Microreplicated Pad Conditioner for Copper and Copper Barrier CMP Applications

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Abstract— Metal-free micro-replicated conditioning disks are applied to the development of Cu and Cu barrier CMP processes for 22nm technology nodes. Compared with traditional pad conditioners with diamond grits embedded in metal matrix, the micro-replicated conditioners demonstrate lower within-wafer non-uniformity, more stable end-point time, more uniform and controllable pad wear, lower defectivity, and longer pad life time. Used pad analyses provide insights into the effectiveness of conditioning and guidelines for further process improvement.

Keywords- Cu CMP; pad conditioning; microreplication.

I. INTRODUCTION

Pad conditioning has been the vital and integrated step during both oxide and Cu CMP in order to obtain and maintain an acceptable removal rate and stable process performance. The step helps maintain optimal pad surface roughness and porosity, ensuring slurry transport to the wafer surface and the removal of CMP residuals. Without conditioning, the pad surface will "glaze" and removal rates will decline rapidly.

Diamond disks are the most widely utilized for pad conditioning in the industry today. The grit size, lay-out, and surface morphology of the diamond in the disk matrix all play critical roles in the rates and uniformity of CMP [1-3]. Given the ionic strength of the slurries and the nature of the abrasives, however, chemical or abrasive wear of the conditioner itself can be sufficient enough after hours of service such that rates and uniformity begin to drift. In fact, one recent study indicates that diamond micro wear and corrosion of metal substrate both occur during Cu CMP [4]. The debris of diamond wear can result in heavy scratches on Cu surface. In addition, the corrosion of conditioner metal substrate and hence the introduction of metallic ions onto wafer surface will pose serious reliability concerns for Cu interconnects.

In this work, two novel metal-free, microreplicated pad conditioners, M1 and M2 are demonstrated for Cu and Cu barrier CMP. These pad conditioners are made with precisely engineered surfaces designed to provide pad cutting and cleaning action while maintaining the desired surface topography and low pad wear rates. Microreplication allows each pad conditioner to be manufactured with the exact same abrasive surface, thus reducing CMP process variability. Figure 1 shows a typical diamond grit surface of a conventional pad conditioner compared with that of a microreplicated conditioner.

Fig. 1. Paradigm shift to new pad conditioning technology.

The differences between disks M1 and M2 designs are shown in the micrographs in Figure 2. M1 has regular square pyramid structures with about 75% primary features with sharp tips and a small height offset from secondary features yielding a medium to low aggressive conditioner.

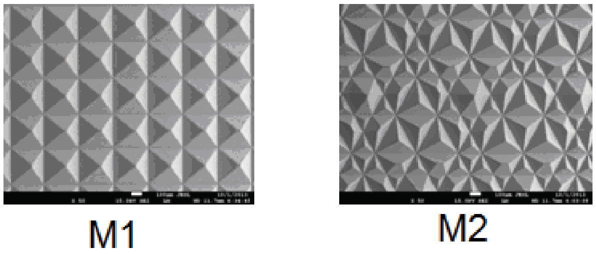


Fig. 2. SEM micrographs showing surface of M1 and M2 conditioners with microreplicated structures.

On the other hand, M2 has a variety of complex multi faceted structures with 5% primary features. These sharp-tipped features have a larger height offset from secondary ones as compared to M1, yielding a more aggressive conditioner. In both pad conditioner designs the number of primary abrasive tips determines the relative aggressiveness of the disks.

Both M1 and M2 disks are applied to Cu and Cu barrier

CMP step for pad conditioning. Traditional diamond grit disk, such as the one shown on the left of Fig. 1, is used as the reference. Impacts of these different pad conditioners on end-point time, removal rate, Rs and its WiWNU, and defectivity will be demonstrated. Post CMP analysis on the used pads and conditioners will be presented and the results will provide guidelines for further process improvement.

II. EXPERIMENTAL

All the CMP work in this study is conducted on 300mm CMP polishers with a 3-platen process and the same consumable set, unless specified otherwise. 300mm wafers with Cu metallization based on 22nm design rules are utilized for all the experiments. The 1st platen removes the bulk Cu by end-point while the 2nd platen polishes off the remaining Cu by end-point control, followed by a timed over-polish step to clear Cu residues. The 3rd platen process removes barrier, hard mask materials, and polishes into the low-*k* inter-level dielectric (ILD). A standard hard pad is used in both 1st and 2nd platen processes while a soft pad is applied to the 3rd platen barrier polish step. 3 different pad conditioners are evaluated in this study: Disk A, a traditional diamond grit conditioner; and disks M1 and M2, which are micro-replicated conditioners as shown in Fig. 2.

