Water Outlet Design of Wet Cleaning Bath for 300-mm Diameter Silicon Wafers

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Water motions influenced by an outlet of a batch-type 300-mm diameter silicon wafer wet cleaning bath were experimentally and numerically studied in order to quickly remove the contaminants from the bath. The outlet consisting of a pinhole arrays (PA) near the top edge of the bath side wall was designed and evaluated along with an ordinary overflow (OF) outlet. The experiment showed that the amount of a blue-colored ink, used as a tracer, in the bath having both the OF- and the PA-outlets decreased faster than that in the bath having only the OF-outlet. Simultaneously, the amount of the blue-colored ink that returned to the bath bottom was reduced by using both the PA-outlet and the OF-outlet. The numerical calculations also showed that particles in the bath quickly went out through the PA-outlet.

An advanced semiconductor material surface should be maintained clean for the electronic device fabrication.1,2 The batch-type wet cleaning method, using ultrapure water and chemical reagents in a batch, has been very popular for cleaning the surface of small and large diameter wafers.3–18 The water flow in the wet cleaning bath has been continuously studied16–19 in order to improve the productivity of the cleaning process. While the contaminants, such as small particles, were detached and transported away from the wafer surface, they frequently returned to the wafers following the water recirculation. Thus, the water flow in the bath should be further studied in detail.

The water recirculation is considered to be formed by an asymmetric water injection and the insufficient cross section of the outlet.19,20 In our previous study,16 the water injection nozzle consisting of dual tubes was designed taking into account the pressure distribution in the nozzle for injecting the water in the normal direction with the asymmetric water velocity distribution. While the efficiency of contamination removal from wafers is dominated by the direct water injection to the wafers from the water nozzles, the recontamination is influenced by the recirculation which may be caused by the outlet design. The water outlet design should be studied, next.

The wet cleaning bath for the semiconductor materials process has preferred the overflow outlet in order to effectively remove many particles floating on the water surface. The overflow outlet is equivalent to the outlet having a significantly thin cross section along the top edge of the four side walls. In order to remove the contaminants through the overflow outlet, a large and fast stream is necessary near and toward the top edge of the bath side wall. Consequently, such a fast stream requires large and fast recirculations which simultaneously and unfortunately take some contaminants back to the wafers. Thus, a new water outlet design is expected for governing the entire water flow in the bath.

In this study, the water outlet of the wafer wet cleaning bath was studied both experimentally and numerically from the viewpoint of expanding the outlet cross section. For this purpose, pinhole arrays were formed near the top edge of the bath side wall. The entire water flow was studied by water flow observations and numerical calculations taking into account the transport phenomena. The changes in the water flow determined by the pinhole arrays were evaluated.

Experimental Procedures and Numerical Calculation

Figure 1 shows the ordinary batch-type silicon wafer wet cleaning bath15 which was designed for cleaning 300-mm diameter silicon wafers having a significant amount of mud-like waste remaining after the surface grinding. Figures 1a and 1b are the front view and the right side view, respectively. Six 300-mm-diameter silicon wafers were placed at the center of the bath bottom. A cassette, not shown in this figure, supported the wafers. For the water flow observations, particularly for observing the tracer motions between the wafers, 300-mm-diameter transparent glass wafers were used instead of the silicon wafers.

The water was introduced from the two water injection nozzles placed at the right and left bottom of the bath. The water was injected in the normal direction from the nozzle body.17 Each nozzle supplied water at the flow rate of 8.5 L min−1. The total water flow rate was 17 L min−1. The water injected from the nozzle went through the spaces between and around the wafers. Finally, the water overflowed from the top edge of the bath side wall. This bath had the function of ultrasonic wave irradiation from the entire bath bottom without any disturbance. The directions of the water injected from the nozzles were visualized using a tracer, such as blue-colored ink, and were captured by a VTR camera.

Figure 2 shows the batch-type wet cleaning bath having the pinhole arrays near the top edge of the bath side wall. The pinhole diameter was 2 mm. The position of the pinholes was 20, 30 and 50 mm from the top of the bath side wall, taking into account the typical horizontal water flow along the water surface observed in this study. The distance between the pinholes in the horizontal direction was 30 mm; one horizontal array had 38 pinholes. The water flow rate supplied from the water injection nozzle was exactly the same as that for the bath shown in Fig. 1. The water went out through the arranged
Figure 2. Geometry of wafer wet cleaning bath having pinhole arrays as the outlet. (a) front view and (b) right side view. There were pinhole arrays consisting of many 2-mm-diameter pinholes at 20, 30 and 50 mm from the top edge of the bath side wall for the water outlet.

pinholes. Simultaneously, the rest of water overflowed from the top of the bath side wall.

