

Comparing the Effectiveness of Knobby and Ridged Post-CMP Cleaning Brushes

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Because residual slurry particles can cause defects that affect product yields, it is critical to remove them from substrate surfaces.

Whether used to remove excess metal or oxide from IC chips or thin-film data-storage disks, chemical-mechanical polishing or planarization (CMP) has become an increasingly important and rapidly growing technology. Most CMP combines chemical activity with abrasion of the treated substrate by slurry particles, which results in a very flat surface. Once the slurry has been applied, however, it must be thoroughly removed so that residual slurry particles will not interfere with subsequent processing. Any particles left behind can have an adverse effect on the outcomes of downstream process steps, creating imperfections ranging from bumps or pits to regions of excessive electrical resistance. Post-CMP cleaning is usually accomplished with a deionized-water or dilute cleaning agent rinse and some mechanical action, generally contact with one or more rotating roller “brushes,” while the product itself is rotated and sprayed. Commonly made of a high-porosity foam such as polyvinyl acetal (PVA), the brushes help dislodge ultrafine slurry particles and direct the contaminated rinsewater away from the product surface. Figure 1 shows a schematic of a typical dual-roller brush setup. The post-CMP cleaning process and various scrubbing systems have been described in detail elsewhere.^{1,2} The importance of post-CMP cleaning to defect reduction also has been covered in the literature.³ After discussing the contact and fluid mechanics of the rinse-and-brush process, this article focuses on two brush geometries and presents experimental data that compare their effectiveness.

Post-CMP Cleaning Mechanics

As with other wafer- or disk-cleaning technologies, post-CMP rinsing and brushing must be safe as well as effective. That is, the brush itself should cause no harm, such as scratching the substrate or introducing chemical or particulate contamination, while it helps remove particles and sweeps the rinsewater from the product surface. Understanding how CMP brushes achieve these goals requires a consideration of contact and fluid mechanics.

Contact Mechanics. Roller brushes are designed so that, even when compressed during use, there are high and low regions (islands and grooves) that help channel the fluid flow—much as automobile tires are designed to do—to improve contact and minimize hydroplaning. The schematic in Figure 2 illustrates several aspects of the brush-product contact. As the raised regions of the brush slide across the product being cleaned by the rinse fluid, they contact slurry particles and move them along, while the lower regions of the brush form channels for directing the rinsewater away from the product surface. There is minimal opportunity for further polishing of the surface by particles during this process because of the softness of the foam brush material and the depth of the lubricating layer.

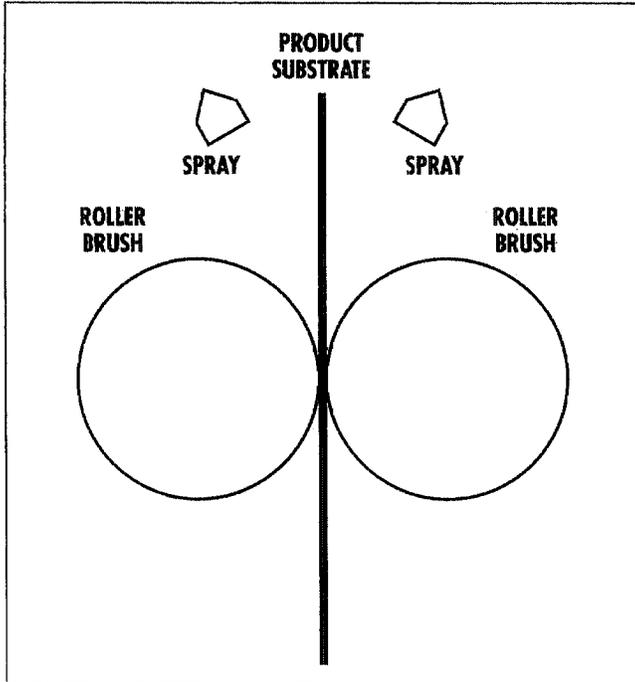


Figure 1: Schematic of a dual-roller brush setup used to remove slurry residuals. The product rotates while rinsewater is sprayed onto it and two brushes rotate across its surfaces.

