MODELING OF PATTERN DEPENDENCIES IN ABRASIVE-FREE COPPER CHEMICAL MECHANICAL POLISHING PROCESSES

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Abstract

We present a density-step-height based pattern dependent model for abrasive-free copper chemical mechanical polishing (CMP) processes, and show comparisons with experimental data. The model uses Hooke's law to establish a mathematical relationship between effective polishing pressure and step height. It uses this dependence together with the empirical relationship between the removal rate and the polishing pressure, to construct removal rate diagrams for the process. From these diagrams, equations for dishing and erosion, as functions of polish time and layout patterns can be derived. We also discuss the limitations of the model, and propose extensions for overcoming them.

Introduction

In conventional copper CMP processes, polymeric polishing pads, and slurries containing silica or alumina abrasives are used. These polishing processes lead to dishing and erosion that can be excessive when significant overpolishing is done [1-3]. To reduce these pattern dependent problems, abrasive-free copper CMP processes are currently being developed, and preliminary results show great promise [4 - 6]. Abrasive-free copper CMP processes use the same polishing pads and polishing machines used in conventional copper CMP processes. However, they use slurries that contain no abrasive particles, unlike those used in conventional copper CMP processes. An example of an abrasive-free slurry is the Hitachi C430-1 [4 - 6].

Abrasive-free copper CMP processes are typically non-Prestonian in nature, with respect to the polishing of copper. This means that the copper removal rate does not vary linearly with the polishing pressure. Hence, all copper CMP models developed on the basis of Preston's equation do not necessarily apply to abrasive-free copper CMP processes. In this paper, we present the first model of pattern dependencies in abrasive-free copper CMP processes.

Copper CMP processes, prestonian or otherwise, comprise three intrinsic stages: bulk copper removal, barrier removal, and overpolishing [1]. The key to modeling abrasive-free copper CMP processes is to first establish a mathematical relationship between removal rate and polishing pressure for a given relative speed, consumable set and slurry flow rate. This relationship is then used together with the Hooke's law based pressure versus step height (or dishing) relationship to construct removal rate diagrams in each intrinsic stage of the polishing process. Removal rate diagrams are plots of removal rates versus step height or dishing. From these diagrams, we can formulate equations for the bulk copper thickness evolution, the bulk copper clearing time, the barrier clearing time, and the amounts of dishing and erosion.

Model Formulation

Intrinsic Stage 1: Bulk Copper Removal Stage

This stage involves the polishing of the overburden copper. We are interested in calculating the copper thickness evolution as well as the time it takes to clear the bulk copper across the die. Figure 1 shows the functional relationship between removal rate and pressure for the polishing of copper, barrier, and oxide, with the use of the Hitachi C430-1 slurry. This relationship depend on relative speed, slurry flow rate, pad type, and concentrations of chemicals in the slurry. Our goal is not to model dependence on these parameters; rather, we empirically characterize and approximate the removal rate as a function of pressure for a given consumable set and CMP process. In this case we find that the polishing of oxide and the barrier material are Prestonian in nature, while that of copper is non-Prestonian. There exists a cutoff pressure p_0 at and below which the copper removal rate is approximately zero, and a breakpoint pressure p_2 at which the slope of the copper removal rate versus pressure curve changes. The applied pressure is p_1 (based on the downforce setting on the CMP tool), and r_1 is the blanket copper removal rate at this pressure.

Figure 2 shows the relationship between the effective polishing pressure and step height. This curve is based on Hooke's law. It indicates that when the initial step height is very large, there is no pressure exerted on the down-area. The pressure on the up-area on the other hand is directly proportional to the applied polishing pressure p_1, and inversely proportional to the effective copper pattern density ρ_{Cu}, at very large step heights. The effective copper pattern density is based on a weighted average of the as-plated copper pattern density, computed over a length-scale called the planarization length [7]. This length is a function of the process parameters such as pressure and relative speed, and the consumables used.

