**Effect of Retaining Ring Slot Designs, Conditioning Discs and Conditioning
Schemes on the Slurry Bow Wave Width during
Chemical Mechanical Planarization**

Leticia Vazquez Bengochea^{1*}, Yasa Sampurno^{1,2}, Calliandra Stuffle¹, Fransisca
Sudargho², Ruochen Han¹ and Ara Philipossian^{1,2}

*¹ Department of Chemical and Environmental Engineering,
University of Arizona, Tucson, AZ 85721 USA*

² Araca Inc., Tucson, AZ 85718 USA

This study investigates the effect of various retaining ring slot designs, conditioning schemes and conditioning disc types on the width of the slurry bow wave formed at the leading edge of the retaining ring during polishing. A method using high-speed videography is employed for visualizing and quantifying slurry bow wave width. In contrast to many limitations associated with previous techniques, this new method allows the use of a concentrically grooved pad with its natural white color commonly used in industrial applications. In general, results show that polishing with a retaining ring having rounded-angle slots, and a full-face conditioner, generates wider slurry bow waves. In contrast, using a retaining ring with sharp-angle slots, in combination with a conditioner having CVD-coated protruding vanes results in narrower bow waves. Compared to *ex-situ*

conditioning, *in-situ* conditioning causes narrower bow waves due to its inherent role in transporting the slurry through periodic sweeping. Using Fast Fourier Transformation (FFT), bow wave width fluctuations are converted from time domain to frequency domain, showing a consistent spectral fingerprint. Major peaks are observed at frequencies of 1, 2, 4, 8 to 9, and 12 to 14 Hz for all experiments and they are attributed to the carrier, platen and conditioning disc rotation and oscillation, as well as to the presence of slots on the retaining ring.

* Corresponding author: Leticia Vazquez Bengochea

Email: leticiavazben@email.arizona.edu

1. Introduction

Chemical mechanical planarization (CMP) has been widely used in integrated circuit manufacturing to achieve global and local planarity for the stringent lithography requirements in multilevel interconnects. During this process, a wafer is held by a rotating carrier and a retaining ring and pressed down against a rotating polishing pad. Simultaneously, a slurry containing chemicals and abrasive particles is injected near the pad center and transported to the region between the wafer and the pad, where both mechanical and chemical forces polish away the wafer's topography, resulting in a planar surface.^{1,2} Slurry currently accounts for as much as 50% of the total cost of ownership (COO) of the CMP module and it is regarded as the most expensive consumable in the process.³ The process is not efficient as most of the injected slurry is wasted due to advection by centrifugal forces before it reaches the pad-wafer interface. Several studies have shown that slurry utilization efficiency varies with different polishing conditions in

a range from 2 to 22%.^{4,5} Therefore, optimizing the process parameters to increase the fraction of slurry that is efficiently employed would result in a reduction of the COO, as well as a significant decrease in the environmental impact of the process.

Several methods have been employed to study slurry distribution on the pad and its transport to the pad-wafer interface. Liao et al. studied the slurry bow wave formed at the leading edge of the retaining ring during polishing.^{6,7} From the videoclips obtained in a previous work by Philipossian et al.⁸, the thickness of the slurry film beneath the wafer has been qualitatively correlated to the amount of slurry in the bow wave for different retaining rings. As such, retaining rings that allow a higher amount of slurry to flow in the pad-wafer region result in less amount of slurry forming at the bow wave, and vice versa.^{7,8} In CMP, the retaining ring plays an important role in preventing the wafer from slipping out. It also improves removal rate uniformity at the periphery of the wafer, and it facilitates slurry transport to the pad-wafer interface through its many slots. The effect of retaining ring slot design on slurry film thickness atop the pad, and the thickness of the resulting bow wave have been previously investigated by employing an ultraviolet enhanced fluorescence (UVEF) technique coupled with image analysis.^{7,9} However, in those studies images were taken at a low frequency of 5 Hz due to the limitation of the technique, which required a dark ambient. The technique also was limited to black pads as light-colored pads would naturally fluoresce under UV excitation and render the results unusable. Recently, our research team has developed a method based on high-speed videography to measure the width of the slurry bow wave.¹⁰ Here, the slurry is tagged with an inert dye that solves the photobleaching issue of the fluorescence technique and removes the limitation of having to carry out tests in dark environments. Moreover, it allows the use of all types of pads (here we have tested an Epic D100 concentrically grooved pad) commonly used in high-volume manufacturing.¹⁰ At an image acquisition

