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Deposition velocity of particles in charge equilibrium onto a flat plate in parallel airflow under the influence of simultaneous electrophoresis and thermophoresis

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ABSTRACT

Deposition velocity onto a 450-mm-flat-plate in parallel airflow was numerically investigated by considering the influence of simultaneous electrophoresis and thermophoresis on particles in charge equilibrium. Both the face-up and face-down orientations of the flat plate were considered. When the electric field strength was 0 V/cm, the deposition velocity of particles in charge equilibrium was greatly influenced by thermophoresis, in the size range between 0.005 μm and 3 μm. With increasing electric field strength, the deposition velocity of particles in charge equilibrium under the existence of thermophoresis increased for both the face-up and face-down surfaces and the size range of particles affected by thermophoresis became narrower. The electric field of 1000 V/cm appeared to make the deposition velocity of particles in charge equilibrium almost unaffected by thermophoresis. For the face-down surface, the deposition velocity of micrometer-sized particles dropped sharply even with the attractive thermophoresis and electrophoresis, owing to gravitational settling effect. With a strong electric field applied, the deposition velocity of particles smaller than approximately 3 μm onto both the face-up and face-down surfaces was expected to be high, even thermophoresis was repulsive.

1. Introduction

Particulate contamination control is important to yield enhancement in semiconductor manufacturing, as the feature size of integrated circuits decreases. Particle deposition velocity can be used as a measure for assessing the level of particulate contamination of critical surfaces like wafers or photomasks. Particle deposition velocity is defined as the ratio of the number of particles deposited on a surface in a certain time to the number concentration of aerosol particles floating above the surface.

Many studies were conducted to investigate particle deposition velocity onto a wafer in vertical airflow, by considering typical top-down airflow from a cleanroom ceiling. Liu & Ahn (1987) calculated particle deposition velocity by summing the mean mass transfer coefficient and the gravitational settling velocity of particles. Otani et al. (1989), Pui et al. (1990), and Bae et al. (1994) experimentally determined the particle deposition velocity onto a free-standing wafer in vertical airflow by taking diffusion and sedimentation of particles into consideration. Ye et al. (1991), Bae et al. (1995), and Yoo & Oh (2005) assumed a heated wafer in vertical airflow to investigate the effect of thermophoresis on particle deposition velocity.

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Cooper et al. (1989) and Turner et al. (1989) predicted particle deposition velocity onto a flat surface in stagnation flow by considering electrostatic effect. Peterson et al. (1989), Opiolka et al. (1994), and Tsai et al. (1998) examined particle deposition velocity onto a wafer in vertical airflow under the combined effects of thermophoresis and electrophoresis.

Wafers and photomasks are exposed to both parallel airflow and vertical airflow due to transport by an automated system during semiconductor manufacturing processes. Liu & Ahn (1987) suggested an equation to calculate particle deposition velocity onto a wafer in not only vertical airflow but also parallel airflow. Choi & Yook (2010) and Yook et al. (2010) predicted particle deposition velocity onto a wafer or a photomask in parallel airflow by considering diffusion and sedimentation of particles. Woo et al. (2012) estimated particle deposition velocity onto a wafer in parallel airflow under thermophoretic effect. A charge imbalance can be induced when a wafer comes in contact with people and devices or moves on an insulative guide rail in automated processes (Vinson & Liou, 1998). An electric field is then established near a wafer surface and can affect the deposition of charged particles. In a cleanroom, many ionizers are generally used in an effort to reduce electrostatic damage (ESD) and the number concentration of airborne particles is typically low. In other words, with increased rate of ion production and decreased number concentration of aerosol particles, it is expected that charge equilibrium will be quickly reached for aerosol particles in cleanroom environments. Hence, the deposition characteristics of particles in charge equilibrium need to be investigated.

The size of the wafer that is about to be employed in the near future mass production of semiconductors is 450 mm. So far, the particle deposition velocity onto the 450-mm-wafer has not been investigated by considering electrophoresis and thermophoresis at the same time. The objective of this study is therefore to predict the deposition velocity of particles in charge equilibrium onto a 450-mm-flat-plate, simulating the 450-mm-wafer, in parallel airflow under the combined influences of electrophoresis and thermophoresis.

2. Flow simulation

The effect of electrophoresis on the deposition of charged particles on a wafer in vertical airflow was studied (Cooper et al., 1989; Peterson et al., 1989; Turner et al., 1989; Opiolka et al., 1994; Tsai et al., 1998). However, particle deposition on a wafer in parallel airflow under the influence of an electric field has rarely been investigated. Owing to the unavailability of experimental or numerical data on electrophoretic particle deposition in parallel airflow, the particle deposition velocity of charged particles onto a wafer in vertical airflow under a uniform electric field was compared between the present numerical results and the theoretical data obtained by Cooper et al. (1989). Then, the present numerical approach was applied to the prediction of the particle deposition velocity onto a 450-mm-flat-plate in parallel airflow. Therefore, two calculation domains were considered, as shown in Fig. 1.

Figure 1(a) depicts a two-dimensional axisymmetric calculation domain for simulating the flow field around a circular wafer in vertical airflow. The entire domain size was 2500 mm × 8000 mm. The wafer was mounted on a conducting plane. The wafer diameter (d_w) was set as 200 mm as in Cooper et al. (1989). The diameter of the conducting plane was assumed to be 900 mm. The vertical airflow velocity (V_{in}) was varied as 0.0635, 0.127, 0.254, and 0.508 m/s. Figure 1(b) illustrates a two-dimensional calculation domain for computing the flow field around a horizontal flat plate in parallel airflow. The flat plate length (L_p) was assumed to be 450 mm by considering the diameter of the wafer to be employed in mass production of semiconductors in the near future. The parallel airflow velocity (U_{in}) was set as 0.8 m/s by taking into account the range of the velocity of transporting wafers in the cleanroom.

FLUENT v13.0 was used to solve the continuity, momentum, and energy equations. The airflow was assumed to be steady, laminar, and incompressible. Double precision solver and SIMPLE algorithm were chosen. The criterion for convergence was set as 10^{-6} for the continuity, momentum, and energy equations. For both vertical airflow and parallel airflow, the ambient temperature (T_{in}) and pressure (P_{in}) were set as 20 °C and 101.3 kPa, respectively. The grid test was carried out. The number of grids was determined as 1 500 000 for the calculation domain in Fig. 1(a) and 500 000 for the simulation domain in Fig. 1(b), with the minimum grid size of 0.01 mm.

3. Particle deposition velocity calculation

Particle deposition velocity (v_d) is defined as

$$v_d = \frac{J}{C_\infty} = \frac{N_{de}}{tA_{de}C_\infty}, \tag{1}$$

where J is the particle flux onto a surface, C_∞ is the particle number concentration above the surface, N_{de} is the number of particles deposited on the surface, t is the time for exposure of the surface to an aerosol stream, and A_{de} is the area of the surface. According to Yook & Ahn (2009), Eq. (1) becomes

$$v_d = \frac{N_{de}}{N_{in}}\frac{Q_{in}}{A_{de}}, \tag{2}$$

where N_{in} is the number of injected particles at upstream of the surface and Q_{in} is the flow rate of air containing N_{in} particles.