Using Friction Measurements to Characterize Chemical Mechanical Polishing Lubrication Regime

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1 Abstract

A small scaled (1:2) polishing platform was used to examine slurry behavior during polishing. In particular, wafer friction data is used to begin to characterize the lubrication regime during CMP processes. Friction measurements are made non-intrusively during normal polishing operations. Friction data is investigated as a function of conditioning, down force, platen speed, and flow rate. The friction data suggests that all four variables interact to determine the overall lubrication regime. In situ conditioning interacted with platen speed to cause the wafer to oscillate between asperity contact and hydroplaning modes of contact. Platen speed and down force also interacted to determine the onset conditions for hydroplaning. Flow rate had a non-linear effect on the magnitude of the coefficient of friction. Down force always increased the wafer drag except in the hydroplaning contact mode. Both asperity contact and hydroplaning modes of contact were attained under normal CMP conditions.
2 Introduction

One of the most important factors governing polishing performance is the interaction between the pad and wafer. The nature of this interaction determines the polishing mechanism and can be described in terms of the three different lubrication regimes. The three different lubrication regimes include direct contact, partial asperity contact, and full separation (hydrodynamic lubrication). It is unclear whether the pad and wafer are in intimate contact, fully separated by a hydrodynamic layer, or some combination of the two. Research groups have supported hydrodynamic polishing [1, 2, 3, 4, 5, 6], and varying degrees of asperity contact [7, 8, 9, 10].

The goal of this research is to correlate an easily measurable quantity on an industrial polisher to the lubrication regime beneath a wafer during polishing. One such measurement that has been historically used to provide information about the lubrication regime is friction. Maps of friction data over a range of platen speeds and head down forces can be compiled in terms of a Striebeck curve in order to identify the lubrication regime where polishing is being performed. Figure 1 shows a typical Striebeck curve for a journal bearing with the associated fluid lubrication regimes [11]. The y-axis is magnitude of the coefficient of friction. The coefficient of friction is defined as the drag force over the total applied force. Below the x-axis is a dimensional number obtained by dividing the viscosity (Z in Poise) and speed (N in revolutions/minute) by pressure (P in psi). While the x-axis scaling will almost certainly be different for elastohydrodynamic lubrication, the general trend showing the three regimes will most likely apply. Therefore, friction is one of the quantities used to characterize the pad-wafer interaction.

Since the shape of the friction curve is not known a priori, other measurements are required to correlate the friction curve with the polishing lubrication regime. For example, we have started to measure the slurry depth beneath the wafer to provide complementary information on the lubrication regime [12]. Direct slurry depth measurements beneath the wafer are useful in separating the lubrication phenomenon from the pad deformation and are performed using a fluorescence technique. This article will focus on how friction measurements are affected by down force, platen speed, flow rate, and in situ conditioning.
3 Experimental Apparatus

We have created a functional small scale (1:2) version of an industrial silicon dioxide (oxide) chemical mechanical polishing platform in order to measure the behavior of slurry flow. This setup is described in detail in our previous work [12] [13] [14] and therefore only a brief description will be included here. Figure 2 shows our modified CMP setup used to study the slurry flow beneath a wafer. A tabletop Struers RotoPol-31 polisher is used to rotate a 30.5 cm (12") polishing pad. In situ or ex situ pad conditioning can be performed using the device shown in Figure 3. A 75 mm (3") diamond grit wafer co-rotating with the platen conditions the pad by periodically sweeping across the pad radius. The tabletop polisher is mounted on a slider table to allow friction measurements as shown in Figure 4. The slider table’s position is fixed using a strain gauge so that one can measure the force (wafer drag) required to keep the table from sliding. The force is typically sampled at 100 Hz for 10 seconds. We calibrated the strain gauge by applying known forces on the slider table and found that the measurements were repeatable to within 3.5% of the applied load. The RotoPol head has been replaced with a 20” industrial rated drill press that both rotates and applies down force to a 75 mm (3") wafer. Typical removal rates were between 1000 to 3000 Angstroms/min. The wafer used in this study had a bowed surface because of edge fast polishing. The height difference between the wafer’s center to edge was approximately 12 microns. Since we perform measurements of fluid parameters using an optical technique known as dual emission laser induced fluorescence or DELIF [15], the wafer must be transparent and a pure silicon wafer cannot be used. Instead, a glass wafer that is transparent to visible light is used. Many of the polishing parameters including platen speed, down force, slurry delivery, and conditioning speeds are computer controlled and monitored.
4 Methodology

