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Implementing a static control program to increase the efficiency of wet cleaning tools

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A case study focusing on the effects of electrostatic bonding determines that cleaning processes are more effective at removing particles when downstream process tools employ ionization.

M*uch has been written about* the effects of static charge on contamination control in semiconductor manufacturing. It is well documented that in cleanrooms or clean environments, static charge on wafers attracts contaminants out of the air. In fact, when wafers are highly charged, that effect is often the dominant source of contamination.[1] Another effect of particularly high levels of static charge is electrostatic bonding.[2] This effect causes particles to attach themselves to the wafer surface, making their removal nearly impossible.

One of the greatest contributors to static-charge generation on wafers is the wet-cleaning process. For that reason, control of static charge in wafer-cleaning tools is particularly important. The purpose of the study presented in this article was to determine whether the wafer-cleaning process can be enhanced by controlling static-charge generation in the manufacturing process.

Static Charge and the Cleanroom

High levels of electrostatic charge commonly develop in cleanrooms. The objects in semiconductor cleanrooms

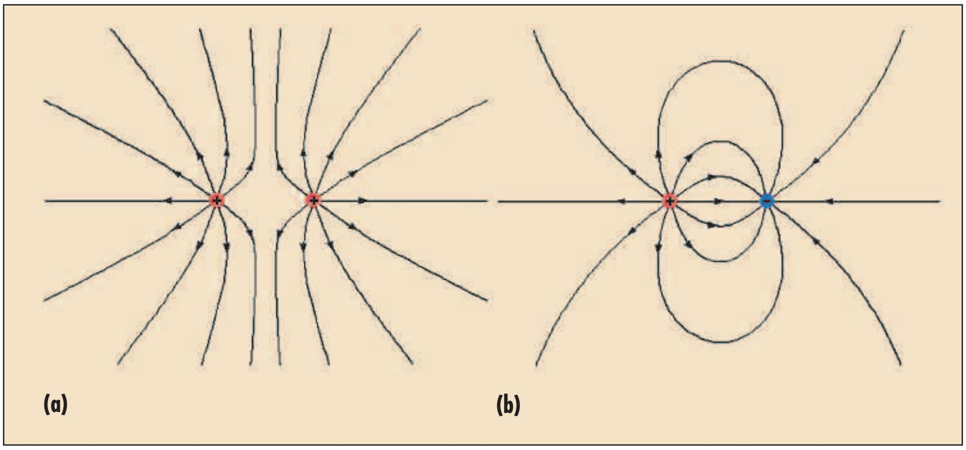

Figure 1: Schematic diagram of electrostatic field lines between (a) two positive charges and (b) a positive and a negative charge.

(facilities surfaces, tools, wafers, process materials, etc.) are ideally suited for triboelectric charging. Dissimilar solids and liquids that come into contact with and then separate from each other always transfer some charge from one material to the other. When the materials separate, significant voltage can be generated.

The materials used in cleanrooms include many excellent insulators, such as quartz and Teflon. In fact, the insulative coating on the surface of a wafer is typically SiO_2, which is glass. Since insulators do not conduct electricity, the only paths to ground for dissipating surface charge where insulators are used are through conductive films of contaminants that may reside on insulator surfaces or through high humidity levels.

At the 45-nm node, a 22-nm defect is critical. At that size, a particle is subjected to 400,000 psi of pressure, which is likely to bond it so strongly to the wafer that it becomes part of the wafer itself.

Unfortunately, because of clean-manufacturing protocols, the materials in cleanrooms are almost entirely devoid of surface contamination. Hence, there is no way for a charge to find a path to ground from insulating objects, resulting in exceptional levels of static charge in cleanrooms. In addition, processing protocols require tightly controlled humidity levels in the 30–40% relative humidity range, which is low enough to defeat charge-reducing effects on insulators.