frequency of 240 frames per second (as opposed to 5 frames per second with UVEF), this new method provides more meaningful data for slurry flow analysis.

In addition to the retaining ring slot design, conditioning disc type and conditioning scheme affect slurry bow wave formation. As the pad interacts with the wafer, its asperities collapse. Hence, sufficient pad conditioning is needed to regenerate pad asperities and provide the necessary surface topography. For this purpose, a conditioning disc is pressed down on the pad and moved radially at a certain sweeping frequency. There are two conditioning schemes that have traditionally been employed in CMP, namely, *in-situ* (i.e., pad conditioning during wafer polishing) and *ex-situ* (i.e., pad conditioning in between wafer polishes). The selection of the conditioning scheme and the type of conditioning disc has been shown to affect removal rate and polishing process performance.^{2,11-13} However, its effect on slurry distribution over the pad and, particularly at the bow wave, have not been investigated. Our study aims to quantify the width of the slurry bow wave formed on the leading edge of the retaining ring using two different retaining rings with different slot designs, two different types of conditioners and the two conditioning schemes. All polishes are conducted on a concentrically grooved pad with its natural white color commonly used in high-volume manufacturing. The work employs a high-speed videographic method with subsequent image analysis algorithms developed by our research team.¹⁰ To further elucidate the fundamental physical phenomena behind the fluctuations in the bow wave, Fast Fourier Transformation is employed to analyze its spectral fingerprint. These fluctuations are then attributed to the polishing process kinematics.

2. Experimental Apparatus and Image Analysis

All experiments were performed on an Araca APD-800 300-mm polisher and tribometer. The detailed description of this apparatus is provided elsewhere.^{14,15} An Epic D100 concentrically grooved pad (manufactured by Cabot Microelectronics Corporation) was used along with the Fujimi PL-4217 slurry containing 17.8 mg/L of a water-based black dye (by Sargent Art). Black dye was selected to provide the highest contrast ratio between the slurry and the white polishing pad for the image analysis. The dye concentration was low enough so that the flow characteristics of the slurry would not be affected. No wafers were polished for any of the experiments. The sliding velocity and pressure were kept constant in all experiments at 1 m/s and 3 PSI, respectively.

Tests were performed using two poly-ether-ether-ketone (PEEK) retaining rings with different slots designs, manufactured by Entegris Inc. Both rings had 18 equidistant 3 mm wide slots on their periphery. The shapes of the retaining ring slots are shown in Fig. 1. The first retaining ring (RING1) had sharp angles while the second one (RING2) had slots that were rounded on both edges. For each ring, bow wave width was analyzed at two slurry flow rates (200 and 300 mL/min), two different conditioning schemes (*in-situ* and *ex-situ*) and two different conditioner types as follows: the A153L (manufactured by 3M) and referred to as DISC1 and the Morgan Advanced Materials 4S845P4F5, referred to as DISC2 (see Fig. 2). While DISC1 had a full-face design, the working surface of DISC2 had eight, 0.045 in wide, protruding CVD-coated spiral vanes.

Prior to any test, the pad was broken-in for 20 minutes using DISC1 rotating at 95 RPM with a downforce of 4.5 kgf. During break-in, ultra-pure water (UPW) was injected near the pad center at a flow rate of 300 mL/min. The kinematics of the conditioner were kept the same at all times. *In-situ* conditioning was performed with both discs. For the *ex-situ*

case, only DISC2 was employed. The experimental matrix with the 12 different combinations tested in this study is shown in Table 1.