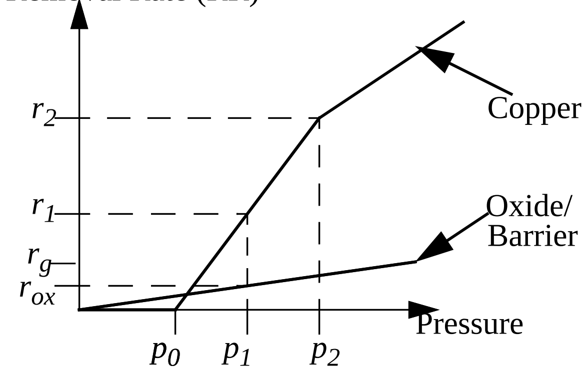

Fig. 1: Removal rate versus pressure for copper, oxide and barrier polish.

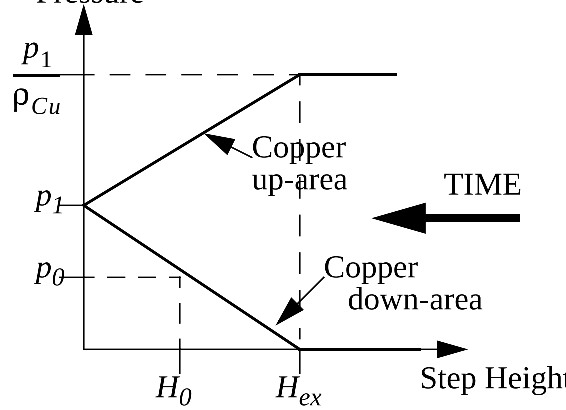

Fig 2: Pressure versus Step Height

As the step height decreases, a critical step height (denoted by H_{ex}) is reached below which the effective pressure exerted on the down-area increases linearly, while that exerted on the up-area decreases linearly. This trend continues until a negligible step height or ideally zero step height at which the pressure exerted on both the down and up areas is equal to the applied polishing pressure p_1. The parameter H_{ex} is a function of line width and line space or pattern density, as well as process parameters. The smaller the line width, the smaller the value of H_{ex}. Figure 3 illustrates the concepts of step height, down-area and up-area.

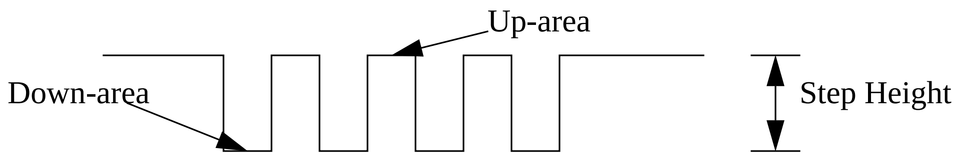

Fig 3: Illustration of step height, down-area and up-area

By combining figures 1 and 2, we can construct the removal rate diagram for the bulk copper polishing stage. This removal rate diagram depends on the magnitude of p_1/ρ_{Cu} compared to p_2. If p_2 is greater than p_1/ρ_{Cu}, the removal rate diagram is that shown in figure 4. Otherwise, the removal rate diagram is shown in figure 5. It is important to observe that the critical step height below which the removal rate of the down-area is non-zero is H_0 as opposed to H_{ex}, which is the critical step height at which the down-area effective pressure becomes zero. This is due to the non-zero cutoff pressure p_0 below which the removal rate is zero. The relationship between H_0 and H_{ex} is given in equation 1. In the case where the CMP process is Prestonian (i.e., $p_0 = 0$, and the slope of the removal rate versus pressure curve remains constant), H_0 is equal to H_{ex} [1]. Furthermore, at H_{ex}, the up-area removal rate is not necessarily equal to the applied polishing pressure divided by the pattern density, as is the case in a purely prestonian copper CMP process [1].

$$H_0 = \left(\frac{p_1 - p_0}{p_1}\right) H_{ex} \qquad \text{Eq. 1}$$

Having $H_0 < H_{ex}$ implies that abrasive-free CMP processes have very high planarization efficiency. Planarization efficiency is defined as one minus the amount removed in the down-area divided by that removed in the up-area. The higher the planarization efficiency of a given process, the faster the step heights are removed, and the easier it is to get a planar surface before the bulk copper is completely cleared (depending on how thick the plated copper is). This could reduce dishing and surface non-uniformity by reducing the amount of overpolishing required.

