Chemical Mechanical Planarization of Copper Damascene Structures

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We describe the chemical mechanical planarization (CMP) of copper damascene structures using an IC1400 pad and four different types of slurries. Two alumina-based slurries and two silica-based slurries were evaluated. After successful removal of the excess Cu, we examined the topography of the planarized structures using scanning electron microscopy. The effects of the CMP process on spacer erosion, Cu line recess, corrosion of submicrometer Cu lines, liner removal selectivity, and contamination of the patterned structures are presented. It was found that minimizing the etch rate (~10 nm/min) of the slurry is required to achieve reproducible removal rates and unrecessed structures. No dishing was observed with the utilized pad. We also show that corrosion is prone to occur in low Cu pattern density areas and that the removal of the liner material (tantalum) remains problematic because of its chemical inertness.

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Copper is beginning to replace aluminum as the interconnect metal in integrated circuits (IC). Not only has Cu the ability to reduce the resistance-capacitance product (RC) delay due to its lower resistivity, but also increase the circuit reliability because of its higher electromigration resistance.1-4 The use of reactive ion etching (RIE) to pattern Cu is impractical, because volatile Cu compounds form only at elevated temperatures.5 The damascene process provides a solution to the problems arising from the lack of a directional metal etch capability.6-8 In this approach, the dielectric is patterned by RIE (Fig. 1a), followed by the liner and metal deposition (Fig. 1b). The liner becomes necessary when using Cu as an interconnect material to prevent the rapid diffusion of the Cu into the dielectric. The final step in this process is chemical mechanical polishing (CMP) that removes the excess metal and provides global planarization9 (Fig. 1c). The planarization capability is an important advantage of the CMP process. It prevents problems associated with the increase of the number of interconnect layers in the multilevel metallization of ICs, where the topography of device structures increases significantly as additional layers are stacked on top of one another.10

In order to achieve ideal planarized structures as shown idealized in Fig. 1c, the CMP process has to remove the metal and the liner material evenly without eroding the underlying dielectric. Therefore a high metal and liner to dielectric selectivity is necessary. Low selectivities can lead to the erosion of patterns during overpolishing, which is necessary because the removal rates across the wafer are usually not constant. Also, longer polishing times are required for regions of low pattern density (low density of metal lines) to remove the larger amounts of metal situated on top of the spacers (see Fig. 2a, right column). During the overpolishing, regions of high metal pattern density tend to erode faster since less metal needs to be removed to planarize the structures and less dielectric needs to be removed to erode the spacers. A high metal pattern density is equivalent to a low dielectric density; therefore areas of high metal pattern densities show higher metal and dielectric removal rates.11

**Figure 1.** Cross-sectional view after the different process steps for the damascene technique: (a) Patterns are etched into the SiO2. (b) Liner material and metal are deposited over the whole surface of the patterned wafer. (c) CMP removes the excess liner material and metal. The metal remains only in the gaps (trenches/holes) to form the interconnects.

**Figure 2.** (a) The time needed to planarize a structure, i.e., to remove the excess metal to obtain an isolated metal line, depends on the pattern density. Less overburden needs to be removed in high pattern density areas (left column) as compared to low pattern density areas (right column). (b) When the high pattern density structures are planarized (left) areas of low pattern density still show some residual metal. (c) During the overpolishing the patterned dielectric (left) erodes faster as compared to the unpatterned. The dotted line indicates the original, uneroded dielectric thickness. The end point of the CMP process is reached when no residual metal is found in the low pattern density areas (right).
The problems associated with the homogeneous removal of the metal overburden in low and high pattern density areas can be solved by depositing a sufficiently thick film of metal, since in this fashion the metal is already planarized before the polishing pad reaches the metal/dielectric interface during the CMP process. However, this approach is not feasible for the liner material, which makes achieving high liner/dielectric selectivity very important. Ta and/or TaN liners are frequently used for Cu interconnects. Ta is a hard (mineral hardness: 6.5) and chemically inert metal, which makes it difficult to remove.

