Tribology Case Studies for Copper Removal Optimization

Norm V. Gitis
Center for Tribology Inc.
www.cetr.com
Jerry Jin, David Craven
Lam Research Corp

Introduction

In examining pad properties, this paper will concentrate on the properties related to the pad material, principally because this is perhaps the easiest, most fundamental study of pad parameters, and is of most universal applicability for CMP users.

Surface roughness would qualify for attention because of its overwhelming impact on material removal characteristics. We will reflect on surface roughness to the extent that it shows up in coefficient of friction. However, there are many aspects of surface roughness that are important, and would necessitate a paper it there own right. But it would perhaps be useful to comment on some measures of surface roughness. Two common measures of surface roughness are Ra and Rq (the arithmetic and root-mean-square averages respectively). The tribology of many common surfaces are such that the differences between these two measurements is slight. However for CMP, a simple use of these measures are radically different in the results they produce, with neither one of them being a good representation of the active removal agent. The problem is the inherent confounding of the plateau roughness with the pore structures. The only measure that is useful to a tribological understanding of the pad performance is the roughness of the plateau. The effect of the pores as a slurry reservoir is essential to the big picture, but simply becomes noise to the tribological measure of surface roughness. Some tools have emerged in an effort to separate these effects (padIMAGER[1] , Wyko NT3300[2])

Perhaps the most practical measure of the pad surface quality would be that of coefficient of friction. The mechanical nature of the pad surface is most practically demonstrated through its ability to provide a frictional effect on the contacting surface. Whether the surface is uniformly rough or pitted with pores is not of primary concern when the principle processing effect is a direct result of the friction generated. Likewise, the addition of slurry onto the surface will change the dynamics of the surface roughness in ways that are difficult to estimate by first principles; but these effects can be seen immediately through their impact on the coefficient of friction. Thus the coefficient of friction serves as an integrated measurement of the essential mechanical effect of pad on the surface being processed. The power of this is illustrated in fig.1, where the coefficient of friction was measured through the polishing of a Copper/Low-k dielectric film stack[3]. It is clear that the change in value of the coefficient of friction can be used as a sensitive marker for the transitions across these material interfaces.

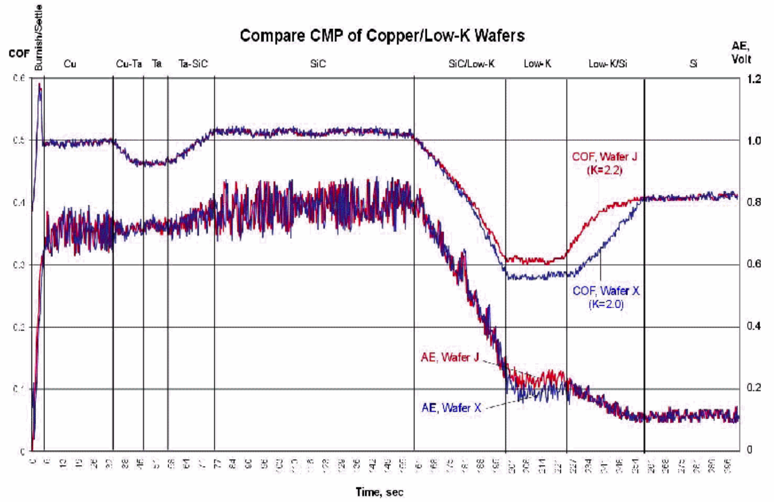


Fig.1: Sensitivity of coefficient of friction (and acoustic emission) to changes in interface material layers

Fig.2: CMP Tester model PMT from Center for Tribology Inc.

Experimental Approach

The static and dynamic characteristics were studied for several different pads. The coefficient of friction measured at the polish head (during polishing of copper wafers) as well as at the conditioner disk for conditioning processes. The tool used was CMP Tester, Model PMT(fig. 2), at the Center for Tribology, Inc. in Campbell CA. The system consisted of a rotary axis for wafer mounting with precision translation and rotational motions. Rotational motion can be varied between 0.1 and 1,000 rpm, and the close-loop servo provides precision downforce from 0.001 N to 100 N. Torque, coefficient of friction (COF), and contact high-frequency acoustic emission can all be measured in real time at a total sampling rate of 20 kHz (along with other measures, such as normal force and pad wear). This bench-top tester was used to examine both the inherent operational pad parameters (such as COF) as well as static pad parameters, (such as loading responses, deformation, and creep).

