Diamond Conditioner Wear Characterization for a Copper CMP Process

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(Received May 8 2006, Accepted August 1 2006)

Conditioner wear, copper polish rates, pad temperature and coefficient of friction (COF) are measured for two novel Mitsubishi Materials Corporation designs during an extended wear and polishing test. Both designs are coated with a Teflon^{TM} film to reduce substrate wear and chemical attack. Using optical interferometry, changes in the coating that result in gradual changes in diamond exposure are measured. Theories of the COF, conditioning, and polishing are applied to explain the observed performance differences between the designs.

Keywords : Conditioning, Diamond wear, Copper polishing

1. INTRODUCTION

It is well known that pad conditioning is necessary to prevent removal rate decay in CMP processes. However, depending on the process kinematics, the ionic strength of the slurry and the concentration and nature of slurry abrasive particles, chemical or abrasive wear of the conditioner itself may be sufficient to require replacement of the disc within a few tens of hours. It is therefore critical to develop materials and designs for diamond conditioning discs that resist corrosion and abrasive wear while effectively refreshing the surface of the pad during CMP.

In this study, two novel Mitsubishi Materials Corporation diamond conditioners with different designs were used in a copper CMP process. The surface of each conditioner was coated with a polytetrafluoroethelene (PTFE or Teflon^{TM}) film to reduce substrate wear and chemical attack. Each diamond disc was used to condition multiple IC1000^{TM} flat pads in a wear test comparable in duration (30 hrs) to commercial disc lifetimes. Periodically during the wear experiments, the conditioner was installed on a separate polishing tool for *in situ* polishing of copper wafers. Real time shear force, pad temperature and copper removal rate were measured. Optical interferometry and optical microscopy were performed on selected areas of the conditioner surfaces before and after wear testing in order to characterize changes. Relationships between the coefficient of friction, temperature, removal rates and changes in the discs are then explored theoretically.

2. EXPERIMENTAL

Figures 1 and 2 show the two novel Mitsubishi Materials Corporation 100 mm diameter 100-grit blocky type diamond conditioners used in this study. Figure 1 is the Mosaic design, in which diamonds are distributed randomly at 34/mm^2 except in roughly circular diamond-free zones that are arranged in a hexagonal close packed pattern. Figure 2 is the triple ring dot, or TRD design. In this design, diamonds are randomly placed at 35/mm^2 on three concentric circular rings of raised circular dots or pillars and on a raised outer ring punctuated by eight flow channels. Both conditioner surfaces were coated with 10 μm of PTFE to protect them from corrosion and abrasive wear.

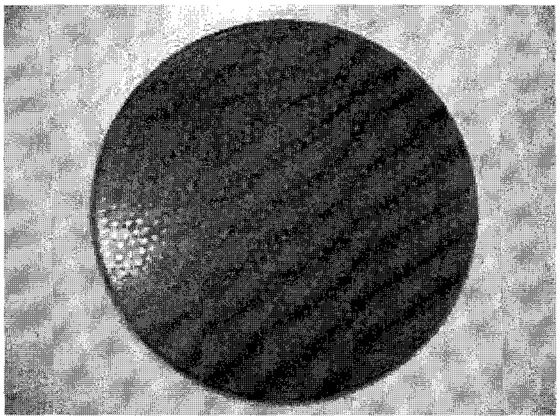

Fig. 1. Mitsubishi materials corporation mosaic design.

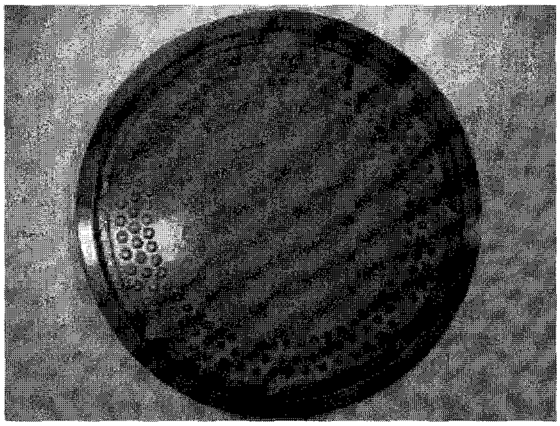

Fig. 2. Mitsubishi materials corporation TRD design.

For each conditioner, the experiment consisted of an initial copper wafer polishing phase on a 200 mm Fujikoshi polisher followed by ten 3-hour cycles of accelerated wear testing on a 100 mm polisher. Each wear cycle was followed with a copper wafer polishing measurement on the 200 mm polisher.

