Pressure Distribution Control on Surface Conformable Polishing in Chemical Mechanical Planarization

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An original polishing mechanism with a triple layer pad was developed as a surface conformable polishing mechanism in CMP (Chemical Mechanical Planarization). According to the polishing mechanism, removal profile can be controlled by base plate curvature through an assist pad made of elastic material. A pad system supported by an envelope plane composed of five wafers contributes to make a wafer level paralleled to a pad level relatively during polishing. As the result, a static pressure distribution can be transferred precisely to a dynamic polishing profile regardless of strong shearing force by polishing. In order to verify the polishing removal controllability, an original pressure distribution analysis was developed by an actual pressure distribution measurement around an entire pad surface. The analyzed pressure distribution profile was in good agreement with the actual polishing profile. From the result that the static pressure profile can be transferred to the polishing profile precisely, it was verified that the polishing mechanism is reasonable for surface conformable polishing system in CMP. The developed polishing mechanism was satisfied with both local planarizing polish and global uniform polish by making use of bending stiffness of surface layer pad regardless of wafer curvature. In this report, the developed polishing mechanism was described on the purpose of removal profile control. Pressure distribution is controlled by curvature height of a base plate which is laid under the triple layer pad. Then, an original pressure distribution analysis was developed to guide pressure integration profile from an actual pressure measurement. The pressure integration profile estimated by base plate curvature was compared with the actual removal profile of a wafer by polish. As the result, it was demonstrated that the adjusted pressure profile under a static condition is in good agreement with an actual removal profile by polish.

Configuration of Polishing Mechanism

Fig. 2 shows a wafer chuck configuration. In the developed polishing mechanism, a wafer is sucked rigidly by vacuum force on a plane surface by a wafer membrane and the wafer is fixed with a wafer chuck. A neutral plane of a wafer is fixed with the curvature eliminated during polishing. Under a condition that reference surface is fixed, an original composition of a pad provides controlled pressure to a wafer surface. In the former report, it was demonstrated that developed polishing mechanism was satisfied with both local planarizing polish and global uniform polish by making use of bending stiffness of surface layer pad regardless of wafer curvature. In this report, the developed polishing mechanism was described on the purpose of removal profile control. Pressure distribution is controlled by curvature height of a base plate which is laid under the triple layer pad. Then, an original pressure distribution analysis was developed to guide pressure integration profile from an actual pressure measurement. The pressure integration profile estimated by base plate curvature was compared with the actual removal profile of a wafer by polish. As the result, it was demonstrated that the adjusted pressure profile under a static condition is in good agreement with an actual removal profile by polish.

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Vacuum line
Wafer chuck
Wafer
Chuck table (SUS)

Fig. 2. Wafer chuck configuration.

Fig. 3. Pad composition in this system.

wafer chuck. Wafer curvature such as warp or bow is eliminated by the sucking force by vacuum. Under the condition, a long range of height variation of the wafer surface corresponds to wafer thickness variation. Uniform removal polishing conforming to the height variation is required under the condition. In addition, by sucking a wafer, a wafer position is fixed at both regular distance and height in a retainer ring, even if the wafer is under shearing force during polishing process. To fix wafer position in the retainer rigidly leads to controlling wafer edge polishing precisely.

Table I. Physical property of the pad material.

| Material          | Young’s modulus E (Kgf/mm²) | Poisson ratio | Thickness H (mm) |
|-------------------|-----------------------------|---------------|-----------------|
| Assist pad        | Nitrile-butadiene rubber ID No. NBR-30H10t Katsura Roller Co., Ltd. | 0.136 | 0.2 | 10 |
| Support film      | Poly-ethylene terephthalate | 460 | 0.3 | 0.15 |
| Surface pad       | Polyurethane impregnated in non-woven fabric ID No. 50330-103 V-0.15 Fujibo Ehime Co., Ltd. | 11.7 | 0.2 | 1.27 |

