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Analysis of Correlation between Pad Temperature and Asperity Angle in Chemical Mechanical Planarization

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Abstract: Chemical mechanical planarization (CMP) is a technology widely employed in device integration and planarization processes used in semiconductor fabrication. In CMP, the polishing pad plays a key role both mechanically and chemically. The surface of the pad, consisting of asperities and pores, undergoes repeated cycles of glazing induced by polishing followed by the recovery of roughness by a conditioning process applied during CMP. As a polymer material, the pad also experiences thermal expansion from changes in temperature. Such changes can be expressed in terms of surface roughness values, but these do not fully capture the actual changes to the pad surface. In this study, the change in pad temperature occurring during CMP was analyzed with regard to its effect on the asperity angle, and the influence on CMP outcome was assessed. The changes in the surface asperities according to the steady-state pad temperature were evaluated using various measurement methods. The change in pad roughness was characterized in terms of the asperity angle, and the contact state predicted according to temperature were validated by measuring the contact perimeter, the number of contact points, and related values. Through Scanning Electron Microscope (SEM) and micro-CT analysis, it was confirmed that in the continuous polishing process and the conditioning process, the changes in asperity angle due to changes in pad temperature affect the polishing outcome.

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1. Introduction

Chemical mechanical planarization (CMP) has become an essential process in the semiconductor industry, in keeping with the industry's trend toward increased miniaturization and higher integration. The CMP process is carried out by a combination of mechanical and chemical elements for local and global planarization [1–4].

In CMP, material removal occurs as a result of friction between the wafer surface, the polishing pad, and the abrasive particles in the slurry under a chemical reaction caused by the chemical components of the slurry [5]. The polishing pad is one of the most important consumables. It is attached to the bottom plate, and polishing proceeds by the relative pressure caused by contact between the pad and the wafer. For ideal polishing, the pad should maintain uniform and rough contact. This can control the overall pad asperity height, minimize pad deformation, minimize the pad wear rate, and maintain the pad's material properties [6–8].

Pad-related research has long been conducted by many investigators in the field of CMP because the pad has a key influence on polishing patterns and efficiency. Predicting and managing the profile of the pad surface is an important consideration for improving polishing efficiency. John McGrath and Chris Davis [9] reported the correlation between the degeneration of the pad surface and the material removal rate during processing. Li et al. [10] proposed a mathematical model to predict the pad surface shape resulting from diamond disc conditioning. Researchers have also explored the effect of pad temperature changes on pad performance in terms of the pad's material properties. Li et al. [11]

investigated the performance of SiO in CMP as a function of the pad's water soaking time, its conditioning, and its surface temperature. J.C. Yang et al. [12] examined the phenomenon of pad surface hardening at various process temperatures and developed an effective method to minimize changes in the mechanical properties of the pad surface. Although such studies have solved many pad-related challenges, research on the shape of the pad asperity itself is still lacking. Most of the asperity-based material removal rate models assume a simple cylindrical shape. It is true that the shapes of the asperities are quite irregular, and there are aspects that are difficult to consider. However, typical changes that affect the result, such as the angle of the asperities, need to be considered.

In this study, therefore, we investigate how the pad temperature changes that occur during CMP cause changes to the pad surface. Unlike previous works that focused only on changes in the pad surface roughness, this study considers the changes in the pad asperities themselves. This approach is believed to be useful for identifying phenomena that have been difficult to assess using the surface roughness factor alone.

2. Material and Methods

2.1. Polishing Pad

A polishing pad is made of foamed-polyurethane material with a porous structure and is generally constructed in the form of a soft sub-pad and a relatively rigid top pad bonded together. As shown in Figure 1, the entire pad consists of asperities and pores, each of which has a major influence on the polishing outcome. The pad is an important consumable because it performs the role of applying mechanical energy directly to the wafer surface during the rotation action. Because of its porous structure, however, the surface is rough and irregular. Therefore, it is necessary to keep the surface of the top pad, the part that is in direct contact with the wafer, in an optimal state. When the wafer and the pad come into contact during the polishing process, the wafer surface is hard and brittle, whereas the pad is typically of a softer material. Because of this difference in material properties, the pad asperities are worn down by the friction generated during polishing. The worn condition of a pad is indicated by "glazing", and polishing efficiency decreases rapidly after this point is reached. The surface of the glazed pad fails to fulfill its role because the asperities cannot maintain their shape [13,14]. Thus, a way is needed to restore the shape of the asperity surface, and a conditioning process is used to accomplish this. In the conditioning process, the worn pad surface is cut using uniform diamond particles. By this means, the surface is returned to an optimum state for polishing, and polishing efficiency is also increased [15,16].

