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ORIGINAL ARTICLE

Effect of CMP conditioner diamond shape on pad topography and oxide wafer performances

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Abstract Chemical mechanical polishing (CMP) performance is often determined by the pad surface texture, which is mainly controlled by using a pad conditioner: usually, a diamond disk comprising numerous diamond grits attached to a flat metal substrate by means of brazing with an alloy. During the conditioning process, the diamonds interact with the pad surface to mainly remove the glazed layer and restore pad asperities. Selection of the appropriate diamond shape is crucial for obtaining the desired pad properties, conditioner life, and wafer removal rate. In this investigation, three different diamond shapes were carefully fabricated: (1) "sharp," a sharp-edged diamond; (2) "blocky," a high-quality crystalline diamond; and (3) "mixed," a combination of sharp and blocky diamonds. Three new disks were fabricated using the above mentioned diamond shapes. Pad surface characterization was carried out to compare the new disks with conventional diamond disks, and the effect of the diamond shape on the wafer removal rate was studied. Oxide CMP tests revealed that the "mixed" diamond grit provided the highest wafer removal rate and the best uniformity. As compared to a conventional diamond disk, it also achieved a higher wafer removal rate and a better uniformity while consuming less pad material. On the other hand, if the dressing stability is the major concern, the use of "blocky" diamond grit is recommended because it provided the most stable wafer removal rate over a conditioning time of up to 20 h. However, if the dressing capability is the major concern, the use of "sharp" diamond grit is suggested because it provided the highest pad cut rate.

Keywords Chemical mechanical polishing · Polyurethane pad · Diamond conditioner

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1 Introduction

As multilevel interconnection and narrow wiring have become critical challenges in the ultra large scale integration technology, several planarization and polishing technologies have been investigated in order to overcome these challenges. Chemical mechanical polishing (CMP) has been recognized as the most effective planarization process that can be used in semiconductor manufacturing for the interlevel dielectric, low K, and damascene metallization processes [1]. CMP is achieved by bringing the wavy wafer surface into contact with rotating polishing pad as tiny particles containing in the slurry are applied to the wafer/pad interface [2]. During the polishing process, the top points of the wafer are rubbed against the high points of the pad. The slurry that permeates the pad top contains submicron-sized abrasives, and reaction chemicals gradually corrode the top points of the wafer. As a result, the wafer bottom becomes flatter and smoother. During wafer polishing, the reaction product gradually accumulates in the pores and asperities of the pad surface, leading to the so-called glazing of the pad [3]. The polishing rate of the wafer then drops substantially [4, 5]. To continue the CMP, the polyurethane pad that is used to hold the slurry must be dressed periodically to maintain its surface texture that is optimized for polishing wafers efficiently.

The dressing tool is a pad conditioner or a diamond disk that has a multitude of diamond grits held to the flat surface