Fig. 3 shows a pad composition in this system. Compared with normal polishing configuration, this system applies for a wafer face up configuration. The pad is composed of triple layers. Table I shows a physical property of the pad material. First layer is composed of a surface pad. The surface pad is constituted by a normal polishing pad with hydrophilic property such as IC1000 made of porous polyurethane. The first layer pad plays a role to hold some extent of slurry and to polish a wafer surface. Second layer is composed of a support film. The support film is constituted by a polyethylene terephthalate film for commercial use which is an extension proof material under wet condition. The film is pasted entirely on the back side of the surface pad. The support film plays a role to provide stiffness to the surface pad. Therefore, the stiffness of the support film fulfills a local planarization function against fine protruding parts on a patterned wafer. Third layer is composed of an assist pad. The assist pad is constituted by a segmented rubber material which features a property of stable pressure distribution without deformation under repeated stress condition. The assist pad is laid under both first layer of the surface pad and second layer of the support film. The assist pad plays a role to provide a stable pressure distribution to a wafer regardless of wafer inherent thickness variation, thermal deformation of platen or pad thickness variation dependent on the error of pad pasting operation. It is possible for the surface pad to conform to a long range height variation on wafer surface.

Fig. 4 shows a base plate curvature for pressure distribution control. The base plate with a small curvature is laid under the assist pad. The base plate plays a role to control polishing pressure distribution to a wafer. The adjustment of small curvature height of the base plate contributes to control the polishing pressure distribution to a wafer. Then, the assist pad plays a role to relieve the curvature height of base plate also. Accordingly, controlled uniform polishing pressure can be applied to a wafer surface with absorbing wafer height variation. In the pad configuration, a pressure distribution applied to the wafer is not affected by the flatness deterioration attributed to a thermal deformation of the platen because the assist pad absorbs the thermal deformation. The curvature profile of the base plate provides a good controllability on a pressure distribution applied to a wafer. As the result, the wafer surface can be polished uniformly as a surface conformable polishing mechanism regardless of the inherent wafer curvature.
Fig. 5 shows a comparison of relative attitude between a pad and a wafer. In a typical traditional polishing mechanism, polishing head leveling was flexible enough to conform to pad surface by using a gimbal joint mechanism. In some reports, the wafer level change is suggested under a lubrication condition on polishing. However, the wafer level fluctuation means a pressure distribution fluctuation from a pad under a dynamic condition. If the wafer level fluctuation is accepted positively under shearing force from a pad, the pressure distribution to a wafer has much influence on various tribological factors from a pad, eg. pad dressing condition, slurry lubrication or pad speed. Under the condition, even if pressure distribution was adjusted carefully under a static condition, the wafer level fluctuation makes the adjusted pressure distribution spoiled. Therefore, in this development, the relative level between a wafer surface and a pad surface was focused on securing a stable pressure distribution during polishing. In order to maintain the pressure distribution during polishing, a wafer level must be paralleled to a pad level consistently even if a strong shearing force works wafer surface by polishing. The consistent parallel level between the pad and the wafer should result in a good correlation between a static pressure profile and a dynamic removal profile. Fig. 6a shows a overview of the polishing machine configuration. Fig. 6b shows a cross sectional view of the polishing machine mechanism. The machine has five heads to hold wafers. Platen with the pad is positioned with the face down. Five wafers are positioned with the faces up. The five wafers move with a planetary gear. In this polishing mechanism, each wafer chuck keeps horizontal leveling by thrust bearing with high stiffness. Relative leveling precision among the five wafer chucks is within 5 microns. The pad system including the platen is supported by an envelope plane consisted of five wafers. According to the polishing mechanism, no matter how strongly the shearing force on the wafer works by polishing, the relationship between the wafer surface and the pad surface is kept to be parallel without tilting the wafer surface. Because the pad system including the platen with a large inertia is supported by a constant envelope plane formed by five wafers chucked rigidly. Therefore, the pressure distribution between the wafer and the pad is constant during polishing.

Next, a pad attachment mechanism is a critical issue to reproduce pressure distribution between a wafer and a pad. In the traditional system, a polishing pad used to be attached to a platen with an adhesive tape. However, it is difficult to attach a polishing pad on a platen uniformly without any non-uniform undulation. Fig. 7 shows a pad attachment mechanism. The surface polishing pad is tightened on an assist pad by lifting an outer ring supporting the pad. Then, the surface polishing pad conforms to a surface profile of the assist pad. In the method, adhesive tape is not necessary on attaching the pad to the platen. Pressure distribution variation caused by pad attachment operation becomes very small enough to be negligible. As the result, the controlled uniform pressure distribution made by the assist pad can be transmitted to a wafer through both the support film and surface pad. On exchanging a pad, it is good if only a support film and a surface pad exchange without exchanging both the assist pad and
base plate which make a pressure distribution. Therefore, the polishing pad attachment mechanism leads to uniform pressure distribution reproducibility to a wafer.