Before any data was acquired a microporous urethane pad (no sub-pad) was placed on the platen where it was conditioned for 10 minutes using a diamond grit (163 micron) wafer that both rotates about its own axis and oscillates across the pad. The physical properties of the Freudenberg FX-9 polishing pad are shown in Table 1. A 1:1.5 dilution of Cabo-Sperse SC1 slurry was continuously fed onto the pad during conditioning at approximately 35 cc/min. Head and platen rotation rates were set at 60 rpm during conditioning. The head speed remained at 60 rpm for all tests. Once conditioning was completed, measurements were conducted on the pad. Friction measurements were made on two polyurethane pads (Freudenberg FX-9) on two different days. The pad was continuously conditioned during all friction measurements. A range of CMP parameters were investigated; platen speeds from 30-180 rpm, wafer pressures from 14-42 kPa (2-6 psi), and flow rates from 20-50 cc/min.

[Table 1 about here.]

5 Results

There were two dominant features in the friction curve regardless of the pad manufacturer, platen speed or down force. Figure 5 shows a typical friction measurement taken on a Freudenberg FX-9 pad rotating at 30 rpm with 14 kPa (2 psi) down force. Note that there is a dominant frequency at 0.5 Hz or 30 rpm. This feature is present in all friction curves and the dominant frequency always matches the platen rotational frequency. The sinusoidal pattern did not appear when the polisher was running but the wafer was not in contact with the pad, therefore the pattern was attributed to a mechanical effect. Measurements on the platen showed that the platen height varied by as much as 0.38 mm (0.015 inch) in one rotation. Efforts to reduce this irregularity using shim stock reduced the amplitude of the sinusoid but did not eliminate it. A precise method of leveling the table will be required to eliminate the problem.

[Figure 5 about here.]
More importantly, in situ conditioning caused large fluctuations in the friction values at high platen speeds. The conditioner’s motion periodically feeds and starves the wafer of slurry, as shown in Figure 6. The friction is the lowest when the conditioner is located closest to the center of the pad and directing slurry toward the front of the wafer and highest when the conditioner is directing slurry away from the wafer. When slurry is directed toward the wafer the fluid appears to provide a fluid bearing. Figure 7 shows the conditioner’s effects on the friction curve at platen rotation rates of 90 and 150 rpm. Note that the platen’s mechanical effects are still present but the overall friction signal is modulated at the conditioner’s oscillation frequency of 0.125 Hertz. The lower drag values result from the conditioner directing slurry to the wafer while the higher friction values result from the conditioner directing slurry away from the wafer.

[Figure 6 about here.]

[Figure 7 about here.]

Figure 8 shows a typical map of the coefficient of friction as a function of platen speed and wafer down force when the conditioner is not starving the wafer. The slurry flow rate was 20 cc/min.

[Figure 8 about here.]

There are several trends that are apparent in Figure 8. The coefficient of friction increases with an increase in down force except at high platen speeds. The increase in the coefficient of friction with down force suggests that the pad-wafer interaction changes with a change in down force. The change in the interaction may be the result of pad deformation, a change in the orientation between the pad and wafer, or a change in the fluid film thickness. As mentioned previously, friction data alone cannot characterize the pad-wafer interaction and therefore more data is required to understand the trends.