Previous data[3] had demonstrated the utility of COF measurement for quality control of both pads and slurries (fig. 3 & 4) in the identification of outliers. It was hoped that the investigation of static and dynamic COF measurements would prove useful in understanding pad behavior and performance.

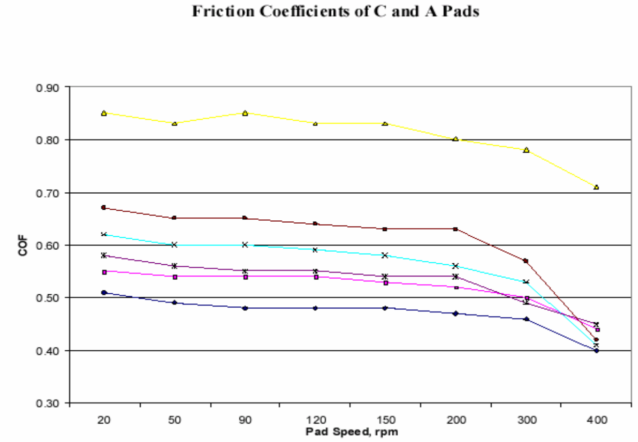


Fig. 3: Use of COF as a quality control tool for pads

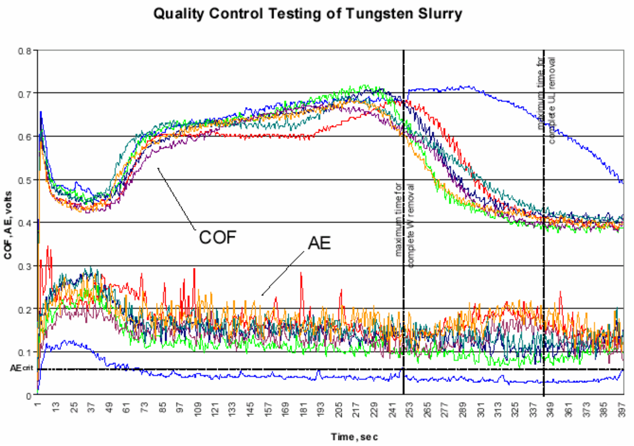


Fig. 4: Use of COF as a quality control tool for slurries

The primary study was a comparison between two different pads to examine their static and dynamic characteristics and observe any differences in processing behavior. The coefficient of friction was measured (as well as the RMS fluctuations in the measurements) on both a copper disk and the conditioning disk during the experimental trails. The results are tabulated in tables 1 & 2 (for the copper polishing and the conditioning respectively) and plotted in the graphs of fig. 5 & 6. The behavior is consistent, with the pad 2 displaying a higher coefficient of friction and a lower RMS fluctuation.

