# *In situ* Metrology for Glass and Copper CMP

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## Abstract.

The objective of this project is to acquire *in situ* data including wafer-scale friction forces, material removal rate for glass wafers and copper Damascene structures, and small-scale force measurements during chemical mechanical planarization (CMP). 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), and pad grooving (flat, XY grooved, AC grooved, concentric grooved). In most cases we are polishing either BK7 glass wafers using fumed silica polishing slurries, or copper patterned wafers with Fujimi Planerlite 7107 slurry. For glass wafers , average CoF values ranged from 0.45 to 0.57 and for copper damascene structures, CoF varied from 0.37 to 0.48. Material removal rates are on the order of hundreds of nanometers per minute. 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

Chemical mechanical planarization (CMP) has become a key enabling technology in the semiconductor fabrication process and looks to remain in place for the foreseeable future. As the industry continues its pursuit of greater transistor density, reduced costs, and smaller environmental footprint, CMP needs to produce even more planar surfaces for highly stacked interconnection, ideally while reducing consumable usage [1]. To meet these future imperatives, a more complete understanding of the phenomena observed in CMP is required. However, there is only limited *in situ* empirical data for CMP. 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 [2]. The goal of the research described in this paper is to obtain real time data that can be used for glass and copper CMP. The effects of processing parameter variation on polish quality, which may be related to synchronously measured characteristics such as coefficient of friction (CoF), can contribute to the optimization of the CMP process. This research presents real time data during glass and copper CMP including force measurements at the pad/wafer interface as

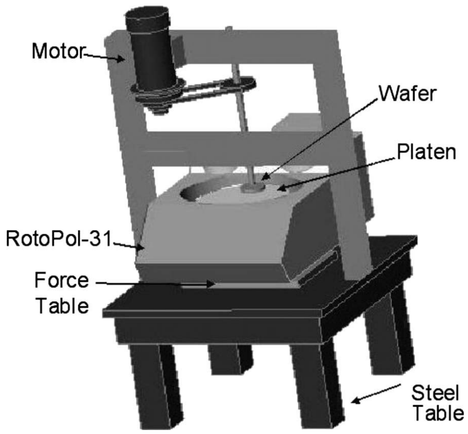

**Fig. 1.** Schematic of the polishing rig.

functions of process parameter change [3-6].

Experiments were conducted on a Struers RotoPol, model no. 31 which is shown in Fig. 1. A 4 in. diameter diamond grit impregnated metal disk conditions the polishing pad during experiments. The platen speed is controlled from 0-120 rpm, resulting in relative pad-wafer velocities of 0 to 1.3 m/s at the wafer center. The entire apparatus sits atop a steel table isolated from the floor by vibration damping inserts. An ATMI force table is used for global force measurements. For all experiments, slurry flow rate was nominally 50-70 $cm^3$/min.

## Force Measurements Using Silicon Substrate

The quality of planarization achieved during CMP can be strongly affected by the type of mechanical interactions present at the pad-wafer interface. Force measurements during polishing can be used to determine some of the mechanisms that are present. In particular, undesirable stick/slip phenomena are easily identified both in force data and wafer pitch and roll.

At the macro scale, both *in situ* CoF and wafer pitch and roll are examined and *ex situ* measurements of MRR are being studied [7]. Macroscale force and moment data are acquired using a force table with the capability to measure forces in three dimensions. CoF is computed as the ratio of the lateral vector force resultant divided by the vertical force. Synchronously to measuring CoF, we also measure the pitch and roll of the wafer using three laser displacement sensors focused on the back side of the wafer. Post processing of the three dynamic displacements yields dynamic pitch and roll. MRR is computed by measuring, via stylus profilometry, the change in depth of a 100 micron wide groove etched into the glass at multiple locations across the wafer.