All of the curves in Figure 8 tend to decrease to a very low value above platen speeds of 100 rpm or 0.9 m/s. This trend suggests that the wafer is starting to hydroplane at high platen speeds. A higher down force causes the friction curves to plateau at higher platen speeds because the fluid film thickness decreases with an increasing applied load. It is somewhat surprising that once the coefficient of friction reaches its minimum
value it becomes nearly independent of platen speed. A higher platen speed should produce greater shear stress in the fluid between the pad and wafer. However, a simple calculation of the wall shear stress indicates that the drag on the wafer due to the fluid shear is negligibly small assuming a linear velocity gradient between the pad and wafer and a 30 micron gap width. One can estimate the shear force \( F_{\text{shear}} \) as:

\[
F_{\text{shear}} = \int \int \mu \frac{dV}{dy} \bigg|_{y=0} dx \, dz \approx \mu \frac{dV}{dy} \ast A \approx 1 \times 10^{-3} \frac{kg}{m \ast s} \left( \frac{0.5 \text{m}}{30 \times 10^{-6} \text{m}^3} \right) \pi (0.038 m)^2 = 0.076 \text{N},
\]

where \( \mu \) is the absolute viscosity, \( V \) is the relative velocity between the pad and wafer, \( y \) is the coordinate perpendicular to the pad surface, \( A \) is the wafer’s area, and \( x \) and \( z \) are coordinates in the plane of the pad surface. The calculation shows that the drag force due to fluid shear is 0.076 Newtons or 0.017 lb, which translates into a coefficient of friction that is smaller than 0.001. Thus, increasing the platen speed by a factor of two would also produce a change in the drag that would fall within the uncertainty of the measurement system. Therefore, something other than fluid shear must be the source of the frictional forces.

First, the above calculation is oversimplified. If the wafer were completely separated from the pad, it stands to reason that the actual gap between the pad and the wafer would be much smaller than the measured fluid depth because of the pad asperities. Also the fluid gradient may be more complicated than a simple linear function and the added friction of polishing is not included in the calculation.

Finally, at higher pressures and low platen speeds, a local maximum occurs in the coefficient of friction; possibly due to changes in pad deformation. The pad is a viscoelastic material and as such it has the characteristics of a viscous fluid at low deformation rates and the characteristics of an elastic solid at high deformation rates. Therefore, a greater force would be required to move the wafer at a faster rate through the (viscoelastic fluid) pad at low deformation rates. This trend continues until the local maximum in the coefficient of friction, after which either the wafer begins to separate from the pad or the pad begins to move too fast to deform beneath the wafer. The pad’s resistance to deformation at high platen speeds may explain flat region of the graphs when the wafer is slurry starved (not hydroplaning). To determine if this hypothesis
is plausible, one would need to measure the time scales and magnitude of pad deflection and viscoelastic constants.

Friction maps of down force and platen speed were created for the two different Freudenberg pads at three different flow rates (20 cc/min, 35 cc/min, and 50 cc/min). Figure 9 shows the friction data with the conditioner located towards the center of the pad and each data set appears to follow the same trend. Figure 10 shows the friction data with the conditioner located towards the edge of the pad (slurry starved case) and the data sets appear to have more scatter than those in Figure 9. Note the large difference between the shape and magnitude of the friction curves when the wafer is slurry starved versus slurry fed. Clearly, fluid mechanics is playing a large role in the pad-wafer interaction over the entire range of parameters examined. That is, 50 cc/min caused the highest friction, followed by 20 cc/min, and finally 35 cc/min. As expected, neither curve resembles the Stribeck curve for a journal bearing. Additional types of data, such as the fluid film thickness and wafer orientation relative to the pad are required to fully understand the friction data. We recently have demonstrated the ability to measure the fluid film thickness and the wafer’s orientation relative to the pad [12] and intend on using this technique to correlate the friction data to the polishing lubrication regime. This will be accomplished by simultaneously measuring the fluid film thickness and friction data, the results of which will be included in future publications.

