Measurements of Slurry Film Thickness and Wafer Drag During Chemical Mechanical Planarization

1Chan, E., 1Rogers, C., 1Manno, V.

1Tufts University Medford, MA
2University of Arizona, Tucson, AZ
3Cabot Microelectronics, Aurora, IL
4Intel Corporation, Santa Clara, CA

1 Abstract

Chemical mechanical planarization (CMP) is a polishing process used in the semiconductor industry for the manufacture of silicon integrated circuits. In this research, temperature and friction force at the pad-slurry-wafer interface are examined during real time polishing with in situ pad conditioning. Most experiments are performed on a 1:2 scale laboratory tabletop rotary polisher with variable pad speed and wafer down force control. An experiment was also run on a commercial polisher, the SpeedFam-IPEC 472. Dual emission laser induced fluorescence (DELIF) techniques are used to optically measure the temperature directly beneath the wafer during polishing through a two camera imaging system. An infrared camera and a thermocouple are alternately used to measure bow wave temperatures. For most tests, a low abrasive concentration slurry was used to minimize polishing of the glass wafers during the course of an experiment. All tests in this study were done using ungrooved dyed Freudenberg FX-9 polishing pads.

2 Introduction

The experimental work in this thesis employs a scaled down rotary polisher system based upon the industrial SpeedFam-IPEC 472 polisher. Ordinarily, the 472 planarizes 150 mm (6 inch) wafers on 600 mm (24 inch) polishing pads. Typical
industrial process parameters include applied wafer pressures of 27.6 kPa (4 psi), relative wafer-polishing pad linear velocities of 0.5 m/s (30 rpm pad velocity), and slurry flow rates of 200 ml/min. Our 1:2 scale experimental system, closely constructed and modified to approximate full scale rotary polishers such as the SpeedFam-IPEC 472, maintains industry performance specifications and characteristics closely. Then, to further understand CMP, advanced measurement techniques are applied to investigate planarization parameters. The experimental system planarizes in full automation with user supplied input parameters.

3 Laboratory Scale Polisher System

Replicating industrial lubrication and planarization characteristics demands accurate system parameter scaling. Physical size reductions conforms to equation 1 such that the ratio of the polishing pad area, $A_p$, to the wafer area, $A_w$, is held constant. Consequently, the polishing pad diameter scales down from 600 mm (24 inch) to 300 mm (12 inch) with a corresponding wafer diameter reduction from 150 mm (6 inch) to 75 mm (3 inch).

$$\frac{A_p}{A_w} = \text{Constant} \quad (1)$$

Applied wafer pressure and wafer-polishing pad relative linear velocities velocities, the two most important parameters to material removal according to Preston’s equation, are also scaled to mimic the industrial environment. Applied wafer pressure, a function of wafer area, is simply scaled on a 1:1 basis; it is a function of the wafer area. Relative velocities of industrial scale rotary polishers are maintained according to equation 2. Therefore as rotational velocities of the wafer, $\Omega_w$, and pad, $\Omega_p$, match, a constant relative linear velocity across the wafer is achieved. At 60 rpm wafer and polishing pad speeds, the corresponding relative linear velocity across the wafer is 0.47 m/s, which is close to the 0.50 m/s SpeedFam-IPEC 472 operating condition. Consequently, similar planarization rates and operating temperatures are reached.

$$\frac{\Omega_p \cdot r_p}{\Omega_w \cdot r_w} = \text{Constant} \quad (2)$$
Equation 3 dictates the introduction of the slurry into the system. The relationship between the relative linear velocity, \( r_{wp} \Omega_p \) and the ratio of slurry flow rate, \( Q \) to polishing pad area \( (A_p) \) is held constant.

\[
\frac{Q}{A_p \cdot r_{wp} \Omega_p} = Constant
\]  

(3)

The \( r_{wp} \) variable in equation 3 is the radial location of the wafer center in respect to the polishing pad center. Although initially calculated to 25 ml/min, insufficient fluid lubrication led to typical experimental flow rates of 50 ml/min.

