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DRESSING CHARACTERISTICS OF ORIENTED SINGLE DIAMOND ON CMP POLYURETHANE PAD

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□ *Diamond conditioners or dressers are commonly used to dress polishing pads that are applied in the chemical mechanical polishing (CMP) of silicon wafers for integrated circuits. In this work the fundamental characteristics of dressing action on the polyurethane pad are investigated for dressing by a single diamond with various shapes (point-cutting, line-cutting and face-cutting), and the polishing rates of silicon dioxide by the resulting pad are studied. Experimental results reveal that a groove with ridges on both side walls is formed as the diamond is moved over the pad. The cutting action dominates when the point-cutting is responsible for dressing. On the contrary, the plowing action plays a major role under face-cutting. A large spring back reduces the protrusion of the diamond in contact with the pad surface as groove depth is smaller than dressing depth. The use of point-cutting is beneficial since it results in the least damage to the pad and a higher but less variable polishing rate.*

Keywords chemical mechanical polishing, diamond conditioner, polishing pad

INTRODUCTION

Chemical mechanical polishing (CMP), a surface planarization process, is adopted to fabricate silicon wafers to produce a globally planar wafer surface. CMP also enables the miniaturization of features, memory devices and other sophisticated chips in ultra-large scale integration (Chen et al., 2005; Ishizuka et al., 2007). CMP performance can be optimized by several process parameters, such as equipment and consumables (diamond conditioner, polishing pad and slurry) (Kim et al., 2006; Lei et al., 2004;

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Sung et al., 2007). A typical orbital-type CMP system has two main parts – polishing action and dressing action (Figure 1).

The polishing action takes place between a semiconductor wafer and polishing pad. During the CMP process, a silicon wafer is held on a carrier with its face pressed against the polishing pad attached to a rotating polishing platen. Both the wafer carrier and platen rotate in the same or opposite directions to generate relative motion between the wafer and pad. At the same time, slurry, which contains abrasive particles in a chemical solution, is supplied to form a liquid film between the wafer and pad. The slurry chemically attacks the wafer surface, thus weakening or breaking molecular bonds on the wafer surface such that wafer molecules can be mechanically removed by the abrasives during the polishing process. The dressing action occurs between a diamond dresser and polishing pad.

During polishing, the reaction product gradually accumulates on the pores and asperities of the pad surface, leading to so-called pad glazing (Hooper et al., 2002; Steigerwald et al., 1997). Glazing is undesirable as it often leads to decreased wafer removal rate over time without pad conditioning, and increases the risk of inducing micro scratches (Achuthan et al., 1996; Baker et al., 1997; McGrath et al., 2004).

For CMP to continue, a diamond pad conditioner is typically employed periodically and continually either in-situ dressing, in which conditioning is conducted during wafer polishing or in ex-situ dressing, in which conditioning is conducted after wafers have been polished, to regenerate the asperity structure of the pad. Currently the diamond pad conditioner is a circular metal substrate with multiple polycrystalline diamond grits electroplated or brazed on its flat surface (Figure 2). Although the diamond pad conditioner has a regular distribution of diamond grits, the tips of diamond grits are not at the same height. Furthermore, diamond grits

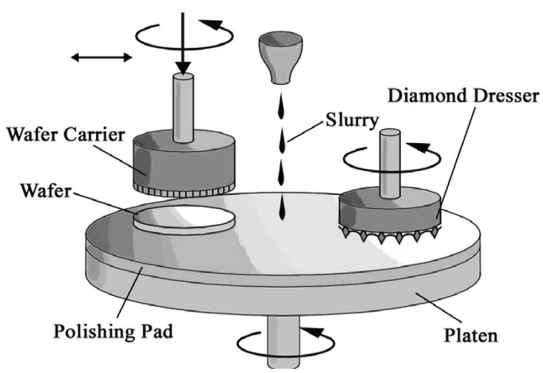

FIGURE 1 The CMP layout includes a rotating pad, a feeding slurry, and a rotating pad dresser.

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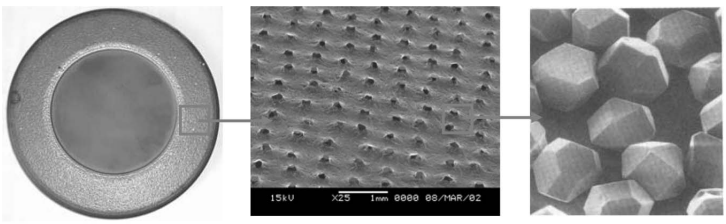

(a) (b) (c)

FIGURE 2 (a) Diamond conditioner, (b) SEM micrograph of diamond grits attached to a flat substrate by brazing to form cutting tips, and (c) the crystal morphology of grown diamond grits.

differ in shape and can be oriented differently as the shape of diamond grits is generally cubo-octahedral (Figure 2). Therefore, the dressing behaviors of polishing pads are unpredictable. Accordingly, a fundamental understanding of dressing action on the polyurethane pad is required.

