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# Thermophoretic Control of Submicron-sized Particulate Recontamination\*

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Thermophoresis is the movement of particles in a thermal gradient. It has the advantages of being simple to set up and to carry out. Here, it is used to prevent the recontamination of emitted particles smaller than 0.5  $\mu\text{m}$  during the dry laser cleaning of particles not chemically bound to the substrate. Its use permits the efficiency of such dry laser cleaning to be greatly improved. A comparison between the thermophoretic and laminar flow techniques is carried out, showing that thermophoresis is more efficient.

*Keywords:* Laminar flow; Laser cleaning; Recontamination; Thermophoresis

## INTRODUCTION

Contaminant deposition onto semiconductor surfaces during manufacture is a major cause of low product yields in the microelectronics industry. Despite a controlled, filtered environment during production, it is not possible to achieve completely particle-free conditions on the manufacturing line. Laser cleaning is a simple, fast and

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chlorofluorocarbon-free technique developed recently to remove contaminants from semiconductor wafer surfaces.

There are two types of laser cleaning presently used; both have been discussed in great detail in the literature [1–9]. The first, called steam cleaning [1, 2], transfers the laser energy absorbed by the substrate to a liquid (usually water) condensed onto the surface; the liquid acts as both an energy transfer medium and an adhesion force reduction agent. It is highly efficient, especially for chemically (*i.e.*, hydrogen-) bonded particles. The second, called dry cleaning [1–3], does not use a liquid condensed onto the surface but transfers the energy directly to the substrate. It is substantially less efficient, particularly against chemically-bonded particles. Its advantage over steam cleaning is that it is compatible with cluster tools.

We have successfully removed submicron-sized organic and inorganic particles from silicon wafer surfaces by both steam and dry cleaning, using CO<sub>2</sub> [4, 5] and excimer [6, 7] lasers. The detailed experimental descriptions of dry and steam laser cleaning, and quantitative analyses of the adhesion and removal forces active in each, have been given in our previous papers [7–9].

During laser cleaning, the viscous drag force of the atmosphere slows down the velocities of ejected particles and causes the particles to be suspended in the air a few centimeters above the cleaned surface [2]. These particles may recontaminate the cleaned surface. In order to obtain a higher laser cleaning efficiency, the recontamination by ejected particles must be reduced or eliminated.

Several techniques have been developed to solve the recontamination problem. The simplest one is to place the wafer to be cleaned face down [1, 4] so the particles removed can be drawn away from the surface by gravity and inertia. Another technique is to use a laminar gas flow [10]; a laminar flow maintains a stable, stationary boundary layer whose thickness is determined by the choice of gas or by the pressure. Once the contaminant passes through the boundary layer, it becomes entrained in the bulk gas flow. However, the laminar flow technique is not compatible with cluster tools. In this paper, we apply thermophoresis to dry laser cleaning, which greatly increases the cleaning efficiency of removing particles having no chemical bonds to the substrate surface [8, 9].

## THEORY

The mechanisms that determine the transport of these particles are convection, diffusion, gravitational settling, inertia, electrostatic force, thermophoretic force and turbulence. The Brownian diffusivity of an aerosol particle is much smaller than gas diffusivities, owing to the massive size of the particle compared with a gas molecule. For example, for spherical particles of 0.05–1.0  $\mu\text{m}$  diameter in air, diffusivities range from  $2.4 \times 10^{-3}$  to  $2.8 \times 10^{-5} \text{ m}^2/\text{s}$  [11]. Thus, the effects of particle diffusion can normally be neglected. The electrostatic force can, depending on the polarity between the particle and the surface, either increase or decrease the possibility of particle recontamination. In our clean room, as elsewhere, air is continually changed. Airflow fluctuations exist almost everywhere; such an airflow has the feature of unsteady laminar flow but differs from the turbulence in a tube flowing at high Reynolds numbers because of its much lower velocity, weaker diffusion and dissipation of eddy energy, and larger scale. Airflow fluctuations are the primary reason for particle recontamination.

The force arising from a temperature gradient acting on particles suspended in a gas has long been the subject of theoretical and experimental investigations [12–19]. This thermophoretic force experienced by a particle is produced by the greater kinetic energy of gas molecules on the higher temperature side of the particle, thereby driving the particle to the region of lower temperature. The thermophoretic force is directly proportional to the local temperature gradient and is given by the following equation for an isolated sphere [20]:

$$F^T = -\frac{9\pi\eta^2 r_p}{\rho_g T} \left( \frac{1}{1 + 3(\lambda/r_p)} \right) \left( \frac{(k_g/k_p) + 2.2(\lambda/r_p)}{1 + 2(k_g/k_p) + 4.4(\lambda/r_p)} \right) (\nabla T)_\infty,$$

where  $\eta$  is the viscosity of the gas,  $\lambda$  is the mean free path of the gas,  $\rho_g$  is the density of the gas,  $T$  is the absolute temperature of the particle,  $k_g$  and  $k_p$  are the thermal conductivities of the gas and the sphere, respectively,  $r_p$  is the radius of the sphere and  $(\nabla T)_\infty$  is the overall temperature gradient in the gas at large distances from the sphere. In

our experimental environment,  $\lambda \approx 0.066 \mu\text{m}$ . During dry laser cleaning, the gas environment is air. We calculate the thermophoretic forces acting on  $0.1 \mu\text{m}$  polystyrene latex (PSL) particles as a function of the temperature gradients, as shown in Figure 1(a). In the

