In-Situ Investigation of Wafer-Slurry-Pad Interactions during CMP

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The objective of this project is to acquire in-situ data during chemical mechanical planarization (CMP) including slurry film thickness and flow, wafer-pad contact, wafer-scale friction, and small-scale shear force measurements**.** The unifying project goal is to utilize a consistent set of experimental data to develop better physical understanding of material removal rate (MRR) and polish quality during CMP. All measurements were taken on a modified Struers RotoPol-31 table top polisher in which the wafer carrier has been replaced by a computer-controlled shaft. The polisher sits atop a vibration-isolated, 3-axis, 6DOF force table to monitor wafer-scale forces and moments between the wafer and the platen. Dual Emission Laser Induced Fluorescence (DELIF) is used to characterize the slurry layer between the polishing pad and the wafer during polish. This method can be used to acquire optical data because we have replaced the standard opaque wafer with an optical BK-7 glass disk. At the same time, we are developing micro-machined, MEMS-based sensors to measure small-scale asperities and fluid shear forces and correlate these forces to macro-scale force and MRR data.

Keywords: Chemical Mechanical Planarization (CMP), DELIF, contact, shear forces, COF, MRR

1. Introduction

The semiconductor industry relies heavily on chemical mechanical planarization (CMP) to create planar surfaces for the deposition of integrated circuits (IC). As the IC features continue to shrink with the advances in technology, the need for a surface planarization increases [1]. In-situ data acquisition during CMP is difficult due to the complexity of the concurrent processes, combined with the opaque nature of the components and complex geometries, which limit measurement options. Typically, CMP data have been gathered after polishing and, as such, do not fully characterize the events present during polishing. Models have been developed to explain the phenomena [2], but there is only limited empirical data to test these models. The effects of processing parameter variations on polish quality, which can be measured through characteristics such as material removal rate (MRR), are not fully understood and therefore cannot be manipulated to optimize the CMP process [3]. The objective of the research described in this paper is to obtain real time data during CMP that can, in turn, be used for model development and validation. In-situ fluid and force measurements at the pad/wafer interface, both possible indicators of polish quality, are examined as functions of process parameter changes [4,5,6]. The relevance of this research is to understand polish quality indicators, such as MRR, and their impact on consumable consumption.

A one half scale CMP rig has been assembled using a Struers RotoPol-31 table top polisher, shown in Figure 1. A 7.62 cm diameter polishing pad is used and data is taken between 30 and 60 rpm. A motor driven shaft is attached to an aluminum frame built around the RotoPol to drive a 1.27 cm BK-7 optically clear glass wafer, allowing optical measurements under the wafer. Down force is applied through the shaft. Cab-O-Sperse SC-1 slurry is utilized at a dilution of 3:2. The entire polishing machine sits atop a force plate that measures both forces

and moments in three-dimensional space. The force table is positioned atop a steel table equipped with vibration isolation [4].

