One of the issues in chemical mechanical planarization (CMP) is that it can be difficult to gather fundamental data that can be used to understand what is happening during the process. Many of the advances in understanding and subsequent improvements in CMP have come about through innovative metrology. For example, measurements of the friction force between the pad and wafer have provided fundamental information about the lubrication regime of the process. The same measurements have also been used in end point detection to determine when one layer has been removed and another exposed. Similarly, key advances in our understanding of CMP have come about as a result of the application of pad thermal imaging, measurements of the pressure of the fluid between the wafer and pad, capacitance distance measurements of wafer bending and head tilt and confocal microscopy of pad surfaces.

In this paper, we describe a simple laser tilt measurement system that has been used to monitor the pitch of a novel slurry injection system (SIS). The laser measurements provide some insight into the behavior of the injection system during typical processing procedures, such as pad rinsing and wafer polishing. These insights help explain the important factors underlying the performance of the injector. As a side effect, the measurements also uncover an unsuspected behavior of the polisher.

The Slurry Injection System (SIS)

The SIS used in this study, and its performance have been described in detail elsewhere. The particular model of the SIS employed here was developed for the AMAT Mirra polisher (Fig. 1). The functional part of the system is the injector body, which is rectangular and has a bottom made of PEEK (polyetheretherketone). The bottom is patterned and flexible and is meant to be held in close contact with the pad using a light load. The system is connected to the polisher through gimbal points that sit well in front of the device and close to the pad surface; these points therefore can apply only small pitching torques to the body. Slurry is applied through one or more tubes that protrude through the cover of the device. The slurry feeds into a narrow open channel in the bottom and is distributed in the radial direction of the polishing pad. Slurry is then advected from the channel by the moving pad surface and emerges from the trailing edge of the body as a thin film. The polishing head consequently has a very small bow wave compared with what happens when slurry is dripped from a tube at the end of the standard slurry applicator (called point application or PA here). For this reason, there is less direct slurry loss from the bow wave. Used slurry, on further rotation of the platen, then encounters the leading edge of the injector body and much of it is squeegeed off the pad. Rinse water is also squeegeed, as are potentially harmful particles and debris from pad conditioning.

The experiments reported here were all performed on a 200 mm R&D polisher, the APD-500, made by Fujikoshi Machinery Corp and instrumented by Araca, Inc.’s proprietary hardware. The slurry injection system (SIS) was mounted on the polisher in approximately the same position relative to the wafer as on the AMAT Mirra system. Blanket oxide wafers were polished at 3 PSI for 1 minute using Cabot Microelectronics Corp. SS25 slurry applied at 90 ml per min on a Dow IC-1010 k-groove pad. The platen and head rotation rates were 38 and 42 RPM, respectively. In-situ conditioning was performed using a 3M A165 conditioner at 11 sweeps per min. The pad was rinsed with water from a tube at the platen center at 2 liter per min for 30 sec at 38 RPM. When comparing the SIS with point application from a slurry tube, the latter was placed approximately at the same location as the injection point of the SIS.

To illustrate the utility of the laser system, we focus on one set of experimental results, shown in Fig. 2, where removal rates from point application, SIS Design A (which has a patterned bottom) and SIS Design B (which has a plain, un-patterned, bottom that lacks even a
slurry channel) are compared. All wafers were run using the process described above with water rinsing between each wafer polish. We see from the figure that, relative to point application, Design A enhances silicon oxide removal rate by about 11% while Design B produces an enhancement of only about 5%. The objective in this paper is to obtain some insight into why this happens.

The Laser Tilt Measurement Setup

Figure 3 shows a schematic of the laser measurement setup. A small laser pointer is affixed to the frame of the polisher and pointed at a mirror mounted on the cover of the slurry injector. Laser light reflected from the mirror produces a spot at a point on the ceiling of the laboratory several meters away from the mirror. Since the laser path is perpendicular to the long axis of the injector body, movement of the spot indicates changes in the pitch of the injector. Movement of the spot toward the polisher occurs when the trailing edge of the injector body is rising relative to the leading edge while movement away from the polisher indicates the opposite. The pitch of the body is taken to be positive when the leading edge is down (see inset of Fig. 3). For a reason to be explained shortly, we take horizontal distances to the right of the mirror to have a negative sign.