Pad wear rate (PWR), surface roughness (Ra), and dynamic coefficient of friction (COF) of a standard hard pad tested with 3 different conditioners are summarized in Fig. 3. Disk A shows much higher PWR than the 2 microreplicated disks, although all 3 generate about the same surface roughness on the pad. Meanwhile, despite the high PWR, disk A actually shows the lowest COF among the 3 conditioners. In this case, the different tribological behavior can be attributed to the surface configuration of conditioner, whether it is the diamond grit on disk A, or the microreplicated pattern on disks M1 and M2. This point will be elaborated in the discussion session later. Usually, low-level and highly-stable COF between pad and conditioner is desirable for maximum conditioning efficiency. This point will be elaborated later.

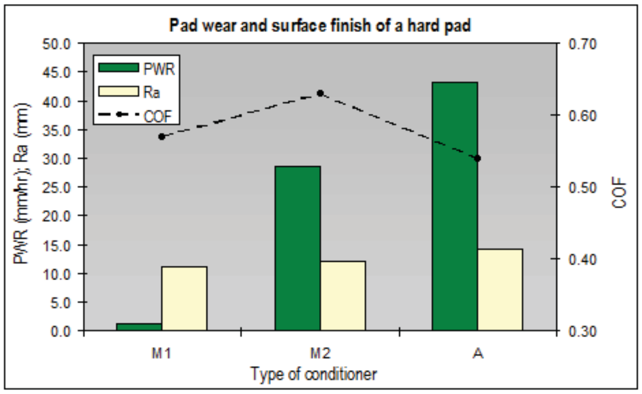


Fig. 3. Pad wear rate, surface roughness, and dynamic coefficient of friction of a standard hard pad tested with the 3 different types of conditioners evaluated in this study.

III. RESULTS AND DISCUSSION

A. Cu end-point time control

Platen-1 Cu end-point time is plotted as a function of pad wafer count in Fig. 4. Two different conditioners installed across multiple CMP tools are compared in this case: disks A *vs*. M2.

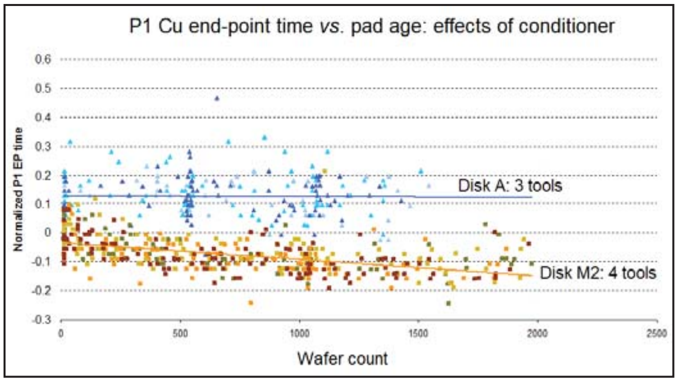


Fig. 4. Normalized platen-1 Cu end-point time *vs*. pad wafer counts with 2 different conditions: A *vs*. M2.

Disk A results in wide variation in P1 end-point time up to 1000 wafer counts across 3 CMP tools. On the other hand, disk M2 shows tighter end-point time across 4 CMP tools, up to ~ 2000 wafer passes on the pad. The result suggests the microreplicated M2 conditioner helps maintain consistent removal rates across pad life time better than disk A does.

The similar trend can be observed on P2 process as well as shown in Fig. 5. In this case, a less aggressive microreplicated conditioner, disk M1 is applied to P2 process *vs*. the traditional disk A. Apparently, M1 disk maintains shorter end-point time with much tighter variation than disk A. It also demonstrates the opportunity for pad life extension beyond 2000W as well.