3D scan image of pad coupon

Figure 1. 3D scan image of pad coupon taken by micro-CT and schematic diagram of pad surface.

2.2. Methods of Pad Surface Characterisation

Physical properties of the polishing pad change according to temperature and undergo thermal deformation [17,18]. However, research on how it expands and changes during

thermal expansion is insufficient. The process for observing the change in the state of the surface with changes in the pad temperature is illustrated in Figure 2. First, a position was precisely marked on the surface of the pad sample to enable the surface to be inspected before and after heating. Then, the pad sample was heated by direct contact with a hot plate. The temperature was increased from 20 °C (room temperature, RT) to 80 °C. The surface was examined with a confocal microscope both before and after heating.

Figure 2. Components and testing stages in examination of pad surface before and after change in temperature.

2.2.1. Confocal Microscope

Characterization of the pad surface using a confocal microscope was preliminarily investigated with a reference pad and several sample pads that were heated from 30 °C to 80 °C. The reproducibility of the change was confirmed by applying the same location and measurement conditions. In general, the change in asperities according to temperature or the abrasion of asperities occurring during the CMP process is strongly related to the surface roughness height factor [19]. Therefore, a comparative analysis was performed on the surface roughness factors, focusing on the values of R_a (arithmetical mean height), R_p (maximum profile peak height), and R_v (maximum profile valley depth). Figure 3a is a set of SEM images showing the changes in the pad surface according to temperature, and Figure 3b is a graph showing the surface roughness results for each heated pad. The pad used in the experiment was performed after applying a short conditioning process to evenly distribute the entire pad surface. In Figure 3a, by comparing the SEM images of the pad heated to 30 °C (room temperature) with those treated with higher temperatures (40–80 °C), it was confirmed that the height distribution changed as the temperature increased, and it was observed that a circular pore shape became apparent at the higher temperatures. In addition, this trend could be confirmed in the measured surface roughness values as shown in Figure 3b. While the change of the pad surface was insignificant in the low-temperature area close to room temperature, the surface roughness values all showed a tendency to increase above a certain temperature (50–60 degrees). Therefore, through this measurement, it could be predicted that the change of the surface according to the pad temperature is the main change in the height distribution of the surface as shown in Figure 3c.

However, given the measurement principles of the confocal microscope, the height distributions established in this way are relative values, and therefore the pore shapes at high temperatures could not be accurately determined. Thus, evaluation using an additional measurement method was deemed essential.

Figure 3. (a) Confocal microscope images, (b) surface roughness values according to steady-state surface temperature of the pad and (c) changes in the pad surface depending on the temperature expected through confocal microscope measurement.

2.2.2. Scanning Electron Microscope (SEM) and Micro-CT

SEM and micro-CT were used to take additional measurements to resolve the uncertainty in the pad surface shape due to the limitations of the confocal microscope for taking measurements. Figure 4a is a set of top-view images taken by SEM, and Figure 4b is a set of cross-sectional images taken by micro-CT. In Figure 4a, the change in the pad surface according to temperature can be clearly seen. At the lower temperatures, it is observed that the asperities on the surface are inclined in a wavelike shape, and there is a space underneath them that is thought to be a pore. At the higher temperatures, on the other hand, the wave-shaped asperities, which were characteristic at the lower temperatures, are not visible, and the pores appear in complete form. From this, it can be inferred that the pores were covered by the conditioning process at low temperatures and were revealed by the change in the shapes of the asperities as the temperature increased. This inference is confirmed by the cross-sectional images taken by micro-CT (Figure 4b). From this cross-sectional observation, it was also possible to know that the asperities occurred with the increase of the pad temperature, and the appearance of the pores was also confirmed. Through this, unlike the change of the pad surface according to the temperature expected in Figure 3c, the actual pad surface was predicted to show a change in which the asperities that were laid out gradually rise as the temperature increases, as shown in Figure 4c. In order to analyze this phenomenon closely, detailed data of the asperity angle and result values such as the contact area and number of contact asperities at the top area were measured.

