Thermal, Tribological, and Removal Rate Characteristics of Pad Conditioning in Copper CMP

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High Pressure Micro Jet (HPMJ) pad conditioning system was investigated as an alternative to diamond disc conditioning in copper CMP. A series of comparative 50-wafer marathon runs were conducted at constant wafer pressure and sliding velocity using Rohm & Haas IC1000 and Asahi-Kasei EMD Corporation (UNIPAD) concentrically grooved pads under ex-situ diamond conditioning or HPMJ conditioning. SEM images indicated that fibrous surface was restored using UNIPAD pads under both diamond and HPMJ conditioning. With IC1000 pads, asperities on the surface were significantly collapsed. This was believed to be due to differences in pad wear rates for the two conditioning methods. COF and removal rate were stable from wafer to wafer using both diamond and HPMJ conditioning when UNIPAD pads were used. Also, HPMJ conditioning showed higher COF and removal rate when compared to diamond conditioning for UNIPAD. On the other hand, COF and removal rates for IC1000 pads decreased significantly under HPMJ conditioning. Regardless of pad conditioning method adopted and the type of pad used, linear correlation was observed between temperature and COF, and removal rate and COF.

Keywords : High pressure micro jet (HPMJ), Coefficient of friction (COF), Removal rate, Chemical mechanical planarization (CMP)

1. INTRODUCTION

Copper CMP has become an increasingly important process due to the lower resistance and improved electromigration advantages that copper possesses relative to aluminum in multi-level interconnects[1]. In CMP, pad conditioning is a critical process to restore collapsed pad asperities and to break-up glazed areas on the pad surface[1-3]. With insufficient pad conditioning, the pad becomes flattened or glazed with particles clogging the pores of the pad and forming a layer of slurry residue and other foreign particulates, resulting in lower material removal rates and higher wafer-level defects[1-3]. To date, diamond disc conditioning is a commonly adopted process for achieving constant and uniform material removal rate across the wafer during CMP. However, there are several issues with this process such as reduced pad life and generation of scratches on the wafer due to some poorly mounted diamonds.

In an attempt to overcome these issues, a High Pressure Micro Jet (HPMJ) pad conditioning method has been investigated as an alterative to diamond disc conditioning. During conditioning, the HPMJ system sprays high-pressure (up to 20 MPa) water droplets onto the pad to slowly wear and refresh the pad while simultaneously cleaning the surface of slurry residues and other embedded particles. Previous results have shown that HPMJ pad conditioning has the potential to achieve clean surface as well as clean grooves in ILD CMP applications[4,5].

In this study, ex-situ diamond conditioning or ex-situ HPMJ pad conditioning was performed using Rohm & Haas IC1000 or Asahi-Kasei EMD Corporation (UNIPAD) concentrically grooved pads in order to evaluate and compare the performance of HPMJ pad conditioning in copper CMP. Results are discussed in terms of scanning electron microscopy (SEM) images, pad wear rate, pad mechanical properties, copper removal rate and COF.

2. INTEGRATED HIGH PRESSURE MICRO JET (HPMJ) PAD CONDITIONING SYSTEM

The HPMJ system can pressurize UPW, or any other type of solution such as slurry, from 3 to 20 MPa. The pressurized fluid is then sent to an accumulator to absorb any fluctuation, and moved to a high-pressure filter that removes particles before sending the fluid to the nozzle through an automatic valve. The nozzle is positioned on a traverse arm above the pad that allows the nozzle to move over the surface of the pad such that the entire pad surface can be treated. The nozzle is specially designed to create high-pressure miniature droplets, which are ejected onto pad surface to remove slurry waste particle and to condition pad. Details regarding droplet size distribution, average kinetic energy and pressure distribution at the pad level can be found elsewhere[4]. An important feature of these studies is the real-time acquisition of COF (ratio of shear force to normal force). Details of how COF was acquired during these types of conditioning experiments may be found elsewhere[5,6].

3. EXPERIMENTAL PROCEDURE

Experiments were performed on a scaled polisher[4-6]. Rohm and Haas IC1000 and Asahi-Kasei EMD Corporation (UNIPAD) concentrically grooved pads were used. For each experiment, 50 copper wafers were polished for 2 minutes each at a constant pressure of 1.5 PSI and a sliding velocity of 1.1 m/s. Fujimi PL-7102 slurry containing hydrogen peroxide as the oxidant was used at a flow rate of 80 cc/min.