### 3.1 Table Top Polisher

A Struers RotoPol-31 table top polisher unit serves as a surrogate to an industrial rotary polisher such as the SpeedFam-IPEC 472. Although limited to only 150 rpm and 300 rpm velocities by the manufacturer, the integration of a Mitsubishi Frequl frequency modulator controller into the drive unit extended the working range, 20 rpm to 300 rpm \( \pm 1 \) rpm. With no used slurry processing or recycling, waste is channeled into containers for proper disposal.

For experimental measurements, an array of control and measurement systems are integrated into table top polisher. Independently controlled parameters include wafer applied pressure, wafer rotational velocity, slurry flow rate, and conditioner oscillation and rotational speeds. Meanwhile, advanced measurement technique systems characterize friction, pressure, fluid film thickness, and temperature at the wafer-slurry-polishing pad interface. Figure 1 is a schematic of the integrated system.

[Figure 1 about here.]

### 3.2 Polisher Head

A Sears 20 inch drill press replaces the standard wafer carrier head mechanism of the RotoPol-35. Modified with a Dayton \( \frac{1}{2} \) HP motor, drill press rotational velocities ranged continuously from 0 rpm to 160 rpm. Manual velocity adjustments are conducted directly by adjusting the Dayton motor’s amplifier. Absolute rotational velocity calibrations are calibrated and verified with a tachometer.

To achieve variable applied wafer pressures, a weighted traverse is also integrated into the already modified polisher
head. Located atop the drill press, the subsystem consists of a lead screw driven carriage riding on two linear rails. A standard gymnasium 25 lb plate mounts on top of the carriage while a Servo Systems precision stepper motor drives it back and forth. On one end, the traverse rests on the rotating quill directly attached to the wafer while the other end is free to pivot about the main drill press support column. Thus, the load is applied directly to the wafer with minimalized generation of external moments.

To relate carriage position, which is controlled by the LabVIEW interface, to discrete wafer applied pressures, the system is calibrated using a force transducer.

### 3.3 Wafer

The inclusion of the DELIF optical measurement technique in experiments necessitated usage of transparent BK-7 glass wafers as a surrogate for traditional opaque silicon wafers. BK-7 glass was chosen due to its widespread availability and structural similarities to silicon. These wafers have a diameter of 75 mm (3 inch) and thickness of 12.5 mm (1/2 inch). A gimbal joint mounts the wafer directly to the drill press drive shaft. The wafers, being relatively inexpensive, are considered as disposable. Like real silicon wafers, the BK-7 wafers surfaces are imperfect, so they are classified by their degree of convexity or concavity. Shown in figure 2(a), convex wafers possess a shape that conforms to the pad surface while concave wafers possess a non-conforming shape as shown in figure 2(b). A stylus profilometer is utilized to generate precise line scans of the wafer curvature. Two perpendicular line scans across the wafer diameter are typically conducted to characterize a wafer.

[Figure 2 about here.]

### 3.4 Polishing Pads and Conditioning

This research exclusively features Freudenberg’s flat FX-9 polishing pads. Composed of a closed cell polyurethane pore structure, the FX-9 is similar to the industry standard Rodel IC-1000. In particular, the FX-9 polishing pads are featured here due the manufacturer’s ability to dye them to enable our fluorescence measurements techniques. To date, no measurable differences due to the dyeing have been found.
During CMP, not only do polishing pad asperities compress, but slurry debris fills and clogs pores. The result is a "glazed" surface, which adversely affects planarization performance. To counteract glazing, the polishing pad surface is conditioned by a 163 grit diamond disc to abrade and remove slurry particles while simultaneously reopening pores. Mounted on a rotating gimbal type PPS (polyphenylene sulfide) carrier, the diamond disk rotates as it is swept radially across the polishing pad surface (system shown in 3). Sweep and rotational rates are controlled through the LabVIEW interface. Conditioning may be either conducted ex situ, between wafer polishes, or in situ, during wafer planarization. In this work, all conditioning is done in situ to prevent glazing.

Despite the benefits, several drawbacks exist. The oscillation due to the sweeping motion of the in situ polishing pad conditioning arm periodically starves and overloads the wafer with slurry. These periodic fluctuations in the fluid lubrication can affect planarization. Extensive investigations of condition effects were studied by Coppeta [1]. Premature wear and damage to the polishing pad may occur due to excessive conditioning [2].

