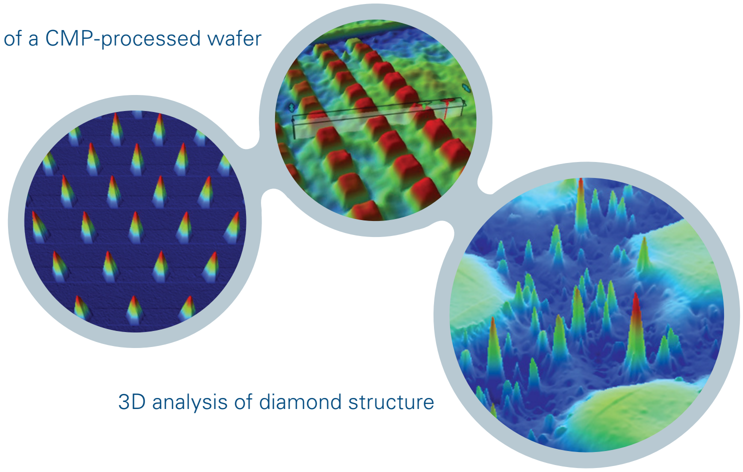


Field of view of a CMP-processed wafer

DLC-coated designed-structure pad

3D analysis of diamond structure

Application Note #564

Characterization of CMP Processes with White Light Interferometry

Faster computer and electronic processors require smaller features for integrated circuits (IC), which in turn require smaller and smoother substrate surfaces. Chemical mechanical polishing (CMP) has become one of the most critical semiconductor fabrication technologies because it offers a superior means of removing unwanted topography in interlevel dielectric layers and achieving sufficient planarity for the creation of the IC or hybrid bonding for advanced packaging. The planarization performance of CMP process is significantly influenced by the polishing conditioner pad and the CMP conditioner. Therefore, much research has been done in the development and choice of the CMP pad/conditioners and the overall CMP conditioning process. This application note describes the measurement and analysis advantages that white light interferometry (WLI) offers for the various CMP components. It also details an improvement study that investigated asperity behavior of the fluid layer under the wafer during the CMP process and revealed the effects of polishing and conditioning on the pads, as well as wafer polish results.

Chemical Mechanical Polishing Technology

CMP, also known as planarization, is a process of smoothing a wafer surface with the combination of chemical and mechanical forces (see Figure 1). The process uses an abrasive and corrosive chemical slurry liquid in conjunction with a conditioning pad that is typically much larger in diameter than that of the wafer being planarized. The conditioner pad and wafer are pressed together by a dynamic polishing head that is rotated with different axes of rotation with the slurry. This removes material and tends to even out any irregular topography, making the wafer flat (planar). This process is typically necessary to set up the wafer for the formation of additional circuit elements. For example, CMP can bring the entire surface within the depth of field of a photolithography system, or can selectively remove material based on its pad position. Typical depth-of-field requirements are down to angstrom levels for the latest 5-nanometer technology roadmap.

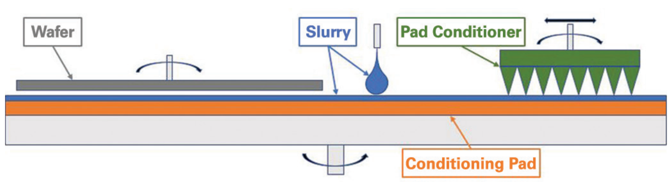
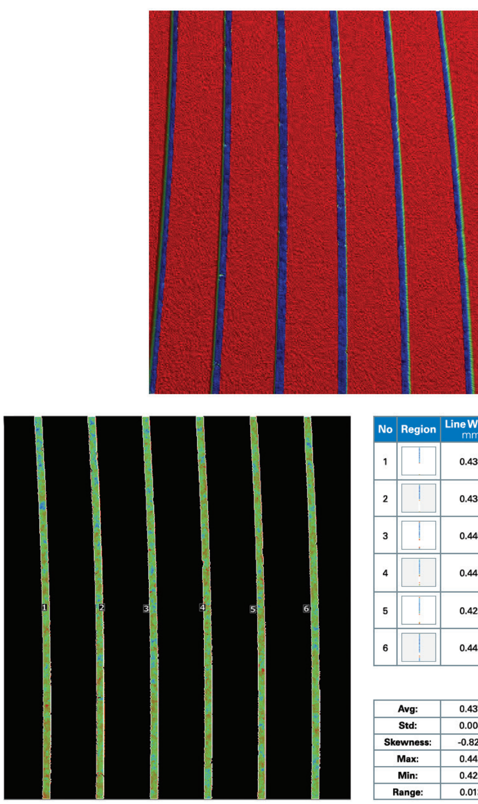


Figure 1. Typical functional principles of a CMP process.