The bow wave formed at the leading edge of the retaining ring at different conditions was recorded using a SC1 High-Speed Video camera (manufactured by Edgertronic). A schematic representation of the experiment setup is shown in Fig. 3. The camera was set on greyscale mode at an ISO of 400 and a shutter speed of 1/400. An f/stop value of 5.6 was selected for the aperture, and two 18 Watt LED light sources were employed for additional illumination to allow for proper image acquisition. The resolution of the images was 1280×1024 pixels with the video acquisition speed set at 240 frames per second. Using such a configuration, a total of 20 seconds of video (i.e. 4,800 frames) could be recorded for each test. To allow the usage of a common baseline and fair comparisons among different polishing conditions, the camera was kept at the same position and angle at all times, including during all baseline tests. The detailed description of the camera configuration and experimental setup is provided elsewhere.¹⁰

The pad was rinsed with UPW in between each polish test. Since mixing between residual rinse water and freshly injected dyed slurry at the onset of every polish caused a high variability in the actual dye concentration on top of the pad, each polishing process was intentionally lapsed for 20 seconds prior to videography (i.e., video capture was initiated after 20 seconds of polishing time) to ensure uniform slurry-dye concentration atop the pad.

Images obtained from the high-speed videography camera were then processed using our customized software written in LabView.¹⁰ The same two regions of interest located along the bow wave at the leading edge of the retaining ring (named as “Region 1” and “Region 2” as shown in Fig. 3) were fixed to allow fair comparisons among all test combinations. Since the slurry was tagged with a black dye and injected onto a white pad, black pixels

in the image were identified as those covered by the slurry. The image analysis software then proceeded to perform batch calculations and reported the bow wave width at the leading edge of the retaining ring as a function of time as explained in great detail elsewhere.¹⁰ Finally, Fast Fourier Transformation (FFT) was employed to convert the fluctuations of the bow wave width from time domain to frequency domain. The spectral information regarding the bow wave width fluctuation was then rationalized based on the kinematics of the process.

3. Results and Discussion

Fig. 4 shows an example of the raw bow wave width as a function of time for RING1 during *in-situ* conditioning with DISC1 at a slurry flow rate of 200 mL/min. While only the raw bow wave width data will be used for calculating average bow wave width and FFT reported later on in this chapter, a 10-point moving average is first applied to the results for better visualization (see Figs. 5 and 6). Later on, an average bow wave width for each combination is calculated by integrating the area under the curve (i.e. the bow wave width) and dividing it by the total time (i.e. 20 seconds). To provide easier comparisons, Fig. 7 summarizes the average bow wave width for all combinations.

3.1. Effect of flow rate

From Figs. 5 and 6, it can be observed that the bow wave is consistently wider at a slurry flow rate of 300 mL/min compared to 200 mL/min. As flow rate is increased, a higher volume of slurry is delivered to the pad and, therefore, more slurry is available to form at the bow wave. As expected, the bow wave width in “Region 1”, closer to the slurry injection point, is consistently wider than that in “Region 2” (which is closer to the edge

of the pad). As “Region 1” is closer to the injection point, it has a higher slurry availability and, consequently, a wider bow wave. In addition, when the retaining ring rotates from “Region 1” to “Region 2”, a large fraction of the slurry has already been transported inside the pad-wafer region through slots and grooves. Therefore, the bow wave formed in “Region 2” is mainly governed by the hydrodynamic boundary layer on the retaining ring wall, as already discussed in detail by L. Vazquez Bengochea et al.¹⁰ As such, the bow wave width in “Region 2” is not significantly affected by changes in the conditioning disc, conditioning scheme or retaining ring slots design, and the results for “Region 1” are more relevant in this study.