In many semiconductor processes, charge is generated on wafers and other surfaces. If an insulator or isolated conductor becomes charged, it will remain charged indefinitely. For example, when an end effector touches a wafer with an oxide coating and then separates from it again, the wafer does not discharge to ground. In the wet-cleaning process, DI water comes into contact with the wafer surface and is separated from the wafer by the spin dry process. Because of its high resistivity (>18 MΩ-cm), DI water can result in high tribocharging levels on the wafer surface.

Electrostatic Forces in the Cleanroom

Electrostatic Attraction. Electric fields emanate from charged objects. These fields exert force on other charged objects in the field, a phenomenon known as electrostatic force. Fields originate on positively charged surfaces and terminate on negatively charged ones (or find a path to ground). Figure 1 depicts electrostatic field lines between two positive charges and between a positive and a negative charge.

The contaminants remaining in a fab's filtered air consist of extremely small particles, which are not perfectly charge neutral. They have either too many or too few electrons. Because of their charge, airborne particles are driven on the electric field lines. In other words, they become electrostatically attracted to charged surfaces in a process called electrostatic attraction (ESA).

When an electric field becomes greater than 500 V/in. (a moderate field as measured in a fab), the electrostatic forces acting on a charged particle are greater than the aerodynamic forces. Under these conditions, particles tend not to be swept away by the vertical laminar airflow in the cleanroom environment, but rather are driven across it by the electrostatic forces.[3] This phenomenon greatly reduces the ability of laminar flow to prevent particle settling or sedimentation and is a major cause of contamination in working semiconductor fabs.

Electrostatic Bonding. It has been reported that the magnitude of an attractive force on a very small particle on a wafer surface can be large enough to create a contact pressure of hundreds of bar (~1500 psi).[2] Particles on a charged wafer can be subjected to forces that are large enough to drive the first few atomic layers of the particle into the crystalline atomic matrix of the wafer. Referred to as electrostatic bonding, this phenomenon occurs when the atoms of a contaminant come into intimate contact with a wafer surface so that the atoms are within the range of van der Waals forces. While the difficulty of blowing off electrostatically attracted dust is well known in everyday life, the concept of bonding is not well documented. In theory, electrostatic bonding makes it difficult, if not impossible, for conventional cleaning techniques to remove contamination on a charged object.

The concept of electrostatic bonding implies that some particles on the surface of a charged wafer cannot be removed using even an aggressive cleaning process, because the unique physical contact resulting from electrostatic bonding makes the particle a part of the wafer. If that is the case, it is expected that actively discharged wafers will have dramatically lower contamination levels than nondischarged wafers. This article describes an experiment that was conducted at IBM's 300-mm fab in East Fishkill, NY, in which processes with and without static-charge control were compared.

Experimental Background

It has long been known that wafers undergoing the wet-cleaning process emerge with some amount of residual particles.[4] It is postulated that the cleaning process cannot remove such particles or adds them through sedimentation or electrostatic attraction. The particles-per-wafer-pass (PWP) value, the standard metric for tool cleanliness based on the average number of particles added to the wafer during a single pass through a tool, depends on the different behavior of these particle sources. The PWP value is typically specified by the tool vendor for a given minimum particle size.

Cleaning Residuals. While the various types of cleaning processes have different efficiency levels, the particle-removal percentage for any given process (e.g., particle-removal efficiency) is expected to be a constant, ρ. That must be the case if the particles are randomly distributed over the wafer surface and are independent of each other. Each particle experiences a cleaning force that, on average, is the same as that for any other particle. However, cleaning efficiency varies widely depending on whether the particles have bonded to the wafer surface.

Sedimentation. The number of particles that land on the surface of a wafer depends on the cleanliness of the tool. For the purposes of this evaluation, tool cleanliness is defined as a constant, P_s, and is the PWP value that is normally provided by the vendor.

ESA. The rate of attraction of contaminating charged particles is proportional to the magnitude of the electric field in the laminar-flow field above the wafer. In general, this field is proportional to the electrical charge, q, on the surface of the wafer and the length of time that the wafer is exposed to the environment while charged. The ESA value is expressed as $P_E = \alpha qt$, where P_E is the number of particles electrostatically attracted, α is a constant of proportionality that depends on the tool geometry, and t is the wafer exposure time.

