Impact of Environmental Temperature on the Performance of Copper CMP Slurries

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Chemical Mechanical Planarization (CMP) has emerged as an enabling technology to planarize metal and dielectric substrates for the fabrication of advanced semiconductor devices [1]. Typical variables in the CMP process include down-force, table-speed, conditioning type and process, slurry type and flow-rate, pad structure type and microstructure. The requirements of a robust CMP process require minimum variation in the consumable characteristics and tool quality. Process temperature defined as the interfacial temperature between pad-wafer and slurry is an important parameter that needs to be characterized in order to achieve repeatability. As the industry is moving towards larger and larger wafer size, this is particularly important.

Process temperature is an important parameter which governs the reaction rate and the physical properties of the slurry hence impacting the CMP results [2]. The friction and the exothermic reactions taking place are the main sources of the temperature rise. The temperature at the pad-wafer-slurry interface plays an important role in the final dishing and the erosion values in the features. This is evident from the fact that an increase in the interfacial temperature would typically favor a faster chemical reaction and hence higher static etch rate [3]. As a result, a larger amount of copper could be dished from the metal lines. High process temperatures also may reduce the life time of CMP consumables such as the polishing pad [4]. Viscosity of the slurry is another key property that is affected by the change in the temperature [5]. Viscosity variations change the rheology of the slurry affecting the slurry flow mechanism at the wafer-pad interface. The local temperature can also affect slurry properties such as pH, concentration of slurry components and mechanical properties of the pad.

In this paper CMP process temperature and its effect on the CMP output variables such as material removal rate, planarization efficiency and dishing have been studied in detail. The effect of the process temperature on the slurry physical properties and in turn on the CMP process has also been investigated in detail. Pad temperature was measured and correlated to the interfacial temperature between the pad and the wafer in this study. First-step Cu slurries with different abrasives have been investigated in this paper.

Experimental details

Slurries employed: First-step Cu slurries with different slurry chemistry/abrasive particle combinations have been employed in this study. The impact of the process temperature in terms of the particle nature has been elucidated in this study. Organic abrasive slurry based on proprietary formulation has been compared with commercially available alumina based slurry.

Testing wafers: 8'' Cu blanket wafers with $15000A^0$ PVD deposited Cu on a stack comprising of $250A^0$ Ta, $5000A^0$ thermal oxide and Si substrate have been used in the investigation. SKW 6-3[6] patterned wafers with $10,500A^0$ electroplated Cu over $1000A^0$ Cu seed layer deposited on SiO_2 trenches $5000A^0$ deep with $250A^0$ Ta as barrier was used. The SKW 6-3 wafers had features ranging from 100 µm to 0.18µm with varying pattern-densities.

Monitoring temperature: Pad temperature on the trailing edge of the carrier was monitored during the polishing process. The pad temperature can be approximated as representative of the interfacial temperature which was difficult to monitor with the available equipment. The temperature readings were obtained using an Infra-red temperature gun. Temperature vs. polishing time were plotted and analyzed for blanket wafers.

Slurry viscosity measurements: The variation of the viscosity of the slurry with the temperature was studied with a traditional viscometer. The viscometer employed for the testing was a Canon-Fenske Routine viscometer which is made of glass.

The time taken for the slurry to traverse between two marked points was noted. The viscosity value is equal to a constant times multiplied by the time. The constant was obtained by measuring the time required by DI water and back calculating the constant from the known value of the viscosity. This method was repeated for different temperatures of slurry. Typically three readings were taken at a particular temperature and the values are averaged to obtain the final values of viscosity.

Blanket wafer polishing: 8'' copper wafers were polished using the slurries mentioned earlier. The thickness on the Cu wafers was measured using the RS-35 resistivity mapping tool whereas. Measurements were carried out on two diametrically perpendicular directions before and after polishing to calculate the material removal rate and the WIWNU. The surface quality of the polished wafers was examined under the Burleigh Horizon Optical profilometer. Wafer polishing was carried out on the Westech 372M wafer polisher and the Strasbaugh n-Hance tools. Temperature-time profiles were compared at different temperature conditions.

