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Novel diamond conditioner dressing characteristics of CMP polishing pad

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ABSTRACT

A diamond pad conditioner or dresser is required to regenerate the asperity structure of a pad used in chemical mechanical polishing (CMP). A conventional diamond dresser (CDD) is made by attaching discrete diamond grits to the flat surface of a substrate. Although the CDD has regularly distributed diamond grits, the tips of diamond grits are not leveled to the same height. Additionally, diamond grits have different shapes and orientations. A newly designed diamond conditioner, called the advanced diamond dresser (ADD), is made by sculpting a sintered polycrystalline diamond substrate to form identically shaped tips with diamond pieces of equal height, rather than by attaching individual diamond grits to a metal substrate. The dressing characteristics of pad surface textures are compared with those of a CDD. Experimental results reveal that the ADD can create asperities of the pad more uniformly than the CDD. Not only the dressing rate of the ADD is reduced by about 30% but also the stable pad surface texture is formed more quickly than the dressing can be performed using the CDD, extending pad life. The polishing rate of the ADD exceeds that of the CDD. The polishing rate varies with the polishing time, which is less for ADD than for CDD.

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1. Introduction

Chemical mechanical polishing (CMP), a planarization process, is adopted to fabricate silicon wafers to produce globally planar wafer surfaces. CMP also enables the miniaturization of features, memory devices and other sophisticated chips in ultra-large scale integration (ULSI) [1–4]. In the CMP process, a rotating wafer is polished against a rotating polyurethane pad. The top pad surface is permeated with slurry containing chemicals reagents – either a hydrated layer of oxide materials or a passivated layer of metal materials – formed in a chemical reaction. Abrasive particles on top of the pad asperities are employed to remove this reaction layer. Polishing of the wafer causes gradual accumulation of the reaction product into the pores and the asperities of the pad surface, resulting in the so-called glazing of the pad. Accordingly, the polishing rate of the wafer falls substantially [5–8]. To enable the CMP to continue, the polyurethane pad used for holding abrasive particles must be periodically dressed by a diamond pad conditioner to maintain its surface texture and to regenerate the asperity structure of the pad optimized for efficient polishing of wafers.

The current CMP diamond pad conditioner contains numerous diamond grits on the flat surface of a metal substrate, formed by either electroplating nickel or brazing with alloy. The diamond grits used for CMP dressers are industrial diamonds. Although the conventional pad conditioner contains regularly distributed diamond grits, the tips of diamond grits are not leveled to a single height. Additionally, diamond grits have various shapes and orientations and so their dressing behaviors are unpredictable [9]. Liao et al. [10] studied the fundamental characteristics of the dressing action on a polyurethane pad firstly by using a single diamond in various orientations, with various dressing parameters and dressing paths. They noted that a groove with pile-up on both side-walls forms as the diamond moves over the pad. The diamond orientations dramatically affect the asperities on the pad, and point-dressing is a more effective means of cutting than is plowing. In contrast, plowing is the major mechanism responsible for this surface topology when dressing involves face-dressing. The height of the ridge varies with dressing depth and dressing path, less for point-dressing than for face-dressing and line-dressing, explaining the preference for point-dressing.

The Applied Materials Company, as the leading maker of polishers, is advancing the electrolysis chemical mechanical polishing (ECMP) technology by the electrical oxidation of copper upon contact with high points of pad asperities, to cope with delicate dielectric layers [11]. Rohm and Haas Electronic Materials

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IPR2024-00534
Samsung Electronics Co. Ltd. et al v. Chien-Min Sung

Company, a major pad supplier, is introducing a new pad (EV4000) whose surface has a much greater compressibility than the conventional IC1000 pad, which has been the industrial standard for CMP [11]. As new polishing pads and polishing machines are being sought, better and more reliable pad conditioners are required. The ideal conditioner should have exactly the same shape, size and orientation as diamond grits, and the spacing between the diamond grits should be identical [12]. This work presents a novel design for diamond pad conditioners based on the pattern forming of sintered polycrystalline diamond (PCD) composites to form specifically shaped cutting tips. The new diamond pad conditioner contains identically shaped tips and diamonds of equal height. The dressing characteristics of pad surface textures were studied by comparing with the conventional diamond conditioner. This investigation contributes to the understanding of conditioning techniques and further improvement of the CMP process.