In order to keep track of the conditioner oscillation and location, a linear potentiometer is utilized to follow the radially moving diamond disk. The potentiometer linear voltage response is calibrated to the distance from diamond disk center to polishing pad center. Measured distances possess an accuracy of within 0.125 inches.

3.5 Slurry Delivery

Cabot Microelectronic’s Cab-O-Sperse SC-1 in a 3.1 wt% slurry is the abrasive lubricant utilized in this work. Comparatively diluted by industry standards, a lower abrasive percentage was required to minimalize polishing of the BK-7 wafers. This is significant in maintaining consistent wafer shapes for each data set. Properties of the 3.1 wt% solution include a viscosity of 1.13 cp¹ and a shear rate of 8239 $\frac{1}{\text{sec}}$. Compositionally, the slurry consists of 100 $\text{nm}$ fumed silica particles suspended in potassium hydroxide (KOH).

The slurry is delivered to the CMP system by a Masterflex peristaltic pump (figure ??). Its non-intrusive nature is critical, for typical intrusive methods are susceptible to contamination, corrosion, and clogging. With 14 gauge

---

¹The viscosity values are measured at a constant temperature of 24°C courtesy of Dan Airey at Cambridge Applied Systems.
norprene Tygon tubing, the delivery is capable of flow rates of up to 250 mL/min. The tubing, along with all other slurry solution vessels and containers are opaque to block light from affecting the optical technique’s dyes. Although the actual flow rate is manually dialed in, an optical encoder on the pump enables real time flow rate display in the LabVIEW interface. Manually calibrated, flow rates are precise to within ±0.5 ml/min.

Though fluorescent dyes are added to the slurry solution for the DELIF fluid film thickness and temperature measurements, concentrations are always at most one gram per liter. Consequently, no real performance alteration is expected to result.

4 Measurement Techniques

The physical dimensions of chemical mechanical planarization, on the order of tens of micrometers, do not allow typical off the shelf intrusive measurement techniques. In addition, the complex nature of the planarization process at the wafer-slurry-polishing pad interface only further intensifies the challenge to accurately conduct in situ parameter measurements. As a result novel approaches to in situ friction, pressure, fluid film thickness, and temperature measurements have been developed.

Although the purpose of this current research is in the further development and application of dual laser induced fluorescence, each of the measurement techniques will be reviewed briefly in the following sections.

4.1 Friction

The frictional force at the wafer-slurry-polishing pad interface is measured to investigate the mechanical abrasion at work during CMP. The system utilizes a slider force table sandwiched between the table top polisher and a 136 kg solid steel isolation table to measure friction force. Comprised of two plates mounted on linear rails, movement is constrained to the tangential direction with respect to the polishing pad. The forces, due to movement, are measured by a force transducer mounted between and affixed to both plates. The forces are due to the wafer-slurry-polishing pad interface since that is the origin of motion and only point of contact between the table top polisher and the bolted down drill press.
Friction force measurements $C_f$ are typically the mean of one thousand points sampled at 100 Hz during steady state planarization conditions. In this research, results are represented as the raw friction force per unit wafer area (kPa), but other researchers often represent friction data normalized by the applied wafer pressure to obtain the dimensionless coefficient of friction $C_f$.

$$C_f = \frac{F_f}{F_{df}}, \quad (4)$$

In equation 4, $C_f$ is the coefficient of friction, $F_f$ is the force of friction, and $F_{df}$ is the applied wafer pressure at wafer center. To compare $C_f$ data to the raw friction force per unit wafer area reported here, multiply the $C_f$ value by the corresponding applied wafer pressure ($F_{df}$). It is important to note that due to time averaging, friction measurements include fluctuations due to the effects conditioner oscillation, system non-uniformities, and other background noise. More discussion concerning those effects were studied by Lu [3].

4.1.1 Calibration and Measurement Uncertainty

The slider force table’s force transducer outputs a voltage which corresponds to a physical force. To calibrate the voltage, the top plate of the slider force table is pulled in the tangential direction by an array of hanging weights; figure 4 depicts the calibration process. With a set of voltages and corresponding forces, a best fit line such as the one shown in figure ?? is interpolated. Typically, the linear fit has a correlation coefficient of $R^2=0.9991$.