One example of a widespread CMP technology advancement that required new processes is when the semiconductor industry transitioned from aluminum to copper conductors. Different fabrication techniques were adopted, including the use of metal barrier layers and different methods for patterning the metal. In this process, the underlying insulating layer is patterned with open trenches where the conductor should be. A thick coating of copper that significantly overfills the trenches is deposited on the insulator, and CMP is used to level the copper to the top of the that insulating layer. Copper within the trenches of the insulating layer is left to become the patterned conductor. Since diffusion of copper into surrounding materials degrades their properties, a metal barrier layer must surround all interconnections. With successive layers of insulator and copper, a multilayer structure is created. Without the ability to remove the copper coating in a uniform fashion and to stop repeatedly at the copper-insulator interface, this CMP technology would not be successful.

Conditioning Pads and Pad Conditioners Use and Inspection

CMP conditioning pad surface characteristics are particularly important because they affect the real area of contact, friction, wear, and lubrication in the polishing process. The conditioner pad is usually constructed of a of urethane polymer with many existing patterns that either change the surface rigidity or the pad's ability to hold the slurry. Bruker's WLI profilers can stitch large areas of the conditioning pads and perform automatic analyses, including depth, width, and surface finish as an example.[1] These analysis parameters, which can't be analyzed using most other measurement equipment especially contact measurement techniques, are instrumental for the trench features to retain slurry and remove debris (see Figure 2).



No	Region	Line Width mm	Mean µm	Ra µm	Volume mm^3
1		0.438	-623.477	31.376	-5.950
2		0.434	-628.419	32.069	-5.939
3		0.440	-628.571	31.585	-6.027
4		0.441	-620.729	32.418	-5.961
5		0.429	-615.128	37.454	-5.754
6		0.442	-627.861	29.380	-6.048

	Line Width mm	Mean µm	Ra µm	Volume mm^3
Avg:	0.437	-624.031	32.380	-5.946
Std:	0.004	4.916	2.466	0.095
Skewness:	-0.820	0.712	1.135	1.082
Max:	0.442	615.128	37.454	5.754
Min:	0.429	-628.571	39.380	-6.048
Range:	0.013	13.444	8.074	0.294

Figure 2. Conditioning pad automatic analysis.

The conditioner pad surface itself is "conditioned" with some form of diamond grit or diamond-like carbide (DLC) coated pad conditioner that is performed both before and during the CMP process. Most commonly, a rotating pad conditioner disc is moved against the conditioning pad surface at a constant load. The structure of the pad conditioner slowly cuts the conditioning pad surface, maintaining the surface against abrasive wear, plastic deformation, polishing debris accumulation, and other degrading factors. This conditioning interaction opens closed cells, improves slurry transport, and provides a consistent polishing surface and removal rate over time, regenerating the peaks and valleys of the conditioning pad.