During the initial copper wafer polishing phase, the conditioner was used to break in an IC1000^{TM} K-grooved pad for 30 min at 0.4 PSI using deionized (DI) water as the lubricant. The same pad and the same conditioner kinematics were subsequently used for all copper polishing experiments. Pad break-in was followed by 10 minutes of pad seasoning using 200 mm, 99.99 % pure copper discs. The shear force was monitored to insure that stable values were achieved prior to copper wafer polishing. The metal stack of the 200 mm copper wafers that were used consisted of 1.5 μm of electroplated copper on top of a 0.1 μm PVD copper seed layer and a 0.025 μm TaN barrier. Each copper wafer was polished for 1 minute at 2.5 PSI and a sliding velocity of 1.2 m/s. An Ohaus Analytical Plus balance was used to weigh wafers before and after polishing to determine the mean removal rate. The polishing slurry in all phases of the experiment consisted of 11.9 volume parts of Cabot Microelectronics Corporation iCue 5001^{TM} slurry and 1 volume part of 30 % H_2O_2 applied at 220 ml/min on the 200 mm tool and 80 ml/min on the100 mm tool. The pad temperature was measured using an infrared camera with accuracy of 0.1 °C at a frequency of 3 Hz. During all polishing runs, shear force measurements were taken at 1000 Hz and the average COF was obtained by dividing the average shear force by the applied normal force.

After the initial wafer polishing phase, the conditioner was attached to the wafer carrier of the 100 mm polisher and used to abrade an IC1000^{TM} flat pad at 2 PSI and 0.62 m/sec for 3 hours. No polishing was performed during this accelerated wear phase, but Cabot Microelectronics Corporation iCue 5001^{TM} slurry was applied as in a normal copper process. The conditioner was then reinstalled on the Fujikoshi polisher and used to polish 200 mm copper wafers on the original pad to complete the cycle. Polishing was preceded by dressing of the pad at 0.4 PSI with DI water for 5 minutes, followed by 5 minutes of copper disc polishing with *in situ* conditioning. The shear force was again monitored until stable values were achieved. Wafer polishing conditions were identical to the initial polishing phase.

Optical interferometry was performed on the diamond conditioner surface both before and after the 30-hour conditioner wear and polishing process using a Veeco NT-3300 optical profiler. A template was used to select the analysis regions to insure that the same areas were imaged before and after the extended wear test. Optical microscopy photographs were also taken of the analysis regions before and after testing.

2.1 Copper polishing results

As seen in Fig. 3, the mean COF measured when the Mosaic design was used increased monotonically from 0.37 to 0.54 during the first five cycles, and then fluctuated around 0.5 for the remaining cycles. While the initial temperature showed no trend with time (Fig. 4), a gradual increase in the difference between the mean and initial pad temperatures can be seen in Cycles 0-5. This increase is related to the increase in the COF during the same cycles. Variations in COF also can be seen to follow variations in the pad temperature. Figure 5 shows the measured copper removal rate. Except for the initial polish, the removal rate follows the same trend as the COF and the mean pad temperature.

When the TRD design was used as the conditioner, there was a gradual upward trend in the COF from about 0.25 to about 0.37 except for dips at Cycles 2 and 6 (Fig. 6). The COF induced by the TRD design is less than that

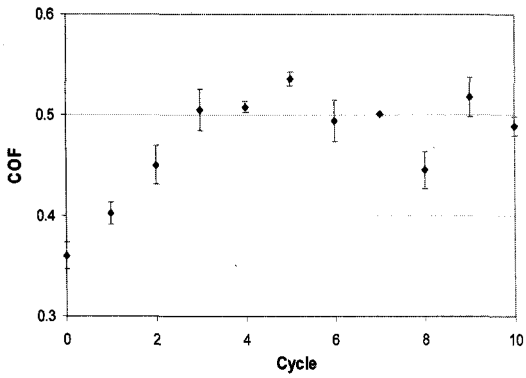

Fig. 3. Mean COF during copper wafer polishing using the Mosaic conditioner design.

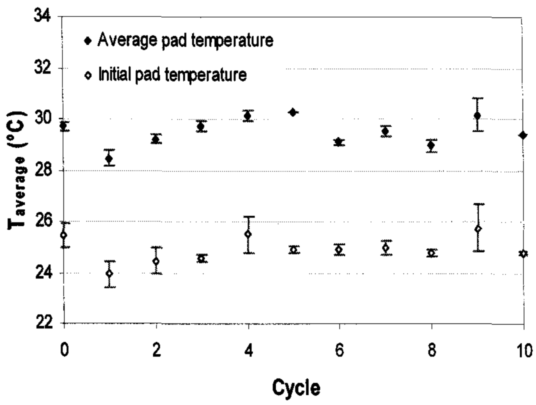

Fig. 4. Pad temperatures measured during polishing using the Mosaic conditioner design.

