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ORIGINAL ARTICLE

Analysis and improvement of the pad wear profile in fixed abrasive polishing

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Abstract Fixed abrasive polishing has some advantages in generating good planarization surfaces with low defects. The surfaces after polishing have better uniformity, and the material removal rate is much higher than that of the traditional chemical mechanical polishing using loose abrasives. One of the most important factors that have significant effects on the uniformity of the polished surface is the pad wear profile. The pad wear profile after a long time of polishing is almost concave, and it has been challenging to create a flat surface. Therefore, there is a requirement for creating a better pad wear profile to improve quality of machined surfaces in chemical-mechanical polishing processes. In this paper, kinematic aspects of the effects of operation parameters on the pad wear profile are investigated, combining with conditioner sizes, pattern, and positions. Based on that, a new model, including new designs of the conditioner and pad, is proposed. This new model has created a convex pad wear profile instead of a concave one. According to the result of the new model, the pad shape after the conditioning process is more uniform than the old one conditioned by the old model. The result was validated by an algorithm which was validated by the experiments reported in our previous paper.

Keywords Chemical mechanical polishing · Fixed abrasive pad · Kinematic analysis · Pad wear profile

1 Introduction

Chemical mechanical polishing (CMP) is a planarization process which creates a surface with high levels of planarity and low defects. The workpiece surface is held by a rotating carrier and faced against a rotating pad surface. The pad surface is refreshed by a rotating conditioner. This conditioner also oscillates in the pad radius direction.

Both the conditioner and the workpiece surface cause the pad surface wear with time. The pad wear rate is affected by many factors [1, 2], such as soaking time, conditioning pressure, and the pad's and conditioner's properties. Many investigations have shown that the conditioner effect is the most significant factor for the pad wear profile. After long polishing periods, the pad is almost concave which results in the non-uniformity of polished surfaces. It has been challenging to create an improved pad surface [3]. Therefore, it is important to improve the conditioner to create a better pad wear profile and as a result better workpiece surfaces.

There are two types of pads used in the polishing: a soft pad with loose abrasives and a hard pad with abrasives embedded on the pad's surface, which is called the fixed abrasive pad [4]. Many researchers have shown that the hard pad gives better uniformity but worse roughness surfaces, compared to the soft pad. In this study, the fixed abrasive pad conditioning is further investigated based on our previous work [5]. The effects of many parameters, including operation parameters, sizes, patterns, and position of conditioners, on the pad wear profile were investigated. Based on that, a new model of the chemical mechanical polishing was proposed to get a better pad wear profile. This model was a combination of a new design of both

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the conditioner and the pad. A program reported in the previous research [5] was used to simulate the pad profile created by the new model.

2 Literature review

Many researchers have used kinematic analysis to investigate the conditioning process [5–8]. However, almost all the above research studies are about the soft pad, not the fixed abrasive pad. Feng [9] showed that when the dimension of the conditioner decreased, the uniformity of the pad wear profile increased. In addition, patterns of the grain distributions on the conditioner surfaces had no effect on the pad wear profile generation. However, there are two problems of the research. First, the pad wear profile after a long time of polishing was always concave. Second, the grain distributions were on the same area of the conditioner surfaces.

Baisie et al. [10] also investigated different patterns of grain distributions on the conditioner surfaces to optimize the conditioning processes. Their research concluded that the sweeping profile of the conditioner affected the pad profile [11]. They proposed a flat pad profile, but “there always exist some transition regions in the pad shape near the pad center and the pad periphery” [3]. It causes the concave shape of the pad wear after a long time of polishing. They suggested reducing the conditioner disc size to minimize the transition regions. However, a small conditioner can cause other problems such as some unconditioned pad area and large amount of time to finish conditioning the whole pad surface.

Kincal and Basim [12] proposed three types of sweep motions of conditioners including a commonly sinusoidal sweep, a custom sweep 1 in which the sweep is adjusted so that the conditioner disk spends a fixed time in each zone, and a custom sweep 2 in which the conditioner disk spends an equal amount of time per unit pad area. They concluded a smaller conditioner and the custom sweep 2 improved the pad thickness uniformity. Besides, by extending the sweep of the conditioner beyond the pad edges, the transition regions can be reduced.

