Pad Surface Thermal Management during Copper Chemical Mechanical Planarization

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A pad surface thermal management system was developed to improve copper removal rate within wafer non-uniformity by locally adjusting the pad surface temperature. The system consisted of one or more thermal transfer modules, which contacted the pad surface during polishing. Hot or cold water circulated between the thermal transfer module and an external heater or cooler. With the module placed on the pad surface, heat conduction occurred between the module and the pad surface, producing a localized pad surface with higher or lower temperatures. As such, it was expected that local removal rates would change accordingly due to the temperature-sensitive nature of copper chemical mechanical planarization (CMP). In this study, the system was used to adjust the “center-fast” removal rate profile to illustrate its effect during the process. Results showed that, when two thermal transfer modules were employed, local removal rates in the wafer center region decreased significantly while the removal rates near the wafer edge were maintained thereby significantly improving within wafer removal rate non-uniformity.

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CMP has been widely used to planarize copper dual damascene structures in the integrated circuit (IC) manufacturing through combined chemical and mechanical means. 1–3 CMP performance is characterized by some parameters such as removal rate, within wafer removal rate non-uniformity (WIWRRNU), step height reduction efficiency, and defect density. 4–10 WIWRRNU is a critical parameter to determine film thickness planarity on a global (i.e. wafer-scale) level. This is essential for the dimensional accuracy required for the subsequent photolithographic processes. 11 For copper CMP, it has been widely observed that material removal rate across the wafer is non-uniform. 12–16 The variation in material removal rate across wafer surface impacts WIWRRNU and resolving this issue continues to be an area of intense focus in the industry.

As such, several methods have been proposed to improve WIWRRNU during CMP. Mau proposed a face-up polisher, allowing the pad to move from the wafer center region to its edge region to improve WIWRRNU. 17 Shendon invented a soft backed wafer carrier head to improve WIWRRNU. 18 In addition, tremendous work has focused on the application of the multi-zone wafer carrier head. 19–24 For instance, Wang et al. proposed a multi-chambered carrier head, which is capable of applying different polishing pressures across the wafer surface to achieve an improved WIWRRNU. 19 Kajiwara et al. and Chen also invented similar multi-zone carrier heads. 22–24

While the above methods help improve WIWRRNU, they are quite costly (often times comprising more than 10 percent of the original capital expense of the entire polisher) and require the introduction of a new generation of polisher or costly retrofitting of the existing polisher.

The objective of this study is to show the feasibility of adopting a new, and much more economical, method to improve WIWRRNU during copper CMP that is solely based on intentional local temperature manipulation of the pad. In this paper, this alternative approach is referred to as pad thermal management, or PTM.

The PTM System

Previous studies have shown that copper removal rate is highly sensitive to the pad surface temperature during a chemically-limited CMP process. 25–27 For example, assuming a chemical removal rate that is Arrhenius in nature, given a slurry activation energy of 1 eV, a 10°C change in the pad surface temperature can easily double copper removal rate. 22 Higher pad surface temperatures lead to hotter polished substrates. This causes enhanced oxidation reactions on the substrate surface and therefore a higher copper removal rate. 23 Because of this temperature sensitivity, it is possible to locally, and intentionally, adjust copper removal rate to improve WIWRRNU by locally adjusting the pad surface temperature.

Figure 1 schematically shows the top view of a polisher with the PTM system. The system consists of one or more non-rotating thermal transfer modules which may be lined up along a holding bar and placed on the pad surface. The bottom side of each thermal transfer module incorporates a heat transfer disc made of silicon carbide as shown in Fig. 2. Silicon carbide is selected as the material of choice for its high thermal conductivity, 28 its wear resistance, its purity and its current acceptability and adoption in CMP as the premier substrate material for high-end CVD diamond discs which also happen to contact the pad surface during the process.

