Removal of Fine Particles from Wafer Surface by Pulse Air Jets†

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Abstract

Removal of fine particles from wafer surface by air jets was experimentally investigated in order to seek an effective surface-cleaning method which uses no cleaning liquids. Monodisperse polystyrene latex particles with diameter between 0.25 and 3.3μm were deposited on a silicon wafer by gravitational settling and removed by air jets from a rectangular nozzle. Particles were blown off the moment the air jet struck the wafer surface, and afterwards no particle reentrainment occurred. This suggests that the sequential pulses of air jets are effective for the removal of fine particles. By exposure of wafer surface to sequential pulse air jets, particles with a diameter as small as 0.25μm were almost completely blown off the surface. The experimental results also indicated that the removal efficiency of particles per pulse air jet, which is the ratio of number of particles reentrained during an air jet exposure to that before the exposure, is kept constant for each exposure to sequential pulse air jets.

1. Introduction

Wet cleaning methods with ultra-pure water and other cleaning liquids are most commonly used to remove particles from wafer surfaces. However, wet cleaning methods have several drawbacks, such as recontamination of the surfaces by dissolved chemicals during rinsing and drying process, water marks, COPs (crystal originated particles), etc. Furthermore, wafers are usually processed under high vacuum condition so that the adsorbed water on wafer surface is claimed to cause some defects in the products. Therefore, most of the problems arising in the wet cleaning method seem to ensue from the use of liquids itself. The present work aimed at developing an effective dry cleaning method without using liquids or solvents, and studied the limitations of air blowing method for wafer surface cleaning.

Reentrainment of particles from surfaces has been studied mainly from the viewpoint of particle's dynamic behavior, for instance, resuspension of particles from powder layers, reentrainment of particles from walls, and they were recently reviewed by Masusaka et al. However, few data have been reported on the reentrainment of particles with diameter smaller than several micrometers, and no previous studies have been conducted from the viewpoint of surface cleaning. Therefore, only limited knowledge can be obtained on how surface material, air jet velocity, particles size, and particle material affect the removal efficiency. In the present work, as a fundamental study for developing a dry cleaning method, the influences of particle condition (mainly particle size) and air jet condition were experimentally investigated under well-defined condition where monodisperse spherical particles of polystyrene latex (PSL) are blown off from a smooth surface of silicon wafer.

2. Experimental setup and procedures

Since adhesion force between particles and surface is affected by many factors, we tried to conduct experiments by excluding factors such as electrostatic force and humidity effect. In preparation of particle-deposited wafer, PSL particles were neutralized by a neutralizer with 241Am, and deposited on wafer surface by gravitational settling. We may use impactors to deposit particles, but the adhesion force distribution would be broader than that by the gravitational settling because of the large difference in the impaction
velocity of particles. Further, we can deposit particles uniformly in a large region of surface by gravitational settling.

Fig. 1 shows the dimensions of acrylic nozzle used in the present work, and the whole experimental setup is shown in Fig. 2. Rectangular nozzle with crosssection of $5 \times 0.5 \text{mm}^2$ was used to clean a large surface area of wafer. In the experiments, particle adhered wafer was placed on a grounded metal disc and exposed to air jet from the nozzle. The air jet blow was operated by solenoid valve controlled by a personal computer. The particle adhered wafer was prepared by using the apparatus shown in Fig. 3. PSL particles were generated by Collison atomizer followed by neutralization with $^{241}\text{Am}$ neutralizer and then introduced into a sedimentation chamber. The humidity of the aerosol stream was 20–25 %RH. The particle deposited wafer was stored in a desiccator for more than 12h.

Particles on the wafer were observed under an optical microscope connected to a VTR. Image of particles on the wafer before exposure to the air jet was processed with an image analyzer to obtain binary image, and stored in video memory. The image was compared with that after the air jet exposure, and the particles removed from wafer were counted. The removal efficiency of particles was obtained as the ratio of removed particles to those initially deposited on the wafer in the region of $1 \times 4 \text{mm}^2$ around a stagnation point of air jet where the highest removal efficiency of particles was attained. The counting of particles was conducted by dividing the area into 16 regions and the number of particles counted by each run is at least 1600 before the air jet exposure.

3. Determination of experimental conditions

The present work was aimed at studying the possibility of air jet cleaning for wafer surface. Consequently, nozzle-wafer surface clearance, jet impinging angle, air jet blowing period were fixed at a constant value which gives the highest removal efficiency. The determination of the optimal conditions of these factors are as follows.

First, removal efficiency was measured by changing the nozzle-surface clearance at a fixed jet impinging
angle and air pressure. As a result, removal efficiency was found to be constant at a clearance between 6mm and 12mm, but it decreased when the clearance was less than 6mm or greater than 12mm. Therefore, the clearance was fixed at 6mm for the rest of the experiments.

Fig. 4 shows the influence of jet impinging angle on the removal efficiency. These data were obtained by exposing the wafer for 60s to air jet with a pressure plotted on the abscissa. The figure also shows the reproducibility of the data by error bars when the jet impinging angle is 90 degrees. As seen from the figure, the removal efficiency increases as the jet impinging angle becomes smaller. Further, observation of wafer surface by optical microscope showed that the wider area was cleaned by the air jet at a smaller impinging angle. Consequently, smaller impinging angle is preferable for the removal of particles. However, because of the confinement of the nozzle structure, the impinging angle was set at 30 degrees for the rest of the experiments.