The two important consumables for the CMP process are the pad and the slurry. The choice of the polishing pad influences the planarization rate. A harder pad planarizes a surface faster and causes less dishing of the metal lines. The role of the slurry can be separated into two aspects: particles and chemistry. The choice of the particles is important to prevent defects, since large or clustered particles can scratch the surface during CMP. This can lead to defects in the spacers degrading the isolation of the metal line, or it may cause defects in the metal line itself. The choice of the slurry chemistry, such as pH value and etch rate, influence the metal removal rate, the metal/dielectric selectivity, as well as undesired etching and corrosion of the metal lines.

These issues can affect both the fabrication and ultimate performance of an IC device. We describe the results of experiments on the polishing of patterned Cu samples using several slurries. Special attention was given to the corrosion behavior of the slurries utilized since Cu does not passivate as readily as other metals, e.g., Al. This can lead to the localized dissolution (corrosion) of Cu lines.

### Experimental

**CMP tool.**—All polishing results in this paper were obtained with a Cybeq 3900 (Cybeq Nano Technologies, San Jose, CA) wafer polisher and planarization system. This tool is a three-axis polisher consisting of a head (wafer carrier), a carousel, and a platen as described previously. The down force on the wafer is set by air pressure applied uniformly to the head. For the blank polishing experiments, the polishing pressure was varied between 19 and 33 kPa and the linear polishing velocity between 26 and 48 m/min. Although the Cybeq 3900 tool is capable of polishing six wafers simultaneously, for practical reasons, all experimental runs were performed with one or two wafer heads. A mounting pad (DF 200/buffed poromeric film, Rodel, Inc., Newark, DE) and a Delrin retaining ring with an inner diameter slightly greater than that of the wafer were used on the head to hold the wafer in place during polishing. This setup allows for easy placement and removal of the wafer from the carrier without damage and contamination. This tool incorporates an *ex situ* pad dressing which is used to recondition the surface of the pad after a CMP run. For experiments in which the pad was reconditioned, the pressure exerted by the dresser on the pad was set to 20 psi.

**Samples.**—Polishing was performed on 150 mm diam Si wafers that were either covered with a thin film of Cu or thermally grown SiO₂. In order to investigate the removal rate selectivity of Cu to SiO₂, the 150 mm copper and oxide wafers were polished simultaneously. The patterned Cu samples (damascene structures) utilized were partial wafers 2 × 2 cm in size consisting of an array of different sized trenches. These patterned structures as well as the blanket Cu wafers contained a Ta liner 50 nm thick to prevent diffusion of the copper into the oxide. The thin films of pure Cu for blanket and patterned wafers were sputter-deposited with a thickness of 2.3 μm. The thermally grown oxide had a thickness of 1.5 μm.

To study the removal of the liner material we polished partial wafers, (2 × 2 cm) coated with 350 nm of Ta or TaN, independently from the Cu CMP experiments but under the same experimental conditions.

**Consumables.**—The polishing experiments were conducted with four different slurries: the Rodel slurry QCTT1010 (slurry A₁) and three experimental slurries labeled slurry A₂, S₁, and S₂. The properties of the slurries are shown in Table I. Slurry A₁ and experimen-

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<td>A₁</td>
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<td>A₂</td>
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<tr>
<td>S₁</td>
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<td>S₂</td>
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Figure 3. Particle size distribution as measured with a laser scattering analyzer. The mean particle diameter for slurry S₁ is smaller than that for A₁, but S₁ shows a small, second peak (inset) at larger particle sizes.
sheet resistance at nine fixed points on the wafer. For the selectivity studies, the thickness and uniformity of the SiO$_2$ wafers were measured using an ellipsometer which was capable of scanning the wafer in one direction to yield information about the thickness profile of the wafer.

We measured the etch rates of Cu, Ta, and TaN by placing these samples in 150 mL of the four slurries listed above for 20 min. The dispersions were agitated for the entire duration of the experiment. The Cu samples were obtained from the same batch of 150 mm Si wafers that were utilized in the polishing experiments and their thickness was determined before and after using a four point probe. We verified the etch rates of Cu in slurry A$_1$ for etching times of 5, 10, and 67 min. The results reproduced the rate given in Table I, which leads to the conclusion that no acceleration in the etch process occurs with time. Hence, the etch rates for an exposure time of 20 min should be the same as for short exposure times during the polishing process.