From the removal rate diagrams shown in figures 4 and 5, we could formulate eqautions for the step height reduction as well as the copper thickness (up and down areas) evolution. These equations can be used to solve for the time it takes to clear the bulk copper at any spatial position of interest, within the die.

Intrinsic Stage 3: Overpolishing

Overpolishing occurs because of wafer level polishing non-uniformities, plating non-uniformity, and pattern differences across a die. Overpolishing leads to dishing, erosion, and surface non-uniformity. Figure 6 shows the relationship between the effective polishing pressure and copper dishing. Because the effective blanket copper removal rate is greater than the effective blanket oxide removal rate, as polishing progresses (assuming that we start from a flat surface), the copper in the trenches recesses below the oxide in the spaces. Hence the copper in the trenches is the down-area, while the oxide in the spaces is the up-area. As polishing progresses and dishing increases, the effective polishing pressure on the copper in the trenches decreases linearly, while

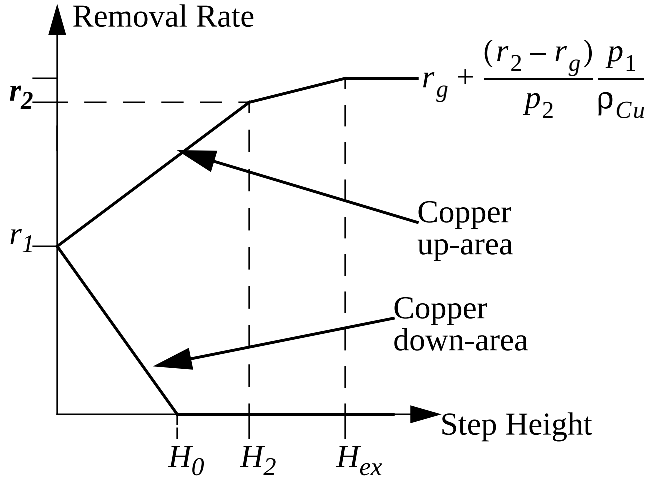

Fig. 4: Removal rate versus Step Height for p_1/ρ_{Cu} greater than or equal to p_2

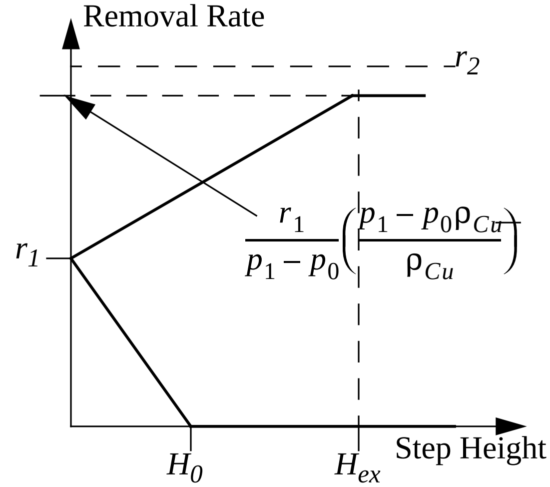

Fig. 5: Removal rate versus Step Height for p_1/ρ_{Cu} less than p_2

that on the oxide in the spaces increases linearly. At a critical dishing denoted by d_{max} (maximum dishing), the pressure on the copper in the trenches becomes zero, while that on the oxide in the spaces peaks at p_1/Φ_{ox}, where p_1 is the applied pressure, and Φ_{ox} is the overpolish stage oxide pattern density. The overpolish stage oxide pattern density is equal to one minus the overpolish stage copper density Φ_{Cu}. It is computed over a much shorter length scale compared to the planarization length used in computing the copper pattern density ρ_{Cu} in intrinsic stage 1.

