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PATTERN AND PROCESS DEPENDENCIES IN COPPER DAMASCENE CHEMICAL MECHANICAL POLISHING PROCESSES

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ABSTRACT

In this paper we present experimental data that shows the dependence of copper dishing and oxide erosion on pitch and pattern density, as well as on polishing process parameters including table speed, down force, and process sequence. Specifically, the data shows that the degree of dishing and erosion strongly depends on both the processing parameters and layout factors (density and pitch). We find that a multiple step polish is able to achieve better polishing results compared to a single step polish process. Furthermore, we observe an interesting break point for both erosion and dishing at an oxide line space of approximately 100μm. It is also observed that the interaction distance, the length over which a pattern parameter is computed, is significantly shorter than that of conventional oxide polish.

I. INTRODUCTION

The semiconductor industry is gradually replacing Al with copper as the metal of choice for interconnects in ICs. Copper has lower resistivity and higher electromigration immunity compared to Al. However, unlike Al, copper can not be easily plasma etched, and one must resort to a damascene process and use CMP (Chemical Mechanical Polishing) to remove the excess copper and barrier materials, thereby accurately defining the copper lines in the trenches.

To ensure that there is no residual copper and barrier material in the region between the trenches, and hence no shorting of any two copper lines, requires that one clears excess copper and barrier material everywhere on the die and wafer. This requirement typically implies overpolish in some regions of the die and wafer, leading to dishing of copper and erosion of oxide. Dishing is defined as the vertical distance between the final oxide level and the lowest point within the copper line after CMP. Erosion, on the other hand, is the difference between the oxide thickness as deposited and the oxide thickness after CMP. This is illustrated in Fig. 1 [1].

Copper dishing and oxide erosion lead to considerable surface non-planarity and cause various process integration problems. They also reduce the cross sections of the copper lines and dielectric spacings, leading to an increase in interconnect resistance (signal delay times) and related deterioration of device performance. There is therefore a pressing need to understand their dependence on pattern density (copper line width divided by pitch) and pitch (copper line width plus oxide space), as well as on polishing process parameters such as table speed, down force, etc., all in an effort to develop an optimized copper damascene process.

II. EXPERIMENTAL METHODOLOGY

A. DESIGN OF EXPERIMENT

A short flow process is carried out to simplify the process and to minimize sources of variation from non-CMP processes. All processes are carried out using 8” (200 mm) wafers. First, 0.8 μm of TEOS is deposited on a bare silicon wafer. Then, oxide is patterned and etched all the way to silicon to form 0.8 μm deep trenches in the deposited oxide for the metal lines. Second, 25 nm of a barrier layer is deposited, followed by copper deposition of a seed layer and 1.5 μm thick copper electroplating.

Two sets of CMP experiments were then carried out. For proprietary reasons, specific details of polishing pads, slurries, and CMP machines are not detailed in this paper. In the first experiment, CMP process conditions are varied to study the impact on dishing and erosion performance. These splits are all performed with the same consumable set (set “S1”), with process conditions summarized in Table 1a. The back pressure is set at 1.0 psi. The goal in this experiment is to set the down force to a constant but different value for each of the three process splits, but to adjust the table speed and carrier speed such that the bulk removal rate of copper will be the same for all three process splits. The polishing time is held approximately constant for all three process splits to achieve the same amount of overpolish; specifically, wafers are targeted at 0% overpolish (just cleared) whereby both the copper and the barrier material on top of the oxide in large unpatterned oxide regions have been completely removed.

In the second experiment, summarized in Table 1b, we compare a single step polish (i.e. the slurry and process conditions are held constant throughout the polish) to a three step polish, both with consumable slurry and pad set “S2” and a constant back pressure of 2.85 psi. In the third substep, a novel process modification was made to decrease the amount of chemical reaction and increase the mechanical component in the polishing. The polishing values are chosen such that the overpolishing time is the same for both the single step and the three step polishing processes. As in the first experiment, wafers are targeted at 0% overpolish.