The removal rates were further analyzed by fitting them with a power function (see below). The quality of the fits were evaluated by comparing the model $R^2$ values. Good fits to the experimental data have $R^2$ values close to unity.$^{19}$

### Results and Discussion

**Blanket polishing**.—The polishing of Cu utilizing slurries A$_1$, A$_2$, and S$_1$ yielded removal rates as shown in Fig. 4. The rates of removal for slurry A$_1$ and A$_2$ are monotonicallly increasing with polishing pressure and velocity. Slurry S$_1$ does not exhibit this increase. All rates decrease slightly at the intermediate velocity value. If one fits the experimentally obtained rates with the power function, $RR = kp^av^b$, where $k$, $p$, and $v$ are constants, the pressure on the wafer and the linear velocity, respectively, one obtains the fits as shown by the straight lines on the graphs. Pressure and velocity of a polishing process indicate how much mechanical action is exerted onto the wafer’s surface, determining the degree of abrasion. At the same time, the wafer surface is exposed to modifications by the slurry chemistry. The fitting parameters $a$ and $b$ indicate, how strong the removal rate responds to changes in the mentioned mechanical action. An in-depth discussion of the mentioned power function is published elsewhere.$^{17,18}$ The values of $a$ and $b$ are given in Table II. They clearly indicate a sublinear dependence of the removal rate on pressure and velocity. Comparing the values of $a$ and $b$ for slurry A$_1$, we see that the latter is larger, revealing the dominant influence of the velocity on the removal rate. Table II also lists the model $R^2$ values. The power function fit for slurry A$_2$ is not as good as for A$_1$ (see $R^2$ values). The removal rates at 37 m/min and at pressures of 19 and 26 kPa deviate noticeably from the fit.

Unlike slurries A$_1$ and A$_2$, slurry S$_1$ does not exhibit a monotonic increase of the Cu removal rate with increasing pressure and velocity. All rates decrease slightly at the intermediate velocity value. The power function fit for slurry S$_1$ cannot be considered successful. However, since our fitting program fits all measurement points simultaneously, the values $a$ and $b$ state the overall dependence of the removal rate on pressure and velocity. Even though the fit cannot be used to predict the removal rate, it averages the increase of the removal rate with increasing pressure and velocity. If one compares the fitting parameters of all three slurries, one can observe that the two alumina-containing slurries (slurry A$_1$ and A$_2$) have similar $a$ and $b$ values, whereas the values for the silica slurry (slurry S$_1$) are substantially larger. Apparently, the difference in chemistry between the commercially available slurry A$_1$ (QCTT1010) and the S$_1$ slurry has little influence, whereas the difference in slurry particle material, i.e., alumina or silica, causes a significant change in the discussed values.

Figure 5 displays the selectivity of Cu to SiO$_2$ for slurry A$_1$, which decreases with increasing process parameters of pressure and velocity. The best selectivity of 206:1 was obtained for a pressure of 19 kPa and 26 m/min. This observation together with the low rates are evidence that the SiO$_2$ removal, in contrast to the copper, is dominated strongly by mechanical abrasion. The selectivities for the slurries A$_2$, S$_1$, and S$_2$ were comparable to those obtained with A$_1$.

The removal and etch rates of Ta and TaN utilizing the slurries A$_1$ and S$_1$ were negligible. Therefore, it is reasonable to assume that Ta and TaN, similar to SiO$_2$, are only removed through mechanical abrasion. However, in some cases, for the slurry A$_1$ and in all cases

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**Table II.** Fitting parameters $k$, $a$, $b$, and model $R^2$ values for all three slurries investigated.

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<th>Slurry</th>
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<th>$a$</th>
<th>$b$</th>
<th>$R^2$</th>
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<tr>
<td>A$_1$</td>
<td>$18.9 \pm 3.0$</td>
<td>$0.38 \pm 0.03$</td>
<td>$0.71 \pm 0.03$</td>
<td>0.991</td>
</tr>
<tr>
<td>A$_2$</td>
<td>$25.8 \pm 9.5$</td>
<td>$0.33 \pm 0.07$</td>
<td>$0.64 \pm 0.07$</td>
<td>0.923</td>
</tr>
<tr>
<td>S$_1$</td>
<td>$3.9 \pm 5.3$</td>
<td>$0.76 \pm 0.27$</td>
<td>$0.78 \pm 0.24$</td>
<td>0.620</td>
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for the slurry S1, it was found that the liner film had partially delaminated after polishing. Further investigation revealed that for the alumina slurry A1, the liner film delaminated only as a result of the four point probe measurement prior to polishing. The film peeled only in the direct vicinity where the probe had touched the sample. The four point probe measurement is invasive, i.e., it introduces defects into the surface of the film. The Ta liner possesses high internal stress when deposited on SiO2. Therefore, these films easily lose adhesion (peeling) when subjected to surface damage. It is possible that the small amount of larger particles present in slurry S1 (see inset of Fig. 3) introduced surface defects in the Ta film that caused the observed delamination.