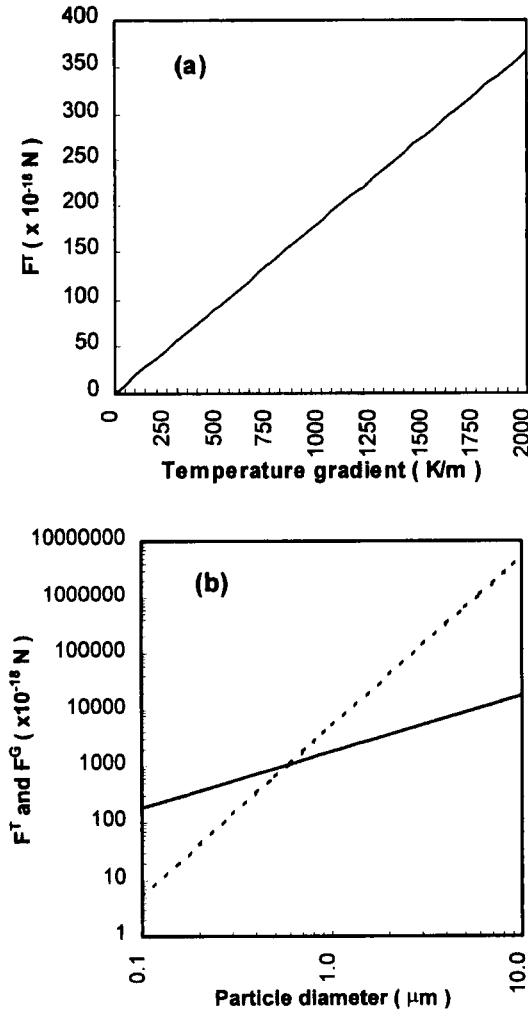


FIGURE 1 (a) The thermophoretic force acting on  $0.1 \mu\text{m}$  PSL particles as a function of the temperature gradient; (b) the thermophoretic force (solid line) and gravitational force (dashed line) acting on PSL particles as a function of the particle diameter. The particles are at  $60^\circ\text{C}$  and the temperature gradient is  $10 \text{ K/cm}$ .

calculation, we assume the particles to be spheres and the particle temperature is taken to be 60°C, the same as the temperature of the front wafer surface in our experiments, to be described shortly. By taking a typical temperature gradient of 10 K/cm, which is what we use experimentally, the thermophoretic and gravitational forces are compared in Figure 1(b) as a function of particle diameter. For particles smaller than 0.5  $\mu\text{m}$ , the thermophoretic force is greater than gravity and the difference between them increases dramatically with decreasing particle diameter. Thus, the thermophoretic force is much more effective than gravity in pulling the free submicron-sized particle away from the surface, and greatly reduces the possibility of particle recontamination by airflow fluctuations. For larger particles, more than a few microns in diameter, their greater inertia and gravity pull them from the surface. They are not easily influenced by airflow fluctuations. These predictions have been verified in our experimental work. To our knowledge, we are first to use thermophoresis during laser cleaning to decrease particle recontamination.

It is difficult to quantify the relationship between the thermophoresis force and the laser cleaning efficiency. This is because: (1) particle adhesion forces and laser removal forces predominate in determining the laser cleaning efficiency; (2) recontamination by ejected particles near the cleaned surface will decrease the efficiency; (3) how far the particles are ejected and the possibility of recontamination are affected by the airflow fluctuations. Despite this, our experimental data, given in the following section, clearly show that laser cleaning efficiency is improved by thermophoresis, and in the range predicted in Figure 1.

