The main objective of this investigation is to verify if “smart” groove designs can increase slurry utilization, by controlling the amount of slurry transferred from the pad grooves to the pad area-wafer interface, resulting in process optimization. Based on previous studies concerning Logarithmic-Spiral as well as Concentric Slanted grooves, two groove designs were selected to be evaluated and compared to the popular industrial groove design (concentric grooves) under reduced slurry flow rate conditions during copper polishing. The effect of several process parameters were investigated, including pad groove design, applied wafer pressure, and slurry flow rate. Theoretical examination of the experimental data was performed by applying a three-step copper RR model, in order to establish the effect of groove designs on the chemical and mechanical mechanisms present during copper chemical mechanical polishing (CMP).

Theoretical Approach

**RR model.**—A three-step model combined with a previously developed flash heating thermal model is used to theoretically evaluate RRAs for all pads tested in this study. A detailed description of the three-step model can be found elsewhere. A summary of this model is described here. The proposed three-step model is represented in Eq. 1, where $\text{CuOX}^*$ designates a species on the surface of the wafer.

$$\begin{align*}
\text{Cu} + \text{OX} & \rightarrow \text{CuOX}^* \\
\text{CuOX}^* & \rightarrow \text{CuOX} \\
\text{CuOX} & \rightarrow \text{Cu} + \text{OX}
\end{align*}$$

1
During step 1, copper on the surface of the wafer is oxidized at a constant rate $k_1$. The oxidized copper is removed through both mechanical abrasion (in step 2) at a constant rate $k_2$ and dissolution by complexing agents in the slurry (in step 3) at a constant rate $k_3$. The governing equation for the RR model is

$$RR = \frac{M_w k_1 (k_2 + k_3)}{\rho \ k_1 + k_2 + k_3}$$

where $M_w$ and $\rho$ are the molecular weight and density of copper.

The oxidation model based on cation migration to represent measured copper oxide growth profiles as a function of temperature. Detailed derivation of this copper oxidation model can be found elsewhere. The rate constant for step 1 in the RR model has the following expression

$$k_1 = \frac{p_{ox}}{M_{w,ox}} \exp \left( -\frac{W}{kT} \right) \exp \left( -\frac{qa}{2kT_x} \right)$$

where $M_{w,ox}$ and $p_{ox}$ are the molecular weight and density of copper oxide. $N$ is the number of cations per unit area, $\Omega$ is the volume of oxide formed per cation, and $f$ represents the frequency of atomic vibrations. The quantity $N\Omega f$ is taken to be equal to $10^4$ cm/s. $W$ is the potential barrier an ion has to overcome in order to move from

Figure 1. (Color online) The groove designs evaluated in this study. (a) The LNSP pad and (b) the Concentric Slanted grooves (Plus 20° and Concentric grooves).

Figure 2. (Color online) Proposed mechanism for the macro- (a) and micro- (b) effects of slanted grooves on slurry flow during CMP.

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one interstitial site to another, $k$ is Boltzmann’s constant, and $T_{\text{bar}}$ is the average temperature at the surface of the wafer. $q$ is the proton charge, $1.6 \times 10^{-19}$ C, and $a$ is the interatomic distance assumed to be $4 \AA$, the lattice constant for Cu$_2$O,$^{12}$ $E$ represents the potential across the oxide, and $x$ is the oxide film thickness.

The rate constant used to characterize the dissolution of the copper oxide is extracted from a one-dimensional model, where the diffusion of the complexant through a by-product film appearing on the wafer surface after etching controls the process. Detailed derivation of this dissolution model can be found elsewhere. The rate constant for step 3 in the RR model has the following expression

$$k_3 = \frac{-A \exp\left(\frac{-E_a}{RT}\right)}{(x - X)}$$

where $E_a$ and $A$ are modified activation energy and Arrhenius pre-exponential constant, respectively. $R$ is the ideal gas constant and $T_{\text{bar}}$ is the average temperature at the surface of the wafer. $(x - X)$ represents the thickness of copper oxide that grows on the wafer surface during CMP. All variables in Eq. 3 and 4 are either known constants or have been experimentally determined a priori, except for $x$ and $(x - X)$, which both represent the thickness of oxide in the wafer surface at a given time.