Pad conditioning during polishing was performed ex situ using diamond disc or HPMJ pad conditioning methods. Ex-situ diamond conditioning was performed in conjunction with UPW for 15 seconds. A 2-inch diameter, 100-grit diamond disc was used at a pressure of 0.5 PSI, a rotation rate of 30 RPM and a sweep frequency of 0.33 Hz. Ex-situ HPMJ conditioning was conducted for 10 seconds with Fujimi PL-7102 containing hydrogen peroxide. A fluid pressure of 10 MPa, a fan angle of 25 °, flow rate of 770 cc/min, an actuator angle of 90 ° (i.e. normal to the pad surface) and nozzle-to-pad distance of 15 mm were used.

During the polishing process, one thousand shear force data points were collected per second and their values were averaged and divided by the applied normal force to calculate the average coefficient of friction (COF). Removal rates were calculated by determining the weight of the copper wafer prior to and after polishing using a microbalance with an accuracy of 0.01 mg. The loss of pad mass was divided by total conditioning time to calculate pad wear rate. A TA Instruments 2980 dynamic mechanical analyzer was used to measure pad storage modulus. After each marathon run, a 5 × 5 mm pad sample was analyzed using a JEOL JSM-T300 scanning electron microscope.

4. RESULTS AND DISCUSSION

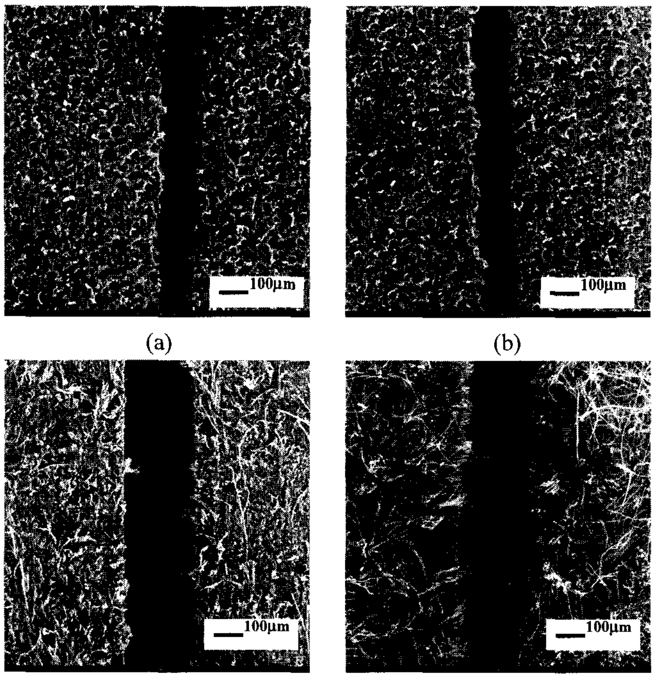
4.1 Pad wear, storage modulus and surface texture

Pad wear rates and pad storage modulus are summarized in Table 1. Results indicate that UNIPAD has higher pad wear rate compared to IC1000 for both pad conditioning methods, implying that UNIPAD is much softer than IC1000. For both pads, wear rates are reduced by about two-thirds when HPMJ conditioning is used, suggesting that pad life can be extended due to the lower pad wear rate. Regarding pad storage modulus as a function of temperature, IC1000 gives a value of 296 and 210 MPa at 20 and 40 °C, respectively. While UNIPAD yields a value that is more than 1.5 times larger (i.e. 45 % of drop in storage modulus at given temperature) implying that UNIPAD becomes significantly softer as pad temperature is increased.

Pad surface images of IC1000 and UNIPAD after both conditioning methods are shown in Fig. 1. In the case of IC1000, SEM images reveal pad asperities on the surface to be partially collapsed under diamond conditioning and significantly collapsed under HPMJ conditioning, implying that the pad conditioning methods adopted may not be enough to re-establish pad asperities. By contrast, the UNIPAD SEM images show that the fibrous surface

Table 1. Summary of pad wear rate and storage modulus for IC1000 and UNIPAD.

Pad	Pad Wear Rate (μm per min)		Storage Modulus (MPa)	
	Diamond Conditioning	HPMJ Conditioning	20 °C	40 °C
IC1000	0.53	0.27	296	210
UNIPAD	1.15	0.78	1665	915



(c) (d)

Fig. 1. SEM images of IC1000 (upper) and UNIPAD (bottom) after (a & c) diamond.