Figure 4. (a) SEM top-view images, (b) micro-CT cross-section images according to steady-state surface temperature of the pad and (c) changes in the pad surface depending on the temperature expected through SEM and micro-CT measurement.

3. Results

3.1. Micro-CT Analysis of Pad Asperity

Figure 5a shows the average value of the measured angles of the surface asperities at each pad temperature. The average value of each asperity was calculated by connecting the central point of the asperity end and the central point of the asperity support, and the reliability was increased by measuring more than 100 asperities for each pad sample. It was found that the angles of the pad asperities increased linearly as the pad temperature increased. A comparison of the pad surface at 20 °C and at 80 °C shows that the asperity angles differed by a factor of approximately 1.5. The micro-CT cross-section and top-view images in Figure 5a likewise show that there was a difference in the inclination of the asperities. At 20 °C, the asperities were lying almost flat, and there was less contact with the surface. At 60–80 °C, in contrast, the asperities were directed upward, and there were many points of contact with the surface. A comparison of the asperities at 60 °C and 80 °C indicates that the asperity angles at both temperatures were high but the overall distributions of the asperities were different. In contrast to the asperities at 60 °C, those at 80 °C were relatively blunt and concentrated, and multiple asperities fused together to form large asperities.

Figure 5b shows the results of analyzing the measured cross-section and top-view micro-CT images by layer along the Z-axis. Each layer is considered to be the thickness of a 0.9-micrometer pixel; the 10th layer is thus 9 µm from the top. An analysis of the top surface, which makes direct contact during polishing and can affect the actual outcome, found that the perimeter (i.e., the contact perimeter) and the number of contact points (i.e., the number of contacting asperities) both increased at the higher temperatures. These results are believed to show an increase in the contact perimeter value and the number of contacts in the top portion due to an increase in the asperity angle according to temperature. At 80 degrees, it was found that the surface became blunt due to the excessive elevation and the formation of large asperities via the fusion of multiple asperities, as described above. Generally, the contact state of the asperities is closely related to the removal rate in the CMP process [20,21]. is believed to be affected by changes in the asperities' contact states due to the asperity angles, as described in this section, and the experiment was performed to examine this effect.

Figure 5. (a) Micro-CT images (cross section and top view) and data on the surface asperity angles according to pad temperature and (b) the surface asperities' characteristics (perimeter, number of contacts) according to pad temperature.

3.2. Experiment

3.2.1. Experiment Conditions

An experiment was conducted to confirm the effect of the angle change of the surface asperity according to the pad temperature on the material removal rate. The experiment was carried out under two conditions as shown in Table 1.

First, a series of CMP runs, each 1 min long, were carried out continuously without any conditioning process, using fumed silica as the slurry. The purpose of the runs conducted under this first condition was to examine the reduction in material removal rate due to the continuous CMP process performed without conditioning, from the viewpoint of the change in the surface asperity angle rather than from the viewpoint of simple surface roughness. In addition, as can be seen in the schematic diagram of these experimental runs in Figure 6a, an attempt was made to check whether the differences in polishing and angle patterns arise with changes in pad temperature, which were artificially induced by using heated slurry under the same process conditions.

Table 1. Experiment conditions.

CMP Parameters	Conditions [Experiment 1]	Conditions [Experiment 2]
Polisher	Poli-500 [GnP Technology]	Poli-500 [GnP Technology]
Pad (Top/Bottom)	IC/Suba	IC/Suba
Wafer [inch]	8 (SiO ₂)	8 (SiO ₂)
Pressure (Head/Retainer) [psi]	2/3	2/3
Velocity (Head/Platen) [rpm]	93/87	93/87
Pad temperature [°C]	42, 55, 69 (Polishing)	26, 42, 58, 69 (Conditioning)
Polishing time [min]	1 min per 1 cycle	1 min
Conditioning	Ex-situ	Ex-situ

Figure 6. Illustration of (a) continuous CMP process experiment with temperature control (without conditioning) and (b) conditioning effect experiment with temperature control.