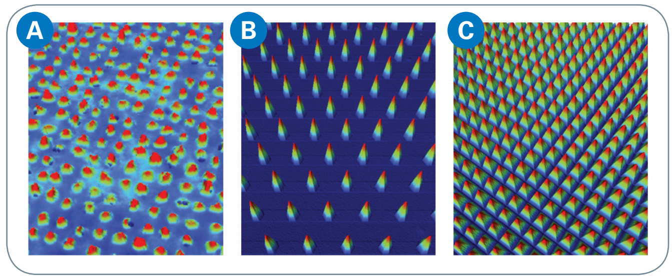
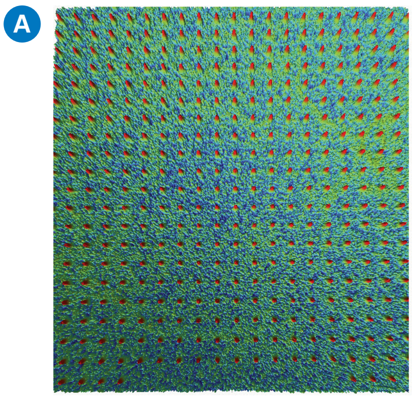
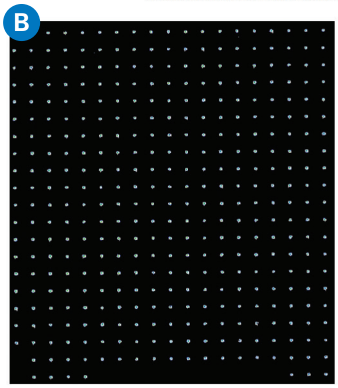


Figure 3. (a) Diamond pad versus two DLC-coated designed-structure pad conditioners (b and c).

Simultaneously, slurry abrasive particles slowly wear the pad conditioner structures that contact the conditioning pad surface. When surfaces are brought together, the initial contact will occur on the tallest asperities of the surfaces. As the force on the surfaces is increased, these asperities deform, and shorter asperities start to contact each other. The established relationship between reduced asperity height on the conditioner pad due to continued polishing and the consequent decrease in reliability and removal rate on the wafer is well documented.[2] A less than optimum conditioning process results in a relatively rapid degradation of the removal rate. Too aggressive conditioning decreases pad life, and over time the conditioner pad itself will wear and jeopardize the polishing process. Factors like diamond crystal size, diamond crystal morphology, crystal surface density and the DLC-coated designed structure (as seen in Figure 3) have all been investigated to develop the ideal conditioning process for the parts being polished. Bruker's Vision64® software can automatically detect and analyze these structures for height, pitch, placement, density, area, volume, diameter, and overall surface finish, as seen in Figure 4 using Vision64 Multiple Region analysis. WLI is a superior measurement technique for these applications since it can get into these small areal structures not obtainable with contact measurement systems while maintaining the nanometer vertical resolution and repeatability required for this semiconductor industry application.





No	Region	Area µm²	Diameter µm	Mean µm	Pitch mm	Rp% µm
1		27092.895	217.662	77.495	0.997	89.427
2		26969.152	215.157	78.180	1.000	87.139
3		30254.816	216.672	76.599	0.992	88.147
4		28125.158	242.762	77.801	1.022	89.574
5		21368.217	194.103	78.644	0.998	90.939
6		31.404.311	231.263	78.472	0.978	91.349
Avg:		21975.076	178.219	73.967	0.999	83.642
Std:		12024.167	87.821	5.940	0.017	10.483
Skewness:		-1.137	-1.267	-1.296	-0.297	-1.274
Max:		35956.699	274.823	81.055	1.082	97.166
Min:		32.564	6.506	61.781	0.871	62.172
Range:		35924.136	268.317	19.273	0.212	34.994

Figure 4. (a) 3D optical image of designed pad, and (b) automatic detection/analysis of the designed pad conditioner.

The Vision64 automatic Multiple Region analysis performed for qualification of the production pad conditioner structures was able to easily find, detect and flag structures that didn't meet pre-defined tolerances for data logged parameters (see the graph in Figure 5). In this example, the Peak % height for each structure was logged to the database with pass/fail criteria that easily found debris, as well as chipped, and partially missing structures (e.g., defects exceeding the red tolerance bands in Figure 6).

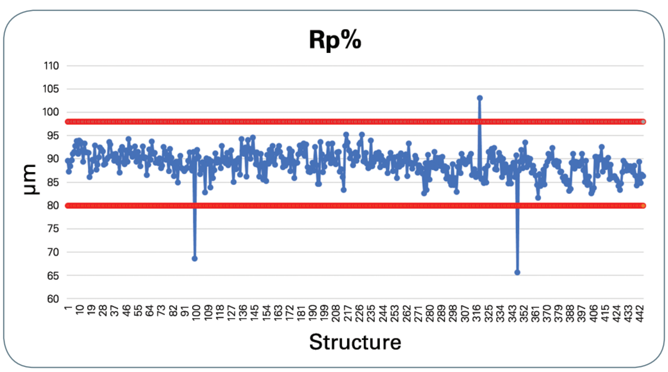


Figure 5. Individual peaks inspection of a pad conditioner logged to a database with Pass/Fail criteria.