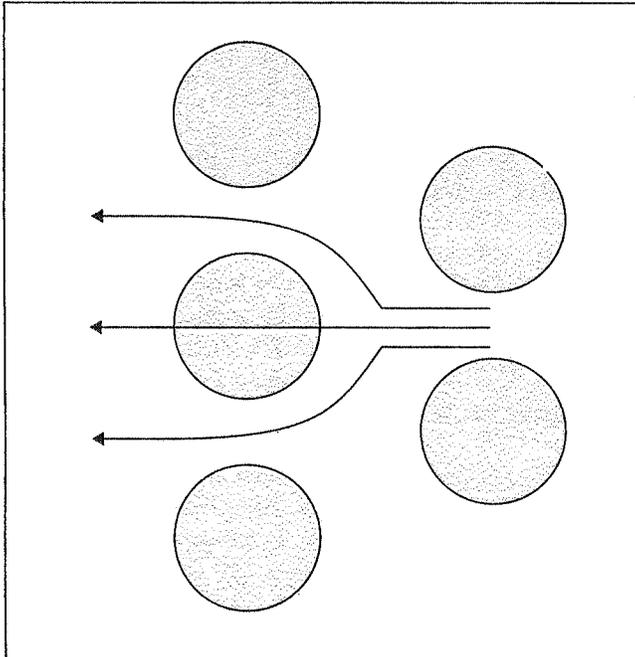


Figure 2: Schematic of a knobby brush's contact with the product, showing rinsewater flow in the channels around the brush's higher regions.

One method used to ensure proper brush-product contact is to arrange the brush's high regions so that they are compressed by a standard 2 mm. The pressure at the contacts will depend on the elastic modulus (E) of the foam, which is the pressure (stress) per unit of fractional compression, as expressed in the equation:

$$E = dP/(dL/L)$$

where dP is the pressure increase and dL/L is the fractional compression of an element of length (in this case the brush's outer contact radius minus its inner support radius). The elastic modulus of the foam will depend, in turn, on the elastic modulus (E'), a constant of proportionality (k'), and porosity (e , the void-volume fraction) of the bulk material from which it is made. The relationship between the two moduli can be approximated using the following equation:⁴

$$E = k' E' (1 - e)^2$$

This relationship allows some tailoring of the foam elasticity by tailoring porosity, even after the chemical makeup of the bulk material has been specified.

Fluid Mechanics. There are two important size scales in the fluid mechanics of the post-CMP cleaning operation. One is microns, roughly the size of the particles being removed and of the hydrodynamic boundary layer formed by the motion of product, fluid, and roller brush. The other scale is centimeters, roughly the size of the product itself, where the large-scale motion of the fluid is important for thoroughness of slurry removal.

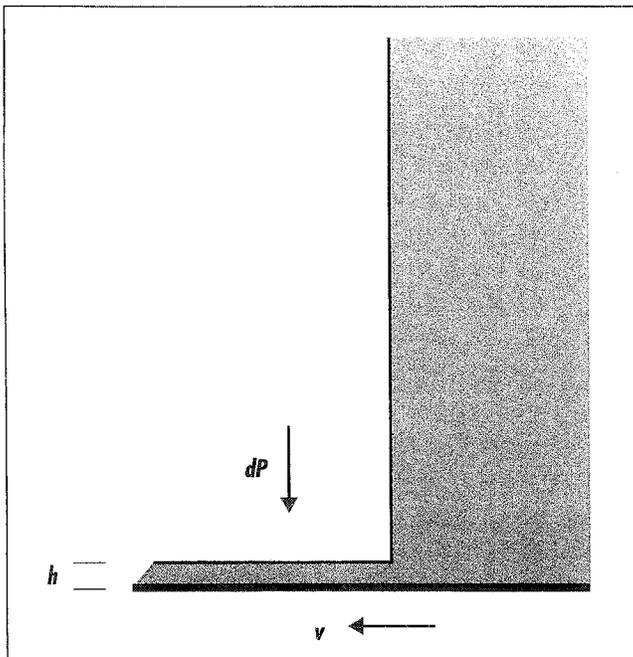


Figure 3: Schematic of brush contact with the product, showing the hydrodynamic interaction between the product, the liquid, and the brush.