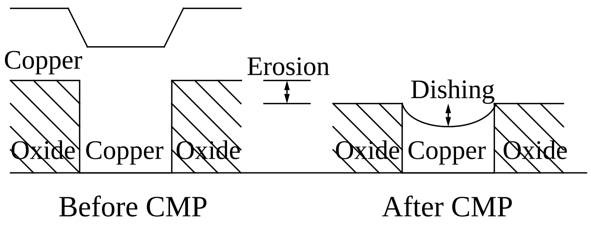


Figure 1. Copper dishing and oxide erosion defined.

TABLE 1.a Polishing Experiment #1

Process	Down force (psi)	Platen speed (rpm)	Carrier speed (rpm)
A	2.0	70	40
B	3.5	60	60
C	5.0	35	35

TABLE 1.b Polishing Experiment #2

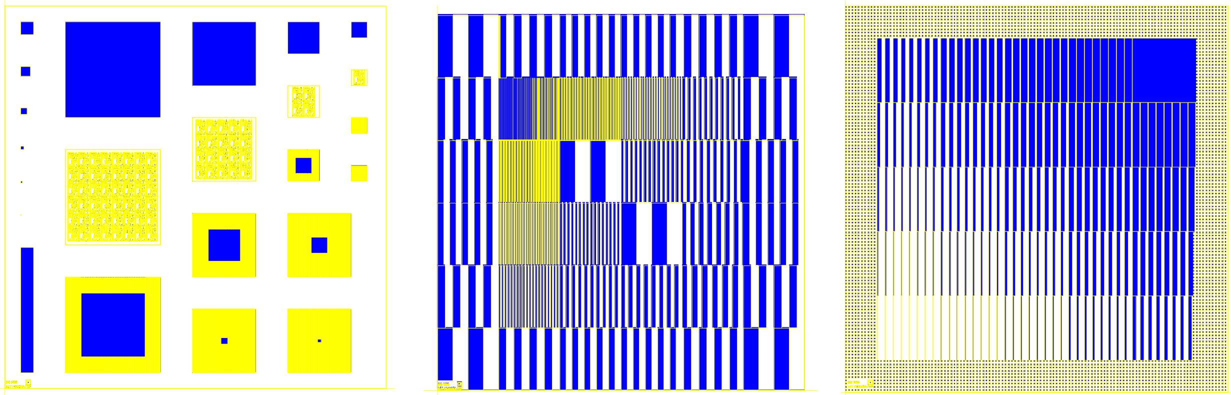
Process	Down force 1 (psi)	Down force 2 (psi)	Down force 3 (psi)	Orbital speed (rpm)
M **(Multstep)**	5	2	2	320
S **(Single step)**	3	-	-	285
(Down force 1 is for step 1, etc.)				

B. CHARACTERIZATION MASK SETS

Figure 2 shows the mask set used in this study. Mask 2a is an area mask that contains structures with varying sizes ranging from 20 µm x 20 µm to 3 mm x 3 mm. Each structure is filled with different patterns such as solid block, 50% density lines, and metal 1 pattern of a conventional adder circuit. Mask 2b is a pitch mask that contains vertical lines with pitch values in the range 2 µm - 1000 µm, at a constant pattern density of 50%. Mask 2c is a density mask with pattern densities in the range 4% - 100%, and a fixed pitch of 250 µm. These masks have an outer dimension of 12 mm x 12 mm, and were designed for physical as opposed to electrical measurements. They have previously been used to study oxide CMP pattern dependencies [2].

C. METROLOGY

We measured copper dishing with the use of a Tencor profilometer (P10), and verified our results with AFM measurements. Oxide erosion, on the other hand, was measured using a Tencor UV1250 optical tool. SEM measurements were done to verify the line width of the copper lines, the width of the oxide spaces, and the oxide thickness measurements done with the UV1250. In order to average out the variation that occurs within the wafer, we measured test structure sites on nine dies on each wafer and averaged these to obtain a single value for each site measurement for use in dishing and erosion analysis and plotting.



a. Area Mask b. Pitch Mask c. Density Mask

Figure 2. Characterization Mask Set

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figs. 3 - 8 show the results of our polishing experiments, where in each plot the values for dishing or erosion are normalized to the maximum values observed. Figure 3a is a sample profilometry scan of a 400 µm pitch line, 50% pattern density structure, while Figure 3b is a scan of an entire 500 µm x 500 µm block with vertical lines of 20 µm pitch and 50% pattern density. We can infer from the short length over which the erosion profile reaches a "steady state" value near the transition region of oxide and copper lines in Figure 3b that the planarization length or the interaction distance (distance over which a pattern parameter is computed) for copper polish is significantly shorter than that observed for conventional oxide polish. The interaction distance in this case seems to be in the order of 50 µm to 100 µm, compared to on the order of 3 mm to 5 mm for conventional oxide polish [2].

