A Statistical Analysis of Key Parameters in Slurry Transport beneath a Wafer during Chemical-Mechanical Polishing

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1 Abstract

A small scaled (1:2) polishing platform was used to examine slurry behavior during chemical-mechanical polishing. In particular, we examined the slurry and mixing using a five factor three level statistically designed experiment. The five factors examined were platen speed, flow rate, down force, pad grooving and pad manufacturer. Each of these parameters were examined with in situ conditioning and ex situ conditioning. Residence Time Distribution analysis revealed that the slurry mean residence time beneath a wafer depended upon all of the main factors except down force, and main factor interactions were significant. In situ conditioning had a large effect on both the slurry mean residence time and slurry mixing. All other parameters being equal, in situ conditioning was shown to increase the rate of slurry mixing by 60 percent and increase the slurry’s mean residence time by 60 percent compared to ex situ conditioning.

2 Introduction

There are very few experimental studies on slurry transport in CMP processes even though many researchers have commented on the importance of slurry fluid mechanics in polishing [1-10]. Characterizing slurry flow is important in understanding the role of slurry fluid mechanics in polishing and determining how to optimize the slurry’s effectiveness. With these goals in mind, we have studied five basic CMP parameters in order to determine how they influence slurry transport. Our previous research investigated trends in slurry
transport caused by individually changing each of these five CMP parameters [11]. This paper extends that work by systematically studying the effects of all five parameters through a statistically designed experiment. The five parameters investigated are platen speed, slurry flow rate, down force, pad topography, and pad manufacturer. The results of the statistically designed experiment show how the five parameters individually and collectively influence slurry transport.

3 Experimental Apparatus

In order to characterize the polishing process, we have constructed a tabletop polishing platform which is a 1:2 scale model of an industrial IPEC 472 polisher. A detailed explanation of the experimental apparatus can be found in our previous work [11,12] so only a brief description will be included here. Figure 1 shows the 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. The standard 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. Since we are measuring fluid parameters using an optical technique known as dual emission laser induced fluorescence or DELIF [13], 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. Two high-resolution spatially aligned 12-bit digital cameras are used to measure the fluorescence beneath the wafer. In situ or ex situ pad conditioning can be performed using a conditioning device. A 75 mm (3”) diamond grit wafer co-rotating with the platen conditions the pad by periodically sweeping across the pad radius. Many of the polishing parameters including platen speed, down force, slurry delivery, and conditioning speeds are computer controlled and monitored. In addition, the computer synchronizes the camera to the polishing process so that we can interrogate the wafer at any point in the polishing process.

[Figure 1 about here.]
4 DELIF Measurement Technique

The DELIF technique uses the fluorescence from two different dyes each fluorescing at different wavelengths to measure mixing, fluid depth, or temperature and is described in detail in Coppeta and Rogers [11-13]. The fluorescence from one dye contains the information about the parameter of interest as well as the laser distribution and film thickness information. If mixing is the desired parameter, fluorescence from the second dye will contain the laser distribution and film thickness information. Normalizing the fluorescence of the first dye by the fluorescence from the second dye causes the resulting ratio to be a function of mixing only. Since we are using an imaging technique, we obtain spatial information on the mixing across the wafer. Our previous work (Coppeta et al [14,15]) has shown that by injecting tagged commercially available slurry with two fluorescent dyes, slurry mixing, entrainment beneath the wafer, residence time on the pad, and film thickness can be measured. For the purposes of this paper, we are concerned with the slurry mixing only.

5 Methodology

Each case in the statistically designed experiment followed a standard data acquisition procedure. Each polishing pad was conditioned for 10 minutes with the diamond grit conditioner. During conditioning the platen speed was set to 60 rpm and the flow rate was set to 35 cc/min. Immediately after the 10 minute conditioning period, mixing data was acquired with in situ conditioning. The conditioner was then removed followed by additional mixing measurements (ex situ conditioning data). The entire process for each case required about 50 minutes to complete, 20 minutes with in situ conditioning, 20 minutes without in situ conditioning and 10 minutes of conditioning prior to data acquisition.