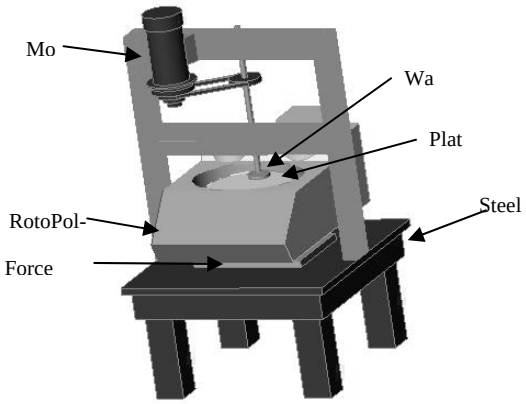

Figure 1. The CMP experimental rig used to gather the in-situ data

2. Contact and Fluid Measurements

The polishing finish and MRR that accrue during CMP are influenced strongly by the fluid-structure interactions at the wafer-slurry-pad interface. Several fluid measurements are being taken collectively at a variety of scales in the current project. Pad asperity scale contact is quantified using a technique called Dual Emission Laser Induced Fluorescence (DELIF) to measure fluid film thickness, which can lead to the determination of contact. DELIF has been used to attain high-resolution 3D slurry layer and polishing pad profiles [7] and is capable of measuring instantaneous slurry layer thickness during the polishing process [8]. The difficulty with fluorescent imaging of fluid films is that both the information about the fluid layer thickness and information about the excitation source are contained in the signal [9]. DELIF is a ratiometric fluorescent technique in which one fluorescent image is divided by the other to cancel the effect of the excitation source. The resulting image has intensity values only dependent upon fluid layer thickness [10]. In our CMP DELIF system, the two fluorophores are the polishing pad, as polyurethane has a natural fluorescence when exposed to UV light, and Calcein, a dye that is dissolved into the slurry. The pad emits at 420 nm, near the peak absorption of the Calcein, which in turn emits at 530 nm. The emission is captured using two optically aligned cameras, each with its own filter to measure either pad or Calcein fluorescence [5]. While pad-wafer contact has been measured ex-situ using both interferometry [11] and confocal reflectance interference contrast microscopy [12], DELIF can be used to quantify contact during polishing, though the results are less accurate. Wafer-scale fluid measurements also being gathered are the fluid flow paths around and under the wafer, which provide insight into slurry utilization and the debris removal paths.

The data presented herein are the most recent DELIF-based contact measurements [13]. Each DELIF image has the dimensions 520x696 pixels. The points of contact must be greater in size than the resolution of the imaging system, 2.5 μm/pixel, in order to detect contact. If the pixel intensities in the DELIF ratio image are placed into a histogram as in Figure 2, the height distribution in each image can be examined to detect pad-wafer contact at the low intensity extreme where the fluid layer thickness approaches zero. The shape of the high intensity extreme of the distribution represents the pad pore structure [14]. The low intensity extreme of the distribution contains pad-wafer contact information [15]. If a wafer is placed onto the pad, the tips of the pad asperities should compress and flatten. The resulting DELIF image will contain a larger number of dark pixels where the asperities are flattened. As contact increases, the number of low intensity pixels also increases, leading to a redistribution of the points in the histogram. Ideally, all points of contact will appear at one place in the histogram, but the system noise cause a smearing of the histogram. Effectively, an inflection point will appear in histogram at the low

intensity extreme at the point of pad-wafer contact [14,15]. Figure 2 (left) shows this inflection point. The vertical line in Figure 2 (left) shows an intensity threshold value that can be used to determine points of contact from the original image. Figure 2 (right) and Figure 3 shows increasing contact area with increasing down force applied to the wafer [8]. The contact percentages are calculated by summing the area under the distribution to the left of the threshold value. Contact percentage between 0-0.28% have been detected for a pad-wafer velocity = 0. Techniques are in development for measuring dynamic contact percentages (pad-wafer velocity > 0).

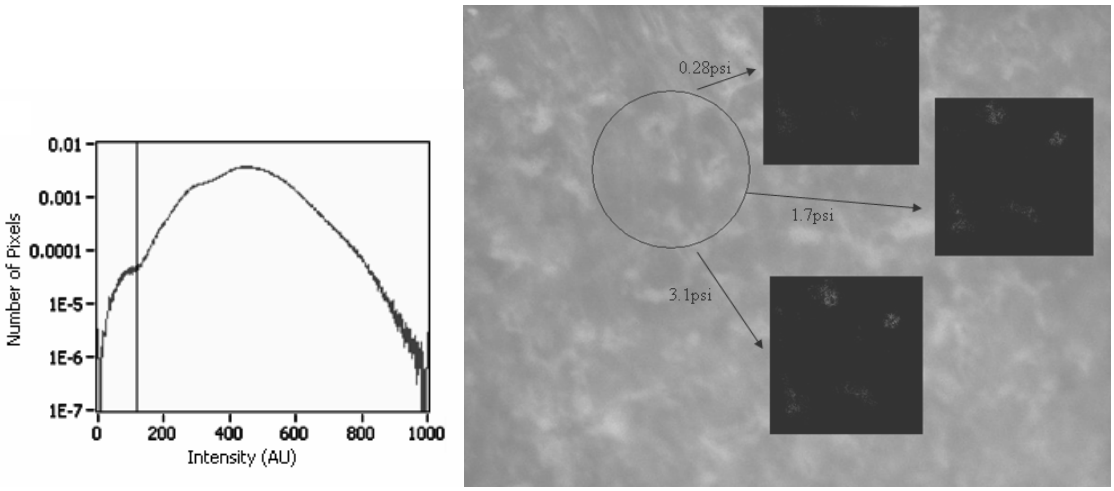

Figure 2. (left) Height distribution for a DELIF image that shows pad-wafer contact. The contact threshold is indicated by the vertical line. The y-axis is normalized to the total number of pixels in the image. (right) A DELIF image and its contact points as applied wafer pressure is increased.

