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Tribological Approaches to Material Removal Rate during Chemical Mechanical Polishing

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In this study, the effect of the friction and wear of a polishing pad on the material removal rate of a silicon oxide wafer was investigated during chemical mechanical polishing (CMP) with ceria slurry. Further, the effect of surface properties of the polishing pad, such as surface roughness and hardness, on the variation in the material removal rate was examined. From a tribological viewpoint, the in-situ friction force was monitored during the CMP process, and wear of the polishing pad was controlled by different types of conditioners. After CMP, the pad surface roughness was measured by optical profiling and scanning electron microscopy. Experimental results showed that the material removal rate was almost linearly proportional to the friction force between the pad and the wafer surface, irrespective of the properties of the pad. Experiments on the dependency of the pad wear rate on the material removal rate showed that the material removal rate increased with a decrease in the pad wear rate. Experiments and pad characterization confirmed that such a correlation was attributed to the pad surface roughness and the friction force.

Key words: semiconductor, defect, surface, wear, chemical mechanical polishing (CMP)

1. INTRODUCTION

Currently, chemical mechanical polishing (CMP) is a commonly used technique in integrated circuit (IC) fabrication because only CMP can provide both local and global planarization of a wafer, and its usage has dramatically increased since IBM first launched the CMP process in semiconductor industries [1]. During semiconductor processing, the etching-deposition process produces an irregular surface with step height, and for the subsequent patterning by photolithography, the wafer surface should be planarized to meet the depth of focus (DOF) requirements. Further, with a reduction in the size of the device node, a flatter surface is required. As the device shrinkage is close to the resolution limit of photolithography, studies on the fabrication of a 3D stacked device have become more popular and attract considerable attention in the IC industries. CMP is one of the key processes for fabricating a stack structure. Moreover, wafer scale bonding technology, which is an emerging process for the next generation packaging like Through Silicon Via (TSV) [2], requires optimal CMP performance too [3-4]. Therefore, the usage of CMP has increased considerably. In order to satisfy the various requirements for the fabrication of advanced device structures by CMP, fundamentals of the CMP process should be well understood. All the parameters that govern the CMP performance, such as material removal rate, selectivity, planarity, and defects are closely related, and therefore, it is very difficult to achieve an overall understanding of the CMP process.

The CMP process is basically a tribochemical reaction [5-8] that involves friction, wear, lubrication, and their interplay, all of which are included in tribology. The very basic mechanism of CMP is that a chemically softened surface is removed by mechanical contact with abrasive particles. However, it is a much more complex process that is not controlled merely by chemical-mechanical reactions. A schematic of a CMP polisher is shown in Fig. 1. The details of the CMP process are as follows. During CMP, the rotating wafer presses against the rotating polishing pad and slurry is supplied to the pad through a supply system. The polishing pad is conditioned during CMP with a conditioner having many small diamond grits in order to refresh the pad surface to maintain CMP performance [1,5,7]. The wafer surface reacts with the chemical slurry and is softened so that the material can be easily removed by the mechanical action of the abrasive particles in the slurry; these chemical-mechanical processes occur simultaneously [1]. The combined effect of the chemical reaction and the mechanical abrasion results in the removal of a considerably larger amount

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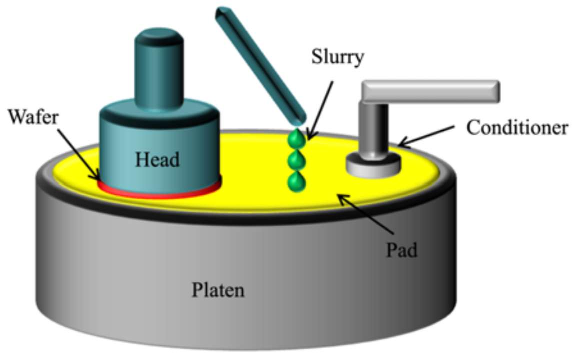


Fig. 1. Schematic of the CMP polisher used in the experiment.

of material than that in other etching processes. Chemical etching or mechanical abrasion alone cannot achieve such a high material removal rate.