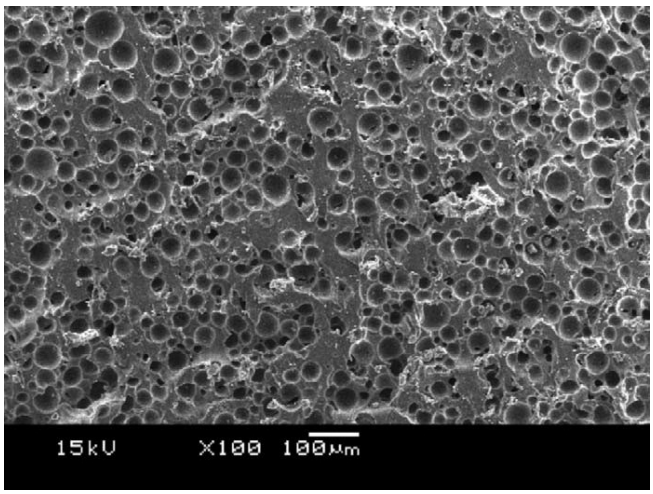


Fig. 1. SEM images of unused pad surface (IC1000).

2. Experiment

2.1. Polishing pad

The polishing pad used herein is an IC 1000 without grooves, manufactured by Rohm–Haas from polyurethane-based foam. The pads are skived or cut from a cake. Foam density, open or closed cells, cell shape and intrinsic polymer properties determine the final properties of the pad. Polyurethane pads contain a distribution of asperities, pores and grooves. The pore volume represents approximately 35% of the total volume, but can be varied by altering the manufacturing conditions. The isolated pores are spherical with diameters in the range 20–50 µm [13–16] (Fig. 1). The asperities of the pad surface are important since they determine the area of contact with the surface of the wafer.

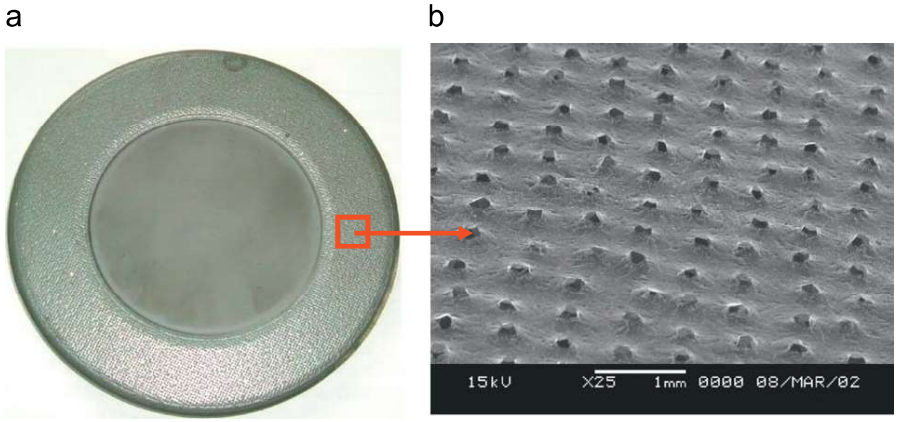


Fig. 2. (a) Conventional diamond dresser (CDD) and (b) an SEM micrograph of diamond grits attached to a flat substrate by brazing to form cutting tips.

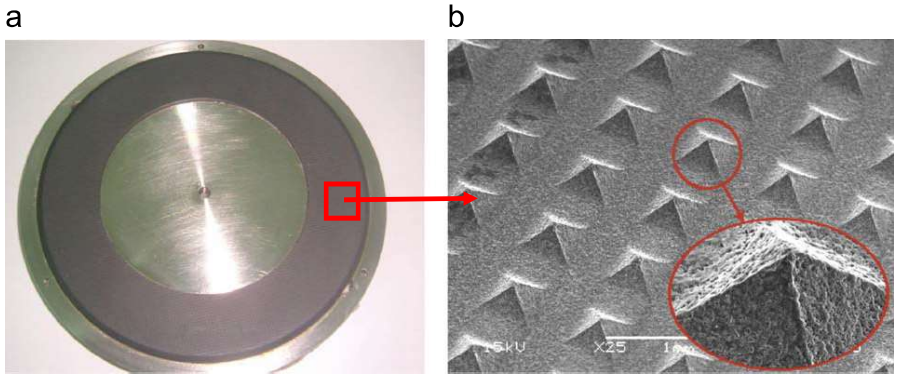


Fig. 3. (a) Advanced diamond dresser (ADD) and (b) an SEM image of cutting pyramids formed on the surface of a polycrystalline diamond.

Sung Exhibit 2003
IPR2024-00534
Samsung Electronics Co. Ltd. et al v. Chien-Min Sung

