In Situ Characterization of the Mechanical Aspects of CMP

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Abstract The objective of this project is to acquire *in situ* data during chemical mechanical planarization (CMP). This includes wafer-pad contact percentages and slurry film thickness, slurry flow patterns and flow velocity, wafer-scale friction force, and small-scale force measurements. The principle experimental platform used is a heavily instrumented Struers RotoPol-31 table top polisher. Measurements are taken for a variety of downforces (0.3-2.5 psi), pad-wafer relative velocities (0-1.0 m/s), pad grooving (flat, XY grooved, and AC grooved), and slurry injection points. In most cases we are polishing BK7 glass wafers using fumed silica oxide polishing slurries. Dual Emission Laser Induced Fluorescence (DELIF) has been employed to measure slurry thickness and pad-wafer contact percentage *in situ*. Slurry thickness under the wafer is on the order of 0-100 μm, and mean measured contact percentage is on the order of 0.3%. Slurry flow patterns and slurry velocities are measured *in situ* using flow tracers. Both qualitative (flow visualization) and preliminary quantitative (particle image velocimetry) data have been gathered. A combination of force and laser sensors have been used for synchronous, *in situ* measurements of COF and wafer orientation. Average COF values ranged from 0.45 to 0.57. We find that the wafer pitches nose up relative to the rotating polishing pad with mean values on the order of 0.3 degrees and peak-to-peak variation on the order of 0.4 degrees. Micromachined force sensors have been developed for use in characterizing local, *in situ* shear forces. The sensors show the polishing forces acting on 50-100 micron diameter structures to be highly variable in time with magnitudes between 0 and 300 micronewtons and time scales on the order of milliseconds.

Introduction

The semiconductor industry relies heavily on chemical mechanical planarization (CMP) to create planar surfaces for the deposition of integrated circuits (IC). As IC feature sizes continue to shrink, the requirements on surface planarity increase [1]. In order to support improvements to the polish process in both performance and efficiency, *in situ* mechanical characterization is needed. Acquiring such data during CMP is difficult due to the complexity of the concurrent processes, the opacity of some components, complex microscale geometries, and the presence of the slurry. Typically, CMP data have been gathered after polishing or in *ex situ* experiments which may not be fully representative of the *in situ* mechanics of 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].

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, resulting in pad-wafer relative velocities at the wafer center of 0.3 – 0.6 m/s. A motor driven shaft is attached to an aluminum frame built around the RotoPol to drive a 1.27 cm diameter 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, an oxide polishing fumed silica slurry, is utilized at various dilutions. 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].

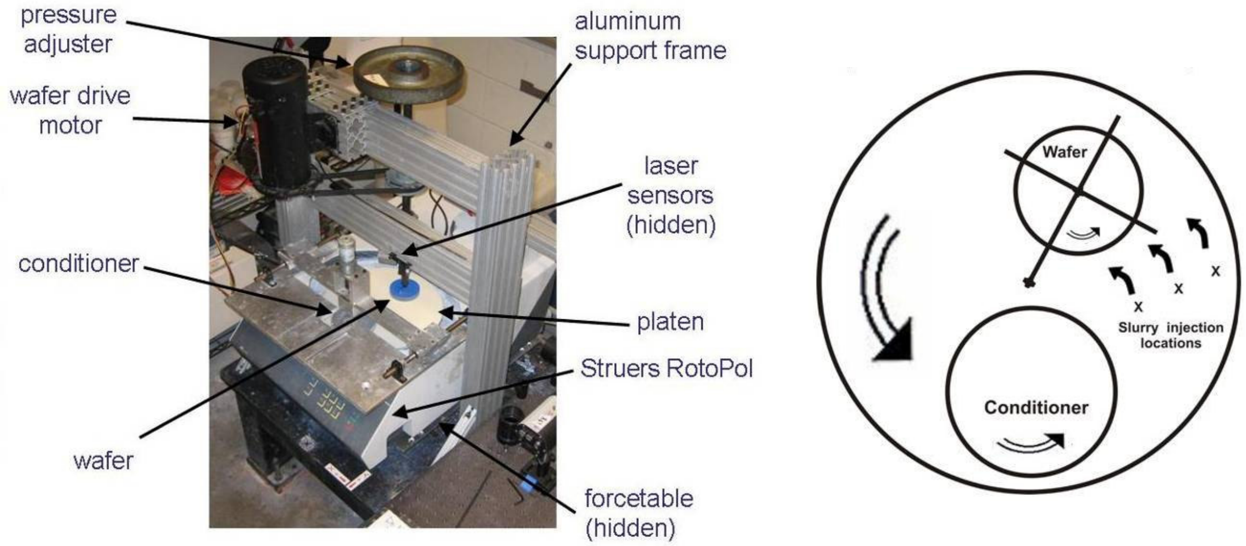


Figure 1 The CMP experimental rig used to gather the in-situ data.