3.2. Effect of slot design

Figs. 5, 6 and 7 show that RING2 (i.e., the retaining ring with rounded slots) results in consistently wider average bow waves than RING1 (i.e., retaining ring with sharp slots). These results can be partially explained using the schematic diagram shown in Fig. 8. Slurry transport through the slots at the leading edge of the retaining ring can be attributed to two different mechanisms, as illustrated in Fig. 8 top. The first mechanism is slurry transport through the bow wave formed on the retaining ring wall that is affected by the rotation of the ring, denoted as Mechanism – 1. The second mechanism, denoted as Mechanism – 2, transports slurry via pad grooves and land areas. The combination of both mechanisms leads to the formation of slurry streamlines through the retaining ring slots. As our illustrations in Figs. 8 bottom show, we hypothesize that as the retaining ring continuously rotates counterclockwise, the slurry streamlines that are just entering the slots will collide and get redirected by the sidewalls. In the case of RING2, the rounded feature of the sidewall allows slurry streamlines that impact the wall above the blue dashed line (as shown in Fig. 8 bottom right) to escape the slot and flow back to the

bow wave area at the leading edge of the retaining ring. As such, the fraction of slurry that escapes out contributes to the bow wave by increasing its width. In contrast, for RING1, the sharp edge of the sidewall is more effective in preventing the escape tendency explained with RING2 (see Fig. 8 bottom left). As such, RING1 continuously delivers more slurry towards the inner part of the retaining ring as compared to RING2. Consequently, less slurry availability is observed in the bow wave area using RING1 compared to RING2 and causes a narrower bow wave for RING1.

3.3. Effect of conditioning scheme

For *in-situ* conditioning polishing (i.e., black and dashed red lines in Figs. 5 and 6), the bow wave width graphs show four primary peaks within the 20 second interval. Such a frequency coincides with the conditioner's sweeping action and, particularly, when the conditioner moves from the center to the edge of the pad. As the conditioner sweeps radially, it delivers excess slurry from the puddle formed at the center of the pad to the leading edge of the retaining ring. This results in a higher slurry availability and, therefore, a thicker bow wave as evidenced by the four major peaks in Figs. 5 and 6. On the other hand, when the conditioner sweeps from the edge of the pad to its center, there is no excess slurry that can be accessed and transported by the disc, therefore, the bow wave width remains relatively stable as evidenced by the nearly constant width in between each pair of major peaks.

As expected, the four primary peaks are no longer present with *ex-situ* conditioning, and slurry availability at the retaining ring is relatively stable during the 20 second interval, since there is no conditioning and therefore no slurry transport associated with it. Any

fluctuations in the bow wave width that are not related to the conditioner's sweeping action can be attributed to the polisher's kinematics as discussed in detail in Section 3.5.

During the intervals when the conditioning disc is moving from the edge to the center (i.e., 0 to 0.8 s, 2.8 to 6.1 s, 8.1 to 11.5 s and 13.5 to 17.0 s and 19.0 to 20.0 s), Figs. 5 and 6 show that the bow wave width for *in-situ* conditioning cases (i.e., black and dashed red lines) are consistently lower than those in the corresponding periods of time for *ex-situ* conditioning (i.e., blue line). For example, the top-left graph in Fig. 5 shows the results for "Region 1", with RING1 at a flow rate of 300 mL/min. In this case, the average bow wave width in the intervals mentioned above for *ex-situ* conditioning, *in-situ* conditioning with DISC1 and *in-situ* conditioning with DISC2 are calculated at 10.0, 8.5 and 7.9 mm, respectively. In the case of *in-situ* conditioning scheme, some slurry is transported by the conditioner when it sweeps from the pad center to the pad edge. Therefore, once the conditioner reaches the pad's edge, a fraction of the slurry transported by the disc is discarded as waste stream. This effect decreases the total volume of slurry on the pad during polishing which contributes to a lower slurry availability at the leading edge of the retaining ring. Consequently, when *in-situ* conditioning is employed, the higher amount of slurry discarded as waste decreases the slurry availability near the retaining ring, resulting in a narrower bow wave.