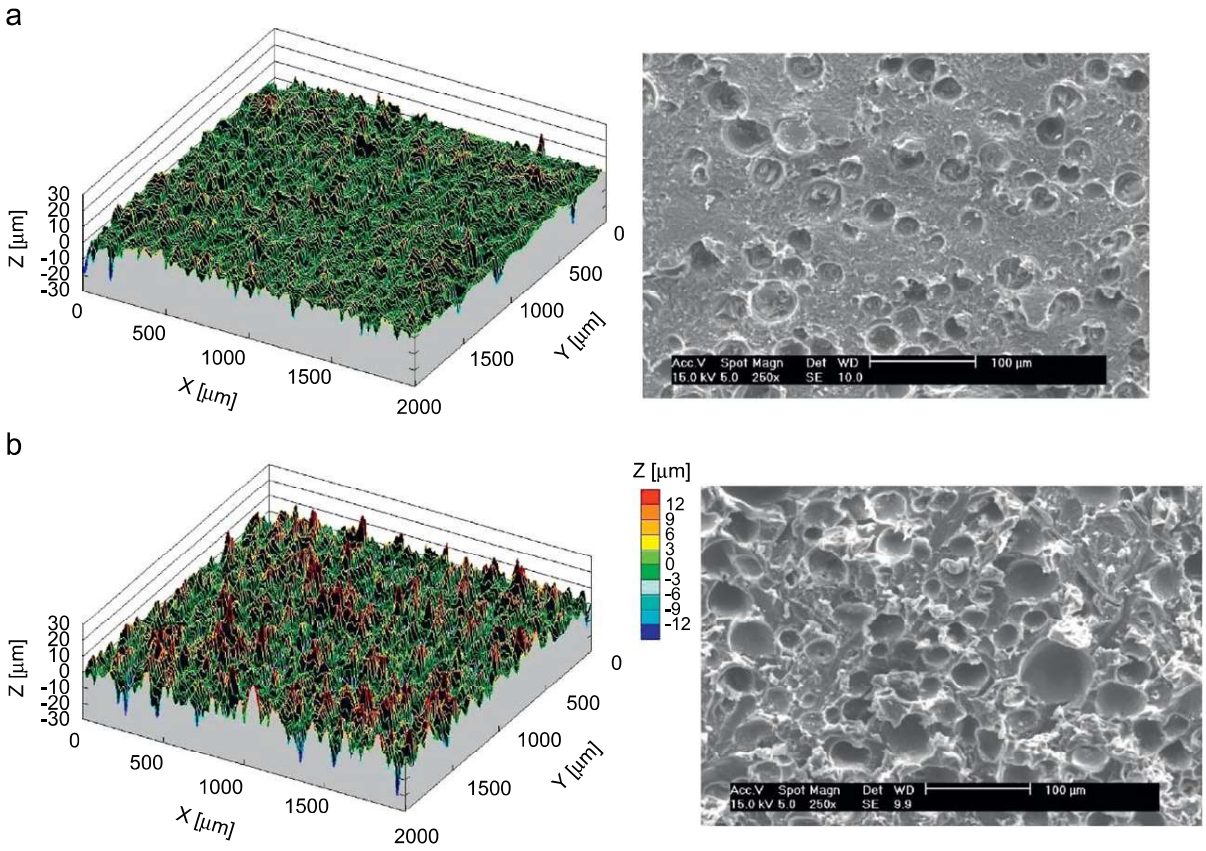


Fig. 4. The images of the pad surface formed by (a) ADD and (b) CDD.

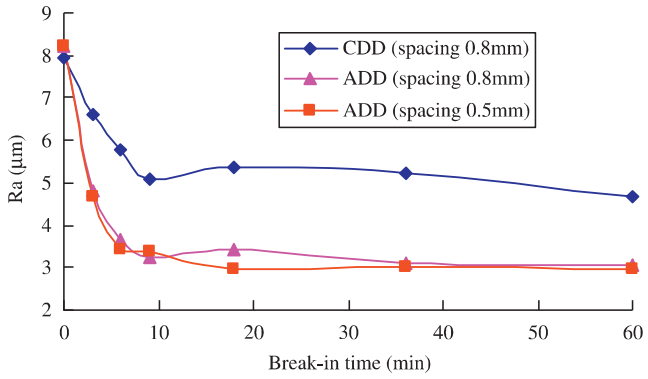


Fig. 5. Variation of surface roughness R_a with break-in time.

2.2. Conventional diamond conditioner

A conventional diamond pad conditioner contains single-crystalline diamond grits of length 200 μm, for example that are attached to a metal substrate such as stainless steel by either electroplating of nickel or brazing with an alloy. The conventional diamond pad conditioner used herein is the DiaGrid dresser, manufactured by Kinik Company of Taiwan; it is bonded with metal using a brazed nickel alloy. In this work, the DiaGrid dresser is called the conventional diamond dresser (CDD). The diameter of the brazed diamond disk was 100 mm, the spacing between diamonds was 800 μm and the diamond protrusion was 100 μm, as presented in Fig. 2.

2.3. Novel diamond conditioner

The novel design of a diamond dresser is based on the forming of a pattern in a strong polycrystalline diamond material that is sintered at ultra-high pressure about 6 GPa and high temperature approximately 1350 °C. The PCD substrate is formed from intergrown matrix microscopic diamond grains (e.g. 10 μm) with a volume occupancy of over 95%. Each diamond grain is strongly supported by merging with surrounding grains and so the global structure is virtually a continuous diamond mass. Restated, PCD contains a micron-scale powder of diamonds, fully sintered together. The PCD dresser is called the advanced diamond dresser (ADD) in this study. Such an advanced diamond disk is manufactured by wire electrodischarge machining to yield cutting pyramids of a particular size and designed shape, as displayed in Fig. 3. The diameter of the advanced diamond disk was 100 mm, the spacing between diamonds was 800 and 500 μm and the protrusion of diamonds was 100 μm.