[Figure 4 about here.]

However, cross experimental measurements are influenced by the shifting of the force transducer’s baseline voltage when powered on or off. The offset by itself is minimal, for day to day and run to run variations of the offset amount to typically less than 0.2 kg (0.5 lbs), which translates into a coefficient of friction variation of less than 0.009 at a 13.8 kPa (2 psi) applied pressure and less than 0.003 at a 41.4 kPa (6 psi) applied pressure. However, to minimize measurement variations, the current offset voltage is read prior to every experiment and then subtracted from every subsequent data point.
Due to variations such as the offset, frictional measurement uncertainties are concluded to be slightly greater than that of calibration uncertainty. Exact repeatability as been shown to differ with changes in experimental conditions and parameters too [3].

4.2 Dual Laser Induced Fluorescence Techniques

Dual emission laser induced fluorescence, or DELIF, is a relatively non-intrusive optical technique for scalar measurement. Fundamentally, fluorescence is the emission of electromagnetic radiation by a substance whose molecules are excited into higher energy states through the absorption of incident radiation. In our case, light in the visible spectrum is emitted by the molecules of dyes stimulated by ultraviolet light. The fluorescence intensity emitted by a dye is the function of excitation intensity and amount of absorbed light [4]. Quantitatively, it may be calculated by the equation

\[ I_f = \Phi \cdot I_e \cdot Abs, \]  

(5)

where \( I_f \) is the measured fluorescence intensity, \( \Phi \) is the quantum efficiency of the dye in solution, \( I_e \) is the intensity of the excitation energy source, and \( Abs \) is the amount of light absorbed by the dye. In one dimension, the fluorescence intensity of a volume of dyed solution excited by a single beam of light may be represented by

\[ I_f(b) = I_e \cdot A_f \cdot \Phi \cdot \epsilon(\lambda) \cdot C \cdot dl, \]  

(6)

where \( b \) is the distance traveled by the laser beam through the dye solution, \( I_f \) is the measured fluorescence intensity at the distance \( b \) through the solution, \( I_e \) is the intensity of the excitation energy source at the same distance \( b \) through the solution, \( A_f \) is the fraction of the fluoresced light collected, \( \epsilon \) is the molar absorptivity as a function of wavelength \( \lambda \) or pH in the case of pH dependent dyes, \( C \) is the molar concentration of the dye, and \( dl \) is the length of the sampling volume along the path of excitation.

Although equation 6 physically quantifies dye fluorescence, ancillary dye fluorophor behavior such as photoquenching or photodegradation is not considered. Photoquenching occurs when dye fluorescence responds nonlinearly to linear changes of excitation energy. Photodegradation is decomposition of dye fluorophor by the excitation
energy; often times, this follows prolonged exposure. Affecting most dyes in varying degrees, $I_f(b)$ can be typically characterized by a time dependency due to decomposition.

In addition to photoquenching and photodegradation, many other factors influence and complicate dye fluorescence. Chemical changes such as pH, temperature, or excitation energy variations directly impact dye fluorescence spectra behavior. A non-uniform flow field in the $b$ location renders temperature or pH sensitive dye fluorescence intensity calculations incredibly difficult. Thus, parameters along the path of the laser light $dl$ assumed constant in equation 5 would no longer be so. Sever complications also arise with excitation energy fluctuations, physical light reflections, and environmental noise such as ambient light. These types of errors and others are comprehensively discussed by Coppeta and Rogers [5].

Due to the multitude of influences on dye fluorescence, single dye techniques for absolute measurements tend to be error prone. While it is possible to develop highly complex calibrations to limit some of the factors, usage of dual laser induced fluorescence, DELIF, is a much simpler alternative. In DELIF, two dyes are utilized in solution, and normalization of one to the other eliminates many of the issues that would otherwise require calibration. Typically, fluorescence intensities of a passive scalar dependent dye is normalized by a non passive scalar dependent dye. With respect to CMP, passive scalars include fluid film thickness and temperature. Equation 6 becomes,

$$Fluorescence \text{ Ratio} = \frac{I_{1f}}{I_{2f}} = \frac{\epsilon_1(\lambda) \cdot C_1 \cdot \Phi_1}{\epsilon_2(\lambda) \cdot C_2 \cdot \Phi_2}.$$  

(7)

As a result of normalization, the effect of excitation energy source variations, light reflections, and other non-uniformities along the path of light $dl$ on fluorescence measurements are minimized. Figure 5 depicts the four principle steps in the DELIF measurement technique.

