Tribology of Retaining Rings in Chemical Mechanical Planarization

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Stribeck and Stribeck+ curves helped determine the tribological mechanisms in the ring-slurry-pad interface. Both methods gave consistent results with the lubrication mechanism starting at "boundary lubrication" and transitioning to "mixed lubrication" as pseudo-Sommerfeld numbers increased. COF for PPS rings were higher than PEEK. They were also higher for inter-level dielectric (ILD) processes as compared to copper. Stribeck curves were used to infer wear rate information about the ring, which in conjunction with Stribeck+ curves could help choose process parameters that balanced wafer removal with ring wear. Data cluster shapes were shown to be due to shear and normal force fluctuations.

***Introduction* –** In CMP, a chemically-rich slurry containing abrasive nanoparticles is first delivered to the pad surface and allowed to form a thin film across the surface of the rotating polishing pad. A patterned wafer, having some gross topography, is then inserted within a carrier and held in place by a plastic retaining ring containing slots on its periphery for slurry access into the pad-wafer interface. The wafer and retaining ring assembly are then pressed face down against the pad which itself contains many surface asperities as well as deep grooves. Over time, a combination of chemical and mechanical effects remove the “up-features” of the wafer thereby resulting in local and global planarization of the workpiece.

One of the more effective methods for understanding CMP fundamentals, especially when it comes to the mechanical effects involved, is through tribological studies where the objective is to exploit frictional forces to remove a certain amount of material from the wafer while ensuring that the same forces are low enough to extend the useful life of the ring as well as the pad. Our research team has successfully shown the utility of traditional Stribeck curves in determining the lubrication mechanisms involved in the pad-slurry-wafer interface in CMP [1-3]. In our recent works, [4-6] we have also introduced a new method for determining an “improved” Stribeck curve (which we have called the “Stribeck+ curve”) that has yielded more useful tribological information while dramatically reducing consumables as well as experimental time compared to the traditional means. The key point that we have emphasized in our work is that the Stribeck+ curve does not assume normal force to be constant throughout the polishing process as we can measure it, as well as the shear force, instantaneously.

We believe that it would be highly beneficial if we could determine whether the utility of the Stribeck+ curve can be extended to retaining rings. This would help process engineers, tool makers and consumables suppliers to better understand the tribology within a given set of consumables, at certain process conditions, and aim to process robustness as well as increase ring life without compromising wafer removal rate. Here, we set out to tribologically test identically shaped broken-in PPS and PEEK rings having 18 equidistant peripheral slots (3-mm in width and depth), using copper and ILD slurries at various pressures and velocities to determine whether we can attain the above objectives.

***Experimental Apparatus and Procedure* –** All tests were done on an Araca APD-800 polisher and tribometer equipped with proprietary force transducers suitable for acquiring real-time shear and normal force at high (i.e. up to 1,600 Hz) frequencies [7]. Attached to the carrier head (needed to polish our 300 mm wafers) was an interface template with a retaining ring and backing film assembly. To isolate the COF in the ring-slurry-pad interface, the polishing process was performed without a wafer. Prior to polishing and data acquisition, a new CMC D100 concentrically grooved pad was broken in for 30 mins with deionized water using a 3M A165 diamond disc at a normal load of 44.5 N, a rotation rate of 95 RPM and a sweep frequency of 0.17 Hz. The same recipe was used for the *in-situ* conditioning during ring polishing. The ILD and copper slurries employed were Fujimi PL-4217 and PL-7106, respectively. Both slurries contained silica-based nano-particles and were pre-diluted as per the manufacturer’s specifications. In all cases, the slurry flowrate was 200 ml per min. For generating the Stribeck+ curves, we performed only one 3-minute polishing run with a multitude of gradual yet continuous changes (e.g. time-dependent ramp-ups and ramp-downs) in polishing pressure and sliding velocity. During each 3-minute run, normal forces and shear forces were instantaneously measured at 1,000 Hz. Table I shows the conditions for each step involved in constructing the Stribeck+ curve.

Each ramp-up or ramp-down step took approximately 2 seconds. The same pressure and velocity combinations were used to carry out the discrete runs needed to construct each Stribeck curve.