Patterned wafer polishing: SKW 6-3 patterned wafers were polished with the slurries discussed earlier. The over-burden Cu was removed in steps until a thickness of $1000A^0$ was left on the wafer. Step-heights, dishing and erosion values were measured using Ambios XP-2 profilometer. Planarization Efficiency (PE) was calculated for the first step of the polishing process. Soft-landing was then employed by reducing the down-force in order to reduce the mechanical component contributing to the dishing and the erosion. The dishing and erosion values were measured on three different dies of the polished patterned wafer in a direction perpendicular to the notch. Wafer polishing was carried out on the Westech 372M polisher and Strasbaugh n-Hance tool employing the IC-1000 pad. Planarization efficiency and final dishing values were compared for the different slurries under different temperature conditions.

Results and Discussion

The temperature-time profile of a typical CMP process is shown in Figure 1. The temperature at the interface rises at a faster rate for the initial part of the process followed by a steadier rise in the later part of the polishing process. The temperature of pad, wafer and slurry increase until the heat generated by friction and chemical reaction exactly balance the heat conveyed by the spent slurry, lot in the air, carrier and platen [7]. As also shown in Figure 1, the initial and final temperature can be regulated by cooling the slurry.

Figure 2 shows another method of temperature control which involved the temperature reduction only for the last quarter of the polishing time. As evident from Figure 2 a steady drop was observed in the interfacial temperature due to the cooling. Both cooling described in Figures 1 and 2 resulted in a decrease of 10-15% in the blanket wafer removal rate which is relatively unimportant in terms of the overall slurry performance. The possibility of reducing the temperature of the interface opens up new avenues to reduce the unwanted topographies such as dishing and erosion commonly introduced due to the CMP process. Careful optimization of the process allows us to maintain the rates and hence not sacrificing the throughput but reducing the dishing by selectively reducing the temperature towards the end of the metal clearing process.

The impact of process temperature on patterned wafer polishing was tested by polishing patterned wafers at identical conditions at two different temperature conditions. Planarization efficiency and final dishing values were compared in both the cases for each of the slurry. The reduction in the processing temperature resulted in opposing effects in case of slurries containing alumina and organic abrasives. The slurry consisting of alumina abrasives resulted in 70% reduction in the final dishing values with almost no reduction in the planarization efficiency values. In case of the organic abrasive slurry the planarization efficiency reduced to half thereby increasing the final dishing values to almost three times the original value. The PE and the final dishing values at the two different temperature conditions have been shown in Figures 3 and 4.

The nature of the abrasive particle seems to be the dominant factor determining the impact of the reduced temperature on the process. Alumina being a harder abrasive promotes the mechanical component in the CMP process. The role of mechanical shearing of the surface complex formed, by the abrasives is more prominent in case of alumina as compared to organic abrasives where the polishing is not mechanically dominant. The elevated temperatures increase the thermal energy of the reacting species thereby favoring a faster reaction rate. This is because the motion of the particles becomes faster increasing the chances of the collision between the interacting particles and molecules. The abrasive particles gain some extra momentum that favors the removal of the reaction by-products much faster than at normal room temperatures. These effects are hence controlled at the lower temperatures.

The increased dishing at the lower temperature polishing in case of the organic abrasive slurry was because the patterned wafer did not achieve planarity during the course of the polishing. The result obtained contradicts the [8] dependency of planarization efficiency only on the ratio between the removal rate to the static etch rate of the slurry.