The heat transfer disc (with a diameter of 50 mm) is completely sealed along its periphery as well as its upper region by a housing module made of an acetal resin. The inner space of the housing is designed to be large enough to act as a reservoir allowing hot or cold water (from an external heater or chiller) to be brought in and out of the system via external tubing thus acting as an energy source, or sink, during the process.

On a rotary polisher, due to pad rotation, an annular pad surface region with higher or lower temperatures can be produced with the PTM. 29 Heat exchange takes place in a continuous fashion as water enters and exits through the outlet tubing and returns to the external heater or chiller. The PTM is designed such that the location of the thermal transfer module relative to the pad center is adjustable. 29 In addition, it should be noted that these modules are placed on the pad surface near the leading edge of the wafer carrier head, which allows local heating or cooling of the pad surface just before it comes into contact with the wafer surface. It should be also noted that no built-in chiller is used to directly heat or cool the platen during polishing in this study.

Experimental

200-mm blanket copper wafers were polished on an Araca APD-800 polisher and tribometer equipped with the unique ability to acquire real-time shear force and down force during polishing. 30,31 A 3M A2810 diamond disc was used to condition a 32-inch IC1000 K-groove pad during wafer polishing at a conditioning down-force of 44.5 N. Each wafer was polished for 1 minute at 10.3 kPa and
1.0 m/s. Prior to wafer polishing, the diamond disc was used to break in the pad for 30 min with deionized (DI) water. The diamond disc rotated at 95 RPM and swept at a frequency of 10 times per minute across the radius of the pad surface. Pad break-in was followed by pad seasoning during which the shear force was monitored to ensure that stable values were achieved prior to monitor wafer polishing.34

The slurry, dispersed at 300 ml/min, consisted of 7 volume parts of Hitachi Chemical HS-2H-635-12 slurry, 7 volume parts of DI water and 6 volume parts of 30% ultra-pure hydrogen peroxide. Two blanket monitor copper wafers were polished with and without the PTM system, respectively. Local copper removal rates were determined by the thickness of the copper film measured before and after polishing using a four-point probe. Two perpendicular diameter scans containing 98 points were performed to measure the thickness of the copper film across the wafer surface. The mean values of these two lines were reported as a function of the distance from wafer center. In addition, during wafer polishing, the pad surface temperature was measured in real-time with a 1 Hz acquisition frequency using a FLIR infrared video camera. A customized computer program was then used to extract values of temperature from the thermal images.28,35

Results and Discussion

In Fig. 3, the gray dashed line shows the removal rate profile as a function of distance from the wafer center when the PTM system is not
installed on the polisher. Conditions having to do with this particular process are selected such that a gross “center-fast” removal rate profile is attained whereby the wafer center region (i.e. from -50 to +50 mm) is polished faster than the wafer edge regions thus resulting in a high WIWRRNU.

In the case of the “center-fast” removal process, properly reducing the local removal rates at the wafer center region will help improve WIWRRNU. As such, the PTM system is employed to reduce the local removal rates on the wafer center region by lowering temperature of the pad surface that corresponds to that location.

First, the PTM system with a single thermal transfer module is tested. Figure 4 schematically shows the position of the module, which is placed on the pad surface such that the center of its heat transfer disc (incorporated at the bottom of the module, see Fig. 2) corresponds to the center track of the wafer. An external chiller connects to the thermal transfer module and introduces cooled water with a constant temperature of 2°C.

Figure 5a shows the thermal image of the pad surface with the single thermal transfer module. Different colors represent different pad surface temperatures. The color bar is shown on the right hand side of Fig. 5a. As evident from Fig. 5a, an annular pad surface region with lower temperature is produced by the thermal transfer module. The point “SP01” is in the region where the module makes contact. The other three spots (i.e. “SP02” through “SP04”) are outside of this region toward the edge of the wafer. An external chiller connects to the thermal transfer module and introduces cooled water with a constant temperature of 2°C.

