Slurry Supply Mechanism Utilizing Capillary Effect in Chemical Mechanical Planarization

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A novel slurry supply mechanism that utilizes the capillary effect was designed. In the mechanism, a fiber array is positioned on the pad, and the slurry is evenly distributed along the radius of the pad by exploiting the capillary effect. Setting the proper height of the slurry supply mechanism from the pad surface and grooves enables selective slurry supply only to the pad surface, so that old slurry fallen into the grooves does not mix with newly supplied slurry. Experimental evaluation revealed that, in the case of concentrically grooved pads, the removal rate did not differ significantly between the proposed slurry supply mechanism with fiber array and the point-use supply mechanism. In the case of polishing pads with orthogonal grooves, the removal rate of the proposed mechanism using a wafer of 300 mm in diameter at a slurry supply rate of 50 ml/sec was greater than that of the conventional slurry-nozzle supply mechanism. Finally, in the case of pads with orthogonal grooves deepened from 0.5mm to 0.7mm, the proposed mechanism again had a higher removal rate than the conventional mechanism. It was demonstrated that the proposed slurry supply mechanism made efficient use of slurry for polishing.

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Chemical Mechanical Polishing (CMP) is widely used as an indispensable process for device manufacturing. Currently, the delivery of a uniform slurry supply to the groove pads is important for improving polishing uniformity. The pressure distribution is a very important factor that greatly influences the polishing shape. The approach to analyze the pressure distribution between the wafer and pad is treated as solid-to-solid contact model.1 If the wafer is tilted with respect to the pad due to the frictional force of polishing, the pressure distribution varies depending on the frictional force.2 In order to maintain the designed pressure distribution stably, it is important to maintain a stable contact regime including the lateral leveling between the pad and the wafer even under shearing stress condition during polishing.3

On the other hand, polishing is performed by interposing slurry on the basis of stable contact state between the wafer and the pad.

In a case that slurry is interposed between the pad and the wafer, it is treated as solid-liquid-solid problem. In many cases, various models using lubrication theory have been proposed.4–6 As well as the pressure distribution, uniform supply of slurry is an important factor for improving polishing uniformity.7 In the conventional slurry supply mechanism, slurry is supplied from the slurry nozzle to the pad, and the slurry is spread across the pad using the pad grooves.8,9 The slurry also plays a role of not only abrasives due to polishing but also improving the thermal stability of polishing.10,11 In order to efficiently distribute the slurry, a slurry injection system has been proposed.12,13 In addition to the slurry injection system, the groove of the pad also plays an important role in order to evenly distribute the slurry.14

One study has shown that the distribution of the slurry depends on the design of the pad grooves.15 Another has shown that the mean residence time of slurry changes depending on the groove shape and change in the coefficient of friction (COF).16–18 The slurry mean residence time (MRT) has been shown to be a linear function for COF.19 The other study has shown that fine structure such as slant of the pad groove influence the slurry distribution.20 The pad groove patterns can be roughly divided into two types. One is a radial or orthogonal pattern that emphasizes slurry distribution.21 The other is a concentric or spiral groove pattern that emphasizes slurry mean residence time.22

In the former type, as the pad rotates, the slurry immediately spreads over the entire pad; however, some slurry is not delivered to the pad surface, but instead is discharged from the groove. As a result, much slurry is wasted and slurry consumption is increased.

In the latter type, on the other hand, most of the slurry is supplied to the pad surface as the pad rotates, and this improves polishing.

However, the slurry in the pad grooves, even that which contains polishing debris and agglomerated secondary particles, will often leave the grooves with the introduction of new slurry. The mixed slurry including polishing debris and agglomerated secondary particles will then spread over the pad and deteriorate polishing performance as originating a lot of defects.23 As a result, many scratches may be produced on the wafer surface (Figure 1).

In order to solve such essential problems, the following points are pointed out as design guidelines for the slurry supply mechanism and pad grooves.24,25

- To minimize slurry use volume.
- To provide uniform supply of slurry
- To discharge debris by polishing
- To prevent particle redeposition

Therefore, this study proposed a novel slurry supply mechanism utilizing the capillary effect.26 Exploiting this mechanism, it also proposed an efficient slurry supply system that avoids mixing fresh with old slurry.27,28

Using a prototype of new slurry supply mechanism, the evaluation of the polishing characteristics in the case of a pad with high dispensing capacity revealed that it is possible to obtain a uniform polishing profile with a high removal rate even with a small amount of slurry, as compared with the conventional supply method using a slurry nozzle.

Configuration and Characteristics of the Proposed Slurry Supply Mechanism

Slurry containing abrasive particles is considered to be a viscous liquid. When this liquid makes contact with a solid surface, it assumes a meniscus shape. Figure 2 shows a stress diagram of this event. The surface tension of the liquid is reduced as the latter spreads over the solid surface, due to the interfacial tension provided by the solid.