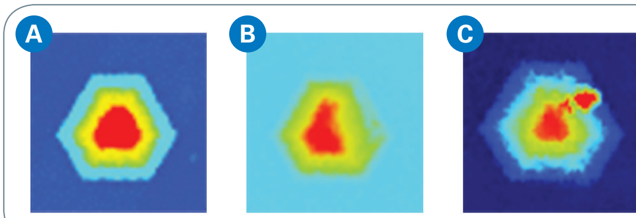
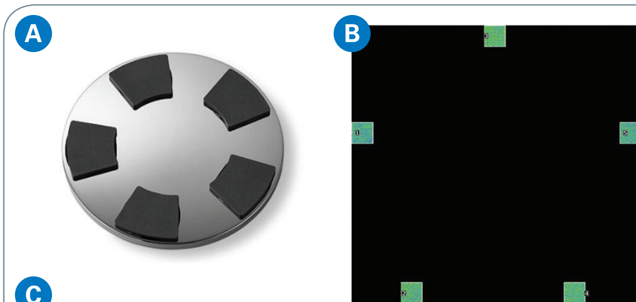


Figure 6. (a) Good structure, (b) missing peak causing LOW Rp%, and (c) debris causing HIGH Rp%.

Commonly, the designed pad conditioner is evenly spaced around the outside of a larger mounting platen, as seen in Figure 7a. Bruker's WLI profiler with a self-calibrating laser can perform the detailed analysis on each of the five mounted pads and can stitch those pads together without capturing any images from the in-between base platen itself, which saves a great amount of time.[3] This type of superior remote measurement capability allows for verification that the pads are mounted on the platen at the correct location, tilt angle and planarity (see 7b-c). Any of the WLI measurements can be exported into customer software for custom analysis and print evaluation. An additional advantage of the self-calibrating laser is that the optical profiler self-calibrates on every measurement, reducing the drift and environmental effects that are common with other measurement systems. This feature on high-end WLI systems delivers superior accuracy and repeatability. Contact Coordinate Measurement Machine (CMM) can't combine the needed lateral resolution for each individual pad due to the fine features and high aspect ratios, nor can they perform remote pad location inspection.



No	Region	Mean µm	R Mean µm	R Tilt °	R Tilt Angle °	R X Tilt °	R Y Tilt °	Ra µm	Rq µm	Rt µm
1		-4.693	0.000	0.000	0.000	0.000	0.000	11.803	16.382	174.877
2		2.515	7.208	0.647	105.273	-0.170	0.624	12.370	17.222	167.693
3		5.474	10.167	3.148	127.959	-1.937	2.482	10.296	14.895	153.260
4		1.222	5.916	3.112	101.817	-0.637	3.046	10.009	14.427	147.062
5		-3.405	1.288	3.954	85.521	0.309	3.942	10.934	15.775	165.303
Avg:		0.223	6.145	2.715	105.143	-0.609	2.524	11.082	15.740	161.639
Std:		3.772	3.200	1.241	15.138	0.836	1.214	0.891	1.005	10.080
Skewness:		-0.032	-0.369	-0.891	0.309	-0.634	-0.539	0.221	0.128	-0.214
Max:		5.474	10.167	3.954	127.959	0.309	3.942	12.370	17.222	174.877
Min:		-4.693	1.288	0.647	85.521	-1.937	0.624	10.009	14.427	147.062
Range:		10.167	8.879	3.308	42.437	2.245	3.318	2.361	2.794	27.815

Figure 7. (a) Mounted Designed Pad structures, and (b and c) Automatic Analysis of Mounted Pad Conditioners.

For our study, stitched WLI measurements were taken on a new pad conditioner and then compared to a used pad that was removed from production due to poor CMP yield results. By just comparing the average mean height of the mounted pads between the new and used pad, indicated that the pads were mounted within height specification since any mounting angle of those pads are averaged out (see Figure 8a). Similar results would be obtained by a general microscope or CMM. However, the WLI also has the capability to measure the mounting angle of each pad, which clearly indicated that Pad 3 was mounted at an extreme X-Y angle, yielding the poor CMP results seen in the graphs in Figure 8b.