In this study, the effect of friction and wear of the polishing pad on the material removal rate is intensively investigated. Each tribological event is considered separately. Moreover, this study covers only the dielectric CMP process.

2. EXPERIMENTAL PROCEDURES

The CMP experiments were conducted using a GNP Poli-762 polisher (G&P Technology Inc., Korea). The Poli-762 polisher has a piezoelectric sensor that can measure the in-situ friction force between the pad surface (asperities) and the wafer surface during CMP. The piezoelectric sensor detects the strain induced by the polishing, and the strain is converted to an amplified electric signal. The output voltage represents the friction force. The details of the experimental conditions are as follows: the carrier (head)/platen velocity is 113 rpm/120 rpm, the carrier down pressure is 3.8 psi, and the slurry flow rate is 200 ml/min. A 12-in blanket wafer deposited with thermally grown tetraethyl orthosilicate (TEOS) oxide was used for the experiments. The material removal rate was obtained by thickness measurement of the TEOS blanket wafer before and after CMP using the ST-5000 tool from K-MAC Corporation, Korea, which uses a 12 V, 100 W halogen lamp as the reflectometer. Ceria-based slurry was used in the experiments. Different types of polishing pads were used in order to investigate the effects of the friction force on the material removal rate and the surface changes. The properties of each polishing pad are listed in Table 1. Pad wear was controlled by adopting different conditioners with different diamond grades. A low-grade conditioner contains rough diamonds, whereas a high-grade conditioner contains diamonds with smooth edges. Polishing pads, conditioners, and slurry were provided by vendors of CMP consumables. Before wafer polishing, pad break-in was carried out with deionized (DI) water for 15 min, and 19 dummy wafers were used to obtain the rough pad

Table 1. Properties of polishing pads

Pad	Relative Hardness	Pore Size (μm)	Groove Type	Friction Force (kgf)
(A)	1	55	XY	73
(B)	1	29	Concentric Circular	67.5
(C)	0.754386	26		76
(D)	0.45614	70		93
(E)	1.157895	15		39
(F)	0.947368	50		68.5

surface. After the CMP tests, the polishing pad surface was examined using WYKO NT1100, a noncontact optical profiler, from Veeco Instruments. Samples of the pad were obtained by cutting the pad surface, and an area of 1.2 mm × 1.0 mm was scanned using the optical profiler for the measurement of surface roughness.

3. RESULTS AND DISCUSSION

The friction force between the polishing pad and the wafer surface was monitored when the TEOS blanket wafer was polished for 1 min using Poli-762. The friction force originated from the wafer-pad direct contact, and therefore, it is strongly influenced by pad surface morphology. The behaviors of the material removal rate with respect to the hardness of the pad and the friction force are shown in Figs. 2 and 3, respectively. In Table 1, the friction forces of each polishing pad are given as well. The polishing conditions are described in the above chapter in detail and the experimental conditions are the same for all data points. Although the pads were obtained from different vendors and their properties differ from each other, the material removal rate is inversely proportional to the hardness of the pad and directly proportional to the friction force, irrespective of the physical properties of each pad, as shown in each figure. In terms of the hardness effect, a hard pad is known to be favorable for material removal rate in the silicon oxide CMP process because

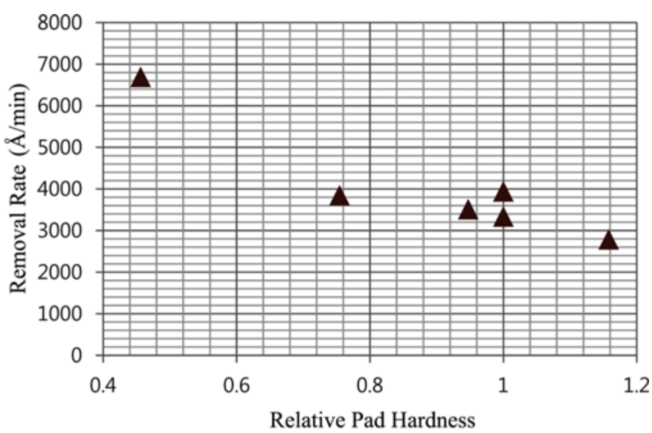


Fig. 2. Removal rate as a function of pad hardness.