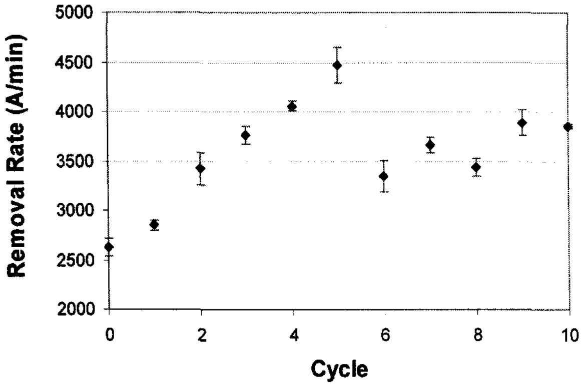

Fig. 5. Copper polish rates measured using the Mosaic conditioner design.

of the Mosaic design, indicating that the conditioners produced different pad surface topography and mechanical contact conditions with the same accelerated wear process. As for Mosaic, the initial temperature does not show a systematic increase or decrease with time (Fig. 7), but there is a slight increase in the temperature rise with the number of cycles that is consistent with the gradual rise in the COF. Similar to the Mosaic design, there is a correlation between the measured temperatures and the COF. The mean pad leading edge and initial temperatures are about the same as for Mosaic even though the COF is considerably lower. There is again a strong correlation between the copper removal rate (Fig. 8) and both the pad temperature and the COF.

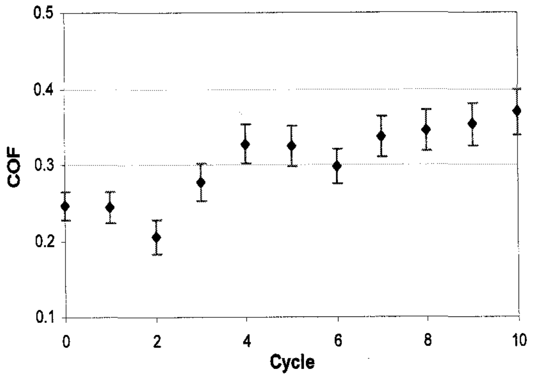

Fig. 6. Mean COF during copper wafer polishing using the TRD conditioner design.

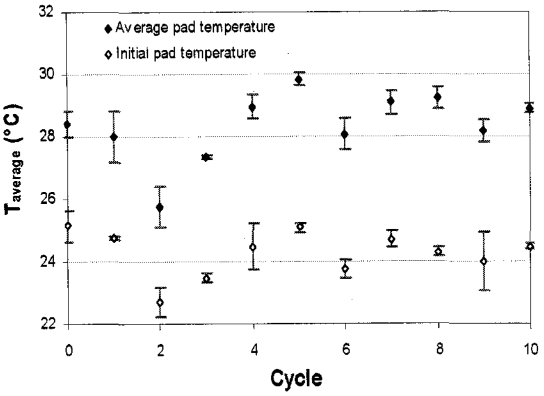

Fig. 7. Pad temperatures measured during polishing using the TRD conditioner design.

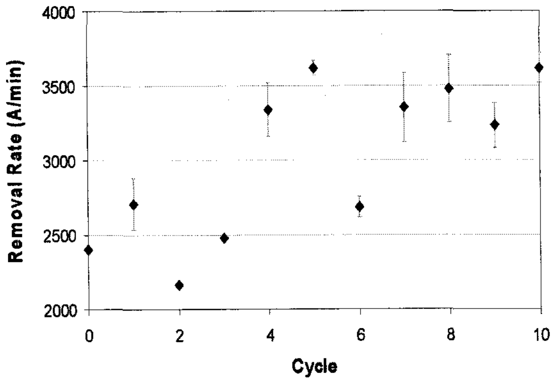

Fig. 8. Copper polish rates measured using the TRD conditioner design.