As a first approximation, a constant value for the characteristic oxide thickness (i.e., $7 \AA$) was considered. The selection of the value for the copper oxide thickness is based on the following arguments attempting to accurately represent the actual physical system:

1. The physical restriction established by the copper-oxygen bond length in copper oxide (1.85 Å) is satisfied with a copper oxide thickness in the range of $7 \AA$. This also facilitates CMP RRs in the 1000–10,000 Å/min range.$^{10}$

2. The calculated thicknesses of interest in CMP correlate to the growth of a few monolayers on the surface of the wafer. Previously, experimental evidence reported initial fast copper oxidation rates, which resulted in four to six monolayers of copper oxide formation in very short times.$^{14}$

3. A previous study hypothesized [based on coefficient of friction (COF) data obtained from copper CMP experiments using abrasive-free slurries] that the cycle growth and subsequent removal of the passivation layer formed was on the order of milliseconds.$^{18}$

The calculated oxidation times required to grow a thickness of $7 \AA$ is also on the order of milliseconds.

4. Finally, based on confocal microscopy analyses, the physical constraints established by the pad-wafer contact mechanism are satisfied with the selection of a characteristic copper oxide thickness of $7 \AA$ for an IC-1000 pad (or similar) to be used in the three-step RR model.$^{13,15}$

The mechanical RR constant is assumed to be proportional to the frictional power density

$$k_2 = C_{\text{f}} \text{COF} \ p \ V$$

where $C_{\text{f}}$ is the proportionality constant (mol J$^{-1}$), COF is the average COF, $p$ is the applied pressure, and $V$ is the sliding velocity.

**Flash heating temperature model.**—The average reaction temperature at the wafer surface $T_{\text{bar}}$ used for the rate of oxide growth and the rate of oxide dissolution, is hypothesized to be a combination of the average leading edge pad temperature and the temperature generated by asperity tip flash heating$^{18}$

$$\bar{T} = \bar{T}_{p} + \Delta \bar{T}_{f}$$

where $\bar{T}_{p}$ is the measured average leading edge pad temperature at each ($pV$) condition and $\Delta \bar{T}_{f}$ is the mean flash temperature increment, given by

$$\Delta \bar{T}_{f} = \frac{\zeta (r_w c_w)}{\bar{p}V^{1/2}} \cdot \text{COF} \ p \ V$$

In Eq. 7, $\zeta (r_w c_w)$ is a tool-dependent parameter that depends on the wafer radius $r_w$ and distance $c_w$ between the wafer and pad centers. For the IPL-FMC 200 mm polisher used in this study $\zeta = 0.781 \text{ m}^{1/2}$, $B'$ is a model parameter that depends on pad mechanical properties, such as thermal conductivity, density, and heat capacity. COF is the average COF, $p$ is the applied wafer pressure and $V$ is the sliding velocity. During the characterization of experimental data we control $p$ and $V$, measure $T_{p}$ and COF, and extract $C_{\text{f}}, B'$, and $\epsilon$ to minimize the root-mean-square (rms) error between the model and the measured RRs.

**Experimental Procedure, Consumables, and Apparatus**

The FMC-IPL 200 mm polisher was used for all experiments. Detailed description of the apparatus can be found elsewhere.$^{19}$ Polishing was performed on three Rohm and Haas foamed polyurethane pads with different groove designs: LNSP, Plus 20°, and Concentric grooves. An ultraprecision pad grooving machine, CMP 1000S from Toho Engineering Co., was used to create these patterns on flat IC-1000 pads. In all cases, the grooves were 1 mm deep and 0.5 mm wide. Prior to data acquisition, each pad was conditioned for 30 min with 100 mm diamond-disk at a pressure of 3.4 kPa, a rotational velocity of 30 rpm, and a sweep frequency of 0.33 Hz using ultrapure water (UPW). Break-in was followed by pad seasoning using 99.99% pure copper disks, 200 mm in diameter, until a constant COF was achieved. Typically, five dummy runs were needed to obtain a constant COF.