By combining the pressure versus dishing diagram with the removal rate versus pressure diagram shown in figure 1, we construct the removal rate versus dishing diagram shown in figure 7. We see that when the surface is flat i.e., when there is no dishing, the removal rate of the copper is the effective blanket rate r_1, while that of the oxide is the effective blanket oxide rate r_{ox}. As the polishing progresses, the removal rate of the copper reduces linearly while that of the oxide increases linearly. Ultimately, a steady state dishing (denoted by D_{ss}) is reached at which point the copper and oxide removal rates are equal.

It is important to observe that the dishing at which the copper removal rate becomes zero is d_0, as opposed to d_{max}. This is because of the cutoff pressure p_0 below which the removal rate of copper is zero. The relationship between d_0 and d_{max} is given in equation 2. For a purely Prestonian copper CMP process, d_0 is equal to d_{max}. Having $d_0 < d_{max}$ implies that significantly lesser steady state dishing is obtained for abrasive-free copper CMP processes compared to conventional CMP processes with the comparable process parameters. Also, because of the extremely low effective blanket oxide removal rate, the oxide erosion obtained in abrasive-free copper CMP processes is low, even for extreme overpolishing amounts.

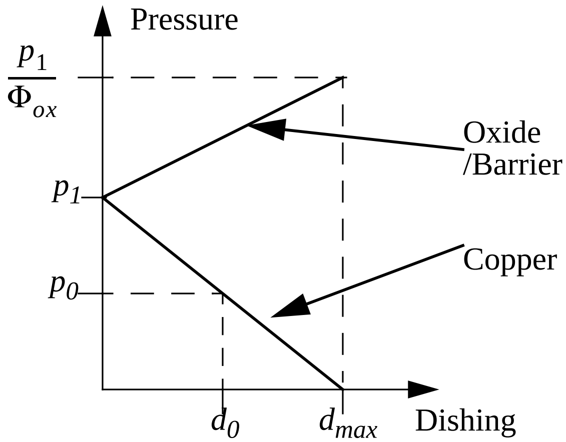

Fig. 6: Pressure versus Dishing

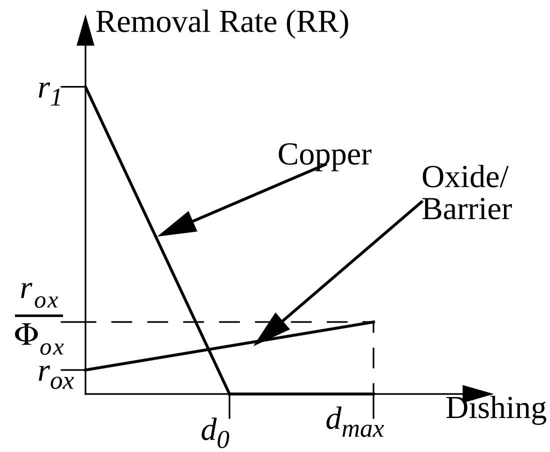

Fig. 7: Removal Rate versus Dishing

$$d_0 = \left(\frac{p_1 - p_0}{p_1}\right) d_{max} \qquad \text{Eq. 2}$$

From the removal rate diagram in figure 7, we can write equations 3 - 4 for the removal rates of copper (RR_{Cu}) and oxide (RR_{ox}), in the overpolish stage. From these equations, we derive the mathematical relationships for dishing (D_{Cu}) and erosion (E_{ox}) as given in equations 5 - 12. The layout pattern dependency of dishing and erosion is contained in the variables d_{max}, and Φ_{Cu}. For abrasive-free copper CMP processes (specifically where the Hitachi C430-1 slurry is used), we find that d_{max} is a function of line width and the overpolish stage copper pattern density Φ_{Cu} ($\Phi_{Cu} = 1 - \Phi_{ox}$). The larger the line width, the higher the value of d_{max}. Also, the higher the copper density, the higher the value of d_{max}. This density dependence is contrary to what is observed in conventional copper CMP processes.