Despite normalization, spectral conflict errors often times arise with systems of multiple dyes [1]. Type I conflicts arise when dye "A" and dye "B"’s emission spectra overlap, so discerning individual fluorescence intensities is impossible. Type II conflicts, taken advantage of by fluid film thickness measurements, arise when the fluorescence spectra of dye "A" overlaps with absorption spectra of dye "B" while the absorption spectra of dye "B" remains unaffected by
changes in the passive scalar being measured. As a result, dye "B” absorbs the emission of dye "A” with a dependent being the path length traveled by the emission of dye "A” through dye "B.” The longer the distance, the greater the opportunity for absorption by dye "B.” Due to this attenuation of dye A and none so for dye B, their ratio is path length dependent. Finally, type III conflicts are the same as type II except that a second variable arises, for the absorption spectra of dye "B” also varies with passive scalar.

4.2.1 Fluid Film Thickness

As discussed in the previous chapter, the system approaches boundary lubrication as the fluid film layer between wafer and polishing pad thins, while hydrodynamic lubrication is approached as it thickens. Through the path length dependency of Type II spectral conflicts, DELIF is utilized to characterize the fluid film thickness. A general overview is presented here, but a complete description of this measurement technique, comprehensive application, and limitations are described by Coppeta [1], Coppeta and Rogers [5], and Lu [?].

In order to achieve type II spectral conflict path length dependency, which is analogous to the fluid film thickness, two principle requirements needed to be met.

- Fluorescence of dye A (emitter) overlaps with absorption of Dye B (absorber)
- Dye B absorption spectra unaffected by changes in passive scalar

Complying with the requirements, Calcien (Fluorexon) played the role of the absorber of Coumarin 4 (4 Methyl-Umbelliferone) emission. There is a direct overlap of the absorption spectra of Coumarin 4 with the emission spectra of Calcien. Concentrations of 1.0 g/l and 0.25 g/l of Calcien and Coumarin 4, respectively, are utilized. The strongest and peak emission of Coumarin 4 occurs at 450 nm in 25°C. When excited by light at 350 nm, the peak absorption spectra of Calcien occurs at 490 nm at 25°C. Calcien strongest and peak emission is at 500 nm. To separate and examine Coumarin 4’s behavior as it is attenuated by Calcien absorption, the fluorescence is filtered to the 455 nm to 500 nm bandwidth. To discern between the dye fluorescences, Calcien fluorescence output is filtered to the 550 nm to 600 nm bandwidth. Although divergent from Calcien’s peak emission, this is required to minimize capture of Coumarin’s slightly overlapping fluorescence tail.
With this setup, film thickness increases at the wafer-slurry-polishing pad interface lead to increases of emission in both dyes. Because of absorption, the net Coumarin fluorescence, $I_{2f}$, will decrease while Calcien fluorescence, $I_{1f}$, increases before capturing by the cameras. Thus, in accordance with the film thickness increases, the measured fluorescence ratio, as described by equation 7, increases. An absolute film thickness measurement accurate to within 5 $\mu$m with a relative accuracy of about 1 $\mu$m is then attained by calibration.

The fluorescence of Calcien and Coumarin 4 is individually captured by two independently filtered digital cameras. A custom optics system is used to ensure that the cameras image the same exact spatial fluorescence. For acquisition, the fluorescence path follows seven basic steps.

1. Emission through BK-7 wafer by the Calcien and Coumarin 4 dye solution
2. Optical magnification by a 135 mm lens
3. Low frequency noise reduction by a 650 nm short pass filter
4. Split identically by a 50 mm 50/50 cubic beam splitter
5. Filtering (Calcien: 550 nm to 600 nm, Coumarin 455-500 nm)
6. Travel through aperture
7. Individual capture by two 12-bit high resolution CCD cameras

The exterior of the optical system is shown in figure ??, and internal components such as the beam splitter and filters are shown in figure 6(b).

