**Correlating Coefficient of Friction and Shear Force to Platen Motor Current in Tungsten
and Interlayer Dielectric Chemical Mechanical Planarization
at Highly Non-Steady-State Conditions**

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Correlations between shear force and platen motor current (PMC), as well as those between coefficient of friction (COF) and PMC were investigated for various tungsten and interlayer dielectric (ILD) chemical mechanical planarization (CMP) cases where the processes were highly non steady-state. We chose to initially focus on non-steady-state conditions because we believed the relationships among shear force, COF and platen motor current to be clearer as opposed to steady-state conditions. Shear force, normal force and PMC data were collected from twelve different Stribeck+ curves at an acquisition frequency of 1,000 Hz and analyzed in order to determine any emerging trends. For the 12 cases, involving 8 pre-polished blanket CVD tungsten and 4 silicon dioxide blanket wafers, it was discovered that PMC closely mirrored shear force as evidenced by a high average correlation coefficient (0.955) and coefficient of determination (0.916) obtained from all runs. For COF vs. PMC, the average correlation coefficient and coefficient of

determination for all cases were 0.758 and 0.608, respectively. These average values were dragged down by 5 cases in which the dominant tribological mechanism was found to be “boundary lubrication” where COF changed minimally with pseudo-Sommerfeld number.

Introduction and Motivation

For the past 4 decades, and with no end in sight, chemical mechanical planarization (CMP) has enabled IC manufacturing in achieving economically-viable global and local planarity across the entire wafer surface. During CMP, a rotating wafer is pressed onto a rotating pad (often made of a polymeric material) while a slurry containing chemicals and abrasive nanoparticles is applied atop the pad which is then transported to the pad-wafer interface through a combination of polisher kinematics and centrifugal forces aided by the pores and grooves of the pad. When done properly, 3-body contact caused by the pad surface asperities, slurry abrasives nanoparticles and the wafer surface lead to the uniform removal of material from the wafer surface. ⁽¹⁻⁵⁾

Based on the above description, albeit simplified, it is obvious that tribology ought to be intimately linked to our understanding of various contact-related nuances of the process. An impressive body of experimental and numerical work, that is fundamental in nature, has been published by our research group, as well as others, focusing on the tribological aspects of polishing wafers in tungsten ⁽⁶⁻¹⁰⁾ and interlayer dielectric (ILD) ⁽¹¹⁻¹⁵⁾ applications. These studies have all focused on the real-time measurement of the pad-slurry-wafer coefficient of friction (COF) through precise extremely reliable, accurate and precise measurement of the shear and normal forces encountered in CMP which required fitting the CMP polisher with costly friction plates (which are quite large

and complex, and may not always be suitable for certain types of polishers), force sensors, multiplexers and signal amplifiers. The scientific literature is filled with alternate methods⁽¹⁶⁻³⁰⁾ of inferring the coefficient of friction in CMP with the most popular of such alternate methods centered around measuring platen motor current (PMC)⁽³¹⁻⁵⁵⁾. During CMP, the wafer and the platen co-rotate at desired velocity setpoints. The pad-slurry-wafer interface undergoes a myriad of 3-body interactions, which due to the frictional forces involved, may facilitate, or resist, platen and wafer rotation. As such, in order for the polisher to control the angular velocities to the desired setpoints, torque motor characteristics must change due to an increase or decrease in the frictional energy loss component. Hence, for rotary-type polishers, the torque current of the carrier and the platen may be monitored using an induction-type loop current sensor attached directly to the DC motor current line, which gives an indication of the frictional forces present in the pad-slurry-wafer interface. While this method is much more cost-effective compared to the traditional COF method noted above, signal-to-noise ratios get somewhat deteriorated due to the many moving parts and gears that at times tend to interfere with the true motor current being captured and recorded. If our research could indicate that PMC data was able to replace shear force data, it would have widespread positive implications for IC manufacturers because it would enable one to monitor that pad-slurry-wafer interfacial conditions without the need to retrofit polishers used in high-volume manufacturing with expensive ancillary equipment such as friction plates, directional force sensors, multiplexers and signal amplifiers.

During the past 7 years, our research group has performed several tribological studies during which we have generated Stribeck+ curves^(56,57) using a single 300-mm blanket wafer (i.e. deposited with CVD tungsten, ECP copper or PETEOS-based silicon dioxide films) in an effort to shed additional fundamental light on the contact mechanism(s) in CMP. Results of most of these studies have been

published previously ^(56, 57) where, in parallel with collecting shear and normal force data at 1,000 Hz, we happen to have also collected platen motor current (PMC) data at the same frequency. It must be noted that we have never analyzed, nor reported on, this metric. In our present study, for each of these studies involving Stribeck+ curve generation, we set out to systematically: (a) Define details of the respective process conditions; (b) Analyze all shear force and PMC data-pairs along with all the COF and PMC data-pairs as a function of polish time; (c) Correlate the experimental outputs to each other; and (d) Draw conclusions from the results.

