better performance compared to the current process-of-record.

In most commercially available CMP polishers, slurry is applied near the pad center as shown in Figure 5.1(a). As the pad rotates during polishing, a large amount of fresh slurry flows directly off the pad surface without entering the pad-wafer interface. Such mechanism results in very low slurry utilization efficiencies (Philipossian and Mitchell 2003; Meled et al. 2011). Several other methods have been proposed for applying or injecting slurry onto the pad surface. For example, Mok proposed an apparatus for spraying slurry onto the pad surface rather than streaming it near the pad center (Mok 1999). Chamberlin et al. proposed a slurry injection technique involving spraying pressurized slurry over the pad through multiple nozzles (Chamberlin et al. 1999). Chiou et al. proposed a slurry injector having multiple adjustable nozzles (Chiou et al. 2002). Chang proposed a method for dispensing slurry through multiple nozzles to distribute the slurry
over the entire wafer track (Chang 2005). While these methods help deliver fresh slurry to the pad surface, however, none of them prevent the mixing of spent slurry and residual rinse water with fresh slurry during polishing.

Polishing processes continuously generate spent slurry on the pad surface. Spent slurry contains pad debris (from conditioning and pad wear), diamond chips (from conditioning diamond disc) and chemical by-products. Studies have shown that these can decrease material removal rate and increase polishing defects (Meled et al. 2011; Kwon et al. 2012). To mitigate such issues, large amounts of ultrapure water (UPW) are dispensed to rinse the pad between polishes (i.e. the pad rinsing step) to reduce the amount of polishing by-products on the pad surface. Following the pad rinsing step, appreciable amount of residual rinse water still reside on the pad land areas as well as inside the pad grooves. When fresh slurry is injected onto the pad surface during polishing, it mixes with the residual rinse water and gets diluted. Since most industrially-relevant slurries result in lower removal rates when further diluted with water, over-the-pad mixing of water and slurry is not favorable. It is fair to say that the current standard pad center slurry application method and the previously proposed slurry application or injection methods do not provide efficient slurry utilization and leave significant room for improving polishing performance.

As an alternate method, Meled et al. and Mu et al. investigated a slurry injection system (SIS) which is aimed to shorten the slurry mean residence time (MRT) on the pad surface (Meled et al. 2011; Mu et al. 2016). In both studies, the SIS was placed adjacent to the wafer on the pad surface covering the whole wafer track as shown in Figure 5.1(b). The SIS facilitated the delivery of fresh slurry into the pad-wafer interface. In addition, the SIS effectively blocked the spent slurry and residual rinse water from re-entering the pad-wafer
interface and, therefore, allowed a higher fraction of the fresh slurry delivered to the polishing region. As a result, the SIS achieved a significantly lower slurry mean residence time, higher removal rate, and lower polishing defects than the standard pad center area slurry application method (Meled et al. 2011; Mu et al. 2016).

Figure 5.1: Top views of a polisher with (a) the standard slurry application method, (b) a SIS design that covers the whole wafer track and (c) a SIS design that covers only the outside half of the wafer track.
It must be emphasized that Meled *et al.* and Mu *et al.* employed a SIS design that covered the whole wafer track on the surface of the polishing pad as shown in Figure 5.1(b). As a matter of a fact, some of CMP systems designed for high volume manufacturing have particular space restrictions that will not allow implementation of SIS units that cover the entire wafer track on the surface of the pad. Such space restrictions are typically associated with oscillations of the conditioner and the wafer carrier head. As a continuation of both Meled and Mu’s works, this study investigates a SIS design that cover only the outer half of the wafer track as shown in Figure 5.1(c). This study aims to understand if a shorter SIS unit can provide similar benefits as the full-size SIS design. In addition, an ultraviolet enhanced fluorescence (UVEF) technique is employed to qualitatively measure the slurry availability on top of the pad prior to its entry into the pad-wafer interface. Results, when compared to the standard pad center slurry application method, help confirm the main mechanism responsible for the enhanced removal rate associated with the SIS.

### 5.2 Experimental Procedure

The standard pad center area slurry application method and a novel method for slurry injection system were used to apply slurry onto the pad surface. Figures 5.1(a) and 5.1(c) show the top views of a polisher with the standard slurry application method and the SIS design that only covers the outer half of the wafer track. For the standard pad center area slurry application method (what we will henceforth refer to as “Point Application” or “PA”), the slurry is applied above the pad center. For the SIS, the system consists mainly of an injector and an injector mount. The injector has a rectangular shape which is attached to the injector mount with the connecting rods. The bottom of the injector is in contact with
the surface of the polishing pad. The mount is used to securely attach the entire assembly to the body of the polisher. A single slurry inlet port is placed on the top of the body which matches an outlet at the bottom of the body (at the trailing edge). Fresh slurry is introduced through the slurry line from the slurry tank where it flows into the inlet and then flows out through the outlet into a channel machined into the bottom of the injector body which helps to evenly spread the fresh slurry onto pad surface during polishing. A full description of SIS can be found elsewhere (Borucki et al. 2014). In one test configuration, a hybrid slurry injection method is employed. The rationale behind this hybrid injection method is discussed in detail in Section 5.3 of this chapter.

All polishing tests were performed on an Araca APD-800X polisher a full description of which can be found elsewhere (http://www.aracainc.com/media/pubs/Polisher_and_Tribometer_300mm.pdf). A 3M A165 diamond disc was used to provide in-situ conditioning on an IC-1000 K-grooved pad (manufactured by Dow) at a conditioning down-force of 44.5 N. Each wafer was polished for 1 minute at 27.6 kPa and 1.5 m/s. Before polishing, the diamond disc was used to break in the pad for 60 minutes with DI water. The disc rotated at 95 RPM and swept at a frequency of 10 times per minute across the radius of the pad surface. The diamond disc, pad, and wafer rotations were counter clockwise. Pad break-in was followed by pad seasoning during which the shear force was monitored to ensure that stable values were achieved prior to monitor wafer polishing.

The Semi-Sperse® 25 slurry (manufactured by Cabot Microelectronics), diluted with water to a final solids content of 12.5% by weight, was used as the polishing slurry. Slurry flow rates were set at 150 and 250 ml/min. 300-mm blanket oxide wafers were polished for all injection schemes. Before and after polishing, a reflectometer from
SENTECH Instruments GmbH was used to measure the oxide film thickness on each wafer. This allowed the computation of silicon dioxide removal rate for each test.