2.4. Experimental apparatus

The dressing experiments were performed using a commercially modified polishing machine with a variable speed and a polishing plate with a diameter of 200 mm, on which a polishing pad was mounted. The diamond pad conditioner was attached to a holder, which was connected to a head that rotated at 120 rpm. A polyurethane pad was mounted on a table disk that rotated at 110 rpm. The applied load was about 60 N. After the pad had been dressed, its surface topology was examined using a stylus-type 3D surface roughness measuring instrument. The radius of the

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Samsung Electronics Co. Ltd. et al v. Chien-Min Sung

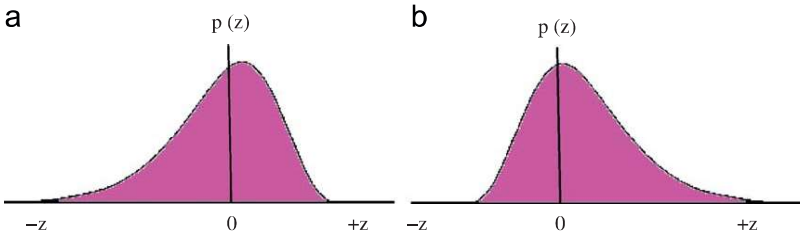


Fig. 6. Schematic drawing of the notion of skewness: (a) negative skewness and (b) positive skewness.

diamond tip probe, the nose angle and the measuring force were 5 μm, 90° and 4 mN, respectively. Measurements were made using three images. Each image was made over 50 scan curves and 35,000 points within the $2\,\text{mm} \times 2\,\text{mm}^2$ area of the pad. In the figures given in the next section, the values of roughness are the averages of three measured values. The reliability of the measured roughness data is approximately equal to the statistically averaged value of 150 measurements. A scanning electron microscope (SEM) was utilized to observe the morphology of the pad, including the pores.

The polishing experiments are conducted 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 to specimens, and a dispenser is used to supply slurry. The specimens are oxide wafers with a thickness of 8000 Å and dimensions of $18 \times 18\,\text{mm}^2$. The specimens are attached to a holder that is connected to a wafer carrier head that rotates at 120 rpm. A polyurethane pad is mounted on a table disk that rotates at 110 rpm. The applied pressure is about $0.4\,\text{kg cm}^{-2}$. The polishing slurry used in the experiments is SS25, produced by the Cobat Company. The thickness of the oxide layer on wafers is measured before and after polishing using a system that is commonly applied to measure the thickness of thin films, with a measurement range of 100–1,50,000 Å. The data reported herein are measured at 17 positions.

3. Results and discussion

Fig. 4 shows representative example images of the pad surface obtained using the stylus-type instrument and SEM after 60 min of dressing using ADD and CDD, respectively. In the figure, CDD forms an uneven texture with variable asperities. The ADD dresses the pad more uniformly, markedly reducing the amount of slurry that is required in the CMP process. Most pores remain round, like those of the unused polishing pad, after dressing by the ADD dresser. In contrast, when the CDD was used, the pores become irregular and rough. As a result, substantially more slurry is used in the CMP process.

In general, a new pad must be polished before the wafers in the break-in stage to establish a baseline pad surface, since a new pad has an amplitude or wavelength of tens of microns, spread over the top of the pad, because of the thickness variations and the surface waviness [17,18]. Restated, break-in refers to the process of conditioning to define the initial pad surface texture. Fig. 5 compares the average surface roughness R_a in a break-in process obtained using ADD and CDD. In the figure, the surface roughness R_a of the pad that was dressed using the ADD is substantially less than that obtained after dressing using the CDD. The surface roughness R_a declines with the break-in time up to about 6 min for the ADD and up to 6–9 min for the CDD. It remains constant as the break-in time is increased further, indicating that the dressing of the ADD is effective and reproducible. This reproducibility may ensure the consistency of wafer polishing by CMP. The results also confirm that a stable pad surface structure is established faster using the ADD than the CDD because the number of effective cutting tips of the ADD dresser exceeds that of the CDD since the former has identically shaped tips and diamond pieces of equal height.