Experimental Apparatus

An Araca APD-800 polisher and tribometer was used to perform all tungsten and copper polishing experiments. ⁽⁵⁸⁾ This system is a single-platen research and development polisher and tribometer designed to process substrates that are 200 as well as 300 mm in diameter. The APD-800 is equipped with signal acquisition hardware such as direction-dependent load cells, as well as Araca Inc.'s FSX-800 proprietary signal analysis software. This feature provides the unique ability to acquire accurate real-time shear force and down force measurements (in our experiments, data capture frequency for all parameters was set at 1,000 Hz, although we could have used frequencies as high as 2,300 Hz at the expense of requiring a much larger computational power). Additionally, the APD-800 contains a single-point infrared (IR) temperature sensor used for measuring real-time pad surface temperature data during polishing. On this tool, the non-oscillating counterclockwise wafer carrier and its drive mechanism sit on a friction table attached to the frame. A load cell connected to the table measures the main component F_y of the friction force vector. This component runs perpendicular to the line connecting the platen and carrier centers. The radial

component F_x of the friction force is not measured but is known to be small from experiments on a similar 200 mm tool. ⁽⁵⁹⁾ The head does not use a contacting retaining ring (which is why our CMP processes run at somewhat lower temperatures compared to those in HVM). Instead, a non-contact wafer backing film attached to a water-filled template holds the wafer. The platen and its drive mechanism sit on four load cells that monitor the total force F_z transmitted by the wafer to the pad. This includes both the applied load and any fluid forces that develop in the interface. All forces are measured at 1,000 Hz. There is no feedback between the normal force load cells and the carrier. Inside of the carrier, behind the wafer, there is an air chamber that applies the polishing force. An electro-pneumatic transducing regulator controls the chamber pressure. Pressure adjustments can occur but are much slower than the force acquisition frequency. The applied load is periodically checked and calibrated on a static platen. A more detailed description of the polishing system can be found elsewhere. ⁽⁵⁸⁾ In addition to the force acquisition hardware and software, the APD-800 is also equipped with carrier, platen and conditioner motor currents data acquisition, amplification and recording hardware all capable of data acquisition at up to 2,300 Hz. In all of our tests, we measured these metrics at 1,000 Hz and have chosen to only report on the platen motor current (PMC) due to its higher signal-to-noise ratio compared to the other two motor currents. It must be noted that the acquisition clocks that managed the shear force and PMC data were off by appx. 250 ms from each other. We had to take this into account during our signal analysis and reporting.

Experimental and Analytical Procedures

In this report, 12 different and highly non-steady cases (denoted as Cases 1 – 12) were studied. The non-steady state conditions were determined by systematically varying the sliding pressure and velocities in a given process throughout predetermined polish times. The blanket wafer type, pad, slurry, conditioning pad, conditioning process recipe, and polishing time were varied depending on the specific case.

For Cases 1 – 6, 300-mm pre-polished blanket CVD tungsten wafers were used together with DowDupont IC1000 K Groove pads. For Cases 7 and 8, the pre-polished blanket CVD tungsten wafers were 200 mm in diameter also in conjunction with DowDupont IC1000 K groove pads. For Cases 9 – 12, we used 300-mm plasma enhanced tetraethoxyorthosilicate (PETEOS) based blanket silicon dioxide wafers.

For the first six cases, the hydrogen peroxide based slurries used were Versum DP1142-1 (Case 1), Versum DP1142-2 (Case 2), Versum W5880-1 (Case 3), Versum W5880-2 (Case 4), Versum W5880-3 (Case 5), and CMC W7801 (Case 6) all flowing at 250 cc per minute. In these cases, pads were broken-in for 30 minutes using a Saesol 4DNS80AMC1 disc rotating at 70 RPM with a generic sinusoidal sweep schedule. The rotational velocity of the pads was maintained at 80 RPM. In between polishes, *ex-situ* conditioning was performed for 30 seconds at a downforce of 6.75 lb_f. The DP1142-1 and DP1142-2 slurries were high-selectivity (to silicon nitride) slurries with varying amounts of a certain proprietary additives. As for W5880-1, W5880-2 and W5880-3 slurries, they had varying amounts of colloidal silica nano-particles (1.5, 2.5 and 3.5 percent by weight, respectively) and were especially formulated so that there were no detectable changes in their formulation chemistries.