In addition to the above test, a UVEF technique was employed to qualitatively visualize measure the slurry availability on top of the pad surface (Liao et al. 2012; Liao et al. 2012). Before taking images, the embossed Politex pad (manufactured by Dow) was conditioned using a 3M PB32A brush for 30 minutes with UPW at a conditioning force of 13.3 N. In all experiments, pad conditioning was performed in-situ. The slurry for the UVEF experiments consisted of 1 volume part of Fujimi PL-7103 slurry, 4 volume parts of DI water and 0.5 g/L of 4-methyl-umbelliferone. Pad rinsing was performed in between polishes using UPW. The experimental setup is shown in Figure 5.2. Ultraviolet (UV) light from two light emitting diodes was projected onto the leading edge of the carrier head. As the slurry was tagged with a fluorescent dye (i.e. 4-methyl-umbelliferone), the UV light excited the dye in the slurry causing it to fluoresce. The intensity of the emitted fluorescence was proportionate to the amount of the slurry (i.e. the thickness of the slurry film) (Liao et al. 2012; Liao et al. 2012). A high resolution charged coupled device camera was employed to record the emission of fluorescent light on the leading edge of the wafer carrier head. The images were then analyzed via a customized software written in LabVIEW® (Liao et al. 2012; Liao et al. 2012).
5.3 Experimental Results

Several published reports indicated that 300-mm CMP processes typically employ slurry flow rates ranging from 250 to 300 ml/min to achieve optimum material removal rates (RR) (Meled et al. 2011; Jiao et al. 2012; Kangda et al. 2013; Jiao et al. 2011). In a separate study, Wang et al. showed that RR increases with the PA slurry flow rate, however, it eventually reaches an asymptote where further increases in slurry flow rate no longer affects removal rate (Wang et al. 2011). Philipossian et al. showed that the slurry utilization efficiency (defined as the portion of slurry that flows through the pad-wafer interface, divided by the total amount of slurry applied) actually decreases with an increase in slurry flow rate (Philipossian and Mitchell 2003). Simply increasing slurry flow rate until a certain level may help achieve higher RR in several cases, however at a disproportionality higher consumable cost. Therefore, in this study, polishing using the PA method at a slurry flow rate of 250 ml/min (henceforth referred to as “PA-250”) is
considered as the baseline process. Figure 5.3 summarizes the removal rates for all slurry injection methods (to be elaborated in detail later on in this section). As expected, PA at reduced slurry flow rate (i.e. 150 mL/min, henceforth referred to as “PA-150”), yields lower RR than PA-250. Several published results have reported a similar finding whereby removal rates are shown to decrease with slurry flow rate (Meled et al. 2011; Wang et al. 2011). One reason for this observation is that at the reduced flow rate, less slurry is available to be transported to the pad-wafer interface (Liao et al. 2012; Sampurno et al. 2005). Another reason is the degree of slurry mixing: As discussed in the introduction section, during polishing, the fluid residing on the pad surface contains spent slurry, polishing by-products (i.e. pad debris and chemical by-products) and residual rinse water from the pad rinsing procedure performed between polishes which do not contribute to RR (Meled et al. 2011; Sampurno et al. 2005). The fresh slurry injected on top of the pad surface gets diluted by mixing with spent slurry and residual rinse water. The net effect is the reduction of the fraction of fresh slurry delivered to the polishing region (i.e. between the pad and the wafer) where the removal mechanism occurs. At reduced slurry flow rate (i.e. the PA-150), the fraction of fresh slurry becomes even lower thus leading to a lower RR (Meled et al. 2011; Mu et al. 2016; Sampurno et al. 2005). As a matter of a fact, the traditional PA method does not provide a mechanism to promote a higher fraction of fresh slurry. Based on the explanation above, it can be inferred that both the degree of slurry mixing and slurry availability affect RR during polishing process.

Previous studies showed that slurry mean residence time (MRT) of a certain CMP process is an indicator for the degree of slurry mixing such that a higher value of MRT means more mixing between the freshly injected slurry and spent slurry, as well as residual
rinse water (Meled et al. 2011; Mu et al. 2016). Therefore, lower values of MRT are desirable in CMP since more fresh slurry is being delivered to the pad-wafer interface at a faster rate. Meled et al. and Mu et al. has shown that SIS significantly decreases slurry MRT compared to the PA method (Meled et al. 2011; Mu et al. 2016). Furthermore, Mu et al. concluded that the dispersion number is lower with SIS, which accounts for the lower MRT (Mu et al. 2016).

Figure 5.3: Summary of removal rate data.

The mechanism can be further explained with the UVEF images shown in Figure 5.4. With the PA injection scheme, a thick bow wave containing spent slurry and residual rinse water is formed directly at the leading edge of the wafer carrier head as shown in Figure 5.4(a). Consequently, the PA method allows more spent slurry and residual rinse water to re-enter the wafer-pad interface. In contrast, as the SIS is placed in front of the leading edge of the wafer carrier head, it prevents spent slurry and residual rinse water from re-entering the pad–wafer interface during polishing. Figure 5.4(b) shows the UVEF image
of a polishing process using a SIS design that covers only the outer half of the wafer track. Similar to a regular SIS design (i.e. covering the whole wafer track), the bow wave was formed at the leading edge of the SIS during polishing. Due to the centrifugal force of the platen and wafer rotation, most of the polishing by-products, spent slurry and residual rinse water dominantly reside closer to the edge of the pad rather than to the center of the pad. Therefore, having a smaller SIS design that covers only the outer half of the pad is still desirable. As shown in Figure 5.4(b), a SIS design that covers the outer half of the wafer track can effectively block polishing by-products, spent slurry and residual rinse water from re-entering the pad-wafer interface. The thick bow wave formed at the leading edge of the SIS closer to the edge of the pad confirms that the spent slurry and residual rinse water are effectively blocked from re-entering the pad–wafer interface and guided off from the pad surface to the drainage. Furthermore, by using the SIS, the fresh slurry is less diluted with the spent slurry and residual rinse water, leading to higher fraction of fresh slurry that enter the pad-wafer interface.

Figure 5.4: Bow wave formation on the polishing pad using: (a) PA method, and (b) the SIS.
SIS increases the slurry availability and reduces the degree of mixing of the fresh slurry with the spent slurry and residual rinse water. As a result, using the SIS at a reduced slurry flow rate can achieve similar removal rates compared to PA (Meled et al. 2011; Mu et al. 2016; Liao et al. 2012). Previous studies on the SIS (that fully cover the whole wafer track) showed that SIS at a slurry flow rate of 150 ml/min achieved the same removal rate as PA at a slurry flow rate of 250 ml/min (Meled et al. 2011; Mu et al. 2016; Liao et al. 2012). Referring back to Figure 5.3, using a SIS that only covers the outer half of the wafer track, at a flow rate of 150 mL/min (referred to as “SIS-150”), yields a RR that is significantly lower than the PA-250 and only slightly higher than the PA-150. In this configuration, the slurry injection port on the SIS coincides with the center of the wafer track. Due to rotation and centrifugal forces of both platen and wafer, the injected fresh slurry is then mainly distributed on the outer half of the wafer track as illustrated by red color in Figure 5.5. Therefore, injecting the slurry in the center of the wafer track reduces slurry coverage in the pad-wafer interface, as entering fresh slurry is now reduced to one-half of what was observed when PA and full SIS designs were used. Furthermore, centrifugal forces act more rapidly to pull the slurry off of the pad surface as the fresh slurry in injected closer to the edge of the pad. Therefore, in this configuration, while SIS is still effective in blocking the spent slurry and residual rinse water, slurry availability is greatly reduced as it only covers the outer half of the wafer track. To increase slurry availability on the inner half of the wafer track while still taking the benefit of SIS to block the spent slurry and residual rinse water to re-enter the pad-wafer interface, a hybrid system is proposed as shown in Figure 5.6.
Figure 5.5: Coverage of fresh slurry on wafer track (red) using slurry injection system with slurry injection point coincide with the center of wafer track.