Copper Polishing		
	COF	RMS COF fluctuations
pad 1	0.217	0.031
pad 2	0.287	0.004

Table 1: Copper Polishing COF and RMS fluctuations

Conditioning		
	COF	RMS COF fluctuations
pad 1	0.523	0.093
pad 2	0.656	0.023

Table 2: Conditioning COF and RMS fluctuations

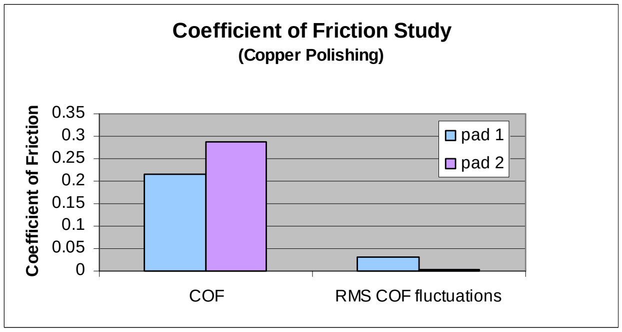


Fig. 5: Coefficient of friction study for copper polishing

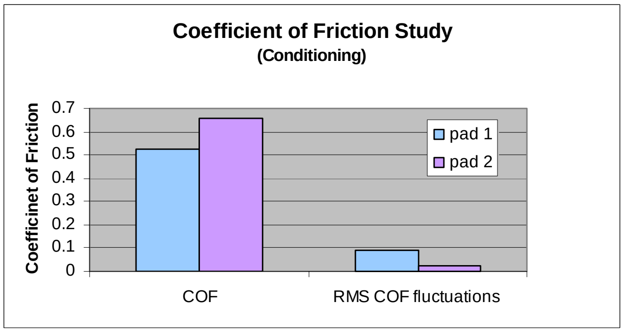


Fig. 6: Coefficient of friction study for conditioning

These pads were also examined for visco-elastic behavior of loading, deformation, and creep. The loading required to achieve 0.2mm of deflection was measured (N) for both fast and slow loading scenarios. Again the data was fairly consistent; pad 2 displayed evidence of greater visco-elasticity over pad 1 with lower load values for both fast and slow response, larger creep response for both short and long time intervals, and greater deformation (table 3 and figures 7 – 9).

Visco-elastic Parameter Study					
Pad	Loading		Deformation	Creep	
	slow	fast		10 sec	60 sec
pad 1	130	145	15	4	5
pad 2	96	119	22	5.4	7.1

Table 3: Visco-elastic parameter study

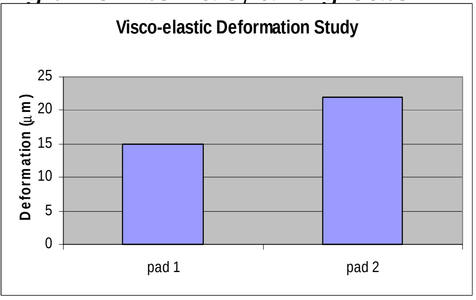


Fig. 7: Visco-elastic deformation study

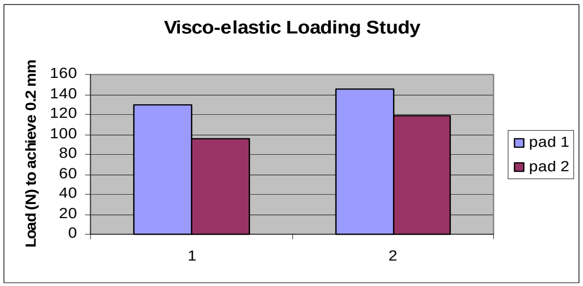


Fig. 8: Visco-elastic loading study

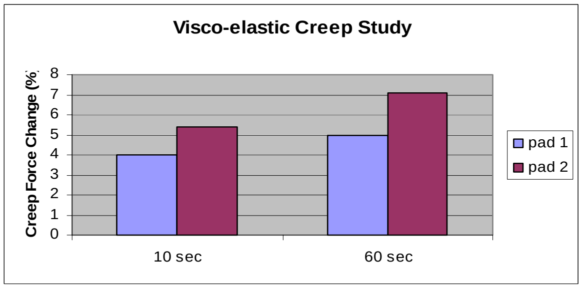


Fig. 9: Visco-elastic creep study

There have been previous studies linking coefficient of friction with material removal rate, one of which is was presented to the CMPUG 9/2002[4], illustrated in fig. 10. The two belts examined in this study also indicated a similar trend (table 4 and fig. 11). It is interesting to note that the removal rate demonstrated by belt 2 was higher than belt 1, and both the standard deviation of the removal rate results as well as the across-wafer non-uniformity were lower. More data, however, should be gathered to substantiate these results.