Li et al. (1995) found that a rougher pad surface removed more material than smoother pad surfaces. Lawing (2005) studied the effect of pad conditioner down-force on polishing rate for IC1000/Suba. It is found that a polishing rate threshold is observed at around 5 lb conditioner down-force. Below 5 lbs the polishing rate drops with decreasing down-force. Above 5 lbs the polishing rate saturates. Kim et al. (2004) proposed that the surface roughness parameter of the IC1400 pad, R_a or R_q, is weakly related to the wafer removal rate. Stein et al. (1996) used optical interferometry to measure the surface roughness of the pad. They pointed out that the R_a of the pad remained constant after the first 5 min of polishing. Hence, the decrease of the polishing rate in between 5 and 60 min in polishing oxide was not associated with the change of R_a of the pad surface.

However, Oliver et al. (2000) found a strong correlation between R_a of the pad and the decay of the wafer removal rate when conditioning was suspended. They concluded that the removal rate was a sensitive function of R_a. Park et al. (2007) showed that the surface roughness of pad, reduced peak height (R_{pk}), has a strong correlation with the material removal in CMP. Although various investigations have addressed pad surface roughness and CMP performance, no comprehensive fundamental study of pad surface topography dressed by diamond grits has been performed.

In this study, the characteristics of the grooves on a pad surface dressed by a single diamond under various shape conditions are investigated. The polishing rate in polishing silicon oxide by the resulting pad is studied. This study would contribute to the understanding of conditioning techniques and further to improve the current CMP process.

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EXPERIMENTS

The experimental procedure in this paper is depicted in Figure 3. The single diamond dresser is a DiaGrid dresser, manufactured by Kinik Company, Taiwan. The diamond is about 600 μm in diameter. It is made of cubic (100) and octahedral (111) planes, and can be oriented in various directions relative to the pad surface. The experiments in the paper include three shapes of the diamond. The process by which the (100) plane of a diamond is in contact with the surface and participates in dressing, is called "face-cutting". The term "line-cutting" denotes a process in which the crest line of the diamond is parallel to the pad surface and perpendicular to the cutting direction when the (100) plane of the diamond is oriented 55° from the normal of the pad. "Point-cutting" is adopted herein when dressing is conducted by the apex of the diamond, as displayed in Figure 4. The polyurethane pad is an IC1000-A2 without grooves manufactured by Rohm and Haas Electronic Materials Company.

Approximately one third of the volume of the pad constitutes isolated voids whose diameters are in the range of 20–50 μm. All of the pad surface topographies are generated on a computer numerical control (CNC) machining center. The dressing depth can be adjusted to a precision of 1 μm. The single diamond dresser mounted on the spindle chuck is dragged across a polyurethane pad that is trued in advance, as shown in Figure 5.

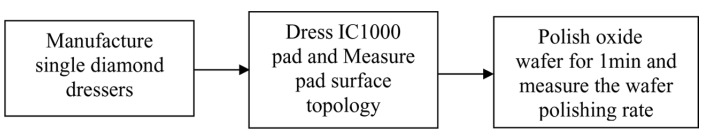

FIGURE 3 Experimental procedure.

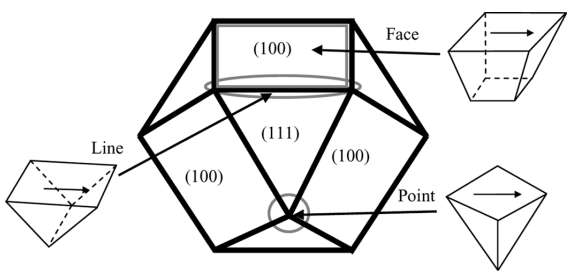

FIGURE 4 Geometries of single diamond and three kinds of diamond shape.

