


Acknowledgements

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References


The preliminary results show that in the hydrodynamic regime, there is a net upward pressure force exerted on the wafer. Further development of the numerical model could allow predictions of removal rate in an industrial CMP system.

We also have demonstrated that the performed diamond conditioning has a negligible effect on slurry mixing within the uncertainty of the measurement. Conditioning did increase the intensity of the fluorescence by a factor of two indicating that conditioning increases the thickness of the slurry layer between the pad and wafer. We currently are working toward quantifying this thickness. Finally, we examined the slurry age or compositional gradient beneath the wafer and found that there were significant differences between the Embossed Politex pad and the IC1000 pad. The IC1000 pad showed a gradient in the slurry age (or percentage of new slurry) only in the inner third of the wafer, with the rest of the wafer containing a relatively constant slurry age. The Embossed Politex pad showed a linear gradient across the wafer. The difference between these two cases is explained in terms of the Politex pad mixing mechanism. The Politex pad traps fluid in the valleys or macro-structure of the pad, which reduces mixing of fluid from one part of the pad with fluid from another part of the pad. This is in contrast to an IC1000 pad where fluid separation can only occur on length scales equal to the pad microstructure if at all. In the case of the IC1000 pad the microstructure does not appear to effectively trap the fluid and therefore slurry gradients are smoothed and reduced beneath the wafer. This argument is also supported by the fact that conditioning does not have a large effect on the IC1000 mixing characteristics.
pulse of new slurry while the Politex pad line was taken 8.1 seconds after the beginning of a pulse. These times were chosen to correspond to the maximum observed gradient in each case. As shown in figure 5, the IC1000 maintains a composition gradient only in the inner third of the interrogation region while the embossed Politex pad supports a linear composition fluctuation across the entire interrogation region. Therefore, in comparison with the IC1000 pad, the Politex pad decreases slurry mixing beneath the wafer.

![Figure 11. Slurry composition (age) gradient across wafer versus position](image)

Conclusion

In conclusion we are developing a method of determining and predicting the effect of slurry flow at any platen speed. The work is being performed in combination with an experimental study to verify the application of boundary conditions for the numerical simulation. The numerical model presented in this paper is a simplified version of an actual chemical mechanical planarization system. The results presented give a general indication of the expected results for a more refined numerical description.
and unconditioned pad. The dark circular region at the top of the image is the mounting post to the glass wafer. Fluorescence intensity is proportional to the brightness of the image shown. The fluorescence intensity and thus the film thickness increase by a factor of two after conditioning, all other parameters being equal. We are currently working to correlate the fluorescence intensity into an absolute slurry film thickness.

Finally, it is interesting to observe the different slurry age gradients beneath the wafer as a function of pad type. Figure 11 shows how the slurry composition changes across the wafer at a particular point in time. That is, an arbitrary line across the wafer (shown left) was selected from the interrogation region and analyzed along with the same line in each of the other two cases. This vertical line on the wafer coincides with the radial line of the pad. The y-axis is calculated by subtracting the mean slurry age along the line from the slurry age at each point along the line. Therefore, all zero values on the plot would indicate all of the slurry beneath the wafer is the same age or contains the same percentage of new fluid. The data were smoothed once using a three point averaging scheme for clarity. The two IC1000 lines were taken 12 seconds after the beginning of a
mechanism is likely very different from a flat IC1000 pad that would spread and mix new slurry introduced onto the pad. Figure 9 also shows that the performed conditioning does not have a large effect on either the entrainment time or the amount of mixing with most differences falling within the uncertainty of the measurement.

In addition, the accuracy of the technique on a Politex pad versus the accuracy on an IC1000 pad is evident. The Politex results are smoother and show a higher repeatability. Run to run variations for the Politex pad differ by no more than 2% whereas the IC1000 results differ by about 4%. This difference can be attributed to the fact that the IC1000 pad exhibits an intrinsic fluorescence that increases the uncertainty of our measurement technique. The Politex pad does not fluoresce.