The formulation of the model in the barrier removal stage is similar to that in the overpolishing stage. From the equations of the barrier removal stage, we can solve for the time it takes to clear the barrier, and the dishing that results when we have just cleared the barrier. This dishing is denoted by d_3, and the time to clear the barrier plus that to clear the bulk, at a particular location, is denoted by t_3.

$$RR_{Cu} = \begin{cases} r_1\left(1 - \frac{D_{Cu}}{d_0}\right) & 0 \le D_{Cu} < d_0 \\ 0 & d_0 \le D_{Cu} \le d_{max} \end{cases} \qquad \text{Eq. 3}$$

$$RR_{ox} = r_{ox} + r_{ox}\left(\frac{1 - \Phi_{ox}}{\Phi_{ox}}\right)\frac{D_{Cu}}{d_{max}} \qquad 0 \le D_{Cu} \le d_{max} \qquad \text{Eq. 4}$$

$$\frac{\partial D_{Cu}}{\partial t} = RR_{Cu} - RR_{ox} \qquad \text{Eq. 5}$$

$$\frac{\partial E_{ox}}{\partial t} = RR_{ox} \qquad \text{Eq. 6}$$

$$D_{Cu} = d_3 e^{-\frac{(t-t_3)}{\tau_3}} + D_{ss}\left(1 - e^{-\frac{(t-t_3)}{\tau_3}}\right) \qquad t \geq t_3 \qquad \text{Eq. 7}$$

$$E_{ox} = A(t-t_3) + B\left(e^{-\frac{(t-t_3)}{\tau_3}} - 1\right) \qquad t \geq t_3 \qquad \text{Eq. 8}$$

$$\tau_3 = \frac{d_0 d_{max} \Phi_{ox}}{r_1 d_0 (1-\Phi_{ox}) + r_{ox} d_{max} \Phi_{ox}} \qquad \text{Eq. 9}$$

$$D_{ss} = (r_1 - r_{ox})\tau_3 \qquad \text{Eq. 10}$$

$$A = r_{ox} + \frac{r_{ox}}{d_{max}}\left(\frac{1-\Phi_{ox}}{\Phi_{ox}}\right) D_{ss} \qquad \text{Eq. 11}$$

$$B = \frac{r_{ox}}{d_{max}}\left(\frac{1-\Phi_{ox}}{\Phi_{ox}}\right)(D_{ss} - d_3)\tau_3 \qquad \text{Eq. 12}$$

Experiment

We polish several blanket wafers to study the relationship between removal rate and polishing pressure, for the Hitachi C430-1 slurry. Figure 1 portrays this relationship with p_0 equal to 3.0 psi, and p_2 greater than 6.0 psi. We then polish six wafers patterned with the MIT/SEMATECH 854 mask, for 143 s (end-point time), 152 s, 161 s, 172 s, 203 s, and 262 s respectively, in order to study the pattern dependencies of dishing and erosion, as well as the dependency of dishing and erosion on overpolish time. The polishing pressure is 4.7 psi (i.e., p_1 = 4.7 psi) and the corresponding blanket rate is 5200 A/min (i.e., r_1 = 5200 A/min).

The experimental data show that dishing is a function of time, line width and copper pattern density in the overpolish stage. The larger the line width, the greater the dishing. Also, the greater the copper pattern density in the overpolish stage, the higher the dishing. We conjecture that this density effect is due to the formation of Cu^{2+} ions as a by-product of the Hitachi C430-1 slurry. The higher the copper pattern density, the higher the concentration of Cu^{2+} ions that is formed, which increases the effective copper removal rate and hence causes more dishing. The dishing dependency on pattern density is contrary to what is observed in conventional copper CMP processes.