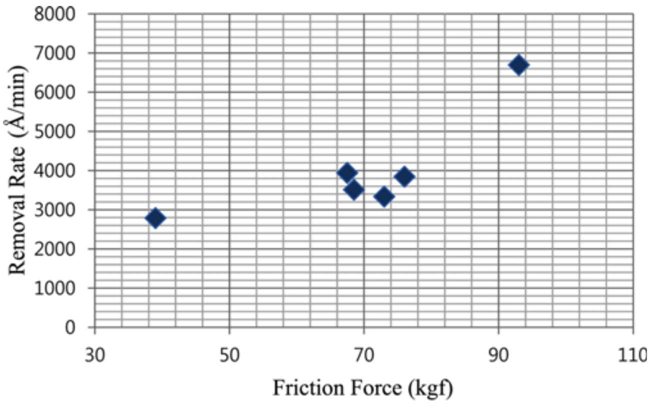


Fig. 3. Removal rate as a function of the friction force between the pad asperity and the wafer surface.

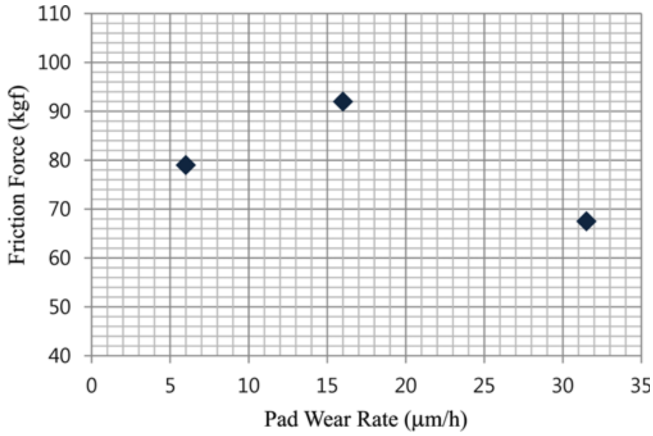


Fig. 4. Friction force as a function of pad wear rate.

of the high contact pressure applied to the wafer surface, as predicted by Preston's equation [1].

However, particularly for the ceria CMP process, silicon oxide is removed by the strong bonding of Ce-O-Si at the wafer surface [9-10] and the lump of silicon oxide attached to ceria particles is removed: this removal is not governed soley by Preston's rule. Therefore, the interplay between the pad contact area, interaction of the particles with the oxide, and friction force is used to determine the material removal rate. This interplay indicates that from the viewpoint of pad contact, a soft pad is possibly more likely to increase the removal rate because its asperity can easily be deformed. Therefore, the combined or competitive effect of these two aspects (contact pressure and contact ratio) determines the material removal rate when ceria slurry is used.

Figure 2 shows the effect of the implementation of a soft pad on the material removal rate. The dynamic contact can be represented by the in-situ friction force, and the results shown in Figs. 2 and 3 indicate that the TEOS removal rate is more dominantly controlled by friction force than the high contact pressure. In the current experiments, depending on the pads, the friction forces were in the range of 30–100 kgf. From the CMP mechanism, it is known that a high friction force enhances the chemical reaction by increasing temperature and that it also boosts mechanical abrasion, which leads to high material removal. However, in this experiment, temperature increase had no pronounced relationship with the material removal rate.