It is hence clear that the change of temperature affects the physical properties of the slurry which causes the drop in the step-height reduction efficiency. The physical parameter that was studied with the variation of the slurry temperature was the viscosity of the slurry. It is clear from Figure 5 that the viscosity increases with the reduction in the slurry temperature. This clearly suggests that the step-height reduction efficiency is directly affected by the viscosity of the slurry. Viscosity changes the flow mechanism of the polished by-products hence impacting the PE. The increase in the viscosity increases the shear stress to such an extent that it becomes equal at the top and the bottom of the step-height thereby causing the reaction by-products to be removed at an equal rate at the top as well as the bottom areas as mentioned above.

The increase in the viscosity for all the slurries tested was found to be in the same order suggesting the hardness of the particles and the slurry viscosity as two parameters interplaying and determining the PE in the studied case. It is entirely possible that due to the harder nature of the abrasives in case of alumina the abrasive action might disrupt the passivation film formed i.e. breaking the continuity of the film formed at top and bottom areas of the topography. This mechanism if true would help in the maintenance of the high SHRE observed in both the cases of the slurry temperature for alumina. In case of the organic particle the increase in the viscosity might be the parameter that governs the PE at the lower temperature. The increase in the Hershey number[5] with the increasing viscosity might further contribute in preserving the continuity of the film at both the top and bottom areas of the topography not disturbed due to the softer nature and different kind of interaction with the oxidized film in case of the organic particle.

Conclusions

The impact and importance of process temperature in CMP was studied and demonstrated in this paper. It is hence clear that with proper control of the interfacial temperature would help in reduction of the conductor line dishing without sacrificing the throughput. The impact of the processing temperature does not rule out the possibility of dependence on the chemistry of the Cu slurry, since the heat generated during the process is also very much dependent on the slurry chemistry.

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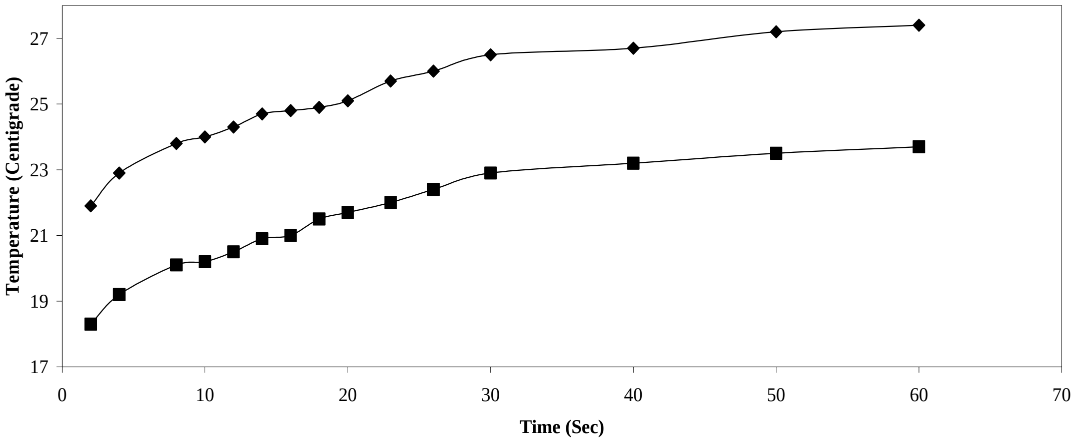

Figure 1. Typical temperature vs. time profile during blanket wafer polishing at room and lower temperature conditions.