All the improvements mentioned above are efficient in the CMP processes. However, there is no suggestion in creating a convex pad wear profile. Especially, they focused on the traditional CMP. In this article, the conditioning process in fixed abrasive polishing is investigated to improve the pad wear profile by creating a convex pad shape.

3 Materials

All of the research in this article is based on our previous paper [5]. The paper proposed a model to model pad wear shapes caused by a conditioner. The model is established on kinematic analysis of trajectory paths of conditioner grains. It is validated by experiment results with fixed abrasive pad.

In the model, the pad surface was divided into small areas. Based on the kinematic motions of the conditioner and the pad, trajectory paths of the conditioner abrasive grains were modeled. A program was built to count the number of passes of the paths on the small areas. In addition, if in the first time step and the second time step, the coordinates of the small areas are the same, the number of passes is increased by 1. For that reason, the number of passes in the model is an expression of not only the effect of cutting density of grains but also the contact time between the grains and the small area. The number of passes was changed to a negative value so that the more the number of passes was, the deeper the pad area was. The cross section of the pad was shown on the oscillation direction of the conditioner. This curve represented the profile of the pad shape.

3.1 Effects of the conditioning process parameters

The conditioning process parameters, such as the speeds of the conditioner and the pad, and the oscillation velocity of the conditioner can affect the pad wear profile. By extending the model developed previously [5], effects of those parameters were examined. The rotation speeds of the pad and the conditioner are n_p and n_c revolutions per minute (rpm), respectively. The oscillation speed of the conditioner is n_o strokes per minute (strokes/min) as shown in Fig. 1. When the oscillation speed increases from 1 to 10 (strokes/min), the shapes of the pad wear are almost unchanged (Fig. 2). Similarly, the effect of the conditioner speed on the pad wear profile is small. When the conditioner speed increases from 1 to 100, the pad wear profiles are almost the same. When the pad speed is small, the change of the speed creates a significant change in the pad wear profile. When the pad speed increases, the pad wear profile tends to be stable (Fig. 2).