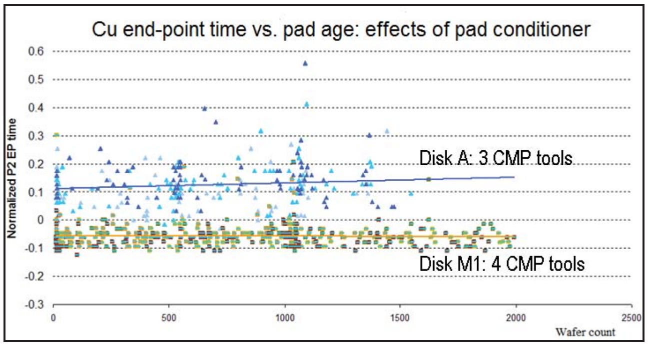


Fig. 5. Normalized platen-2 Cu end-point time *vs*. pad wafer counts with 2 different conditions: A *vs*. M1.

B. Removal rates uniformity and stability

The within-wafer Rs non-uniformity (Rs NU) is plotted against platen 1 conditioning time with disks A vs. M2 in Fig. 5. The same pad and conditioning parameters are applied with both disks. Resistance test structure with 50% pattern density based on 22nm ground-rule is probed.

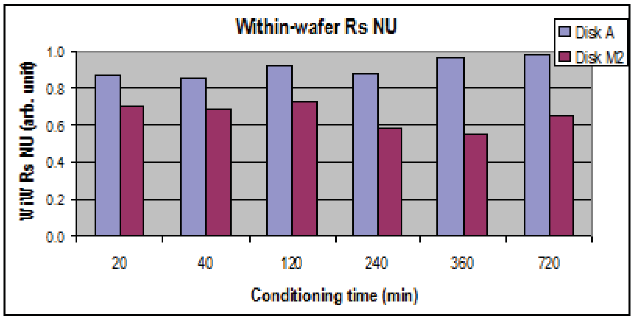


Fig. 6. Effects of platen 1 Cu conditioner on within-wafer Rs NU of 22nm wafers: disks A vs. M2. Conditioning down force = 5lb in both cases.

As displayed clearly in Fig. 6, disk M2 yields lower Rs NU than disk A consistently regardless of the conditioning time. The results suggest the M2 disk dresses the pad in the way that gives rise to more uniform removal of Cu within the wafer than the traditional disk does.

Microreplicated conditioner is also applied to the platen 3 process on the soft pad for barrier polish. The amount of low-*k* SiCOH dielectric removal is plotted against P3 wafer count on Fig. 7. Wafers polished with conditioning (with disk M1) and without conditioning are grouped separately for comparison.

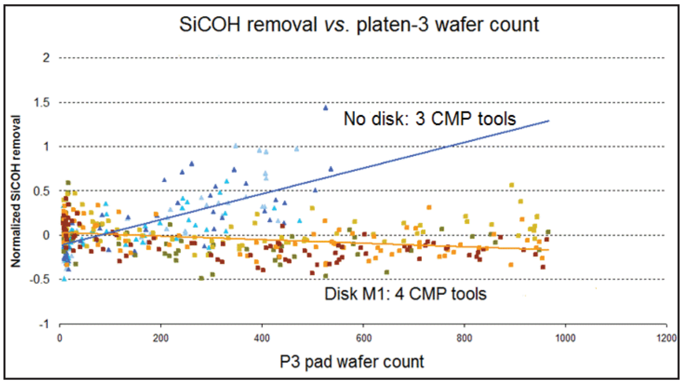


Fig. 7. Normalized platen-3 SiCOH dielectric removal *vs.* pad wafer count with and without conditioning with disk M1.

Without pad conditioning, the amount of SiCOH removal increases with increasing wafer count on platen 3. On the other hand, with conditioning using disk M1 on the pad, SiCOH removal remains at about the same level with much tighter distribution consistently up to about 1000 wafer counts on the pad.

C. Defect reduction

The results strongly suggest the conditioning of the soft P3 pad with a microreplicated disk such as M1 is the key to stabilize the SiCOH removal throughout pad life. It turns out that such pad conditioning step also helps reduce the scratch defects as shown in Fig. 8. Without pad conditioning, high scratch defect density appears throughout the pad life. With conditioning, on the other hand, scratch defects are reduced to a low level without much excursion. The combination of stable SiCOH removal from Fig. 7 and low level of scratch defects from Fig. 8 opens up the opportunity for pad life extension beyond 1000 wafer passes.