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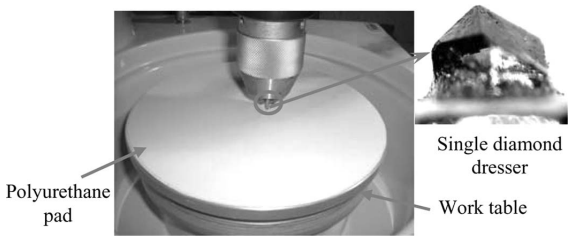

FIGURE 5 Schematic drawing of dressing test.

The polishing experiments are performed using a table-top polisher. Its speed is adjustable. The pad is mounted on the polishing plate with a diameter of 200 mm. During polishing, a power head applies a specific load on the specimens and a dispenser is used to supply slurry. The specimens are oxide wafers having a thickness of 8000 Å, and dimensions of $18 \times 18\,mm^2$. The three specimens are attached to a holder that is connected to a wafer carrier head rotating at 120 rpm. A polyurethane pad that is trued in advance using a single diamond dresser is mounted on a table disk rotating at a speed of 110 rpm. The applied pressure is about $0.4\,kg\,cm^{-2}$. The polishing slurry adopted in the experiments is SS25, supplied by Cobat Company.

After the pad is dressed, its surface topology is measured by stylus-type three dimensional surface roughness measuring instrument (SE3500k, Kosakas Company, Japan). The radius of the diamond tip probe, the nose angle and the measuring force are 5 μm, 90° and 4 mN, respectively. Measurements are made over a $2\,mm \times 2\,mm$ area of the pad. The measurements enabled the quantitative determination of ridge and groove. For each image 6 sites are measured, and measurements are conducted on 3 images. In the figures given in the next section, the values of ridge and groove are the average of these 18 measured values. The thickness of the oxide layer on the wafers before and after polishing are measured by a system commonly used for measuring the thickness of the thin film, with a measurement range of 100 to 150,000 Å. The data reported herein are measured at 17 sites. A Scanning Electron Microscope (SEM) is also employed to examine the pad morphology, such as pores and grooves.

RESULTS AND DISCUSSIONS

Wear of Polyurethane Pad in Conditioning

Figure 6 shows a representative example of images of pad surface measured by stylus-type instrument and SEM after line-cutting under a

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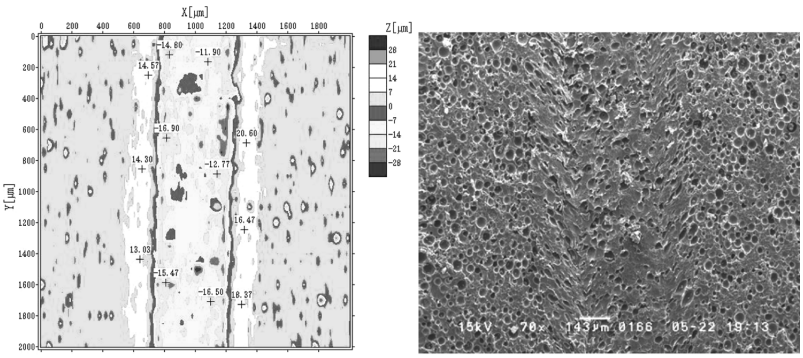

(a) (b)

FIGURE 6 The images of the pad surface formed by line-cutting: (a) measured by contact profilometer and (b) Scanning electron microscope (SEM).

dressing depth of 200 μm. The dressing depth is defined as the depth of cut of diamond grit into the pad. During the formation of the grooves, pad material is deformed and ridges on both sides of the groove are created as the diamond moves over the pad. These ridges will become the highest points on the pad in contact with the wafer surface. From a tribological perspective, the dressing action on the polyurethane pad by a diamond is a typical abrasive wear process. Material removal from a surface via plastic deformation during abrasion can occur by plowing action and cutting action, as shown in Figure 7 (Bhushan, 1999).

In the plowing process, the material is displaced along the side of the groove. In the cutting form of abrasive wear, the material is removed from the pad surface. From Figure 6, the schematic of the cross section of a groove and side ridges created by line dressing can be approximated by that displayed in Figure 7. In the figure, the quantities A and B are two side ridge areas, and C is groove area, D is ridge height and E is groove depth. The A and B can be approximated by the area of a triangle. It is computed by multiplying the ridge height by the ridge width and divided by 2. The C can be approximated by the area of a rectangle for

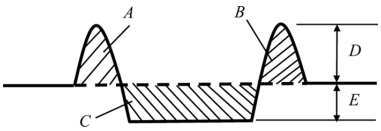

FIGURE 7 Schematic diagram of the cross section generated by line-cutting: A and B are two side ridge areas, C is groove area, D is ridge height and E is groove depth.