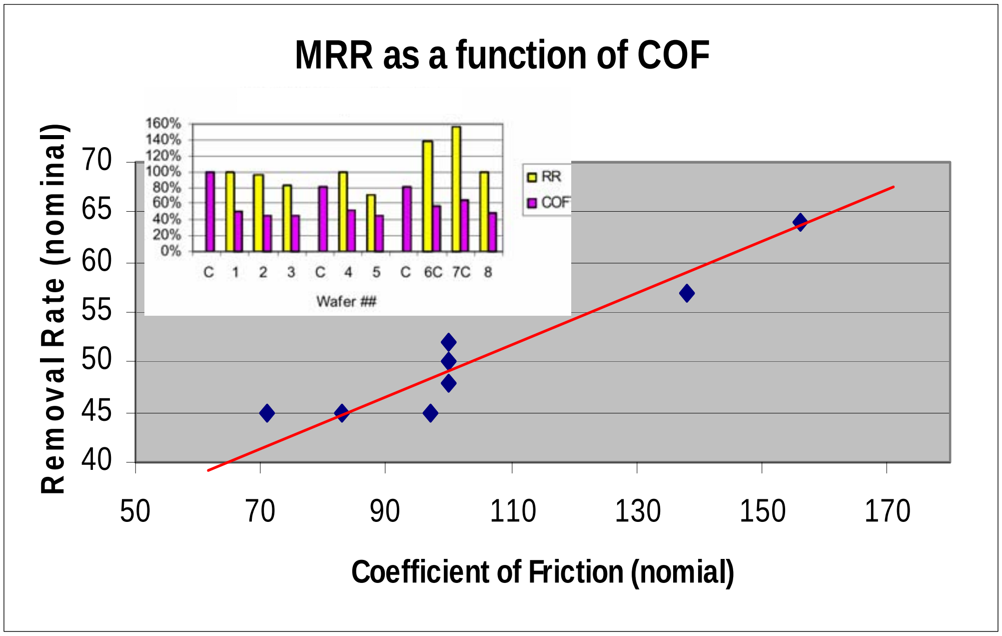


Fig. 10: Material removal rate as a function of COF

	Belt 1	
Grand Ave	3644.571	6.428571
stdDev	250.3683	0.786796
%stdDev	6.869623	12.23905
	Belt 2	
Grand Ave	4848.75	5.1125
stdDev	200.291	1.010569
%stdDev	4.130777	19.76663

Table 4: Statistics for Copper removal belt study

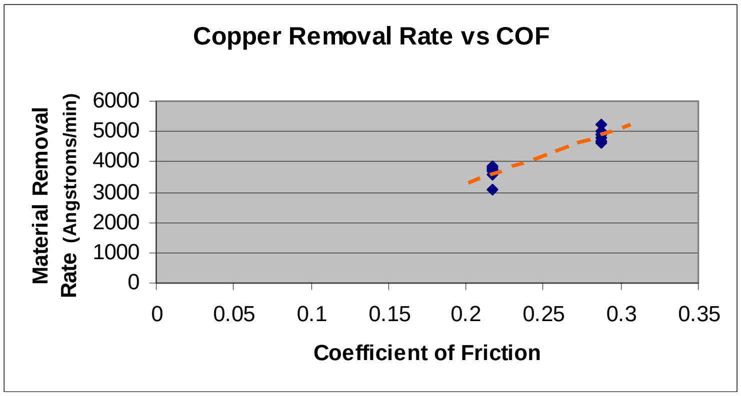


Fig. 11: Copper removal rate vs COF

The study was extended to view the COF uniformity of one belt in the vertical direction by sampling the coefficient of friction at various depths as the pad was worn down. The COF was sampled at the surface, and then again at 0.5, 1, 5, and 10 mils depth. Table 5 and fig. 12 display the results, from which it is apparent that the effective coefficient of friction can vary by about 3% for small changes in pad depth to nearly 10% over some ranges. One might expect from this that the consistency of the process removal rate might vary with time if the pad material properties are not well controlled during manufacturing.

Pad Depth	COF	RMS COF
0	0.33	0.008
0.5	0.31	0.01
1	0.31	0.005
5	0.3	0.006
10	0.3	0.009