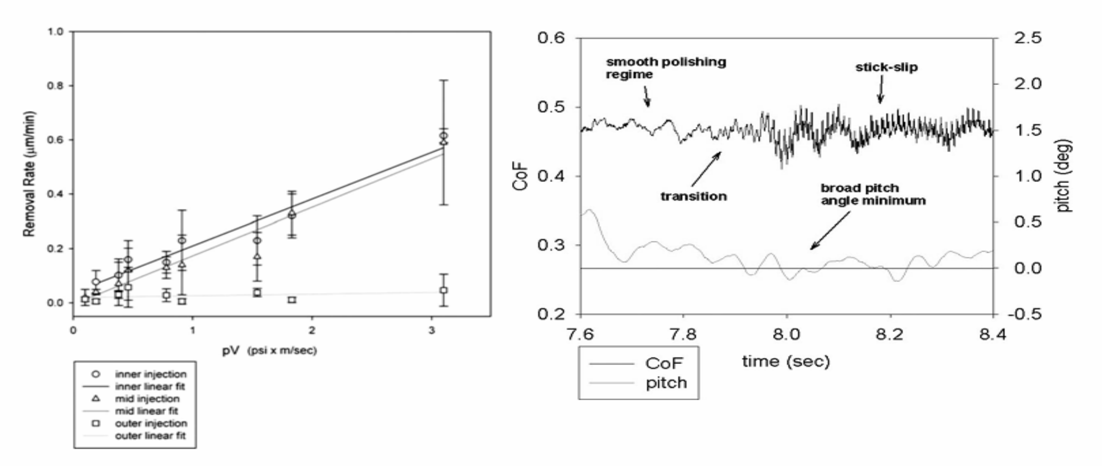

**Fig. 2.** Glass polishing results. (Left) MRR vs. pressure times velocity for 3 slurry injection locations. (Right) A snapshot of time domain data for CoF and wafer pitch angle. Note how the friction regime transition is associated with a local minima in the pitch. All data is for 12 % by weight fumed silica slurry concentration.

Glass polishing removal rate data are presented in Fig.2 (left). Three curves are given for three different slurry injection points. The data is plotted in a Prestonian manner against the product of downforce and pad-wafer velocity. The error bars in these plots are the standard deviation we calculated based on measurements at three locations on the wafer. At both the inner and mid-injection locations, MRR exhibits Prestonian behavior. The inner location appears to exhibit a slightly higher MRR, but this is within the measurement uncertainty. For the outer injection location, MRR is essentially zero within the uncertainty of our measurement technique. We postulate that the outer injection perturbs slurry transport so that mean slurry residence time at the planarization interface is greatly increased, reducing the amount of slurry particles with free surface area available to remove material from the wafer, thus reducing removal rate. In other words, the dynamics of slurry transport as well as the age of the slurry underneath the wafer are radically different for the inner and midinjections vs the outer injection. This hypothesis is supported by slurry flow visualization data reported elsewhere for the same experimental setup [8].

Fig.2 (right) illustrates synchronous CoF and pitch angle data for glass polishing. Average CoF ranged from 0.45 to 0.57. We found that the wafer pitches front edge 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. For glass polishing, planarization experiences a transition from smooth polishing to stick-slip as the pitch angle decreases to a local minimum, as seen in Fig.2 (right).

## Force Measurements with Cu Damascene Structure

*In situ* mechanical characteristics (microscale shear forces and CoF) that result from process parameters can provide insight into polish quality such as structural damage and removal rate associated with CMP. The correlation between structural damage and mechanical characteristics are being investigated at a variety of scales in the current project. Test structures were patterned on glass wafers to study damage to structures. The basic test structure is illustrated in Figure 3. It consists of a metal thin film (Ti/Cu) deposited over a patterned $SiO_2$ trench (1 μm deep) structure. Two types of structures (serpentine and straight) and two kinds of suspensions (slurry mixture and pure DI water) were used. For the slurry mixture, one part slurry (Fujimi Planerite 7107) : six parts DI water was blended and 33 mL of 30% hydrogen peroxide ($H_2O_2$) was added per liter of slurry suspension.

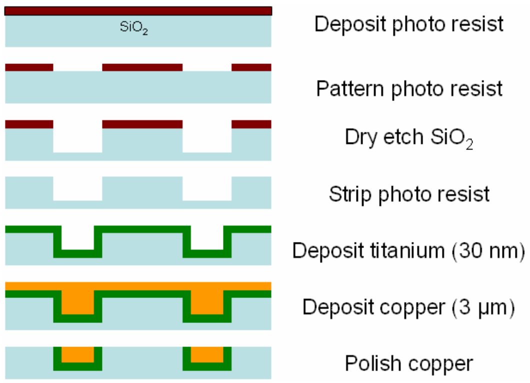

**Fig. 3.** Damascene fabrication with CMP.

CMP was performed using a JSR Micro pad and Fujimi PL 7107 slurry. Three different downforces (0.22 psi, 0.47 psi, 0.71 psi) were exerted over 5" diameter retaining ring and wafer assembly. Fig. 4 presents before- and after-CMP features. 25 μm wide copper wires were successfully patterned on a glass wafer after CMP process. Visual examination of after-CMP showed a promising level of CMP consistency across the 4" wafers.