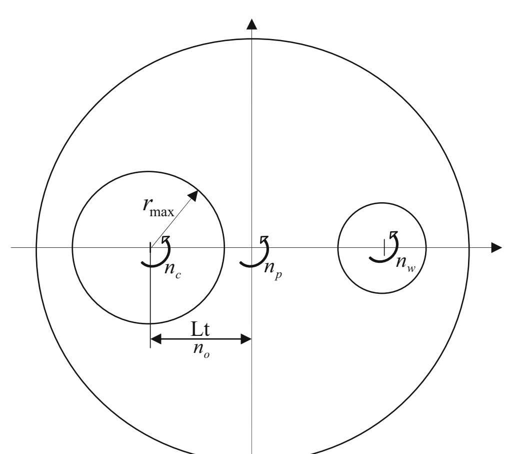
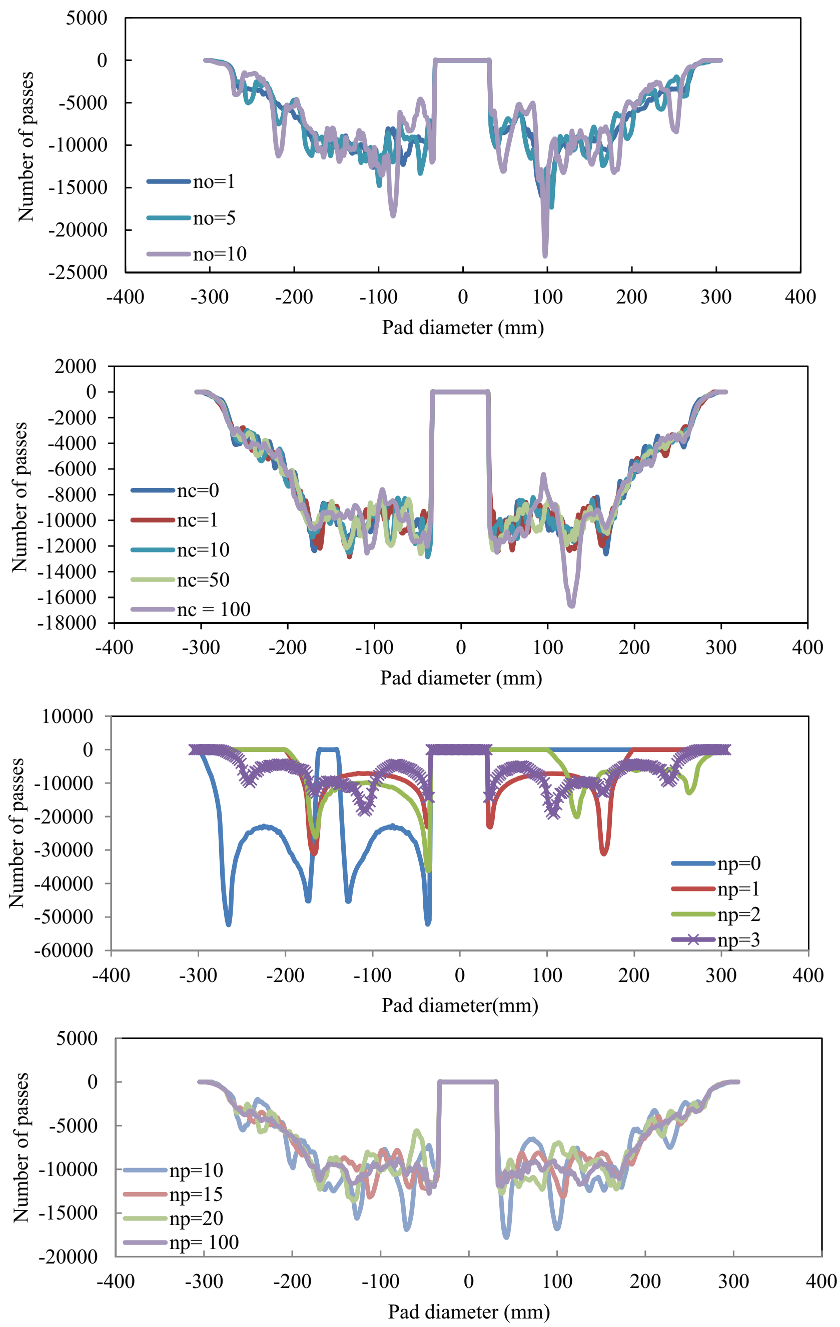


Fig. 1 Schematic of the fixed abrasive polishing process

Fig. 2 Effects of operation parameters on the pad wear shape



It can be concluded that the pad speed is one important factor affecting the uniformity of the pad wear profile. The more the speed of the pad is, the better the pad surface is after the conditioning process. However, there are not many differences in the pad wear profile when the pad speed is above 10 rpm.

3.2 Effects of sizes, patterns, and positions of the conditioners

The patterns on the conditioners affect the pad wear profile in some ways. Figure 3 shows pad wear profiles created by different patterns. The conditioner was static in this analysis. Therefore, the effect of the conditioner only impacted on the pad area below the conditioner, and it did not affect the other area of the pad. If abrasive grains cover the circle surface of the conditioner, the pad wear profile looks like a valley (Fig. 3c). When the abrasive grains are distributed on the conditioner from r_{min} to r_{max}, it creates a convex pad wear profile with deeper cutting near the pad center (Fig. 3a, b). The total number of abrasive grains distributed on the conditioner did not influence the pad wear profile but affected the cutting depth on the pad part which is conditioned.