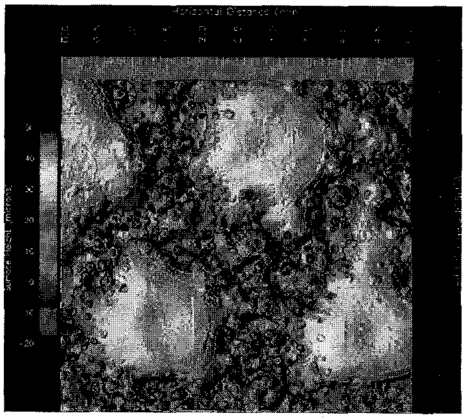

Fig. 9. Interferometry image of an area of a new Mosaic disc.

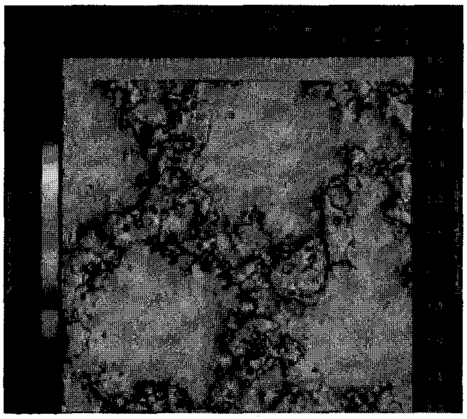

Fig. 10. Matched interferometry image of the same area as in Fig. 9 after Mosaic disc wear testing.

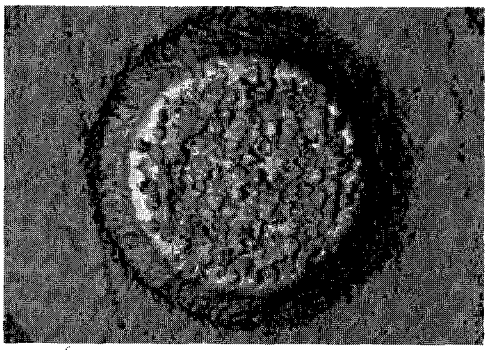

Fig. 11. Interferometry image of a new TRD pillar.

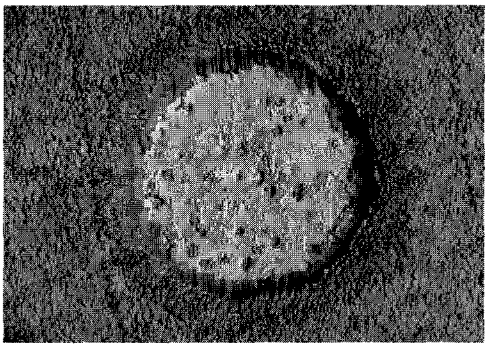

Fig. 12. The pillar in Fig. 11 after wear testing.

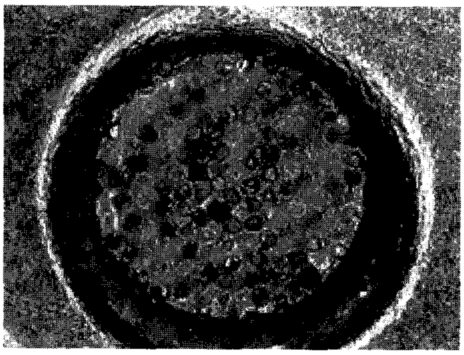

Fig. 13. Optical image of the new pillar in Fig.11.

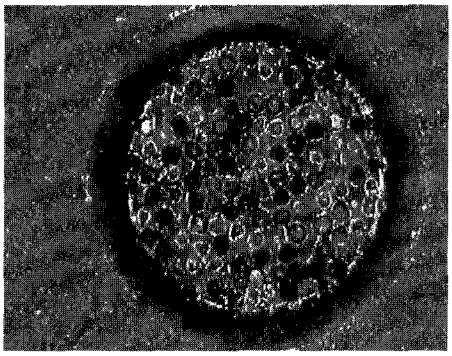

Fig. 14. Optical image of the used pillar in Fig.12.

2.2 Conditioner wear analysis

The method for matching and analyzing new and used interferometry images is described in[1]. Figures 9 and 10 show matched new and used images of the Mosaic conditioner in a region near the disc center. Coating material from the diamond-free zones appears to have been laterally displaced by shear forces and plastic deformation, partly or totally covering some of the adjacent diamonds. Contours around several diamonds taken at the same level can also be seen to tighten on the used conditioner, indicating that PTFE coating immediately surrounding some of the diamonds has also been displaced and that these diamonds are active.

