TECHNIQUE FOR AEROSOL FLOW CHECK IN DIFFERENTIAL MOBILITY ANALYZER AND ITS INFLUENCE ON CLASSIFICATION PERFORMANCE

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The flow pattern of aerosol and sheath air in a cylindrical annulus of a Differential Mobility Analyzer (DMA) is critical to determine the classification performance of the DMA. In the present work, a new technique to check aerosol flow inside the DMA is proposed and the influences of aerosol flow distortion and broadening on the classification performance are investigated by means of the Tandem DMA method. As a result, it is found that (1) the annular flow inside the studied DMA is a fully developed laminar flow with a negligible mixing between aerosol and sheath air when the aerosol flow rate is less than 3 l/min and the sheath air flow rate is 17.5 l/min, (2) a larger width of aerosol entrance slit causes uneven distribution of aerosol flow in the circumferential direction, and (3) both the uneven distribution and broadening of the aerosol flow lead to a broader band of classified particle electrical mobility, as well as a shift of peak electrical mobility to a smaller range. These results suggest that aerosol flow inside a short-type DMA is more sensitive to the flow rates and its structure compared to the conventional TSI type DMA.

Introduction

In advanced industries such as electronics and precision machine manufacturing, the measurement of size and concentration of airborne particles is of growing importance in order to control particle contamination. Through the semiconductor manufacturing process, particles deposit on the surfaces of semiconductor devices, and lead to defects which reduce product yield. There are several reports forecasting that particles down to about 0.018 μm will be a critical size to the yields of 1 Gbit DRAMS. Therefore, semiconductor manufacturers need to detect and control aerosol particles down to this size.

Among the various methods developed for the analysis of submicron aerosol particles, the differential electrical mobility analyzer (DMA) has become the most common instrument in recent aerosol research. A DMA is a powerful instrument widely used in classifying and generating monodisperse particles under 0.1 μm in diameter. Liu and Pui (1974) and Knutson and Whitby (1975) improved a cylindrical DMA with coaxial flow described by Hewitt (1957). The DMA developed by Knutson and Whitby (1975) was capable of classifying and analyzing particles down to the nanometer size range. They introduced the concept of transfer function and experimentally determined it. Later, Kousaka *et al.* (1986) showed that

Brownian diffusion severely limits the resolution of DMA for particles smaller than a few tens of nm. Since the aerosol is introduced into the column through a narrow annular slit, the DMA transmission efficiency drops significantly for particles below 20 nm due to diffusion losses in the annulus and other flow passages. Further, long residence time in the classification region results in substantial Brownian diffusion broadening of the transfer function for ultrafine particles. Kousaka *et al.* (1986) investigated the effect of Brownian diffusion on the transmission efficiency by varying the ratio of aerosol flow rate to sheath flow rate, and achieved better mobility resolution by shortening the analyzer column. More radical design changes were made by Winklmayr *et al.* (1991), and it brought dramatic improvements in classification performance for 1 to 1000 nm particles. Inlet losses were reduced with the adoption of tangential aerosol entry, resulting in an accessible size range down to 1 nm. They developed several DMAs with different structures for different size ranges. High resolution was achieved for ultrafine particles by the use of a short analyzer column, while a DMA for classifying larger particles employed a longer column. Other mobility analyzer geometries, *i.e.* parallel circular disk types, and radial types, have been reported. Pourprix *et al.* (1990, 1994) reported a mobility classifier that employs a circular geometry to deposit particles on a disk with a known relationship between particle size and location on the disk.

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Fig. 1 Differential mobility analyzer for classifying nano-particles (Otani *et al.*, 1995)

However, DMA performance has been checked only by means of the Tandem DMA method, which gives overall performance, *i.e.*, transmission efficiency or transfer function. The transmission efficiency varies with many factors. The factors that affect DMA classification performance can be divided into two groups; those relevant to particle intrinsic motion (such as deposition loss and spreading of aerosol flow by particle Brownian diffusion) and those related to the DMA structure and operating conditions (design dimensions, preciseness in machining, alignment of constituent parts of DMA, aerosol and sheath air flow rates). Because the factors belonging to the latter group lead to a distortion of annular aerosol flow in the DMA, visualization of the annular aerosol flow is an effective and direct method to check the outcome of these factors. This paper proposes a new method to check aerosol flow inside the DMA, and discusses the influences of aerosol flow distortion on classification performance.