If the angle of incidence and reflection of the laser beam at the mirror is $\beta$, and the pitch of the injector relative to the pad surface is $\alpha$, than one can see that increasing the pitch angle decreases the angle of incidence, so that

$$\Delta \beta = -\Delta \alpha. \quad [1]$$

If $\beta_0$ is the static angle of incidence, then the (negative) horizontal distance $x$ from the mirror to the spot is related to the distance $h_c$ from the mirror to the ceiling by

$$x = -h_c \tan(\beta_0). \quad [2]$$

Therefore, for small changes in angle,

$$\Delta x = -h_c \sec^2(\beta_0) \Delta \beta = h_c \sec^2(\beta_0) \Delta \alpha. \quad [3]$$

From the known geometry and known static incidence angle ($58.9^\circ$), we then conclude that if $x$ is measured in mm and $\alpha$ in degrees, then

$$\Delta \alpha = 7.52 \times 10^{-3} \Delta x. \quad [4]$$

The change in injector pitch can therefore be estimated from the horizontal movement of the laser spot. Movement of the spot toward the polisher corresponds to an increase in pitch angle. In order to quantify the location of the laser spot, a scale is affixed to the lab ceiling next to the spot (Fig. 4) and a video is made of both the scale and spot during each experiment. The scale is oriented so that larger readings correspond to spot movement toward the polisher and therefore to increasing forward pitch. The video is later split into individual JPG frames using the open source utility FFmpeg, and the JPG frames are converted to ASCII PPM (Portable Pix Map) files. Each frame is then analyzed with an internally developed image analysis program. The program automatically locates the scale marks, which are black, and the laser spot, which is red. The centroid of the laser spot is then calculated and the x-coordinate is determined relative to the scale marks. This procedure makes it possible to measure the location of the spot relative to the scale even if there is some movement of the video camera. The entire procedure is automated once the video is downloaded.

Fig. 5 illustrates the sensitivity of the measurement technique. In this figure, the injector is initially sitting flat on a stationary pad and is monitored for a short time to establish a baseline. The slurry flow and platen rotation are then started at about 7 seconds into the video. When the platen starts, the injector pitches down briefly (increasing $x$ on the scale) and then up (decreasing $x$) for the remainder of the time. The signal during platen rotation can be seen to be periodic with a period approximately equal to the platen period, 1.58 sec. The periodicity is due to the interaction of the injector bottom with irregularities, such as a pad window, bubbles trapped between the pad and the platen, variations in pad thickness, and platen run-out. Changes in spot location relative to the baseline can be converted into changes in pitch using Eq. 4.
 Injector Tilt Experimental

We next show some experiments comparing injector bottom Designs A and B. The first experiment (Fig. 6) compares the change in pitch of both designs during a 30 sec, 2 liter per min water rinse. In Fig. 6, the change in laser spot location has been converted to a change in pitch angle using Eq. 4 and the mean pitch angle during the baseline period has been set to zero; i.e., the graph shows the change in pitch relative to the baseline. We see that both injectors tilt leading edge down when platen rotation begins and that the pitch declines gradually with time as the amount of water on the pad reaches steady state. There is no difference in pitch response between the two designs even though the contacting bottoms of the two are very different.

In the second experiment, we measure the tilt of Design A, which had the patterned bottom, during the entire sequence of steps used to polish one of the wafers in Fig. 2. The result is shown in Fig. 7. We see that when the platen starts, the leading edge pitches down relative to the baseline, similar to what happens during a rinse, except that the pitch then gradually increases rather than decays as the initial fluid load is squeegeed off. When the wafer touches down on the pad, the pitch change is suddenly reversed. During subsequent polishing, the pitch then gradually increases during each rotation until the head is raised, when there is a sudden increase in pitch. The pitch then returns to zero when the platen is turned off.

Because of the involvement of the polishing head, the sudden pitch change that occurs when the head touches down or disengages was investigated further with SIS on a static platen. This was done using both a cool polisher, and after running the polisher sufficiently long to warm up the platen bearings. The results are shown in Fig. 8. In both cases, it is clear that the platen itself tilts slightly when the head is engaged and returns to level when the head is lifted; i.e., we interpret the result as meaning that the angle of SIS relative to the platen does not change but rather that platen itself tilts due to the load from the head. While the total pitch change is only about half of what is observed on a turning platen, we believe that this is the explanation for sudden pitch changes observed at the beginning and end of polishing. For this reason, we remove the platen pitch change from the polishing data to obtain an estimate of the change in pitch of SIS relative to the pad (Fig. 9).

Finally, in Figure 10 we show the platen tilt corrected pitch change for the Design B SIS (with the plain bottom) for one of the removal rate wafers reported in Fig. 2. The evolution of the pitch change for Design B is similar to that for Design A except that the change in angle over the entire process is much larger. Based on the width of the SIS bottom (38.1 mm), Fig. 10 implies that the trailing edge of the bottom at the time of greatest pitch is about 0.1 mm higher than the leading edge. This is a substantial distance considering that the total surface height variation of the land areas of an IC pad is usually less than 50 microns.
In fact, if the injector mouth of SIS is that, at all times, the bottom must remain in contact with the pad in order for the device to work.\(^\text{10}\) In fact, if the injector were to be lifted off the pad at the injection point, the removal rate would be exactly the same as for point application since SIS would then be just an elaborate slurry delivery tube. The depressed performance for Design B may then be due to the fact that the tilt increases the thickness of the fresh slurry film, making it closer in form to the film produced by point application.