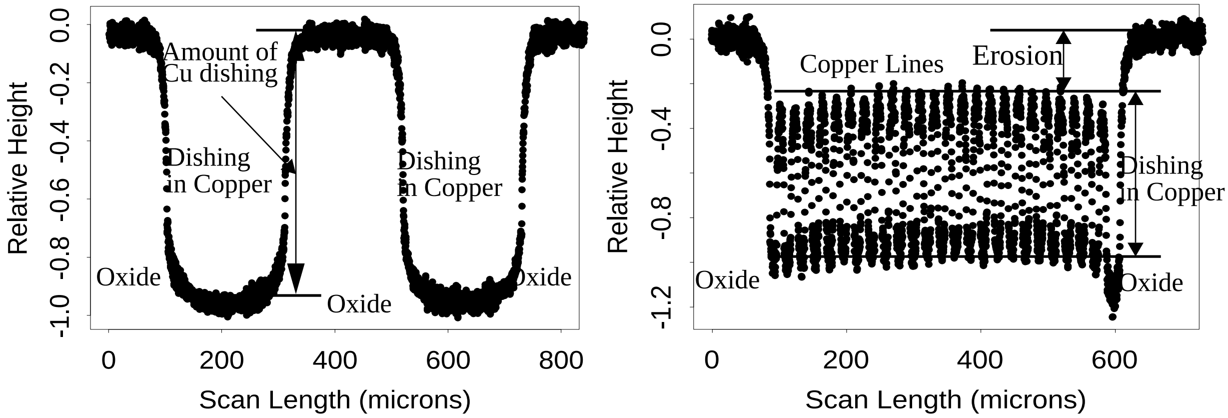
Figure 4a shows a graph of dishing versus solid copper block size, and Figure 5 shows graphs of dishing versus pitch for a constant pattern density of 50% (metal line width equals oxide line space). From these figures, we observe that dishing increases with line width (for a fixed density) as expected [1, 3, 4]. Figure 6 shows graphs of oxide erosion versus pitch for 50% pattern density. It is clear that there is a considerable dependence of erosion on oxide line space for low line space values. This is in agreement with the results presented by Fayolle et al. [3], but different than Steigerwald et al. [1] where oxide line space or pitch dependence of erosion is not observed or explored.

Steigerwald et al. [1] and Fayolle et al. [3] present results which show that oxide erosion increases with pattern density. Figure 7, which shows graphs of oxide erosion versus pattern density for a fixed pitch of 250 µm, confirms their findings. Examining both figures closely, we find that the amount of oxide erosion only becomes significant at higher pattern densities, with a break point occurring at approximately 60% pattern density. This break point corresponds to an oxide line space of 100 µm. We observe a similar break point in the plots of erosion versus pitch for 50% pattern density (Figure 6). As seen from these plots, there is a break point at the pitch of approximately 200 µm (50% pattern density) which again corresponds to an oxide line space of 100 µm.

This interesting break point phenomena can also be seen in Figure 4b which shows a plot of dishing versus pattern density for a fixed pitch of 250 µm. Again as expected, dishing increases with higher pattern density because of an increase in the copper line width. However, the amount of dishing reaches its peak in the 60% - 70% density range (which corresponds to line spaces in the range 100 µm - 75 µm), and suddenly decreases beyond that point. We speculate from these observations that for oxide line spaces greater than approximately 100 µm, the oxide is able to support the physical pressure of pad (i.e. mechanical distribution of the load across the oxide dominates). This break point phenomenon also explains the sudden decrease in dishing in Figure 4b because beyond the break point the oxide is no longer able to support the pad and an accelerated oxide polish occurs, resulting in increased erosion and reduced dishing.