Fujimi PL-7102 slurry was used for pad seasoning and for the actual polishing experiments. The slurry is composed of colloidal silica abrasive particles with an average diameter of 35 nm. The slurry was prepared by adding 1 part of PL-7102, 9 parts of UPW, and 0.3 parts of 30% by weight hydrogen peroxide. The slurry pH after adding the UPW and hydrogen peroxide was close to neutral ($\text{pH} \approx 6.8$). Slurry was supplied at the center of the pad at two different flow rates: 220 and 110 cc/min. In this study 99.99% pure copper disk, 200 mm in diameter, were polished using in situ conditioning for 80 s at applied wafer pressures of 6.8, 10.3, 13.7, and 17.2 kPa (1.0, 1.5, 2.0, and 2.5 psi) and sliding velocity of 1.20 m/s (96 rpm). Each experimental condition was repeated once in order to estimate repeatability. The copper disk and platen rotated counterclockwise at the same rate during polishing, in order to keep a constant sliding velocity under the wafer. After polishing, the wafers were rinsed with UPW and dried immediately.

An Ohaus precision balance (readability 0.0001 g) was used to measure the weight pre- and postpolishing to determine the RR. An infrared video camera capable of measuring temperature in the range $-40$ to $2000^\circ$C with an accuracy of $\pm 2^\circ$C and a resolution of $0.1^\circ$C was used to record the pad surface temperature. Measurements were taken at a frequency of 5 Hz at five points along the leading edge of the wafer. Real-time shear force measurements were taken simultaneously along with the real-time IR thermal data.

**Results and Discussion**

**RR.—** The first aspect analyzed in this study is the performance of these pads in terms of copper removal when slurry flow rate is reduced. Figure 3 shows the comparison of the RR obtained with the selected groove designs at 50% reduced flow rate, to that obtained with the common industrial pad at full flow rate conditions (220 cc/min). By setting the RR behavior observed with the Concentric groove pad under the operating conditions evaluated (pressures and sliding velocity) and at full flow rates as standard, then the results presented in Fig. 3 show a 45 and 17% increase in RR for the pads Plus 20° and LNSP, respectively, when they are used to polish copper discs under the same operating conditions except for a two times reduction in flow.
By reducing the amount of slurry on the pad, the mechanical and chemical mechanisms of the system are affected. The groove designs seem to positively affect the process, favoring copper removal while reducing slurry consumption as much as 50%. These encouraging findings support the idea that through smart groove design the CMP process can be optimized to reduce COO and environmental health and safety (EHS) issues.

Effect on the mechanical and chemical mechanisms of copper CMP. — When polishing under reduced flow rate conditions with the pads used in this paper, fluid distribution and transport of slurry at the pad-wafer interface changes, affecting the mechanical and chemical mechanisms of the system. The evaluation of the shear force and pad temperature measured during polishing can provide an indicator of these effects.

Figure 4 shows the mean shear force measured between the pad and the wafer for the pads and the Concentric groove pad under the process conditions previously described. As expected, the pads Plus 20° and LNSP present similar higher shear force, at a 50% lower flow rate, than the Concentric groove pad at full flow rate. Lower flow rates result in thinner lubricant film between the wafer and the pad, therefore a higher degree of contact (mechanical abrasion) between the pad and the wafer is observed. This provides a better understanding of the effect of the evaluated groove designs on the mechanical mechanism of the CMP process and partially explains the RR behaviors presented in the previous section.