Figure 3 shows the state when two parallel plates are inserted. The liquid surface assumes a meniscus shape along the wall. In the case, a capillary bridge is formed between the two plates and a wicking effect
Table 1. Slurry flow condition dependent on pad groove type.

| Slurry flow condition | Pad groove type |
|-----------------------|-----------------|
| Good dispensing       | Radial grooves  |
| Low slurry consumption| Concentric grooves |

**Figure 1.** Slurry flow condition dependent on pad groove type.

occurs. At that time, the pressure of the liquid surface between the fibers can be expressed by the following equation:

\[
\Delta P = \frac{2 \sigma \cos \theta}{w},
\]

where \( \Delta P \) is the equivalent capillary pressure induced by the surface tension, \( \sigma \) is the surface tension of the interface, \( \theta \) is the contact angle, and \( w \) is the width or space between the fibers.

Similarly, when there is a bundle of fibers with vertical density, the horizontal stress state of the liquid, as it spreads among the fibers, is similar to the former state of the liquid surface in the vertical direction.

**Figure 4.** shows a cross-sectional view of the horizontal stress state of the liquid in such a fiber array. By using a plurality of fibers in a three-dimensionally continuous configuration, the slurry is naturally and uniformly distributed throughout the fiber array.

**Figure 5.** shows the proposed slurry supply mechanism.

The mechanism is positioned above and parallel to the radius of the pad. The slurry supplied to the top of the mechanism is continuously fed from the supply mechanism directly onto the pad, without forming droplets.

The following four capabilities, outlined below, are built in to the proposed slurry supply mechanism.

- Slurry guidance
- Capillary-type dispensing
- Selective supply based on fiber contact
- Redistribution

**Slurry guidance.**—**Figure 6.** shows a schematic diagram of the slurry guidance function. By extending the fiber to the point where it makes contact with the pad surface, it is possible to continuously supply slurry along the fiber surface to the pad surface, utilizing interfacial tension, without producing droplets. By bundling the fibers uniformly, a capillary bridge is formed in the space between the fibers, which enables the slurry to be efficiently transported along the fiber walls. In addition, the capillary force varies with the sectional meniscus shape.\(^{29,30}\)

It is possible to transport the slurry at a constant flow rate, down the fibers, based on the surface area of the minute space between the fibers. The capillary force can also be controlled by the viscosity of the slurry and the density of the fibers.

**Capillary-type dispensing by wicking and impregnation (impingement).**—**Figure 7.** shows the slurry dispensing function by the fiber array. The fiber array enables uniform penetration of the liquid.\(^{51}\) For example, when there is a minute space formed by the fiber array, the slurry is efficiently distributed throughout this space, due to wicking and impregnation, based on the interfacial tension acting on the slurry and the fibers.\(^{32,33}\) This enables uniform distribution of the slurry. In this way, even highly viscous slurry can be efficiently distributed over the pad surface, regardless of the groove pattern or the rotational speed of the pad.

**Slurry retention and selective supply to the pad surface.**—**Figure 8.** shows the principle of selective slurry supply to a grooved pad.

By utilizing the capillary force, it is possible to temporarily retain the slurry on the fibers.

Therefore, the distance from the fiber tip to the pad surface is adjusted such that the tip never touches the bottom of the pad grooves, but remains in contact with the pad surface. As a result, it is possible to selectively supply the slurry only to the pad surface, not to the pad groove.

**Redistribution.**—Even if the slurry is not supplied uniformly to the pad surface, excess slurry on the pad surface is wicked up into the fibers and redistributed over the entire pad surface as it passes through the fiber array.\(^{34}\) Establishing a proper gap between the fiber members.

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\( \gamma_s = \gamma_L \cos \theta + \gamma_{sl} \)

**Figure 2.** Stress state of liquid on solid surface.

**Figure 3.** Stress state of liquid around a fiber surface.
Figure 4. Cross-sectional schematic view of stress state of liquid among fiber array.

Figure 5. Concept of slurry dispense method by utilizing capillary effect.

Figure 6. Slurry guidance function.

Figure 7. Slurry dispensing function by the fiber array.

Figure 8. Principle of selective slurry supply to a grooved pad.

Figure 9. Slurry distribution diagram from supply of fresh slurry to debris drainage using the proposed slurry supply mechanism.

and the pad surface enables this redistributive wicking into the fiber, and uniform slurry distribution over the pad, due to the capillary effect.

With these capabilities in mind, the slurry distribution of the proposed slurry supply system was evaluated.

Prototype of the Slurry Distribution System and its Evaluation

Figure 9 shows slurry distribution diagram from supply of fresh slurry to debris drainage using the proposed slurry supply mechanism.

The slurry applied directly to the pad surface directly enters the gap between the wafer and the pad, and is used for polishing. The slurry used for polishing falls into the grooves of the pad, together with the polishing debris.