In order to determine jet blowing time, time change of removal efficiency after the jet exposure was measured. Fig. 5 shows that the removal efficiency increases to a certain value the moment the air jet blow is started and it afterwards remains almost constant, which indicates that the particles are removed instantly by the air jet blow and that the continuation of jet blow gives almost no further increase in the removal efficiency. Therefore, the duration of air jet blow was set at 1s. The result shown in Fig. 5 actually gave us the motive for the present work, i.e., one may increase removal efficiency by exposing wafer to pulsed air jets repeatedly. Hereafter, our effort was concentrated to study the effectiveness of pulsed air jets.
The experimental conditions with relevant factors which gave the maximum removal efficiency are shown in Table 1. The test particle size was changed from 0.25 to 3.3μm, and the air jet pressure was between 100 to 500 kPa. Incidentally, the interval of pulsed air jet was taken to be 3s because the removal efficiency was invariant for the jet interval. 3s is the minimum time period required for air pressure to recover after the air jet blow.

Table 1 Experimental conditions

| Surface material     | Silicon wafer |
|----------------------|---------------|
| Particle material    | Polystyrene latex (PSL) |
| Particle diameter    | d_p [μm]      |
|                      | 3.3, 2.0, 1.1, 0.55, 0.25 |
| Air pressure (gauge) | P_u [kPa]     |
| Distance between surface and nozzle-tip | l [mm]     |
| Jet impinging angle  | θ [deg]       |
| Duration of air jet  | t_d [s]       |
| Jet interval         | t_i [s]       |
| Relative humidity    | [%]           |

4. Removal of particles by pulse air jets

Fig. 6 shows the change in the total removal efficiency by the pulse air jets as a function of number of exposures. The figure clearly shows that the removal efficiency increases with number of air jet exposures, and that particles with diameter larger than 0.55μm are completely removed from the surface after ten exposures at a pressure of 500kPa. Removal efficiency of 0.25μm particles remains lower compared to other particles, however it increases further with increasing the number of exposures, as shown in Fig. 7. After a hundred exposures to the air jet with pressure of 500kPa, almost 90% removal efficiency is attained. These figures give the proof on how the repeated exposure to pulse air jet is effective for the removal of fine particles.

Removal efficiencies plotted in Figs. 6 and 7 were the total removal efficiency, which is the number fraction of removed particles to initially deposited particles. From these figures, we may calculate removal efficiency per an exposure to pulse air jet, which is the number ratio of removed particles by a single exposure to those before the exposure. The removal efficiency per pulse air jet exposure is plotted in Fig. 8 as a function of number of exposures. The remarkable result shown in the figure is that the removal efficiency remains almost constant during the exposures to consecutive pulse air jets. One would
speculate that the removal efficiency should decrease with number of exposures because particles with a small adhesion force would be removed easily and thus the particles with a larger adhesion force would remain on the surface. The invariableness of removal efficiency per pulse air jet may result from preservation of adhesion force distribution, as shown in Fig. 9.

When the removal efficiency per pulse air jet is constant regardless of number of exposures, it can be related to the total removal efficiency by the following equation.

\[
    r_n = r_0 + (1 - r_0) r_0 + (1 - r_0)^2 r_0 + \ldots + (1 - r_0)^n r_0 = 1 - (1 - r_0)^n \tag{1}
\]

By taking the logarithm of both sides, we obtain

\[
    \ln(1 - r_n) = n \ln(1 - r_0) \tag{2}
\]

Therefore, if the fraction of particles remaining on the wafer \((1 - r_0)\) is plotted against number of exposures on a semi-logarithmic paper, we should obtain a straight line. In Fig. 10, the fractions of remaining particles are plotted on a semi-logarithmic paper to see whether the relationship given by Eq.(2) holds or not. As clearly seen from the figure, the fraction of remaining particles decreases linearly on a semi-logarithmic paper, corroborating the consistency of Eq.(2). Consequently, if the removal efficiency per pulse air jet is known, the total removal efficiency can be predicted by using Eq.(2).

Conclusions

Through the experiments on the removal of particles from wafer surfaces, the following results were obtained.

1) Reentrainment of particles occurs the moment the air jet hits the wafer surface, and further exposure of wafer to steady air jet does not bring a further increase in the removal efficiency.

2) Repeated exposure to pulse air jet can remove particles as small as \(0.25\,\mu\text{m}\) which cannot be blown off by the steady air jet.

3) During the repeated exposure of wafer to pulse air jets, removal efficiency per pulse air jet remains constant regardless of the number of exposures. Therefore, by knowing the removal efficiency per pulse air jet, one can predict the total removal efficiency after a given number of air jet exposures.

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Nomenclature

- \(d_p\) = particle diameter [m]
- \(d_n\) = nozzle width [m]
- \(l\) = distance between surface and nozzle tip [m]
- \(n\) = number of pulse air jets [-]
- \(P_u\) = air pressure upstream of nozzle (gauge) [Pa]
- \(r\) = removal efficiency of particles [-]
- \(r_0\) = removal efficiency of particles per pulse air jet [-]
- \(r_n\) = cumulative removal efficiency by \(n\) pulse air jets [-]
- \(t_i\) = interval between pulse air jets [s]
- \(t_d\) = duration of pulse air jet blow [s]
- \(\Theta\) = jet impinging angle on surface [deg]
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