Figure 5.6: Coverage of fresh slurry on wafer track (red) using a hybrid system.
Figure 5.6 illustrates the hybrid system that combines both SIS and PA (what will henceforth be referred to as “Hybrid”). In this case, fresh slurry streams are injected contemporaneously to the SIS as well as to point application (PA) at 50 and 100 ml/min, respectively. The total slurry flow rate remains the same at 150 ml/min (i.e. 40 percent reduction from the 250 ml/min using the regular PA method). The main purpose for having slurry injected through the PA is to facilitate the availability of fresh slurry in the inner half of the wafer track. In the inner half of the wafer track, slurry dilution (with spent slurry and residual rinse water) is unavoidable since SIS does not cover this region. However, the dilution is expected to be significantly less pronounced than the outer half of the wafer track. Similarly, the location of the SIS is kept constant (i.e. covering the outer half of the wafer track) in order to effectively block the spent slurry and residual rinse water from re-entering the pad-wafer interface as previously explained. At the same time, slurry is injected via SIS to ensure enough availability of fresh slurry on the outer half of the wafer track.

In summary, the hybrid system is expected to provide enough availability of fresh slurry covering the whole wafer track and to still cause the removal of spent slurry and residual rinse water. As shown in Figure 5.3, the Hybrid-150 yields RR that is comparable or slightly higher than the PA-250. Compared to PA, the hybrid system accommodates delivery of fresh slurry as it covers the whole wafer track and increases the fraction of fresh slurry delivered to the pad-wafer interface (i.e. polishing region where the removal mechanism occurs) by squeegeeing off the spent slurry and residual rinse water.
Table 5.1: Summary of UVEF images analysis.

<table>
<thead>
<tr>
<th>Region 1</th>
<th>Slurry Injection Scheme</th>
<th>Average UVEF Intensity (A.U.)</th>
<th>Standard Deviation (A.U.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PA-250</td>
<td>53.5</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>PA-150</td>
<td>48.8</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>SIS-150</td>
<td>27.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Hybrid-150</td>
<td>44.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region 2</th>
<th>Slurry Injection Scheme</th>
<th>Average UVEF Intensity (A.U.)</th>
<th>Standard Deviation (A.U.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PA-250</td>
<td>66.0</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>PA-150</td>
<td>57.1</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>SIS-150</td>
<td>41.8</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Hybrid-150</td>
<td>59.9</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Figure 5.7: Regions 1 and 2 for UVEF analysis on the polishing pad with the SIS (left) and without the SIS (right).

To further explain the above results, a UVEF technique is employed to qualitatively measure slurry availability on top of the pad surface. Table 5.1 summarizes the average UVEF intensity throughout the polishing time obtained by analyzing UV-enhanced fluid
film on the two regions depicted in Figure 5.7. Regions 1 and 2 are located on the inner and outer half of the wafer track, respectively. Both regions are located on the pad prior to the entering of the slurry in the pad-wafer interface. With the SIS installed, both regions are intentionally set between the SIS and wafer carrier head. For a fair comparison among PA, SIS and hybrid systems, the location for both Regions 1 and 2 is kept the same. It is important to note that UVEF intensity in this study does not measure an exact fluid film volume, but rather a relative slurry availability based on findings in a previous study (Jiao et al. 2012). The UVEF intensity increases with slurry availability and vice versa. In addition, such a technique is not intended to exactly quantify the composition of the fluid film (i.e. spent slurry, fresh slurry, and residual rinse water). As shown in Table 5.1, PA-250 results in the highest UVEF intensity measured in both Regions 1 and 2. This is intuitive because this particular slurry application method uses the highest flow rate and has no mechanism for squeegeeing off the spent slurry.

Compared to PA-250, PA-150 decreases the UVEF image intensity by approximately 9% and 14% in Regions 1 and 2, respectively. Such decreases are expected due to reductions in the injection of fresh slurry. It must be noted that a controlled pad rinsing procedure with UPW (that contains no fluorescence dye) is performed prior to every polish. As such, the amount of residual rinse water on the pad is the same prior to every polish on both the PA-250 and PA-150. At a reduced slurry flow rate (i.e. PA-150), the freshly injected slurry is diluted more with the residual rinse water. Furthermore, a lower slurry flow rate takes a longer time to replace the residual rinse water with the dyed slurry. Since the mechanisms of slurry injection and fluid removal are essentially the same between PA-250 and PA-150, such reduction in image intensity associated with PA-150
confirms a lower fraction of fresh slurry to overall fluid on the pad during polishing compared to PA-250. As a result, RR of PA-150 is lower than that of PA-250.

Figure 5.3 shows that the RR of the SIS-150 is marginally higher than PA-150. In the meantime, Table 5.1 shows that when changing the slurry application mechanism from PA-150 to SIS-150, the UVEF image intensity decreases significantly by approx. 45% and 27% in Regions 1 and 2, respectively. Compared to PA, SIS incorporates a mechanism that squeegees off the residual rinse water as well as the spent slurry that contains the dye. During polishing, while the spent slurry has a reduced polishing capability (in term of RR) compared to fresh slurry. But the dye component itself is not degraded in term of fluorescence intensity. By effectively squeegeeing off the spent slurry, SIS-150 is artificially showing less slurry availability compared to PA-150 as shown by its lower UVEF image intensity. In fact, SIS prevents the spent slurry from re-entering the pad-wafer region and, therefore, the UVEF image intensity associated with SIS in Regions 1 and 2 can be regarded as a much higher fraction of the fresh slurry (i.e. less dilution with spent slurry). Compared to PA-150, the significant drop of UVEF intensity with SIS-150 in Region 1 is attributed to the absence of slurry injection in the inner half of the wafer track. As a result, only spent slurry contributes to the UVEF intensity with the SIS-150 in Region 1. Region 2 of the SIS-150 has a significantly higher intensity than Region 1 since the fresh slurry is injected through the SIS that covers the outer half of the wafer track (i.e. Region 2). The UVEF technique shows that even though SIS-150 can effectively squeegee off the spent slurry and residual rinse water, the fresh slurry is mainly available only to the outer half of the wafer track.