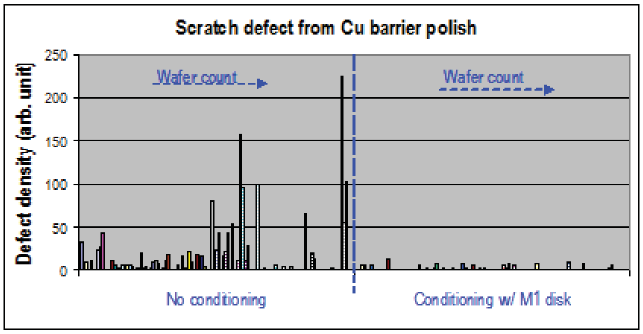


Fig. 8. Effects of platen 3 Cu barrier conditioner with M1 disk on defect density of 22nm wafers. Conditioning down force = 2lb.

The surface topography of a brand new embossed platen-3 soft pad and one after 4-hr of conditioning marathon test with M1 disk is shown in Fig. 9. After 4-hr of marathon conditioning, the peak-to-valley height reduces from 480µm on the new pad to about 425µm on the used pad. The topography remains intact and there is sufficient pad materials left after marathon. The result suggests that there is pad life remaining after the moderate conditioning by M1 disk. More detailed used pad analysis will be presented in the next section.

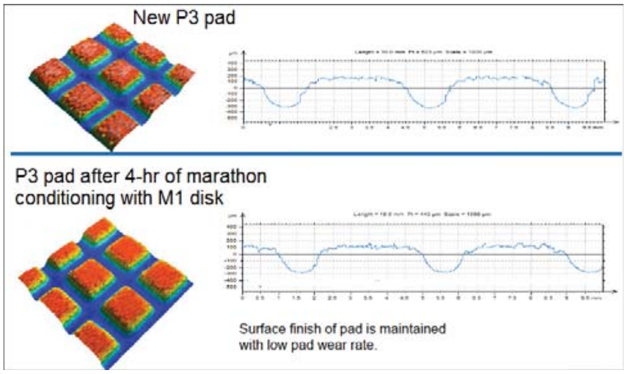


Fig. 9. Topography of a new embossed P3 pad and a P3 pad after 4-hr of marathon conditioning with M1 disk. The peak-to-valley height is 480µm and 425µm of the new and used pads, respectively.

It should be noted that the common practice in Cu barrier CMP is to use a soft pad on the platen-3 process for concern over defects such as scratches. Without proper conditioning, debris will build up and pad glazing would occur, leading to rate instability and defect generation. On the other hand, conditioning on soft pad application inevitably reduces pad life time. In the present study, we demonstrate that rate stability, scratch reduction, and pad life extension can all be accomplished through conditioning on a platen-3 soft pad with a microreplicated disk with moderate and uniform wear rate.

D. *Used pad analysis*

The groove depth and remaining thickness of the P1 and P2 pads (both being the same hard pad) after 2000 wafer passes of conditioning are shown in Fig. 10. As presented in Figs 4 and 5 previously, the P1 and P2 pads are conditioned by M2 and M1 disks, respectively.

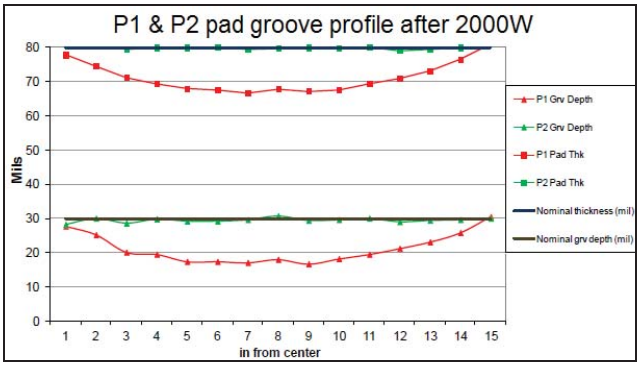


Fig. 10. Groove depth and remaining thickness of P1 and P2 pads after 2000 wafer passes of conditioning.