[Figure 6 about here.]

In post-processing after capture, each image must also be aligned both orthogonally and rotationally to ensure ratioing of the same exact fluorescence area. Prior to the experiment, orthogonal alignment is achieved through software manipulation of a region of interest (ROI) in a particular image. After the ROI is selected, both identical images, (figures 7(a) and 7(b)), are cropped and shifted horizontally and vertically until the are perfectly on top of each other. An aligned image of low font size text is shown in figure 7(c). On the other hand, rotational alignment is achieved through manual adjustment of the rotation stage.

[Figure 7 about here.]
Sensitivity wise, the pair of 768 x 512 pixel CCD Photometrics Sensys cameras are capable of a linear response to light intensities down to less than 0.1% of their entire 12-bit dynamic range. Lengthy exposure times of typically 3000 ms per fluorescence image were necessitated due to the relatively low excitation energy of the ultraviolet lamps. To even further strengthen the signal, “binning” or combining adjacent pixels to increase overall image imaging intensities may be also needed despite a compromise in resolution.

Due to the long exposure time, each image is a temporal average of the entire length of exposure. Already a temporal average, each image is then spatially averaged to obtain a representative mean ratio. Typically, a steady state measurement is the calibrated mean five such averaged image ratios.

Calibration is achieved by correlating known absolute fluid film thicknesses to their corresponding DELIF ratios. Known thicknesses are produced using a custom fabricated two microscope slide structure, as shown in figure 8. With a steel shim used as an offset at one end, the two microscope slides are epoxied together. The resultant cavity between the two slides often varies from around 10 µm at the non-shimmed end to 100 µm at the shimmed-end. Exact gradients differ with the slides used, placement of shim, and amount of epoxy. To quantify the gap gradient between the two microscope slides epoxied together, profilometer scans of one side is taken in respect to the other while filled with water to simulate the surface tension of slurry solution. The difference between the scans is gap gradient. Figure 9 shows that there is a significant difference in the calibration between dry and wet scanned slides. This technique assumes the slides are perfectly uniform in thickness, and also parallel in the cross gradient direction.

To ensure experimental accuracy, calibration is done immediately prior to each experiment. Static fluorescence images are taken of the dual slide calibration structure cavity while filled with the dyed slurry solution (figure 10(a)). The captured fluorescence ratios are then plotted against the quantified gap gradient inferred from the profilometer scans to produce calibration curve such as ones shown in figure 10(b). Fluorescence ratios seem to increase in linearity as the gap height (fluid film thickness) increases.

By examining day to day calibrations, Lu [?], found that despite high individual slide repeatability, slide to slide
consistency is varied. Film thickness fluorescence ratios occurring in range of 0.4 to 0.8 were characterized by a calibration deviation of at most ±5 μm about the mean.

Overall, Lu [3] characterized the precision of the fluid film thickness technique to be within ±1 μm with an accuracy with respect to the current absolute calibrations of at best ±5 μm. Although the technique accurately measures the physical fluid film thicknesses, the rough surface along with entrapped dyed slurry of the polishing pad make an absolute measurement difficult. As a result, there is no true absolute polishing pad “surface,” so all thickness measurements are from the wafer surface to some mean depth within the polishing pad.

As with typical fluorescence based measurement techniques, outside parameters, such as pH and temperature, influence fluorescence. Ideally, any variations in flow field of measurement would be normalized by the two dye system. The dyes also exhibit fluorescence spectra non-linearity, especially at extreme thicknesses. Photodegradation of Calcien leads to a mean fluorescence ratio drop of almost 40% within 5 minutes of ultraviolet lamp excitation. However, during CMP, there is a constant inflow of new dyed slurry solution. Research by Coppeta [1] do shows that after 80 seconds, there is completely new slurry underneath the wafer.

In addition to dye photodegradation, polishing pads can behave similarly as well, which alters its inherent fluorescent behavior. This adversely affects measurement continuity by altering the background noise taken into account by calibration.