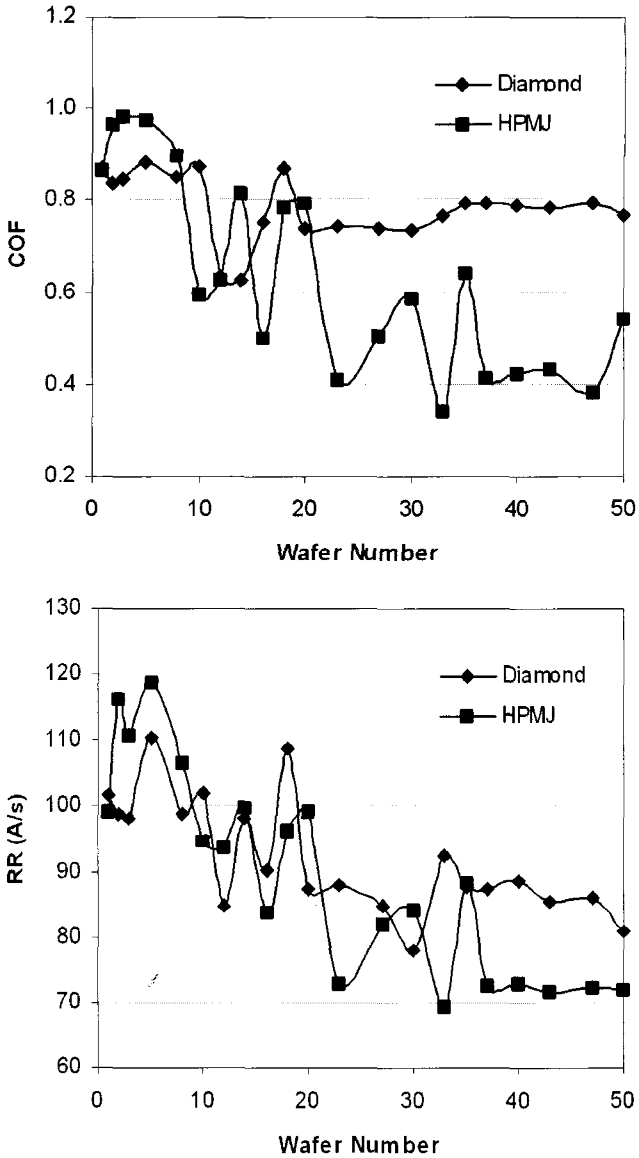


Fig. 2. COF (upper) and removal rate (bottom) results for IC1000.

is restored under both conditioning methods. This is likely due to higher pad wear rate of UNIPAD compared to IC1000. SEM images of UNIPAD also show the fibrous surface to be worn with diamond conditioning compared to HPMJ conditioning possibly due to the higher wear rate for diamond conditioning.

4.2 Removal rate and COF

The results of COF and removal rates for IC1000 using diamond and HPMJ conditioning methods are shown in Fig. 2. Fig. 3 summarizes the results of COF and removal rates for UNIPAD under diamond conditioning and HPMJ conditioning. Results indicate that with HPMJ conditioning, COF and removal rate decrease significantly from 1.0 to 0.4 and from 120 Å/s to 70 Å/s respectively for IC1000. Diamond conditioning with IC1000 showed instability from wafer to wafer for both COF and removal rates. These observations are believed to be partially due the fact that IC1000 has lower wear rate than UNIPAD, suggesting that pad cut rate is not enough to re-establish asperities that have collapsed during polishing. SEM images also show that pad asperities did not re-establish with IC1000 using both conditioning methods, causing COF and removal rate to drop. By contrast, COF and removal rate were stable from wafer to wafer using both conditioning methods when UNIPAD was used. SEM images indicate that the fibrous surface was restored under both conditioning methods due to high pad wear rate compared to IC1000.

These results are consistent with previous reports showing a logarithmic decay of removal rate with insufficient pad conditioning and a stabilized removal rate with proper pad conditioning[1-3]. With UNIPAD, COF and removal rates are higher with HPMJ compared to diamond conditioning due to differences in pad temperature discussed below.