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 instantaneous profiles are collected at a rate of 2 images per second with a 6 nanosecond exposure time per image. DELIF is capable of measuring pad wafer contact greater than 0.1% over an imaging region measuring approximately 2.2 mm^2 [9]. The image analysis methods used to determine pad-wafer contact is described in [10].

DELIF data has been collected during CMP using a Cabot Microelectronics D100 polishing pad. Figure 1 shows an example of a DELIF image that has been analyzed for contact percentage. Figure 1 shows 0.26% contact and the points of contact have been highlighted. Contact was primarily observed on a ridge between grooves on the D100 polishing pads. There is some concern that contact near the edges of grooves may be lost due to the optical effects of the bright groove, so it is possible that additional contact near the groove edge is not detected. Pressure (P) and velocity (V) values were varied during data collection. A set of 500 images were collected for PV condition. The pad was continuously conditioned throughout the run. The contact percentages from the 500 run images were statistically analyzed to extract trends in contact percentage with pressure, velocity and conditioning time.

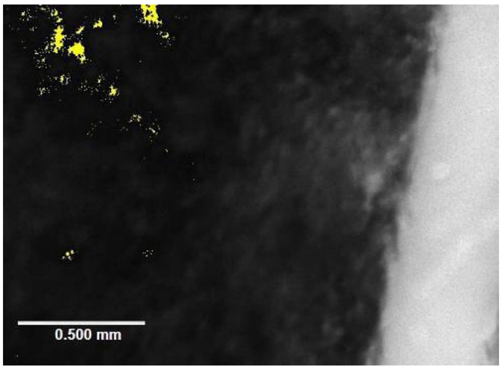
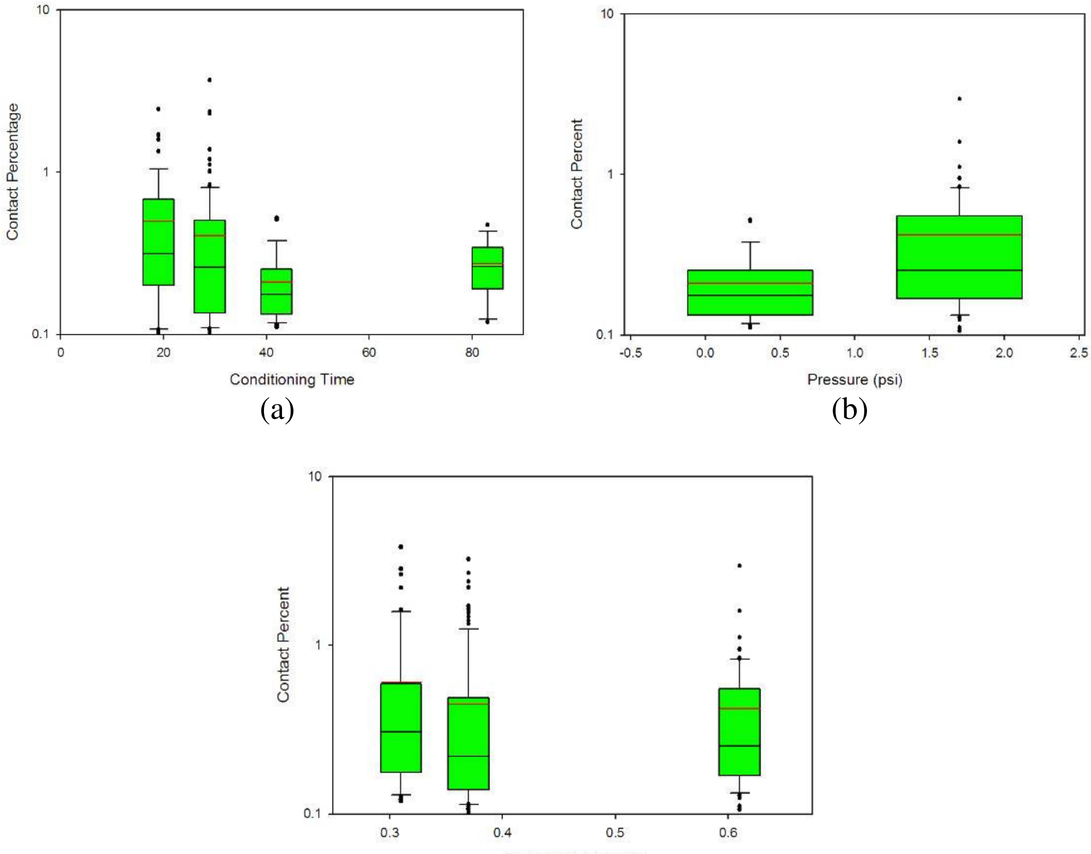