Table 5: Pad Depth and COF values

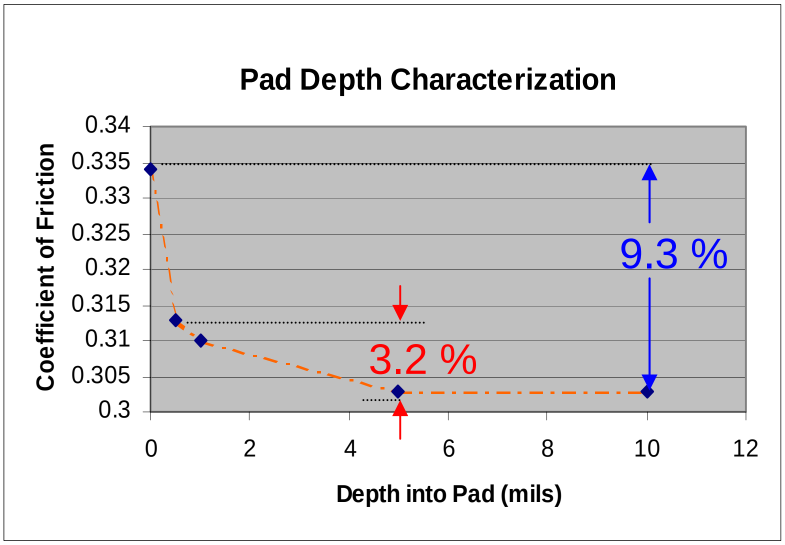
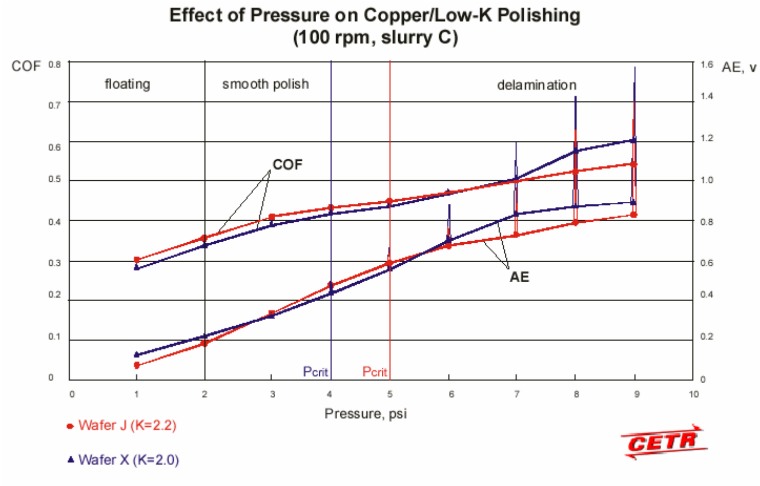


Fig. 12: Pad Depth Characterization

The implication for low-k dielectrics can be drawn from the results depicted in fig. 13. These data show the effects of the coefficient of friction from a series of runs made on two wafers. The interaction regimes are demarcated, including the COF region that correlated with low-k film delamination[3].



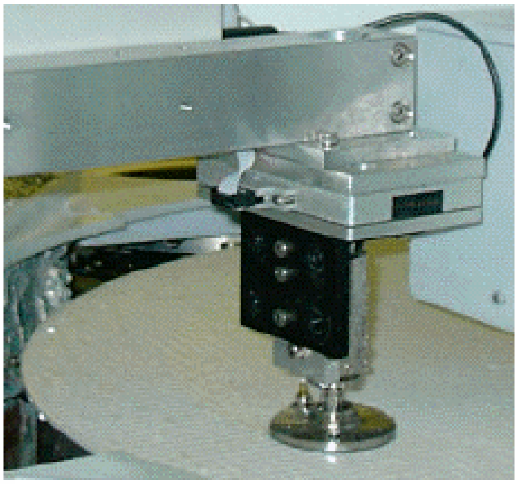


Fig. 13: Effect of Pressure on Copper/low-k Polishing

Fig. 14: PadProbe^{TM} instrument for in-situ COF measurements

Summary

The important result from these experiments is that a real-time monitoring of the coefficient of friction during production polishing could provide valuable information about the nature and health of the process, from pad and slurry performance control to real-time endpoint support.

Fill this requirement, the Center for Tribology has produced a non-invasive PadProbe^{TM} which can be easily installed on any CMP tool to provide in-process feedback on the two critical parameters of coefficient of friction and pad wear (fig. 14).

In conclusion, this study has displayed data supporting the early indication that coefficient of friction is a critical parameter in the CMP process. Tools are available for real-time monitoring, which provide potential for closed-loop control of important transitions, performance variations in consumable materials, and process irregularities.

1. T. Vo “Polishing pad characterization with in-situ metrology instrument”, CMPUG 090402 - PadIMAGER: Tessellation, San Jose
2. A. Scott Lawing “Polish rate, Pad surface morphology and pad conditioning in oxide chemical mechanical polihsing” ,Proc. 5th Symposium on CMP, 5/12/2002 Electrochemical Society
3. Norm V. Gitis “Quantitative function testing of consumables using a bench-top CMP tester”, CMPUG 0901
4. Norm V. Gitis “PadProbeTM for quantitative control of pad surface conditions and wear”, CMPUG 090402