There are no significant differences observed in Figs. 5 and 6 when it comes to bow wave width for the two conditioning schemes in "Region 2". The average bow wave width results in "Region 2" for *in-situ* and *ex-situ* conditioning (shown in the bottom graphs in Fig. 7) differ in a range of just 1 to 5%. We consider that, with such low variability, the results are equal for the two conditioning schemes. This is in agreement with the explanation given earlier, where we stated that the slurry bow wave in "Region 2" is mainly governed by the boundary layer formed on the retaining ring wall.¹⁰ As such, it is

expected that the bow wave width is not affected by the disc or the conditioning scheme, since they would not affect the boundary layer formation.

3.4. Effect of conditioning disc during in-situ conditioning

As mentioned in Section 3.3, Figs. 5 and 6 show the presence of four primary peaks in the bow wave width during the 20 second interval for all the experiments using *in-situ* conditioning. The frequency of these peaks is similar regardless of the type of disc employed. However, Fig. 7 shows that the average bow wave width associated with DISC1 is consistently higher than with DISC2 in “Region 1”. As shown in Fig. 2, DISC1 is a full-face conditioner having a uniform surface. When DISC1 sweeps radially across the pad, it can only transport a thin slurry film that is trapped between its surface and the surface of the pad. On the contrary, DISC2 with its eight protruding spiral vanes can retain some amount of additional slurry between them. When DISC2 sweeps across the pad, its vanes can retain a larger volume of slurry and transport it to the pad’s edge, where it finally leaves the pad and is discarded as waste stream. Consequently, there is a higher volume of slurry that is being discarded by DISC2 which accounts for the narrower bow wave (by as much as 10%) as compared to DISC1.

As in the case of the conditioning scheme, no significant differences are observed in the bow wave width formed in “Region 2” when the different discs are employed. The average bow wave width (Fig. 7) shows that the results for DISC1 and DISC2 vary in a range from 0.5 to 2.5%. As expected, the results are considered similar, because the bow wave width is governed by the thickness of the boundary layer.

3.5. Analysis of the system kinematics

As mentioned previously, the results of the bow wave width over time show very high fluctuations, and we believe that those fluctuations can be attributed to process kinematics. To prove this hypothesis, FFT is employed to convert the bow wave width data from time domain to frequency domain (as shown in Fig. 9) where, for each case, the x-axis represents the frequency associated with the fluctuation, and the y-axis shows its amplitude. A logarithmic scale is used to show a larger range of spectral amplitudes. The Nyquist frequency is the maximum frequency that can be computed at a given sampling rate to be fully processed, and it can be calculated as half the sampling frequency.¹⁶⁻¹⁷ As the camera acquisition speed is 240 frames per second, a maximum frequency of 120 Hz can be processed. However, we have chosen to truncate the x-axis at 20 Hz, since the fluctuations in the bow wave width are dominated only by low frequencies. The results for the FFT analysis for the two different flow rates (200 and 300 mL/min) show the same spectral pattern and trends, with major peaks emerging at the same frequencies. Therefore, to avoid showing repetitive results, only the spectral analysis for the highest flow rate is reported here. As shown in Fig. 9, a consistent spectral fingerprint emerges for all conditions tested. In these graphs, all frequencies are rounded up to the next highest whole number. Major peaks for all conditions are shown at 1, 2, 4, 8 to 9, and 12 to 14 Hz which are identical to what we have reported previously.¹⁰