The polishing debris that has fallen into the grooves of the pad is rinsed off the pad after polishing.

Conventionally, the pad grooves have a major role in the transport and distribution of the slurry, but in the proposed system the grooves are utilized to dispose of the polishing debris. The following effects of the configuration may be expected.

- The new slurry is continuously and uniformly dispensed, along the radius of the pad, by the capillary phenomenon.
- Only the slurry supplied to the pad surface, not the pad groove, is used for polishing.
- The new and old slurry never mix, and slurry is used efficiently in one way.

As described above, it is possible to efficiently polish even a small amount of slurry, and thus slurry consumption can be significantly reduced. In addition, polishing is not affected by polishing debris, such as agglomerated secondary particles. Therefore, it is expected that polishing scratches, resulting from the presence of polishing debris, will be greatly reduced in number and severity.

Figure 10 shows a top view of each arrangement including the slurry supply mechanism. After pad conditioning in order from the pad rotation direction, slurry is supplied onto the pad surface directly with the supply mechanism, and then is guided to the polishing area. During polishing, the in-situ conditioning was performed to roughen the pad surface. The slurry retaining capacity on the pad surface is increased by supplying the slurry only to the roughened pad surface immediately after pad conditioning.

Figure 11 shows the photograph of the slurry supply mechanism extended to radial direction of the pad. Figure 12 shows the close-up photograph of the slurry supply mechanism. Table I shows the specifications of the slurry fiber array. In the proposed slurry supply mechanism, a beam consisting of a slurry supply pipe and nylon fibers is positioned over the pad in the radial direction. The supply pipe anchors the upper ends of the fibers. The slurry flowing from the supply pipe flows down along the fiber walls to the pad surface. The slurry supplied to the upper part of the nylon fibers is uniformly distributed along the radius of the pad by the capillary effect.

By ensuring continuous contact between the fiber tips and the pad surface, the slurry is continuously supplied to the pad without generating liquid droplets. As a result, the slurry is distributed uniformly over the entire surface of the pad. Since the fiber tip height is adjusted...
such that the fibers never make contact with the pad groove walls, the slurry is supplied only to the pad surface.

**Evaluation of the Removal Rate with a Small Amount of Slurry**

Since the proposed slurry supply mechanism distributes slurry efficiently, it was expected to enable a high removal rate, even with a small amount of slurry. Therefore, the removal rate and the polishing profile were evaluated, with a small amount of slurry flow, using two different pad-groove patterns.

Table II summarizes the experimental conditions. A wafer of 300 mm in diameter, with an oxide film, was used for the experiment.

Figure 13 shows removal rate comparison between conventional and proposed supply mechanisms in the case of a concentrically grooved pad and a slurry flow rate of 100 ml/min. Since the slurry overflows from the groove of the pad due to the centrifugal force of the pad, regardless of which slurry supply mechanism is used, the slurry stays on the pad and most of the slurry contributes to polishing. Accordingly, the results showed a roughly equal removal rate for both mechanisms.

Figure 14 shows removal rate comparison between conventional and proposed supply mechanisms using orthogonally grooved pads with high dispensing capacity at a slurry flow rate of 100 ml/min. Even when orthogonally grooved pads were used, the removal rates of both slurry supply mechanisms were equal. This suggests that if the slurry flow rate is higher than a certain level, the pattern of the pad grooves has little influence on the removal rate.

Figure 15 shows removal rate comparison between conventional and proposed supply mechanisms using the same type of pads as in Figure 13, but with a lower slurry flow rate of 50 ml/min. In this case, the removal rate was slightly higher at 6.5 nm/min in the proposed supply mechanism, as compared with the conventional mechanism. This suggests that, in the case of the conventional mechanism, some slurry was dispelled from the grooves without contributing to polishing. In the case of the proposed mechanism, all the slurry was supplied to the pad surface and contributed to polishing. However, the difference between the two results was small, and significant slurry reduction was not achieved.

Furthermore, in the case of shallow pad grooves of 0.5mm in depth, the proposed slurry supply mechanism supplies a small amount of slurry overflowing from the grooves in addition to the slurry supplied to the pad surface. Therefore, it is considered that the amount of slurry relatively increased near the center of the wafer, and the removal rate became relatively high.

Next, the depth of the orthogonal grooves was deepened from 0.5mm to 0.7mm, and the removal rates were compared, using a small amount of slurry at 50 ml/min.

Figure 16 shows removal rate comparison between conventional and proposed supply mechanisms. When the groove depth was increased to 0.7mm, the removal rate greatly decreased in the case of the conventional nozzle-supply mechanism. The polishing profile did not change significantly. On the other hand, in the case of the proposed slurry supply mechanism, the removal rate at 0.7mm was similar to that at 0.5mm. The polishing profile was uniform. It is considered that, in the case of the conventional nozzle-supply mechanism, when the pad grooves are deepened, little of the slurry that has fallen into the grooves rises to the surface of the pad, so that the removal rate reduced.