It should be noted that the thermal image around the module as shown in Fig. 5a is not directly affected by the freshly injected slurry as it does not flow directly to the heat transfer module region. As shown in Fig. 1, due to the counter-clockwise rotation of the platen and the polishing head, most of the freshly injected slurry flows directly to the leading edge of the polishing head. The freshly injected slurry immediately affects the polishing process and the pad temperature in the wafer-pad polishing region. After passing the polishing region, the pad surface of the wafer track retains a thin layer of used slurry. Therefore, the thermal images (i.e. captured around the heat transfer modules located on the wafer track near the leading edge of the polishing head) essentially represent the temperatures of the pad surface with very thin used slurry film before it enters the polishing region.

The pad surface temperatures at these four spots (i.e. “SP01” through “SP04”) are extracted and summarized as a function of polish time as shown in Fig. 6a. As expected, “SP01” has significantly lower pad surface temperatures than those of the other three spots. For comparison, Fig. 6b summarizes the pad surface temperatures on these same four spots as a function of polish time when the PTM system is not installed on the polisher. By comparing Fig. 6a with Fig. 6b, one can summarize that “SP02” through “SP04” have similar temperatures with and without the PTM system while the temperature associated with “SP01” is significantly lower (on average, by 3.2°C) when the PTM system is used. It is therefore expected that the local removal rates near the wafer center region will be reduced.

Figures 6a and 6b show an initial decrease in pad surface temperature, followed by a gradual rise in temperature afterwards regardless whether the PTM system is installed or not. As the body of the pad/platen retains heat generated from the previous polishing runs, the initial pad surface temperature is higher than the temperature of the fresh slurry. As such, when the fresh slurry is applied on the pad to polish the next wafer, it cools down the pad surface globally during the initial 10 to 15 sec polishing. Afterwards, as more frictional heat is generated, the pad temperature shows an increasing trend.

During in-situ pad conditioning, the diamond disc conditioner induces additional heat transfer path to the pad as it moves the slurry on
Figure 6. Pad surface temperature comparison with (a) and without (b) the PTM system (with the single thermal transfer module).

Figure 7. Schematic of wafer rotation at (a) $t = t_1$, (b) $t = t_2$ and (c) $t = t_3$ with the single thermal transfer module. Both pad and wafer are rotating in a counter-clockwise fashion.

The dwell time (i.e. the contact time) of a point at the wafer surface (e.g. a random point B on the blue color circle in Fig. 7a) contacting the lower temperature region can be calculated via the following equation,

$$t = \frac{\text{length of Arc I} + \text{length of Arc II}}{\text{perimeter of the circle}} \times \text{polish time}$$

Arcs I, II (in pink color) and the circle (in blue color) are shown in Fig. 7a.

Figure 8 shows the dwell time as a function of distance from the wafer center with the single thermal transfer module. Results show that a point in the wafer region from $-25$ to $+25$ mm has the longest dwell time of 60 sec. This indicates that a point in this wafer region always contacts the annular region during polishing.

In comparison, a location within the wafer from $\pm 25$ to $\pm 100$ mm only periodically contacts the annular region such that its dwell time ranges between 10 and 60 sec. As a result, the entire wafer surface is cooled and hence local removal rates decrease across the whole wafer surface, as observed in Fig. 3. Therefore, the PTM system with a single cold module placing on the wafer center track does not improve WIWRRNU significantly in this particular case.

In order to reduce local removal rates on the wafer center region while maintaining removal rates at the wafer edge region, the PTM system, this time with two thermal transfer modules, is tested. Figure 9 schematically shows the positions of these two modules on the pad surface. The cold module, same as before, is placed on the wafer center track where chilled water, at $2^\circ$C, is introduced. On the other hand, a hot module is employed with the intention to heat the wafer edge region, this time, using $34^\circ$C water.

Figure 10 shows the thermal image of the pad surface with the two thermal transfer modules. As evident in Fig. 10, annular pad surface regions with both lower and higher temperatures are produced.

Figure 11 summarizes the pad surface temperatures on the four spots.
Figure 8. Dwell time analysis with the single thermal transfer module.