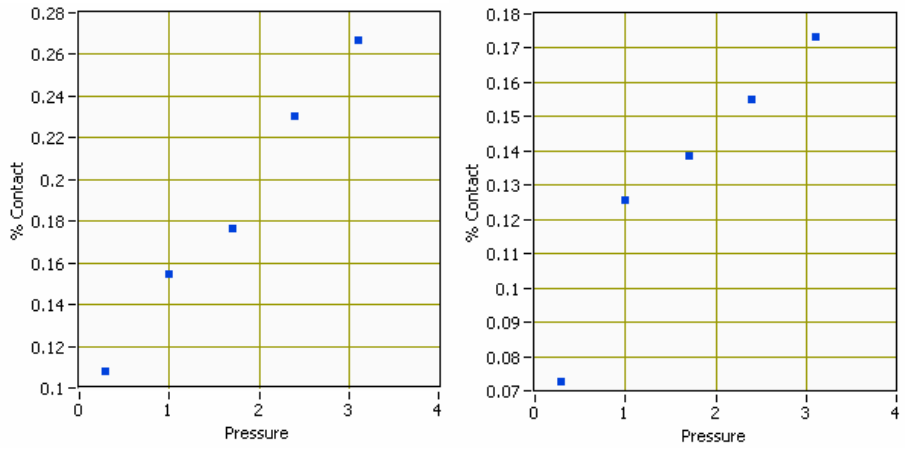

Figure 3. Pressure (psi) versus contact percentage for typical DELIF images.

In addition to slurry film thickness measurements, particle image velocimetry (PIV) is utilized to measure the wafer- scale flow fields during CMP. PIV is advantageous for CMP as it is non-intrusive and the optical measurement apparatus does not change the native flow [16]. Rather than probes, tracer particles are added to the fluid and their fluorescence is utilized [17]. The PIV project is composed of two phases: i) programming a fully automated PIV program in LabView 8.0 and ii) gathering data images during the CMP process. As of the writing of this paper, the first phase is complete and the second phase is underway. Developing an in house PIV data acquisition program allows for customization and keeps the cost of the project low. Particle displacement vectors are calculated using a cross-correlation technique that employs fast Fourier transforms (FFT's) [18]. This process is repeated for the whole image and a vector field is created. The written program has been tested against standard images from Okamoto [19]. At reasonable interrogation areas, the error in the displacement calculations can be reduced to about

.5%, which is an error of .02 pixels. There are several technical challenges in acquiring PIV data in the test rig. These include the unavailability of bilateral image access, the desired scale ranges, which in turn favors UV lights over laser excitation sources, and finally the selection of tracer particles that do not alter the flow, yet provide a sharp contrast with the surrounding media [16].

3. Force Measurements

The degree of planarization achieved during CMP is largely a result of the removal mechanisms. Force measurements during polishing can be used to predict the mechanisms present, such as stick/slip and the relationships between wafer, pad, and slurry. Until recently, in-situ force measurements were lacking and limited the validation of a variety of CMP models in the literature [20]. Currently, in-situ force measurements are being studied at two separate scales. At the macro scale, both in-situ coefficient of friction (COF) and wafer positioning are examined and ex-situ measurements of MRR are being studied [4]. In addition, a MEMS-based shear force sensor has been developed and successfully integrated into the CMP rig [6].

Macro-scale force and moment data are acquired using a force table with the capability to measure forces in three dimensions, thus providing COF, and moments about all three axes. The table is positioned directly below the polisher. Wafer spatial orientation relative to the pad-platen rotational plane is measured using three laser displacement sensors that are used to detect three independent wafer positions. With the newly developed wafer positioning ability, both measurements of CoF and wafer position can be taken concurrently.