Figure 3 shows an idealization of the hydrodynamic interaction between the product, the liquid, and the raised regions of the brush. As noted above, compression of the brush produces a local pressure increase, dP . As the liquid on the rotating product approaches the area between the raised region of the brush and the product, the liquid slows, and as it squeezes through that gap, the pressure increases. Although details of the brush geometry have some impact on this

hydrodynamic spacing (h) between the brush surface and the product, it can be approximated by the following equation:⁵

$$h = \sqrt{[0.16 \mu v w / dP]}$$

where μ is the viscosity of the liquid, v is the local relative velocity of the product and the brush surface, w is the width of the raised surface in the direction of relative motion, and dP is the pressure increase on the brush surface. For a cleaning system using water, which has a μ of 0.017 poise, if $v = 10$ cm/sec, $w = 0.5$ cm, and $dP = 0.1$ atm, or 100,000 dyn/cm², the hydrodynamic boundary layer thickness would be $h = 3.7$ μ m, which is much larger than the typical slurry particle size. Using higher pressures, smaller raised regions, and lower relative velocities would reduce the boundary layer, so that slurry particles would be removed more efficiently. One can go too far in lowering h , however, leading to simultaneous physical contact between brush, particle, and product, which might produce scratching.

Brush-particle contact, fluid viscous shear, and fluid impact pressure (proportional to v^2) are likely to be the major contributors to slurry particle dislodgment. Reducing the gap between the raised regions of the brush and the product increases both the likelihood of brush-particle contact and the shear stress applied by the fluid to the product (and to surface slurry particles). The shear stress is proportional to the fluid viscosity, the relative velocity, and the reciprocal of the gap ($\mu v/h$). Raising the local relative velocity of the product and the brush will increase the impact pressure, which should also favor particle dislodgment.

In the post-CMP cleaning system shown in Figure 1, where the product rotates with its axis horizontal while rinsing liquid is sprayed on it and brushes on either side provide scrubbing action, the spray momentum, gravity, the centrifugal force from the rotating product, and the sweeping action of the brushes provide the large-scale fluid motion. The area swept of liquid and particles per unit of time is determined by multiplying the contact line by the product's relative velocity with respect to the brush. The product's velocity will be greatest at its outer edges, and this can provide the greatest relative velocity. If the brush is turning in the same direction as the motion of the products, the relative velocity will obviously be less than if product and brush were turning in opposite directions. Depending on rotation speeds and product and brush dimensions, there can be regions where there is no relative velocity between the two, but such a situation would be unlikely to occur in a well-designed system.

Knobby versus Ridged Brush Designs

Figure 4 shows examples of knobby and ridged (also called spline) brush geometries. The knobby geometry consists of a set of cylinders raised at right angles to the curved brush surface, whereas the ridged geometry has a series of continuous raised strips at right angles to the curved roller surface of the brush and parallel to its axis. If the relative motion of the brush and product is such that there is always a relative velocity in one direction, then both geometries will sweep away rinsewater. The difference is that a row of knobs does not provide 100% coverage. A fraction f of the liquid will not be swept until the next row of knobs is in contact with the product. An upper estimate of the fraction swept by a row of knobs is the diameter of the knobs (D) times the number of knobs in the row (N) divided by the length (L) of the brush ($f = ND/L$). This is an upper estimate because some of the liquid flowing toward the knobs will actually flow under them or around them. Even after two rows contact the product surface, there is a probability that some liquid will bypass both of them. This probability is determined by multiplying $(1 - f)$ $(1 - f)$. For example, if a 200-mm-long brush has 17 7-mm-diam knobs per row, its swept fraction f would be 0.6, and its liquid-bypass probability would be 0.16.

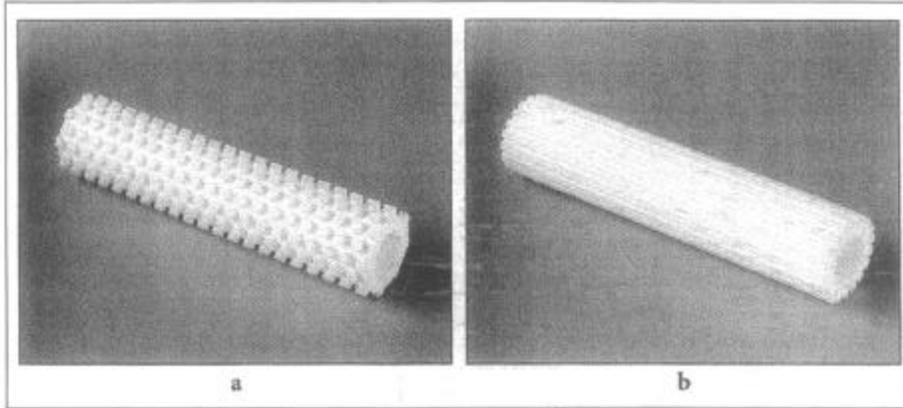


Figure 4: Examples of roller brushes: (a) with a knobby geometry, and (b) with a ridged geometry.