Compared to SIS-150, the Hybrid-150 increases UVEF intensity of Regions 1 and
2 by approximately 40% and 30%, respectively. In Region 1, the sharp increase in intensity is attributed to the addition of slurry injection on the inner half of the wafer track. As a result, it increases the fraction of fresh slurry to the overall fluid and hence the slurry availability in the inner half of the wafer track. The increase of intensity in Region 2 also outlines the effect of full wafer track slurry coverage as illustrated in Figure 5.6. The rotation of the platen-wafer ejects the slurry from the inner half of the wafer track toward the outer half of the wafer track. Such a mechanism, combined with the fresh slurry injected through the injector, increases slurry availability in Region 2 and thereby causing higher UVEF intensity. Using the hybrid method, the combined mechanisms of the full slurry coverage and the squeegee effects (of spent slurry and residual rinse water) increase the fraction of fresh slurry while maintaining slurry availability on top of the polishing pad during polishing.

5.4 Conclusion

This work has shown that slurry availability and the extent of slurry mixing (i.e. among fresh slurry, spent slurry and residual rinse water) dramatically influence removal rates. The ultraviolet enhanced fluorescence (UVEF) technique showed that injecting fresh slurry solely on the center of wafer track reduces slurry availability in the pad wafer interface as it only covered the outer half of the wafer track. Removal rates were found to decrease with slurry availability accordingly. A higher degree of slurry mixing decreased the fraction of fresh slurry and, consequently, lowered the removal rate. In this study, a novel slurry injection system (SIS) was installed on top of the polishing pad that covered only the outer half of the wafer track. UVEF technique confirmed that most of the fluid
(i.e. slurry and residual rinse water) predominantly resided closer to the edge of the pad rather than near the center of the pad. Therefore, the SIS that covered only the outer half of the wafer track was still effective in blocking the spent slurry and the residual rinse water. Such mechanism facilitated the increase in the fraction of fresh slurry on the polishing pad during polishing. In contrast, standard pad center area slurry application did not have a similar mechanism to block the spent slurry and residual rinse water.

Results further indicated that slurry injection position and the novel SIS played important roles in slurry mixing characteristics and slurry availability on top of the pad. Injecting fresh slurry at a higher flow rate and at a location closer to the pad center area generally increased slurry availability. By using a hybrid system (i.e. a combination of slurry injection through the shorter SIS and a standard pad center area slurry application), the polishing process benefited from higher slurry availability and higher fraction of fresh slurry than the pad center area slurry application and the shorter SIS, individually. This was verified by the UVEF technique.
CHAPTER 6
EFFECT OF SLURRY INJECTION SYSTEM POSITION ON REMOVAL RATE FOR SHALLOW TRENCH ISOLATION CHEMICAL MECHANICAL PLANARIZATION USING A CERIUM DIOXIDE SLURRY

In this chapter, the effects of ultrapure (UPW) water dilution of a ceria-based slurry on silicon dioxide removal rates were investigated. Results indicated that removal rates increased with dilution up to a slurry to UPW ratio of 1:7.5 before reaching a plateau in the pre-mix dilution case. The concentration of Ce$^{3+}$ was thought to increase with dilution up to a ratio of 1:7.5, resulting in an increase in ceria-silica binding and therefore an increase in removal rates. Further dilution resulted in reduced friction and temperature which halted any further increases in removal rate as mechanical limitations offset the benefits of increasing Ce$^{3+}$ concentrations. Mixing the slurry and UPW at point-of-use resulted in a similar removal rate trend to pre-mixing, but with higher removal rates at each dilution ratio due to reduced particle agglomeration. A novel slurry injection system (SIS) was employed at various rotation angles as measured from the leading edge. Each SIS angle produced a different retaining ring bow wave thickness, which led to different extents of dilution and therefore different removal rates. The SIS at -8° produced the highest removal rates of all angles at an average value of 2,595 Å/min. A third dilution ratio test was performed using point-of-use mixing through the SIS at -8°, which resulted in a similar removal rate trend as the previous tests but with dramatically higher removal rates at each dilution ratio. The increased removal rates could potentially allow IC manufacturers to reduce process times or reduce slurry use, thus reducing the amount of slurry waste, leading to considerable improvements in EHS considerations.
6.1 Introduction

Chemical mechanical planarization (CMP) is an enabling technology in integrated circuit (IC) manufacturing that achieves local and global surface planarity through combined chemical and mechanical means. It should be noted that in certain CMP processes, slurry cost may represent up to 50% of the total cost of ownership (COO) of the CMP module (Holland et al. 2002; Philipossian and Mitchell 2003). In addition to concerns regarding COO, CMP slurries tend to contain hazardous chemicals, posing significant environmental, health, and safety (EHS) issues. Due to the severity of the cost and environmental problems, reducing slurry usage on a per wafer polished basis without negatively impacting process outcomes is of the utmost importance.

In the past, multiple studies have focused on increasing slurry utilization efficiency or reducing slurry use. Bibby et al. proposed a slurry reprocessing system that rejuvenated spent slurry to standard slurry conditions (Bibby et al. 1997). Sampurno et al. investigated the effects of changing the location of slurry application on slurry availability and slurry utilization efficiency (Sampurno et al. 2005). Wei et al. proposed a slotted retaining ring design that allowed more slurry to enter the pad-wafer interface (Wei et al. 2010). Chamberlin et al. proposed a slurry injection technique involving spraying pressurized slurry over the pad through multiple nozzles (Chamberlin et al. 1999). Mok proposed an apparatus for spraying slurry onto the pad surface rather than streaming it near the pad center (Mok 1999). Chiou et al. proposed a slurry injector having multiple adjustable nozzles (Chiou et al. 2002). Rosales-Yeomans et al. proposed a “smart” pad groove technology to facilitate better slurry transport to the pad land areas beneath the wafer (Rosales-Yeomans et al. 2008). Philipossian and Mitchell showed that slurry utilization
efficiency could be modeled, and then experimentally improved, by conducting residence
time distribution (RTD) analysis (Philipossian and Mitchell 2003). Further, mean residence
time (MRT) calculations using the proposed RTD models showed that decreasing the MRT
resulted in a more efficient use of slurry (Philipossian and Mitchell 2004). Finally, Meled
et al. and Mu et al. investigated a novel slurry injection system (SIS) which has the ability
to both reduce the slurry MRT and also redirect the ultrapure water (UPW) and spent slurry
away from the pad-wafer interface (Meled et al. 2011; Mu et al. 2016).

In the case of the Slurry Injection System (SIS), the removal of spent slurry and
ultra-pure water (UPW) from the pad surface plays a critical role in reducing slurry use.
This is because a majority of commercial slurries generally exhibit a reduction in removal
rate with an increase in dilution (Bielmann et al. 1999; Tamboli et al. 2004; Srinivasan et
al. 2015). However, certain class of slurries with ceria particles as their abrasive ingredient
have been reported to exhibit an increase in removal rate with increasing dilution
(Srinivasan et al. 2015). Further, as shallow trench isolation (STI) applications become
more prevalent, more semiconductor manufacturers are gravitating towards ceria slurries
owing to their high silicon oxide to silicon nitride selectivity (Srinivasan et al. 2015;
Abiade et al. 2006; Tuyen et al. 2000). Therefore, it is important to understand how to
increase the slurry utilization efficiency for ceria slurries in order to reduce COO in STI
applications.