The water flow in the baths shown in Figs. 1 and 2 were numerically calculated taking into account the governing equations for the conservation of mass and momenta using the Fluent software (ANSYS, USA). Typically 13000 virtual particles having the diameter of 10 nm were generated on a horizontal plane crossing the wafer center in the bath. The motion of particles was traced utilizing the obtained water flow till they went to the outside of the bath. The time for each virtual particle leaving the bath was recorded.

Results and Discussion

Pinhole diameter.—The water flow rates going to the outside of the bath through the pinholes were measured as shown in Fig. 3. Pinholes having various diameters at various distances from the top edge of side wall were used. When the pinhole diameter was 1 mm, the water flow rate was zero cm$^3$ s$^{-1}$ hole$^{-1}$ at 10 and 20 mm from the top of the bath side wall, because the gravitational potential energy was low. With the increasing distance from the top of the bath side wall, the water flow rate increased. However, the 1-mm-diameter pinholes supplied a very low flow rate, for example, about 0.5 cm$^3$ s$^{-1}$ hole$^{-1}$ even at 40 and 50 mm distance. In contrast, for the 3-mm diameter pinhole, the water flow rate was significantly high. The minimum and maximum values were about 2.5 and 5 cm$^3$ s$^{-1}$ hole$^{-1}$ from 10 to 50 mm distances, respectively. The 2-mm diameter pinholes produced a water flow rate between about 1 and 2 cm$^3$ s$^{-1}$ hole$^{-1}$ from 10 to 50 mm distances. The total water flow rate by the 1- and 3-mm diameter pinholes was significantly lower and higher, respectively, than 17 L min$^{-1}$. In contrast, the total water flow rate by the 2-mm diameter pinholes at 2, 3 and 5 mm distances was 12 L min$^{-1}$. This value enabled the water flow rate of 5 L min$^{-1}$ for the overflow outlet. The 2-mm diameter pinholes were selected for use in this study.

Water flow observations.—Figures 4 and 5 show the water flow, visualized using the blue-colored ink tracer, from the front view and the side view, respectively. The tracer was injected from the thin tube inserted at the mid height positions between the 1st and 2nd wafers and at that between the 3rd and 4th wafers. Because these results were the same, Figs. 4 and 5 show the tracer motions between the 3rd and 4th wafers. Figures 4a1 and 5a1 show the tracer position at zero seconds,
Figure 5. Tracer motions in front view at 0, 6.5, 11 and 13 seconds after injected from the wafer center. (a1)-(a3): no pinholes and (b1)-(b3): pinhole arrays at the top edge of the bath wall.

that is, immediately after the tracer injection. The tracer immediately went up to the water surface through the space between the 3rd and 4th wafers. At 6.5 s, the tracer reached the water surface and spread over the entire water surface, as shown in Fig. 5a2. At 11 s, the tracer went down along the right and left side walls, as shown in Fig. 4a2. Fig. 5a3 shows that the tracer spread over the upper half of the bath. As shown in Fig. 4a3, at 16 s, the tracer advanced along the bath bottom and reached the center bottom of the bath. The tracers which came from the right and left sides met and changed their direction to upward. Figures 4a1–4a3) indicate that there were two large water recirculations on the right and left halves of the bath.

The water flow influenced by the pinhole arrays is shown in Figs. 4b1–4b3 and Figs. 5b1–5b4. Similar to the water flow shown in Figs. 4a1–4a3 and Figs. 5a1–5a3, the tracer immediately went up to the water surface at 0 s, as shown in Figs. 4b1 and 5b1, through the space between the 3rd and 4th wafers. As shown in Fig. 5b2, the tracer spread over the water surface. At 11 s, the tracer spread over the water surface from left to right and went down along the right and left side walls, as shown in Fig. 4b2. While this motion in Fig. 4b2 might be similar to those in Fig. 4a2, the depth of the tracer in Fig. 4b2 was shallower than that in Fig. 4a2. This difference indicated that the water recirculating motion influenced by the pinhole arrays, in Fig. 4b3, was shallower than that without pinholes, in Fig. 4a3. At 11 s, the tracer in Fig. 5b3 still stayed near the water surface. The advanced edge position of the tracer at 16 s in Fig. 4b3 was still near the left and right side walls and had not yet reached the bath bottom, while those without pinholes at the same second already reached the center of the bath bottom as shown in Fig. 4a3. At 13 s, the tracer position in Fig. 5b4 still seemed to stay near the water surface.