Second, for conditioning of the glazed pad, runs were conducted to assess the asperity shape recovery and the removal rate after the conditioning process according to variations in temperature. Conditioning was performed at four temperatures. Details of this second set of runs are given in Table 1 and Figure 6b.

3.2.2. Continuous CMP Runs According to Pad Temperature

As mentioned in the introduction section, the asperities of the pad induce direct contact between the slurry particles and the wafer, and the pores increase the flow of the slurry and act as a trap to store the polishing residue. Especially in the oxide CMP, since the oxide film can be removed by mechanical contact compared to the chemical effect, the asperities and pores developed on the pad surface act advantageously and enhance the Material removal rate (MRR) [22]. In this study, in order to investigate these phenomena more clearly, the change in the angle of the asperities according to the temperature during the CMP process was observed.

A series of CMP experiments, each for 1 min, were performed continuously with fumed silica slurry on a break-in pad without conditioning process, as shown in Figure 7a. It could be observed that the removal rate gradually decreased as the CMP process progressed under three pad temperature conditions. The removal rate considered to be additionally necessary for the conditioning process was set to 140 nm/min. After certain runs (42 °C, 5th run; 55 °C, 12th run; 69 °C, 18th run), the removal rate tended to be very low. Even within these trends, when the pad temperature was high during this CMP process, the removal rate was higher, and the reduction rate of the removal rate was low relative to that at the lower temperatures. In addition, when the removal rate in the range of 140 nm was obtained for each condition, the conditioning process was performed, and it was confirmed that the removal rate and the asperity angle were recovered. From Figure 7b, it can be seen that the pattern of the asperity angle at this time is similar to the pattern of the removal rate. Thus, this investigation of the relationship among pad temperature, removal rate, and asperity angle found that the tendency for the asperity angle to increase has a positive effect on the contact with the wafer and further influences the MRR.

Figure 7. (a) Material removal rate trend and (b) the angles of the asperities according to the pad temperature during a continuous CMP polishing process without a conditioning process.

Figure 8 shows SEM images of the pad surface after the CMP process at three pad temperatures. For each temperature, it can be seen that the asperity angle was somewhat increased on the pad surface in the initial CMP run. Similar to the asperity angle results in Figure 7b, the pad surface image also showed an elevated asperity angle at high temperatures. At lower temperatures, however, the asperities were inclined and pressed for a relatively short time, whereas at the higher temperatures, the asperity angle was maintained for a longer run time, and pores remained even in the state in which the pad was glazed. It can be inferred that this is because at low temperatures, the asperities are simply subjected to pressure, whereas at higher temperatures, they are subjected to pressure and at the same time the angle is increased, and pores at the bottom are exposed. The increase in pores that was seen during high-temperature polishing causes an increase in the slurry flow and traps a large amount of the residue that is created during polishing. Therefore, this experiment found that an increase in asperity angle and an increase in pore formation at high temperatures may increase the polishing rate and delay pad wear.

Figure 8. Pad surface SEM images of pad surface according to pad temperature in a continuous CMP polishing process without a conditioning process.

The schematic of asperity change on the pad surface in a continuous polishing process can be represented as shown in Figure 9. In the polishing process, the pad is pressed by the polishing load. In this case, when polishing at a relatively low temperature, the effect of increasing the angle of the asperity due to the pad temperature is insignificant, and as a result, only the effect of the asperity being pressed by polishing load occurs. However, during high-temperature polishing, the pad asperity angle increases along with the wafer pressurization, so that the asperity angle decreases slowly, and a large number of pores remain on the surface even when glazed.

Figure 9. Schematic images of the change of the asperity angle according to the pad surface temperature during continuous CMP without conditioning.