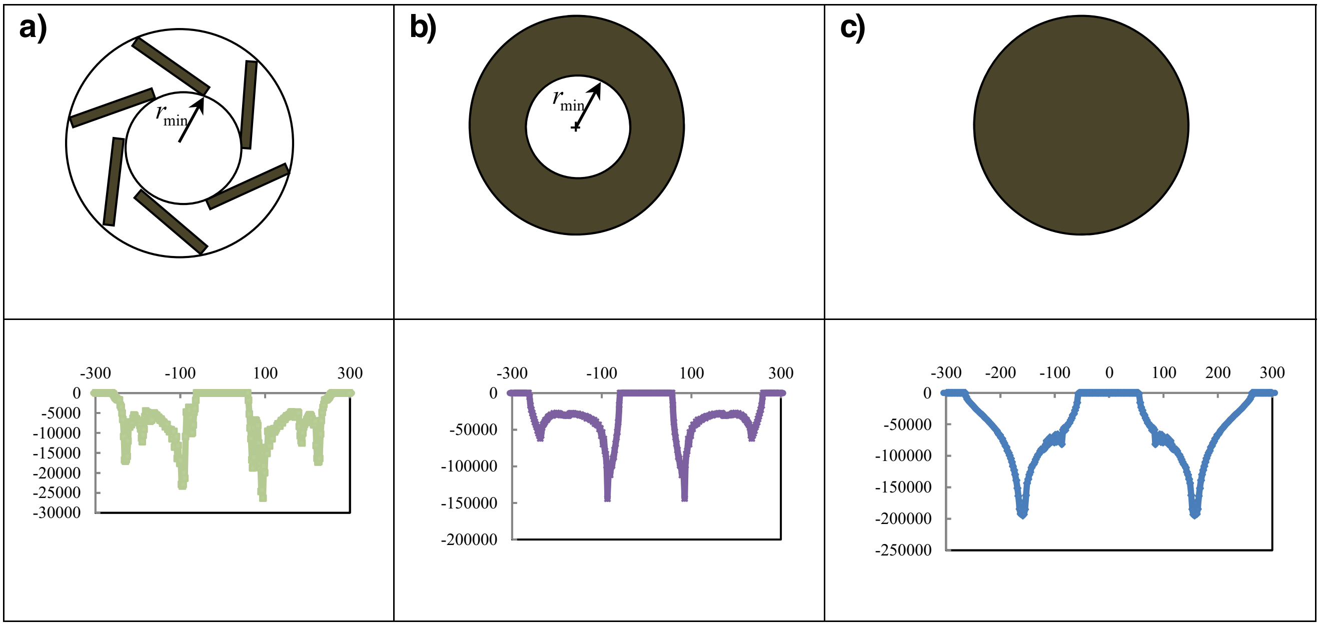


Fig. 3 Effects of conditioner's patterns on the pad wear shape when the conditioner placed static (only rotation, not oscillation)

The pad wear profile is sensitive to the conditioner sizes. As shown in Fig. 4, if the conditioner size decreases, the uniformity of the pad wear profile increases. However, if the conditioner size was too small, the conditioner did not cover the whole pad surface in the conditioning process. That means that the pad is not conditioned completely. The best value of the radius is about 30 mm. With this size of the conditioner, the pad is refreshed perfectly with acceptable uniformity.

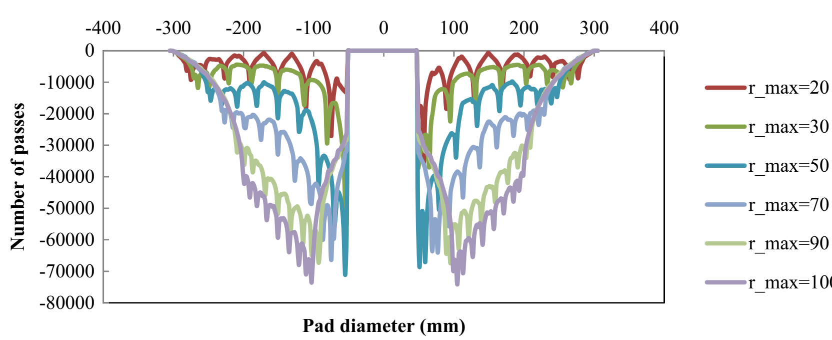
The position of the conditioner also played a significant role in forming the pad wear profile. Figure 5 presents the pad wear profile after conditioning with different positions of a static conditioner. The conditioner only rotated around its axis but not oscillated. The more close to the pad center the conditioner position is, the deeper the concave pad shape is.

4 Discussion and improvement

As shown in Sect. 3.1, the conditioner process parameters did not change the concave shape of the pad. Therefore, the pad wear profile cannot be improved by investigating those parameters. On the other hand, the pad size and the conditioner size affect the uniformity of the pad wear profile. The distribution of the grains on the conditioner is also an issue. The pad wear profile depends on the cutting density and the time contact between the pad surface and the conditioner grains [5]. The distribution of the grains on the conditioner surface determines the cutting density on the pad surface. In addition, the pad design also affects the pad wear profile [12]. Therefore, the best way to improve the pad wear profile is changing the conditioner and pad design.