The color appearance by the tracer in Figs. 4b1–4b3 and Figs. 5b1–5b4 was entirely thinner than that in Figs. 4a1–4a3 and Figs. 5a1–5a3. This difference indicated that a considerable amount of tracer could quickly go out through the pinhole arrays placed at the bath side walls.

The effect of the pinhole arrays at the side wall on the water flow is schematically shown from the side view in Fig. 6. Figure 6a shows the water motion in the ordinary bath without pinholes. The water rises through the space between the vertically arranged wafers. After reaching the water surface, the water flow turned to the front and back directions. Thus, the thick water layer horizontally moving along the water surface is formed. When the water reached the bath side wall, some part of the water overflows and leaves the bath, while the rest goes down along the bath side wall. The water flow reaches the bath bottom and returns to the bath center. Such water motions in the front and back directions shown in Fig. 6a might similarly occur in the right and left halves in the bath, as shown in Figs. 4a1–4a3. The formed recirculations transport the remaining contaminants.

The water flow in the bath having the pinhole arrays is schematically shown in Fig. 6b. The water rises between the wafers, then turns to the side wall along the water surface. The water layer then reaches the edge of the bath side wall. Some portion of water overflows for leaving the bath similar to Fig. 6a. The other portion goes out through
the pinhole arrays; the rest goes down to cause the recirculation. Because the pinhole arrays at 20, 30 and 50 mm from the wall top are expected to work like the wide water outlet, the water horizontally moving along the water surface in the bath having the pinhole arrays is expected to be slower than that without the pinholes. The effect of the wide outlet cross section is considered to explain the difference in the water flow between those with and without the pinhole arrays at the bath side walls, shown in Figs. 4 and 5.

**Numerical calculation.** — In order to theoretically evaluate the effect of the pinhole arrays, the water flow in the wet cleaning bath was numerically calculated. Figure 7 is the vector diagram showing the water motion on the vertical cross section between the 3rd and 4th wafers. The pressure contour lines are shown in Fig. 8 with the typical water flow path.

Figure 7a shows the water motion in the ordinary bath without the pinholes. The water rises to the water surface in the center region of the bath. The water turns in the horizontal direction toward the side wall. At the top edge of the side wall, the water is divided into two motions, such as the overflow toward the outside of the bath and the downward flow for the recirculation. These motions are schematically shown using the red dotted lines in Fig. 8a. The water flow rate supplied from the water injection nozzle must be the same as that going out by the overflow. Here, the overflow outlet is equivalent to the significantly thin outlet. Thus, the pressure of the horizontally moving water along the water surface should become high. This makes the thick and fast horizontal water flow near the water surface. The pressure in the ordinary bath having no pinholes was evaluated at 18–20 Pa, as shown in Fig. 8a.

The water motion in the bath having the pinhole arrays is shown as the vector diagram in Fig. 7b. The water rises and turns in the horizontal direction. The water that reached the top edge of the bath side wall is divided into the three paths, such as the overflow, the outward flow through the pinhole arrays and the downward flow along the bath side walls. These motions are schematically shown utilizing the red dotted lines in Fig. 8b. The total cross section of the outlet in Fig. 7b, which is the summation of the overflow outlet and the pinhole arrays, is greater than that without pinholes in Fig. 7a. The water can smoothly leave through the pinhole arrays. Thus, the water flow in the horizontal direction along the water surface has a lower pressure, thinner layer and slower velocity than those in Fig. 7a. Figure 8b shows that the pressure is 6.3–7.5 Pa in the bath having the pinhole arrays. Figure 8 shows that the pressure in the bath can be shifted from 18–20 Pa to 6.3–7.5 Pa by adding the pinhole arrays.

The pressure contour lines shown in Fig. 8 are briefly explained. The pressure trends in the bath with and without the pinhole arrays resemble each other. Most of the water injected from the water nozzle goes to the wafer. However, small amount of water directly go to the corner edge of the bath bottom, in the region of which the pressure is high. The horizontal water flows oriented to the center of the bath from right and left sides meet and change direction together to upward. The upward flow reaches the water surface and again change the direction to be horizontal. These changes in the flow direction appear as the high pressure regions at the top and bottom of the center of bath.