Figures 8 and 9 illustrate the effect of pattern density on dishing. The figures show profilometry scans for two structures with the same line width, but different pattern densities respectively. Clearly, the higher density structure has more dishing. The pattern density effect on dishing is also seen when one compares the dishing of an isolated line to the dishing of an array of lines having a line width equal to that of the isolated line. The array structure dishes more than the isolated line because the array structure has a higher copper pattern density.

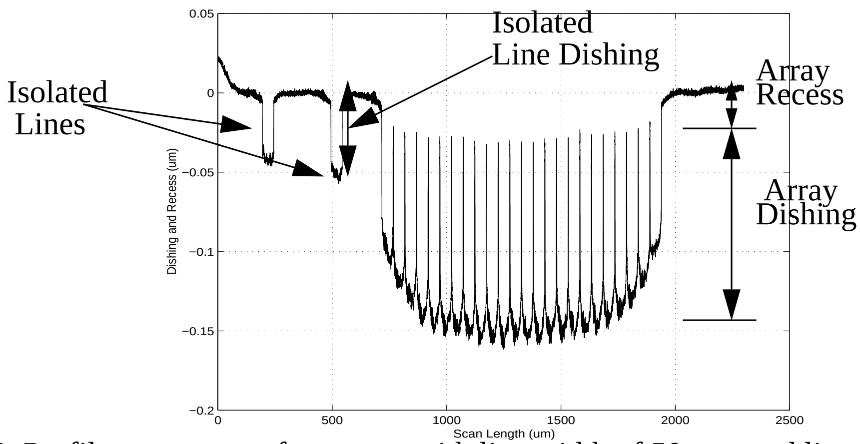

Fig 8: Profilometry scan of structure with line width of 50 μm, and line space of 1 μm

Possible explanations for the line width effect on dishing are the presence of Cu^{2+} ions, and the ease with which the pad can bend into the trench to exert pressure on the copper line. The wider the line, the more Cu^{2+} ions that are formed and the higher the dishing. Figures 9 and 10 show profilometry scans for two structures having the same pattern density but different line widths. The larger line width structure has a somewhat larger dishing.

Oxide erosion is primarily dependent on the overpolish stage oxide or copper pattern density, and the overpolish time. The lower the oxide pattern density (i.e., the higher the copper pattern density), the larger the oxide erosion. Also, the higher the overpolish time, the larger the oxide erosion. However, because the oxide blanket removal rate for abrasive-free copper CMP processes is extremely small, the amount of oxide erosion obtained is very small, even with excessive overpolishing.

Experimental Data versus Modeling Fit

We extracted the modeling parameters for the given process from the experimental data, by minimizing the sum of squared dishing and erosion errors (errors are equal to model prediction minus experimental data). For the overpolish stage, the modeling parameters are r_1, r_{ox}, d_{max}, and the length scale over which to compute the pattern density. We set r_1 = 5200 A/min and

r_{ox} = 13.6 A/min (these values correspond to the blanket copper and oxide removal rates respectively). From the profilometry scans we observe that dishing peaks in a finite region at the center of an array. The size of this finite region remains relatively unchanged for all the arrays. This finite region's size and its distance from the edge of the profilometry scans indicates that for this process, the length over which density in the overpolish stage must be computed is approximately 500 μm.

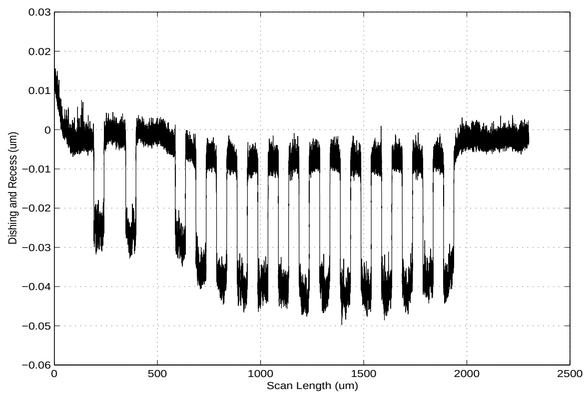

Fig 9: Profilometer scan of structure with line width of 50 μm and line space of 50 μm