In order to capture the mixing history for each case, the camera system acquired a series of sequential images whenever a pulse of “new” slurry was injected onto the polishing pad. New slurry refers to the fluorescent dye used to tag the slurry. The slurry supply onto the pad is never interrupted, however, new slurry is periodically pulsed into the supply line for a duration of 60 seconds. Before new slurry is introduced, images of the wafer were acquired to ensure that new slurry from previous pulses was not present beneath.
the wafer. Images were typically acquired at 0.5 Hertz for up to two minutes in order to capture the entire mixing history beneath the wafer. The exposure time for each image was 700 milliseconds. The cameras were focused on a rectangular area 2.25 cm by 3.8 cm located on the front part of the wafer. This image area is focused onto approximately 260,000 pixels of the CCD. Therefore, each point in the mixing history represents the average of 260,000 data points.

Slurry transport was systematically studied using a statistically designed experiment. The experimental design was a five factor three level matrix created to determine the significant factors influencing slurry mixing beneath the wafer. We performed the 46 cases over two weeks to complete the statistically designed experiment. The five factors examined were platen speed, down force, flow rate, pad groove depth, and pad manufacturer. The three levels of each variable are displayed in Table 1. The pad groove pattern chosen for this study consisted of a regular intersecting orthogonal channel pattern (x-y pattern) shown in Figure 2; the dark squares represent the high points of the pad while the white lines represent the grooves machined into the pad surface. The bottom of the grooves are flat. The right schematic in Figure 2 shows a blown up view of a section of the pad with relevant dimensions. The range for each factor represents common industrial conditions that have been scaled for the tabletop polisher. Our main goal with this study is to establish how common CMP parameters influence the slurry transport beneath a wafer.

6 Analysis

The mixing curves were analyzed using the Residence Time Distribution technique (Froment and Bischoff [1990]). The mean residence time was used to measure the slurry transport efficiency. The mean residence time (MRT) is the average time the slurry spends beneath the wafer and is:
\[
MRT = \frac{\int_0^{\infty} t \frac{dF}{dt} dt}{\int_0^{\infty} \frac{dF}{dt} dt},
\]

where \( F \) is the mixing curve (percent of new fluid versus time) obtained for a step input (60 second pulse here) and \( t \) is time measured in seconds. The variance term is the amount of slurry mixing and is:

\[
\sigma^2 = \frac{\int_0^{\infty} (t - MRT)^2 \frac{dF}{dt} dt}{\int_0^{\infty} \frac{dF}{dt} dt}.
\]

Both statistics require the time derivative of the mixing curve, which introduces a fair amount of error into the calculation, because the time resolution in the experiments was rather coarse (0.5 Hz). Therefore, a function that has an asymmetrical sigmoidal shape was fit to the data and the derivative of this function was used to calculate the slurry MRT and variance. This function is

\[
F = \frac{kt^n}{1 + kt^n},
\]

where \( k \) and \( n \) are constants and \( t \) is time. This function has been proposed by Racz et al. (1998) [16] for polymer cure kinetics. This mixing model is heuristically derived for the case of slurry mixing in Coppeta et al. [11,12]. The correlation coefficients between the model fit and the actual data for all 46 cases examined was greater than 0.99 for the ex situ conditioning cases and greater than 0.97 for the in situ conditioning cases. The lower correlation coefficient with in situ conditioning is caused by the oscillations in the mixing curves due to the conditioner’s motion [11,12]. These oscillations are described earlier in Coppeta et al. [11,17] and are caused by the conditioner’s motion that periodically directs slurry toward and away from the wafer.
7 Results

Figure 3 shows an example of the mixing history beneath a wafer with a best fit line using the k-n function. Only the first half of the mixing history is shown since the second half of the mixing curve has exactly the same shape but inverted. Time zero is defined by the moment when the new slurry reaches the pad. As slurry is entrained, more of the fluid volume under the wafer is tagged, causing the volumetric percent of new slurry to approach 100%. In the example shown, all of the fluid under the wafer has been replaced with tagged (new) slurry 30 seconds after injecting new slurry onto the pad. Since mixing measurements were made under the wafer, one can see the time delay between when the new slurry is first introduced onto the pad (time zero) and when the new slurry is entrained beneath the wafer as evident in the rise of the mixing curve.

[Figure 3 about here.]

The fitted data from each case in the statistically designed experiment is used to calculate the slurry MRT and variance as described above. Figure 4 shows the mean residence times for the in situ and ex situ conditioning cases. In situ conditioning increases the mean residence time for all of the grooved pad cases and decreases the mean residence for all of the flat pad cases. The mean residence time for the in situ cases was 25.5 seconds (standard deviation of 11.7 seconds). The mean residence time for the ex situ cases was 17.8 (standard deviation of 8.2 seconds). The large MRT’s for cases 21, 30, and 41 are the result of slow platen rotation rates.