By adding copper dishing to oxide erosion, we get the total amount of copper loss in the trenches. Figure 8 shows the total normalized copper line thickness loss plotted as a function of pitch, for 50% pattern density (that is, when line width and space are each equal to half the pitch). The figure shows that the total normalized copper line thickness loss (and hence the increase in copper resistance caused by dishing and erosion) varies linearly with the logarithm of the pitch, for large pitch structures and a pattern density of 50%.

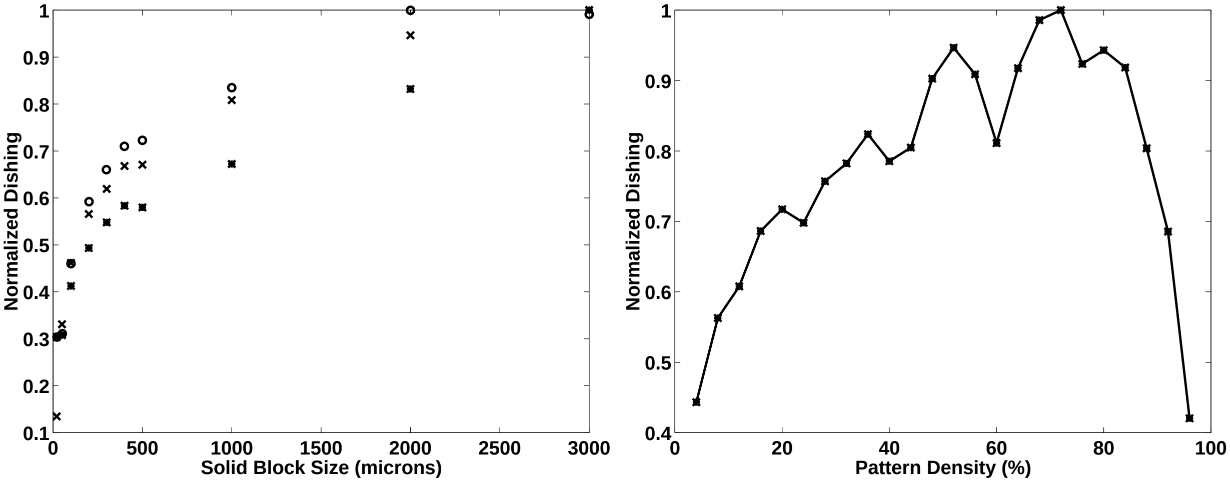
From Figures 4 - 8, we see that the trends in dishing or erosion on pitch or pattern density are similar across all polishing conditions. However, the amount of dishing and erosion depends strongly on the polish settings as manifested by the shift in the curves in Figures 4 - 8 when these parameters change values [5]. This observation is different than reported by Stavreva et al. [6], but we can observe this effect from both polishing experiments. For example, it can be clearly seen from the figures for the polishing experiment #2 that the multistep process results in appreciably better performance than the single step process, and similar dishing and erosion dependence is observed for the polishing experiment #1 where one process setting results in better performance than the other ones.



a. Profilometry scan of a 400μm pitch, 50% density structure.