Figure 4 depicts CoF data from two separate experimental runs in which only particle loading was varied. On the left, there is a consistent, smooth polish at a slurry dilution of 3:2, which is composed of three parts slurry and two parts deionized water. On the right, a more dilute 5:1 ratio displays a greater degree of stick-slip as evidenced by the increase in the standard deviation of the CoF. In the future, CoF data taken at a variety of polishing parameters will be combined with the wafer orientation measurements and MRR measurements. A variety of insights can be derived from this combination of data. For example, the relationship between stick-slip, as determined by CoF and wafer position, and MRR can be determined. These data might also produce a technique to predict polish quality based on a combination of these three factors. Ultimately, the macro data will be correlated to MEMS based micro-scale measurements and a link between the two regimes can be more thoroughly examined.

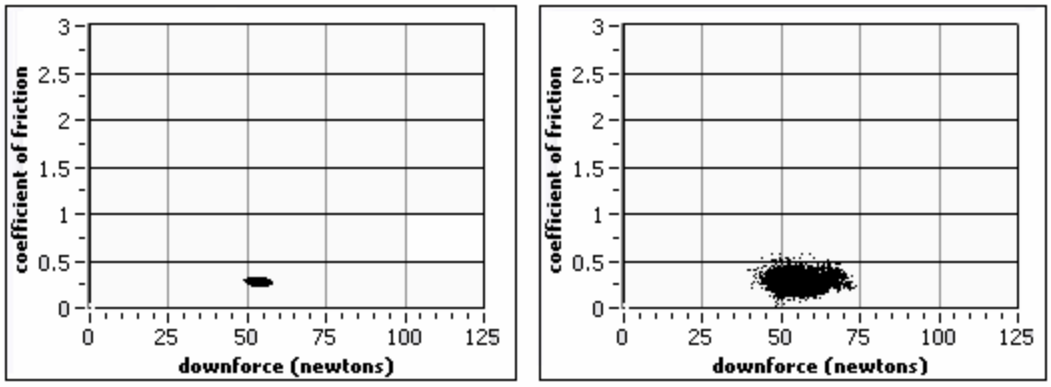

Figure 4 (left) The COF as a function of down force through a polishing run at 3:2 slurry dilution with 12% particle loading. The polish is smooth as the COF value of .28 varies slightly by +/- .01 throughout the experiment. The down force also remains constant at 53.73 N with a standard deviation of 1.55 N. (right) With decreased slurry concentration to a dilution of 5:1 and 5% particle loading, the polish becomes less smooth with a COF of .26 that varies by +/- .04. The down force also is less consistent with a value of 54.38 N and a standard deviation of 2.74 N.

MEMS based sensors with a dynamic range of 5 to 700 μN have been successfully fabricated for the measurement of small-scale forces due to asperity-wafer interaction. The

sensors, consisting of arrays of poly-dimethyl-siloxane (PDMS) recessed micro-posts, range in height between 75 µm and 85 µm and have diameters of 40-100 µm. Figure 5(left) shows a perspective micrograph of the three dimensional structure of recessed posts. An IC1000 polishing pad was used in preliminary experiments to test the sensor, which replaces the wafer, under relevant CMP conditions. Pressures of 0.57 – 1.7 psi were applied to the sensor and shear forces during pad rotations of 30 rpm and 60 rpm were characterized. A high speed optical microscopy setup integrated with the CMP test rig, described in [6], provided approximately 2 µm per pixel at a rate of 10,000 frames per second, sufficient for viewing micro post deflections due to individual asperity contacts during polishing. An example of a deflecting post can be seen in Figure 5(right). Maximum shear forces, present during large deflection events, range from 10 µN to 270 µN. Shear forces at 30 rpm, shown in Figure 6, were markedly larger than shear forces at 60 rpm and a strong trend was observed between increasing post diameters and increasing shear forces. A temporal analysis of asperity contacts was also conducted. The amount of time that the sensor was measurably deflected reduces by approximately 50% when polishing pad speed is increased from 30 rpm to 60 rpm.