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Ex. 1021, Page 1

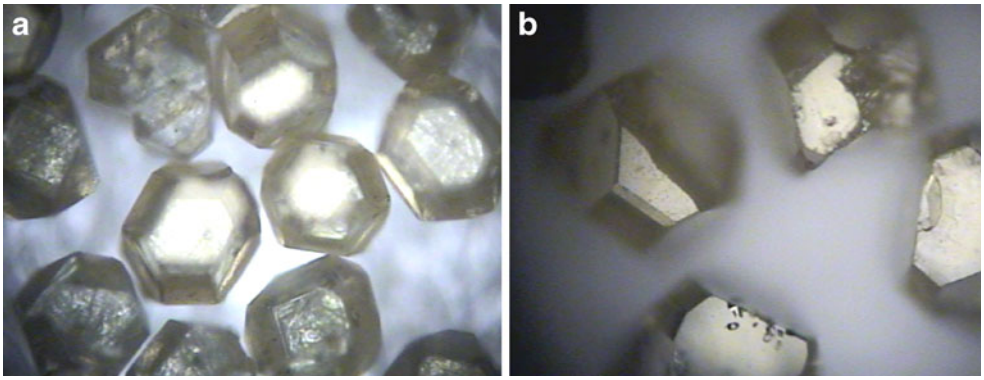

Fig. 1 Shape of diamond grits **a** blocky grits and **b** sharp grits

of a metal substrate by means of brazing with an alloy. Previous studies have contributed to the design of pad conditioners and pad dressing process. Zimmer and Stubbmann [6] pointed out that the grit size, shape, crystalline orientation, distribution density, degree of protrusion of the diamonds, and substrate planarity will all affect the dressing rate of the conditioner. Baker [7] investigated the pad surface created during conditioning and its influence on polishing performance. He pointed out that pad surface topology is determined by the conditioning grid, and not conditioning parameters. Chang and Jeng [8] reported a design-of-experiment procedure for optimizing conditioning parameters, including grit size and grit density, for better conditioning performance. Their results showed that the maximum pad wear rate can be achieved by using a 100-grit diamond disk with (grit density: 100) in these experiments. Sung and Pai [9] pointed out that the number of working diamonds is markedly influenced by the levels of the diamond grits. They also mentioned that the tip height distribution of conventional CMP pad conditioners is intrinsically large due to the variation in the grit size and diamond orientation. Garretson et al. [10] investigated the optimal design parameters of the pad conditioner from the viewpoint of wafer removal rate and uniformity. They proposed that a conditioner with a flatter substrate would result in a better dressing rate. Rikita et al. [11] pointed out that the diamond grit size, shape, crystalline orientation, distribution density, degree of protrusion of the diamonds, and the substrate planarity all affect the dressing rate of the conditioner. Chen et al. [12] investigated the effect of diamond distributions, diamond pitch, and arrangement and concluded that diamond distribution depends on the number of diamonds but does not change the shape of the distribution. Tsai et al. [13] studied a revolutionary pad conditioner design in which a structure was carved out of a sintered polycrystalline diamond matrix to form identically shaped tips, called the advanced diamond dresser. They proposed that this dresser can create asperities on pads more uniformly than a conventional diamond conditioner can. Yeh et al. [14] investigated development of a pad conditioning simulation module with a diamond dresser for CMP application. A series of parametric studies are performed to investigate the influence of key geometric or processing parameters for a pad conditioning process in terms of optimizing the conditioning performance. They pointed out that the size of the dresser disk is certainly an important parameter in term of the dressing efficiency. Tso et al. [15, 16] performed investigations to discuss the effect

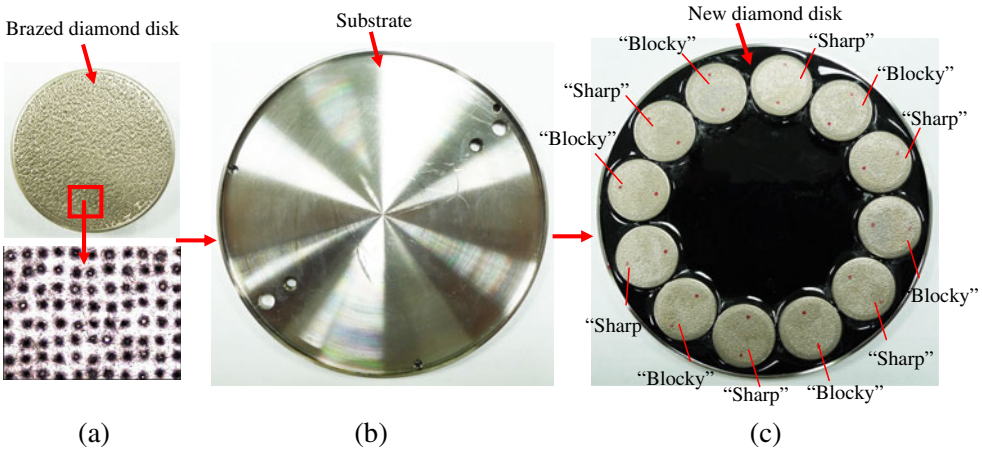

Fig. 2 The manufacturing steps for a new diamond disk: **a** a small brazed diamond disk contains single crystal diamond grits that are attached to a metal substrate by brazing with alloys, **b** a cylindrical substrate was fabricated from stainless steel, **c** 12 brazed diamond disks were attached to the mounting substrate with epoxy

Table 1 Diamond conditioners' parameters

Diamond conditioner ψ 108-5 W	Cutting pitch (μm)	Diamond grits size (average; μm)	Diamond grit shape
CDD (sharp)	500	120	Sharp diamond grit
CDD (blocky)	500	120	Blocky diamond grit
CDD (mixed)	500	120	Mixed (sharp and blocky)
DG (blocky)	500	120	Blocky diamond grit

of pad aging, soaking, the PH level of slurries, conditioning load, conditioning speed, and conditioning time. In addition, based on their experimental results, an empirical formula on the dressing rate was proposed.

In this study, three different diamond shapes were prepared and three new disks were fabricated using the three diamond shapes. The disks were designed to improve the leveling of the diamond grits and reduce the number of diamond grits. Pad surface characterizations were carried out by comparing the disks with conventional diamond disks. The effect of diamond shape on the wafer removal rate was also studied.

2 Experimental procedures

2.1 Preparation of diamond disks

We fabricated our new diamond disks as follows. Firstly, two different diamond shapes were carefully fabricated, as shown in Fig. 1: (1) "sharp," a sharp-edged diamond; and (2) "blocky," a high-quality crystalline diamond. Two types of brazed diamond disks were then fabricated using these two diamond shapes. The diamond grits (about 500 grits) were arranged on a flat stainless steel substrate and attached by brazing with alloys. The diameter and thickness of the cylindrical substrate were 10 and 5 mm, respectively, as shown in Fig. 2a. Secondly, a cylindrical mounting substrate with a diameter of 108 mm and a thickness of 5 mm was fabricated from stainless steel using a computer numerical control machine center, as shown in Fig. 2b. Finally, 12 brazed diamond disks were mounted in a predetermined pattern on the mounting substrate with epoxy; this was followed by curing and cleaning to finish the new diamond disks, as shown in Fig. 2c. In this study, three new types of diamond disks were manufactured and used: (1) only sharp diamond grits were used across the entire disk; that is, 12 brazed diamond disks were fabricated using the sharp diamond grit and were mounted on the substrate. (2) Only blocky diamond grits were used across the entire disk; that is, 12 brazed diamond disks were fabricated using blocky diamond grits and were mounted on the substrate. (3) A combination of sharp and blocky diamond grits were used across the entire disk; that is, six brazed diamond disks containing blocky diamond grits and six containing sharp diamond grits were mounted on the substrate. The distribution of sharp and blocky diamond grits on the disks is shown in Fig. 2c.