Groove depth and remaining thickness on P1 pad both show a bowl shape profile across the radius. The groove depth at pad center and edge, where no conditioning is experienced, is about 30 mil (~762 μm), which is the same as that of a new pad. The groove depth at mid-range of the pad (i.e., ~ 8-in from center) is about 17.2 mil (~ 437 μm), or 43% decrease from that of a new pad. Meanwhile, the pad thickness reduces by 16%, from 80 mil (2032 μm) at center and edge to 67.3 mil (1709 μm) at mid-range. Overall, the used P1 pad is close to its end-of-life (i.e., ~ 50% reduction in groove depth). Further tuning in conditioner and wafer sweep profiles for more uniform wear across the pad radius should provide the opportunity for pad life extension beyond 2000 wafer passes.

Interestingly, the data in Fig. 10 shows almost no change in groove depth and pad thickness on P2 pad, after 2000 wafers of conditioning and polishing. In other words, the P2 pad is "under-conditioned" with the M1 disk. Nevertheless, this doesn't seem translate to any problem as evidenced from the stable P2 end-point time from Fig. 5, implying stable rates up to 2000W. The result suggests a more aggressive pad conditioning can be accommodated for the P2 process. It also provides the potential for pad life extension beyond 2000W.

Laser confocal microscope is employed to further analyze the surface morphology across the radius of the used pads. Probability density function (PDF) of the measured surface height is extracted to assess the uniformity of pad surface and the effectiveness of conditioning. The PDF of measured pad asperity height, h, can be expressed in form of exponential distribution as:

$$PDF\,(h) = \mathrm{B}^{*}\exp\,(-h/\lambda) \qquad (1)$$

where B is a constant and λ is the decay length, which can be interpreted as a measure of surface abruptness or standard deviation of surface asperities.

The typical surface morphology of used P1 and P2 pads are displayed in Fig. 11. The used P1 pad exhibits uniform distribution of surface height with good balance of asperities (+) and pores (-). Meanwhile, the surface of used P2 pad is apparently dominated by asperities. Early sign of pad glazing can be detected too.

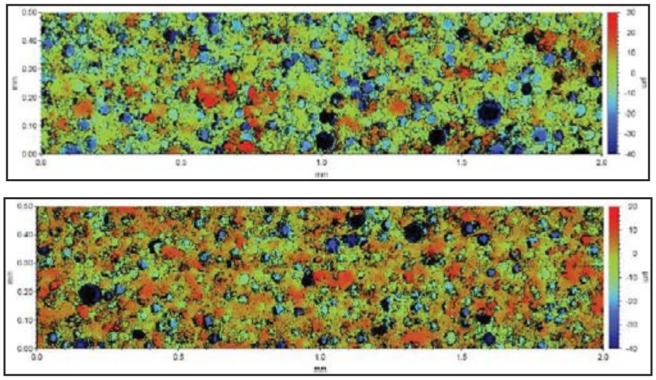


Fig. 11. Interferometry images showing the surface morphology of a used P1 pad (top) and used P2 pad (bottom), after 2000 wafer passes. Scan area = 500μm x 2000μm.

The histogram of surface height information from Fig. 11 is reproduced numerically in Fig. 12 and Fig. 13 for P1 and P2 pads, respectively. PDF is extracted at 1-inch interval from pad center to edge and overlaid for comparison.

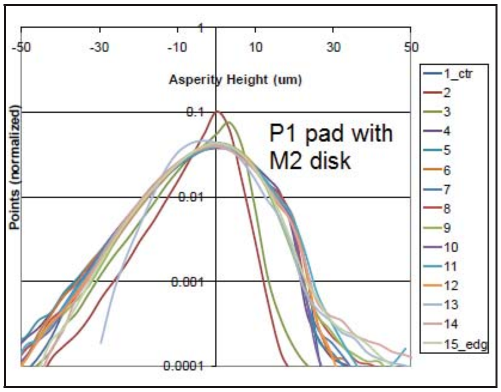


Fig. 12. Surface height PDF as a function of pad radius of a used P1 pad with M2 disk after 2000 wafer passes.

In general, P1 pad wears consistently from center to edge, except for 2", 3", and 13". Overall, its PDFs are well centered without much skewness except at 2" and 3". On the other hand, compared with P1 pad, the used P2 pad shows even better overlay of the PDF plots except at 11" from center. However, the density functions across the radius are all heavily skewed towards the right (+), which suggest the pad surface is dominated by “peaks” or asperities. In other words, the used P2 pad surface shows much less open pore area. It looks like a new pad with hardly any material removed after service. The above finding confirms the groove depth and remaining pad thickness results in Fig. 10.