Figure 1. DELIF image of a CMC D100 pad showing highlighted points of contact on the left side of the image. The bright section on the right side of the image is a pad groove.



(a) (b)

(c)

Figure 2. Glass polishing with 12% by wt. fumed silica slurry and an AC-grooved CMC D100 pad. (a) Contact vs. conditioning time with P=0.3 psi, V=0.6 m/s. (b) Contact vs. pressure for V=0.6 m/s. (c) Contact vs. velocity for P=1.7 psi.

Figure 2a shows the results measured using DELIF for conditioning versus contact percentage. The data presented in figure 2a include the data from conditioning times 19, 29, 42, and 83 minutes with constant pressure and pad-wafer velocity. We observe a decrease in contact with conditioning time over 42 minutes of conditioning. The data sets for conditioning times at 19 min and 29 min do not show a statistically significant difference (p-value = 0.244). However, there is a strong statistical difference between conditioning times at 19 min and 42 min (p-value = 0.002), and times 29 min and 42 min (p-value = 0.032). This observed decrease in contact with conditioning time is consistent with measurements made by Borucki, et. al. [11]. If the contact area is increasing as previous results have shown, the contact areas are probably becoming smaller than the resolution limit of our detection method. The contact percentage increases a small amount between conditioning time 42 min and 83 min. This change is barely significant (p-value = 0.073). The in-situ contact behavior measured using DELIF supports the previously observed ex-situ measurements done by Rohm and Haas [12]. These data suggest that the pad has been fully conditioned at 42 minutes and asperity wear may be occurring after 42 minutes. The recommended conditioning time from the manufacturer for this pad is at least 20 minutes.

Figure 2b shows the contact percentage trend at 0.3 psi and 1.7 psi. The velocity for these 2 runs was held at 0.61 m/s. There is a clear increase in the mean contact percentage when the pressure is increased from 0.3 psi to 1.7 psi. The results of a Student t-test showed that these two data sets have a statistical significant difference (p-value = 0.021).

The contact percentage trend with pad-wafer relative velocity, V, is shown in Figure 2c,. The pressures were held constant at 1.7 psi as velocities were changed. Figure 2c shows that the mean contact decreases with increasing velocity. However, this trend in the means is not statistically significant considering the spread in the data. Results of a Student t-test show that a change in velocity from V = 0.31 m/s to V = 0.37 m/s produces the most statistically significant change in contact percentage (p-value = 0.130). The difference in contact percentage between V = 0.37 m/s and V = 0.61 m/s is not statistically significant (p-value = 0.758). The overall dependence of contact area on pad-wafer relative velocity seems to be weak for the tested velocity ranges.

In addition to slurry film thickness measurements, flow visualization and particle image velocimetry (PIV) were utilized to measure the wafer- scale flow fields during CMP. The flow visualization studies focused upon the impact of slurry injection location and pad type on near wafer slurry flow patterns and slurry utilization. In particular, injecting the slurry at radial positions equivalent to the outer region of the wafer track led to distinctly different flow fields than those obtained from mid-radial and inner injection locations. The outer injection cases were characterized by slurry bypass, poor slurry utilization, and slurry starvation in the inner (radial) regions of the wafer. AC-grooved pads appear to use the deposited slurry most efficiently while XY grooved pads sometime exhibited upstream (of the wafer) slurry recirculation zones.

The PIV work complemented the flow visualization studies. If achievable, PIV is advantageous for CMP applications as it is non-intrusive and the optical measurement apparatus does not change the native flow [13]. Rather than probes, tracer particles are added to the fluid and their fluorescence is utilized [14]. 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. 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) [15]. This process is repeated for the whole image and a vector field is created. Our algorithm has been tested against standard images from Okamoto [16]. At reasonable interrogation areas, the error in the displacement calculations can be reduced to about .5%, which is an error of .02 pixels. There were several technical challenges in acquiring PIV data in the test rig. These include the unavailability of bilateral image access, the desired scale ranges and the selection of tracer particles that do not alter the flow, yet provide a sharp contrast with the surrounding media [13]. The PIV analyses completed were limited to very low rotational speeds (<5-10 rpm) due to camera speed and contrast limitations. However, the data that was acquired provided corroborating evidence for the more qualitative flow visualization studies.