For a wafer that enters the process with N particles and has the charge q, the number of particles on the wafer after processing is expressed in the following equation:

$$N' = (1 - \rho)N + \alpha qt + P_s$$

Thus, the apparent number of particles added is $N' - N$, which can vary dramatically depending on the cleanliness level of the wafer when it is delivered to the tool. The existence of electrostatic bonding further complicates the issue, making PWP even less representative of the cleaning process.

Quantifying the Quality of the Cleaning Process

Since the PWP value is not the ideal way to quantify the quality of the cleaning process, another parameter must be defined. A reasonable metric can be defined based on the type of information that is acquired by optically inspecting the wafer surface for particles.

To perform surface particle measurement, investigators used a Surfscan SP1 unpatterned-surface inspection tool from KLA-Tencor (San Jose), which records not only particle size but also the x and y coordinates of each particle on the wafer. The use of this instrument enabled the investigators to catalog the particle population in detail. That particle catalog consisted of the number of particles added ($\alpha tq + P_s$), known as particle adders, and the number of particles removed (ρN), known as particle subtractors. With that information, the quality of the cleaning process could be determined.

The quality factor, the parameter Q, was defined as:

$$Q = \frac{Subtractors}{Adders} - 1$$

The value 1 was subtracted from the ratio to drive the value of Q to 0 when the cleaning process did not result in a net particle benefit. Hence, a positive Q value indicated a net benefit, while a negative Q value indicated a particle detriment.

A negative Q value does not necessarily signify that a tool is of negative value. While a cleaning tool may be used to remove such coatings as photoresists, it may also add some small particles. Hence, Q is not the only parameter that can be used to characterize a cleaning tool, but it is certainly an important one.

Ionization Case Study

Experimental Procedure. The goal of this study was to determine if electrostatic bonding plays a major role in determining the Q values of cleaning processes on tools with or without ionization. For the purposes of this study, the tools simply acted as sources of contamination; their process functions were irrelevant. For the experiments discussed here, two tools were chosen: a historically very clean tool (PWP <1) and a very contaminated one (PWP ~200).

The experiment used unpatterned wafers with an oxide coating of 1.5 µm on each side to simulate the electrostatic properties of processed wafers. All wafers were transported from tool to tool in conventional front-opening unified pods (FOUPs) containing 25 wafers. All FOUP movements were performed using an automated material-handling system (AMHS)—operators were not allowed to handle the FOUPs manually. The wafers were exposed to the sub–ISO Class 2 environment of the process tool interiors only, never to the fab environment.

Substantial effort was made to eliminate potential sources of systematic contamination from outside the tools and the cleaning process. Monitor wafers were transferred into a FOUP using a wafer-mapping tool that was equipped with air ionization. The FOUP itself had been cleaned five times. Even the FOUP stocker manual loadport was equipped with spot ionizers, as illustrated in Figure 2.

Figure 2: FOUP stocker with spot air ionization used for neutralizing the pod before uploading.

Ionization bars were installed below the fan filter face of the ULPA filter in the equipment front-end module, as shown in Figure 3. That setup assured that the wafers were discharged as the robot moved them from the FOUP, which was docked to the tool, to the process chamber and then back to the FOUP again. In the first run, all of the ionization was turned on. In the second run, the ionization was turned off.

A schematic diagram of the experimental process flow is presented in Figure 4. First, the FOUP containing clean wafers was moved to the surface-scanning tool via the AMHS. After the wafers were scanned, the FOUP was moved to the FOUP stocker, after which it was docked to the target tool. The wafers were transferred into the tool sequentially and then moved to the prealign station, aligned, and then returned to the FOUP. Then the FOUP was undocked and moved via the AMHS back to the stocker. In all, the FOUP was docked to the tool and the wafers were handled 20 times each, amounting to a total of 500 separate wafer-handling operations. This procedure was intended to simulate all wafer-handling operations associated with processing a single photomask layer.