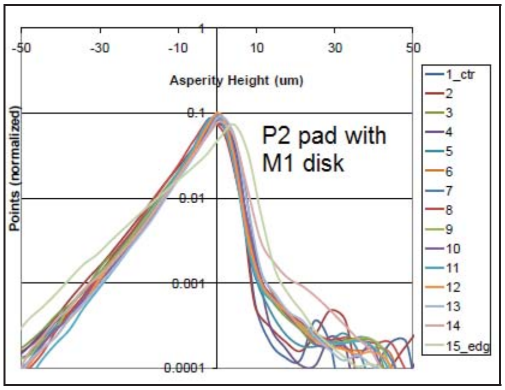


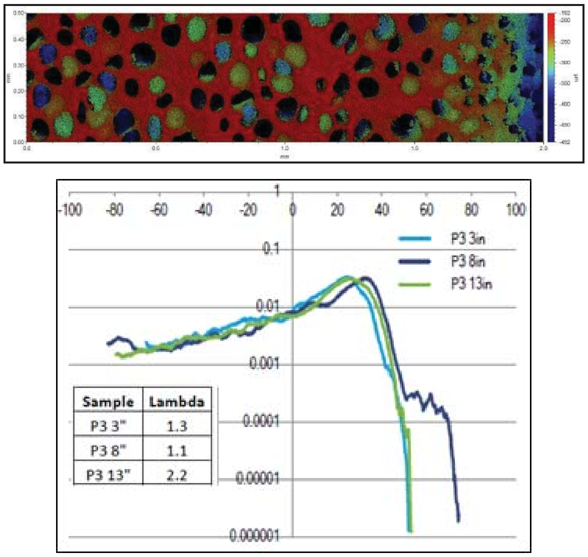
Fig. 13. Surface height PDF as a function of pad radius of a used P2 pad with M1 disk after 2000 wafer passes.

The ideal surface morphology of a CMP pad in service is to have equal and uniform distribution of both asperities and open pores. The asperity contact is critical to material removal, while the open pore area can facilitate the hydrodynamic flow and residue removal. Break-in and proper conditioning are needed to open up the pore area of a new pad. Results from the above pad surface height analysis suggest that, despite the stable polish rates and consistent end-point time, the hard pad on P2 is not conditioned sufficiently enough by the M1 disk. So, conditioning with a higher down force or, changing to a disk with higher wear rate (e.g., M2) may provide a more robust conditioning process from pad surface height point of view.

Similar surface height analysis was performed on the used P3 soft pad after 1000 wafer passes with the M1 disk and the results are presented in Fig. 14.

As shown in Fig. 14, PDF of surface height is extracted at 3”, 8”, and 13” from pad center. All 3 regions show density functions skewing towards the positive height. The result suggests the pad surface is more asperity-dominated, which can be improved with more aggressive conditioning. Also noticed from Fig. 14 is the decay length, λ, is rather low at all 3 regions. Since λ is a measure of the degree of spread of density function, the result implies tight distribution of surface height at local regions. Once again, a more aggressive conditioning process to open up more pore area will modulate the asperity height distribution.

The above analysis provides useful guidelines for pad surface height uniformity improvement. For example, based on the groove depth and remaining thickness results, the global pad wearing profile can be improved by adjusting the conditioner or wafer sweep to preferentially wear more or less on the specific region of the pad. On the micro scale, the histogram data from surface height analysis provides insights into the surface morphology of a used pad, which can help assess the effectiveness of pad conditioning. The above information provides the guidelines for adjusting the conditioning parameters and selection of the proper conditioner for a specific pad.



Sample	Lambda
P3 3"	1.3
P3 8"	1.1
P3 13"	2.2

Fig. 14. Surface height PDF as a function of pad radius of a used P3 pad with M1 disk after 1000 wafer passes.

A recent study by Kim *et al* establishes a model which correlates the materials removal rate (MRR) to topographical and mechanical properties of pad asperities [5]. The key to high MRR throughout the duration of pad life is to maintain a low enough standard deviation of pad surface height. In the context of current study, this means a low λ would be a favorable condition to achieve high MRR.

A further study by Kim *et al* also suggests that even the asperities of a soft pad can generate scratches when they are placed in contact with a relatively hard surface such as Cu [6]. Such *asperity scratches* can be reduced by decreasing the COF between the pad and wafer, and by lowering the standard deviation of pad surface height (i.e., a low λ). In the present study, conditioning of the soft P3 pad by M1 disk brings about dramatic reduction in scratches, compared with the case of no conditioning at all.