Results and Discussions – Fig. 1 shows the traditional Stribeck curves (circular symbols) corresponding to the PPS ring using both copper (red) and ILD (green) slurries. In each case, the 5 data points represent average COF values obtained from individual 2-minute polishes at a given pressure-velocity combination as per Table 1. Fig. 1 also shows the Stribeck+ curves (dots) corresponding to the same polishing conditions. For purposes of comparison, the 5 data points are superimposed on the 180,000 Stribeck+ data points obtained by a single run through multiple pressures, velocities and slurries (copper slurry in orange, and ILD slurry in black). For the copper slurry, the traditional Stribeck curve starts off in "boundary lubrication" with an average COF of about 0.44, and then begins to slightly transition into "mixed lubrication" half-way through where average COF drops to 0.36. The same trend is evident for the ILD slurry with 0.65 as the starting average COF value which then drops to 0.50 at higher pseudo-Sommerfeld numbers. It is clear that, with a single run, Fig. 1 is able to capture all of the trends seen in the individual Stribeck curve data points, and also provide additional valuable information as follows:

- The Stribeck+ curve, being continuous in nature, indicates that anomalous tribological behavior does not exist in between discrete polishing conditions.
- A fascinating commonality becomes evident in the evolution of the shape of data clusters as a function of pseudo-Sommerfeld number which is not just a visual artifact due to the log-log nature of the graph. Here, the ratio of measured variances

in shear force to those of normal force depend strongly on the pseudo-Sommerfeld number. We believe this to be a fundamental aspect of CMP that has so far been overlooked by the CMP community. We plan to report on it soon.

- As seen in the inset diagram in Fig. 1, the data points in each Stribeck+ curve can be replotted with the y-axis representing COF×P×v which we can assume to be proportional to the instantaneous wear rate of the retaining ring from a purely mechanical standpoint [8]. The notion of obtaining an indicator for instantaneous wear rate (or removal rate) from a single 3-min run can be quite powerful and revolutionary. This is a new idea and one that will require further study to be confirmed. Of course, in CMP, a particular pressure and velocity combination gets selected to cause a desired removal and planarization rate on the wafer surface, and not necessarily to reduce ring wear. However, given the fact that, in high-volume manufacturing, the pressure applied to a product wafer is always lower by 1 or 2 PSI than the ring pressure, we believe that our new way of combining the tribological and implied ring wear (or wafer removal) rate plots can help process engineers select desired operating conditions based on their main sets of objectives having to do with planarization rate, wafer throughput and consumables wear.

By way of another example, we performed tests at the same conditions using a retaining ring made of a different material (polyether ether ketone, PEEK) which had the same size and geometry as that of the PPS ring. Over the years, PEEK has emerged as an alternative to PPS for constructing retaining rings. This is due to various reasons such as less shedding, higher wear-resistance, lower COF and lower operating temperature during CMP. Fig. 2, confirms that similar trends exist in the case of the PEEK ring when it comes to Stribeck and Stribeck+ curves, as well as the implied kinetic curve shown in the inset diagram. In Fig. 2, it must be noted that, for a yet to be determined reason, the superimposition does not work as well as that in Fig. 1 as the individual runs associated with the Stribeck curve of Fig. 2 are not always centered inside the respective data clusters of the Stribeck+ curves.

Both figures indicate that COF values for the PPS ring are on average 21 percent higher than PEEK. The higher values are consistent with earlier findings by other researchers [9]. Average COF values are also higher by 55 percent for ILD processes as compared to copper. This is likely due to the higher abrasive content of the ILD slurry (10% by weight) as compared to less than 1% for the copper slurry. Average pad surface temperature for the PPS ring is 9 to 11 °C higher than that of PEEK. Also, in all cases, pad temperature is higher by 2 to 3 °C when the ILD slurry is used as compared to the copper slurry. These temperature differences are quite consistent with, and a result of, their corresponding COF values.

***Conclusions* –** We utilized Stribeck and Stribeck+ curves to tribologically characterize PEEK and PPS retaining rings for copper and ILD CMP. Both methods led us to the same set of conclusions: for a given slurry type COF values for PPS were always higher than for PEEK, and the same relationship held for ILD processes as compared to copper. Pad temperature measurements also corroborated the above finding. Stribeck+ curves were used to construct new kinetic curves which inferred wear rate information about the ring. This information, when used in conjunction with Stribeck+ curves can help identify process parameters that balance wafer removal rate with ring wear rate at a given tribological state. In all cases, a fascinating commonality was seen in the evolution of the shape of data clusters as a function of pseudo-Sommerfeld number indicating the presence of a complex interplay between variances in normal and shear force which will be a subject of our next study.