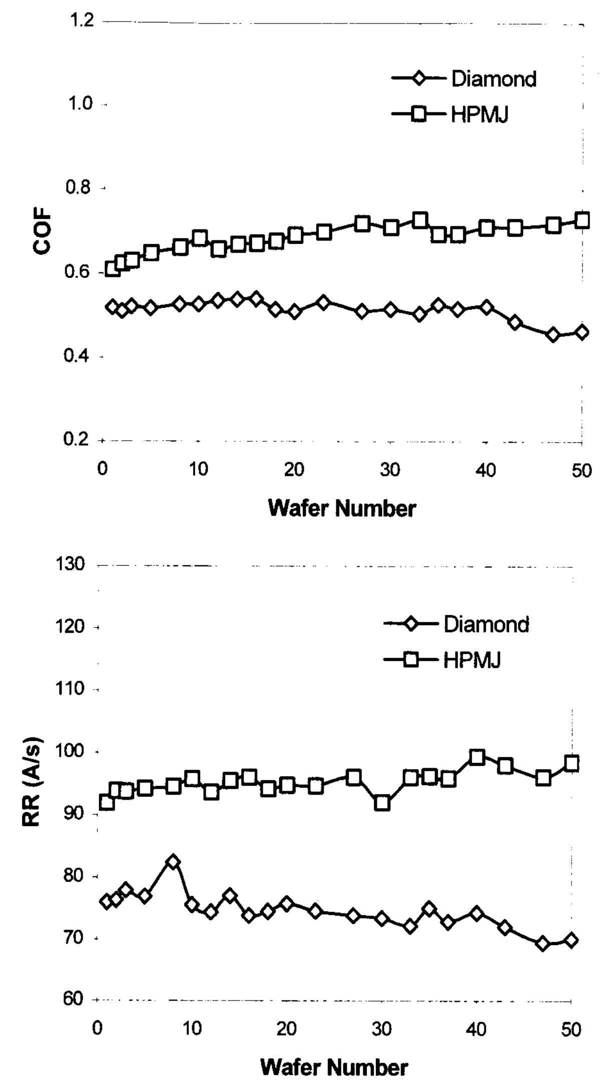


Fig. 3. COF (upper) and removal rate (bottom) results for UNIPAD.

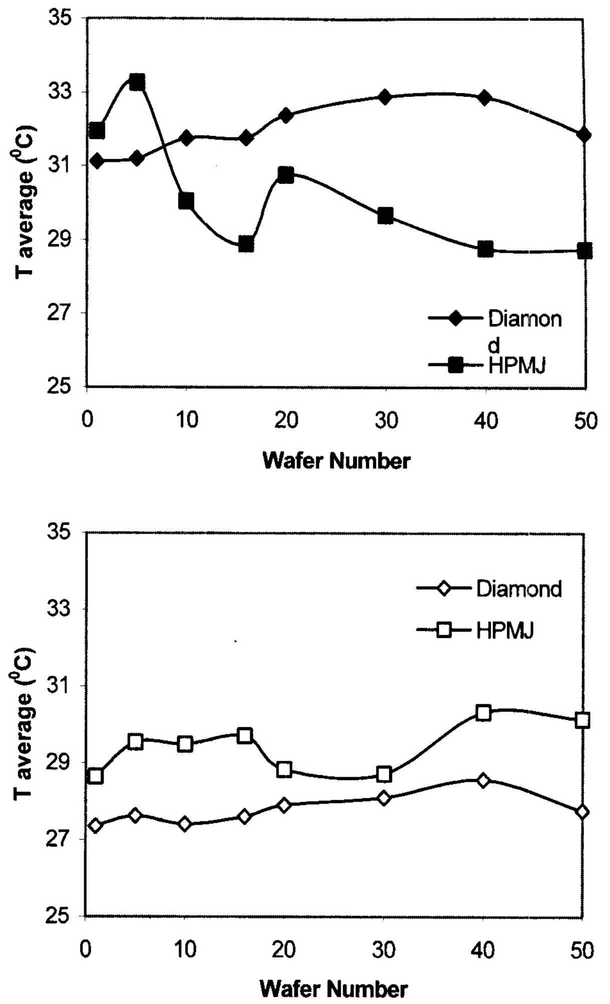


Fig. 4. Average surface temperature for IC1000 (upper) and UNIPAD (bottom).

4.3 Average pad leading edge temperature and correlations with COF and removal rate

Average pad leading edge temperature results for diamond and HPMJ conditioning using IC1000 and UNIPAD are shown in Fig. 4. In the case of IC1000, temperature decreases by as much as 4 °C with HPMJ conditioning, whereas with diamond conditioning, temperature change is around 2 °C. In the case of UNIPAD, average pad temperatures are lower and less variable (only by 1 to 2 °C) for both diamond and HPMJ conditioning methods. The larger thermal stability associated with the UNIPAD is likely due to the fact that its surface microstructure is maintained during conditioning whereas IC1000 undergoes significant asperity collapse throughout the 50-wafer marathon.