This study investigated the effect of water dilution on a ceria-based slurry that has
been widely adopted by the industry, and the possibility of manipulating the position of an
Araca, Inc. model X62X Slurry Injection System (SIS) to effectively increase the dilution
ratio of the ceria slurry entering the pad-wafer interface. By design, the SIS injector body
acts to effectively reduce the re-entry of residual UPW and spent slurry into the pad-wafer interface by causing a barrier and hence the accumulation of fluid at the leading edge of the injector. In past applications, SIS was oriented such that the accumulated fluid was guided to the edge of the pad edge and final drainage. Here, since promoting dilution was desirable, the SIS was subjected to multiple rotation angles, many of which guided the accumulated fluid directly to the pad-wafer interface. This facilitated an increase in dilution and, therefore, a more effective use of the slurry. Silicon dioxide removal rates were measured to indicate slurry performance.

6.2 Experimental Procedure

All tests were performed on an Araca, Inc. APD-800X polisher. A full description of this apparatus can be found elsewhere (http://aracainc.com/wp-content/uploads/2015/10/APD800-brochure.pdf). A 3M A165 diamond disc was used to provide in-situ conditioning on an IC-1000 K-grooved pad (manufactured by Dow) at a conditioning down-force of 44.1 N. Each wafer was polished for 20 seconds at a pressure of 4 PSI and a platen/carrier rotation rate of 77/75 RPM. In each test, 300 mm silicon dioxide blanket wafers were polished using a high selectivity ceria slurry that has been widely adopted by the industry. Before polishing, the diamond disc was used to break-in the pad for 60 minutes with UPW. The disc rotated at 95 RPM and swept radially across half of the pad surface at a frequency of 10 times per minute. The diamond disc, pad, and wafer rotations were counter clockwise. Prior to each monitor wafer polish, two dummy wafers were polished at the proposed configurations to ensure that stable shear force values were obtained.
For the pre-mix dilution tests, the stock ceria slurry was diluted with UPW in volume-by-volume ratios of 1:2, 1:5, 1:7.5, 1:10, and 1:15. For each ratio tested, the stock slurry and UPW were both added to a single stirred slurry tank prior to polishing. The pre-mixed slurry was then dispensed on the pad via standard pad-center point application during polishing. Prior to testing each ratio, the pad was thoroughly rinsed with UPW for 30 seconds at a platen rotation rate of 150 RPM. After rinsing, the pad was dried using a compressed air hose by performing seven 10-second radial sweeps from the pad center to the pad edge while the platen rotated at a rate of 100 RPM. Immediately after drying, the pad surface was saturated with 67 ml of diluted slurry at the same dilution ratio to be investigated. During saturation, the platen was rotated at a rate of 50 RPM. After pad saturation, two dummy wafers and two monitor wafers were polished using the same slurry dilution ratio at a slurry flowrate of 100 ml/min. The entire pre-mix dilution test process was repeated for each dilution ratio.

The point-of-use (POU) tests were performed similar to the pre-mix dilution tests, yet rather than initially mixing the slurry and UPW in a single tank, two separate tanks containing slurry and UPW were fed to a T-valve that mixed both fluids directly at the pad-center dispense point. Slurry and UPW were fed to the T-valve using two separate Masterflex® peristaltic pumps which were calibrated to achieve the desired dilution ratios at a final combined flowrate of 100 ml/min. The dilution ratios of stock ceria slurry to UPW were achieved by mixing volume-by-volume ratios of 1:2, 1:5, 1:6, 1:7.5, 1:10, and 1:15 at the T-valve by modulating the flowrates of each pump. Similar to the dilution tests, the pad was rinsed and dried using the same procedure, yet for these tests the pad was saturated with 200 ml of the dilution ratio to be tested. In the case of the POU tests, pad saturation
was achieved by initially holding separate containers of slurry and water. During the first 3 seconds of the carrier head descending, UPW was poured into the handheld slurry container which was then shaken vigorously. The mixture was then quickly poured onto the pad surface and allowed to saturate the entire pad area in the final 3 seconds prior to carrier head touch-down.

The SIS (manufactured by Araca, Inc.) was comprised of an adjustable injector mount and an injector body. The injector body had a rectangular shape with mounting arms at each end. A single slurry inlet port was present at the top of the injector body, corresponding to an outlet on the bottom of the trailing edge. Fresh slurry entered the inlet port and exited through a precision machined trench on the injector’s bottom. This allowed dispersing of the slurry as a thin layer on top of the pad. Figure 6.1 highlights the features of the bottom of the Araca, Inc. model X62X SIS injector. The upper edge of the injector bottom pictured in Figure 6.1 corresponds to the leading edge of the SIS body. The solid protrusion was weighted by the injector body and provided adequate injector-pad contact. This allowed the SIS to collect excess UPW and spent slurry on its leading edge, and redirect the fluid to a desired destination. By manipulating the rotation angle of the injector body, the fluid accumulation at the leading edge could be guided to either the pad-wafer interface, or the edge of the pad.

Figure 6.1: Bottom design of the Araca, Inc. model X62X SIS.
For the SIS angle tests, the adjustable arms of the injector mount were manipulated such that the body of the SIS could be rotated on the pad surface to a final angle of 12°, 6°, 0°, -2°, -4°, -6°, -8°, and -9° off the leading edge. The angle of SIS is measured relative to a platen radial passing through the mid-point of the leading edge of the injector body. Rotating the SIS in a clockwise direction results in negative angles, while counterclockwise rotation results in positive angles. Figure 6.2 (top), (center) and (bottom) shows the orientation of the 0° reference point as well as the maximum and minimum rotation angles of 12° and -9°, respectively. The slurry was injected through the SIS at a flowrate of 100 ml/min. The slurry was diluted to one volume part stock slurry to two volume parts UPW as per the manufacturer’s specifications. It should be noted that in all cases, the platen and the wafer rotated counter-clockwise. Prior to every polish, the pad was thoroughly rinsed with UPW for 30 seconds at a platen rotation rate of 42 RPM. In order to mimic the actual high volume manufacturing process, there was no pad drying and pad saturation procedure during this SIS angle test.

A stationary camcorder was placed on a tri-pod next to the polisher such that it focused on the leading edge of the carrier head. During polishing, videos were recorded to gather visual data regarding bow wave formation and direction of flow of the fresh and residual slurry. Every angle test was recorded using this set-up.
Figure 6.2: Various SIS angle rotations based on the injector’s leading edge corresponding to: 0° (top), 12° (center) and -9° (bottom).
6.3 A Brief Discussion of Ceria-Silica Interactions

A simplified theory of the ceria-silica removal mechanism is presented in Section 3.2 of this thesis. Based on this simple theory, it is understandable that in certain slurry formulations where the concentration of Ce\(^{3+}\) has already reached a maximum, addition of UPW will only act to reduce removal rate (more on this in the next section). In contrast, formulations in which Ce\(^{4+}\) may be the dominant species, the addition of UPW will promote more Ce\(^{3+}\) species generation hence boost removal rate. Of course, as will be seen in Section 6.4, what starts to offset this effect is the fact that as UPW is added to the system, the concentration of the ceria nano-particles begins to drop which causes removal rates to level off and even reduce slightly as more and more water is introduced. It is partly this delicate balance that dictates whether a certain ceria-based slurry is a “direct slurry” whereby water addition causes rates to drop dramatically, or a “reverse slurry” which enhances removal rate to a certain extent, and then causes the rate to stabilize or even drop somewhat, as water is added to the system. As mentioned earlier, in this particular case, the slurry is a “reverse slurry”.