Fig. 9 shows that the amplitude of the peak using *ex-situ* conditioning (i.e., the blue line) at 1 Hz is consistently lower than its counterpart using *in-situ* conditioning (i.e., black and dashed red lines). This peak can be attributed to three effects, all of them having frequencies that range from 0 to 1 Hz: conditioning disc oscillation, carrier rotation and platen rotation (calculated at 0.19, 0.65 and 0.70 Hz, respectively). When *ex-situ* conditioning is employed, the conditioning disc oscillation does not contribute to this peak and, therefore, it is expected to result in a lower amplitude than that of *in-situ*

conditioning. The peak at 2 Hz, and its harmonics at 4 and 8 to 9 Hz, can also be explained by disc rotation (with a calculated frequency of 1.58 Hz), as well as a harmonic of the peak at 1 Hz. The last major peak observed in the spectral analysis is at a range of 12 to 14 Hz, which can be attributed to the retaining ring slots. Fig. 9 clearly shows that the amplitude of this peak is much higher in “Region 2” than in “Region 1” for all experiments. As the slurry gets depleted in “Region 2”, the high fluctuations are caused by large variations between the slurry film retained on the wall of the ring and the voids in front of the slots. These high fluctuations are suppressed in “Region 1”, since there is always excess slurry in front of the retaining ring and the bow wave width is not affected by the slots.

4. Conclusions

We investigated the effect of the retaining ring slot designs, the conditioning schemes and the conditioning discs on the slurry bow wave width during CMP. The polishing tests were conducted on a concentrically grooved pad with its natural white color. The bow wave formed on the retaining ring wall during polishing was recorded using a high-speed videocamera, at a frequency of 240 frames per second. Results showed that a wider bow wave was formed at higher flow rates and at regions closer to the slurry injection point. It was also observed that the retaining ring with rounded-angle slot design consistently generated wider bow wave width than the retaining ring having sharp-angle slot design. This result indicated that the rounded-angle slots allow some slurry streamlines that start to enter the retaining ring slots to flow back to the outer part of the retaining ring. Compared to *ex-situ* conditioning, *in-situ* conditioning scheme caused narrower bow wave width due to the slurry transport associated with the conditioning disc sweeping. When the conditioner sweeps from the pad center to the pad edge, the disc discards some

amount of slurry to the waste stream, therefore reducing the amount of slurry reaching the retaining ring. Furthermore, conditioning with the conditioning disc having several vanes resulted in a lower bow wave width than the conditioning disc with a flat homogenous surface. The vanes of the disc accommodate extra amount of slurry within the disc that will be discarded to the waste stream when the disc sweeps to the pad edge. Finally, Fast Fourier Transformation was employed to convert bow wave width fluctuations from time to frequency domain. A consistent spectral fingerprint was obtained, and major peaks were observed at frequencies of 1, 2, 4, 8 to 9, and 12 to 14 Hz for all experiments. Those peaks can be attributed to the carrier, platen and conditioning disc rotation and oscillation and to the retaining ring slots.

References

1. J. McGrath and C. Davis. *Journal of Materials Processing Technology* **153-154** (2004) 666-673
2. R. Han, Y. Sampurno and A. Philipossian. *Tribology Letters* (2017) 65:21
3. Slurry COO: Roberts, B., (2014) Available at: <http://techcet.com/wp-content/uploads/2014/10/TECHCETCMPUGBerninFranceR2rev1101014BRoberts.pdf>
4. Y. Mu, Y. Zhuang, Y. Sampurno, X. Wei, T. Ashizawa, H. Morishima and A. Philipossian. *Microelectronic Engineering* **157** (2016) 60-63
5. A. Philipossian and E. Mitchell. *Jpn. J. Appl. Phys.* **42** (2003) 7259-7264
6. X. Liao, Y. Sampurno, Y. Zhuang and A. Philipossian. *Electrochemical and Solid-State Letters* **15** (4) H118-H122 (2012)
7. X. Liao, Y. Sampurno, Y. Zhuang, A. Rice, F. Sudargho, A. Philipossian and C. Wargo. *Microelectronic Engineering*, **98** (2012) 70-73