Matched images of one of the pillars in the TRD design are shown in Figs. 11 and 12. After the wear test, the pillar surface is flat except for a few protruding diamonds. There are two possibilities: either the diamond-containing layer has been largely worn away, or the PTFE coating has simply been smoothed over. In Figs. 13 and 14, we show new and used optical microscopy images of the same pillar. These pictures show that all of the diamonds present at the beginning of testing remain after the wear test. Therefore, the smooth pillar surfaces are due to plastic deformation and smoothing of the PTFE by shear forces. The appearance of a flat surface is due to a difference in the wavelength of light used by the interferometer (80 nm) and the optical microscope. The PTFE coating is opaque at 80 nm but transparent to visible light, so only the coating surface is visible by interferometry. This interpretation is consistent with partial or total obscuration of some diamonds on the Mosaic disc due to movement of coating material from the diamond-free areas.

3. ANALYSIS AND CONCLUSION

First we discuss the temperature data. The mean pad temperature T_p is the sum of the initial temperature T_a and an increment proportional to the COF,

$$T_p = T_a + c_b \mu_k pV \tag{1}$$

where μ_k is the COF, p is the pressure, V is the sliding speed and c_b is a constant. For both conditioner designs, variations in the mean pad temperature can be accounted for by Equation (1). However the data suggest that the COF not only causes variations in temperature but also is affected by it.

We offer one possible explanation. In a previous paper [2], it is shown that the viscous shear contribution to the COF is

$$\mu_{visc} \propto (\mu_0 V / E)^{0.36} R^{-0.19} \lambda^{-0.17} \tag{2}$$

where μ_0 is the slurry viscosity, E is the pad modulus, and R is the mean asperity tip radius of curvature. The parameter λ is a characteristic length that measures how abruptly the rough surface of the pad terminates. A surface with asperities of more uniform height corresponds to a smaller λ. R and λ should be affected by conditioning. A theoretical analysis[3] indicates that when the pad cut rate is low, λ should vary inversely as the number of diamonds participating in cutting. According to Equation (2), softening of the pad modulus E due to an increase in temperature would increase the COF. The softening factor necessary to account for the initial increase in the COF in the Mosaic experiments is about a factor of 3. While not a reasonable change given the observed mean pad temperature, this much softening may be possible if the reaction temperature T at the asperity tips,

$$T = T_a + c_b \mu_k pV + (\beta / V^{1/2+e}) \mu_k pV \tag{3}$$

is responsible for softening. In Equation (3), the additional term represents the asperity flash heating increment[4]. A feedback mechanism is involved: fluctuations in T_a increase the COF, which increases the second and third terms in Equation (3), further increasing the COF.

For the TRD design, there is in addition to the temperature-induced variations in COF (which are weaker than for Mosaic) a slow increase of COF with time. To explain the overall COF increase, we hypothesize that the PTFE layer is quickly smoothed in the early stages of accelerated wear testing. Following this, the layer is slowly thinned by abrasion, gradually exposing more diamonds. This increases the frequency of cutting of each contacting asperity, decreases both R and λ, and increases the viscous contribution to the COF. In the Mosaic design, the COF initially increases due to exposure of individual diamonds due to wear of the PTFE, which similarly decreases R and λ,. This process then either saturates or is compensated for by an increase in the number of diamonds partly or totally covered by migration of PTFE from the unpopulated areas.

The difference in the total number of active diamonds on the two designs, a factor of 2.5 in favor of Mosaic, explains why Mosaic produces a higher COF than TRD. The larger active diamond count produces lower values of both λ and R for Mosaic. If each of these parameters is decreased by a factor of 2.5 in Equation (2), then the viscous contribution to the COF increases by a factor of 1.4. The ratio of the Mosaic to TRD COF for the last 5 wear cycles is in fact about 1.5.

The pad temperature for TRD is also comparable to that for Mosaic in spite of a generally lower COF. A larger value of R for TRD, driven by the lower diamond count, increases the mean contact area per asperity according to Greenwood and Williamson contact theory [5]. Finite element simulations of lubricated heat transfer to the asperity tips then indicate that a larger fraction of the total frictional energy should be partitioned to the pad[4]. This compensates for the lower COF.

For both conditioners, variations in the removal rate are controlled by both the mechanical shear force and by the reaction rates that control the slurry behavior[4]. The chemical rates depend on the temperature, which in turn depend on the mechanical shear force. Thus, removal rates for both conditioners follow the trends in COF and temperature.

Finally, we remark that the PTFE coating on both conditioners provided protection from chemical and abrasive attack. After 30 hours, there is no indication of a decline in performance. For the TRD design, the coating not only reduces the overall COF but also provides a mechanism for gradually exposing more diamonds to the pad.

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