An interesting feature of the pitch plots is the progressive increase in angle, or “ratcheting,” that occurs when slurry is used (Figs. 9 and 10) but does not occur during a water rinse step (Fig. 6). One possible explanation for ratcheting is that the periodic bumps from the pad nudge the pitch up a little on each rotation. The slurry-covered pad surface is evidently able to hold the pitch increments while the water-coated surface is not. On visual inspection, the pad surface during polishing has a distinctively thinner fluid layer than during the rinse because of the difference in flow rate, so the SIS bottom may be in relatively close contact with the pad during polishing but may be hydroplaning on a thicker fluid layer during water rinsing. The ability to hold a pitch increment may also be related to the development of sub-ambient fluid pressures. Measurements and models\(^\text{5,7}\) in similar lubricated sliding situations involving friction-induced pitch indicate that significant suction pressures can develop when the lubricated gap between the contacting object and the pad is both thin and diverging; i.e., when the gap is both small and increases from the leading to trailing edge. Sub-ambient fluid pressures in this configuration draw the body into closer contact with the pad, increasing both the friction force and the pitch in a positive feedback loop. In the present case, the bottom of SIS Design A is patterned specifically to control suction pressure development while the plain Design B should maximize it. Thus, the discovery of larger pitch accumulation for Design B is consistent with the underlying design intent. At sufficiently high speeds, Design B also chatters with visible lifting and falling of the trailing edge. Sub-ambient fluid pressures in this configuration draw the body into closer contact with the pad, increasing both the friction force and the pitch in a positive feedback loop. In the present case, the bottom of SIS Design A is patterned specifically to control suction pressure development while the plain Design B should maximize it. Thus, the discovery of larger pitch accumulation for Design B is consistent with the underlying design intent. At sufficiently high speeds, Design B also chatters with visible lifting and falling of the trailing edge while Design A does not show this behavior, consistent with the laser pitch measurements.

None of the observations of SIS pitch behavior in the present experiments can be easily made with the naked eye – the changes are simply too small. The laser pitch measurements have therefore been a useful tool for understanding what the SIS device may be doing. Also, surprisingly, the measurements uncovered a previously unnoticed but probably harmless tilt in the polisher platen that occurs when the head is engaged. We suspect that something similar should happen on all rotary polishers, but as in the present case, it is probably too small to attract attention.

### Discussion and Conclusions

Why do SIS Designs A and B differ in removal rate performance? The tilt data suggest a partial answer. An important operational element of SIS is that, at all times, the bottom must remain in contact with the pad in order for the device to work.\(^\text{10}\) In fact, if the injector were to be lifted off the pad at the injection point, the removal rate would be exactly the same as for point application since SIS would then be just an elaborate slurry delivery tube. The depressed performance for Design B may then be due to the fact that the tilt increases the thickness of the fresh slurry film, making it closer in form to the film produced by point application.

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### References

1. H. Liang and G. H. Xu, *Scripta Mater.*, **46**(5), 343 (2002).
2. A. Philipossian and S. Olsen, *Jpn. J. Appl. Phys.*, **42**, 6731 (2003).
3. Y. Sampurno, X. Gu, T. Nemoto, Y. Zhuang, A. Teramoto, A. Philipossian, and T. Ohma, *Jpn. J. Appl. Phys.*, **49**, 09FC01 (2010).
4. Z. Li, L. Borucki, I. Koshiyama, and A. Philipossian, *J. Electrochem. Soc.*, **151**(7), G482 (2004).
5. C. Zhou, L. Shan, J. R. Hight, S. H. Ng, and S. Danyulyk, *Wear*, **253**(3-4), 430 (2002).
6. T. Wang, D. Zhao, Y. He, and X. Lu, *Int. J. Adv. Manuf. Technol.*, **67**(9-12), 2903 (2013).
7. S. H. Ng, Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA (2005).
8. C. Elmufdi and G. Muldowney, *Mater. Res. Soc. Symp. Proc.*, **914**, F12.06 (2006).
9. T. Sun, Y. Zhuang, L. Borucki, and A. Philipossian, *Jpn. J. Appl. Phys.*, **49**, 066501 (2010).
10. S. V. Babu (ed), *Advances in Chemical Mechanical Planarization (CMP)*, Elsevier, Ch. 20 (2015).
11. L. Borucki, A. Philipossian, Y. Sampurno, and S. Theng, U. S. Pat. No. 8,197,306.
12. L. Borucki, Y. Sampurno, and A. Philipossian, U. S. Pat. No. 8,845,395.
13. L. Borucki, Y. Zhuang, Y. Sampurno, A. Philipossian, and S. Kreutzer-Schneeweiss, *ECS Trans.*, **52**(1), 591 (2013).
14. Y. Zhuang, Y. Sampurno, C. Wu, B. Wu, Y. Mu, L. Borucki, A. Philipossian, and R. Yang, *ECS Trans.*, **60**(1), 625 (2014).
15. Y. Sampurno, Ph.D. Dissertation, University of Arizona, Tucson, AZ (2008).
16. http://www.ffmpeg.org, last accessed May 27, 2015.