From an applicability standpoint, DELIF cannot be utilized with open cell polishing pads, for dyed slurry can penetrate and embed itself much deeper to skew measurements. Also, the temporal and spatial averaging required to reach measurable fluorescence levels eliminate the option of examining polishing pads and wafers with topography such as X-Y, k-type, or perforated. Averaging would heavily bias measurements towards the much greater topographical depths. From a data acquisition standpoint, averaging also can conceal instantaneous planarization behaviors.

4.2.2 Temperature

Like fluid film thickness measurements, temperature measurements at the wafer-slurry-polishing pad interface takes advantage of DELIF and corresponding ratio normalization. The interfacial temperature importance lies in its direct influence upon the chemical reactions between wafer surface and slurry. Thus, material removal, dependent on the
chemical reactions, can be concluded to be dependent on temperature. In measurements, the DELIF technique simply uses the ratio of pure dye fluorescence emission rather than the emission-absorption of a type II conflict. Besides that, the only differences between the two techniques are the dyes chosen and a need for a temperature rather than thickness calibration. A brief overview of the technique will be presented here; a fully detailed technique development and implementation description can be found in Cornely’s [6] work.

The two temperature sensitive dyes, 2,3-Dicyanohydroquinone (DHPN) at a concentration of 0.25 g/l and Brilliant Sulfoflavin at a concentration of 0.5 g/l, served as the emitters in slurry solution. Brilliant Sulfaflavin, like most dyes, increases in fluorescence intensity as temperature rises, while DHPN behaves in the opposite manner. In regard to equation 7, an increase in the interfacial wafer-slurry-polishing pad temperature results in an overall decrease in the $I_{1f}$ (DHPN) to $I_{2f}$ (Brilliant Sulfaflavin) fluorescence ratio. Due to the near identical nature of the temperature and fluid film thickness technique, the twin camera optical system remained exactly the same all the way down to the filtering for type I spectral conflict avoidance. DHPN was filtered at the 455 nm to 500 nm bandwidth while Brilliant Sulfaflavin was filtered to the 550 nm to 600 nm bandwidth.

Two calibrations are necessary for the temperature measurements. First, the fluid film thickness dependency of the dyes must be eliminated. This is accomplished by determining the thickness dependence of the DHPN and Brilliant Sulfaflavin die set by examining the fluorescence ratio and thickness behavior via the fluid film thickness’s calibration technique. From that behavior, a ”dark noise” value is inferred and can be subtracted to from fluorescence values to eliminate the fluid film thickness effects. Dark noise manipulation leads to a fluorescence ratio that is constant over the thickness gradient of the fluid film thickness calibration slide structure. The elimination of thickness dependency must be performed prior to every experiment to limit day to day variations such a background noise. Cornely [6] found that after the ”dark noise” calibration, the maximum error induced by thickness variations would be less than 0.5°C over the entire range of thicknesses and temperatures observed.

Secondly, the measured dye fluorescence ratios must be calibrated to absolute temperatures. For simultaneous fluorescence and absolute temperature measurements, a thermocouple is applied in parallel with DELIF. By plotting the absolute temperatures with the ratio of the measured dye fluorescences, a linear relationship between the two is achieved. Unlike fluid film thickness calibrations though, this calibration, as shown in figure 11(a), occurs at the end
of experiment. Figure 11(b) depicts an example fluorescent image where the thermocouple is clearly in the region of interest of the imaged fluorescence. A range of temperatures is achieved through gradual heating of the slurry inflow, which typically ranges from 20°C to 40°C. Like the fluid film thickness calibration, the fluorescence ratios are plotted against the absolute measurements to obtain a linear fit. Calibration errors were found to be on the order of 0.33°C.

Like fluid film thickness measurements, ultraviolet lamp induced fluorescence lacks temporal and spatial resolution due to averaging. Each fluorescent image is the spatial average of a 3000 ms temporal average (camera exposure time). Finally, each data point reported is the mean of five of those temporally and spatially averaged images. The standard deviation of temperature fluorescence ratios in a temporally averaged image is less than ±0.25°C, while the overall measurement uncertainty is ±1°C.