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 [17]. 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. At the microscale, we employ a MEMS-based shear force sensor [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. 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 are taken concurrently. The measured COF and wafer pitch angle for 3 different slurry injection locations, at 9 different values of the product of pressure and pad-wafer relative velocity are shown in Figure 3. Positive pitch is wafer "nose up", that is, we find that the leading edge of the wafer is lifted up slightly, on the order of 0.2 degrees. These are all for 12% by weight slurry dilution.

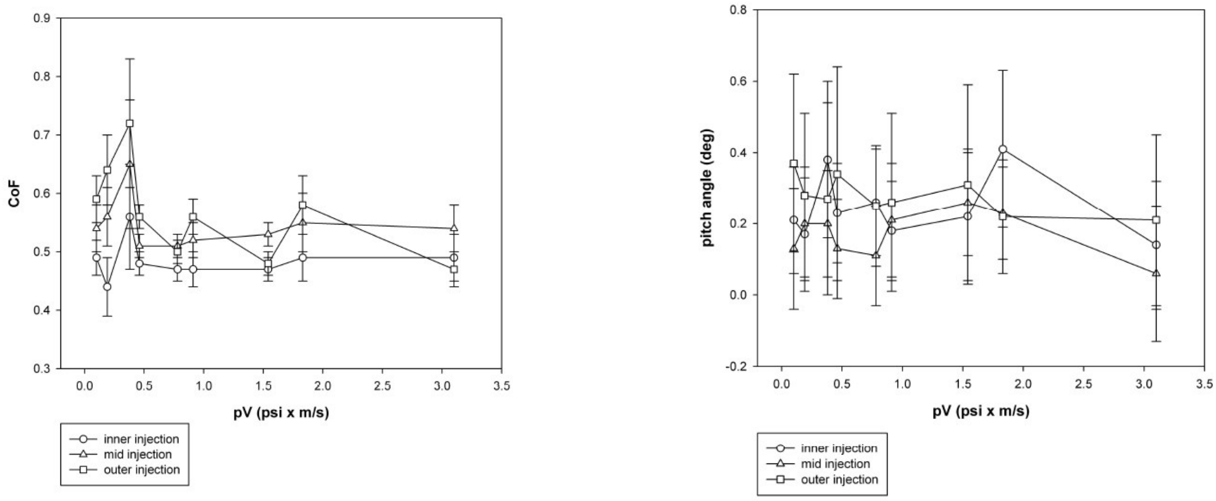


Figure 3 Mean measurements of coefficient of friction and mean wafer pitch during polishing. All data are for 12% by weight fumed silica slurry and an AC grooved CMC D100 pad. Data is presented for a various downforces, pad-wafer relative velocities, and slurry injection points. The error bars show the standard deviation of the data over the course of the run.