Although the arithmetic mean of surface roughness R_a is most commonly considered in quality control, it is insensitive to small changes in profiles and does not provide information on the distributed asperities. In statistics, skewness measures the degree of asymmetry of a distribution. Hence, skewness here characterizes the height distribution of the pad surface. A distribution with no skewness is a normal (Gaussian) distribution, and herein refers to a perfectly symmetrical distribution of peaks and valleys in the pad surface. Skewness in the normalized is given as

$$\text{Skewness} = \frac{1}{\sigma^3}\int_{-\infty}^{\infty} z^3 p(z)\,dz \tag{1}$$

where z is the height of the surface measured, $p(z)$ is the probability distribution function and σ is the standard deviation [19]. Both skewed distributions have one tail that is longer than the other, as presented in Fig. 6. A negatively skewed distribution has a longer tail to the left. The distribution is concentrated to the right, as displayed in Fig. 6(a). Conversely, a positively skewed distribution has a longer tail to the right. The distribution is concentrated to the left, as shown in Fig. 6(b). Bhushan [20] studied the effect of skewness on the real area of contact. He pointed out that the real area of contact increases with the negative skewness. Consequently, the skewness is associated with the sharing of polishing pressure. Negative skewness represents a situation in which more asperities share the polishing pressure and a higher density of asperities is in close contacts with the wafer surface than when skewness is positive.

Fig. 7 plots the height probability distribution of the surface of an unused pad, one dressed by ADD for 18 min and the other dressed by CDD for 18 min. The unused pad has negative skewness as shown in Fig. 7(a), because the polishing pad surface has asperities and randomly distributed intrinsic pores constitute up to a relatively large 35–50% of the total volume [2]. The pore volume dominates the variability of measured surface roughness. The height probability distribution of the pad surface dressed by ADD is a substantially negatively skewed value, about −1.2667 as presented in Fig. 7(b). The skewness associated with the CDD tends toward zero as displayed in Fig. 7(c). The resulting data confirmed that the natural pores at the pad surface cannot be damaged using an ADD. Fig. 8 plots the variation of skewness with break-in time for the ADD and CDD. Significant differences between the pad surface textures are observed. For the CDD conditioner, the skewness increases with the break-in time up to 6–9 min. The ADD increases negative skewness for 6 min. In both cases, skewness remains unchanged as the break-in time is

Sung Exhibit 2003
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Samsung Electronics Co. Ltd. et al v. Chien-Min Sung