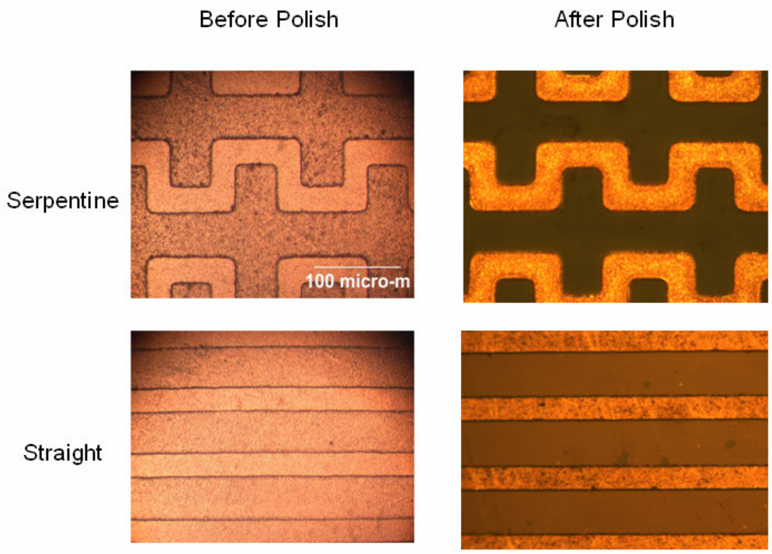

**Fig. 4.** (left) Copper-filled features prior to CMP and (right) post-CMP.

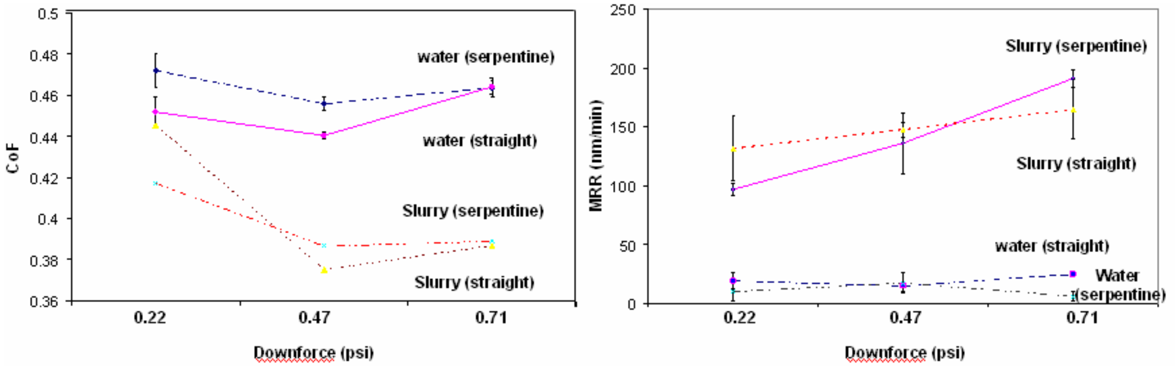

**Fig. 5.** Data for polishing of two types of copper Damascene structures with slurry and with pure DI water. (left) CoF for each downforces (right) MRR for each downforces. All data is for 60 rpm platen speed.

Fig. 5 (left) shows the CoF during copper CMP. There is a fairly wide variation (0.37 to 0.48) – both the pattern (serpentine or straight) and the downforces have a significant impact on CoF. Fig 5 (right) shows MRR during CMP. After polishing MRR was tracked using DekTak 6M stylus profilometer of patterned structures. MRR in the slurry case is 120-180 nm/min and in water is 5-15 nm/min. There is weak upward trend of MRR with downforce.

In order to fabricate Damascene wires at a greater yield and with greater accuracy, slurries have been widely studied for a high removal rate while decreasing defects. However, the copper layer is very sensitive to wet chemicals in the slurry suspension and we also found various defects such as delamination, scratch, and corrosion. The SEM of the polished patterns is shown in Fig. 6. Major defects are large area copper delamination (left) from the surface and chemical corrosion (right) which was found near the edges of grooves because of the chemical reaction of copper with compounds in the slurry and hydrogen peroxide. Ein-Eli *et al.* [9] investigated the electrochemical reactions of Cu in hydrogen peroxide solution. According to them, copper surface immersed in hydrogen peroxide solutions are coated with copper oxides/hydroxides layer. During CMP, self-protective features of copper oxide precipitation are injured. This causes the development of pits at the copper layer, as shown Fig. 6 (right). Even though the defects were observed, immediately rinsing the wafer with DI water after polishing and drying by air blow reduces the number of corrosion defects.