The parameters of the diamond pad conditioners are listed in Table 1. The conventional diamond pad conditioner used—a DiaGrid (DG) disk (Kinik, Taiwan)—contained single-crystal diamond grits (120 μm). The diameter of the DG disk was 108 mm, with a diamond spacing (cutting pitch) of 500 μm and a single type of diamond grits across the entire disk, as shown in Fig. 3. Our developed diamond disk design is referred to hereinafter as the combined diamond disk (CDD) and was also manufactured by Kinik Company, Taiwan. The

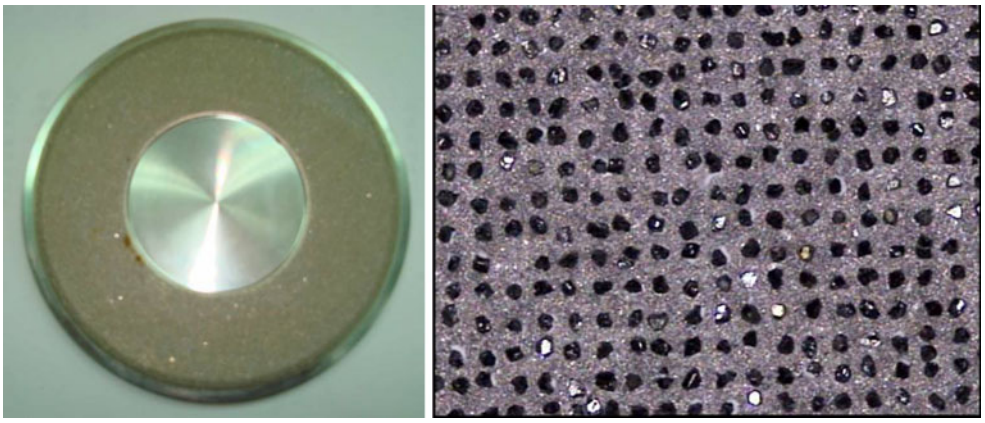

Fig. 3 Appearance of conventional diamond disk

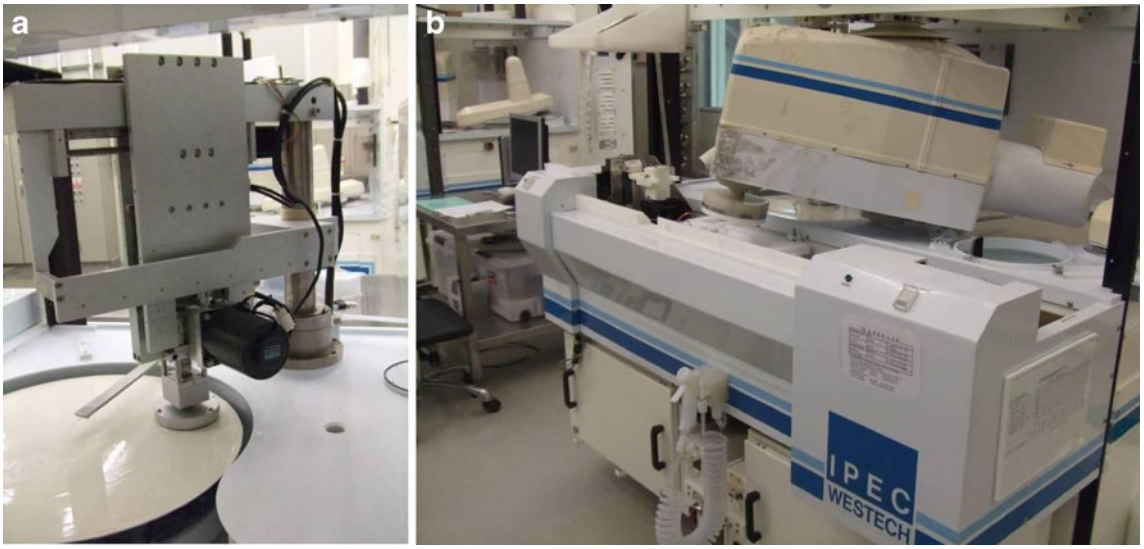

Fig. 4 **a** Dressing system and **b** polishing system

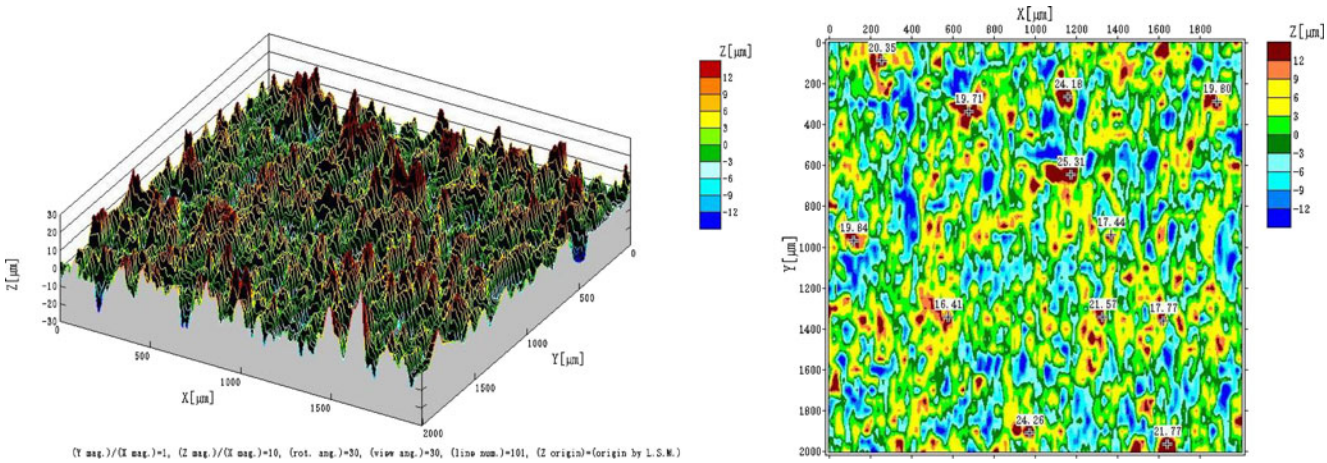

Fig. 5 Representative example of 3D (*left*) and 2D (*right*) profiles of IC1000 pad

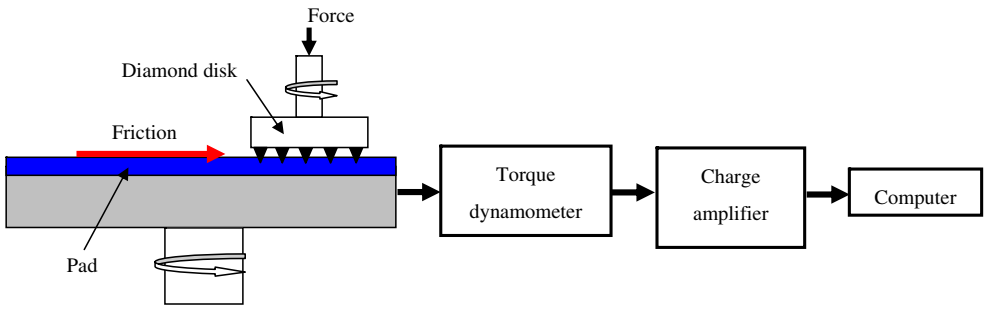

Fig. 6 Schematic illustration of friction force measurement setup

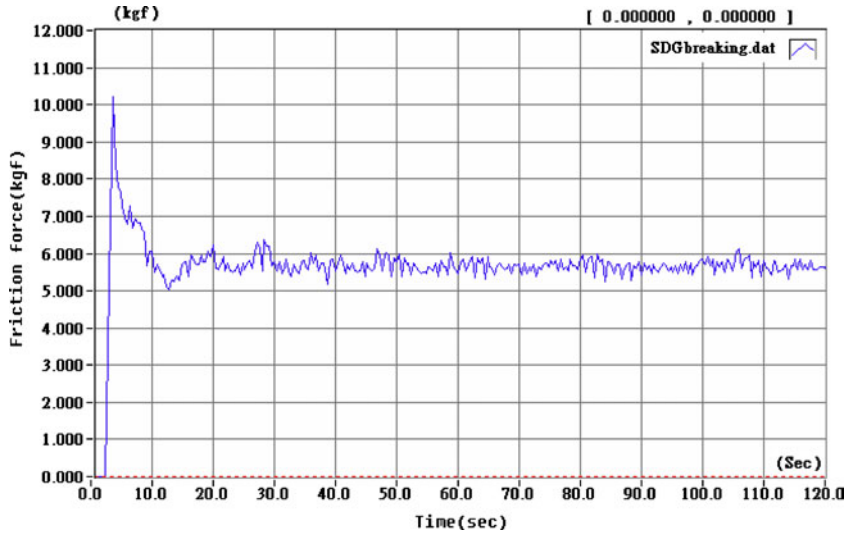

Fig. 7 Representative example of friction signal between wafer and pad with dressing time

diameter and cutting pitch of the CDD were 108 mm and 500 μm, respectively.

2.2 Experimental apparatus

The dressing experiments were conducted using a polishing pad mounted on a commercially modified polishing machine (Fig. 4) that had variable speed control. The diamond pad conditioner was attached via a connecting holder to a rotating head spinning at 40 rpm. A polyurethane pad was mounted on a table disk that rotated at a speed of 50 rpm. The oscillation speed of the conditioner was fixed at about 5 mm/s. The applied load was fixed at approximately 3 kg. After the pad had been dressed, its surface topology was measured using a stylus-type 3D surface roughness instrument. The radius of the diamond tip probe, nose angle, and measuring force were 5 μm, 90°, and 4 mN, respectively. Measurements were made over a 2×2 mm^2 area of the pad. The measurements enabled quantitative determination of the surface roughness values. A representative example of 3D and 2D images of the pad surface are shown in Fig. 5.