The effect of the pad wear rate on the material removal rate was investigated. The result of the pad wear rate is shown as a function of the friction force in Fig. 4. The pad wear rate was obtained by measuring the pad thickness before and after CMP, and the pad wear rate was controlled by the conditioners. The conditioners used in the experiment are introduced in Table 2. In order to prevent inaccuracies of the conditioner geometry on the pad wear rate and the material removal rate, only the diamond grade of the conditioners was set as a variable. As can be observed from the result of Fig. 4, the pad wear rate is inversely proportional to the friction force between the pad and the wafer surface. This is attributed to the pad surface characteristics during CMP. During CMP, the friction force increases with an increase in the asperity contact (or contact ratio), and a repeated polishing condition smoothens the pad surface. Therefore, mild conditioning enhances the friction force but reduces the pad wear rate. The pad surface roughness with respect to the pad wear rate, which is consistent with the relation between the friction force and the pad wear rate described earlier, and the results of the investigation of the pad wear effect on the material removal rate are summarized in Fig. 5. As shown in Fig. 5, the material removal rate is inversely proportional to the pad wear rate, which is attributed to the pad surface degradation (or refreshment), as shown in the plot of the friction force against the pad wear rate in Fig. 4.

Table 2. Conditioner grades and pad wear rates

Conditioner	Diamond Grade [12]	Pad Wear Rate (μm/h)
A	MBG640	31.5
B	MBG650	16
C	MBG660	9