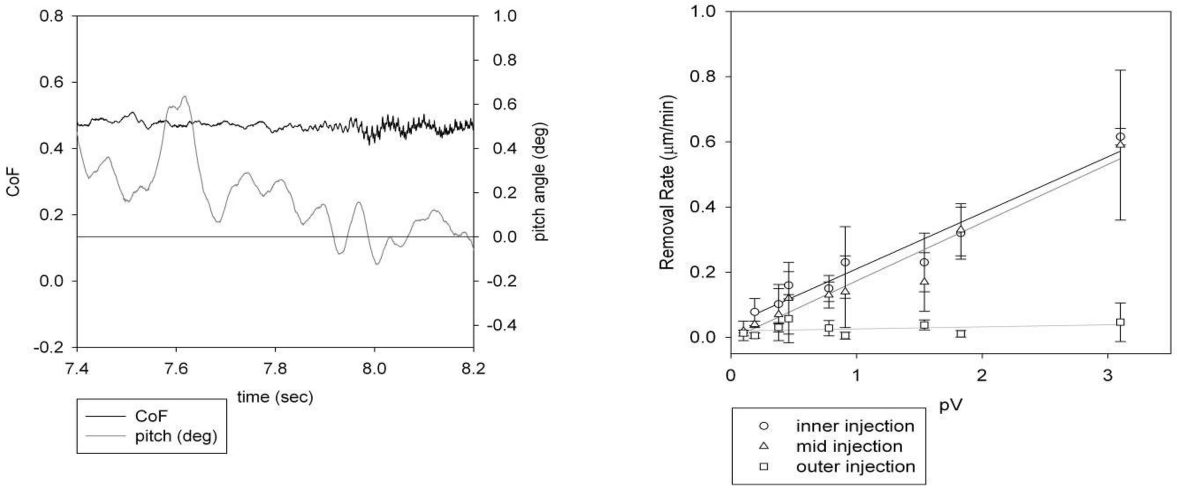


Figure 4 (left) A snapshot of time domain data for COF and wafer pitch angle. Note how the friction regime transition is associated with a local minima in the pitch. (right) MRR vs. pV for 3 slurry injection locations. Inner and mid give essentially the same MRR, but the outer location reduces MRR to, practically, zero. All data is for 12 % by weight slurry concentration.

Figure 4 (left) depicts a snap shot of synchronous CoF and pitch angle data. The planarization experiences a transition from smooth polishing to stick-slip as the pitch angle decreases to a local minimum. This turns out to be a regular feature of friction regime transitions – stick-slip is associated with local pitch minima, although not all local pitch minima are associated with stick slip. Apparently other phenomena are also at work during the regime transitions and it is unclear whether wafer orientation is driving stick-slip or vice versa. Figure 4 (right) displays material removal rate results for a 3:2 slurry dilution over various injection points. Injection locations aligned with the wafer inner edge and wafer midpoint are essentially the same, however injecting at the outer edge of the wafer decreases MRR to zero for all practical purposes. We theorize that slurry residence time is much greater latter case. This injection location dependency points to significant differences in interfacial flows, which could be exploited to maximize MRR and minimize defectivity.

MEMS based sensors have been successfully applied to measure the small-scale forces due to asperity-wafer interaction [6]. The structures are 80 μm tall poly-dimethyl-siloxane (PDMS) cylindrical posts. The post diameters vary from 50 μm to 100 μm. Each post is recessed in a well which leaves a 50 μm wide empty region around the post. The structure is immersed into the polishing slurry and polished. As microscale features on the polishing pad come into contact with the post top, the post deflects. This deflection is observed through the back of the transparent structure using a high speed microscopy setup. Nearly 98% of the wafer surface is planar PDMS; it is only occasionally broken by the annular well region around sensor posts. This allows the majority of the normal force applied by the polishing pad to be carried by the bulk PDMS, thus not compressing or buckling the sensor posts. PDMS is chosen for the structure due to the very low elastic modulus, on the order of 750 kPa. This allows deflections of 5-50 μm to be achieved with lateral forces in the range of 4-400 μN (for different diameter posts). The disadvantage of using PDMS is that it is dissimilar from the oxides and metals that are usually polished by the semiconductor industry. We emphasize that the results in this paper are for polishing of PDMS surfaces, and care must be taken when extrapolating these results to other polishing systems.

Polishing studies were conducted in the tabletop polisher using an ungrooved IC1000 pad (Rodell, Newark, Del.). The fumed silica slurry was diluted to 3% by weight particle loading. An optical system consisting of a Phantom v7.0 high speed camera, a 15 X relay lens, and a 10 X microscope objective is used to determine post deflection during CMP. The video is post-processed to measure the relative displacement of the post top, which is then converted into a force based on ex situ calibration data for the lateral post stiffness. We emphasize again that the surface of the wafer and the sensing structures are manufactured out of the low modulus polymer polydimethylsiloxane (PDMS); this is likely to have a significant impact on the polishing forces, as compared to the polishing of stiffer materials. In addition the wafer is not rotating during the MEMS sensor experiments due to limitations with the optical setup. The polishing pad is rotating. We are not conditioning the pad.