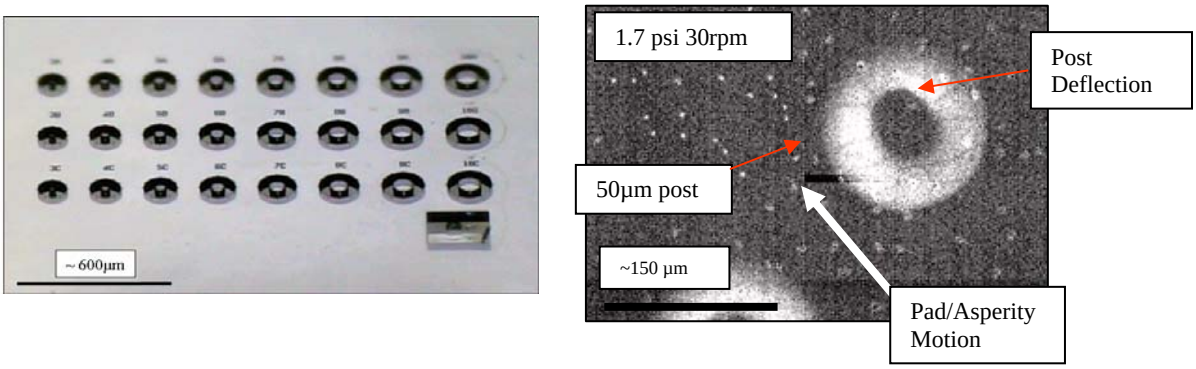

Figure 5. (left)A perspective micrograph of the PDMS posts used to resolve mirco-shear forces. (right) A50 µm post is deflected due to passing asperity interactions at 30 rpm with a 15 lb down force.

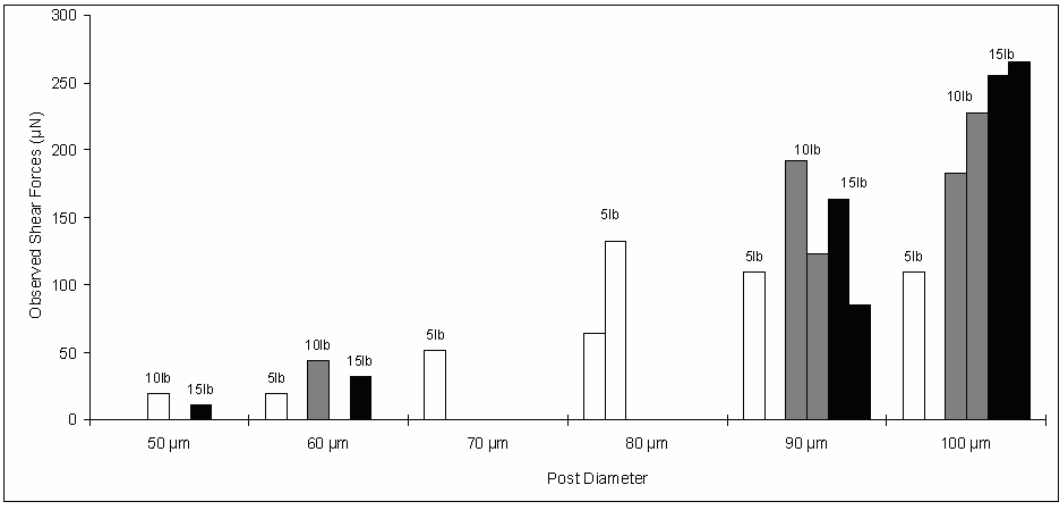

Figure 6. Maximum shear forces observed at 30 rpm and various down forces during polishing of a PDMS wafer with integrated microsensors with no pad conditioning or wafer rotation.

These data are from preliminary experiments examining asperity shear forces for polishing of PDMS structures with an unconditioned pad and no wafer rotation. Further analysis of past experiments as well as future experimentation under additional applied loads and pad speeds is necessary to fully correlate wafer-scale frictional changes to small-scale asperity mechanisms. Additional future work will include the design and fabrication of a micromachined floating-element sensor, which will more closely mimic real polishing surfaces. The

displacement of the sensor due to polishing forces will be observed and measured using the existing optical equipment. The sensor's displacement will provide information about both fluid and asperity forces during polishing.

4. Future Work and Conclusions

Preliminary in-situ force and contact data has been gathered at both the wafer and sub-wafer scale and the techniques proved viable. Fluid measurements of thickness and contact are currently being gathered as well as a technique for pad-scale fluid flow field determination developed. In-situ CoF and moment data and ex-situ MRR data is also available. These will be coupled with MEMS based asperity and fluid shear force measurements to further increase the ability to predict the effect of polishing parameters on polish quality during CMP. The micro and macro scale in-situ measurements for both forces and fluid flow still need to be correlated. These gathered data will yield important insights into CMP and that understanding will help increase polish quality while optimizing the usage of consumables during polishing.

5. References

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