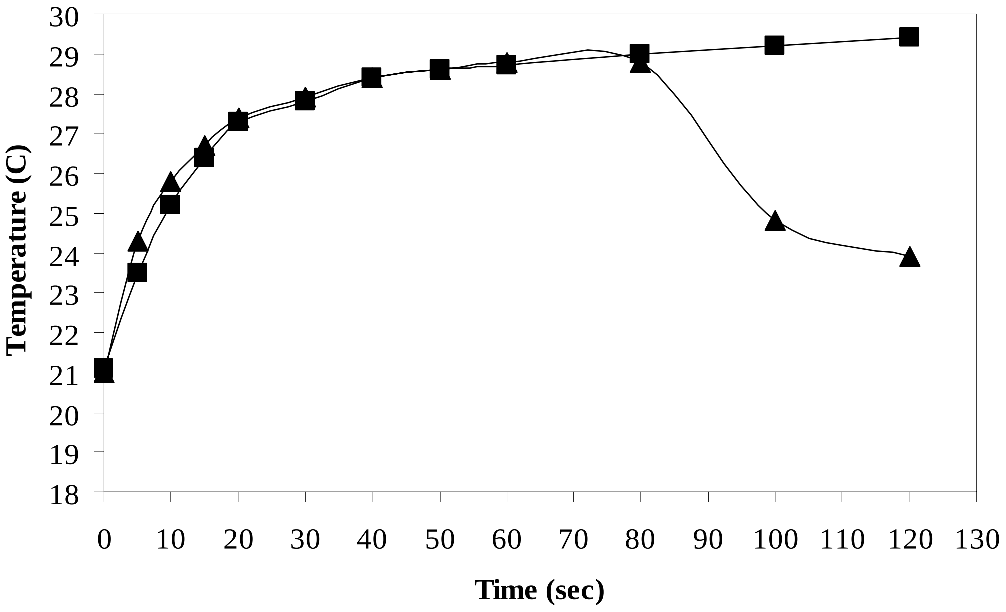

Figure 2. Temperature vs, time profile with an improved cooling process achieving a drop in the interfacial temperature only during the last quarter of the polishing time.

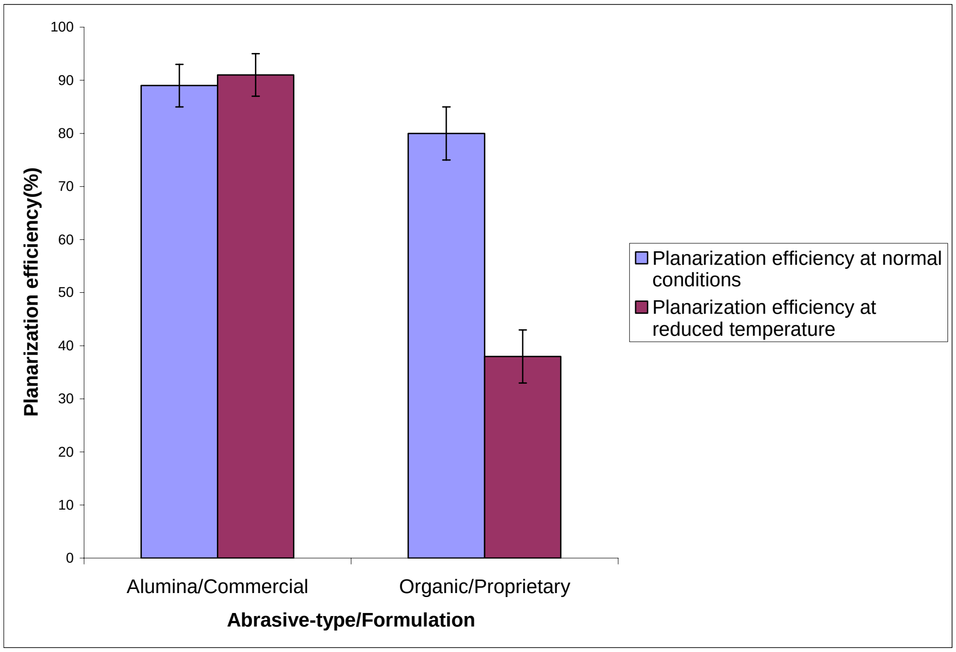

Figure 3: Comparison of PE at different temperature conditions for both the slurries employed.