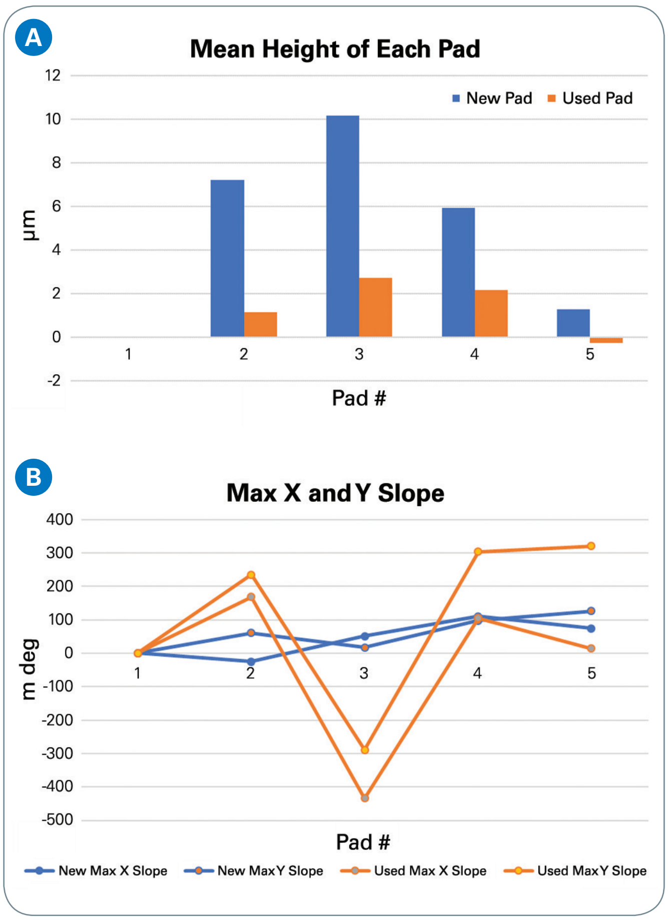


Figure 8. (a) Pad mean height versus (b) X–Y pad tilt angle of a new, good pad versus a used, bad pad.

CMP Wafer Polishing Results

The CMP process continues to evolve, but still has some limitations, which tends to make it one of the highest yield-loss steps in some semiconductor fabrication processes. Besides the physical damage to the wafer that can happen, a main concern is a consistent end-point detection, especially with blind polishing. With this technique it is hard to determine when the desired amount of material has been removed, or that the desired degree of planarization has been obtained, which could lead to "hot spots" across wafer devices. The CMP process also must be monitored to look at such uniformity displacement of dishing and erosion of the devices itself, as well as the isolation barriers. This can also be monitored with Bruker's WLI optical profilers.

The Vision64 software on these systems can subtract both single images and stitched images from within a wafer, or from wafer-to-wafer. A reference image or stitched image is captured, and then subtracted from sequential measurements of similar areas. The subtraction feature can remove pre-image waviness and form, align images run to run, and apply filtering as needed to the pre- and post-subtraction image(s). This is very helpful for monitoring height deviations from growing the wafer or CMP lapping steps (see Figure 9).