6.4 Results and Discussion

*Dilution Studies* – Figure 6.3 shows how material removal rates are affected by the extent of slurry dilution as represented by the amount of UPW added to the slurry in a separate mixing tank prior to its dispense near the center of the pad surface. Initially, silicon dioxide removal rates rise sharply with an increase in the dilution ratio. The rising trend continues up to a slurry to UPW ratio of about 1:7.5. Beyond that, diluting the slurry causes a plateau in the removal rate curve.
Figure 6.3: Silicon dioxide removal rate as a function of UPW addition to the slurry in a separate mixing tank prior to pad-center point dispense.

This trend can be theoretically explained as follows: It is known that the Ce$^{3+}$ ionic species is primarily responsible for the removal of silica as per the mechanisms of Hoshino and Cook which are widely accepted models for ceria-based CMP processes. In addition, the presence of excess water tends to reduce Ce$^{4+}$ to Ce$^{3+}$, thus increasing the efficiency of ceria binding to the silica surface. Through absorbance analysis, Wang et al. has shown that decreasing the concentration of abrasive particles (i.e. increasing the water-to-abrasive ratio) leads to a reduction and eventual loss of discernable Ce$^{4+}$ ions, yielding a presence of only Ce$^{3+}$ in a dilute solution (Wang et al. 2007). So, the initial rising trend in removal rate can be attributed to an ever-increasing concentration of Ce$^{3+}$ species with the addition of water up to a ratio of 1:7.5. Beyond this ratio, it is believed that mechanical (and some other chemical) effects come into play that partially offset the benefits of the chemical binding of the Ce$^{3+}$ species with silicon dioxide. These mechanical effects are due to a reduction in the frictional forces when excessive amounts of water are used. Reduced
friction acts to reduce removal rate in 2 ways: First, at a constant polishing pressure, it lowers the shear force thereby reducing the contribution of the “mechanical” component in CMP (Rosales-Yeomans et al. 2008; Kim et al. 2002; Borucki et al. 2007; Zhang et al. 2011). Second, reduced COF causes process temperature to drop (since less friction translates to less energy dissipation in the form of heat) and reduces the contribution of the “chemical” component in CMP (Kim et al. 2002; Kim et al. 2006; Li et al. 2004). This is because the chemical rate constant in ceria-based CMP processes is exponentially dependent on temperature (i.e. via the Arrhenius relationship) and has been shown by the University of Arizona CMP research team to have an appreciable apparent activation energy of about 0.45 eV (Zhuang et al. 2007). Figure 6.4 shows the trends in coefficient of friction (COF) and pad surface temperature for most slurry dilution conditions reported in Figure 6.3. It is clear that increasing the extent of water dilution reduces COF and the pad surface temperature which supports the explanation above.

Figure 6.4: Average COF (left) and average pad temperature near the trailing edge of the retaining ring (right) for various UPW dilution conditions of Figure 6.3.
Somewhat similar to Figure 6.3, Figure 6.5 shows how material removal rates are affected by the extent of slurry dilution as represented by the amount of UPW added to the slurry at the point-of-use; that is, via a separate UPW line which mixes with the slurry line directly at the dispense nozzle. In this case however, for every condition, removal rates are much higher than those reported in Figure 6.3. This is entirely due to the POU mixing of UPW with the slurry as the experimental procedure and all other parameters are identical to those of the pre-mixed dilution tests (Figure 6.3). During the pre-mixed dilution tests, the stock slurry was mixed with water to the desired dilution ratio and then stirred vigorously as specified by the manufacturer. It is believed that the sudden change in slurry composition when water was added shocked the system by disrupting the equilibrium of the solution. This has been shown in the literature as manifesting itself in the form of time-dependent changes in the zeta-potential thus causing some amount of particle agglomeration (Zhang et al. 2010; Rodea-Palomeras et al. 2010). Furthermore, the chemistry of highly selective slurries (such as this particular ceria slurry) is such that particles tend to agglomerate rapidly (Kim et al. 2002). Because of this, the abrasive particles in the pre-mix dilution tests were thought to be more agglomerated than the abrasives in the POU tests where water was mixed on-demand and at point-of-use and the slurry was not given enough time to agglomerate.

Having said this, the trends in Figure 6.5 are similar to those in Figure 6.3 such that initially, removal rates rise sharply with an increase in the dilution ratio. Again, the rising trend continues up to a slurry to UPW ratio of about 1:7.5. Yet again, beyond that, diluting the slurry causes a plateau in the removal rate curve.
Figure 6.5: Silicon dioxide removal rate as a function of UPW (through a separate feed line) mixed with slurry directly at the dispense point-of-use (POU).

The explanation of trends follows the same logic as in the previous case as evidenced by the real-time COF and pad surface temperature results shown in Figure 6.6 below.

Figure 6.6: Average COF (left) and average pad temperature near the trailing edge of the retaining ring (right) for various UPW dilution conditions and dispense method of Figure 6.5.
**SIS Angle Studies** – Figure 6.7 depicts changes in the silicon dioxide removal rate as a function of the position of the SIS as measured in degrees off of its leading edge. In all cases, the slurry was pre-mixed to a dilution ratio of 1:2 (as per the manufacturer’s recommendation) and was injected through the SIS outlet. Prior to every polish, the pad was thoroughly rinsed with UPW. There was no additional pad drying and pad saturation procedure during this SIS angle study. All other polishing parameters were kept constant throughout the runs. Results show that removal rate increases steadily from the initial average value of about 1,344 Å/min as the angle is reduced from its maximum value of 12 degrees. Removal rate reaches a maximum average value of 2,595 Å/min at -8 degrees and then drops to 2,397 Å/min as the angle is reduced to -9 degrees.