Wafers were processed in several tools before they were cleaned. Before and after cleaning, the wafers were scanned for surface particles. Surface scans were performed using a Surfscan SP1 set to a particle-size threshold of 200 nm. A set of software tools was used to perform prior-level subtraction analysis, enabling the investigators to determine the precise number of particle adders and subtractors associated with each cleaning cycle. The size and coordinates of each particle were recorded for all 25 wafers.

Data Gathering. Four data sets (ionization on and ionization off for both the clean and the dirty tool) were evaluated. Scans were performed before and after ionization was turned on and off, a total of eight scans for both tools. This procedure was performed for each of the 25 wafers in the FOUP. Based on the location and size of each particle, it was possible to sort the particles into three groups:

- A particle on a postclean wafer that had not been present on the preclean wafer (a particle adder).
- A particle on a preclean wafer that was also present on the postclean wafer at the same location.

Figure 3: Ionization bars installed below the fan filter face of the ULPA filter in the equipment front-end module.

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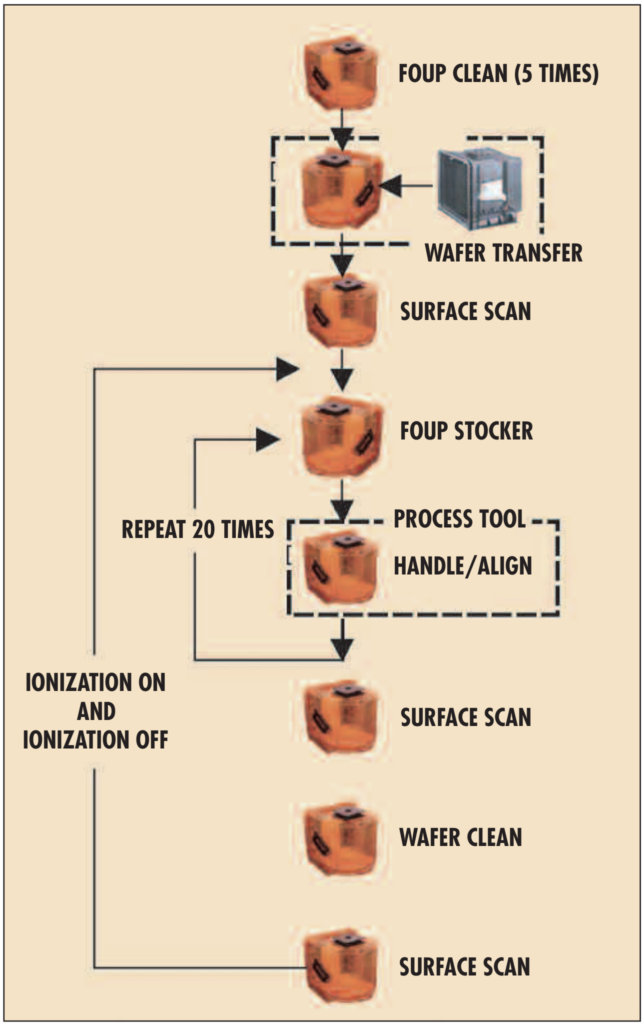

Figure 4: Process flow of the ionization experiment.

- A particle on a preclean wafer that was not present on the postclean wafer (a particle subtractor, a typical result of the cleaning process).

The resulting data enabled the investigators to compare the quality factor, *Q*, of the wet-cleaning tool for wafers contaminated with surface particles resulting from sedimentation only (ionization on) and for wafers contaminated with surface particles resulting from both sedimentation and electrostatic attraction (ionization off). Electrostatic bonding was expected to have a significant effect on the quality factor, which is a measure of how many particles are removed as compared with how many remain after cleaning. Figure 5 presents a schematic diagram of preclean and postclean wafers with added, subtracted, and common particles.