1. Experiments

1.1 Aerosol flow of DMA annulus

The classification performance of a DMA is strongly dependent on the flow inside the DMA. In the DMA, the aerosol flow must merge with the sheath air flow at the aerosol entrance slit without any disturbances and flow through the cylindrical annulus as two immiscible fluids. Any violation of this ideal condition will result in a broadening of transfer function and asymmetry in the electrical mobility distribution of classified particles, and sometimes a shift of peak electrical mobility.

Figure 1 shows a schematic diagram of the DMA used for classifying nano-particles in our previous study (Otani *et al.*, 1995). The aerosol flow pattern in the annulus of the DMA is critical to the classification of particles.

Fig. 2 Detail of exit slit region and location of filter for flow check

Fig. 3 Flowchart of experimental setup for checking aerosol flow

Visualization of the flow distribution in the DMA annulus was carried out by observing the pattern of collected particles on a filter placed 8 mm downstream of the aerosol exit slit. We inserted a filter sheet (medium performance glass fiber filter with low pressure drop, 10 Pa at 5.3 cm/s) as shown in **Fig. 2** (the detail of section A). The whole experimental setup is shown in **Fig. 3**. Solid tracer particles of Rhodamine B were generated by a Collision atomizer and a diffusion dryer. Since the tracer aerosol was introduced into the test DMA without exit aerosol flow, clean sheath air was recirculated after discarding the amount of air which was equal to that of the inlet aerosol. Therefore, both aerosol and sheath air passed through the filter. Under this flow condition, we can observe only the flow pattern of aerosol after merging the sheath air without the influence of exit aerosol flow. When one wants to observe aerosol flow patterns under the influence of exit aerosol flow, the filter should be inserted between the entrance and exit slits. However, the insertion of filter between the slits requires modifications of the DMA.

After introducing aerosol to the DMA for a time period sufficient to distinguish deposited particles on the filter, the DMA was disassembled and the filter was removed. The pattern of deposited particles on the filter gives information on the uniformity of the aerosol flow in the circumferential direction and mixing of the aerosol and sheath air. The deposited pattern of tracer dye on the filter was measured by changing the aerosol flow rate from 1 to 3 l/min and the sheath air flow rate from 10 to 17.5 l/min, and the width of the inlet slit from 1 to 3 mm.

Fig. 4 Schematic diagram of experimental setup for measuring transmission efficiency

1.2 Measurement of transmission efficiency (Tandem DMA Method)

The influences of distortion and broadening of the annular aerosol flow on the DMA classification performance were investigated by the Tandem DMA Method (Kousaka *et al.*, 1985). **Figure 4** shows the setup for the Tandem DMA Method. Polydisperse aerosol particles were generated by heating Ag or NaCl and introduced into the test DMA after passing them through a bipolar ion charger with Am-241 (80 μ Ci). The voltage of the test DMA was set to give the center electrical mobility of classified particles for $D_p = 30$ nm. The particles classified by the test DMA were then fed into the second DMA to measure their electrical mobility distribution. The second DMA had the same dimensions as the first DMA, and was operated at an aerosol flow rate of $q_a = 1$ l/min, and a sheath air flow rate of $q_c = 17.5$ l/min. When the aerosol flow rate of the test DMA was larger than that of the second DMA, the excess aerosol was discarded at the inlet of the second DMA. The inlet and outlet concentrations of the second DMA were measured by a Faraday Cup Electrometer (TSI Model 3068), and the measurement of electrical mobility was carried out by changing the aerosol flow rate q_a , sheath air flow rate q_c and the width of the entrance slit.

2. Results and Discussion

2.1 Effect of entrance slit width and aerosol flow rate on the annular aerosol flow

Figure 5 shows the patterns of deposited particles on the filters when the sheath air flow rate is 17.5 l/min. It is seen from this figure that i) a larger entrance slit width causes uneven flow distribution in the circumferential direction because aerosol flows into the cylindrical annulus at a larger velocity near the aerosol inlet tube, ii) at an entrance slit width of 1 mm, aerosol is distributed evenly in the circumferential direction regardless of its flow rate, and iii) as the aerosol flow rate increases, the thickness of the annular ring of deposited tracer particle increases.

