Journal of Aerosol Science 41 (2010) 911–920

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Particle deposition velocity onto a face-up flat surface in a laminar parallel flow considering Brownian diffusion and gravitational settling

Se-Jin Yook [a],*, Christof Asbach [b], Kang-Ho Ahn [c]

[a] *School of Mechanical Engineering, Hanyang University, Seoul 133-791, Republic of Korea*
[b] *Institute of Energy and Environmental Technology (IUTA), 47229 Duisburg, Germany*
[c] *Department of Mechanical Engineering, Hanyang University, Ansan, Kyunggi-do 425-791, Republic of Korea*

ARTICLE INFO

Article history:
Received 1 December 2009
Received in revised form
9 June 2010
Accepted 22 June 2010

Keywords:
Deposition velocity
Parallel flow
GDSM
Brownian diffusion
Gravitational settling

ABSTRACT

The Gaussian Diffusion Sphere Model (GDSM) was developed and improved to reflect the effects of gravitational settling as well as Brownian diffusion of aerosol particles on deposition velocity onto a face-up flat surface in a laminar parallel flow. The model improvement also includes the applicability of the GDSM to a flat surface of any shape with finite dimensions. When deposition velocity for a face-up circular flat plate of 45 cm diameter, representing e.g. a semiconductor wafer in a laminar parallel flow, was calculated by the GDSM and compared with that by the theory of Liu and Ahn (1987). Particle deposition on semiconductor wafers. Aerosol Science and Technology, 6, 215–224, the agreement was good for the tested particle sizes ranging 0.003–1 μm and free stream velocities ranging 5–500 cm/s. Based on this result, deposition velocities onto the face-up square flat plates with different orientations in a laminar parallel flow, simulating e.g. photomasks, were predicted.

1. Introduction

Particulate contamination control in semiconductor manufacturing is getting important with decreasing feature size. Deposition velocity, which is the ratio of particle flux towards a surface to aerosol concentration above the surface, is used as a measure of particulate contamination level. Many investigations were performed to predict deposition velocity onto a free-standing wafer in an air flow perpendicular to the wafer surface, considering top-down air flow from ceiling in a clean room (Liu & Ahn, 1987; Opiolka, Schmidt, & Fissan, 1994; Otani, Emi, Kanaoka, and Kato, 1989; Pui, Ye, and Liu, 1990; Ye et al., 1991; Yook et al., 2007a).

In a semiconductor fab, a wafer or a photomask is often transported horizontally by a robot, and there appear many situations of air moving over the wafer or the photomask parallel to its surface. Contaminant particles can be transported by the parallel flow and may deposit on the critical surface. After Liu and Ahn (1987), not many studies have been conducted to predict deposition velocity onto a wafer or a photomask surface exposed to a parallel flow. Engelke et al. (2007) and Yook et al. (2007b) investigated particle deposition on both a face-down wafer, simulating an Extreme Ultraviolet Lithography (EUVL) photomask, and a face-up cover plate, when an aerosol from a circular pipe was introduced into the space between two parallel plates. These studies, however, did not examine the deposition velocities onto the

---

* Corresponding author. Tel.: +82 2 2220 0422; fax:+82 2 2298 4634.
E-mail address: ysjnuri@hanyang.ac.kr (S.-J. Yook).

0021-8502/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jaerosci.2010.06.003

parallel surfaces, and the flow pattern was different from that for a horizontally moving flat plate. Yook and Ahn (2009) proposed the Gaussian Diffusion Sphere Model (GDSM) to predict mean mass transfer coefficient over a flat surface exposed to a parallel flow in laminar flow regime by considering only Brownian diffusion as particle deposition mechanism. In the GDSM of Yook and Ahn (2009), however, the effect of gravitational settling of particles was unconsidered.