The effect of average pad temperature on COF is shown in Fig. 5. Results indicate a direct correlation between temperature and COF regardless of the type of pad or the method of conditioning. In a previous paper [7], it is shown that under constant sliding velocity and slurry viscosity, the viscous shear contribution to COF is

$$\mu_{visc} \propto E^{-0.36} R^{-0.19} \lambda^{-0.17} \qquad (1)$$

where E is the pad modulus, R is the mean asperity tip radius of curvature and λ is a characteristic length that measures how abruptly the rough surface of the pad terminates. While sufficient information is not available in this paper on how R and λ vary with the type of pad or the method of conditioning, it is obvious that softening of the pad (and hence its modulus) due to an increase in temperature would increase COF. The softening factor

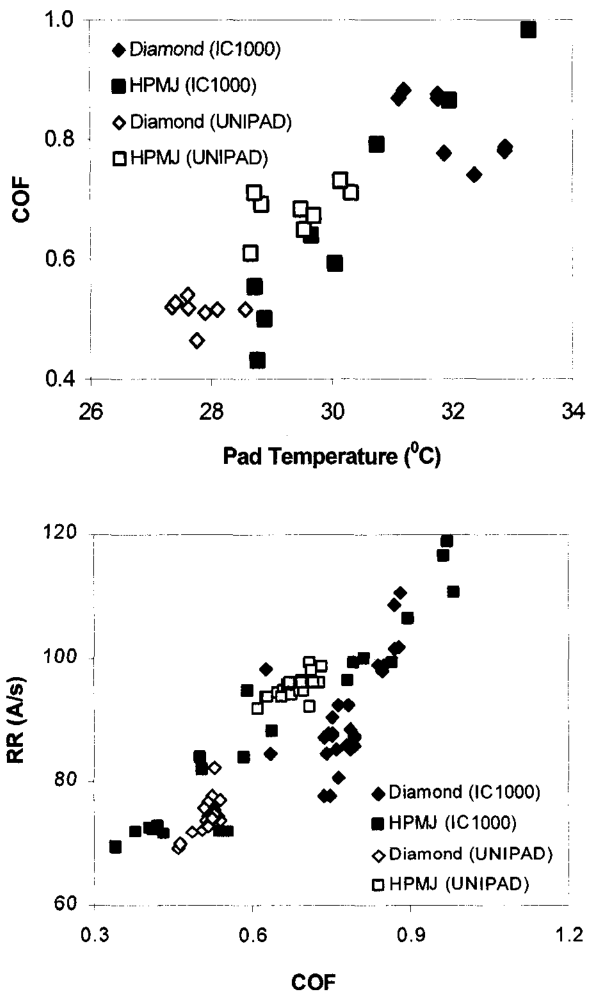


Fig. 5. Correlation between COF and pad average temperature (upper) and COF and RR (bottom) under pad conditioning method adopted and the type of pad used.

necessary to account for the changes in COF observed in this study is about a factor of 2-3. While not a reasonable change given the values of the moduli at various temperatures summarized in Table I, and the observed pad temperature changes of only about 4 °C, this much softening over such a small temperature change in pad temperature may be possible if the reaction temperature T at the asperity tips,

$$T = T_a + c_b \mu_k p V + (\beta / V^{1/2+e}) \mu_k p V \quad (2)$$

is responsible for the softening. In Equation (2), the additional term represents the asperity flash heating increment[8]. A feedback mechanism whereby fluctuations in T_a increase the COF (μ_k), which in turn increases the second and third terms in Equation (2), thus further increasing the COF, may be at work here.

Figure 5 also shows the correlation between COF and copper removal rate under different conditioning methods during the 50-wafer polishing marathon. The dependence of removal rate on COF can be clearly understood given the fact that higher values of COF cause an increase in the reaction temperature, in turn increasing the chemical rate constant associated with material remova[9].

5. CONCLUSION

A series of comparative 50-wafer marathon runs were performed to investigate HPMJ pad conditioning as an alternative to diamond disc conditioning for copper CMP for IC1000 and UNIPAD pads. Relatively stable COF and removal rates values were achieved with both diamond and HPMJ conditioning of the UNIPAD. However, with IC1000, COF and removal rate decreased significantly with HPMJ conditioning and was somewhat unstable with diamond conditioning. Differences in pad wear rate and insufficient asperity recovery issues associated with IC1000 were speculated as the causes of removal rate instability. Results also indicated good correlations between temperature and COF as well as COF and removal rate.

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