Further investigation is established based on the analysis results in Sect. 3.2. When the grains on the conditioner distribute on the same area, from the radius of r_{min} to r_{max}, the pad wear profiles have the same shape (Fig. 3a, b). The lager the number of grains is, the deeper the pad wear profile is. When the conditioner disk size increases, the number of passes increases (Fig. 4). It means that the depth of pad wear d_p is proportional to the area of the conditioner grains A_c. The depth of pad wear also depends on the inside radius of the area of the grain distribution r_{min} (Fig. 3b, c). When the inside radius increased, the uniformity of the pad wear profile increased. In addition, the uniformity of the pad surface in the conditioning process increases when the

Fig. 4 Effects of the conditioner size on the pad wear shape



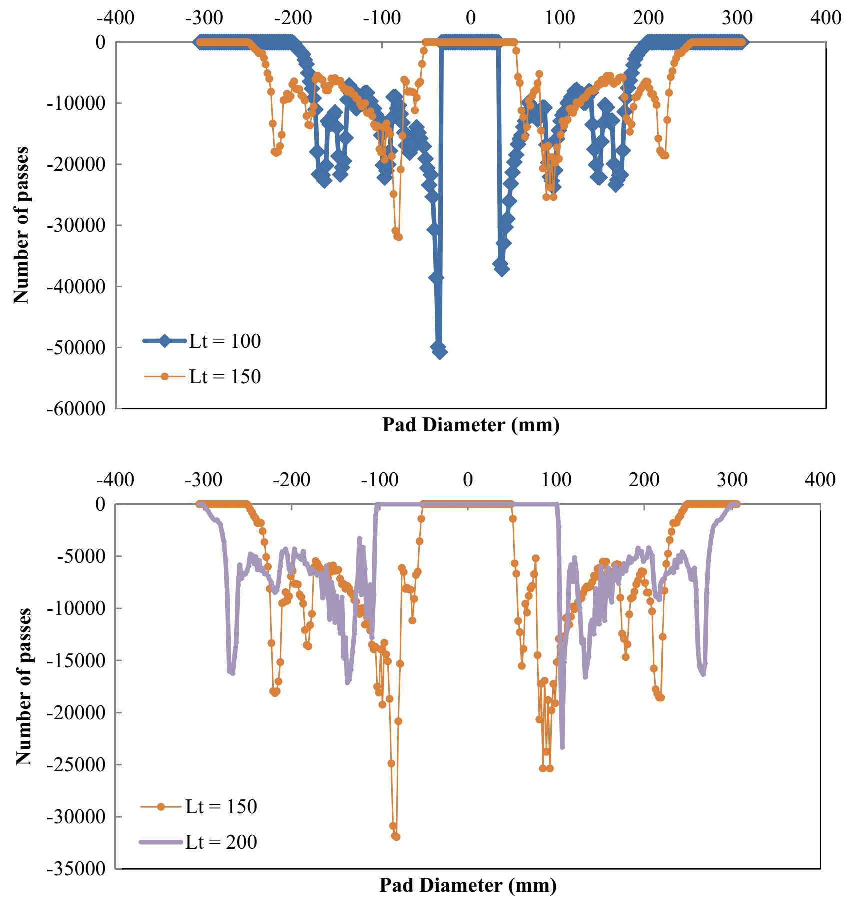


Fig. 5 Effects of conditioner's position on the pad wear shape

distance from the pad center to the conditioner center L_t increases (Fig. 5). Therefore, to improve the uniformity of the pad wear profile, L_t and r_{min} must be as much as possible and the area of the grain distribution must be as small as possible. However, in the conditioning process, the conditioner should not move over the pad center to avoid contact with the carrier on the other side, and the balance of the conditioner must be maintained. Therefore, the biggest value of r_{min} should be around 150 mm, and the value of (r_{max}–r_{min}) should be around 15 mm.