In contrast, brushes with a ridged design provide 100% coverage ($f = 1$) and therefore do not have liquid bypass. In addition, on some commercially available ridged brushes, including those used in the study described below, the ridges are more closely spaced than are the cylinders on typical knobby brushes, another factor that would tend to accelerate fluid removal. The ridged design also can produce a fluid flow akin to the unidirectional airflow found in cleanrooms. This type of flow pattern minimizes the mixing of slurry particles with the rinsewater, facilitating rapid product cleaning.

Some mixed flow is inevitable even with the ridged design, however, because of the hydrodynamic boundary layer between the brush and the product. A plausible model is that slurry particle removal is proportional to the concentration; as expressed in the equation:

$$\frac{dc}{dt} = -kc(t)$$

where $c(t)$ is the concentration (of slurry particles) at time t and k is the rate coefficient, so that

$$c(t) = c(0) \exp(-kt)$$

This exponential decrease has a characteristic time $1/k$, which would be expected to decrease with relative velocity and with the length of the contact line, suggesting that k is proportional to the product of length and velocity. The hydrodynamic boundary layer also depends on velocity, however, so that increasing the relative velocity will not necessarily give a proportional acceleration in particle removal.

$$\frac{c(t)}{c(t_1)} = \left(\frac{t}{t_1} \right)^{(-m)}$$

A second plausible model is that the fractional removal is proportional to the fractional duration of treatment:

$$\frac{dc}{c} = \frac{-mdt}{t}$$

so that:

$$\frac{c(t)}{c(t_1)} = \left(\frac{t}{t_1} \right)^{(-m)}$$

This Power-law relation has sometimes been cited in particle removal studies.⁶

Experimental Methods, Results, and Discussion

An experimental investigation into the comparative effectiveness of knobby and ridged brushes was carried out at Micron Technology’s facility in Boise, ID. For each brush test, alumina CMP slurry particles were deposited by polishing on 24 bare oxide tetraethylorthosilicate (TEOS) wafers, the wafers were subject to post-CMP cleaning, and a light-point defect (LPD)-type wafer inspection instrument (KLA-Tencor, San Jose) was used to count the residual particles. Three brushes of each type were evaluated, and each wafer was brushed for either 10, 20, 40, or 80 seconds.

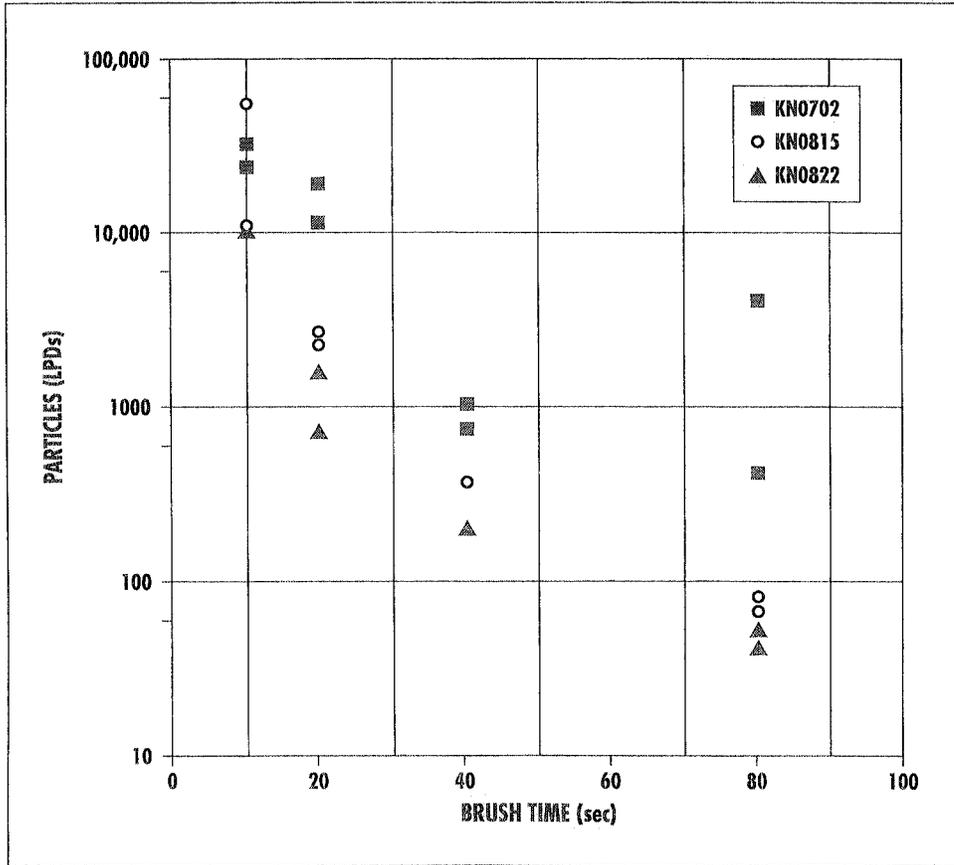


Figure 5: Particle data versus time for three knobby brushes (semilog scale).