[Figure 4 about here.]

Figure 5 shows the results of the mixing curve variance versus case number for in situ and ex situ conditioning. In situ conditioning generally increased the variance indicating an increase in mixing on the pad. The mean variance for in situ conditioning was 0.53 with a standard deviation of 0.15. The mean variance for ex situ conditioning was 0.30 with a standard deviation of 0.09.

[Figure 5 about here.]
Table 2 shows the significant parameters that contribute to the value of the slurry MRT and their respective coefficients for both the in situ and ex situ conditioning cases. The coefficients shown fall within the 95% confidence interval. A normal text “x” indicates that the factor had no significant effect on the MRT. The correlation coefficients were 0.91 and 0.81 for the in situ conditioning coefficients and ex situ conditioning coefficients respectively.

A number of trends are evident in Table 2. The only main factor that does not have an independent effect on the slurry MRT is down force. Interestingly, this factor interacts with platen speed to influence slurry transport only when in situ conditioning is used. It is unclear why the interaction of these two factors influences slurry transport. One possibility is that the microscratches created during conditioning are deformed by the wafer as a function of down force and platen speed. Another possibility has to do with the onset of hydroplaning. Down force and platen speed combine to influence the fluid film thickness beneath the wafer. More data is needed to determine whether either of these hypotheses is correct.

Table 2 also shows that both closed celled pad architectures (Rodel IC1000 and Freudenberg FX-9) decrease the slurry MRT as compared to the open celled architecture used in the Cabot pad. This is shown in the non-linear pad manufacturing term, since the coded values for the closed cell pads are 1 and -1 and the coded value for the open celled pad is 0. Platen speed and flow rate both decrease the mean residence time. The effect of pad groove depth is dependent on the conditioning method used. With in situ conditioning, the slurry MRT is inversely proportional to the groove depth such that a flat pad (groove depth of 0 mils) produces the lowest slurry MRT and a groove depth of 40 mils produces the largest slurry MRT. This trend is not observed with ex situ conditioning. With ex situ conditioning, a pad with a 20 mil groove depth produces the lowest slurry MRT. Both flat pads and pads with 40 mil groove depths had similar slurry residence times, which were higher than residence times with 20 mil grooving.

Table 2 also shows that several factors interact with one another to influence the value of the slurry MRT. The results of these interactions are more difficult to visualize once factors beyond the main ones are considered. Two-dimensional contour plots are helpful in visualizing the combination of all of the factors. To
create contour plots, the significant factors in Table 2 were fit to the slurry MRT data using the parameter’s physical values. Since platen speed interacts with groove depth and flow rate, contour plots of these variables are shown in Figures 6-9. The contours represent the fitted data and are labeled with round plot symbols. The square symbols represent actual data points in the parameter space. It is important to note that the correlation coefficients indicate that the fit data is capable of illustrating trends in the data, but cannot provide predictive values for all possible conditions.

Figures 6 and 7 show the effects of groove depth versus flow rate for the case of in situ conditioning. The value of pressure was 4 psi in both plots, however, pressure has no effect on the ex situ conditioning case and a minor effect on the in situ conditioning case. Although both plots show results for a Cabot pad, pad type is not important to the shape of the contours since it simply causes an offset to the MRT values. This is because pad manufacturer does not interact with any of the other input parameters. Note that at low platen speeds groove depth does not have a significant effect on the slurry MRT, as the overall flow rate dominates the residence time. At low platen speeds the centrifugal force is small, so the bulk fluid motion in the radial direction is controlled by how quickly fluid is replaced. This trend is reversed at high platen speeds where flow rate becomes insignificant and groove depth dominates the slurry MRT. At high platen speed centrifugal force plays a much larger role in the fluid motion. Pad grooving may play such an important role because at high platen speeds, most of the new fluid tends to be forced off of the pad quickly. Therefore, pad grooving allows the fluid to travel beneath the wafer before leaving the pad while flat pads do not provide such a mechanism.

[Figure 6 about here.]

[Figure 7 about here.]

Figures 8 and 9 show the effects of conditioning on the slurry MRT. Both plots are shown for a Cabot pad with a flow rate of 50 cc/min. Note that in situ conditioning reduces the importance of the groove depth. This is because with in situ conditioning the conditioner head influences the bulk fluid motion by retarding the radial direction of slurry flow in the grooves. The conditioner also mixes old and new slurry
on the pad thereby reducing the concentration of new slurry reaching the wafer.