A new design of the conditioner was proposed to get better uniformity of the pad wear profile. The conditioner is a ring with a width of 15 mm and the inside hole diameter of 290 mm, as shown in Fig. 7. It is static, with only rotation, no oscillation. The distance between its center and the pad center is about 160 mm. The pad is modified by creating a hole with a diameter of 200 mm at the pad center. The rotation speeds of the conditioner and the pad can be any value above 10 rpm (Fig. 6).

The profile of the pad wear created by the new model is more uniform than that of the traditional model (Fig. 7). Instead of the concave shape, the new model created a slightly convex shape. Although the area of the pad surface in the new model is less than the old pad because of the hole at the new pad center, the uniformity of the new pad is much more improved. The flat part in the new pad wear shape is much more than the one in the concave shape. It promises better uniformity of the wafer surface in the CMP process.

The convex pad wear profile created by the new model has many meanings in CMP processes. First, it improves the uniformity of the pad surface, and through that, the uniformity of machined surfaces such as wafers and optical components

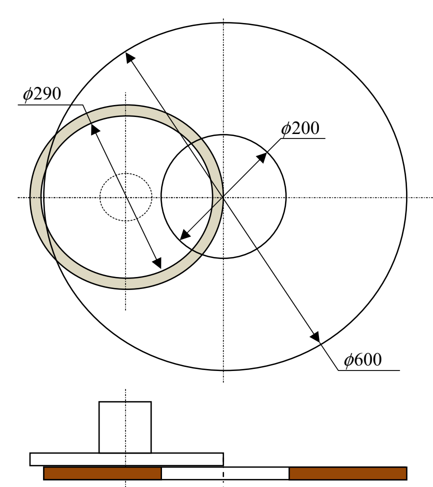


Fig. 6 A new model of the pad and conditioner shapes to improve the pad wear shape

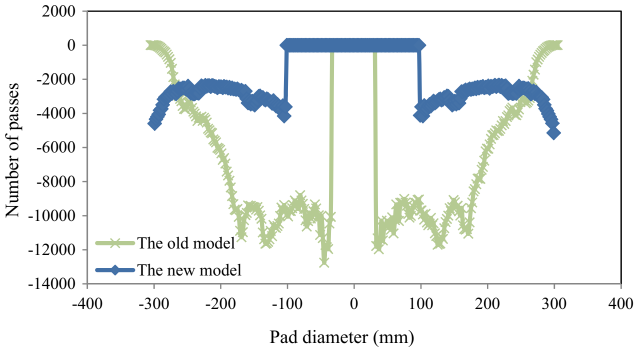


Fig. 7 The improved result of the pad wear shape of the new model compared to the old model

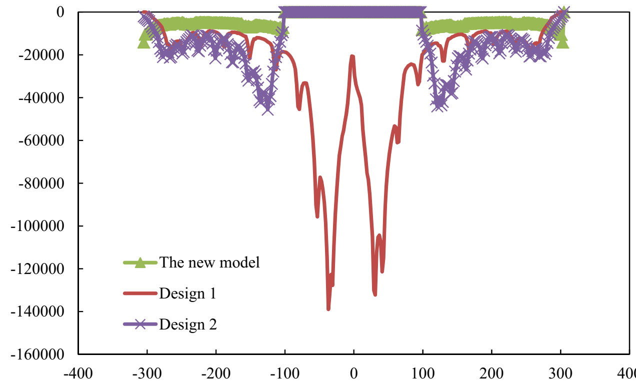


Fig. 8 Comparing effects of the new model, design 1 and design 2

increases. Second, the pad life is extended because the amount of the pad removed in the conditioning process is smaller than that in the old model (Fig. 7). Third, the pad surface is fully refreshed because the new conditioner always contacts the pad areas from inside edge to outside edge. Fourth, the conditioning process eliminates effectively debris created on the pad surface because of the hole at the pad center and the over edge cutting. When debris is created by the cutting actions of abrasive grains of the pad on the wafer surfaces and of the conditioner on the pad surface, it is flown away to the pad hole and out of the pad edge. The lesser the debris on the pad surface is, the lesser defects appear on the workpiece surface in the polishing process.