## **THERMOPHORESIS AND LAMINAR FLOW EXPERIMENTS**

The experimental setup for laser cleaning is the same as that in a previous paper [7], except for the added infrared lamp, used to heat the backside of the silicon wafer, as shown in Figure 2. A thermocouple contacted the backside of the wafer and a transformer controlled the temperature. The temperature at the front side was about 8°C lower than that of the backside. Before laser cleaning, the wafer temperature

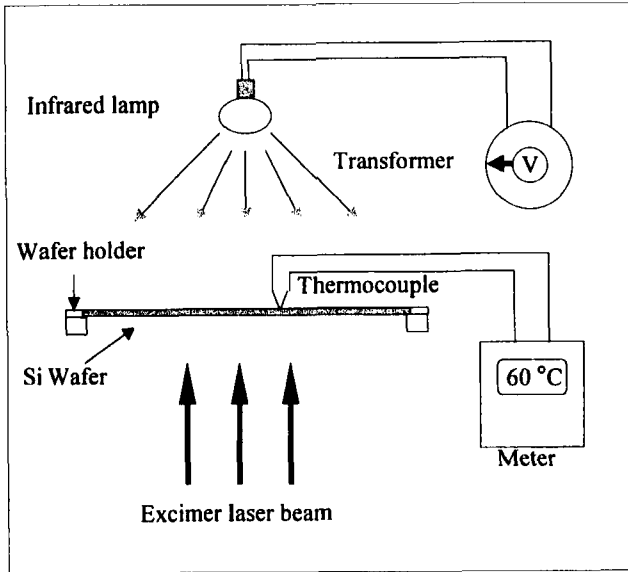


FIGURE 2 A schematic of the experimental system for thermophoresis during dry laser cleaning.

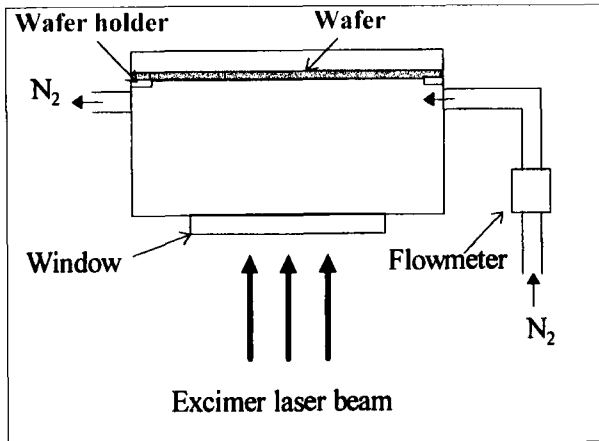


FIGURE 3 A schematic of the experimental system for laminar flow during dry laser cleaning.

reached 60°C, and a 10 K/cm temperature gradient was established. Another method of establishing the temperature gradient was to put a circular cell below the wafer. The cell had a hole to let the laser beam pass through and was filled with liquid nitrogen. We used both 0.2 μm carboxylate-modified latex (CML) particles and 0.3 μm Al<sub>2</sub>O<sub>3</sub> particles for our dry and steam cleaning experiments.

Laminar flow experiments were also carried out, in order to compare efficiencies. The wafer was put in a specially designed chamber, as shown in Figure 3. Nitrogen was introduced into the chamber and the gas flow was controlled by a flowmeter.

## RESULTS AND DISCUSSION

First, during dry laser cleaning, we used identical laser cleaning conditions with and without thermophoresis. The substantial difference in laser cleaning efficiencies for these two processes, using 0.2 μm CML particles, is shown in Figure 4. We see that the recontamination of submicron-sized CML particles was greatly reduced by thermophoresis. The smaller the particle, the more obvious this phenomenon was. For Al<sub>2</sub>O<sub>3</sub> particles, thermophoresis did not improve the dry laser cleaning efficiency because Al<sub>2</sub>O<sub>3</sub> particles are hydrogen-bonded and can not be removed by dry cleaning [8, 9].

During steam cleaning, we found that thermophoresis did not increase the cleaning efficiency in an obvious manner. The cleaning efficiencies for Al<sub>2</sub>O<sub>3</sub> particles with and without thermophoresis were essentially the same. There are two reasons for this: first, particles obtain much higher speeds from the explosive evaporation of the liquid film and their removal distance is greater; thus, the possibility of particle recontamination is smaller, compared with dry cleaning. Second, when the wafer is heated, it is very difficult to control the condensation of vapor onto the wafer surface; the uniformity of the liquid film on the wafer surface was poor and could not be controlled.

We also used an aluminum cell, filled with liquid nitrogen, to establish a temperature gradient near the front surface of the wafer.