In contrast, in the case of the proposed slurry supply mechanism, the slurry is supplied directly to the pad surface, and all of the supplied slurry contributes to polishing. Thus, the direct slurry supply method helps to maintain the removal rate even in the case of deeper pad grooves.

**Discussion**

The slurry in current use is designed on the assumption that it is supplied and distributed through the pad grooves. Therefore, the slurry tends to have low viscosity. This leads to the concern that such low-viscosity slurry does not have sufficient duration time on the pad surface.

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**Table I. Specifications of fiber array.**

| Brush material              | Woven nylon fiber (Showa Kogyo Co., Ltd.) |
|-----------------------------|-------------------------------------------|
| Width                       | 280 mm                                    |
| Height                      | 80 mm                                     |
| Depth                       | 3 mm                                      |
Table II. Experimental conditions.

| Parameter                        | Value                                      |
|----------------------------------|--------------------------------------------|
| Pad                              | Foamed polyurethane Type IC1400 (Nitta Haas Inc.) |
| Slurry                           | Fumed silica slurry Type SS25 (1:1 diluted) |
| Wafer diameter                   | 300 mm                                     |
| Wafer type                       | Oxide film on Si                           |
| Platen diameter                  | 756 mm                                     |
| Wafer pressure                   | 35 kPa                                     |
| Retainer pressure                | 21 kPa                                     |
| Wafer rotation                   | 0.67 s⁻¹                                   |
| Platen rotation                  | 0.67 s⁻¹                                   |
| Polishing time                   | 60 s                                       |
| Nozzle location                  | 30 mm in radial position from pad center   |
| Conditioning                     | In-situ conditioning                       |

The dispersibility and duration of the slurry are also highly dependent on the rotational speed of the pad, i.e. the centrifugal force of the pad. In particular, when high-speed pad rotation is applied, the slurry supplied to the pads may be dispelled by centrifugal force, and make little contribution to polishing. In that case, the process window for the polishing condition becomes narrow. In the proposed slurry supply mechanism, it is also possible to uniformly spread the slurry, utilizing the capillary phenomenon, and to supply the slurry only to the surface of the pad. This also makes it possible to use highly viscous slurries that have traditionally been avoided. Even when the pad rotates at a high speed, if such highly viscous slurry can be applied only to the surface of the pad, the range of polishing conditions expands. It is expected that the specifications of related consumables will likewise be expanded.
In addition, the elimination of polishing debris, through deepening the pad grooves, reduces the likelihood of agglomerated secondary particles remaining on the pad for a long time. In turn, it is expected to reduce the number and severity of polishing scratches caused by such agglomerated secondary particles.

On the other hand, since the proposed slurry supply mechanism increases the exposed area of the slurry, there is a concern that the slurry is dried to form secondary particles especially for a long idle period. In order to deal with the concern, it is necessary to consider the actual use of humidity control devices such as ultrasonic steam device to prevent slurry drying. Furthermore, it is also important to control not to dilute the slurry by humidity control. Although these are issues related to production technology, they need to be improved in the future.

In order to solve the problem of selectively supplying the necessary small amount of slurry on the pad, the slurry distribution mechanism utilizing the capillary phenomenon is theoretically reasonable. In particular, it is considered to be indispensable for uniform distribution of slurry which is a viscous fluid.

**Summary**

1. A slurry supply mechanism utilizing the capillary effect was proposed. A fiber array is suspended to the pad, and the slurry flows from the top of the array. The slurry is evenly distributed within the fiber array, along the radius of the pad, due to the capillary effect. Proper adjustment of the height of the slurry supply mechanism from the pad surface enables the slurry to be dispensed selectively, only to the pad surface and not to the grooves, so that old slurry that has fallen into the grooves does not mix with fresh slurry from the supply mechanism. Utilization of the proposed system was shown to enable a reduction in the consumption of polishing slurry.

2. In polishing evaluation using a small amount of slurry (50 ml/min) and a pad with orthogonal grooves, the proposed slurry supply mechanism exceeded a removal rate of roughly 6.5 nm/min, as compared with the conventional nozzle-supply mechanism. It was demonstrated that the proposed mechanism makes efficient use of slurry for polishing.

3. When the orthogonal grooves of the pad were deepened from 0.5mm to 0.7mm, and a small amount of slurry (50 ml/min) was again used, it was demonstrated that the proposed mechanism had a remarkably high removal rate of 190 nm/min, as compared with a rate of 167 nm/min for the conventional slurry supply mechanism. This is thought to be due to the fact that slurry flow rising from the pad groove decreases as the pad groove becomes deeper.

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