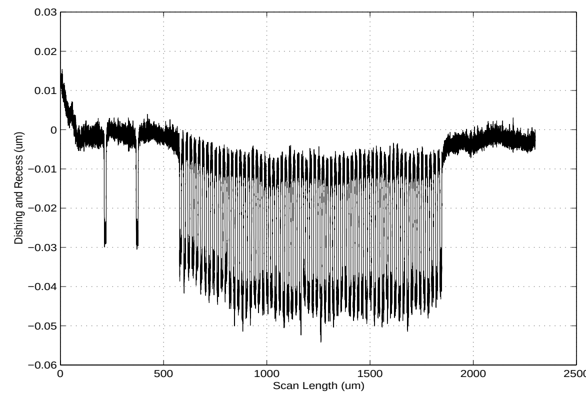

Fig. 10: Profilometer scan of structure with line width of 10 μm and line space of 10 μm

We model d_{max} with the function given in equation 13, and extracted values of 579.63, 0.179, and 0.241 respectively, for the variables A, α_1, and β_1. The variable w in equation 13 denotes line width. The values of the variables t_3 and d_3 in equations 7 and 8 are obtained from the models for the bulk copper removal stage and the barrier removal stage. Because we did not have any experimental data for the bulk copper removal stage and the barrier removal stage, we rewrote the dishing and erosion equations such that the measured dishing and erosion values at end-point time are used as known initial conditions. This means that d_3 is replaced by the dishing at end-point time and t_3 by the end-point time, in equations 7 and 8. In addition, the erosion value at end-point time becomes a new additive constant term in equation 8.

$$d_{max} = Aw^{\alpha_1}\left(\frac{1}{1-\Phi_{Cu}}\right)^{\beta_1} \qquad \text{Eq. 13}$$

Figures 11 - 14 show comparisons between experimental data and modeling fits for the overpolishing stage. The figures show that the model expalins the trends in the data accurately, and also captures the layout pattern dependencies accurately.

Model Limitations

The density-step-height model does not take into account any initial long range thickness differences across the die, in computing the effective polishing pressure. This assumption is flawed, and it becomes problematic when "buttom-up" plating technique is used to electroplate the copper. "Bottom-up" plating introduces severe long range thickness variation across a die because of the different patterns on the die [8]. A sub-micron line width and line space array structure is generally overplated, while a high density array structure is underplated (recessed).

This apparent non-uniformity in copper thickness for the different arrays leads to different initial pressures exerted on the different structures, and these pressures change as the polishing progresses. If this dynamic long range pressure evolution is not taken into account, the copper thickness evolution and the time it takes to clear the bulk copper at a particular location of interest, will be computed incorrectly. To remedy this, we have proposed an integrated contact

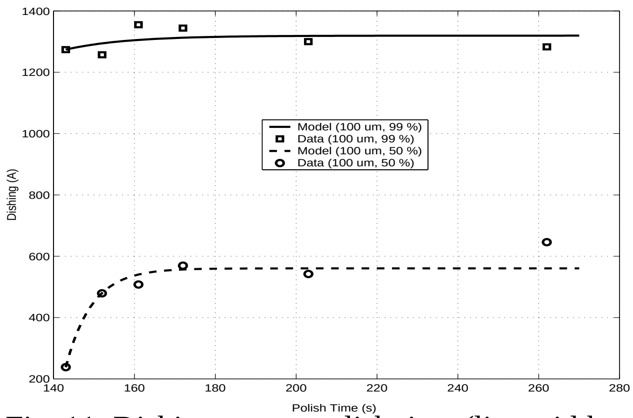

Fig. 11: Dishing versus polish time (line width (in um, copper pattern density in %)