Figure 5 presents the results for the knobby brushes. If the exponential model presented in the previous section had been followed, the counts should have decreased by $c(t) = c(0)\exp(-kt)$, which would have yielded a set of straight lines connecting each brush’s data points on the semilogarithmic plot. However, because different wafers were measured for the different cleaning

times, more scatter is to be expected than if the same wafer were measured repeatedly (which, on the other hand, could have caused artificial results because of the repeated wetting and drying). Straight lines with similar slopes are plausible fits for the data for 10, 20, and 40 seconds of post-CMP cleaning, but the slopes clearly change for the interval between the 40- and 80-second readings, indicating the rate coefficient k had decreased by then.

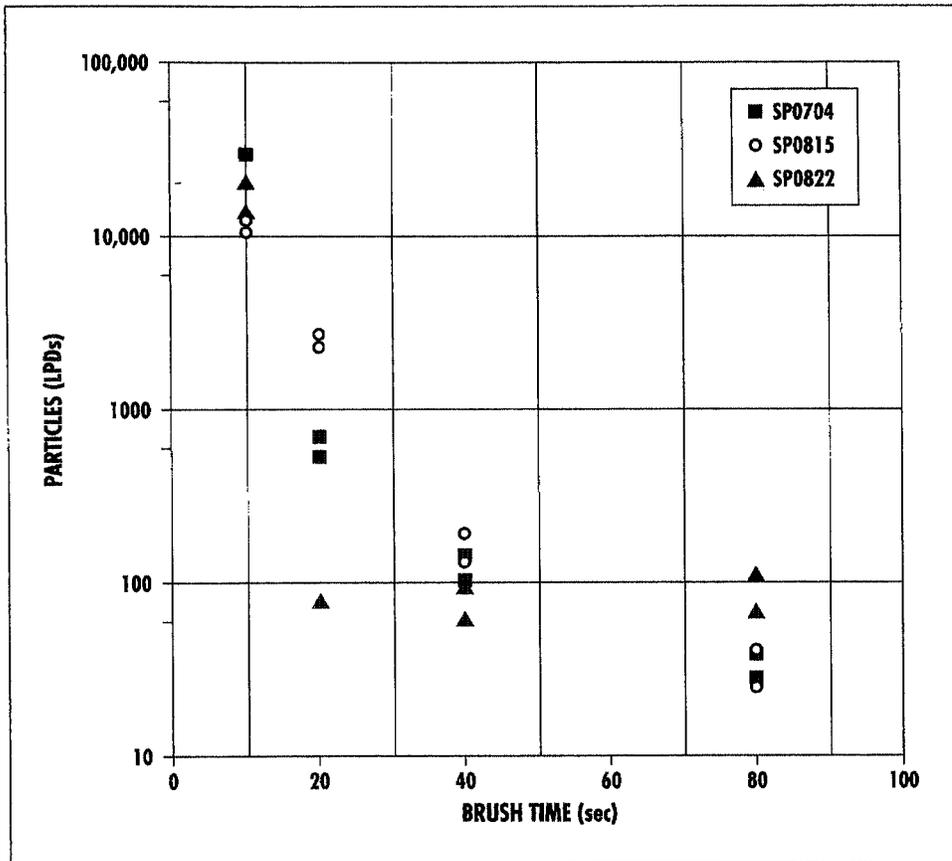


Figure 6: Particle data versus time for three ridged brushes (semilog scale).

Figure 6 shows the results of the same kind of test done with the ridged brushes. The initial rate of cleaning with these brushes was somewhat faster than that for the knobby brushes, but the difference is not statistically significant. The slopes for the interval between the 40- and 80-second data points again differed from those for the earlier readings.