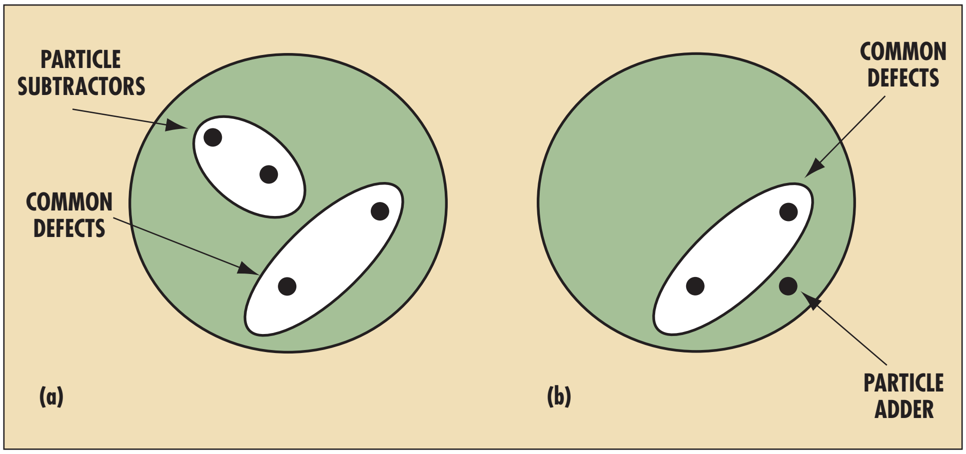

Figure 5: Schematic diagram of (a) preclean and (b) postclean wafers with added, subtracted, and common particles.

Since the process was performed on 25 wafers with ionization on and 25 wafers with ionization off, it was possible to calculate the standard error for 25 measurements of both adders and subtractors. That information was then used to determine the error bars of the *Q* factors for each measurement.

Experimental Results. The results of the study for both the very clean and the dirty tool are shown in Figure 6. In this figure, ionization-off data are shown in red, while ionization-on data are shown in green. The error bars indicate the standard error (standard deviation of the mean).

The data clearly show the effects of electrostatic attraction. If ionization is not implemented in the process steps that precede wet cleaning, the cleaning process tends to introduce rather than eliminate particles. When ionization is employed, the cleaning process efficiently eliminates particles added during previous processes. In the case of both the clean and the dirty tool, the quality of the cleaning process has a 3 standard deviation effect, as shown in Figure 6.

These data indicate that when ionization is in effect, the number of killer particles added by the action of a process tool and its subsequent cleaning step can be lower than the number of particle adders deposited by the process tool alone. In other words, when ionization is activated and operating properly, the cleaning tool removes most particles in the size range studied, which is what the cleaning process is supposed to do.

Wafer Bonding and Particle Size

Studies suggest that as the particle size shrinks, the deposition velocity increases.[5] In contamination control terms, the deposition velocity is the average speed at which particles approach the surface of a wafer, including a recoil effect as particles bounce off of atmospheric gas atoms. The speed at which particles move is considerably higher than the deposition velocity, since particles spend much of the time moving away

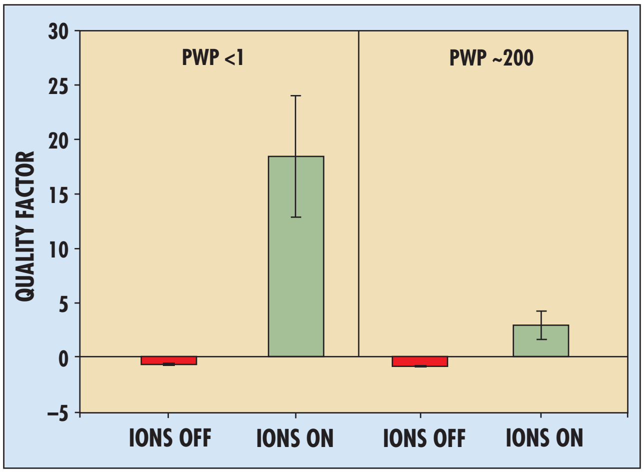

Figure 6: Quality factor of the clean versus the dirty tool run with and without ionization.