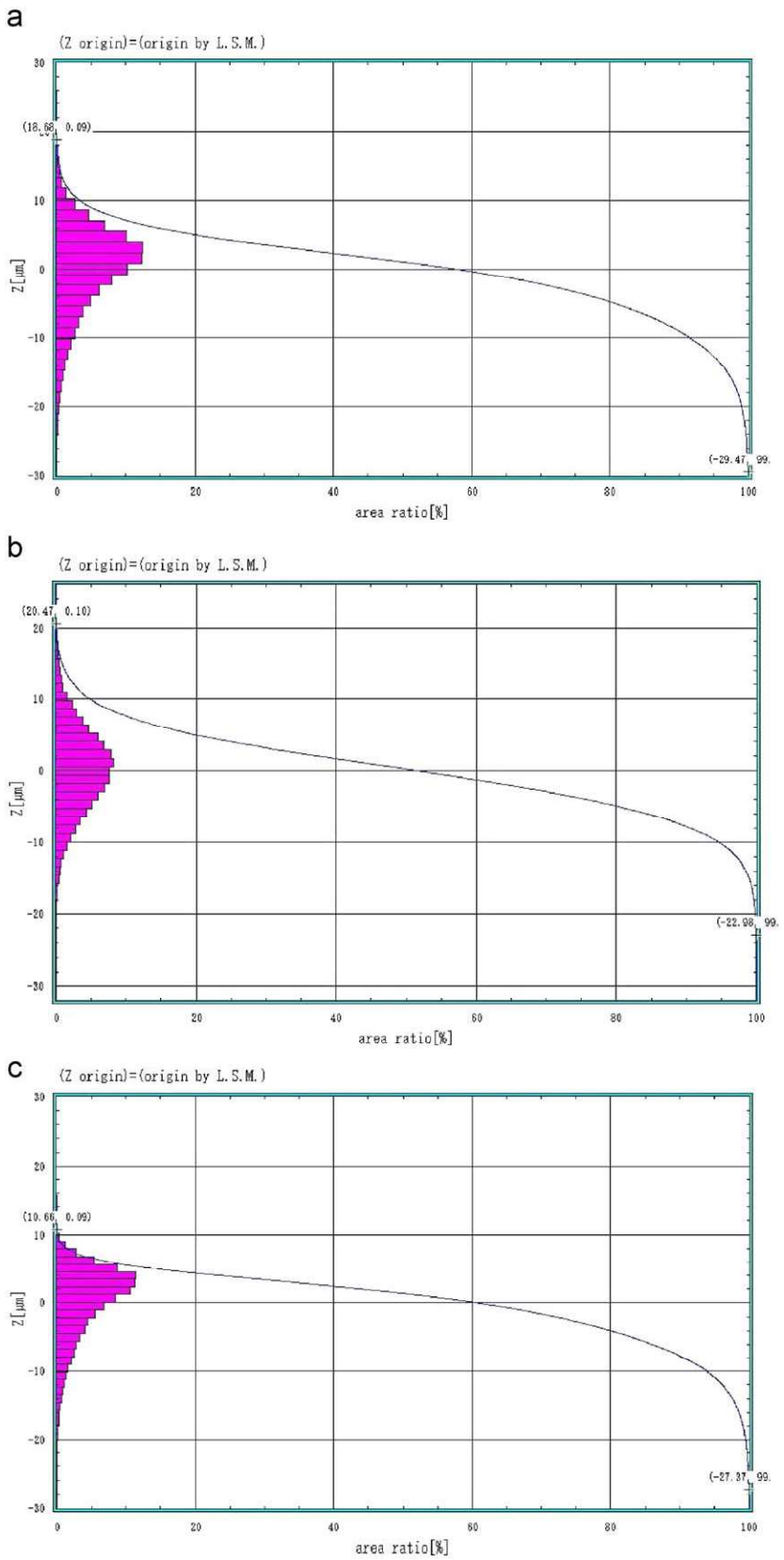


Fig. 7. Representative height probability distributions of the pad surface: (a) unused pad (b) CDD and (c) ADD after 60 min of dressing.

Sung Exhibit 2003
IPR2024-00534
Samsung Electronics Co. Ltd. et al v. Chien-Min Sung

increased further, suggesting that when the ADD is used, more asperities points share the applied load, reducing the contact pressure while the real area of contact between the wafer and the pad is increased. Restated, a more textured pad surface traps more abrasive particles on the asperities. Additionally, the results verified that a stable pad surface structure is established by ADD more quickly than by CDD.

The dressing rate was one of the most important factors that influenced the surface condition of the pad. The amount of pad surface that is removed per unit time is the dressing rate. The dressing rate unit is μm/h in the paper, and it is computed by the pad thickness removed divided by dressing time. A representative example of 3D image of dressing rate measured by a stylus-type instrument is shown in Fig. 9. Fig. 10 plots the variation of the dressing rate with the diamond conditioner. The dressing rate of the ADD is lower than that of the CDD, and the conditioner with a larger diamond spacing (800 μm) provides a higher dressing rate, as expected. Based on the observations herein, the ADD can produce a stable pad surface while consuming less pad material.

Fig. 11 plots the variation in R_a and skewness with polishing time in the absence of conditioning when ADD and CDD are used, respectively. It is found that the surface roughness R_a and skewness drop with the polishing time. This is because the interfacial wear between the wafer and the pad during polishing flattens the asperities of the pad surface. A comparison of the surface roughness values delivered by pads that have been dressed by different dressers is shown in Tables 1 and 2. As shown in Tables 1 and 2, the skewness for the CDD decreases with polishing time from −0.243 at 0 min to −1.188 at 30 min. The surface roughness R_a for the CDD reduces with polishing time from 4.31 at 0 min to 3.53 at 30 min. It is found that the skewness decreases faster than R_a value, implying that the skewness variation of the pad with the polishing time is comparatively sensitive with the R_a value. In addition, for the ADD, the skewness decreases with polishing time from −1.169 at 0 min to −1.75 at 30 min. The surface roughness R_a reduces with polishing time from 3.25 at 0 min to 2.94 at 30 min. The surface roughness parameters for the CDD fall faster than those for the ADD, indicating that the CDD is associated with the faster wearing of pad material and larger changes in the pad surface features during polishing. Accordingly, the ADD is associated with a longer lifetime of the pad.

In general, pad glazing by abraded pad materials and slurry residues is responsible for the drop in the removal rate over time in the absence of pad conditioning. Fig. 12 plots the variation of the polishing rate with the polishing time without conditioning. The polishing rate of the wafer falls substantially as expected. In the figure, the polishing rate of the oxidized wafer of the ADD exceeds that of the CDD, because it is performed by the contact

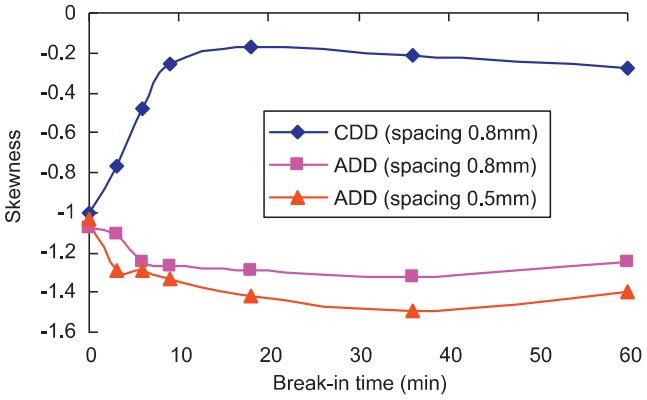


Fig. 8. Variation in skewness with break-in time.