Friction force was extracted with a proprietary tool setup that was internally developed by incorporating a torque dynamometer and a computer data acquisition system, as shown in Fig. 5. The friction force was measured while the experimental conditioner cut on a polyurethane CMP pad, and the friction force signals were displayed on a monitor. Figure 6 shows the variation in the friction signal with dressing time. The friction force increased dramatically in the initial stages of polishing, which was caused by the disk and the polishing pad overcoming the static friction force generated by the applied pressure and the relative motion. A scanning electron microscope was employed to examine pad morphology such as pores and grooves. The pad dressing rate was measured using a linear variable differential transformer.

Polishing experiments were conducted using a Westech polisher (Model 372 M) as shown in Fig. 7. Its speed was adjustable and the pad was mounted on a polishing plate with a diameter of 24 in. During polishing, a power head applied a specific load to an oxide wafer (with a thickness of 8,000 Å and a diameter of 6 in.); a dispenser was used to supply the slurry. The wafer was attached to a holder that was connected to a wafer carrier head that rotated at

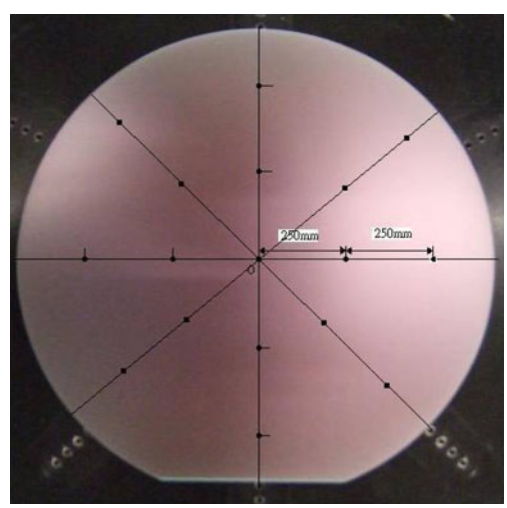

Fig. 8 Measurement positions on wafer

Table 2 Dressing experimental parameters

	Diamond conditioners	DG and CDD
	Polishing pad	IC1000 groove
Dressing parameters	Dressing load	4 kg
	Rotational speed of conditioner	10 rpm
	Rotational speed of pad	40 rpm
	Oscillation speed of conditioner	5 mm/s
	Dressing liquid	D. I. water

40 rpm. A polyurethane pad was mounted on a table disk that rotated at 42 rpm. The applied pressure and back pressure were about 4 and 2 psi, respectively. The polishing slurry used in the experiments was SS-25, produced by the Cabot Company. The slurry flow rate was 150 mL/min.

The friction force was also measured while the experimental wafer was polished on a polyurethane CMP pad. The thickness of the oxide layer on the wafers was measured before and after polishing using a system that is commonly applied to measure the thickness of thin films, with a measurement range of 100–150,000 Å. The data reported herein were measured at 17 positions, as shown in Fig. 8. Details of the dressing and polishing experimental conditions are shown in Tables 2 and 3.

3 Results and discussion

Figure 9 shows variations in the pad cut rate produced by the CDD with sharp, blocky, and mixed diamond grits, and by the DG with the blocky diamond grit. The pad cut rate of the DG was approximately 39 μm/h, which was higher than that of the CDD with sharp and blocky diamond grits, which had pad cut rates of approximately 28 and 22 μm/h, respectively. This is because the DG contained approximately 12,000 diamond grits, whereas the CDD contained only about 6,000 cutters. From an efficiency viewpoint, although the DG had twice as many cutters, its pad cut rate was only 30–40% greater because of the large variation in the height of the tips of the diamond grits on the DG. As a result, the DG disk contained many diamond grits that did not contribute to cutting [17]. This implies that the CDD has a better overall dressing ability and should lead to a reduction in the cost of the conditioner. In addition, among all the diamond disks tested, the CDD with sharp diamond grits provided the highest pad cut rate, indicating that sharper diamonds can remove pad agglomerates and glazed areas more effectively.

The variations in the frictional force between the diamond disk and pad were also studied, as shown in Fig. 9. The frictional force showed a high correlation with the pad cut rate. As a result, the frictional signal can help us understand the pad surface conditions after pad conditioning. In the figure, the highest frictional force of 3.44 kg was

Table 3 Polishing experimental parameters

CMP process parameters	
Down force	4 psi
Back pressure	2 psi
Platen/carrier speed	40/42 rpm
Slurry type	SS-25
Slurry flow rate	150 mL/min
Carrier film	Rohm-Haas R200 T3