In order to cause the overflow exceeding the top of the bath side wall, the water flow must have the high velocity. The collision of the high velocity water to the wall causes the high pressure region, as shown in Fig. 8a. When the pinholes are arranged at the bath side walls, the water easily flow through them. Thus, the pressure only slightly increases at the bath side walls having the pinhole arrays, as shown in Fig. 8b.

The pressure difference caused at the top of the bath side wall is considered to influence the entire water motion. In Fig. 7, the water layer thickness is indicated using $x_i$ in the ordinary bath without pinholes and $x_b$ in the bath having the pinhole arrays. The $x_b$ value is deeper than the $x_i$ value, corresponding to a high and low pressure, respectively. This changes the position of the water recirculation. The depth of the recirculation center in Fig. 7b, indicated by $y_b$, is shallower than $y_i$ in Fig. 7a. Additionally, because the water can smoothly leave the bath in Fig. 7b, the total amount of recirculating water in Fig. 7b is less than that in Fig. 7a. This difference is recognized by the number of red colored vectors, indicating a high velocity, near the side wall. Figure 7b has the less number of red colored vectors than Fig. 7a has. Overall, the major differences in water motion in Fig. 7b from that in Fig. 7a appeared near the water surface and near the side walls. They were caused by the decrease in the resistance to the water flow by the outlet, particularly, by enhancing the outlet cross section.

Because the water flow between the wafers were governed by the water injection nozzle design, the contamination removal efficiency from the wafer surface was expected to be not reduced at the low pressure condition. The overall particle motion between and around the wafers in the bath was evaluated using the entire water flow shown in Figs. 7 and 8. The motion of 13000 particles generated at zero seconds on the horizontal plane crossing the wafer center was traced by the numerical calculation. The number of particles leaving the bath was counted versus time. The solid line in Fig. 9a shows the number of particles leaving the ordinary bath having no pinholes. The first particle leaves at 4.46 s. The number of removed particles significantly increased versus time till about 80 s. The gradient decreases near 100 s. Finally, the number of removed particles saturates after 150 s.

Figure 7. Water flow vectors in the front view on the mid vertical plane between the 3rd and 4th wafers. (a): bath without and (b): with pinholes near the top edge of the bath side wall.

Figure 8. Contour diagram of pressure in the bath (a) without pinholes and (b) with pinhole arrays. Dark dotted circles are the water injection nozzles. Red dotted lines schematically show the major water stream.
The saturated value is about 5900. Thus, there are about 7000 particles remaining in the ordinary bath having no pinholes.

Next, the influence of the pinhole arrays at the bath wall on the particle motion was evaluated and shown as the dotted line in Fig. 9. The first particle leaving the bath having the pinhole arrays is at 2.95 s, which is 1.5 second sooner than that from the ordinary bath having no pinholes. The number of removed particles significantly increases till about 100 s; the gradient decreases near 130 s. After 200 s, the number of removed particles still continue to gradually increase. At 300 s, the number of removed particles from the bath having the pinhole arrays reached about 9600, which is 3700 greater than that from the ordinary bath without pinholes.

Assuming that the period of dipping the wafer in the bath is about 60 s for the wafer production process, the number of removed particles from the bath with and without the pinhole arrays is compared. At 60 s, 4162 and 5522 particles are removed from the bath without and with the pinhole arrays, respectively. This concludes that the rate of removing particles from the bath is improved to 133% by adding the pinhole arrays. Overall, the pinhole arrays at the bath wall make the particles smoothly leave the bath.

The pinhole positions used in this study were chosen from the water flow observation in Figs. 4a1–4a3. When there was not any pinhole, the water layer from the water surface to about 50 mm depth horizontally moved. Thus, the pinholes were set at 20, 30 and 50 mm from the water surface, in order to let the horizontal water flow smoothly go out. In the further study, the pinhole positions and arrangement should be optimized; the wafer surface cleaning should be actually performed and evaluated.

Conclusions

The water flow in the wet cleaning bath was improved by forming pinhole arrays near the top of bath side wall in order to achieve the quick removal of contaminants. The pinhole works as the outlet having the water flow rate of 1–2 cm^2 s^-1 hole^-1 at the distance of 20, 30 and 50 mm from the top of bath side wall. Based on the evaluation by the experiment and the numerical calculation for the batch-type 300-mm diameter silicon wafer wet cleaning bath, the recirculating water layer became slow and thin at a low pressure caused by the pinhole arrays. Simultaneously, the pinhole arrays makes the particles leaving the bath sooner and faster than that in the ordinary bath without pinholes. These conclusions can be understood using the concept of the wide outlet, which reduces the resistivity to the water flow in the bath.