[Figure 8 about here.]

[Figure 9 about here.]

Finally, Table 3 shows the results of analyzing the variance of the slurry age distribution. The correlation coefficients were 0.80 and 0.64 for the in situ and ex situ conditioning cases respectively, implying that more data and/or a more sophisticated model is needed to create a predictive model. It is clear from constant values in Table 3 that in situ conditioning dramatically increases the amount of slurry mixing. Comparing the two types of conditioning, it is evident that in situ conditioning removes the mixing dependency on pad grooving as a main effect. For ex situ conditioning, it is evident that grooving reduces the amount of slurry mixing, implying that grooved pads prevent mixing by keeping adjacent fluid pockets separated, while flat pads allow regions of fluid to mix with their nearest neighbors. Previous research showing large gradients in the slurry age across the wafer with ex situ conditioning confirms this idea [11,12]. In situ conditioning eliminates these gradients by mixing the slurry between adjacent grooves. In situ conditioning also causes the mixing to strongly depend upon the flow rate and the platen speed. This is because the longer the fluid stays on the pad, the greater chance the conditioner has to mix it with other fluid on the pad. This is particularly true at low platen speed where the coefficients predict a 50 percent increase in the variance, all other factors being equal. The same relationship holds for flow rate. At high flow rates, the fluid is displaced off of the pad quickly so that the amount of mixing decreases, while at low flow rates the fluid spends more time on the pad, allowing the conditioner to mix it more efficiently.

Both in situ and ex situ conditioning processes demonstrate some dependencies on groove depth-flow rate factors that may reflect the fluids ability to be transported to the top of the pad. That is, high flow rates and shallow groove depths increase the amount of fluid mixing by allowing the wafer or conditioner to mix the fluid at the top of the pad, while deep grooves and low flow rates tend to allow the fluid to remain isolated at the bottom parts of the grooves.
Finally, the pad structure has a significant effect on the amount of slurry mixing. The open celled pad causes more slurry mixing than does either of the closed celled pads. This is most likely because the open celled pad stores more slurry in the pad, which is then available to mix with slurry traveling across the top of the pad.

[Table 3 about here.]

8 Conclusion

The purpose of this study was to examine the slurry transport dependencies on common CMP parameters. It is evident from the low correlation coefficients in Tables 2 and 3 that the statistically designed experiment used was not sophisticated enough to capture all of the physics of the slurry transport. However, the experiment did accomplish the main goal of identifying main effects and parameter interactions. In this paper, we correlate six CMP input parameters to the slurry transport and entrainment: platen speed, flow rate, down force, pad manufacturer, groove depth, and conditioning were all examined for their influence on the slurry transport. The new slurry entrainment was characterized by the residence time distribution metrics of mean residence time and variance. Through a statistically designed experiment, we have shown that platen speed, pad manufacturer, groove depth and conditioning all significantly affect the slurry transport. In addition, statistical results showed that these parameters are not linear but interdependent upon one another. Further, in situ conditioning was shown to have a large effect on the slurry transport. In general the rate of slurry mixing increased and the rate of slurry transport decreased with in situ conditioning. Down force did not have a main effect but did couple with platen speed to influence slurry transport when in situ conditioning was used.

Future investigations will attempt to correlate the polishing performance to the slurry behavior observed. The mechanism through which slurry flow influences polishing performance and the relative magnitude of this effect are of particular interest. It is believed that illuminating this area of the polishing process will lead to an improved understanding of the overall process. Also, the results shown here will be reproduced.
on an IPEC 372 tool to ensure that all of the scaling arguments apply.

9 Acknowledgments

The authors would like to thank Intel and Cabot corporations for funding this research. We would also like to thank Freudenberg Nonwovens for donating FX-9 polishing pads.
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Figure 2: Schematic of X-Y groove pattern in polishing pads

- \( a \) = 0.208 in.
- \( c \) = 0.25 in.
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<th>Levels</th>
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<td>Slurry Flow Rate</td>
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<td>Platen Speed</td>
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<td>Down Force</td>
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<td>Groove Depth</td>
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<td>Pad Manufacturer</td>
<td>Rodel IC1000, Freudenberg FX-9, Cabot Pad</td>
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Table 1: DOE factors and levels
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| Correlation Coefficient | 0.91 | 0.81 |

Table 2: Mean residence time significant factors
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Table 3: Variance significant factors