An EUVL photomask is vulnerable to particulate contamination, due to the unavailability of pellicles in the EUVL technology (Asbach, Fissan, Kim, Yook, & Pui, 2006; Yook et al., 2007c). Since the equation suggested by Liu and Ahn (1987) to predict deposition velocity in a parallel flow is limited to a wafer, i.e., a circular flat surface, Computational Fluid Dynamics (CFD) simulation needs to be performed and convective diffusion equation should be numerically solved to estimate the deposition velocity onto a square photomask surface in a parallel flow. The objective of this study is therefore to develop a simple model, i.e., by improving the GDSM for predicting deposition velocity from parallel flows onto a face-up flat surface of any shape, which could be circular or rectangular to simulate wafers or photomasks, respectively, in order to avoid solving flow and aerosol concentration fields, which usually require much time, effort and computational resources. Laminar flow regime is assumed by considering the wafer/photomask sizes and horizontal transportation velocities in semiconductor manufacturing.

2. Improvement of Gaussian Diffusion Sphere model by considering Brownian diffusion and gravitational settling

2.1. Deposition velocity onto a face-up flat surface

Gaussian Diffusion Sphere (GDS) is considered as a space within which a particle can diffuse in a certain time from its initial location as shown in Fig. 1, similar to what was originally proposed by Asbach et al. (2008). Particle displacement with time is statistically weighted by a Gaussian distribution with the standard deviation (σ_i) equal to the root-mean-square net displacement by diffusion (Einstein, 1905; Hinds, 1999), i.e.,

$$\sigma_i = \sqrt{2Dt_{r,i}}. \tag{1}$$

Here, D is the particle diffusivity and $t_{r,i}$ is the residence time of the particle within concentration boundary layer. The radius of GDS (R_i) is assumed to be multiple times the standard deviation, i.e.,

$$R_i = n_\sigma \sigma_i, \tag{2}$$

where n_σ is an integer to determine the confidence interval. Note that R_i and σ_i are time-dependent. The center of GDS represents initial particle position at $t_{r,i}$=0. As shown in Fig. 2, probability of the particle to deposit on the surface by diffusion, or f_{ij}, is predicted by calculating the fraction of probability-weighted volume of GDS overlapping with the surface. No overlap of GDS with the deposition surface means zero probability of particle deposition (f_{ij}=0). Full immersion of GDS below the deposition surface implies 100% particle deposition (f_{ij}=1). When the gap distance between GDS center and deposition surface is G_{ij}, the probability of the particle to deposit on the surface can be calculated using Eq. (3) based on the equation suggested by Yook and Ahn (2009). If the center of GDS is located above the deposition surface, i.e., the

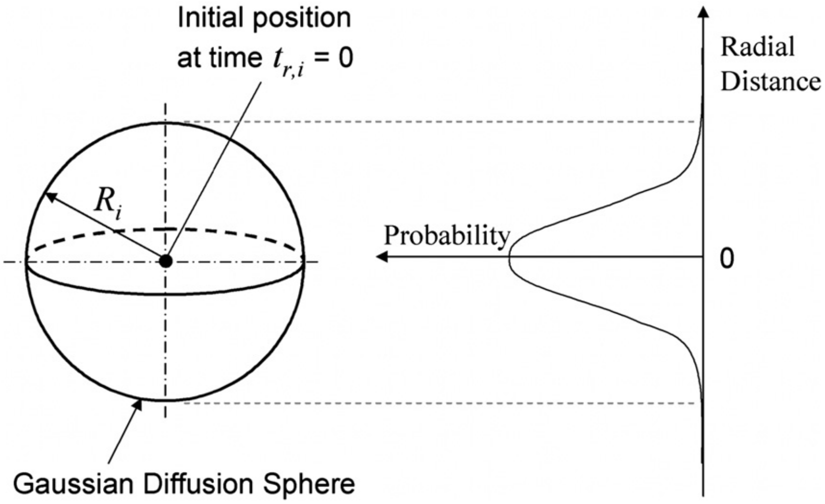

Fig. 1. Concept of the Gaussian Diffusion Sphere.