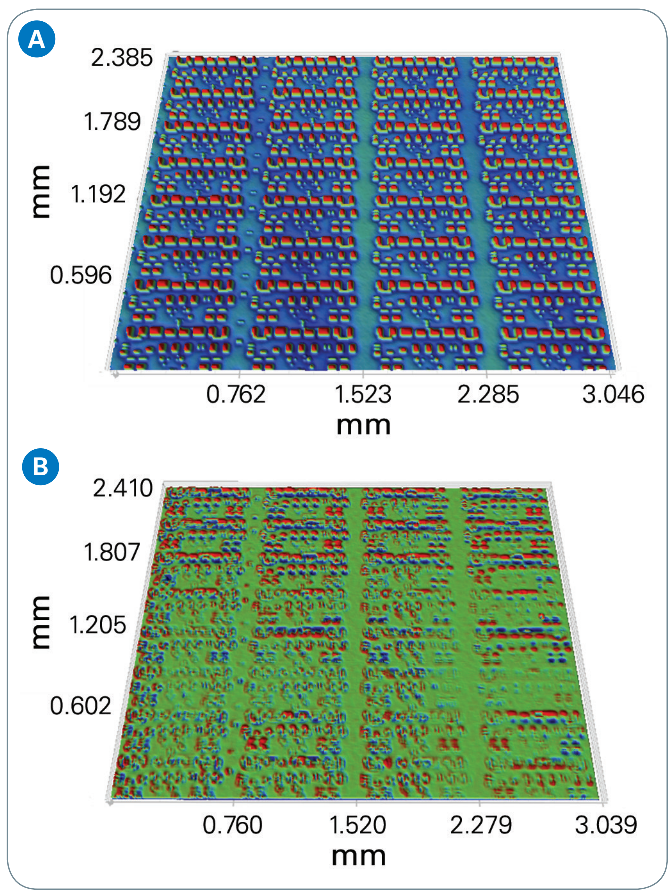


Figure 9. (a) Z-scaled ±70nm reference image, and (b) Z-scaled ±0.8nm subtracted image.

Die flatness is required for die-to-die or wafer-to-die bonding, or with chiplets (dielets) in heterogeneous packaging to ensure correct molecular-level adhesion between opposite surfaces. Nanometer height differences in peaks or valleys consequently creates voids, as well as potential interconnection issues. Likewise, the lateral micrometric resolution is required to ensure the proper capture of such structures as T-Box and via openings. Only the WLI technique can fulfill all the requirements with its combination of angstrom vertical resolution while maintaining the micrometric lateral resolution over large, stitched areas of hundreds of millimeters squared (see Figure 10).

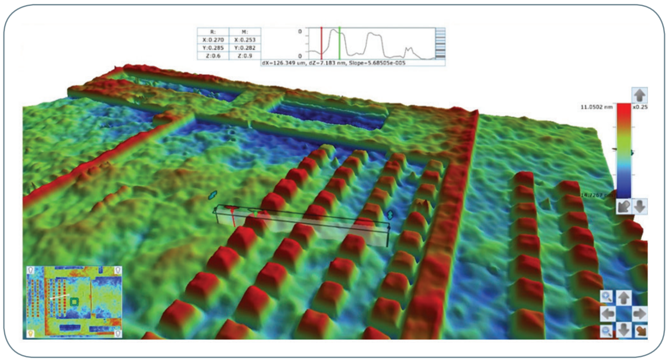


Figure 10. 4.6 x 2.5 mm field of view of a CMP-processed wafer with nanometer structures and T-Box openings.

Research Case Study: CMP Polishing for Characterizing and Evaluating Pad Conditioners

Bruker application engineers worked with academic researchers, a major CMP equipment manufacturer, a semiconductor wafer manufacturer, a conditioning pad manufacturer, and a pad conditioner manufacturer to perform a series of experiments investigating diamond conditioner wear on a CMP tool by comparing WLI images before and after extended controlled wear testing. A Bruker WLI profiler was used to measure feature surface heights, planarity, bow, and pad roughness from 0.1 nanometer to several millimeters. Utilizing a variety of 2D and 3D analyses of the WLI interferometric data, the identified peaks of specific, known diamond structures were compared before and after wear testing. The imaged areas were moderately large, up to 4.3 x 6.5 millimeters through stitched scans, enabling high lateral resolution (~3.24 microns). Shifts in these identified peaks after wear testing allowed the quantification of wear on the conditioning pad. Figure 11 shows a three-dimensional analysis of the same diamond group before and after wear testing. This method was then used to evaluate novel conditioner designs for more efficient and longer lasting CMP pad conditioning.