References

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Table I. Experimental conditions for Stribeck and Stribeck+ curves.

Stribeck+ Step No.	Duration of the Stribeck+ Step (sec)	Pressure (PSI)	Sliding Velocity (m/s)
1	60	2	1.2
2	30	2	1.8
3	30	4	1.8
4	30	6	1.2
5	30	6	1.8

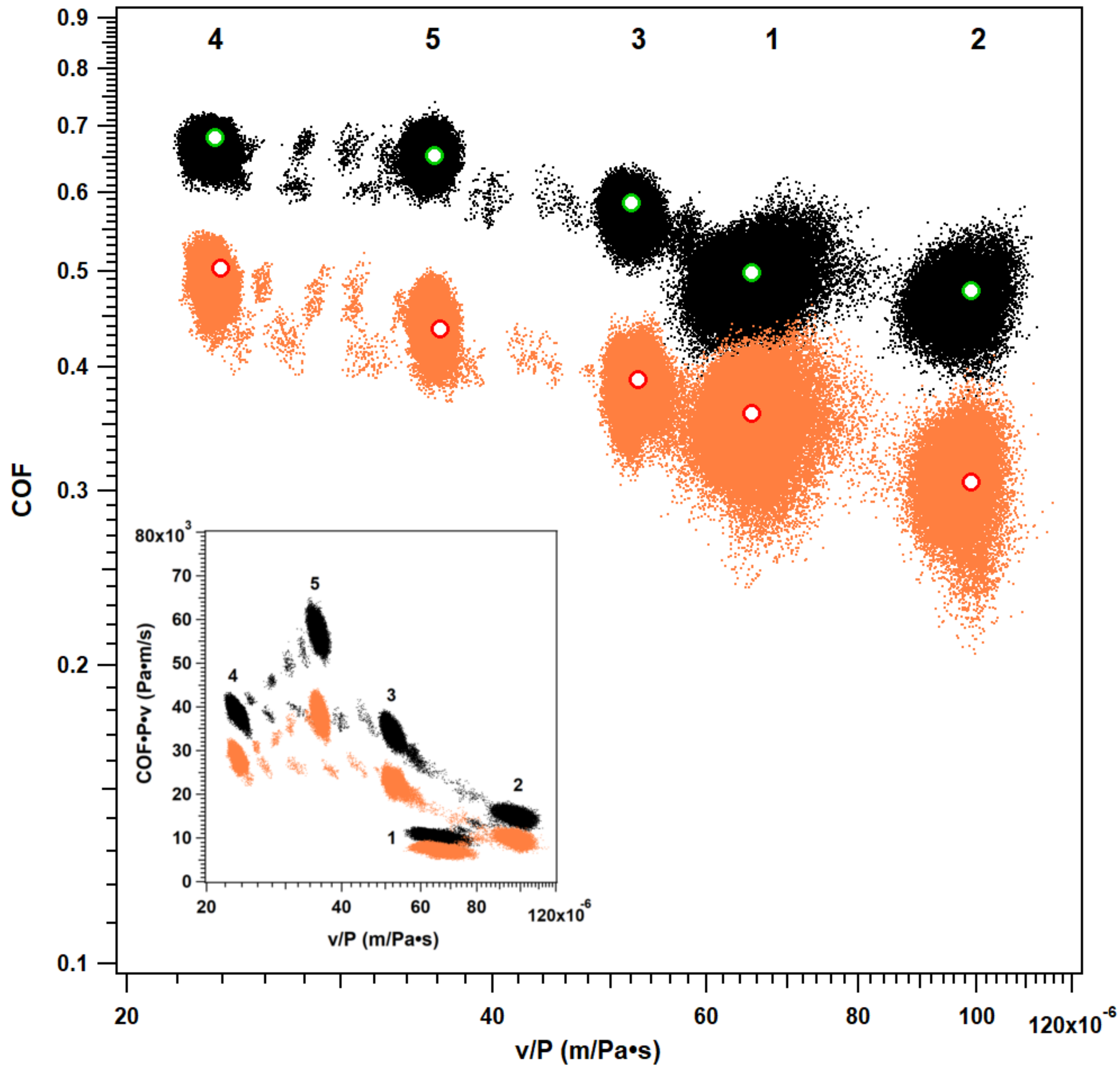

Fig 1. *Stribeck (open circles) and Stribeck+ (clusters) curves corresponding to the PPS ring using PL-4217 (black) and PL-7106 (orange).*

Numbers correspond to step numbers in Table 1.