![Figure 6.7: SIS position as a function of removal rate at a slurry to UPW dilution ratio of 1:2.](image-url)
These trends can be explained by studying the videos of the pad surface (especially at the bow wave in front of the retaining ring) taken for the entire duration of each polishing run. For the sake of brevity, for each angle tested, as depicted in Figure 6.8, we have opted to show the frozen frame at exactly the 7th sec (after polishing has started). The reason for focusing on the 7th sec is due to the presence of flow instabilities and other transient effects during the first 5 secs of the polishing process. The still images of Figure 6.8 indicate that for both rotation angles of 12 and 6 degrees, the interaction of the residual fluid with the SIS is quite similar since the orientation of the SIS directs most of the fluid towards the edge. At 12°, the steady-state bow wave thickness at the retaining ring is at its smallest value, while at 6°, residual fluid creates a slightly thicker bow wave in front of the retaining ring. In contrast, at 0° and -2°, videos show that the residual fluid is directed towards the retaining ring which creates a thicker bow wave. It is interesting to note that the bow wave for these two angles is nearly identical in size which corresponds to the near identical removal rate associated with both of these positions. At even smaller angles, removal rates and associated bow wave thicknesses continue to increase. This increasing trend in the availability (both in terms of bow wave thickness and the amount of time spent on the pad surface) of the slurry that is rich in Ce³⁺ species is the likely explanation for the increase in average removal rate as the rotation angle is reduced. Within the range covered by rotation angles of -6°, -8°, and -9°, there exists both a removal rate maximum, as well as a bow wave that is at its thickest and one that persists the longest. This occurs at -8 degrees which explains the final drop in removal rate as the angle is reduced by just 1 degree to -9.
Figure 6.8: Still images of the retaining ring bow wave thickness 7 secs after platen rotation velocity ramp-up for SIS at various rotation angles.

As previously shown, the silicon dioxide removal rate increases with an initial increase in slurry dilution. In Figure 6.8, during the polishing process, fresh slurry is constantly injected onto the pad through the SIS. Meanwhile, the residual fluid (which has been around for a while and is no longer fresh) creates a bow wave on the leading edge of
the retaining ring the extent of which is governed entirely by the SIS angle. As fresh slurry and residual fluid come into contact with one another at the bow wave, the two fluids mix, creating a dilution effect. Thus, the longer the bow wave persists, and the larger it gets, the further the fresh slurry gets diluted thereby yielding a higher removal rate. This is exactly what is seen when the results of Figure 6.7 are interpreted using the still frames of Fig. 6.8.

Optimum POU Injection with SIS – Having identified an optimum SIS angle of -8 degrees for the process, Figure 6.9 depicts the silicon dioxide removal rate trend as a function of POU dilution using this optimal configuration. Trends once again resemble those shown in Figures 6.3 and 6.5 and are again justified by the companion real-time COF and average pad temperature results of Figure 6.10. The main difference in Figure 6.9 is the dramatic increase in the removal rate at all dilution ratios when the SIS is used. Prior to testing each ratio, the pad was thoroughly rinsed with UPW followed by pad drying and pad saturation as described in Section 6.2. Figure 6.11 summarizes this dramatic rate advantage graphically. The bars are all average removal rates that are normalized to the average removal rate (now set at 100%) associated with the 1:2 dilution ratio in Figure 6.3. When it comes to SIS, at the manufacturer-recommended dilution ratio of 1:2, there is nearly a 3X advantage in removal rate as compared to the pre-mix point application (PA) case. Upon further dilution of the slurry, this advantage is somewhat reduced but still remains quite impressive at around 1.5X to 2X. This suggests that, in principle, IC makers can drop reduce slurry usage by 1.5X to 3X simply because the higher removal rate will allow them to cut their polishing times proportionately. What’s more, in cases where wafer throughput of a polisher is removal rate limited (i.e. as opposed to being limited to wafer handling, rinsing or post-CMP cleaning) a 1.5X to 3X drop in polish time can significantly
boost wafer throughput and CMP module efficiency while reducing the COO associated with consumables and also avoid certain future capital expenditures as more wafers may be processed without adding more polishers. Lastly, since many slurries (including the ceria-based ones) tend to contain hazardous chemicals, reducing their usage will significantly reduce environmental, health, and safety (EHS) issues.

Figure 6.9: Silicon dioxide removal rate vs POU dilution using a SIS positioned at a \(-8^\circ\) angle.

Figure 6.10: Average COF (left) and average pad temperature near the trailing edge of the retaining ring (right) for various UPW dilution conditions and dispense method of Figure 6.9.
Figure 6.11: Average normalized removal rates. The pre-mix 1:2 dilution removal rate of Figure 6.3 has been set to 100% and all results from Figures 6.3, 6.5, and 6.9 are compared.

Figure 6.12: Average COF vs average temperature for all dispense methods and the UPW dilution ratios of 1:5, 1:7.5, 1:10, and 1:15.

The relationship between average temperature and average COF for UPW dilution ratios of 1:5, 1:7.5, 1:10, and 1:15 for all dispense methods is shown in Figure 6.12. As
evidenced, SIS yields a lower pad surface temperature as compared to the Pre-Mix and POU dispense methods. During polishing, a slurry bow wave is created on both the leading edge of the SIS and the leading edge of the retaining ring. Because the slurry starts off at ambient temperature, which is substantially lower than the pad surface temperature, and probably takes minutes to reach steady state, a temperature gradient exists between the pad surface and the slurry bow wave. So for reasonably short polish time (i.e. in the order of a minute or so), this leads to convective cooling of the pad, thus lowering the observed pad surface temperature as compared to the other dispense methods. Despite the lower temperature, which will surely act to lower the chemical rate constant in the removal process, SIS still yields much higher removal rates than both the Pre-Mix and POU dispense methods, which is a testament to its superior performance.

6.5 Conclusion

In this investigation, the effect of UPW dilution on a “reverse” ceria-based slurry was studied. The initial dilution study consisted of pre-mixing the slurry and UPW in a single tank prior to polishing at various dilution ratios. Silicon dioxide removal rates were found to increase with dilution up to a slurry to UPW ratio of 1:7.5, owing to the increasing concentration of Ce$^{3+}$. Beyond this ratio, the removal rate curve plateaued due to excess water reducing the COF and temperature, resulting in the benefits of increased Ce$^{3+}$ concentrations being offset by mechanical limitations. The second dilution study consisted of using two separate tanks containing slurry and UPW which were mixed directly at the dispense POU. Silicon dioxide removal rates were found to follow the same trend as the
pre-mix study, but at higher values for each dilution ratio. This effect is attributed to the change in particle agglomeration between the two studies.

A novel SIS was employed at various rotation angles measured in degrees from the leading edge to investigate the dilution effects of redirecting UPW residing on the pad surface to the pad-wafer interface. The rotation angles were found to correlate with various bow wave thicknesses on the leading edge of the retaining ring. The bow waves served as a dilution source interacting with the injected slurry. An angle of -8° was found to produce the thickest and longest lasting bow wave, yielding the highest removal rates for all angles at an average of 2,595 Å/min. The final study investigated removal rates as a function of UPW dilution using POU mixing through the SIS at -8°. This study again resulted in the same removal rate trend as the prior studies, however, the removal rate at each dilution ratio increased dramatically.

Using the SIS at -8° with this ceria-based slurry has been shown to increase removal rates by 1.5- to 3-fold over pre-mix dilution at each dilution ratio. This removal rate increase could potentially allow IC manufacturers to reduce slurry usage for an STI process, thus reducing the need for handling excess slurry waste. This would reduce the discharge of harmful oxidizers, acids, abrasive particles etc. to the environment, leading to a more environmentally benign semiconductor manufacturing process.
7.1 Conclusions

A number of studies were conducted in order to understand slurry dispense methods as well as the tribological and thermal characteristics of CMP processes. This work further investigated improvements in these topics, such as attaining better slurry utilization efficiency and improving the characterization of tribological and thermal transients during CMP. The investigations are listed separately below along with the primary conclusions reached.