**Pattern polishing.**—Erosion and Cu line recess.—After the initial CMP of blanket Cu wafers, we focused on the chemical mechanical polishing of Cu patterns and compared the four different slurries A1, A2, S1, and S2. Erosion of the SiO2 spacers, dishing and surface topography of the copper lines, scratching, and contamination of the structures were examined.

No scratches were observed for polishing with all four slurries as shown in the micrographs of Fig. 6. The results for slurry S2 are not displayed because no differences were observed when compared with slurry S1.

Figure 7a displays an unpolished set of trenches in a cross-sectional view. The width of the two outer trenches is 3.3 μm and that of the center trench is 3.9 μm. These trenches have a uniform depth of 920 nm and were initially covered with 2.3 μm of Cu. As shown in Fig. 7b, well-planarized structures are obtained after polishing with slurry A1. Upon closer inspection, however, one can observe that the oxide spacers are eroded and although the Cu lines show very little dishing they are slightly recessed.

Figure 8 shows two 1 μm wide trenches with strongly recessed Cu lines. The schematic drawing in Fig. 9 explains this in more detail. If patterns are overpolished they can erode. Because the metal polishes faster than the dielectric, the metal will always stay at or below the level of the neighboring spacer, which causes a thinning of the metal lines as soon as the SiO2 is eroded. Due to pad bending spacers can appear rounded and the adjacent metal lines dished. In addition to dishing, the metal lines can be recessed, so that one observes a step from the spacer down to the Cu wire. The pad we utilized is stiff enough to keep spacer rounding and Cu line dishing to a minimum. For our experiments the amounts of rounding and dishing were small in comparison to the “step” height (see Fig. 9).

Hence, it is reasonable to assume that the metal recess originates mainly from a chemical etch rather than from pad bending. An isotropic etch leaves a Cu line of uniform thickness behind, whereas a line eroded by the pad is thinner at the center than at the edges. This assumption is verified when plotting the Cu line recess vs. etch rate as shown in Fig. 10 for all four slurries. Slurry S2 shows the least amount of Cu line recess while slurry S1 shows the greatest which is consistent with the etch rate experiments on Cu that were mentioned previously. Finally, it should be noted that the SiO2 spacer erosion is comparable for all four slurries.

**Corrosion of submicrometer Cu lines.**—Severe corrosion of Cu lines occurs only for the S1 slurry and only for the smallest Cu linewidth, i.e., 0.69 μm, to be found on this particular type of patterned wafer. Neither the slurry A1, A2, or S2 display the corrosion shown in Fig. 11b. The micrographs in Fig. 11a and c exhibit an uncorroded Cu line of the same type from a sample polished with slurry A2 and S2. The corrosion is presumably caused by the presence of hydronium ions (H3O+). If the Cu is first oxidized (e.g., by oxidizer H2O2) to one of its simple oxides (i.e., CuO or Cu2O) then the hydronium ions (H3O+) facilitate their dissolution.