When the aerosol flows in a cylindrical annulus of DMA with the sheath air in a fully developed laminar

Fig. 5 Patterns of deposited tracer particles on filter when the flow rate of sheath air is 17.5 l/min

flow, the velocity distribution is given by,

$$u(r) = 2 \frac{u_{av}}{1 - \kappa^4 - \frac{1 - \kappa^2}{\ln(1/\kappa)}} \left[1 - \left(\frac{r}{R_2} \right)^2 + \frac{1 - \kappa^2}{\ln(1/\kappa)} \ln \left(\frac{r}{R_2} \right) \right] \quad (1)$$

where $\kappa = R_1/R_2$ and

$$u_{av} = \frac{q_a + q_c}{\pi R_2^2 (1 - \kappa^2)} \quad (2)$$

Therefore, the thickness of the aerosol annular ring, δ , is calculated from the following relationship.

$$\frac{q_a}{q_a + q_c} = \frac{\int_{R_2 - \delta}^{R_2} u(r) r dr}{\int_{R_1}^{R_2} u(r) r dr} \quad (3)$$

On the other hand, when the aerosol and sheath air flow in the annulus are in uniform flow, Eq.(3) is reduced to the following equation.

$$\frac{q_a}{q_a + q_c} = \frac{R_2^2 - (R_2 - \delta)^2}{R_2^2 (1 - \kappa^2)} \quad (4)$$

At a sheath air flow rate of 17.5 l/min, combining Eq.(3) with Eq.(1) gives $\delta = 0.69$ mm for $q_a = 1$ l/min, 1.00 mm for $q_a = 2$ l/min, and 1.26 mm for $q_a = 3$ l/min, while Eq.(4) gives $\delta = 0.25$ mm for $q_a = 1$ l/min, 0.48 mm for $q_a = 2$ l/min, and 0.68 mm for $q_a = 3$ l/min. The measured width of the annular ring in Fig. 5 is 0.65, 0.95 and 1.15 mm, respectively, at $q_a = 1, 2, 3$ l/min, which is in good agreement with those predicted by Eqs.(1) and (3), suggesting that the flow inside the DMA is a fully developed

Fig. 6 Transmission efficiency of DMA when aerosol flow rate is 1 l/min and the sheath air flow rate is 17.5 l/min

Fig. 8 Transmission efficiency of DMA when aerosol flow rate is 3 l/min and the sheath air flow rate is 17.5 l/min

Fig. 7 Transmission efficiency of DMA when aerosol flow rate is 2 l/min and the sheath air flow rate is 17.5 l/min

laminar flow with negligible mixing between aerosol and sheath air because the Reynolds number in the annulus is about 100, and the filter is placed 88 mm downstream from the entrance slit.

Incidentally, the pressure drop of the inserted filter significantly affects the width of deposited particle pattern. When a HEPA-grade filter (pressure drop: 250 Pa at 5.3 cm/s) is used, the measured widths are close to those predicted by Eq.(4) rather than Eqs. (2) and (3). This implies that the use of a filter with a large pressure drop makes the annular flow uniform. Therefore, it is strongly recommended that the filter used for checking the aerosol flow in the DMA should have a low pressure drop.

2.2 Influence of annular aerosol flow on the classification performance

The influence of distortion and broadening of annular aerosol flow on DMA classification performance was studied by measuring the transmission efficiency with the Tandem DMA Method. **Figures 6-8** compare the transmission efficiencies of the test DMA with those predicted by the theory (Kousaka *et al.*, 1985) at a sheath air flow