**Pressure Distribution Analysis**

A correlation between a pressure distribution profile and an actual removal profile by polish is mentioned using an original pressure distribution analysis. At first, the method to transform curvature height of base plate into pressure distribution applied to a wafer is indicated by an original pressure distribution analysis. The pressure distribution analysis was based on an actual pressure distribution measurement.

Fig. 8 shows a schematic diagram of pressure distribution measurement. The pressure distribution is measured by pressure distribution measurement system using a ductile sensor sheet which is used as C-Scan model made by Nitta corp. The sensor sheet includes thin conductive ink coating lines of both row ones and column ones. The principle to measure the pressure distribution makes use of resistance variation at the intersection between row line and column line when down force is applied to the intersection point. As the actual pressure distribution measurement, the sensor sheet is placed on a wafer. The sensor sheet on the wafer is pressed down by a polishing pad with actual static load. Then actual pressure distribution can be measured by the sensor sheet with 240 mm \times 240 mm size. Fig. 9 shows an example of pressure distribution measurement. The sensor sheet can measure pressure distribution with approximate 10 mm pitch resolution within 240 mm square. Therefore, one measurement area corresponds to a wafer area approximately. Pressure distribution map at entire pad area can be obtained by repeating pressure distribution measurement at various positions. Fig. 10 shows a pressure distribution allocation on an entire pad surface. Each pressure distribution map can be measured at 45 degree intervals on the pad surface. A pressure distribution at an entire pad area can be covered at eight positions around pad surface. Entire pressure distribution at all area of the pad is formed by the pressure distribution result at eight positions. Fig. 11 shows an example of a pressure histogram of the concentric pressure band across an entire pad. The entire pressure distribution of the pad surface is divided into twelve concentric pressure bands at same intervals. Each pressure value within each concentric pressure band is averaged from inner radius to outer one around a pad. Then, the pressure histogram is defined by pressure arrays of 12 bands within the area which ranged from 104 mm to 320 mm in radius.

Next, the pressure histogram of concentric pressure bands across a pad is transformed into a pressure integration profile as a function of a wafer radius. Fig. 12 shows a method to transform the pressure histogram into pressure integration profile on a wafer. A circle with a certain radius \( r_k \) within a wafer is focused on. The pressure...
The pressure integration can be calculated at each radius \( r_k \) by,

\[
P_k(r_k) = \frac{1}{2\pi} \int_{\theta_{i,k}}^{\theta_{i+1,k}} \left( \frac{c_i^2}{2r_k R} \left( 1 - \left( \frac{R}{c_i} \right)^2 - \left( \frac{r_k}{c_i} \right)^2 \right) \right) \, d\theta
\]

where \( \theta_{i,k} \) is given by,

\[
\theta_{i,k} = \cos^{-1} \left( \frac{c_i^2}{2r_k R} \left( 1 - \left( \frac{R}{c_i} \right)^2 - \left( \frac{r_k}{c_i} \right)^2 \right) \right)
\]

Accumulation to a certain circle on the wafer can be found by pressure integration from concentric pressure band around a pad. The average pressure of the pressure band with number \( i \) is defined as \( P_i \). A part of the circle with the radius \( r_k \) traverses the pressure band \( P_i \). The angle \( \delta_{i,k} \) of the circle which traverses pressure band \( P_i \) is given by,

\[
\delta_{i,k} = \theta_{i+1,k} - \theta_{i,k}.
\]

Therefore, the pressure integration profile can be obtained by pressure integration applied to the circle with radius \( r_k \).

The pressure integration \( P_k(r_k) \) is a function of wafer radius \( r_k \). Therefore, the pressure integration can be calculated at each radius \( r_k(k = 1, 2, \ldots, n) \) which ranges from zero to outermost radius. As the result, pressure integration profile can be obtained by pressure integration \( P_k(r_k) \) as a function of wafer radius \( r_k \). In addition, the non-uniformity on pressure integration \( PNU \) is defined by,

\[
PNU = \frac{1}{\bar{P}} \sqrt{\frac{1}{n} \sum_{k=1}^{n} (P_k(r_k) - \bar{P})^2}
\]

where \( \bar{P} \) is given by,

\[
\bar{P} = \frac{1}{n} \sum_{k=1}^{n} P_k(r_k)
\]

Based on the method aforementioned above, pressure integration profile was introduced to compare with actual removal profile.