Nevertheless, it is also important to analyze how the chemical mechanism of the process changes under these conditions, the average pad leading edge temperature ($T_p$) measured during polishing can help in this endeavor. The measured values of $T_p$ can provide a good estimate of the mean reaction temperature at the wafer surface during polishing. Figure 5 presents the average pad temperature collected during these experiments for the pads and the Concentric groove pad under the process conditions previously described. The results illustrate a significantly higher average pad temperature for the Plus 20° pad than for the other two pads. The higher shear force measured for this pad, due to the reduction of slurry flow rate, contributes to an increase in the pad temperature during polishing. A previous study\(^{(20)}\) indicated that copper RR is highly sensitive to temperature where higher temperatures increase average RR. Another study\(^{(21)}\) also indicated that as pad temperature increases during polishing, the temperature of the polished wafer increases accordingly. Therefore, assuming that there is no chemical depletion (a good assumption in CMP), copper RR should be higher at a higher pad temperature. This effect is incorporated in the RR model shown in Eq. 3 and 4.

In the case of the LNSP and Concentric grooves pads similar values for $T_p$ are observed. This could seem unusual, due to the higher shear force also measured in the case of the pad LNSP. However, it is important to consider the opposing effects of the two types of groove designs present in this pad. This results in a completely different scenario than in the case of the pads Plus 20° and Concentric grooves.
Editors: The chemical and mechanical rate constants extracted from the polishing conditions and groove designs on the wafer surface. Recalling that this value is the sum of the average pad temperature ($T_p$) and the flash temperature increment ($\Delta T_f$), the results agree very well with the trends previously shown by $T_p$ for each pad groove design. Plus 20° presents the highest relative values of $\bar{T}$ followed by LNSP and finally, with the lowest relative values, Concentric grooves. The results observed in the case of LNSP coincide with the “cooling” theory previously explained due to the presence of the spiral groove design on this pad.

The effect of $T$ on the rate constants representing the chemical mechanisms ($k_1$ and $k_3$) can be seen in Fig. 10 and 11, respectively. Additionally, this analytical exercise provides, through the evaluation of the respective rate constants, means to comprehend the effects of the polishing conditions and groove designs on the chemical and mechanical mechanisms of the process.

![Figure 6](image1.png)  
**Figure 6.** (Color online) Experimental (open symbols) and modeled (closed symbols) RR as a function of $pV$ for Concentric grooves pad during copper CMP.

![Figure 7](image2.png)  
**Figure 7.** (Color online) Experimental (open symbols) and modeled (closed symbols) RR as a function of $pV$ for LNSP pad during copper CMP.

![Figure 8](image3.png)  
**Figure 8.** (Color online) Experimental (open symbols) and modeled (closed symbols) RR as a function of $pV$ for Plus 20° pad during copper CMP.

![Figure 9](image4.png)  
**Figure 9.** (Color online) Calculated mean reaction temperature as a function of $pV$ for each groove design.

Before analyzing the rate constants defining the chemical process, Fig. 9 presents the calculated mean reaction temperature ($\bar{T}$) at the surface of the wafer. This analysis was also performed to find if these effects were revealed in the relative values of the mechanical and chemical rate constants extracted from the model.

Figures 6–8 show the same RR data presented in Fig. 3 with the addition of the RR calculated by the three-step copper RR model for each pad evaluated. Even though in the case of the pad Concentric grooves the rms error is relatively high (450 A/min), the model still successfully predicts the observed RR behaviors in all cases. Additionally, this analytical exercise provides, through the evaluation of the respective rate constants, means to comprehend the effects of the polishing conditions and groove designs on the chemical and mechanical mechanisms of the process.
COF is defined as these process conditions. Figure 12 illustrates the relative values of order to obtain a better understanding of how each pad works under Plus 20°, followed by LNSP, with relative higher values than those for the pad Concentric grooves.

The mechanical contribution of the system was also analyzed in order to obtain a better understanding of how each pad works under these process conditions. Figure 12 illustrates the relative values of $k_2$ as a function of $pV$ for all pads evaluated. The results indicate that the pads presenting the higher and lower degree of mechanical abrasion, at their particular process conditions, are Plus 20° and Concentric grooves, respectively. This also correlates with the highest and lowest RR and $F_{shear}$ values observed for these pads during polishing. In the case of LNSP the relative values of $k_2$ fall approximately midway between those of the other two pads. However, the measured shear force for this pad was basically the same as that of Plus 20°. Recalling the form of $k_1$ set forth earlier in this paper

$$k_1 = C_p \text{COF} \frac{pV}{k_3}$$

where $C_p$ is the proportionality constant (mol J$^{-1}$), COF is the average COF, $p$ is the applied pressure, and $V$ is the sliding velocity.