In general, the highly ordered and repeatable tips and patterns on the M1 disk surface may have contributed to moderate and uniform pad wear. As a consequence, low surface height standard deviation can be maintained to realize the stable removal rates and low scratch benefits. In addition, the microreplication of the tips eliminates the probability of diamond pull-out, further reducing the chance of generating deep and hard scratches caused by diamond grits. Further study is underway to verify the correlation between P3 pad surface height, MRR, and scratch defects.

Also worth mentioning is that although conditioning on a soft pad helps reduce scratches, more polish residue (PR) defects in form of pad debris can be generated due to the cutting of the soft pad by the tips on the disk. Optimization in the post cleaning process is needed to reduce such pad debris defects resulting from soft pad conditioning [7].

E. Used conditioner analysis

Used conditioners from all 3 platens are inspected for wearing and diamond loss by SEM. Fig. 15 shows the tips of 3 randomly selected M2 disks after 2000 wafer passes on P1.

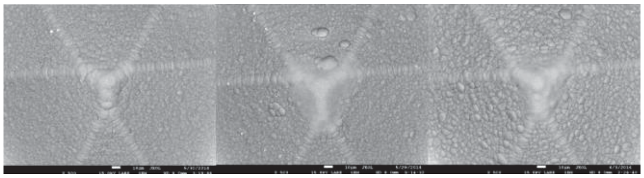


Fig. 15. SEM pictures showing the tips of 3 randomly selected M2 disks after 2000 wafer passes on P1.

All 3 disks show some level of diamond wear. The one in the center exhibits the most wear among the 3. In fact, the P1 pad associated with the disk in the center also shows signs of pad glazing. The result suggests the disks are close to end of life.

Similar SEM pictures for 3 M1 disks after 2000 wafer passes on P2 are displayed in Fig. 16.

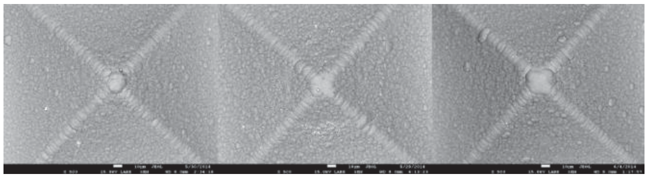


Fig. 16. SEM pictures showing the tips of 3 randomly selected M1 disks after 2000 wafer passes on P2.

The tips for all 3 M1 disks on P2 show very little diamond wear, consistent with their low penetration depth and low pad wear rates. Although the result suggests these M1 disks can service beyond 2000W, pad analysis data from Figs. 10 and 13 indicate more aggressive conditioning would be needed to fully exploit the benefits of M1 microreplicated disk for P2 application.

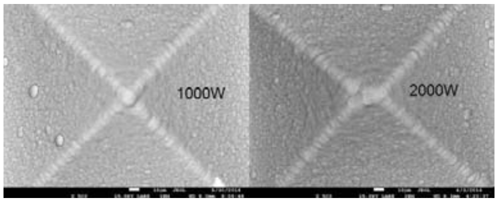


Fig. 17. SEM pictures showing the tips of M1 disks after 1000 and 2000 wafer passes on P3.

SEM pictures for M1 disks after 1000 and 2000 wafer passes on P3 are shown in Fig. 17. Very little difference can be discerned from the tip surfaces between the two disks. The result provides the potential for disk life extension beyond 2000W.

IV. CONCLUSION

Microreplicated pad conditioners are applied to 3-platen Cu and Cu barrier CMP process. These newly designed pad conditioners demonstrate superior performances to traditional diamond grit conditioners by maintaining more stable and consistent removal rates and end-point time in bulk Cu and Cu end-point steps. It also shows consistent low-*k* SiCOH removal and lower scratch defects.

Extensive pad surface height analyses provide insights into the surface height distribution of the used pads and the effectiveness of conditioning. The results not only help refine the conditioning parameters for further process improvement but also assist the selection of proper type of conditioners for specific applications. Finally, SEM inspection of the tips on used microreplicated conditioners show little to no wearing without much diamond loss.

ACKNOWLEDGMENT

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