Limitations include potential problems caused by dye emission spectra non-linearity at temperature extremes. DHPN and Brilliant Sulfaflavin do exhibit less photodegradation than that of Calcien, used in fluid film thickness measurements though. After 5 minutes of constant exposure to a 100 watt ultraviolet lamp, the intensity of DHPN decreases only 6% and the intensity of Brilliant Sulfaflavin decreases just 7%. The net effect of this on the temperature ratio is less than 1% (0.4°C).

An important deviation from the fluid film thickness technique is the transient nature of temperature in CMP. This renders applicable characterizations of in situ temperature difficult. Data shows hysteresis due to continued pad heating. Also, up to 5 minutes are required to reach steady state temperatures, but an industry oxide polish typically lasts only 2 minutes. Thus, unlike steady state fluid film thickness measurements, each temperature measurement was taken after 1 minute of polishing to approximate half the typical oxide polish time.

5 System Integration

To control the 1:2 scale laboratory CMP system, a personal computer equipped with a custom National Instruments LabVIEW 5.1 program functions as the interface and controller. Each subsystem, such as the weighted carriage for variable applied wafer pressures, may be individually controlled via the software instrument panel. Each measurement
technique employs either digital or analog input/outputs for acquisition. All operations are performed in a sequential format; in fluid film thickness measurements, the friction measurement follows the DELIF image capture immediately.

The following list briefly describes the steps required for a typical fluid film thickness experiment.

1. Consumables preparation (pad application, wafer scans, slurry mixing)
2. Optical system setup (focus, alignment, scaling)
3. Offset microscope slide structure calibration
4. Conditioner preparation (assembly, mounting)
5. Polishing pad break-in (preconditioning)
6. Transition to dyed slurry
7. Introduction of experimental wafer into system
8. Experimentation via process condition variations
9. Experiment end and clean-up
10. Data post-processing

To avoid hysteresis, process conditions are run in manner to ensure repeatability. For example, when examining applied pressure effects, the pressure may be varied by first increasing along the range and then decreasing back down the range.

**References**


# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laboratory scale tabletop CMP polishing system [3]</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>Definition of wafer shapes</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Pad conditioning system</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>Schematic of the friction force slider table calibration</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Schematic of the Dual Emission Laser Induced Fluorescence (DELIF) technique</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>Dual camera system</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>Alignment images taken from the dual camera system</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Film thickness calibration slide</td>
<td>26</td>
</tr>
<tr>
<td>9</td>
<td>Dry and wet calibration slide profilometry scans</td>
<td>26</td>
</tr>
<tr>
<td>10</td>
<td>Calibration of calibration slide</td>
<td>27</td>
</tr>
<tr>
<td>11</td>
<td>Temperature calibration setup</td>
<td>28</td>
</tr>
</tbody>
</table>
Figure 1: Laboratory scale tabletop CMP polishing system [3]
Figure 2: Definition of wafer shapes

(a) Convex wafer

(b) Concave wafer
Figure 3: Pad conditioning system
Figure 4: Schematic of the friction force slider table calibration
Excitation $\rightarrow$ Color Detection $\rightarrow$ Ratio $\rightarrow$ Absolute calibration of passive scalar

$$\frac{I_{1f}}{I_{2f}}$$

Figure 5: Schematic of the Dual Emission Laser Induced Fluorescence (DELIF) technique
(a) Nikon enlarging lens with an optics package mounted to 2 Photometrics Sensys cameras

(b) Filter stacks and a cubic 50/50 beam splitter housed inside the optics package

Figure 6: Dual camera system
(a) Alignment image taken with camera 1

(b) Alignment image taken with camera 2

(c) The ratio of the two individual alignment images, \( \frac{\text{camera} 1}{\text{camera} 2} \)

Figure 7: Alignment images taken from the dual camera system
Figure 8: Film thickness calibration slide

Figure 9: Dry and wet calibration slide profilometry scans
(a) Image of the calibration slide filled with dyed slurry

(b) Calibration of fluorescence ratio to an absolute gap height

Figure 10: Calibration of calibration slide
Figure 11: Temperature calibration setup