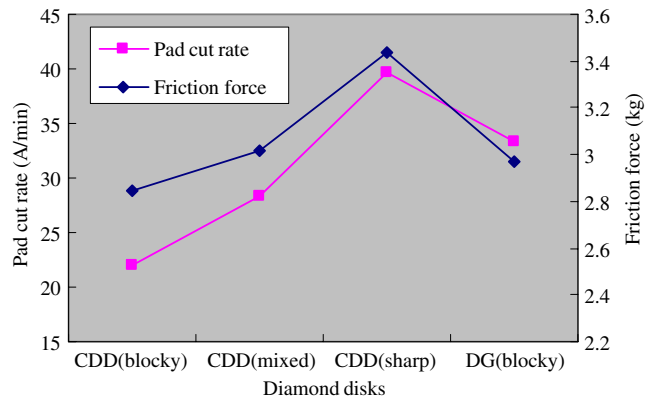

Fig. 9 Variation in pad cut rate and friction force between disk and pad with load dressed by CDD and DG

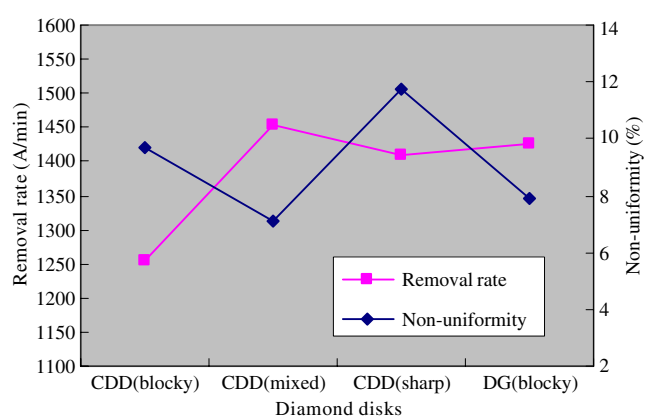

Fig. 10 Variation in wafer removal rate and non-uniformity using pads dressed by CDD and DG disks

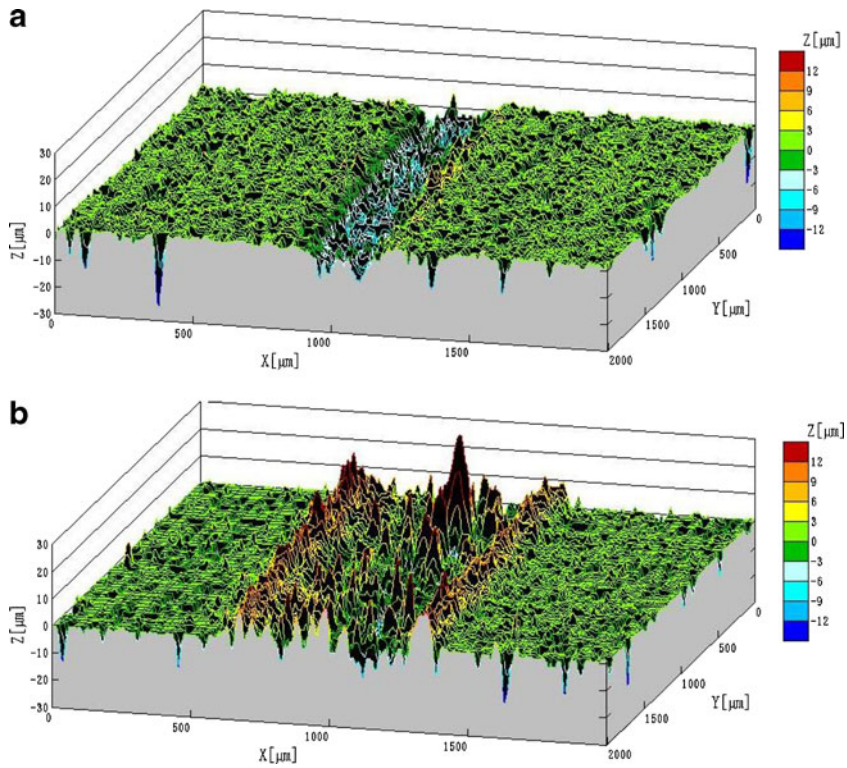

Fig. 11 3D profile of **a** point and **b** face-penetrating pad

obtained with a CDD with sharp diamond conditioning. These results may explain why the pad cut rate for the CDD with sharp grits was the highest.

Figure 10 shows the relationship between the wafer removal rate (RR) and the non-uniformity (NU) on oxide-CMP obtained with pads processed with the CDD and DG disks. RR is defined as the thickness removed in unit time, as shown in Eq. 1:

$$\mathrm{RR} = \frac{T_{\mathrm{pre}} - T_{\mathrm{post}}}{t} \tag{1}$$

where T_{pre} and T_{post} denote the thickness, in Å (10^{-10} m), before and after polishing, respectively.

The NU is defined as the variation of wafer thickness across the wafer surface. The quantitative definition is shown in Eq. 2:

$$\mathrm{NU} = \frac{\sigma}{\mu_x} \times 100\% \tag{2}$$

where, μ_x and $\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\mu_x)^2}{n}}$ are the mean value and the standard variation of n measured thickness x_i, respectively.