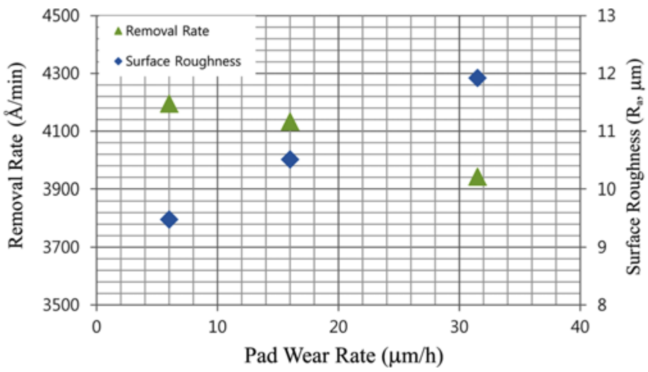
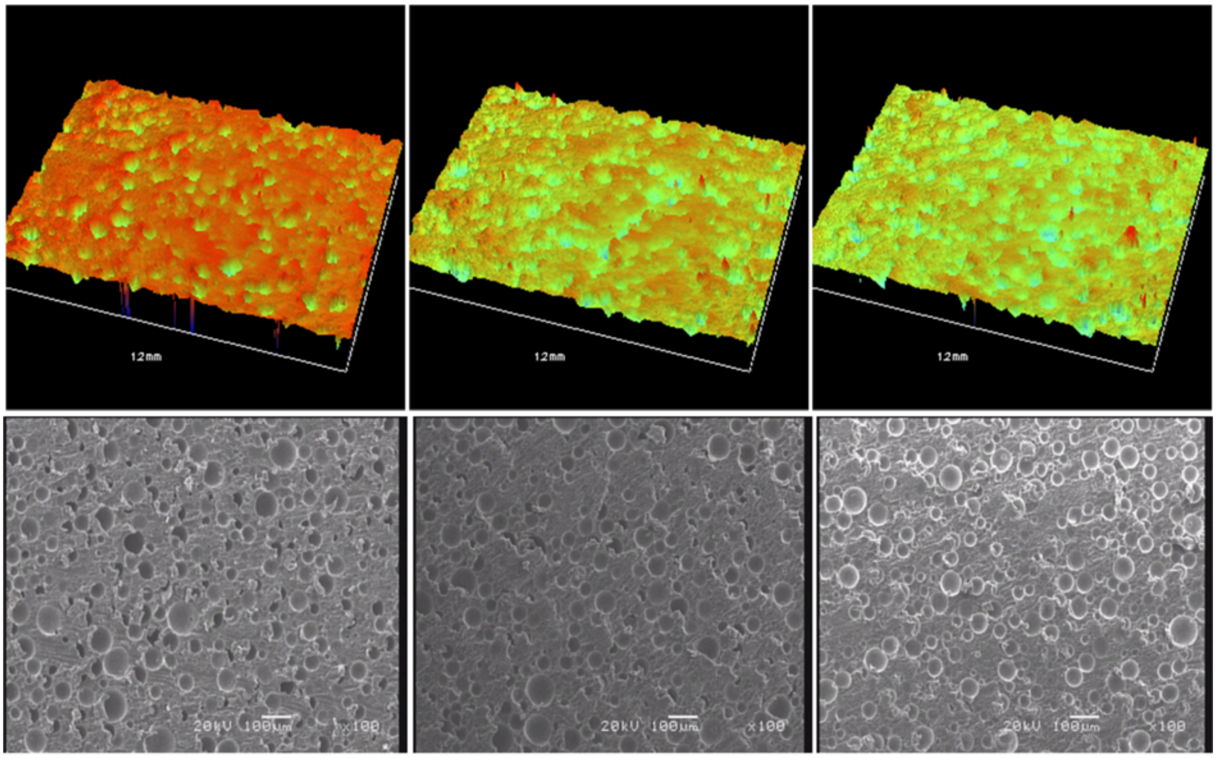
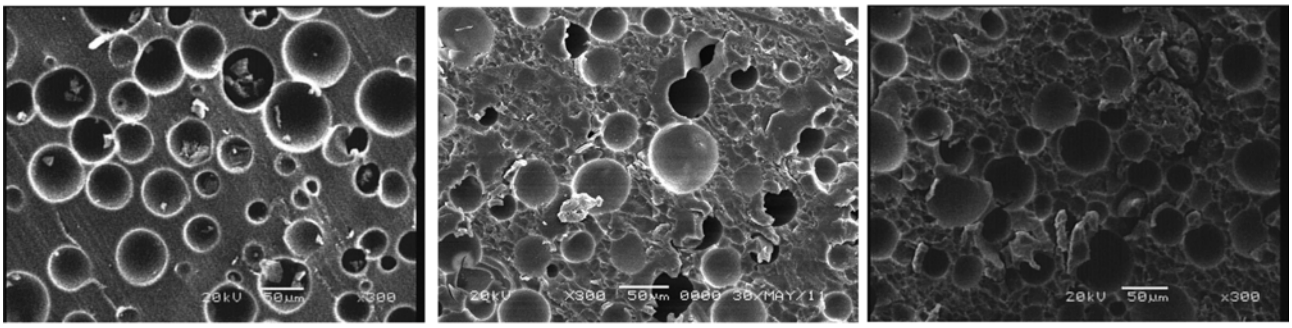


Fig. 5. Surface roughness and removal rate as a function of pad wear rate.



(a) (b) (c)

Fig. 6. Surface images obtained by optical profiling (above) and SEM (below) after CMP with conditioner (a) A, (b) B, and (c) C.



(a) (b) (c)

Fig. 7. SEM image of pad surface (a) before CMP, (b) after 1 h of CMP, and (c) after 4 h of CMP.

With the same conditioner, increasing the conditioner down force yielded the same result. When the conditioner down force is increased, the pad wear rate increases and the material removal rate decreases. When the down force of conditioner C was increased by 1.5 times, the material removal rate decreased by approximately 9%.

The pad surface images obtained by optical profiling and SEM under each conditioning condition are shown in Fig. 6. Although each image does not show the differences clearly, with careful observation, it is evident that the pad surface smoothens in the case of mild conditioning. The SEM images showed that conditioner A produced more pad wear debris and left more apparent conditioner traces than the other conditioners. The pad wear debris is trapped in the pores. The appearance of fresh pad surface happens faster with a higher pad wear rate. From the ceria CMP mechanism, it can be observed that a smooth pad surface can accelerate material removal by increasing the contact probability between the pad asperities and the ceria particles, as described in the previous section. Therefore, compared to the weaker conditioning methods, stronger conditioning of the rough surface could lead to a low material removal rate. This is applicable only to ceria slurry CMP. For the silica slurry, the material removal rate is directly proportional to the surface roughness and inversely proportional to the pad wear rate [11]. However, the results introduced in this paper are different from those in [11].

