# A Comparative Analysis of Common Dry and Wet Wafer Cleaning Methods

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**Abstract.** As the feature size of semiconductor devices continues to approach the physical limit, the impact of wafer surface cleanliness on device performance becomes increasingly significant. Especially in advanced processes below 7 nanometers, single-atomic-layer contamination can lead to a sharp increase in device leakage current and a decline in reliability, which poses a severe challenge to traditional cleaning processes. Meanwhile, the urgent demand for green manufacturing in the global semiconductor industry is also driving the innovation of cleaning technology towards low energy consumption and low emissions. This study discusses the key processes of wafer cleaning in semiconductor manufacturing and compares the basic principles and process flows of traditional wet cleaning and modern dry cleaning. Wet cleaning technology is mature and has stable effects, but it has deficiencies in removing nanoscale contaminants, reducing chemical residues and being environmentally friendly. Dry cleaning, on the other hand, utilizes technologies such as lasers and supercritical $CO_2$ to achieve precise decontamination and reduce the use of chemical reagents. Through comparative analysis, it provides a theoretical basis for further optimizing the wafer cleaning process and improving the device performance. The research is of certain significance for breaking through the yield bottleneck of advanced processes and reducing environmental pollution in chip manufacturing.

**Keywords:** Wafer cleaning, Dry cleaning, Wet cleaning, Semiconductor manufacturing.

## 1 Introduction

In the manufacturing process of semiconductor devices, the wafer cleaning process plays an indispensable role. As integrated circuits continue to develop towards high density, low power consumption and high performance, the requirements for the surface cleanliness of wafers have also increased accordingly. Even extremely tiny particles, organic matter, metal ions, or uneven oxide layers may cause a decline in device performance or failure in subsequent processes [1]. Therefore, efficiently and precisely removing these pollutants has become a key link to ensure the quality of semiconductor devices.

Over the past few decades, wafer cleaning technology has undergone an evolution from traditional wet cleaning to modern dry cleaning. Wet cleaning processes, such as


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Radio Corporation of America cleaning (RCA), Sulfuric Acid Peroxide Mixture cleaning (SPM) and Diluted Hydrofluoric Acid cleaning (DHF), have the advantages of mature technology and stable cleaning effect, and thus are widely adopted in large-scale production. However, as the size of wafers continues to shrink and the requirements for nanoscale processes become increasingly strict, traditional wet cleaning is facing more and more challenges in removing extremely fine contaminants, reducing chemical residues, and being environmentally friendly. Compared with wet cleaning, dry cleaning technology has demonstrated unique advantages in some high-end processes. By using technologies such as lasers and supercritical CO2, dry cleaning can precisely remove nanoscale contaminants and effectively avoid the residual risks and environmental pollution problems caused by the extensive use of chemical reagents.

This article will provide a detailed introduction to the basic principles of wet and dry cleaning processes and the technical challenges they respectively face. By comparing the advantages and disadvantages of different cleaning methods in terms of cleaning quality, environmental impact and application scope, the aim is to provide a theoretical basis for the further optimization of the wafer cleaning process in semiconductor manufacturing.

## 2 Principles and applications of wafer cleaning

### 2.1 Overview of wafer cleaning

Wafer cleaning is a crucial process in semiconductor manufacturing, aiming to remove contaminants from the surface and microstructure of wafers through physical, chemical or physicochemical methods [1]. The contaminants to be cleaned are shown in Figure 1, including but not limited to particles, metal ions, organic matter, oxide layers, etc[1]. Among all the cleaning methods, chemical cleaning is the most widely used. Chemical cleaning is a process that uses chemical reagents and organic solvents to chemically react with or dissolve particles, impurities and oil stains adhering to the surface of objects. To promote the removal of these contaminants, physical measures such as circulation, heating, ultrasonic oscillation or vacuuming are usually combined to separate impurities from the surface. Finally, a clean silicon wafer surface is obtained by rinsing with a large amount of deionized water [2]. These impurities may have adverse effects on the surface of the wafer, affecting the quality of subsequent processes such as photolithography, etching, and deposition, ultimately leading to a decline in product performance or production defects.

With the increasing refinement of integrated circuit manufacturing processes, especially as the size of devices continues to shrink, the requirements for cleanliness in wafer cleaning processes are getting higher and higher. In modern semiconductor manufacturing, the surface cleanliness of wafers directly determines the performance and reliability of devices, so the cleaning process is of vital importance.