**Correlation Between Pressure Integration Profile and Actual Removal Profile by Polish**

Fig. 13 shows actual curvature profile of base plates of both 0 \( \mu \)m convex and 400 \( \mu \)m convex. Both of base plate has a property of symmetry about a wafer center. The base plate profile is a gentle curvature within wafer diameter. The gentle curvature profile contributes to control pressure distribution to a wafer. Fig. 14 shows actual removal profile.
pressure histogram using a base plate of both 0 μm convex and 400 μm convex. In a case of 0 μm convex base plate, a pressure distribution became uniform across a wafer. On the other hand, in a case of using the 400 μm convex base plate, the pressure value at the area of a wafer center was relatively higher than the pressure at a peripheral area. A gentle pressure distribution was formed by a gentle base plate curvature profile. In the case, the assist pad served as a curvature absorber of the base plate of 400 μm convex curvature. In the former report, it was demonstrated that pressure distributions within wafer are coincided within 2 kPa, using the total thickness variation of either 9.6 μm convex or 15 μm concave. Either wafer thickness variation or platen deformation dependent on thermal condition is relatively small enough to be negligible, compared with the convex curvature of 400 μm of the base plate. Therefore, the base plate curvature and the assist pad have a good controllability on forming a gentle pressure distribution to a wafer. Fig. 15 shows a pressure integration profile as a function of wafer radius. The pressure integration profile was calculated by the procedure shown in Fig. 12. The base plate of 400 μm convex made wafer center pressure higher relatively than peripheral part pressure. In the other words, pressure integration profile became a gentle convex profile as well as the base plate profile. The pressure non-uniformity became 9.67% across a wafer. On the other hand, the base plate of 0 μm convex made pressure integration profile uniform across a wafer. The pressure non-uniformity became 2%. In this way, the base plate profile corresponded to the pressure integration profile.

Next, a correlation between pressure integration profile and actual polishing profile was evaluated using the base plates of both 0 μm convex and 400 μm convex. Table II shows experimental condition. As a slurry type, diluted fumed silica slurry was used. An oxide film on 8 inch Si wafer was used for the evaluation. For removal evaluation, film thickness was measured at 49 points within a wafer. Fig. 16 shows an actual removal profile as a function of wafer radius using the base plate of both 0 μm convex and 400 μm convex. The actual removal profile is in good agreement with the pressure integration profile.

![Figure 15. Pressure integration profile as a function of wafer radius.](image)

![Figure 16. Actual removal profile as a function of wafer radius.](image)

**Table II. Experimental condition.**

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Pad rotation                     | 0.75 s⁻¹               |
| Wafer rotation                   | 0.5 s⁻¹                |
| Pressure                         | 28 kPa (4 psi)         |
| Wafer size                       | 200 mm (8 inch)        |
| Film type                        | Thermal oxide on silicon |
| Machine                          | Fine polisher No. SP2000 Sumitomo Metal industries Co., Ltd. |
| Retaining ring                   | Diamond conditioning retaining ring, type #100, Asahi Diamond Industrial Co., Ltd. |
| Surface pad                      | Polyurethane impregnated in non-woven fabric No.50330-103 V-0.15 t, Fujibo Ehime Co., Ltd.Thickness t:1.27 mm |
| Slurry                           | Fumed silica slurry SS25 (1:1 diluted) Cabot corp. |
| Slurry flow rate                 | 1 l/min                |
| Polishing time                   | 150 s                  |