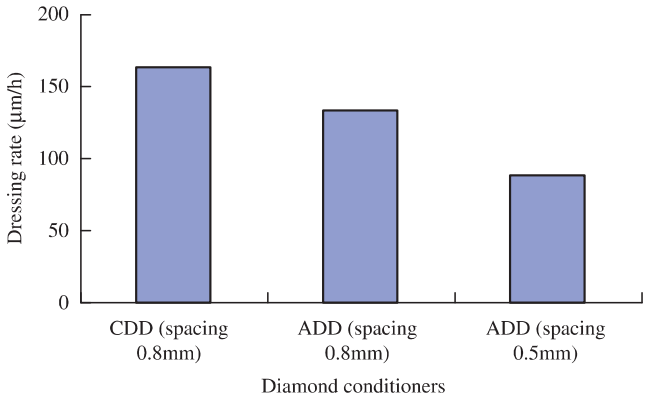


Fig. 10. Variation in dressing rate with diamond conditioners.

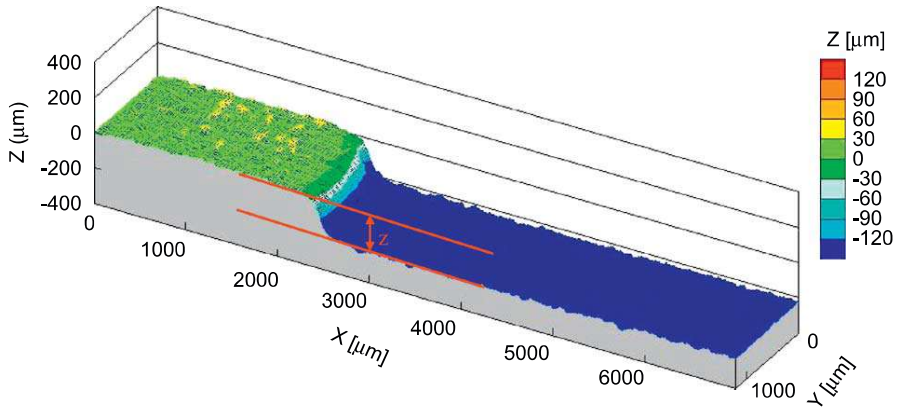


Fig. 9. 3D image of pad surface after 60 min dressing and Z is the pad thickness removed.

Sung Exhibit 2003
IPR2024-00534
Samsung Electronics Co. Ltd. et al v. Chien-Min Sung

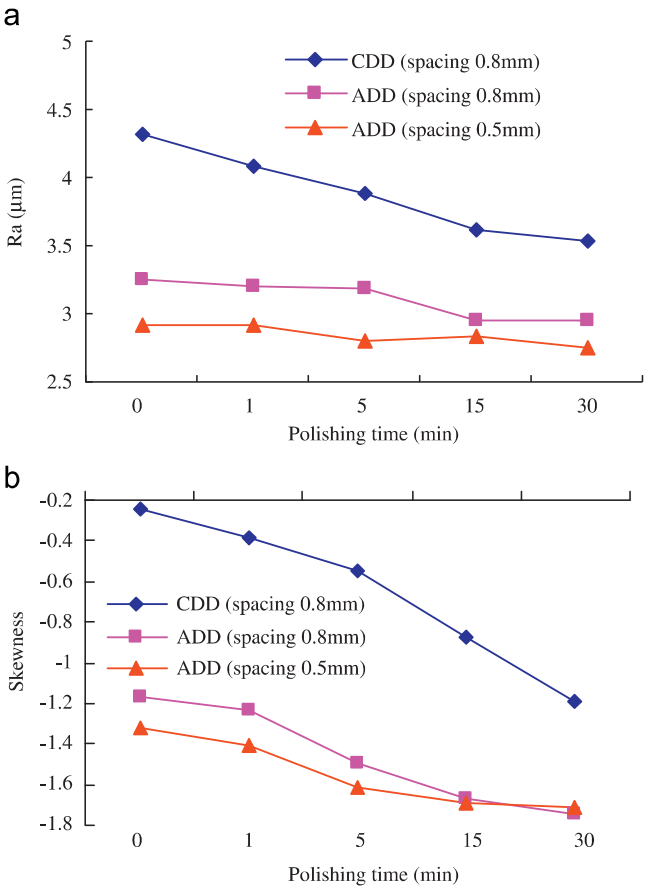


Fig. 11. Variation in surface roughness R_a (a) and skewness (b) with polishing time.

Table 1
Pad surface roughness values (R_a in (μm)) dressed by the different dressers.