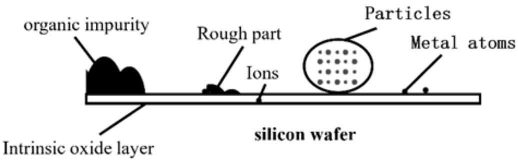


**Fig. 1.** Main sources of wafer contaminants.

### 2.2 Wet cleaning

At present, the mainstream wafer cleaning methods are mainly divided into two categories: wet cleaning and dry cleaning. Wet cleaning technology relies on chemical liquids to remove different types of contaminants through specific chemical reactions. Wet cleaning mainly includes RCA cleaning, SPM cleaning and DHF cleaning, and usually multiple methods need to be used simultaneously.

**RCA cleaning.** Among them, the RCA cleaning technology is the most widely used method, including the Standard Clean-1 (SC-1) and Standard Clean-2 (SC-2) cleaning steps, which have good effects on the removal of organic matter, particles and metal ions respectively [2]. These two items are the core components of the RCA standard cleaning system. The SC-1 cleaning solution is composed of ammonium hydroxide (NH4OH), hydrogen peroxide (H2O2) and ultrapure water (DI-Water) mixed in a specific ratio [3]. This solution exhibits a unique weakly alkaline environment (pH 9-10) and REDOX characteristics in the microelectronic cleaning process. Its cleaning mechanism includes dual action paths: On the one hand, H2O2 forms soluble silicates on the surface of silicon wafers through oxidation reactions, weakening the binding energy between pollutants and the substrate. On the other hand, NH4OH establishes an electric potential barrier on the silicon surface by adjusting the zeta potential and achieves efficient desorption of sub-micron particles through the electrostatic repulsion effect [4]. It is worth noting that the unique chemical kinetic equilibrium of SC-1 can also inhibits the redeposition of particles during the cleaning process. This characteristic makes it a key technology for nanoscale surface cleaning.

SC-2 cleaning solution, as a representative solution in the acidic cleaning stage, is prepared by precisely proportioning hydrochloric acid (HCl), hydrogen peroxide (H2O2) and ultrapure water. As the subsequent cleaning of SC-1, with the synergistic effect of its strong acid property (pH 0-1) and oxidation capacity, it can remove metal impurities and certain organic impurities [5].

**SMP cleaning.** To remove organic contaminants from the wafers, a high-temperature SPM process is required. SPM cleaning solution is prepared by mixing H2SO4, H2O2 and DI-Water in a volume ratio of approximately 2:1 to 8:1. It has the characteristics of strong acidity and strong oxidation capacity at about 90℃ to 280℃, and can remove organic impurities [6]. During the cleaning process, $H_2SO_4$ reacts with $H_2O_2$ to produce active oxygen, which completely decomposes organic matter into carbon dioxide and water, thereby effectively removing organic pollutants [6].

**DHF cleaning.** DHF cleaning is a process of removing the natural oxide layer on the surface of silicon wafers with diluted hydrofluoric acid cleaning solution [5,7]. This method achieves effective cleaning by reacting 1% dilute hydrofluoric acid with silicon dioxide to generate hexafluorosilicic acid. Meanwhile, in a weakly acidic environment, the metals on the natural oxide film will also dissolve into the cleaning solution, achieving the purpose of removing contaminants [7].

### 2.3 Dry cleaning

Compared with wet cleaning, dry cleaning technology shows unique advantages in some high-end processes. By using technologies such as supercritical $CO_2$ and laser cleaning, dry cleaning not only achieves the effect of removing nano-scale pollutants but also reduces the residual risks and environmental pollution problems caused by chemical agents. Laser cleaning relies on short-pulse lasers to drive contaminants away from the wafer surface [8]. Supercritical $CO_2$ cleaning, with its special fluid properties, achieves efficient cleaning under low-temperature and low-damage conditions [9].