**Figure 15.** Pressure integration profile as a function of wafer radius.

**Figure 16.** Actual removal profile as a function of wafer radius.
mentioned above. The result supports that the polishing mechanism was reasonable for pressure distribution control. In addition, the polishing profile speculation was accurate in the polishing mechanism. Fig. 17 shows correlation between pressure integration non-uniformity and actual removal non-uniformity. The horizontal axis indicates pressure integration non-uniformity and the vertical axis indicates actual removal non-uniformity. As well as pressure non-uniformity, if each actual removal is regarded as $R_k$ within a wafer, the removal non-uniformity was given by,

$$
RNU = \frac{1}{R} \sqrt{\frac{1}{n} \sum_{k=1}^{n} (R_k - \bar{R})^2}
$$

where $R$ is given by,

$$
R = \frac{1}{n} \sum_{k=1}^{n} R_k
$$

According to the evaluation between pressure non-uniformity and removal non-uniformity, it was verified that the pressure integration non-uniformity and the actual removal non-uniformity have a strong correlation with a correlation coefficient of 0.99. The result supports that polishing pressure is a dominant factor to determine removal rate strongly. On the assumption that the pressure integration non-uniformity is regarded as $X$ and the removal non-uniformity is regarded as $Y$, the relationship is given by,

$$
y = 0.8937X + 2.2277
$$

In this way, it was verified that pressure non-uniformity is in good correlation with actual removal non-uniformity.

**Discussion**

In the developed system, the pressure integration profile was a good agreement with the actual removal profile precisely. The pressure profile to a wafer can be controlled by a base plate curvature. Then, in accordance with the pressure distribution control, removal profile could be controlled precisely.

On the other hand, it will be quite difficult for the traditional polishing mechanism using a gimbal head to get such a good agreement between pressure integration profile and actual removal profile. Because the wafer level is not constant to the pad surface. The wafer level is susceptible to small lubrication condition, eg. pad conditioning, slurry type and pad surface asperity.9–10 The wafer level fluctuation leads to pressure distribution fluctuation. That means that actual removal profile depends on not only static pressure distribution but also dynamic and lubrication condition. Therefore, actual removal profile does not always correspond to the static pressure integration in the traditional polishing mechanism in principle.

In contrast, in this system it was demonstrated that the static pressure integration profile corresponded to the actual removal profile accurately. The main causes are considered as follows.

- First, according to the original polishing mechanism, the pad surface is supported by envelope plane of five wafers. Therefore, the polishing mechanism could keep relative level attitude paralleled between a wafer and a pad surface regardless of strong shearing force by polishing. As the result, pressure distribution designed under static condition could be transferred into an actual removal profile accurately regardless of dynamic and lubrication condition fluctuation.

- Second, a wafer is held rigidly by vacuum chuck. According to the wafer chuck, wafer inherent curvature is eliminated by the sucking force by vacuum. In addition, the wafer is not curved under down force for polishing. Therefore, a neutral plane of a wafer is maintained as a stable flat plane during polishing. A stable polishing process is performed regardless of wafer type, stiffness and inherent curvature.

- Third, an original triple layer pad was introduced. First layer plays a role to polish a wafer. Second layer plays a role to provide extension proof of surface pad and some extent of bending stiffness for local planarization. Third layer plays a role to relieve base plate curvature and to form gentle pressure profile. The original pad composition provides a stable controlled pressure distribution to a wafer regardless of height variation of wafer surface, thermal deformation of platen or pad thickness variation dependent on pad pasting operation. Consequently, a pressure distribution adjusted in static condition can be transferred to a dynamic polishing profile accurately.

**Conclusions**

1. As an ideal surface conforable polishing mechanism, the original polishing mechanism including pad composition was developed for CMP process. The main features of the polishing mechanism are as follows. Removal profile can be controlled by base plate curvature through an assist pad. The assist pad plays a role to relieve base plate curvature and forms gentle pressure profile.

A neutral plane of a wafer is maintained as a stable flat plane by vacuum chuck regardless of wafer type, stiffness and inherent curvature.

The pad including a platen is supported by an envelope plane formed by five wafers. The mechanism made wafer leveling paralleled to a pad surface under a condition of polishing shearing force. A pressure distribution adjusted under a static condition could be transferred into a dynamic polishing profile precisely.

2. In order to verify the polishing machine mechanism, an original pressure distribution analysis was developed. The analysis is based on an actual pressure distribution around an entire pad surface. A pressure integration profile in a proportion to a base plate curvature was introduced by the analysis.

3. It was clarified that the pressure integration profile is in good agreement with an actual polishing profile precisely with high correlation coefficient of 0.99. The result supported that machine mechanism was reasonable in terms of the correlation between a static pressure condition and dynamic polishing condition precisely.

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