6 Discussion

The friction trends suggest that the lubrication regime could either be described as hydrodynamic or asperity contact depending upon the platen speed, wafer down force, slurry flow rate and conditioning. All of these variables interact with each other to produce the overall lubrication regime. The conditioner has one of the largest effects on the overall fluid flow and thus the lubrication regime. Depending on the conditioner’s position, fluid is either directed toward or away from the wafer, which can cause the contact mode to oscillate.
between asperity contact and hydroplaning lubrication regimes. When fluid is directed toward the wafer the friction decreases, and when the conditioner directs fluid away from the wafer the friction increases. The friction is also strongly influenced by the slurry flow rate and the platen speed. Faster platen speeds tend to decrease the friction, indicating the onset of a hydroplaning mode. Down force always increased the drag on the wafer except at high platen speeds where the wafer is believed to be hydroplaning.

The main goal of this research is to correlate the polishing performance to the fluid behavior. While we are currently working on this aspect of the research, the data we have now suggests that the slurry behavior has a large impact on how the wafer interacts with the pad. Therefore, slurry behavior will most likely have a large impact on the polishing performance. We have several hypotheses, based on physical arguments, on how the slurry behavior may influence the polishing performance. One hypothesis is that the wafer’s angle of attack relative to the pad will have a large impact on the polishing uniformity. Increasing the wafer’s angle of attack is expected to reduce the wafer’s uniformity because of the resulting non-linear pressure distribution across the wafer’s surface. This non-linear pressure distribution when the wafer is not parallel to the pad is expected regardless of whether the wafer is hydroplaning or not. Removal rates and wafer topography maps indicate that our wafer is bowed which may provide direct evidence to support the uniformity’s dependency on the wafer’s angle of attack. The question remains whether the wafer’s bow caused the angle of attack or whether the angle of attack caused the wafer’s bow.

Increasing the amount of pad asperity contact is expected to increase the polishing removal rate. This is because the pad asperities locally increase the pressure between the slurry particles and the wafer. Friction data supports the notion that the wafer hydroplanes above certain platen speeds. At platen speeds above 90 rpm, in situ conditioning may cause the wafer to oscillate between asperity contact and hydroplaning interactions with the pad. Platen speed’s effect on the removal rate would be expected to be linear within a lubrication regime but non-linear during transitions. That is, within either asperity contact or hydrodynamic regimes, increasing the platen speed should increase the removal rate due to an increase in mechanical energy or fluid shear. Conditions that cause a transition between asperity contact to hydroplaning regimes should cause a decrease in the removal rate.
Finally, increasing wafer drag is expected to increase the removal rate because more mechanical energy is being delivered to the wafer surface. This concept may not be true if the wafer is slurry starved. Therefore, platen speed and flow rate are expected to have a more complex effect on the wafer drag because these factors influence whether the wafer is in partial contact with the pad but lubricated, in partial contact with the pad but slurry starved, or completely separated from the pad. Also, the shape and trends in the friction curves were too complicated to ascertain the dependencies from the limited data. The only trend that is clearly evident is that down force increases the wafer drag, although not necessarily the coefficient of friction. This is because the coefficient of friction is a normalized value (wafer drag normalized by the wafer down force) that is expected to change only when the friction mechanism changes.

7 Conclusion

We have shown friction data that suggests that the lubrication regime in chemical mechanical polishing is dependent upon in situ conditioning, flow rate, down force, and platen speed. The combination of these variables can cause the polisher to operate in an asperity contact mode or a hydroplaning mode. Because of the conditioner’s effect on the bulk slurry flow, in situ conditioning can have the strongest effect by causing the polisher to oscillate between the two contact modes even if the other variables are kept constant. Therefore, in situ conditioning is likely to have a large impact on the polishing performance. In general, slurry behavior may have a large affect on polishing performance by influencing the wafer’s angle of attack relative to the pad, the lubrication regime or amount of asperity contact between the pad and wafer, and the amount of friction between the wafer and pad. Future work will involve simultaneously measuring friction and fluid film depth over a larger number of pads and correlating the slurry behavior to the polishing performance.

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to measure removal rates. We would also like to thank Freudenberg Nonwovens for donating FX-9 polishing pads.
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Table 1: Physical properties of Freudenberg FX-9 polishing pads