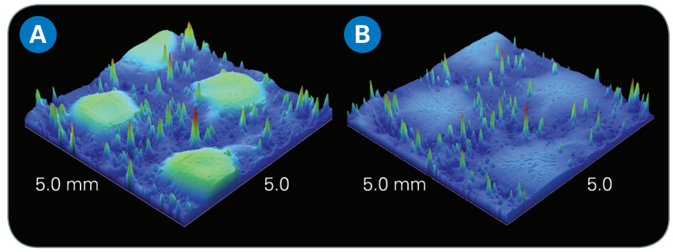


Figure 11. (a) Diamond before testing, and (b) the same diamond after the wear test.

Diamond wear was measured on a conditioning tool by numerical matching of interferometry images taken in overlapping areas before and after extended wear testing. A matching algorithm found the largest common region shared by two images and reoriented the final image to produce the best possible match with the initial image in the binding metallization. Usable results were dependent upon the existence of an area within the pad conditioner, portions of the binding metallization, that was within the focal range of the interferometer and that was far enough from the polishing pad surface to have little or no wear.

By characterizing the images using surface height probability density functions, peaks in the height distributions were identified that corresponded to single diamonds or groups of diamonds. Shifts in the peaks after wear testing then provided an estimate of the mean wear rate. The wear rate was very small, averaging 5 x 10^{-4} microns per minute over 710 minutes. The fact that wear at this level was detected at all was due to the WLI profiler's high resolution and large sample area.

In general, the higher diamonds were found to wear faster than the shorter ones, and diamonds on the outside edge of the tool wore faster than ones in the center. This microwear was also shown to correlate with a gradual decline in pad cut rate. At any time in the life of the pad conditioner, each diamond that produces a furrow on the pad surface should produce both cutting, in which material is removed from the furrow, and plowing, where material is pushed aside. It was theorized that the cut rate decline corresponded to an increase in the proportion of pad material that was plowed rather than cut as the sharp edges and points on the contacting diamonds wore down. From this information, the researchers concluded that the decline in cut rate with conditioner age was caused by an increase in plowing and a decrease in cutting as contacting diamond tips and edges break down.

Later investigations utilizing many of the elements described above were able to characterize extended wear for innovative diamond pad conditioner designs, with an eye toward developing a pad conditioner that would better resist corrosion and abrasive wear while maintaining proper CMP pad polish. The researchers used a Bruker WLI optical profiler to inspect the diamond conditioner surface both before and after the 30-hour conditioner wear and polishing process. A template was used to select the analysis regions to ensure that the same areas were imaged before and after the extended wear test. The experimental designs were coated with a polytetrafluorethylene film to reduce substrate wear and chemical attack.

Periodically during the wear experiments, the pad conditioner was installed on a separate polishing tool for in-situ polishing of copper wafers. Real-time shear force, pad temperature, and copper removal rates were measured. WLI was performed on selected areas of the conditioner surfaces before and after wear testing to quantify changes. Interferometry analysis revealed that the coating material from the diamond-free zones was laterally displaced by shear forces and plastic deformation, and ended up partly or totally covering some of the adjacent diamonds. Contours around several diamonds taken at the same level were also observed to tighten on the used conditioner, indicating that the coating immediately surrounding some of the diamonds had been displaced and that those diamonds were active. Utilizing these results and concurrent data from WLI and thermal observation techniques, the researchers were able to show that the coating on the pad conditioners provided protection from chemical and abrasive attack, proving that there was no decline in performance, even after 30 hours. Further, one of the designs was shown to provide a mechanism for gradually exposing more diamonds to the pad as they wear.

Conclusions

Bruker's WLI profilers have the unique ability to perform fast, three-dimensional, non-contact, high-resolution surface texture mapping at sub-nanometer height scales. This makes these systems an ideal metrology solution for characterizing conditioner pads, pad conditioners, and other aspects of the CMP process, including wafer inspection. The conditioner pads can be audited for trench width and depths while automatically detecting manufacturing defects. Pad conditioners can be measured for structure defect inspection, peak uniformity, surface finish, diamond density, and overall pad bonding to the platen. The final CMP processed devices can also be inspected for CMP planarity and hotspots, over (dishing/erosion) and under polishing, surface finish, widths, depths, and heights, just to name a few. Bruker's 3D optical profilers provide a means for quantifying many aspects of the CMP process and will continue to be invaluable in the pursuit of ever smaller semiconductor features and faster processing, as well as better wafer-/die-level bonding for advanced packaging.

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