![Figure 9. Percentage of new slurry entrained beneath the wafer versus time.](image)

Even though conditioning does not affect the mixing characteristics of the IC1000 pad, the thickness of the slurry layer shows a strong dependence on conditioning. Figure 10 shows a top view of the fluorescence from a wafer subsection of both the conditioned
of the technique applied to flow in front of a wafer. The arrow length is proportional to the magnitude of the fluid velocity. This type of data will be used to compare with velocity predictions obtained by numerical simulations.

Figure 8. Experimentally determined velocity vectors in front of a wafer.

Figure 9 shows the entrainment characteristics of each pad in terms of the spatially-averaged percentage of new slurry entrained in the interrogation region versus time. That is, the percentage of the slurry in the interrogation region that is tagged. The schematic on the left in figure 9 shows the injection and wafer locations on the pad. The graph illustrates several important points. First the Politex pad pulls slurry under the wafer faster than either the conditioned or unconditioned IC1000 pads. Slurry is carried in the valleys of the embossed pad, which prevents efficient mixing with the surrounding slurry. Therefore, a faster build up of new slurry beneath the wafer is observed as new unmixed slurry is carried beneath the wafer in the pad valleys. This entrainment
In addition, the computer synchronizes the camera to the polishing process so that mixing measurements beneath the wafer can be made at any point in the mixing process.

For this paper the head and platen speeds were set to 60 RPM with 4 psi down force on the wafer. The DELIF technique is used to measure fluorescence from two different dyes, each fluorescing at different wavelengths, to measure mixing or temperature. The fluorescence from one dye contains the mixing, laser distribution, and film thickness information while the fluorescence from the second dye contains 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. A complete description of all experimental parameters can be found in our previous work \textsuperscript{10,14}.

Using DELIF we can measure slurry mixing, entrainment beneath the wafer, residence time on the pad, and fluid film thickness. For the purposes of this paper, we are concerned with slurry mixing only.

**Results**

As the numerical simulation predicts, we observed a bow wave in front of the wafer. Although we cannot experimentally measure the fluid velocity gradient between the wafer and pad, we can measure the fluid velocity around the wafer using a technique known as particle image velocimetry (PIV)\textsuperscript{15}. PIV uses two sequential images of seed particles in a flow to make two dimensional velocity maps. Figure 8 shows an example
II. Experimental Data

Experimental Set Up

Figure 7 shows our modified CMP apparatus\textsuperscript{12} used to study the slurry flow beneath a wafer. A tabletop Struers RotoPol-31 polisher is used to rotate a 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 3" wafer. Since we are measuring fluid parameters using an optical technique known as dual emission laser induced fluorescence or DELIF\textsuperscript{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. A 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.

Figure 7. Experimental set up
the pressure measured beneath the wafer could potentially act as an indicator of the type of flow regime in which a particular CMP process is operating. This simple parameter has the potential of being able to predict the amount of material removed from a wafer by a particular polishing system, as well as the lifetime of the polishing pad. Before this type of information can be obtained from pressure, the numerical results should be duplicated using a more realistic model of the CMP process with additional experimental data.

Figure 6. Plot of total pressure along wafer surface
The computed pressure values exerted on the underside of the wafer are plotted in Figure 6. The pressure on the y-axis is normalized by $\rho u^2$. In figure 6 the total pressure the wafer experiences is in the positive y (upward) direction. This implies that in the hydrodynamic regime, where slurry flow and not asperity contact governs polishing, an upward force is exerted on the wafer. This is in agreement with experimental results found by Coppeta, et al., but is not in agreement with results of all CMP researchers. Levert et al. found that their model system generates a negative pressure (suction) beneath the wafer. It is believed that these researchers perform their experiments in the asperity contact regime, whereas Coppeta et al. operate in the hydrodynamic regime. These observations are crucial because they indicate that the magnitude and direction of
by experimental observation. However, the bow wave observed experimentally has a much larger height than the simulation predicts. This discrepancy is attributed to the fact that the linear velocity of the pad in the experimental system (~0.5 m/s) is much higher than the linear velocity of the pad in the numerical simulation (0.05 m/s). Also, a large part of the fluid mass that forms the bow wave flows around the wafer and runs off the edge of the polishing pad. This is impossible to simulate in the 2-D model; the slurry recirculates back and forth between the front and back side of the wafer through the cyclic boundary. In this simplified model, the calculated flow field between the pad and wafer is observed to be uniform and linear, i.e. there is no back flow introduced in the region (see Figures 4, 5 and 6).