It was found that the RR of pads dressed using the CDD with mixed diamond grits (approximately 1,455 Å/min) is slightly higher than that of the pads dressed using CDD with sharp diamond grits (approximately 1,389 Å/min), but significantly higher than that of pads dressed using the CDD with blocky diamond grits (approximately 1,250 Å/min). The highest removal rate and better uniformity were obtained after conditioning with the CDD with mixed diamonds. This result is discussed as follows: Tsai and Liao [18] studied the grooves on pads dressed by a single type of diamond with different parts of the crystal (point, edge, and face) penetrating the pad. They pointed out that the diamond shapes drastically influence the asperities on the pad, and the points penetrating the pad can more effectively cut the glazed area. The face penetrating the pad can effectively form pad asperities.

Figure 11 shows a 3D profile of pad surfaces created by point and face dressing. A careful examination of the finished track reveals that point dressing can

Table 4 Roughness of pad surface dressed by different diamond disks

Diamond disks	Pad surface roughness (Ra; μm)	Coefficient of force (μ)
CDD with sharp diamond grits	3.28	0.563
CDD with mixed diamond grits	3.21	0.608
CDD with blocky diamond grits	2.54	0.544
DG with blocky diamond grits	2.73	0.598

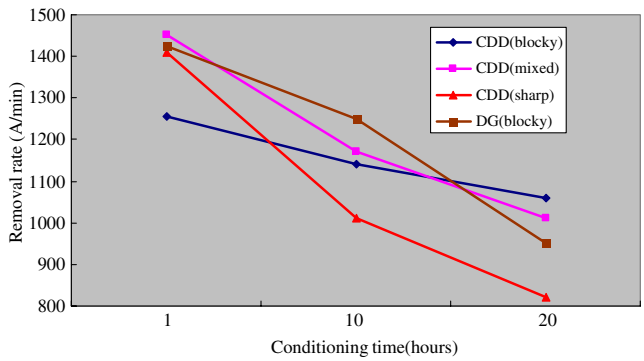

Fig. 12 Variation in wafer removal rate dressed by CDD and DG

produce microgrooves, whereas face dressing can create more asperities. Therefore, mixed diamond grits can provide functions of removing glazed areas as well as restoring pad asperities. This probably explains why the RR of the CDD with mixed diamond grits was high in this study.

To further investigate variations in the wafer removal rate, the frictional forces between the wafer and the pad, as well as the pad surface roughness after conditioning, were studied. Table 4 lists the friction force data for the CDD and DG disks. The coefficient of friction showed a high correlation with the polishing rate. This result is consistent with studies by Lee et al. [19, 20], which showed a linear relationship between the silicon dioxide removal rate and coefficient of force. This may be the reason why the highest polishing rate was obtained by dressing using the CDD with mixed diamond grits.

The variations in average roughness R_a with the different diamond disks are also shown in Table 4. It can be observed that R_a decreases with sharper diamonds. The highest R_a of 3.28 μm was obtained by the CDD with blocky diamond grit. Further, the polishing rate was not proportional to R_a. This can be attributed to the distribution of pores being non-uniform; the pore diameters varied considerably, thus, affecting the surface asperities. Kim et al. [21] proposed that R_a is weakly related to the wafer removal rate. Stein et al. [22] pointed out that R_a remained constant after the first 5 min of polishing. Hence, the decrease in the polishing rate between 5 and 60 min in polishing oxide is not associated with the variations in R_a. In our study, however, R_a and pad cut rate showed a weak relation with the removal rate. However, the coefficient of force had the most significant influence on the removal rate. Thus, friction force control is important to maintain good polishing results.

We investigated the behavior of the wafer removal rate with increasing conditioning time to evaluate disk life. Four types of conditioners were used for up to 20 h on a grooved pad under slurry SS-25. The wafer removal rate was measured every 10 h. Figure 12 shows the wafer-removal rate dependence on the accumulated dressing time. The wafer-removal rate decreased gradually with conditioning time because dulling of the cutting edges reduced the penetration depth of the diamond grits. As a result, the asperity height on the pad top also decreased. Further, thinning of the slurry-permeated layer slows down the polishing rate. Kawakubo et al. [23] pointed out that the pad cut rate gradually decreases with the dressing time because of a decrease in the cutting ability as the sharp edges of the diamond grit are rounded off. Sung [17] pointed out that dulling of cutting tips (Fig. 13) can cause excessive pad deformation with minimal cutting, which reduces the removal of the glazed layers.

To further investigate variations in the removal rate, we observed the pores on the polishing pad after conditioning. As shown in Fig. 14, some pores were filled with residual slurry and chips (Fig. 14d). Residual materials trapped in the pores decreased the area for slurry transport during polishing. The CDD with mixed diamond grits and DG

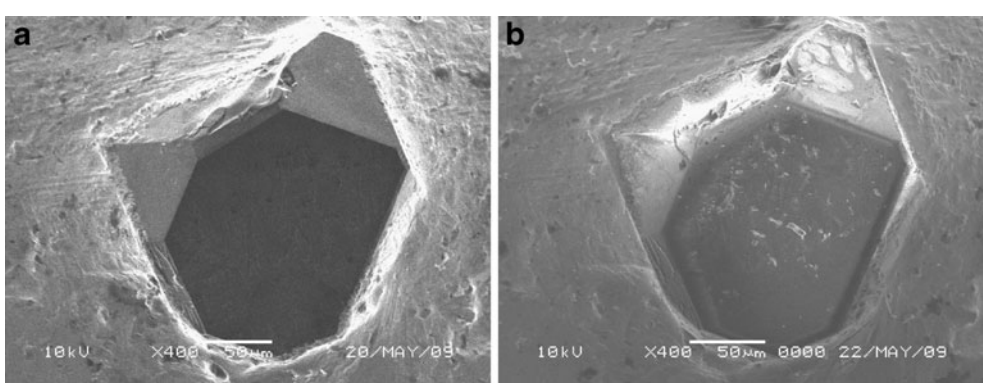

Fig. 13 Images of sharp diamond grit **a** unused and **b** after 20 h of dressing