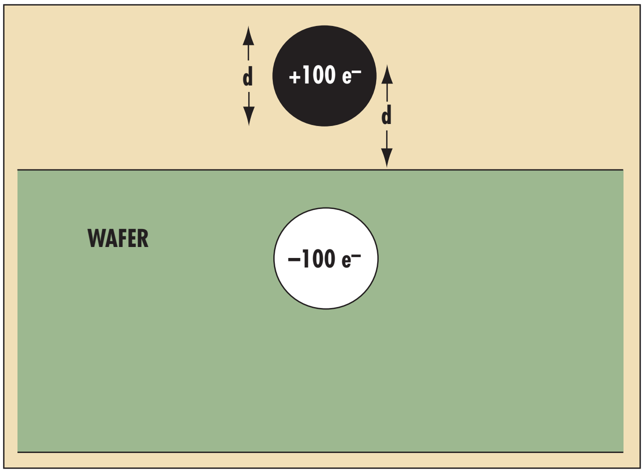

Figure 7: Schematic diagram of image charge technique used to calculate force on a particle.

from the wafer because of elastic collisions.

One way to estimate the relationship between bonding and particle size is to calculate the acceleration of a particle as it approaches the surface of a wafer. For a 1.0-, 0.1-, and 0.01-µm particle, each with just 100 extra electrons, the force on the particle at a distance of one particle diameter from the surface of the conducting wafer can be calculated using the image charge technique shown in Figure 7.

According to Coulomb's law, the electrostatic force on a particle is

$$F = \frac{q^2}{4\pi\varepsilon_0 R^2}$$

where q is the charge of 100 electrons, ε_0 is the permittivity of free space ($8.85 \times 10^{-12}\ C^2/N - m^2$), and the distance of separation is $R = 2d$, where d is particle diameter.[6]

Taking the average atomic number of a contaminant as $A = 10$, numerical results are obtained for the force acting on particles with the following sizes:

- When $d = 1.0$ µm, force = 4.25×10^{-2} psi.
- When $d = 0.1$ µm, force = 4.25×10^{2} psi.
- When $d = 0.02$ µm, force = 4.25×10^{5} psi.
- When $d = 0.01$ µm, force = 4.25×10^{6} psi.

As particles shrink in size, the force acting on them becomes enormous. At the 45-nm device node, a 22-nm defect is critical. At that size, a particle is subjected to 400,000 psi of pressure, which is likely to bond it so strongly to the wafer that it becomes part of the wafer itself.

Conclusion

The efficiency of a wet cleaning tool was shown to be significantly improved when the wafer processing steps preceding the cleaning were performed using static control. This finding strongly suggests that the phenomenon of electrostatic bonding affects the particle removal efficiency of the tool. Based on the estimates presented in this article, the bonding process is expected to increase considerably as acceptable particle sizes decrease to meet the demands of future advanced technology nodes.

To avoid damage to wafers at the 45-nm technology node, it will become necessary to prevent contaminating particles from making contact with the wafer. The importance of maintaining a clean wafer will become more critical to high-yield processing. As demonstrated in this article, it is possible that the ability of a cleaning tool to eliminate particles in the sub-90-nm range will be significantly limited without the implementation of static control.

Acknowledgments

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References

1. SEMI, *Electrostatic Compatibility: Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment*, Document E78-0998 (Mountain View, CA: Semiconductor Equipment and Materials International, 1998).
2. M Yost et al., “Electrostatic Attraction and Particle Control,” *Microcontamination* 4, no. 6 (1986): 18–25, 70.
3. DW Cooper, JJ Wu, and MH Peters, “Deposition of Submicron Aerosol Particles in Integrated Circuit Manufacturing: Experiments,” *Journal of Environmental Sciences* 32, no. 1 (1989): 27, 28, 43–45.
4. G Vereecke, “Issues for Megasonic Cleaning without Damaging” (paper presented at the SCP Global Technologies International Symposium on Wafer Cleaning and Surface Preparation, Boise, ID, June 8–9, 2005).

5. RP Donovan, *Particle Control for Semiconductor Manufacturing* (New York: Marcel Dekker, 1990), 316.
6. JD Jackson, *Classical Electrodynamics*, 3rd ed. (New York: Wiley, 1999), 24.

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