Figure 3. Velocity vector plot at exit region
process conditions\textsuperscript{11}. The density of the slurry is determined experimentally to be similar to that of water (1 x 10\textsuperscript{3} kg/m\textsuperscript{3}), while the viscosity is measured to be between 2 to 10 cP. For this model, viscosity was arbitrarily chosen to be 2 cP. The surface tension coefficient for slurry is 70e-3.

![Figure 2. Velocity plot at inlet to wafer.](image)

The flow field underneath and surrounding the wafer that was obtained from the numerical model is plotted in Figures 2, 3, and 4. The velocities vary from 0.1 to 4 centimeters per second. The velocity vector plot (Figure 2) depicts slurry recirculation at the inlet region of the wafer and pad gap. There also is an acceleration of the slurry fluid at the exit region of the gap (Figure 3). On the volume fraction contour plot (Figure 5), the black regions indicate a volume fraction of unity for slurry, while the white regions indicate a volume fraction of unity for air. Figure 5 indicates that a small bow wave of slurry has formed in front of the wafer. The existence of this bow wave was confirmed.
a thin layer of slurry. A no-slip boundary condition is applied the bottom of the wafer.
In order to simulate the overall environment we applied cyclic boundary conditions to the
right and left sides of the computational domain. That is, the total pressure at the exit of
the computational domain is set to equal the total pressure at the entrance of the
computational domain.

To reduce the amount of nodalization and run time, the diameter of wafer
modeled is very small: 0.25 cm. The actual diameter of wafer used for the experimental
part of this research is 7.62 cm (3 in). At this early stage in the work, we are looking for
a general trend for the pressure distribution under the wafer. The surface profiles of the
model wafer surface and model polishing pad surface were assumed to be smooth, and
the slurry mixture was modeled as a homogeneous fluid without suspended particles.
The reasons for the omission of many of the complexities of the boundaries at this initial
stage of our numerical modeling effort are to reduce computational nodalization and run
time, and to obtain rough initial results that can be easily tested by experiment. The time
step applied to converge the model is 10 microseconds. More advanced representations
of the process will build upon this basic model.

Results
The results obtained from the model developed as described in the previous
section are based on a platen velocity of 5 cm/s in the positive x-direction. The physical
constants used for the air phase are referenced at room temperature (25°C). The slurry
behavior, which has been modeled from SC-1 and SS-25 concentrates, has been
discovered experimentally to have Newtonian fluid behavior under the commercial CMP
free surface of the slurry in front of the wafer (bow wave) is of interest, we used Fluent’s volume of fluid (VOF) solver\textsuperscript{9} to solve the flow of both air and slurry. The VOF solver treats the air and slurry as two immiscible fluids, which allows the two phases (air and slurry) to interact with each other without mixing.

The computational domain constructed is a two-dimensional cross-section of the wafer and polishing pad, as shown in Figure 1. The motion of the platen was simplified; instead of using rotational motion, the pad was represented as a wall with a constant linear velocity $U_{\text{pad}}$ and no-slip boundary condition. Correspondingly, the only moving boundary in the model is the platen, which is solely responsible for driving the flow.

![Figure 1. Computational domain of model](image)

The wafer was assumed to be rigidly attached from above and therefore the distance between the wafer surface and the pad is fixed. The gap between the wafer and platen was set to 40 micrometers based on experimental data\textsuperscript{10}. The pad is already wetted with
are ignored in his simulation. The second model determines the surface removal as a result of erosion due to slurry flow\textsuperscript{7}. It is a two-dimensional model that calculates the surface stress tensor to find the erosion rate using the two-dimensional Navier-Stokes equations.