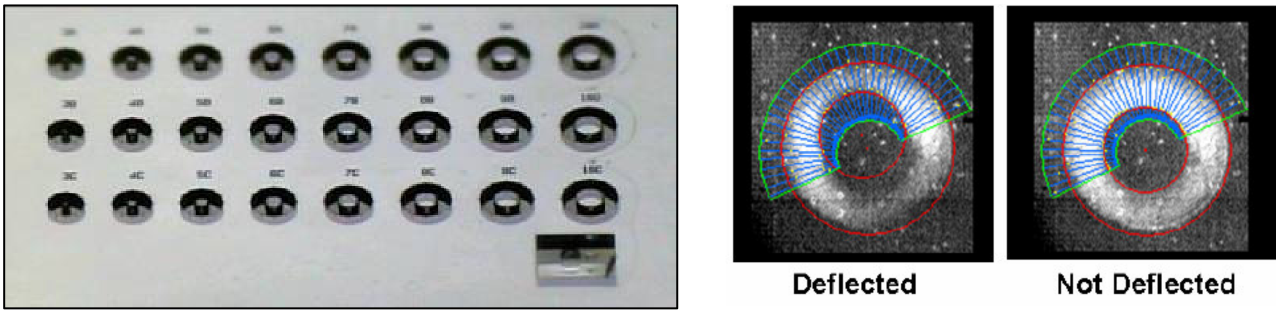

Deflected
Not Deflected

Figure 5. (left) An ex situ perspective micrograph of the PDMS posts. (right) An in situ image taken during polishing showing two frames – one with a deflected and one with an undeflected post. Graphics from the image analysis software used to track post motion are also visible in the figure.

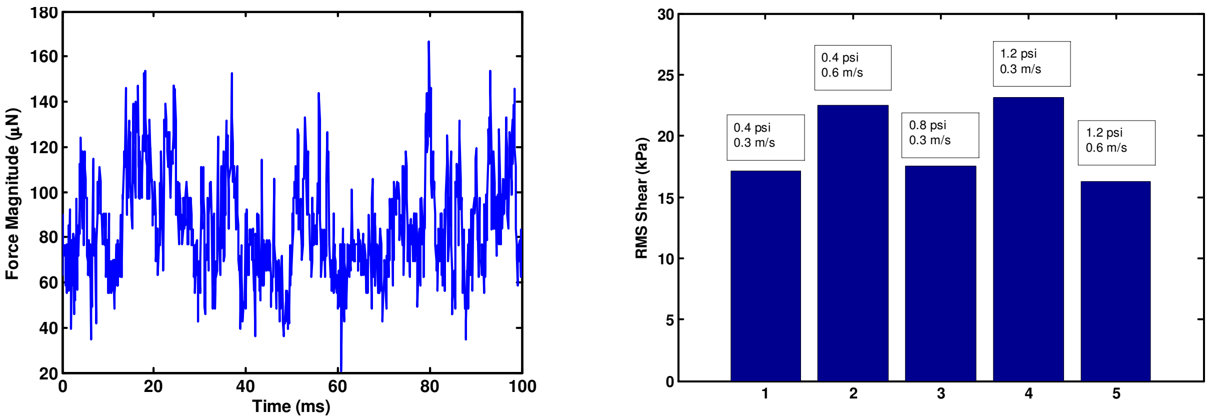


Figure 6 Shear forces observed at a PDMS wafer during polishing. (Left) time trace of the measured shear force on a 80 micron diameter post with 0.3 m/s relative pad wafer velocity and an average distributed downward force of 0.8 psi. (Right) Comparison of the RMS shear force experienced by the micromachined posts under 5 different polishing conditions. The lateral force has been normalized by the area of the post top.

Summary

In situ mechanical data for fluid flow and mechanical forces present during glass polishing have been presented. We varied pad grooving, slurry concentration, downforce, pad-wafer velocity, and slurry injection point and look for the influence on these quantities. Material removal is Prestonian (that is, linear with the product of pressure and velocity), and is strongly influenced by slurry injection location and slurry concentration. The coefficient of friction ranges from 0.45 to 0.57, and is not strongly influenced by downforce, relative velocity, or injection location. Pad wafer contact percentages are on the order of 0.3% and appear to increase with downforce, and decrease somewhat with conditioning time. For our particular experiments, the wafer pitches nose up with an average angle of 0.3 degrees and peak-to-peak variations on the order of 0.4 degrees. The wafer has a mean roll of 0 degrees. Microscale shear forces on 80 micron PDMS post structures are on the order of 0-200 microNewtons. We do not find these microscale forces to vary strongly with downforce or pad-wafer relative velocity. Flow visualization studies show that pad-scale slurry flow is strongly influenced by slurry injection location and pad grooving, but not strongly influenced by downforce or pad-wafer relative velocity. Work is ongoing to improve on and extend some of these measurement techniques to polishing of patterned substrates and polishing of metals. We hope in the future to correlate observations of defectivity in polishing of patterned metal substrates to some of these mechanical measurements.

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