Figure 7 plots both sets of results on log-log axes, where the relation should produce straight lines. From this figure it can be seen that the fits are rather good, suggesting that particle removal had not stopped after 40 seconds but merely slowed. This power-law relationship should also readily allow extrapolation of these results to longer times. The value for m was approximately $1/3$, the cube root. The great majority of the results for the two designs fell between $c(t_1 = 10 \text{ sec}) = 100,000$ and $c(t_1 = 10 \text{ sec}) = 10,000$ light point defects.

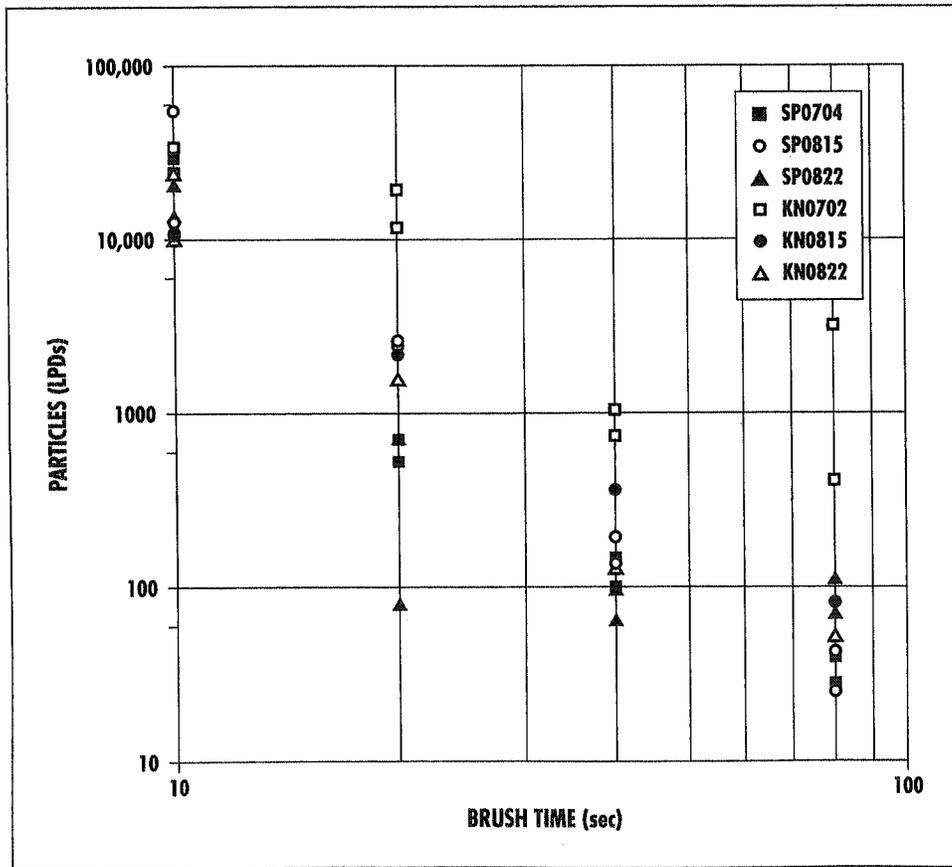


Figure 7: Particle data versus time for both brush designs (log-log scale).

In a related series of tests, much lower levels of slurry contamination were used, and nine different wafers of each design were cleaned. Because the order in which the wafers were cleaned would affect the results, the analysis was done by pairing the wafers (the first wafer cleaned with a knobby brush was paired with the first cleaned with a ridged brush, etc.). Four of the nine pairs exhibited better cleaning by the ridged brushes, a difference that was not statistically significant.

To demonstrate that brush scrubbing is effective on slurries other than those based on alumina, a test was performed in which a drop of a particular kind of slurry (alumina, ceria, fumed silica, or solution-grown silica) was placed on a TEOS wafer, after which the wafer was scrubbed for a specified time. All of the wafers examined after 20 seconds had less than 5% of the particle contamination found on wafers treated with the same kind of slurry after 2 seconds of scrubbing.

Conclusion

As the use of CMP to remove excess coating materials from wafers and thin-film disks has increased, so has the concern with the effectiveness of post-CMP cleans. Because residual slurry particles can cause defects that affect product yields, it is critical to remove them from substrate surfaces. Most cleaning methods use a combination of rinsewater and foam scrubbing brushes. Theoretically, the continuous nature of the contact line between a ridged roller brush and the product being cleaned should lead to better particle-removal results compared with those for a knobby brush with its broken contact line. The experimental results described in this article suggest this is true, but are not conclusive.

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