In the present study, we simulate slurry flow between the wafer and platen in order to determine the pressure distribution and fluid shear stresses on the wafer surface. The purpose of the work is to couple the results with descriptions of the chemical reactions in the slurry in order to determine the overall effect of the fluid flow on the polishing rate. Hydrostatic pressure was determined to affect chemical reactivity at the wafer surface, which governs material removal rate\textsuperscript{8}. These results could then be compared to those of pure mechanical asperity in order to determine the relative contributions of fluid flow and asperity contact to the polishing rate. Ultimately, the complete numerical study will provide a method to predict the effects of slurry flow at any platen speed, and help improve the efficiency and uniformity of wafer polishing.

**Numerical Model**

The software used to simulate the CMP system under study is Fluent, a commercially-available computational fluid dynamics (CFD) code with the capability to model two-phase flow. In this initial stage of the modeling, we were concerned with the flow field and pressure distribution beneath the wafer only; all chemical reactions and thermal effects were neglected. Because the Reynolds number (based on the distance between the wafer and pad) is below 2000, we assumed to flow to be laminar.
cannot easily predict. The numerical approach can predict pressure and velocity beneath the wafer while the experimental approach can predict fluid film thickness and slurry age or mixing beneath the wafer. These sets of complementary data are important in order to obtain a more complete understanding of the fluid mechanics involved. As each path becomes more sophisticated, the abilities of each will expand into overlapping data for direct comparison. In addition, the experimental research provides reasonable boundary conditions for the numerical work. Finally, the experimental research will enable the development of an advanced numerical model that may preclude the need for most experimentation in the future. This paper is divided into two sections; a numerical and an experimental section.

I. Numerical Simulations

The only investigations that consider the effects of slurry flow were performed by Runnels et al. who developed two separate fluid flow models. The first of these, which was the first published work to address fluid flow, was a three-dimensional model that simulated slurry flow between a wafer and pad. The computational domain consisted of a thin disk with the wafer and polishing pad acting as the no-slip boundary conditions on the top and bottom surfaces. The flow outside the disk was simulated on the circumferential surface of the disk, which was also defined as a no-slip boundary. The slurry was allowed to move in and out freely through the circumferential surface by applying a stress free boundary condition. The principal goals of this model were to predict the thickness of the slurry layer and the angle of attack of the wafer as it glides on top of the slurry layer. The polishing mechanism and the structure of the wafer surface
Cab-O-Sperse SC1 slurry was used in a 1:1.5 dilution with water. Mixing data show that conditioning has a negligible effect on the rate of slurry entrainment and mixing, however conditioning has a large effect on the thickness of the slurry layer between the wafer and pad. Conditioning was found to increase the slurry thickness by a factor of two. In addition the gradients in slurry age beneath the wafer were compared among the three cases. The IC1000 pads supported a gradient in the inner third of the wafer only, while the Embossed Politex pad showed a linear gradient across the wafer implying it retains pockets of unmixed slurry in the embossed topography.

Introduction

Little is known about what is occurring beneath a wafer during Chemical Mechanical Planarization (CMP) processes. Both chemical and mechanical mechanisms have been identified as contributing factors to the overall removal phenomenon. However, the relative contribution of each is still poorly understood and requires an understanding of the slurry transport beneath the wafer. Fluid behavior beneath the wafer dictates the polishing mechanism; by transporting the chemical component and/or by allowing the pad to abrade the wafer\textsuperscript{1-3}. Factors such as fluid film thickness, slurry entrainment processes, slurry age, and pad slurry carrying capacity are some of the fluid properties that are likely to influence polishing\textsuperscript{4-5}. We are studying these variables to develop a more complete understanding of the polishing process.

We are pursuing a two-pronged approach to CMP research which incorporates both numerical and experimental work. It is important that both research paths be performed in tandem for several reasons. Each approach provides data that the other
Analysis of Flow Between a Wafer and Pad During CMP Processes

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Abstract:

In this paper we summarize the development of a numerical model for the chemical mechanical planarization (CMP) process and experimentally investigate the effects of pad conditioning on slurry transport and mixing. A simplified two dimensional numerical model of slurry flow beneath a stationary wafer was developed to determine the pressure and shear stress beneath a wafer. The initial results indicate that in the hydrodynamic regime a positive upward pressure is exerted on the wafer. We also examined three cases to study pad effects on slurry transport; polishing with an Embossed Politex pad, an unconditioned IC1000 pad, and a conditioned IC1000 pad.