Fig. 9 Patterns of deposited particles on filter when aerosol flow rate is 2 l/min and the sheath air flow rate is 10 l/min

rate of 17.5 l/min. In these figures, the ratios of particle concentration at the outlet of the second DMA to the inlet concentration, $N(Z_p)/N_0$, are plotted against the ratio of the center electrical mobility of particles classified by the second DMA to that by the first DMA, Z_p/Z_{pc} . At aerosol flow rates of 1 and 2 l/min (Figs. 6 and 7), the measured transmission efficiencies are in good agreement with those predicted, although there is an increase in the measured electrical mobility band because of Brownian diffusion of particles. Since no marked changes in the mobility band and the peak value of $N(Z_p)/N_0$, due to the slit width are observed, uneven distribution and broadening of annular aerosol flow seem to have no significant effect on the classification performance under these flow conditions. On the contrary, in Fig.8 where the aerosol flow rate is 3 l/min, the measured electrical mobility band at a slit width of 3 mm is slightly wider than that at a slit width of 1 mm, both being much wider than predicted, and there is a further electrical mobility peak shift towards a smaller region. Therefore, at an aerosol flow rate of 3 l/min, the broadening of aerosol flow seems to bring a wider electrical mobility band as well as an electrical mobility peak shift towards a smaller value.

When one employs a smaller flow rate of sheath air, an increase in entrance slit width leads to significant

Fig. 10 Influence of annular aerosol flow on transmission efficiency of DMA when sheath air flow rate is 10 l/min

unevenness in annular aerosol flow distribution. **Figure 9** shows the patterns of deposited tracer particles on a filter when aerosol flow rate is 2 l/min and sheath air flow rate is 10 l/min. As seen from this figure, at a slit width of 3 mm, there is no aerosol flow in the opposite side of the entrance tube. Further, even at a slit width of 1 mm, spreading of tracer particles is observed towards the inner electrode, which may result from the mixing of aerosol and sheath air.

The transmission efficiencies under these flow conditions are shown in **Fig. 10**. The measured peak electrical mobility is in agreement with the theoretical one when the aerosol flow rate is 1 l/min, whereas at an aerosol flow rate of 2 l/min, the peak shifts to the smaller electrical mobility range and the bands are much wider than predicted. Because there is no marked difference in transmission efficiency due to the slit width, both broadening and uneven circumferential distribution of annular aerosol flow seem to cause the same effect on the transmission efficiency, *i.e.*, an increase in the electrical mobility band of classified particles, and an electrical mobility peak shift. Incidentally, since such a large deterioration in classification performance at the same flow rates was not reported for the TSI type DMA (Kousaka *et al.*, 1985), the performance of a short-type DMA is considered to be very sensitive to the flow rate of aerosol and sheath air.

Conclusion

In the present work, a new technique of checking aerosol flow in a DMA was proposed, and the influences of broadening and uneven distribution of annular aerosol flow on the classification performance were studied. The main conclusions obtained are ;

(1) annular flow inside the studied DMA is a fully developed laminar flow with negligible mixing between aerosol and sheath air when the aerosol flow rate is less

than 3 l/min and the sheath air flow rate is 17.5 l/min,

(2) a larger width of aerosol entrance slit causes uneven distribution of aerosol flow in circumferential direction,

(3) both uneven distribution and broadening of aerosol flow lead to a broader band of classified particles' electrical mobility as well as a shift of peak electrical mobility towards a smaller range.

These results suggest that aerosol flow inside a short-type DMA is more sensitive to the flow rate, and its structure compared to conventional TSI-type DMA.

Nomenclature

D_p	= particle diameter	[m]
L	= distance between entrance slit and exit slit of aerosol	[m]
N_0	= aerosol concentration at the inlet of the second DMA	[m ⁻³]
$N(Z_p)$	= aerosol concentration at the outlet of the second DMA	[m ⁻³]
Z_p	= center electrical mobility of particles classified by the second DMA	[m ² V ⁻¹ s]
Z_{pc}	= center electrical mobility of particles classified by the first DMA	[m ² V ⁻¹ s]
$u(r)$	= air flow velocity	[m/s]
u_{av}	= average air flow velocity	[m/s]
R_1	= outer radius of center rod of DMA	[m]
R_2	= inner radius of outer electrode of DMA	[m]
r	= radial distance	[m]
q_a	= volumetric flow rate of aerosol	[l/min]
q_c	= volumetric flow rate of sheath air	[l/min]
κ	= ratio of center rod radius to outer cylinder radius (= R_1/R_2)	[—]
δ	= thickness of annular ring of deposited particles on filter	[m]

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