Diamond dressers	Polishing time (min)				
	0	1	5	15	30
CDD (spacing 0.8 mm)	4.31	4.0825	3.876	3.61	3.53
ADD (spacing 0.8 mm)	3.25	3.206	3.19	2.95	2.94
ADD (spacing 0.5 mm)	2.92	2.91	2.805	2.83	2.75

between the wafer and the pad, and ADD can produce more asperities on the pad, which hold more abrasive particles, such that the removal rate is higher. Additionally, the polishing rate varies less with the polishing time for ADD than with CDD, perhaps because the variation in the pad surface roughness with the polishing time is less upon dressing with ADD. As displayed in Fig. 13, the glazed area of pad surface for the CDD is larger than that for the ADD. In the figure, the pores of the polishing pad for the CDD are filled with residual slurry reducing the area of slurry transport during polishing [21].

4. Conclusions

A revolutionary design of pad conditioners is based on the carving of a structure out of sintered polycrystalline diamond

Table 2
Pad surface roughness values (skewness) dressed by the different dressers.

Diamond dressers	Polishing time (min)				
	0	1	5	15	30
CDD (spacing 0.8 mm)	−0.243	−0.3876	−0.5497	−0.876	−1.188
ADD (spacing 0.8 mm)	−1.169	−1.23	−1.5	−1.6678	−1.75
ADD (spacing 0.5 mm)	−1.322	−1.41	−1.678	−1.6925	−1.71

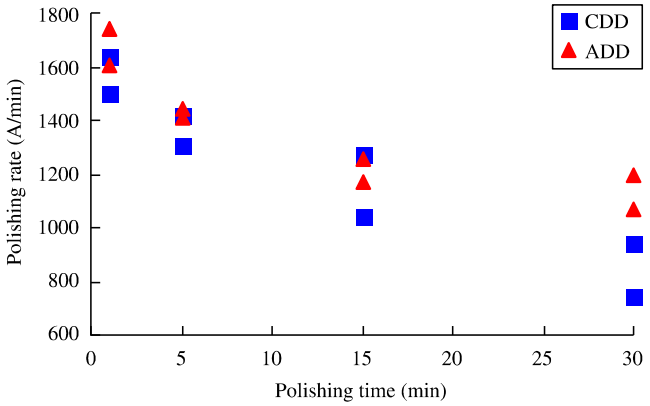


Fig. 12. Variation in polishing rate with polishing time.

matrix to form identically shaped tips and diamond pieces of equal height. The dressing characteristics of pad surface textures are experimentally studied by comparing with the CDD. Based on this investigation, the following conclusion can be drawn.

1. The pad surface roughness R_a of about 3.25 μm dressed using the ADD is less than R_a by about 4.45 μm obtained after dressing using a CDD. The skewness of the pad surface of about −1.2667 dressed by the ADD is also significantly lower by about −0.243 created by the CDD, indicating that the ADD can produce asperities of the pad more uniformly than the CDD during the break-in process.
2. The surface roughness of the pad surface remains constant after 6 min break-in for the ADD, and after 6–9 min break-in for the CDD. The results verified that the stable pad surface structure is established faster using the ADD than dressing performed using the CDD.
3. The dressing rate of the ADD, approximately 130 μm/h lower than that of the CDD, approximately 170 μm/h, indicates the pad is less worn during the break-in process for ADD, and hence the pad life is extended. As a result, reduction of the cost CMP is expected.
4. The polishing rate of the ADD, about 168 nm/min, is higher than that of the CDD, about 157 nm/min. There is less variation in the polishing rate with the polishing time for ADD from 168 nm/min at 1 min to 113 nm/min at 30 min as compared with that of CDD from 157 nm/min at 1 min to 84 nm/min at 30 min. The use of the ADD in the CMP process is recommended.

Sung Exhibit 2003
IPR2024-00534
Samsung Electronics Co. Ltd. et al v. Chien-Min Sung

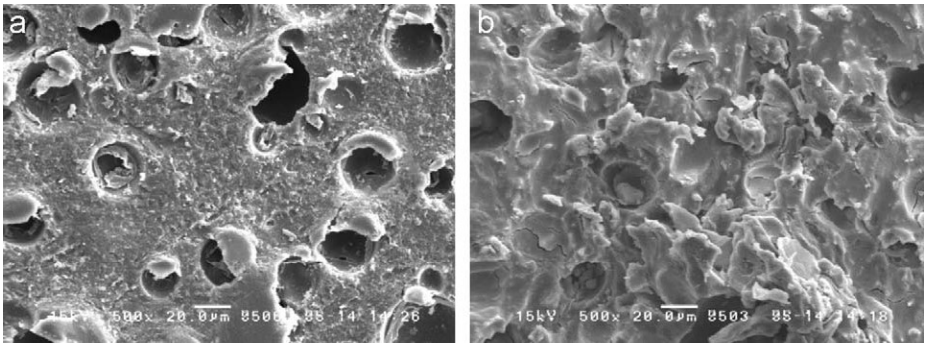


Fig. 13. SEM images of pad surface formed by (a) ADD and (b) CDD without conditioning of 30 min.

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