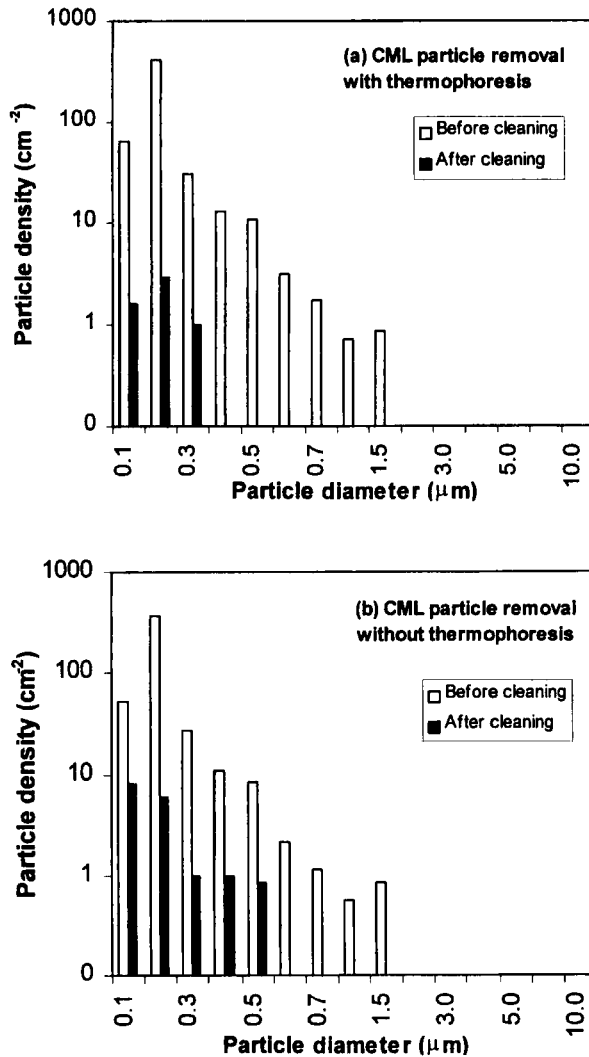


FIGURE 4 The densities of  $0.2\ \mu\text{m}$  CML particles before and after thermophoretic dry laser cleaning: (a) the laser flux was  $363\ \text{mJ}/\text{cm}^2$ , 3 cleaning cycles, and the temperature at the wafer front surface was  $62^\circ\text{C}$ ; (b) the laser flux was  $363\ \text{mJ}/\text{cm}^2$ , 3 cleaning cycles, and the wafer was not heated.

During dry cleaning, the cleaning efficiency was greater than that without thermophoresis, but lower than that using an infrared lamp to heat the wafer. One possible reason is the creation of a fog of water

droplets, condensed from water vapor in the air surrounding the cell, which influenced the homogeneity of the laser beam. During steam cleaning, the cleaning efficiency in this case was again not significantly improved.

In the laminar flow experiment, the gas flow was 4223 ml/min; the Reynolds number,  $R_e$ , in the chamber was estimated by [21]

$$R_e = \rho V D_c / \eta,$$

where  $\rho$  ( $1.25 \text{ Kg/m}^3$ ) and  $\eta$  ( $1.79 \times 10^{-5} \text{ Kg/m/s}$ ) are the density and the viscosity of nitrogen, respectively,  $D_c$  (100 mm) is the diameter of the chamber,  $V$  is the average velocity of the gas flow, which can be calculated by  $V = F_g / D_c h$ , where  $h$  (15 mm) is the height of the chamber, and  $F_g$  is the nitrogen gas flow. Thus, under our conditions,  $R_e$  is about 328, which is much smaller than the critical Reynolds number of 2000 [21]. This means that there was a stable, laminar flow, and a boundary layer at the front wafer surface. In Figure 5, the density of  $0.2 \mu\text{m}$  CML particles before and after dry cleaning is given. We found the cleaning to be significantly improved, but not as much as when using thermophoresis, as shown in Figure 4(a).

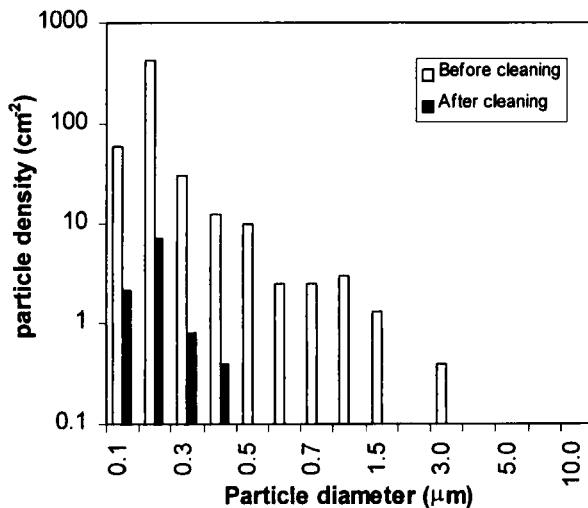


FIGURE 5 The densities of  $0.2 \mu\text{m}$  CML particles before and after laminar flow dry laser cleaning. The laser flux was  $357 \text{ mJ/cm}^2$ , 3 cleaning cycles. The nitrogen flow was 4223 ml/min.

## CONCLUSIONS

From the comparison of different techniques used to reduce particle recontamination, we found that thermophoresis, induced by heating the wafer, has the greatest cleaning efficiency and its experimental setup is the simplest.

## Acknowledgment

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