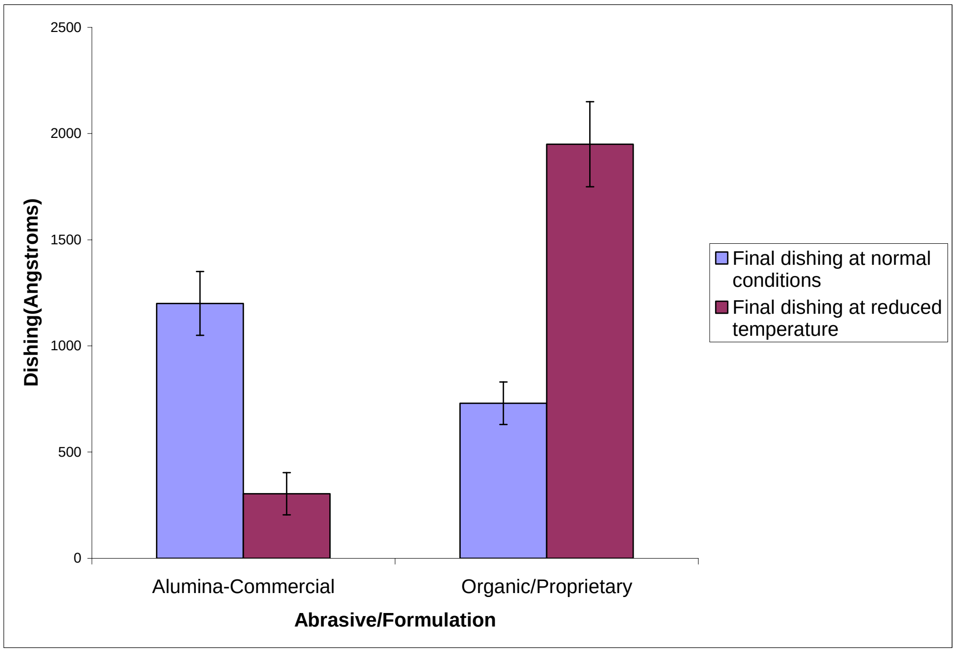

Figure 4. Comparison of final dishing at different temperature conditions for both the slurries employed.

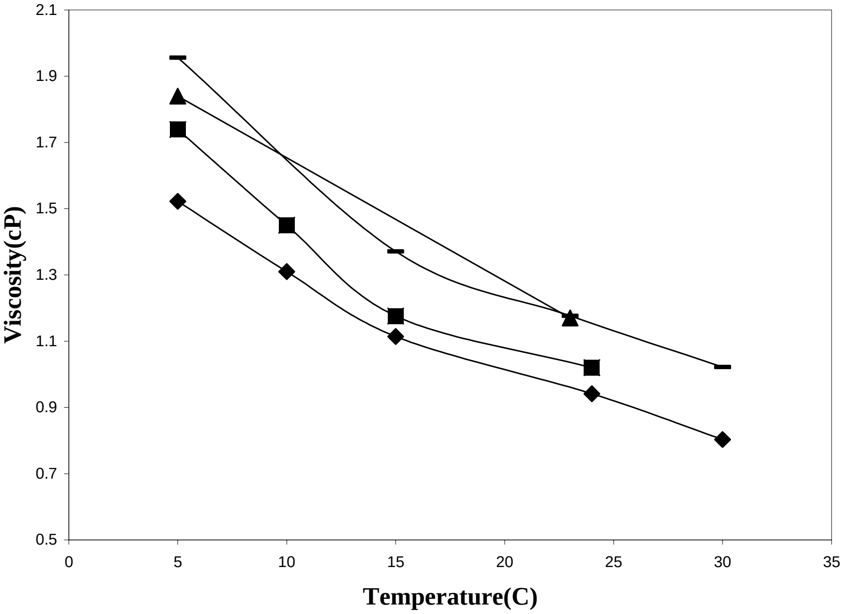

Figure 5.Variation in slurry viscosity with temperature; Data points based on the hyphen symbol denotes the viscosity of organic abrasives based slurry; triangular data points denote the viscosity of silica abrasives based slurry; Square data points denote the viscosity of alumina abrasives based slurry; Diamond data points denote the viscosity of water.