There are some theories about improving a pad wear profile, including using a smaller size of the conditioner and over edge conditioning. Figure 8 shows the effects of the small conditioner with a radius of 30 mm (design 1). The pad shape appears flat from the pad radius of 100 to 250 mm. However, from the pad radius of 0 to 100 mm, the conditioner creates deepest wear on the pad surface. For that reason, the pad deforms and consequently affects the rest of the pad wear profile.

As in the new model, there is a suggestion that the part of the pad from the radius of 0 to 100 mm should be removed. The purpose is to reduce the deformation of pad since the conditioner moves near the pad center. A hole with a radius of 100 mm was generated at the pad center. At first, a conditioner with a radius of 30 mm was used for the conditioning process. The conditioner oscillated around the middle point of the pad area. Its edge moved over the pad edge by a distance of 10 mm. That means that the largest distance between the pad center and the conditioner center is 280 mm and the smallest one is 120 mm. This model was called design 2. However, the result of design 2 is not efficiently in improving the pad wear profile, as shown in Fig. 8. The pad area from radius of 100 mm to radius of 150 mm in design 2 is worse than that in the conditioning process with design 1. That means, in this case, the generated hole on the pad surface helped nothing in the improvement of the pad wear profile.

Both design 1 and design 2 are compared to the new model, as shown in Fig. 8. The new model showed the least material removal of the pad and almost no transition regions near the pad edge. Therefore, the new model is the best one in improving the pad wear profile.

5 Conclusion

In this paper, a new conditioner was developed to create a better pad wear profile. It was based on investigating kinematic aspects of the CMP processes. The rotation speeds of the conditioner and the pad, and the oscillation speed of the conditioner have small effects on the pad wear profile. However, changing the sizes, patterns, and positions of the conditioners generated different pad wear profiles. From there, a new model for the conditioning process, including a new pad and a new conditioner, was developed. This new model has created a convex pad wear profile instead of a concave one. In addition, as the result of the new model, the pad shape after the conditioning process is more uniform than the old one conditioned by the old model.

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References

1. Tso P-L, Ho S-Y (2007) Factors influencing the dressing rate of chemical mechanical polishing pad conditioning. Int J Adv Manuf Technol 33(7–8):720–724
2. Sun T, Borucki L, Zhuang Y, Philipossian A (2010) Investigating the effect of diamond size and conditioning force on chemical mechanical planarization pad topography. Microelectron Eng 87(4): 553–559
3. Li Z, Baisie EA, Zhang X (2012) Diamond disc pad conditioning in chemical mechanical planarization (CMP): a surface element method to predict pad surface shape. Precis Eng 36(2):356–363

4. Tian YB, Zhong ZW, Ng JH (2013) Effects of chemical slurries on fixed abrasive chemical-mechanical polishing of optical silicon substrates. Int J Precis Eng Manuf 14(8): 1447–1454
5. Nguyen NY, Zhong ZW, Tian YB (2014) An analytical investigation of pad wear caused by the conditioner in fixed abrasive chemical–mechanical polishing. Int J Adv Manufac Technol:1–9. doi:10.1007/s00170-014-6490-3
6. Lee S, Jeong S, Park K, Kim H, Jeong H (2009) Kinematical modeling of pad profile variation during conditioning in chemical mechanical polishing. Jpn J Appl Phys 48(12):126502–126505
7. Hooper B, Byrne G, Galligan S (2002) Pad conditioning in chemical mechanical polishing. J Mater Process Technol 123(1):107–113
8. Yeh H-M, Chen K-S (2010) Development of a pad conditioning simulation module with a diamond dresser for CMP applications. Int J Adv Manuf Technol 50(1–4):1–12
9. Feng T (2007) Pad conditioning density distribution in CMP process with diamond dresser. IEEE Trans Semicond Manuf 20(4): 464–475
10. Baisie E, Li ZC, Zhang XH (2013) Design optimization of diamond disk pad conditioners. Int J Adv Manuf Technol 66(9–12):2041–2052
11. Baisie EA, Li Z, Zhang X (2013) Pad conditioning in chemical mechanical polishing: a conditioning density distribution model to predict pad surface shape. Int J Manuf Res 8(1):103–119
12. Kincal S, Basim GB (2013) Impact of pad conditioning on thickness profile control in chemical mechanical planarization. J Electron Mater 42(1):83–96. doi:10.1007/s11664-012-2250-z