For Cases 7 and 8, slurry flow rate was 200 cc per minute. Here, the slurry used was also the CMC W7801. For Case 7, the pad was conditioned by using a 3M A165 CIP disc, and for Case 8, the conditioner was an MGAM 4S845P4F5 disc. Both discs rotated at 95 RPM and the down force for each disc was 10 lbf with a sinusoidal sweep schedule in which the disc swept across the pad 10 times per min.

Case 9 used a CMC D100 concentrically grooved pad with a Merck Klebosol 1508-30 slurry without any dilution (i.e. at 30% by weight solids) at a flow rate of 300 cc per min. The pad was conditioned using a 3M A165 disc rotating at 95 RPM and sweeping using a sinusoidal schedule in which the disc swept across the pad 10 times per min. In-situ conditioning was performed with a down force of 26.7 N.

For Cases 10 – 12, different pads were used. Case 10 used a CMC D100 concentrically grooved pad, Case 11 used a DowDupont IC1000 K Grooved pad, and Case 12, a DowDuPont IC1020 M Grooved pad. These 3 cases used a Fujimi PL-4217 diluted slurry with ultra-pure water (UPW) to a final solids concentration of 10% by weight with a slurry flow rate of 300 cc per minute. The pads were conditioned using a 3M A165 disc rotating at 95 RPM and sweeping using a sinusoidal schedule with a sweep frequency of 10 times per minute. The in-situ pad conditioning was conducted with a downforce of 26.7 N.

The pressures (in PSI) and sliding velocities (in m/s) for each of the twelve cases are listed in Tables I (Case 1 – 3), II (Cases 4 – 6), III (Cases 7 – 8), IV (Case 9), and V (Cases 10 – 12). In this study, normal force, shear force, and PMC data were collected at 1,000 Hz.

As mentioned in the “Introduction and Motivation” section of this paper, the PMC data had never been reported, nor analyzed, until now. By using the computing power of MATLAB R 2018b, a

precise and accurate examination of the trends between the shear force, COF and PMC data was conducted. Accurate and efficient examination of the emerging trends from millions of shear force, normal force and PMC data points was made possible with MATLAB R 2018b. After importing the raw data into MATLAB, we extracted real-time measurements of platen motor current (PMC) and shear force, as well as PMC and COF (which is the ratio of shear to normal force), from the acquisition program. Before conducting any statistical analyses, raw PMC data was shifted by 250 ms to account for the known difference between the two data acquisition clocks as noted earlier. Also, in all cases, velocity and pressure ramp-up and ramp-down sections occurring in the first and last five seconds of the entire process were excluded due to the overwhelming presence of noise in those regions.

As mentioned earlier, in this study we wanted to not only correlate COF to platen motor current, but shear force to PMC as well. The former carries a greater mechanistic significance as it is a key parameter that appears in almost all material removal rate models either by itself or lumped into a mechanical proportionality constant. ^(60, 61) However, since COF contains information about normal force and associated vertical vibrations, data interpretation can at times be complicated. On the other hand, correlating shear force to PMC would allow for analyzing data based on the horizontal torque applied to the platen (as measured by PMC) as a function of shear force in the pad-slurry-wafer interface.

Results and Discussion

Figs. 1 – 12 summarize the results obtained from all cases studied. On the top left-hand-side of each figure, shear force, normal force and PMC values are plotted vs. time. In each case, the first and last five seconds of each run have been excluded from the correlation plots, that is, only the data bound between the two dashed lines was used to generate the correlation plots shown on the right. We had found out earlier that the initial 5-sec ramp-up and final 5-sec ramp-down regions skewed the data because of the excessive amounts of normal force and normal vibrations. On the bottom left-hand-side of each figure, we show PMC values vs. time. On the top right-hand-side of each figure is the PMC vs. shear force correlation plots which indicate the correlation coefficient (R), the coefficient of determination (R^2), and the respective regression line. On the bottom right-hand-side of each figure is the PMC vs. COF correlation plots which indicate the correlation coefficient (R), the coefficient of determination (R^2), and the respective regression line. The data values for both correlation plots are the values in between the dashed line shown on the two plots to the left on each figure.

Regarding shear force vs. PMC, the average correlation coefficient and coefficient of determination for all 12 studied cases were 0.955 and 0.916, respectively. This indicated that, for the predetermined non-steady-state processes being investigated, shear force data could be replaced with PMC data with a high degree of confidence regardless of the type of processes, wafers, and consumables sets used. However, for COF vs. PMC, the average correlation coefficient and coefficient of determination for all 12 cases studied were much lower at 0.758 and 0.608, respectively. The lowest coefficients were observed for Cases 6 – 10 (ranging from 0.355 to 0.714 for R , and from 0.126 to 0.509 for R^2) indicating that when we accounted for normal forces (by calculating COF), the correlations worsened. The reason behind the strong correlations