Inset: Implied ring wear rate as a function of pseudo-Sommerfeld number for PL-4217 (black) and PL-7106 (orange).

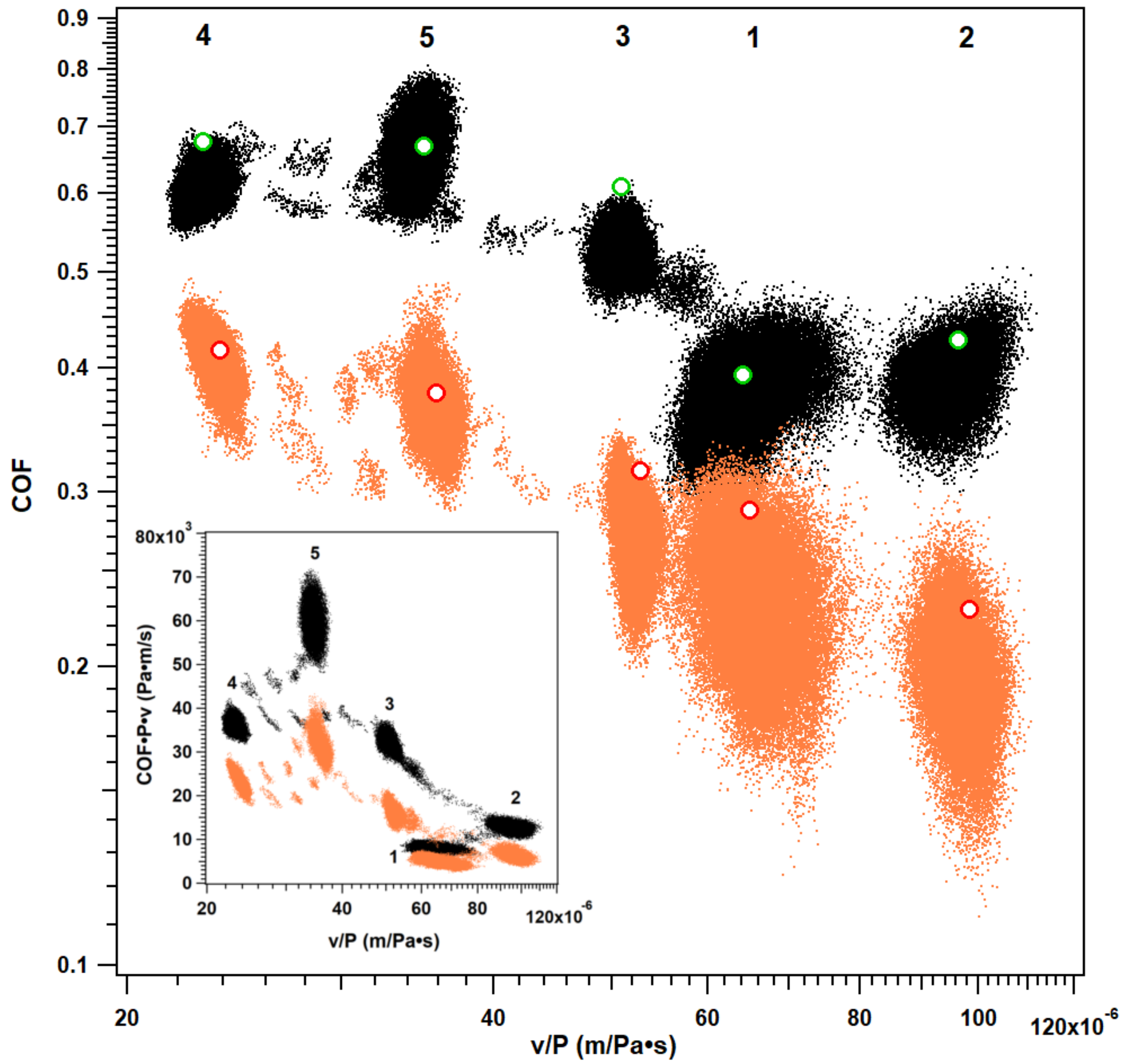

Fig 2. *Stribeck (open circles) and Stribeck+ (clusters) curves corresponding to the PEEK ring using PL-4217 (black) and PL-7106 (orange).*

Numbers correspond to step numbers in Table 1.

Inset: Implied ring wear rate as a function of pseudo-Sommerfeld number for PL-4217 (black) and PL-7106 (orange).