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line-cutting and face-cutting, and obtained by the multiplication of the groove depth and the groove width, while for point-cutting the groove is approximated by a triangle.

For analysis purpose, a plowing ratio is defined as the sum of the areas of two side ridges divided by the groove area. This ratio can be used to evaluate the contribution of plowing action in dressing. There is no material loss and the sum of both side ridge areas equals to the groove area when plowing ratio equals one. The permanent deformation is resulted from plowing action alone in this case. Conversely, when the plowing ratio equals zero, there are no side ridges and the deformation is completely achieved by cutting action. Figure 8 plots the variation of plowing ratios of point, line and face-cutting under dressing depths of 90 μm, 120 μm and 200 μm, respectively. It is found that the plowing ratio generated by point-cutting is smaller than that of line-cutting and face-cutting. This means that cutting action plays a major role. On the other hand, the wear tends to be dominated by plowing action if dressing is conducted by the face-cutting.

Since a typical pad conditioner contains thousands of discrete diamond grits that are bonded to a metal substrate, random scratch patterns on the pad surface are created when a rotating diamond conditioner moves on the rotating pad in practice. A representative example of the stylus and SEM images of cross groove on the pad surface created by line-cutting under a dressing depth of 200 μm is displayed in Figure 9. It is observed that the two sides of the groove are raised. At the four corners of the intersection, the ridges are higher because the ridge created in the first dressing is raised further in the second dressing. In other words these ridges become the highest points on the pad.

As a consequence, the ridges at the intersection will pressurize the rotating wafer and polish away the contact region of the wafer. Moreover, it is found that the groove of the intersection is deeper. The results

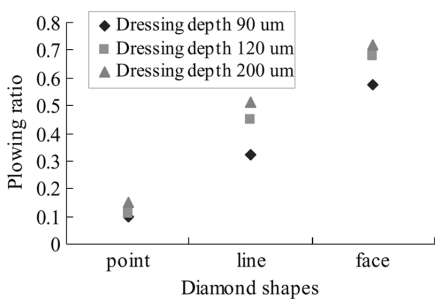

FIGURE 8 Variation of plowing ratio with diamond shapes.

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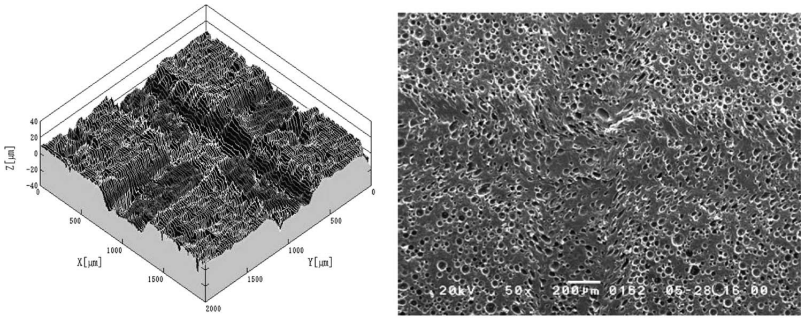
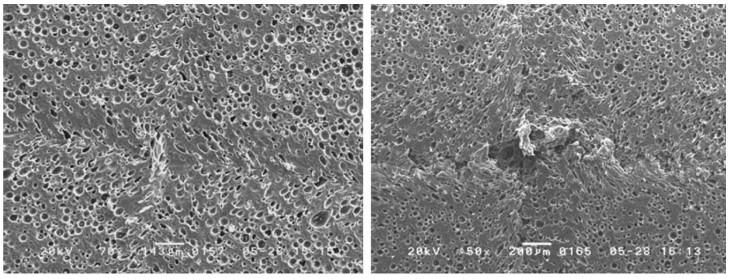


(a) (b)

FIGURE 9 The images of cross path on the pad surface formed by line-cutting: (a) measured by contact profilometer and (b) SEM.

can be attributed to the viscoelastic (time-dependent) property of the polyurethane pad. These results show that in the case of noisy dressing, the groove on the pad is not only irregular, it may also be unnecessarily deeper. As a result, the amount of slurry used in the CMP process may increase substantially. The cross-sectional SEM images of the pad surface created by point-cutting and face-cutting under a dressing depth of 200 μm are also shown in Figure 10. It is observed that the amount of pores of the finished groove for face-cutting is less than that for point-cutting. In addition the largest deformation of pad in the groove of the intersection is produced when the face-cutting is responsible for dressing because face-cutting may press more on the pad than removing material that possibly is troublesome due to their ability to damage the wafer surface.