Moreover, we observed that the degree of corrosion is also dependent on the pattern density. The same Cu lines are less corroded in regions of high pattern density than in areas of low pattern density. Figure 12a displays the strongly corroded Cu line in a low pattern density area, whereas Fig. 12b is taken using an area of high pat-
tern density and shows less corrosion. The fact that only submicrometer Cu lines are subject to corrosion may be attributed to the higher inner stress of small Cu lines. Stress decreases the activation energy for certain chemical reactions. However, the correlation between pattern density and degree of corrosion could be due to the locally different consumption of the hydronium ions. This is explained in more detail in Fig. 13a and b, which are cross-sectional schematics of Fig. 12a and b. One can assume that during the polishing process, a constant flux of hydronium ions is provided to the polished surface. The consumption of these ions depends directly on the amount of Cu present at the wafer surface resulting in high concentrations in areas with only a few Cu lines (low pattern density) and low concentrations in areas with a lot of Cu lines (high pattern density). To the left of the 0.69 μm trench of Fig. 13a is a large spacer, several tens of micrometers wide, representing an area, where no hydronium ions are consumed due to the lack of Cu. This can promote the local increase of H$_3$O$^+$, inducing the corrosion of the nearby Cu line. The small and less corroded Cu line in Fig. 12b is only separated on each side by a relatively narrow spacer followed by a large Cu wire. The local pattern density in Fig. 13b is much higher than in Fig. 13a, providing an increased consumption of the active corrosive substance (H$_3$O$^+$). In regions of high pattern density, the corrosion is only caused by the internal stress of small Cu lines.

Some issues that need further investigation are the Ta liner removal and the correlation between slurry particle material and contamination. Figure 14 shows patterns polished with slurry A$_1$ and $A_2$.
S1, but only the alumina-based slurry displays Ta residues on the SiO2 spacers even though the amount of overpolishing (same amount of spacer erosion) for the two samples are comparable. The difference in the Ta removal could be explained by the differences in the particle size distributions of both slurries. Slurry S1 incorporates small amounts of larger particles that could aid in the delamination of the barrier layer. Chemical effects are unlikely to contribute to this difference, because both slurries have negligible etch rates for Ta. A higher etch rate would yield a higher liner/dielectric selectivity. However, this approach of solving the liner removal issue would introduce problems with the etching and corrosion of the Cu lines.

Figure 15 addresses the issue of slurry particle contamination. In contrast to the slurries A1 and A2, the silica-based slurry S1 reveals fewer slurry particles that adhered to the wafer surface, especially to the Cu lines. The accumulation of surface charges on the slurry particles and the polished surface could be responsible for this. A measure for this charge accumulation is the zeta potential.11 At pH 4, alumina (Al2O3) has a positive zeta potential, whereas that of silica (SiO2) is negative. Metal surfaces always have a negative zeta potential.11 This means that the silica slurry particles are electrostatically repelled from the polished surface, consisting of silica spacers and metal lines, while the alumina particles are attracted in each case. For the alumina slurries, we found most of the particle contamination on the Cu lines as shown in Fig. 15a. It seems that at the given pH, the surface charging of the Cu is significant.

Conclusion

This article described generic issues of the CMP process that may arise form the choice of slurry. We find that the slurry particle type, i.e., alumina or silica, has a significant influence on the dependence of the removal rate on pressure and velocity. Good selectivities were achieved with all four slurries. We have found that in order to yield reproducible removal rates low etch rates of the slurry chemistry are necessary, i.e., on the order of 10 nm/min. Furthermore, low etch rates are required to prevent recess and corrosion of the Cu lines. We have shown that corrosion is prone to occur on small Cu lines located in low pattern density areas. The chemical inertness of the liner material can lead to residues on the spacers that compromise the insulation of the Cu lines. The particle type material can have an effect on the efficiency of the post CMP clean up. Larger amounts of alumina particles adhered to the Cu lines as compared to the silica particles.

Acknowledgments

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Figure 11. Cross sections of 0.69 μm wide Cu lines after polishing with (a) slurry A2, (b) slurry S1, and (c) slurry S2. Only slurry S1 displays severe corrosion.

Figure 12. Pattern density effect on corrosion with 0.69 μm wide Cu lines polished with slurry S1. Small Cu lines showed less corrosion in areas of high pattern density.

Figure 13. Possible explanation for the effect of the pattern density on corrosion (schematic).

Figure 14. Only the sample polished with slurry A1 shows Ta residues on the SiO2 spacers, even though both samples were subjected to the same amount of overpolishing. The small amounts of larger particles (600 nm diam) of slurry S1 could contribute to the delamination of the Ta barrier layer.
Figure 15. The alumina slurries (A₁ and A₂) showed higher counts of particle contamination when compared to slurry S₁. The samples were only rinsed with deionized water and dried with compressed N₂.

References