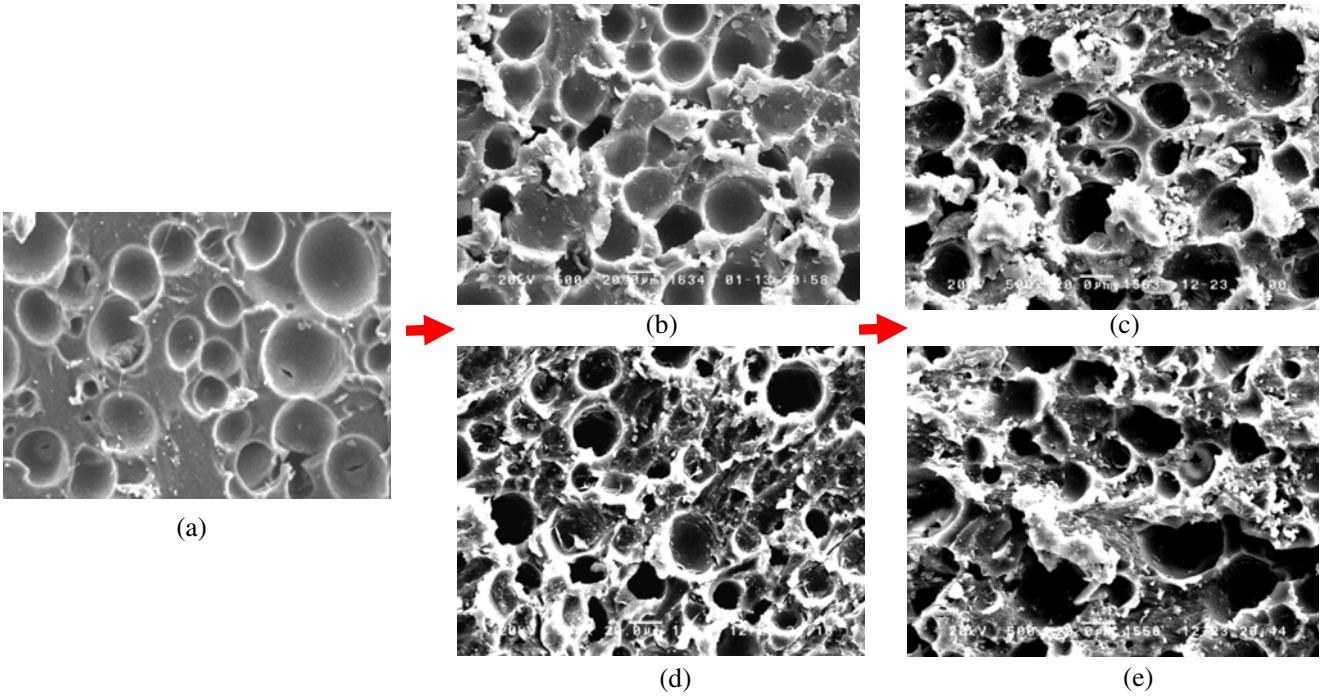

Fig. 14 SEM images of polishing pad: **a** new pad, **b** and **c** dressed by CDD with blocky diamond grit, and **d** and **e** dressed by DG after 1 and 20 h of conditioning, respectively

followed similar curves. The polishing rate of the CDD with blocky diamond grits was stable for an extended duration, in contrast to the CDD with sharp diamond grit, whose polishing rate dropped rapidly. This implies that CDD with blocky diamond grit can sustain the polishing performance of a pad.

4 Conclusion

This paper presents an experimental study of a new design of CMP diamond disks fabricated using three different diamond shapes. The fundamental characteristics of the pad of the newly designed disks are compared with a conventional diamond disk. Considering the pad cut rate, coefficient of force, and wafer removal rate, a CDD fabricated with mixed diamond grit is recommended because it exhibits a higher wafer removal rate and better uniformity while requiring less pad material and only half as many diamond grits. Hence, the pad life is extended leading to a reduction in the cost of CMP. In addition, the number of diamond grits required is significantly lower; approximately 6,000 diamond grits are used in the new disk compared with 12,000 in a conventional diamond disk. On the other hand, if the dressing stability is the major concern, the use of a CDD with blocky diamond grit is recommended because it provided the most stable wafer removal rate over conditioning time of up to 20 h. In addition, among all the diamond disks tested, the CDD with sharp diamond grits provided the highest pad cut rate, which indicates that using the CDD with sharp diamond grits has the best overall dressing capability in the CMP process.

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