(a) (b)

FIGURE 10 SEM images of cross path on pad surface: (a) point-cutting and (b) face-cutting.

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Effect of Dressing Velocity on the Pad

During the CMP process, pad conditioner moves radially inward and outward sequentially on the rotating pad. This leads to various dressing velocities over the entire pad surface. Related quantities of the grooves and ridges created by point, line and face-cutting under dressing velocities of 30, 75, 110, and 150 m/min, respectively and a dressing depth of 100 μm are shown in Figures 11 and 12.

In the figure groove depth of the pad decreases as dressing speed increases. The increase in groove depth also leads to an increase of ridge height. The pad shape becomes concave after enough dressing. Notably, concavity increases as dressing time increases (Chang et al., 2007; Zhou and Davis, 1999). This experimental result implies that the pad surface profile after dressing would be concave due to increased groove depth on the central area of the pad. A conditioning recipe of a pad dresser with an enhanced download force, or the dressing staying for a long time at outer area of pad, in the CMP process is suggested for uniform scratch density and asperity distribution over the entire pad surface.

One of the more interesting observations is that the groove depth is smaller than the dressing depth. The examination of the finished groove

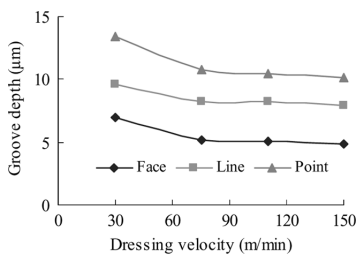

FIGURE 11 Variation of groove depth with dressing speed.

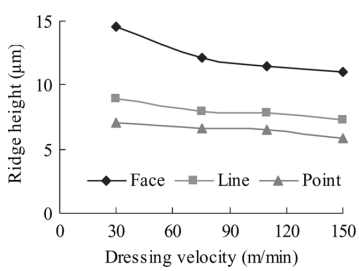

FIGURE 12 Variation of ridge height with dressing speed.

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dressed from Figure 6 reveals the depth of groove created is about 14 μm, but the dressing depth is controlled about 200 μm. It is apparent that the dressing depth is far larger than the final groove depth. Hence the spring back of the pad is about 93%. This is due to the viscoelastic property of the polyurethane pad. Diamond grit that has a dressing depth exceeding the elastic deformation generates a groove with ridges on the both sides. The amounts of spring back for point-cutting, line-cutting and face-cutting are 86%, 91%, and 94% at a dressing depth of 100 μm, respectively (Figure 13). Since a large spring back reduces diamond protrusion in contact with the pad surface, design of a pad conditioner should take into account the height of the exposed diamond.

Effect of Ridge Height on Polishing Rate

Asperity of pad surface resulting from pad conditioning has a critical influence on the polishing rate of silicon wafer in CMP process (Lawing, 2005). Ridges created by diamond grits will become the highest points on the pad in contact with the wafer surface while the grooves promote the transportation of slurry. Figure 14 plots the variation of the polishing rate, ridge height and the final groove depth with the dressing depth created by face, line and point-cutting, individually. In the figures, the polishing rates of the oxidized wafer initially increase with the ridge height, reaching a maximum value at a ridge height of a little bit under 5 μm for face-cutting, of approximately 5 μm for line-cutting and about 8 μm for point-cutting. Then, it starts to drop slowly with further increases of the ridge height. This result can be explained as follows.

When the ridge height is under the optimal value, the ability to hold abrasive particles to remove the reaction product of the wafer will reduce. When excessive ridge height is formed, the wafer is held entirely by the ridges to increase the gap between the wafer and the pad. This will reduce the ability to move the boundary layer existing in wafer surface

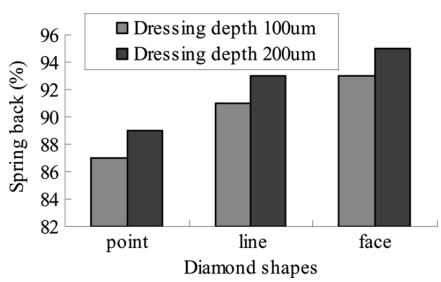

FIGURE 13 Spring back for diamond shapes.