(same locations as “SP01” through “SP04” in Fig. 5a) as a function of polish time using the two modules. “SP01” is in the region where the cold module contacts, while “SP03” and “SP04” correspond to regions in contact with the hot module. “SP02” is located in the middle of the two modules. Compared to Fig. 6b, when the two modules are used, the temperature corresponding to “SP01” is significantly lower (on average, by 2.6°C) while “SP03” and “SP04” have significantly higher temperatures (on average, by 3.3°C), and “SP02” corresponds to a slightly higher temperature (on average, by 1.3°C).

The dwell time (calculated by Eq. 1) of a point at the wafer surface contacting the lower temperature region is summarized in Fig. 12. As discussed previously, the whole wafer surface contacts the pad surface that has lower temperatures. As evident in Fig. 9, besides the lower temperature region, the wafer edge region also periodically contacts the pad surface that has higher temperatures. The dwell time of a point at the wafer surface (e.g. a random point on the blue color circle in Fig. 9) contacting the higher temperature region can be calculated by Eq. 2 and is also summarized in Fig. 12.

\[
    t = \frac{\text{length of Arc I}}{\text{perimeter of the circle}} \times \text{polish time} \tag{2}
\]

Figure 9. Positions of the two thermal transfer modules on the pad surface. Both pad and wafer are rotating in a counter-clockwise fashion.

Figure 10. Thermal image of the pad surface with the two thermal transfer modules. Both pad and wafer are rotating in a counter-clockwise fashion.

Figure 11. Pad surface temperature with the two thermal transfer modules.
Arc I (in green color) and the circle (in blue color) are shown in Fig. 9.

As indicated in Fig. 12, the wafer center region contacts the lower temperature region during polishing where its dwell time ranges from 20 to 60 sec. Therefore, it is expected that local removal rates in the wafer center region will decrease. In comparison, the wafer edge region periodically contacts the pad surface region with higher and lower temperatures, respectively. The dwell time on the lower temperature region ranges from 10 to 20 sec which should reduce local removal rates. On the other hand, the dwell time in the higher temperature region ranges from 0 to 23 sec which should enhance the local removal rates. Combining the effects of these two factors, it is expected that the local removal rates in the wafer edge region will not change significantly.

Figure 13 shows the removal rate profile comparison with and without the PTM system (i.e. with two thermal transfer modules). As expected, local removal rates in the wafer center region decrease significantly. In comparison, local removal rates in the wafer edge region do not change significantly thus significantly improving WIWRNU when two thermal transfer modules are used.

Conclusions

This paper presented the feasibility of using a novel pad surface thermal management (PTM) system to improve WIWRNU by locally adjusting the pad surface temperature. The system successfully showed that “center-fast” removal rate profiles can be modulated and improved during copper CMP. At first, a system with a single thermal transfer module was tested. To help reduce local removal rates near the center of the wafer, a cold module was placed on the pad surface with its center corresponding to the center track of the wafer. Chilled water (2°C) was introduced to the module via an external chiller. Results showed that local removal rates decreased in both the central region of the wafer as well as the edge. Therefore, the uniformity was not improved significantly since the wafer edge region periodically contacted the pad surface region with the lower temperature due to wafer rotation during polishing. As the entire wafer surface was cooled, the local removal rates decreased across the whole wafer surface. In order to reduce the local removal rates in the wafer center region while maintaining the removal rates in the wafer edge region, two thermal transfer modules were then tested. The cold module, same as before, was placed on the wafer center track and cooled water (2°C) was introduced. A hot module aimed to heat the wafer edge region using hot water at 34°C was introduced. Results showed that local removal rates in the wafer center region decreased significantly while the removal rates in the wafer edge region were maintained. As a result, the uniformity was improved significantly: the wafer center region contacted the lower temperature region during polishing thus lowering the removal rates locally; on the other hand, as the wafer edge region periodically contacted the pad surface region with the lower and higher...
temperatures, respectively, the local removal rates in the wafer edge region did not change significantly.

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