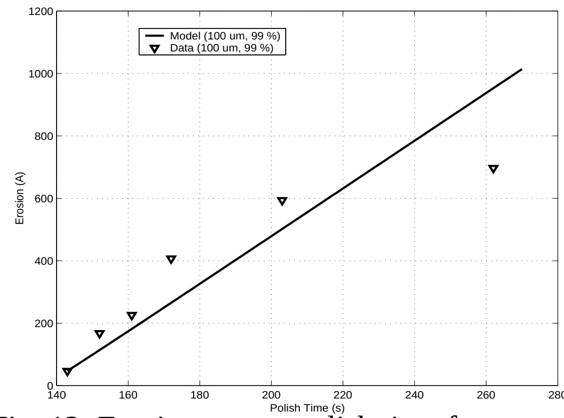

Fig. 12: Erosion versus polish time for structure with 100 um width and 99% Cu density

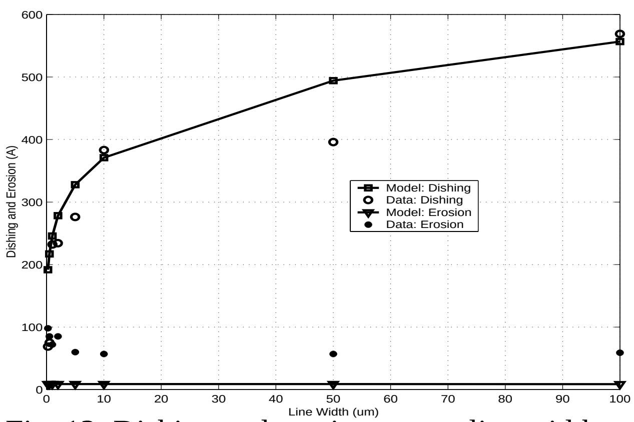

Fig. 13: Dishing and erosion versus line width for 50% density structures (polish time = 172 s)

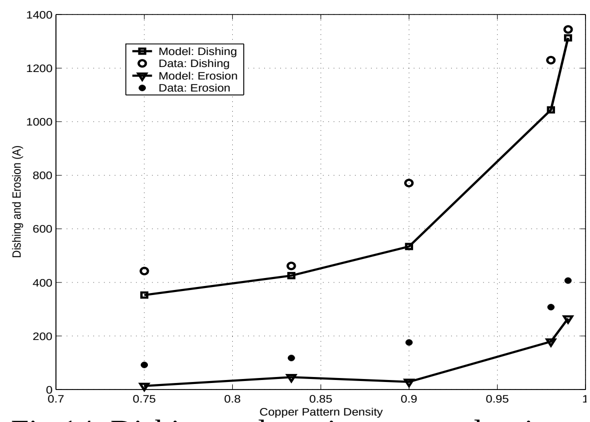

Fig 14: Dishing and erosion versus density (Line space = 1 um; Polish time = 172 s)

mechanics and density-step-height model for CMP processes [9]. The model was formulated for conventional prestonian copper CMP processes, and can easily be generalized to non-Prestonian processes.

The model formulated in this paper is for a single step abrasive-free copper CMP process, where the same pad, slurry, and same polish process settings are used until the bulk copper and barrier material are completely cleared across the die. In a manufacturing setting, a two or three step polish process will be used. In such a case, an abrasive-free slurry might be used in the bulk copper clearing step, while a different kind of abrasive-free slurry or a conventional copper CMP process might be used for the barrier clearing polish step. Our model can be generalized to multi-step processes by constructing removal rate diagrams in the intrinsic stages, for the processes used in the different polish steps [2].

Summary and Conclusion

We have formulated a density-step-height based pattern dependent model for abrasive-free copper CMP processes. The model explains why abrasive-free copper CMP processes tend to have better planarization efficiency during the bulk copper clearing stage, compared to conventional copper CMP processes. It also explains why abrasive free copper CMP processes have lower dishing compared to conventional CMP processes, even when excessive overpolishing is done in the abrasive-free CMP process case.

The model captures the time trend of dishing and erosion as well as their layout pattern dependencies. We have indicated the limitations of the model as formulated in this paper, and have suggested methodologies for overcoming these limitations.

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