8. A. Philipossian, X. Wei, R. Dittler, J. Cheng, Y. Zhuang, C. Wargo and R. Stankowski. Presented at the 13th International Symposium on Chemical Mechanical Planarization, Lake Placid, New York, August 10-13, 2008.
9. X. Wei, Y. Sampurno, Y. Zhuang, R. Dittler, A. Meled, J. Cheng, C. Wargo, R. Stankowski and A. Philipossian. *Electrochemical and Solid-State Letters*, **13** (4) H119-H121 (2010)
10. L. Vázquez Bengochea, Y. Sampurno, C. Stuffle, R. Han, C. Rogers and A. Philipossian. *ECS Journal of Solid State Science and Technology*, **7** (3) P1-P7 (2018)
11. M. Y. Tsai and W. K. Chen. *Int. J. Adv. Manuf. Technol.* (2011) 55:253-262
12. R. Han, Y. Sampurno, M. Bahr, L. Borucki and A. Philipossian. *ECS Journal of Solid State Science and Technology*, **6** (7) P477-P482 (2017)
13. C. Stuffle, R. Han, Y. Sampurno, D. Slutz, S. Theng, L. Borucki and A. Philipossian. *ECS Journal of Solid State and Technology*, **7** (2) P9-P14 (2018)
14. APD-800 Technical Digest. Available at: <http://aracainc.com/wp-content/uploads/2015/10/APD800-brochure.pdf>
15. R. Han, Ph. D. Thesis, University of Arizona, Tucson, AZ (2017)
16. R. Bracewell, *The Fourier Transform And Its Applications*, McGraw-Hill, New York, NY, 1994.
17. E. Brigham and H. Oran, *The Fast Fourier Transform And Its Applications*, Prentice-Hall, Englewood Cliffs, NJ, 1988.

Fig. 1. A typical poly-ether-ether-ketone PEEK retaining ring for 300-mm wafer polishing (left). RING1 with sharp-angle slots (center). RING2 with rounded-angle slots (right).

Fig. 2. The 3M A153L, referred to as *DISC1* (left).
The MGAM 4S845P4F5, referred to as *DISC2* (right).

Retaining Ring	RING1			RING2		
Conditioning	DISC1 <i>In-situ</i>	DISC2 <i>In-situ</i>	<i>Ex-situ</i> DISC2	DISC1 <i>In-situ</i>	DISC2 <i>In-situ</i>	<i>Ex-situ</i> DISC2
Flow Rate (mL/min)	200	200	200	200	200	200
	300	300	300	300	300	300

Table 1. Polishing conditions.

Fig. 3. *Experimental set-up and regions of interest at the leading edge of the retaining ring.*

Fig. 4. An example of the raw bow wave width data as a function of time: RING1, in-situ conditioning with DISC1 at a flow rate of 200 mL/min.

Fig. 5. Bow wave width vs. time for different rings, conditioning schemes and discs at 300 mL/min. In-situ conditioning with DISC1 (black). In-situ conditioning with DISC2 (dotted red). Ex-situ conditioning (blue).

Fig. 6. Bow wave width vs. time for different rings, conditioning schemes and discs at 200 mL/min. In-situ conditioning with DISC1 (black). In-situ conditioning with DISC2 (dotted red). Ex-situ conditioning (blue).

Fig. 7. Average bow wave width for different regions, flow rates and retaining rings.
*In-situ conditioning with DISC1 (black). In-situ conditioning with DISC2 (white).
 Ex-situ conditioning with DISC2 (grey).*

Fig. 8. Slurry transport mechanisms through the retaining ring slots.
General transport mechanisms (top). Transport mechanism for RING1 (bottom left).
Transport mechanism for RING2 (bottom right).

Fig. 9. Spectral analysis of bow wave width at 300 mL/min.
*In-situ conditioning with DISC1 (black). In-situ conditioning with DISC2 (dashed red).
 Ex-situ conditioning (blue).*