b. Profilometry scan of a 500μm x 500μm size block from the area mask

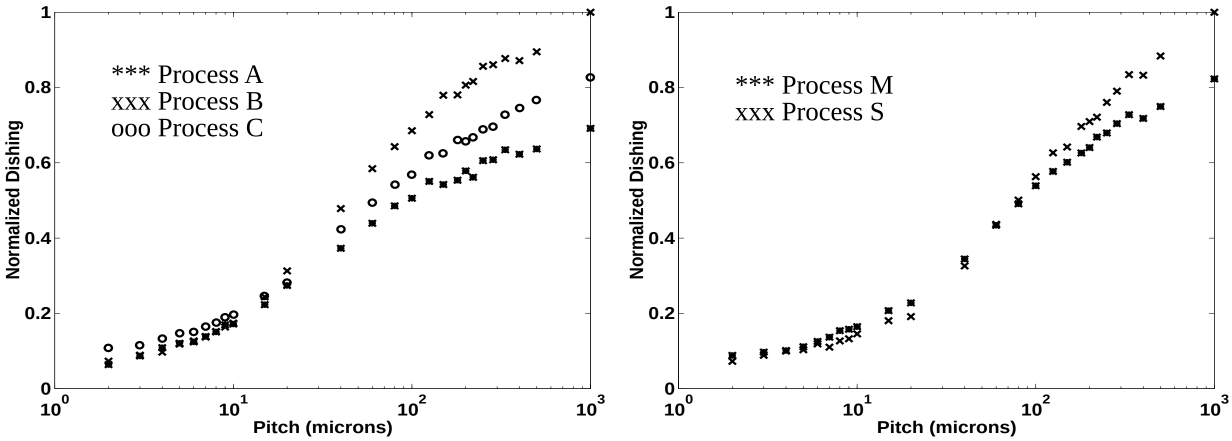
Figure 3. Sample Measurement Traces



a. Copper Dishing vs. Block Size

b. Copper Dishing vs. Pattern Density

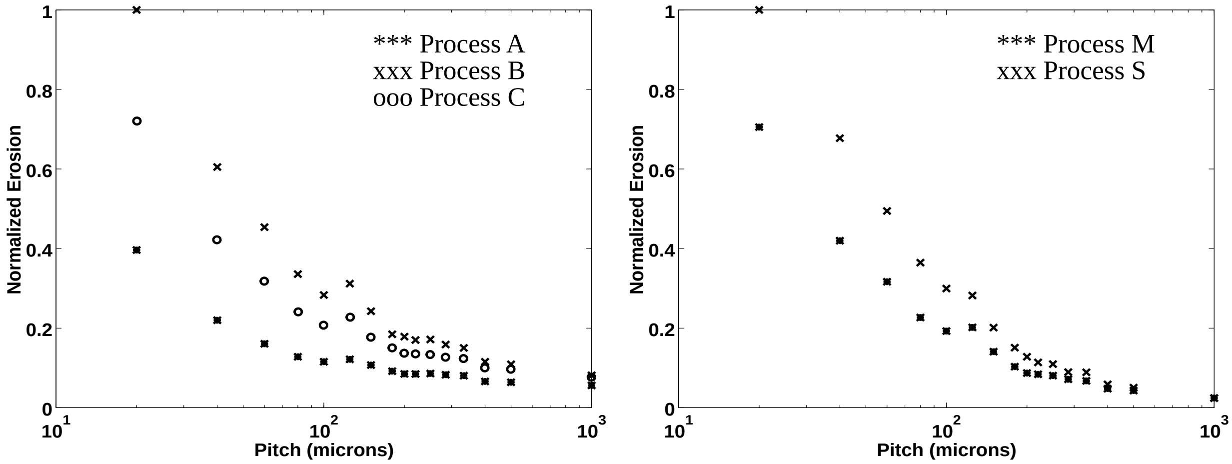
Figure 4. Copper Dishing vs. Block Size and Density



Polishing Experiment #1
(pattern density is 50%)

Polishing Experiment #2
(pattern density is 50%)