Furthermore, with COF defined as

$$\text{COF} = \frac{F_{shear}}{F_{normal}}$$

it can be seen that $k_2$ is directly proportional to $F_{shear}$. Following this line of thought, the relative values of $k_2$ for the pads Plus 20° and LNSP are expected to be close under similar $pV$ conditions.

However, it is important to consider the contribution of the proportionality constant $C_p$ to Eq. 5. $C_p$ essentially accounts for the mechanical properties (micro- and macrotexture) of each pad. The pads evaluated in this study were made with the same material and the only difference among them was the groove design. With this in mind, Table I shows the values of $C_p$ extracted from the three-step copper RR model for each pad. Plus 20° and Concentric grooves present the same value of $C_p$, which is to some extent reasonable. If $C_p$ accounts for the differences in the materials used to produce the pads (i.e., pad microtext) and groove designs (i.e., pad macrotext), then these two pads should have the same value for this proportionality constant. Remember that both pads are made with the same material and both have similar groove design, which is concentric grooves. The grooves in the pad Plus 20° are slanted 20° toward the edge of the pad; however, the groove design is still the same. The difference in the relative values of $k_2$ between the two pads with concentric grooves is accounted for by the differences in the extent of contact between the wafer surface and the pad asperities in each case. This is corroborated through the higher $F_{shear}$ measured in the case of Plus 20°.

In the case of LNSP the same microtext used for the pads with concentric grooves is present. However, the groove design is completely different, resulting in a different value of $C_p$. Although the values of the collected $F_{shear}$ are similar for the pads Plus 20° and LNSP, the lower value of $C_p$ for the latter suggests that this pad is less mechanically active (lower relative values of $k_2$) than the pad Plus 20°. Previous investigations have shown that different groove designs can affect the mechanical properties of the pad by affecting their “hardness,” and hence RR and within wafer nonuniformity (WIMNU) obtained during polishing.

Conclusions

The results presented here showed that copper removal increases, 47% in the case of Plus 20° and 17% in the case of LNSP, when these groove designs are used to polish with a 50% reduction in slurry flow rate. The effects of these process conditions and groove designs on the chemical and mechanical mechanism of CMP are well captured by the measured experimental parameters ($T_p$ and $F_{shear}$), as well as the respective rate constants extracted from the application of the three-step copper RR model to the experimental RR data. The proportionality constant, $C_p$, obtained from the equation defining $k_2$ appears, in this case, to be able to distinguish dif-

![Figure 10](Color online) $k_1$ plotted as a function of $pV$ for each groove design.

![Figure 11](Color online) $k_3$ plotted as a function of $pV$ for each groove design.

![Figure 12](Color online) $k_2$ plotted as a function of $pV$ for each groove design.

Table I. Values of $C_p$ extracted from the three-step copper RR model for each pad.

<table>
<thead>
<tr>
<th>Pad type</th>
<th>$C_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentric grooves</td>
<td>$2.49 \times 10^{-7}$</td>
</tr>
<tr>
<td>Plus 20°</td>
<td>$2.49 \times 10^{-7}$</td>
</tr>
<tr>
<td>LNSP</td>
<td>$2.00 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
ferent types of groove designs for pads made of the same material (microtexture) evaluated under the same process conditions. This study has shown that “smart” groove design can optimize the CMP process in terms of reduction of COO and EHS issues. However, the results presented here have also indicated that the reduction of slurry flow rate also decreases the amount of slurry at the pad-wafer interface. This effect might be even more pronounced when the groove designs are used to polish. The degree of contact between the pad and the wafer are affected producing higher material removal, which can probably generate higher surface defects. The next generation CMP pads must provide sufficiently high contact to achieve higher material removal, without sacrificing surface quality (i.e., achieving lower defectivity).

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References