**Supercritical $CO_2$ (sc$CO_2$) cleaning.** Compared with other gases, $CO_2$ is more likely to enter the supercritical state. At this time, $CO_2$ has the characteristics of both liquid and gas, that is, it has a density similar to that of liquid and a viscosity and surface tension similar to that of gas. Based on these properties, supercritical $CO_2$ can be used as an ideal solvent and can penetrate into the gaps of complex-shaped devices [8]. The sc$CO_2$ cleaning technology relies on the unique physicochemical properties of $CO_2$ in its critical state. By regulating temperature and pressure, it efficiently removes non-polar and weakly polar organic contaminants from the surface of wafers. Since sc$CO_2$ is a non-polar solvent, it can dissolve contaminants such as silicone, low-carbon aliphatic hydrocarbons, and oils, and remove these contaminants from the wafer surface during the decompression process. Meanwhile, this process does not require the extensive use of organic solvents or strong acids and alkalis, thus having the advantages of low residue and environmental friendliness. This combination of controllability and environmental friendliness makes the super sc$CO_2$ cleaning technology an important means to achieve clean, efficient and green manufacturing of wafer surfaces.

**Laser cleaning.** At present, there are various hypotheses about the principle of laser cleaning. The prevailing view is that laser cleaning relies on the thermal expansion effect induced by laser. After the laser irradiates the surface of the substrate, the local rapid temperature rise causes thermal expansion of the material and generates acceleration, enabling the particles adhering to the surface to overcome the adsorption force and fall off. At an appropriate laser power, the substrate only undergoes elastic expansion and will not cause damage to the surface of the silicon substrate [10]. Another explanation points out that due to the presence of nanoparticles, a locally enhanced light field effect is formed in the contact area between the particles and the matrix, causing the substrate to dissociate rapidly in this area, thereby allowing the particles to detach instantaneously. There is also a view that under the action of laser, the moisture in the air will instantly vaporize explosively, generating sufficient impact force to lift the particles off the surface without damaging the substrate. Some people also believe that laser cleaning encompasses all the above three processes simultaneously [10]. Figure 2 shows the basic principle of laser cleaning.

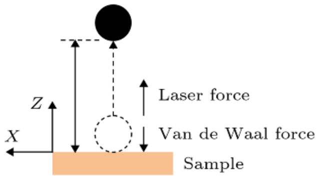


**Fig. 2.** Schematic diagram of Laser cleaning Mechanism.

# 3 Comparison of different cleaning processes

## 3.1 The disadvantages of wet cleaning

**Bottleneck of cleaning effect.** As semiconductor manufacturing processes evolve towards advanced processes below 7 nanometers, the high aspect ratio characteristics of device structures continue to amplify, and traditional wet cleaning systems are facing significant technical bottlenecks. Specifically, the interfacial forces in the solution system produce significant capillary effects in nanostructures with high aspect ratios, resulting in a significant decline in the dynamic performance of fluid transport. This phenomenon of insufficient fluid permeability directly affects the desorption efficiency of photoresists at the micro-nano scale and leads to incomplete removal of developing residues in nanoscale grooves, ultimately affecting the realization of ultra-fine pattern processes and the reliability of devices [9].

**Pollution and waste.** In the traditional wet cleaning process, up to 16 kilograms of pure water, 36 grams of strong acids, strong bases and organic solvents, as well as 350 grams of ultra-pure gas are required to produce 1 gram of semiconductor chip. This process is not only costly and causes serious waste of resources but also generates a large amount of wastewater containing heavy metals and other pollutants, which often causes severe damage to the environment [11].

### 3.2 The disadvantages of dry cleaning

**The objects to be cleaned are limited.** Although the dry method enables the particles adhering to the surface of the wafer to overcome the adsorption force and fall off, it is difficult to remove all impurities, such as some specific organic substances, merely through this physical means. The natural oxide layer on the surface of a wafer usually contains a large number of hydroxyl groups (-OH). These polar groups can form hydrogen bonds or other polar interactions with polar groups in organic molecules (such as carbonyl groups, carboxyl groups, etc.), thereby enhancing the adhesion between organic substances and the wafer surface. Dry cleaning, especially when cleaning materials with complex structures, is difficult to remove through physical methods and needs to be combined with wet cleaning to achieve the purpose of removing organic matter [12].

**The uniformity of cleaning is not good.** Dry cleaning is highly sensitive to process parameters such as laser pulse energy and reaction time. Improper parameter Settings can easily lead to incomplete cleaning or the introduction of secondary pollution. In some cases, to enhance the cleaning efficiency, a higher energy input may be required, which could cause minor damage to the wafer surface. Meanwhile, if the fallen pollutants are not promptly and effectively removed, they may redeposit in other areas, causing secondary pollution problems. Therefore, it is somewhat difficult to achieve stable and uniform cleaning in large-scale production.