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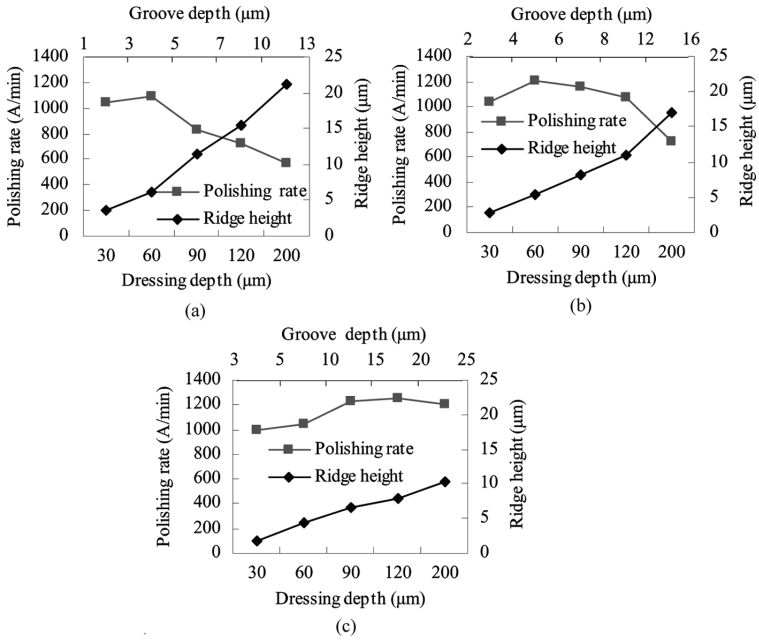

FIGURE 14 Variations of polishing rate, ridge height and final groove depth with dressing depth: (a) face-cutting, (b) line-cutting, and (c) point-cutting.

due to the decrease of shear stress as the film layer thickness is increased (Bhushan, 1999; Runnels and Eyman, 1994). As a result, there is less material removal during the CMP process and the polishing efficiency is decreased. Figure 14 also shows the variation of the polishing rate of silicon dioxide with the dressing depth under three dressing modes. The polishing rate increases initially with the dressing depth, reaching the optimal value from which it begins to drop slowly as the dressing depth is increased further. This optimal value is less than 60 μm for face-cutting, about 60 μm for line-cutting and around 120 μm for point-cutting.

The existence of an optimal dressing depth implies that in designing the conditioner, there is no need to have a large protrusion of the diamond above the metal substrate. It should be made a little higher than this optimal value. By so doing, the diamonds are more strongly held on the substrate while maintaining a high polishing rate. The corresponding final groove depth is approximately 4 μm for face dressing, about 5 μm for line dressing and about 16 μm for pointing dressing. A careful examination of Figure 14 reveals that there is less variation of polishing rate with the

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dressing depth for point-cutting as compared with that of line and face-cutting, implying that the point-cutting should be chosen to ensure a stable polishing rate.

Dioxide polishing typically proceeds with the formation of a hydrated layer by means of a chemical reaction. This hydrated layer is taken away by the abrasive particles that are held on the top of the pad. Materials on the wafer surface are removed by combined chemical and mechanical actions. Figure 15 shows the variation of the polishing rate with the groove density formed by point-cutting under a dressing depth of 100 μm. Groove density is defined as the amount of groove created per unit area. The polishing rate of the oxidized wafer initially increases with the groove density, reaching a maximum value at a groove density of approximately 15%, and then decreases gradually as the groove density is increased further. Although an increase in the groove density facilitates the transport of fresh slurry into the pad surface, and thereby promotes the chemical action, it can also inhibit mechanical action. As a result, excessive groove density causes a reduction of polishing rate. This effect should be taken into account during the CMP process.

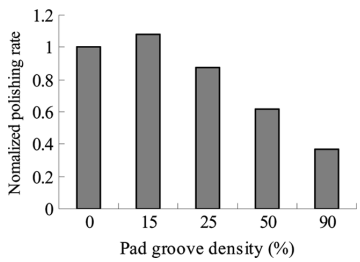

FIGURE 15 Variations of polishing rate with groove density.

CONCLUSION

The grooves of the pad dressed by a single diamond with various shapes were characterized, and the polishing rates of silicon dioxide by the resulting pad were investigated. Experimental results reveal that the shape of the diamond markedly influences the resulting structure of the asperities on the pad. The ridges form along the sides of the groove as the diamond moves over the pad. The polishing rates initially increases and reach a maximum value at a ridge height of under 5 μm for face-cutting, approximately 5 μm for line-cutting and about 8 μm for pointing-cutting. Then, as the ridge height is increased further the polishing rate decreases gradually. Comparing with line-cutting and face-cutting,

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point-cutting removes less amount of the pad. It also results in a higher but less variation of polishing rate during the CMP process.

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