- *Improvements in Striebeck curves for copper and tungsten chemical mechanical planarization on soft pads*

Tribological characteristics and pad temperatures of 300-mm copper and tungsten blanket wafers on a Politex soft pad were studied using a process incorporating a multitude of gradual yet continuous changes in polishing pressure and sliding velocity. Striebeck+ curves were created and analyzed for each process. A few of these curves were also compared to Striebeck+ curves on hard pads previously reported in literature. All copper and tungsten polishes were found to stay in the “boundary lubrication” regime when polishing on the soft pad. Polishing at a lower $v/P$ condition showed a more stable process as indicated by its smaller size data.
cluster. Further, the copper wafers were found to yield a more stable process on soft pads than hard pads. Pad temperature study also showed that all tungsten and copper wafers were found to fall on a universal, linear temperature curve, irrespective of substrate or slurry. A similar linear relationship was found on the two hard pads.

- Slurry injection schemes on the extent of slurry mixing and availability during chemical mechanical planarization

Three methods of slurry dispense (i.e. standard pad-center point application, a SIS that only covers the outer half of the wafer track, and a hybrid combination of both) were tested to characterize silicon dioxide removal rates versus slurry flow rates. Relative slurry film thicknesses were measured using an ultraviolet enhanced fluorescence technique. Pad-center point application yielded a low degree of slurry availability at the pad-wafer interface. The SIS was found to adequately block residual water on the pad surface from entering the pad-wafer interface, thus lowering slurry mixing (i.e. with spent slurry and residual rinse water) and increasing removal rate. However, the injection position on SIS (i.e. located in the center of the wafer track) reduced fresh slurry availability in the pad-wafer interface, therefore reducing removal rates. The hybrid system (i.e. a combination of slurry injection through the shorter SIS and a standard pad center area slurry application) was found to both reduce the amount of slurry mixing, as well as increase the fresh slurry availability at the pad-wafer interface. Results indicated
that the hybrid system yielded similar removal rates to pad-center point application, yet at a 40% reduction in slurry usage.

- *Effect of slurry injection system position on removal rate for shallow trench isolation chemical mechanical planarization using a cerium dioxide slurry*

The effect of UPW dilution on a “reverse” ceria-based slurry was studied. The initial dilution study consisted of pre-mixing the slurry and UPW in a single tank prior to polishing at various dilution ratios. Silicon dioxide removal rates were found to increase with dilution up to a slurry to UPW ratio of 1:7.5, owing to the increasing concentration of Ce$^{3+}$. Beyond this ratio, the removal rate curve plateaued due to excess water reducing the COF and temperature, resulting in the benefits of increased Ce$^{3+}$ concentrations being offset by mechanical limitations. The second dilution study consisted of using two separate tanks containing slurry and UPW which were mixed directly at the dispense POU. Silicon dioxide removal rates were found to follow the same trend as the pre-mix study, but at higher values for each dilution ratio. This effect is attributed to the change in particle agglomeration between the two studies. A SIS was then employed at various rotation angles measured in degrees from the leading edge to investigate the dilution effects of redirecting UPW residing on the pad surface to the pad-wafer interface. The rotation angles were found to correlate with various bow wave thicknesses on the leading edge of the retaining ring. The bow waves served as a dilution source interacting with the injected slurry. An angle of -8° was found to
produce the thickest and longest lasting bow wave, yielding the highest removal
dates for all angles.

7.2 Future Plans

Given the nature and interrelations amongst various critical aspects of CMP, it is
essential to define and characterize problems found within the process and continue to
increase the collective knowledge of the planarization process. Three future studies based
on the work done in this thesis are proposed as follows:

- **Tribological and thermal characterization of CMP consumables**

Chapter 4 of this thesis investigated the Striebeck+ curve and thermal effects of 300-
mm copper and tungsten blanket wafers on a Politex soft pad using an improved
Striebeck method. The results were compared to similar improved Striebeck+
methods using hard pads. Overall, more stable processes were attained by using the
soft pads. Further, using real-time data collected during polishing, a linear
correlation between pad surface temperature and the product of the sliding velocity,
applied wafer pressure, and COF was shown. For an immediate impact, the CMP
community will greatly benefit by investigating Striebeck+ curves for additional sets
of consumable combinations (e.g. pad materials, groove designs, nano-particles,
and slurry additives) and studying the differences in the tribological characteristics
among them. Further, characterizing the pad surface temperature during polishing
using robust analytical methods and mathematical modeling would aid in defining the root cause of temperature data scattering seen in Chapter 4 of this thesis. It must be noted that the current state-of-the-art of direct force measurement methods are expensive to implement in new polishers and even more expensive (or sometimes impossible) to retrofit onto older polishers. Therefore, in the longer term, it would be great to develop a new method or system that can function similar to the force measurement as described in Chapter 4. Such possible systems may include a wireless vibration sensor and a high-speed camera system to acquire any information related to the vibration during polishing.

- **Investigation of slurry bow wave on the leading edge of the wafer carrier using a high-speed camera system**

Chapter 5 of this thesis investigates the silicon dioxide removal rates associated with the slurry injection methods of pad-center point application, a SIS that only covers half of the wafer track, and a hybrid combination of both. An ultraviolet enhanced fluorescence technique is employed to qualitatively measure a relative slurry film thicknesses to investigate the slurry availability and extent of slurry mixing found for each method. Using a high-speed camera system (and associated image amplification software) to quantify the width and the fluctuation of slurry bow wave would provide a better fundamental understanding of the slurry availability attributes during polishing using any slurry dispense methods and flow
rates. This high-speed camera system could enable further improvements in slurry availability and slurry utilization efficiency.

- **Wafer defect analysis using diluted ceria-based slurries in shallow trench isolation CMP applications**

Chapter 6 of this thesis investigated the dilution effects of a widely-adopted ceria-based polishing slurry on silicon dioxide removal rates. Results indicated that the methods of mixing and dilution ratios affected removal rates, COF and pad temperature transients. Further, a slurry diluted with 7.5 parts of UPW using a SIS that was rotated to -8° as measured from the leading edge showed the greatest improvement in removal rate over the manufacturer’s specification of a pre-mix 1:2 dilution ratio. This suggests that, in principle, IC makers can drop slurry usage by 3X simply because the higher removal rate will allow them to cut their polishing times proportionately. In a high-volume IC manufacturing environment, such improvement has to be accompanied with comparable or better wafer level defects. To fully realize the possibility of applying a higher dilution ceria-based slurry in a manufacturing setting, systematic studies must be performed with the focus on wafer-level defects on oxide and nitride layers for each dilution ratio and mixing method described in Chapter 6 of this thesis.
REFERENCES


47. Mudhivarthi, S., PhD Dissertation, University of South Florida, Tampa, FL (2007).