Overall, the traditional wet process cannot meet the cleaning requirements of advanced process wafers and environmental protection standards in future development. However, the dry process still faces many limitations at present and cannot be applied on a large scale. Traditional wet cleaning is mainly targeted at large-scale production scenarios with moderate cleanliness requirements. Its process is mature and the cost is controllable, but it has a high pollution risk, including the discharge of chemical waste liquid and heavy metal residues. Moreover, its efficiency is limited when cleaning nanoscale particles or complex structures with a high aspect ratio. Meanwhile, this technology urgently needs to break through the cleaning bottleneck of high aspect ratio structures and further reduce resource consumption. In contrast, dry cleaning technology is more suitable for high-end processes of advanced manufacturing processes below 7 nanometers. It employs innovative means such as lasers and supercritical $CO_2$, significantly reducing the use of chemical reagents and environmental pollution, which is in line with the trend of green manufacturing. However, it still has limitations in the removal of polar organic substances or chemically bonded contaminants [13]. In addition, dry technology needs to overcome challenges such as optimizing cleaning uniformity, controlling the risk of secondary pollution, and reducing costs. The differentiated characteristics of the two types of technologies provide key references for the selection and iteration of semiconductor manufacturing processes, which need to be comprehensively considered in combination with specific process requirements and environmental goals [14]. Table 1, through a comparative analysis of the principles, advantages and disadvantages, application scenarios, etc. of the dry and wet process, can identify potential process innovations such as combined dry and wet cleaning, bringing new discussion points to the research of wafer cleaning.

**Table 1.** Comparison of dry and wet cleaning processes.

| Comparative item | Wet cleaning | Dry cleaning |
| --- | --- | --- |
| Technical principle | Use chemical liquids to dissolve or oxidize pollutants through chemical reactions | Pollutants are removed by physical or physicochemical methods through energy or fluid properties |
| Typical technology | RCA cleaning (SC-1, SC-2), SPM cleaning, DHF cleaning | Laser cleaning, supercritical $CO_2$ cleaning |
| Advantages | 1. The technology is mature and the cleaning effect is stable<br>2. Applicable to various pollutants (organic substances, metal ions, oxide layers)<br>3. The cost is relatively low | 1. It has a strong ability to remove nanoscale pollutants<br>2. It does not require a large amount of chemical reagents and is highly environmentally friendly<br>3. Applicable to complex microstructures (such as high aspect ratio) |
| Disadvantages | 1. High resource consumption (water, chemicals)<br>2. Wastewater treatment is difficult and the risk of environmental pollution is high<br>3. The cleaning effect on structures with a high aspect ratio is poor | 1. It is difficult to remove polar organic substances (wet methods need to be combined)<br>2. The process parameters are sensitive and can easily lead to secondary pollution damage<br>3. The equipment cost is high and the stability of large-scale production is insufficient |

## 4 Conclusion

This paper systematically compares the differences between wet cleaning methods such as RCA, SPM, and DHF and dry cleaning methods such as laser and supercritical $CO_2$ in terms of process principle, cleaning efficiency, environmental impact, and application scope. It reveals that wet cleaning has stable and reliable advantages in removing organic matter, particles, metal ions, and oxide layers due to its mature chemical reaction mechanism and equipment universality. However, it is accompanied by problems such as a large amount of chemical reagent usage, high wastewater treatment costs, and cleaning dead corners of nanoscale structures; Dry cleaning, which is more environmentally friendly due to its nanoscale precision removal and low chemical residue, is suitable for high-end 7 nm and below processes. However, it is difficult to completely replace wet cleaning due to its limited cleaning objects, sensitive process parameters and secondary contamination. These findings not only provide scientific basis for the optimization of semiconductor manufacturing processes, which helps to reduce production costs and mitigate environmental impacts, but also offer important references for breakthroughs in the cleanliness technology of high-end nano-processes. Looking ahead, technological innovations that combine wet-dry cascade or composite cleaning processes, green low-residue chemical formulas and the recycling of cleaning agents, as well as online monitoring and intelligent control, are expected to achieve efficient, environmentally friendly and low-cost intelligent cleaning solutions while meeting more stringent cleanliness requirements.

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