The variation in the material removal rate with polishing time does not change considerably if ceria slurry is used. Figure 7 shows the SEM images of the pad surface with respect to the pad lifetime. The new pad surface shown in Fig. 7(a) is very clear and smooth, and it has several knife cuts. As CMP progresses, the pad surface morphology becomes rough, as shown in Figs. 7(b) and (c). Figures 7(b) and (c) shows the SEM images after polishing for 1 h and 4 h, respectively. Both images are similar, showing no evidence of time dependent pad surface degradation. Therefore, the results obtained in this experiment, such as correlation between friction force, surface roughness, pad wear rate, and material removal rate, are consistent for the entire pad lifetime in the case of ceria slurry CMP.

4. CONCLUSIONS

This paper describes tribological approaches to analyze the material removal rate of a TEOS blanket wafer in terms of the friction force, roughness, and wear rate of the polishing pad. The experimental results showed that a high friction force between the pad surface (asperities) and the wafer surface accelerated the material removal rate and indicated that the contact behavior played a more important role in controlling the removal rate in the ceria slurry CMP than the physical properties of the polishing pad. When the pad surface was effectively refreshed, the pad wear rate had a close relation with the material removal rate. For ceria slurry CMP, a high pad wear rate decreased the material removal rate by inducing a rough surface. Therefore, the results in this paper suggest that the CMP process should be tribologically optimized to obtain a suitable material removal rate or other parameters governing the CMP performance. Further studies should be aimed at clarifying the mechanism or the combined conditions of the parameters governing the CMP performance. The results in this paper may provide clear indications toward the appropriate selection of CMP consumables, driven by the tribological aspects of CMP.

REFERENCES

1. M. R.Oliver, *Chemical Mechanical Planarization of Semiconductor Materials*, Springer (2004).
2. C. G. Kim, J. S, Moon, and W. J. Lee, *Korean J. Met. Mater.* **49**, 797 (2011).
3. J. Van Olmen, J. Coenen, W. Dehaene, K. De Meyer, C. Huyghebaert, A. Jourdain, Guruprasad Katti, A. Mercha, M. Rakowski, M. Stucchi, Y. Travaly, E. Beyne, and B. Swinnen, *IEEE Int. Conf. on 3D Sys. Integr.,* pp. 1-5, San Francisco, CA, USA (2009).
4. S. W. Yoon, D. W. Yang, J. H. Koo, M. Padmanathan, and F. Carson, *IEEE Int. Conf. on 3D Sys. Integr.*, pp. 28-30, San Francisco, CA, USA (2009).
5. H. Liang and D. Craven, *Tribolgy in Chemical-Mechanical Planarization*, CRC Press (2005).
6. S. R. Runnels and L. M. Eyman, *J. Electrochem. Soc.* **141**, 1698 (1994).
7. Z. Li, K. Ina, P. Lefevre, I. Koshiyama, and A. Philipossian, *J. Electrochem. Soc.* **152**, G299 (2005).
8. T. Kasai, *Tribol. Int.* **41**, 111 (2008).
9. Lee M. Cook, *J. Non-Cryst. Solids* **120**, 152 (1990).
10. T. Hoshino, Y. Kurata, Y. Terasaki, and K. Susa, *J. Non-Cryst. Solids* **283**, 129 (2001).
11. K. H. Park, H. J. Kim, O. M. Chang, and H. D. Jeong, *J. Mater. Proc. Tech*. **187-188**, 73 (2007).
12. http://www.diamondinnovations.com/SiteCollectionDocuments/Grinding/DI%20MBG.pdf.