3.2.3. Conditioning Effects According to Pad Temperature

Figure 10a shows the results regarding the increase in the material removal rate according to the temperature during the conditioning process. The experiment used pads that underwent long-term polishing and glazing without a conditioning process. To set the temperatures of the pads during conditioning at 4 levels (26, 42, 58, and 69 degrees) deionized water at suitable temperatures was provided. Temperature errors of 1–2 degrees occurred at each temperature during processing. In each case, when the polishing process was performed directly after conditioning, it was found that the material removal rate increased proportionally as the pad temperature increased during conditioning [23]. The highest material removal rate increase occurred at 58 °C and trended downward at 69 °C. Figure 10b shows a graph of the asperity angles at each pad temperature. As with the increase in the material removal rate, the asperity angles likewise increased linearly in proportion to the temperature. Thus, it was found that the asperity angles changed according to the pad temperature in the conditioning process as well, and this may have a positive effect on restoring the material removal rate of worn pads. However, at excessively high temperatures such as 69 °C, the material removal rate decreased regardless of the angles of the asperities. This is believed to be caused by the increase in pad residue that occurs during high-temperature conditioning and the resultant clogging of the pores.

Figure 10. (a) Increase amount of material removal rate and (b) asperity angle according to pad temperature during the conditioning process.

To confirm that the asperity angles had genuinely changed, various methods of measurement were used to establish the reliability of the findings, with the results as shown in Figures 11 and 12. Figure 11 shows SEM images of the pad surface when one cycle of the CMP process was performed immediately after conditioning at different pad temperatures. When polishing was performed continuously without conditioning and the pad became worn, the surface was so flat that it was difficult to distinguish the shapes of asperities and pores. As the conditioning process progressed, the surface became rough, and the contours of the asperities were seen. In low-temperature conditioning, it was found that the asperities were highly inclined. In addition, the pores were not perfectly spherical, and they were hidden by the asperities. As the pad temperature increased, however, it was found that the asperity angles also increased. By looking at the front face, it was found that there were definite asperities and that the pores formed perfect spheres.

Figure 11. SEM images of pad surface according to pad temperature during the conditioning process (captured immediately after one cycle of the polishing process at four temperatures: 26, 42, 58, and 69 °C).

Figure 12. Micro-CT surface and cross section measurements examining asperity angles and pore exposure after low and high temperature conditioning processes.

Figure 12 is a image showing the surface roughness for each process condition using a micro-CT measurement. This results also show similar phenomenon. It shows the results of using a micro CT to examine the surface and cross-section shapes when different conditioning temperatures were applied to the same pad. At the lower temperature (26 °C), most of the pores are blocked by asperities, but at the higher temperature (69 °C), the shapes of the pores are clearly seen. In addition, the contact surface profile measurement device was used to examine surface characteristics according to the angles of the asperities.

The asperity change on the pad surface in conditioning process according to pad temperature can be represented as shown in Figure 13. The conditioning process is a cutting process to restore the surface roughness of the glazed pad. The conditioning process at a relatively low temperature only generates a cutting effect without the effect of increasing the pad asperity angle. On the other hand, in the conditioning process at a high temperature, a synergistic effect of the pad asperity angle occurs when the surface is cut by diamond particles. Due to this, the pad surface has a rougher and sharper shape, and eventually the material removal rate at this time is higher.

Figure 13. Schematic images of the change of the asperity angle according to the pad surface temperature during conditioning process.

4. Conclusions

A new perspective on the change in the angles of pad surface asperities occurring during the CMP process has been proposed in this paper. Experiments were performed to clarify the relationship between the temperature of the pad surface and the asperity angle. It was found that as the pad surface temperature increases, the surface becomes rough and the pad topography changes. Through micro-CT and SEM, it was determined that pad asperities are nearly flat at lower temperatures and become vertical at higher temperatures. It was also ascertained that the change in asperity angle affects the contact area, the contact perimeter, and the number of asperities in contact. Patterns in the polishing rate and the behavior of the asperity angle during continuous polishing without any conditioning were characterized according to the pad temperature. When higher temperatures are maintained, the reduction in polishing rate and the change in asperity angle are slowed, which has a beneficial effect on the conditioning process interval and polishing efficiency. During conditioning, the surface result differs according to the pad temperature under the same conditions. The asperity angle recovery rate is proportional to the pad temperature, and the polishing recovery rate is also proportional.

Thus, this study determined that changes in the pad asperity angles play an important role in the mechanical aspects of the CMP process. It is true that the CMP process involves many factors, which interact in a complex manner, and there are many behaviors that cannot be evaluated solely in terms of asperity angles. Nevertheless, it is believed that better conclusions can be drawn by considering the angles of asperities in mathematical planarization models, simulation problems, and research on managing and predicting pad shapes.

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