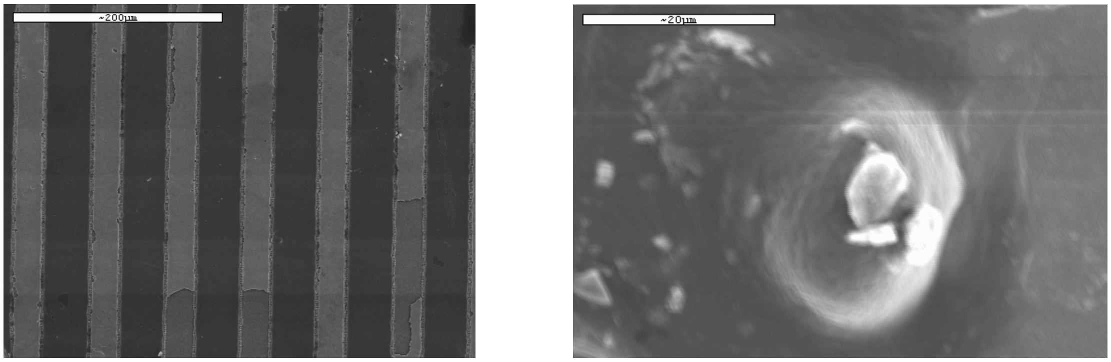

**Fig. 6.** SEM images of the primary defects by copper polishing. Copper delamination (left) and copper corrosion (right).

In addition to wafer scale measurements, micromachined polydimethylsiloxane (PDMS) post structures with a diameter of 80 µm have been applied to the measurement of the microscale shearing forces present at the wafer-pad interface. It is important to note that these results are for the polishing of PDMS, a low modulus silicone elastomer. Thus the forces will be different than those seen in glass and copper polishing. However, the use of PDMS allows high spatial, temporal, and force resolution. The structures are 80 µm high with a bending stiffness of 7 µN/µm. Measurements are captured *in situ* using a high speed microscopy setup at 10,000 frames per second (0.1 ms per frame). Force resolution is on the order of 10 µN. The structures were polished using a stiff, ungrooved pad and 3 wt% fumed silica slurry at relative pad-wafer velocities of 0.3 and 0.6 m/s and global average wafer-pad normal interaction stresses of 0.5 and 0.9 psi (3 and 5.4 kPa). Observed lateral forces on the structures averaged, in time, 80 µN with a temporal standard deviation of 20 µN for both 0.3 m/s cases (0.5 and 0.9 psi). In the 0.5 psi, 0.6 m/s case, the time average lateral force was 110 µN with a temporal standard deviation of 20 µN. A time history of the lateral force on an 80 µm diameter structure is given in Fig. 7.

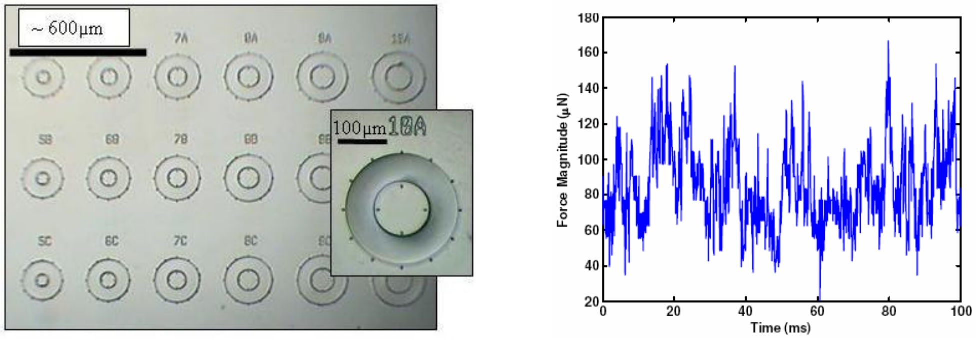

**Fig. 7.** (Left) Microscope picture of an array of PDMS shear forces sensors. (Right) Shear force on a 80 micron diameter post with 0.3 m/s pad-wafer velocity and an average downforce of 0.8 psi.

## Summary

*In situ* data for mechanical forces during glass and copper polishing have been presented. This study gives a range of data which we hope can aid in finding correlations between process inputs (relative velocity, pressure, slurry concentration, and injection location) and process outputs (CoF, wafer orientation, MRR, structural damage, and local microscale shear forces) with the overall goal of broadening the fundamental knowledge pertaining to CMP. For glass wafers, we found that MRR is strongly dependent on slurry injection location, polishing rates dropping to essentially zero for outer injection. The synchronization of CoF and wafer orientation data sets demonstrated friction regime transitions from smooth polishing to stick-slip were associated with local pitch angle minima. For the copper damascene structure, the downforces have a significant impact on CoF during polishing. MRR shows a weak upward tendency with downforce in slurry case while showing low MRR in water case. 25 µm wide copper lines were clearly developed by polishing but defects (particularly delamination and corrosion) are found. Microscale shear forces on 80 micron PDMS post structures are on the order of 0-200 µN. Larger lateral forces were observed for larger diameter structures. Increasing the speed of the polish decreased the lateral forces. Increasing the downforce increased the lateral forces at slow speeds for the largest structures, but had little impact at higher speeds. We are currently working on measuring local shear stresses during copper CMP using a modification to the PDMS post structures. We are also looking at improving the resolution and readout schemes of the MEMS force sensors, with the goal of moving away from the PDMS structures completely in the future.

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