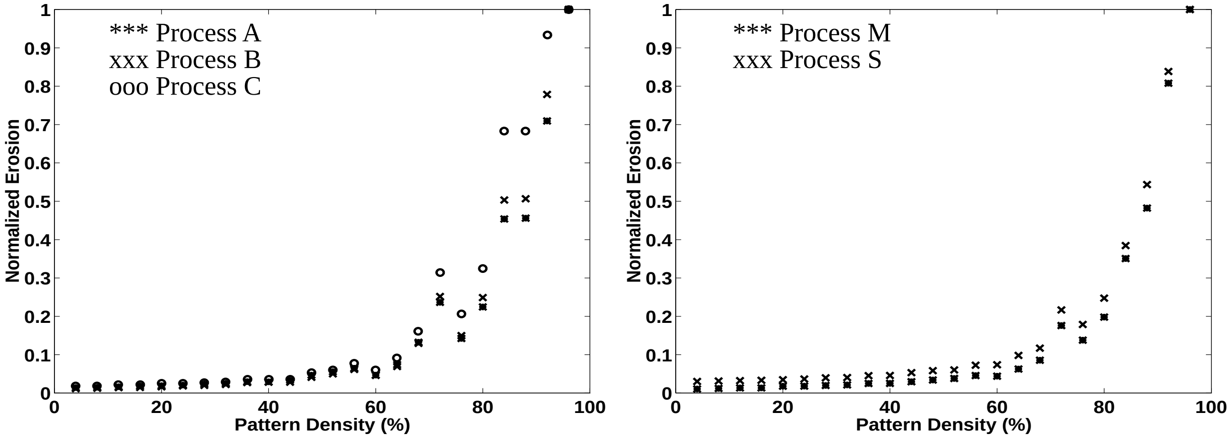
Figure 5. Copper Dishing vs. Pitch



Polishing Experiment #1
(pattern density is 50%)

Polishing Experiment #2
(pattern density is 50%)

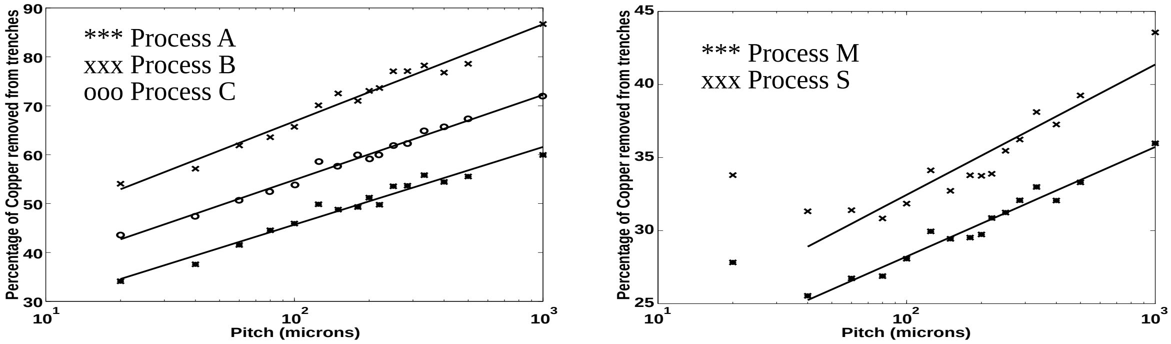
Figure 6. Oxide Erosion vs. Pitch



Polishing Experiment #1
(pitch is 250μm)

Polishing Experiment #2
(pitch is 250μm)

Figure 7. Oxide Erosion vs. Pattern Density



Polishing Experiment #1
(pattern density is 50%)

Polishing Experiment #2
(pattern density is 50%)

Figure 8. Normalized Copper Line Thickness Loss vs. Pitch

IV. CONCLUSION AND FUTURE WORK

In this paper, we have presented copper dishing and oxide erosion characterization in copper CMP for a damascene process. The trends of dishing or erosion with respect to pitch or pattern density are similar for a range of polishing parameters and conditions. However, the degree of copper dishing and oxide erosion depends on both the patterns (pitch and pattern density) and the polishing process parameters (down force, table speed, etc.). We found that a multistep polishing process offers appreciable improvement over a single step process in dishing and erosion performance for the process settings used in this experiment, and a faster throughput is achieved with the multistep polish. Furthermore, our preliminary model fit indicates that the total copper thickness loss caused by combined dishing and erosion varies approximately linearly with the logarithm of pitch for a 50% pattern density structure for large pitch structures. It is also observed that the planarization length or the interaction distance for copper polish is significantly shorter than that observed for conventional oxide polish, and an interesting break point is observed for an oxide line space of approximately 100 µm for both erosion and dishing in both experiments.

Further experiments are in progress to more fully explore the effect of process parameters on these pattern dependencies. In addition, studies are underway to extract dishing and erosion from electrical measurements using a newly designed electrical test mask which includes features at sub-micron dimensions. This mask will enable us to explore issues not apparent with the large features used in this study, study details of the transition region between blanket and dense regions, and explore the break point in polish behavior.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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