seen in Cases 1 – 5, 11 and 12, and the lackluster correlations seen in Cases 6 – 10 are best explained by a closer examination of the Stribeck+ curves themselves as shown in Fig. 13 – 15. For Cases 1 – 5, 11 and 12, because each process is in “mixed lubrication”, or in “boundary lubrication” that quickly transitions to “mixed lubrication” ⁽⁶²⁻⁶⁴⁾, instantaneous COF values change greatly with the pseudo-Sommerfeld number thus allowing a strong correlation between COF and PMC. On the other hand, for Cases 6 – 10, Stribeck+ curves are mostly, if not entirely, in “boundary lubrication” where COF changes only slightly with pseudo-Sommerfeld number. The reasons as to why certain sets of consumables cause the tribological mechanism to be “boundary lubrication” or one that transitions to “mixed lubrication” have been explained in detail in our previous publications. ^(1, 4, 44) In Cases 6 – 10, even though we know that shear forces change dramatically as a function of pseudo-Sommerfeld number, their normal force counterparts change proportionately as well. This fact causes minimal changes in COF as a whole and grossly deteriorates the correlation coefficient and the coefficient of determination values.

Conclusion

This study investigated the correlation between shear force and PMC, as well as that between COF and PMC during highly non-steady-state conditions in tungsten and interlayer dielectric (ILD) CMP processes. The non-steady conditions were created by rapidly changing pressures and velocities within a given run. For the 12 cases studied (8 for tungsten and 4 for ILD), we found that real-time PMC data closely mimicked shear force data as evident from high average values of correlation coefficient and coefficient of determination for all 12 cases. This dependence was intuitive as increasing the load increased the shear force which in turn required motor current to increase in order to keep the rotational velocity of the platen constant. The converse was also true

as decreasing the load caused motor current to drop. As for COF vs. PMC, average correlation coefficient and coefficient of determination for 7 of the 12 cases was quite high. However, for the remaining 5 cases, correlation coefficients degraded significantly. The reason behind the strong correlations seen in the 7 cases, and the lackluster correlation seen in the other 5 cases were explained based on the particulars of the dominant tribological mechanism for each case. In summary, for the non-steady-state processes studied, it became clear that shear force data could be replaced with PMC data with a high degree of confidence regardless of the type of processes, wafers, and consumable sets used. Adopting PMC data in this way has widespread implications for IC manufacturers, most notably for monitoring the conditions at the pad-slurry-wafer interface without the need for installing costly friction plates (that are quite large and complex and may not always be suitable for certain types of polishers), force sensors, multiplexers and signal amplifiers.

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Table I. Polishing Conditions for Cases 1 and 2

CMP Step	Pressure (P, PSI)	Sliding Velocity (v, m/s)
1	2	1.4
2	2	1.8
3	4	1.0
4	3	1.8
5	4	1.8

Table II. Polishing Conditions for Cases 3 – 6

CMP Step	Pressure (P, PSI)	Sliding Velocity (v, m/s)
1	2	1.4
2	2	1.8
3	4	1.0
4	3	1.8
5	4	1.8

Table III. Polishing Conditions for Cases 7 and 8

CMP Step	Pressure (P, PSI)	Sliding Velocity (v, m/s)
1	1.8	1.0
2	3.2	1.0
3	1.8	1.8
4	1.8	2.0
5	2.5	1.8

Table IV. Polishing Conditions for Case 9

CMP Step	Pressure (P, PSI)	Sliding Velocity (v, m/s)
1	6	0.6
2	4	0.6
3	6	1.0
4	4	1.0
5	6	1.5
6	2	0.6
7	4	1.5
8	2	1.0
9	4	1.5

Table V. Polishing Conditions for Case 10 – 12

CMP Step	Pressure (P, PSI)	Sliding Velocity (v, m/s)
1	6	0.6
2	4	0.6
3	6	1.0
4	4	1.0
5	6	1.5
6	2	0.6
7	4	1.5
8	2	1.0
9	4	1.5

Figure 1. Case 1 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 2. Case 2 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 3. Case 3 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 4. Case 4 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 5. Case 5 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 6. Case 6 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 7. Case 7 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 8. Case 8 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 9. Case 9 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 10. Case 10 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 11. Case 11 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 12. Case 12 - Shear Force and Normal Force vs. Time (top left), Shifted PMC vs. Time (bottom left), Correlation Plot of Shifted PMC Data vs. Shear Force Data (top right), Correlation Plot of Shifted PMC Data vs. COF Data (bottom right).

Figure 13. Stribeck+ curves for. (clockwise from top left) Cases 1 – 4.

Figure 14. Stribeck+ curves for. (clockwise from top left) Cases 5 – 8.

Figure 15. Stribeck+ curves for. (clockwise from top left) Cases 9 – 12.