The Precision of Lead Frame Etching Characteristics Using Monte-Carlo Simulations

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The objective of this work was to simulate lead frame etching characteristics to optimize the etching process. Characteristics such as the etching factor and uniformity were investigated for different actual operating conditions, including pressure, distance from the nozzle tip, pipe pitch, and feed speed. The correlation between the etching and spray characteristics was analyzed to develop the etching model. Spray characteristics obtained from an experiment using a phase Doppler anemometer system were then simulated using a Monte-Carlo technique. The etching process model was coded in the Java language. The spray and etching characteristics were correlated with each other and simulated results agreed well with the measured data for a lead frame etching process. The optimal operating parameters under various conditions were successfully determined.

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NOMENCLATURE

E_F = etching factor
E_u = etching uniformity
N = average drop number
U_d = uniformity of the drop number
ε_i = error term

1. Introduction

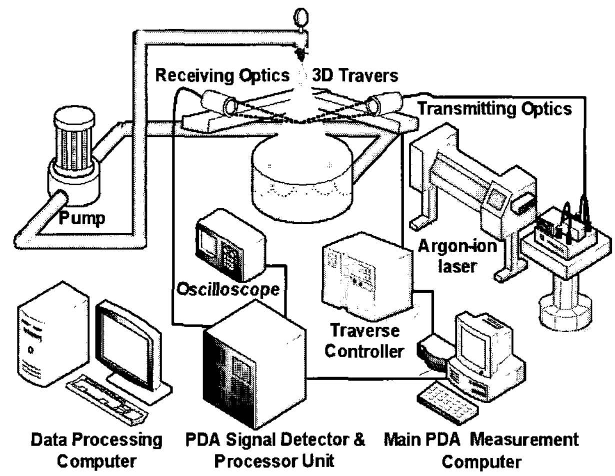
Micro-fabrication techniques have received much attention in recent years because of the trend towards miniaturization and fine pitch in the industrial and technological applications required to produce semiconductor, communication, and electronic components in the field of precision engineering. In particular, the electronics industry uses photoetching techniques to micro-fabricate semiconductors, lead frames, shadow masks, and ball grid arrays. Recently, many studies have attempted to improve photoetching technologies for the micro-electronics industry.[1-3]

Etching characteristics depend on the injection pressure, distance from the nozzle tip, pipe pitch, and nozzle pitch. When a sprayed etchant is used, the quality and productivity of the production process are determined by the spray system and spray characteristics. Therefore, it is necessary to study not only the effect of the dominant etching parameters on the etching characteristics, such as the etching factor and etching uniformity, but also the correlation between the spray and etching characteristics.

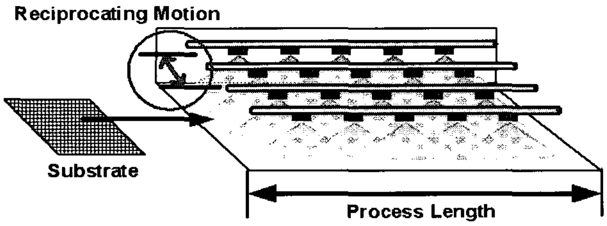
Atomization and spray characteristics are used in various fields of study and industrial applications.[4-6] Allen investigated the effect of the etching time on the depth of etching, line width on lateral etching, and etchant formation on the etching factor.[3] Visser *et al.* investigated the theoretical and practical aspects of the miniaturization of lead frames using double-sided asymmetrical spray etching.[7] They concluded that a reduction in material thickness, a higher etching factor, and asymmetrical etching were necessary to minimize the pitch. Ueda *et al.* investigated the etching kinetics and the absolute limit of the fine patterning accomplished using ferric chloride spray etching.[8] A very large etching factor was required to obtain a small pitch.

Although previous studies have provided some information about the effects of etching parameters, such as the distance from the nozzle tip, injection pressure, and etching conditions and method, on etching characteristics, studies of wet etching applying spray technology have been rare.[9-10] Because of the complexity of the spray etching process and the lack of detailed information, such as the correlation between the spray and etching characteristics, spray etching mechanisms are not yet well understood.

In the present study, etching and spray characteristics were investigated under various conditions. The spray characteristics were investigated by measuring the droplet size and velocity. Correlations between the etching and spray characteristics were analyzed using statistical methods. The etching characteristics were predicted based on simulations of the spray characteristics. This work will provide important information for improving etching characteristics in the micro-fabrication industry.



(a) Schematic diagram of the PDA system



(b) Schematic diagram of the PDA system

Fig. 1 Schematic diagram of the experimental apparatus

2. Experimental Apparatus and Method

Fig. 1(a) shows the experimental apparatus used to analyze the spray characteristics. It consisted of a spray system and a phase Doppler anemometer (PDA) system. The spray system included a pumping system, nozzle, regulator, and pressure gages. The PDA system consisted of an argon-ion laser (Laser Spectra Physics Co.), receiving optics connected to a signal processor, a three-dimensional traverse system, and a PC running SIZEware software (DANTEC Co.). The transmitting and receiving optics had the same focal length of 400 mm. Spray characteristics, such as the axial velocity, Sauter mean diameter (SMD), and impact force, were analyzed for 5000 droplets collected across a spray cross-section.

Fig. 1(b) shows a schematic diagram of the etching process simulated in this study. The front and rear etching chambers, each of which was 900 × 1200 mm, included diposed nozzles and reciprocating pipe lines at the given process conditions. Ferric chloride solution was used as the etchant, which was sprayed when substrate was transported to the etching chamber. A 150-μm thick 42-alloy sheet was used as the metallic substrate for the lead frames. The injection pressure was varied between 0.3 and 0.4 MPa. After the etching test, the width of the etched slots at the metal surface and the etching depth were measured using a three-dimensional optical length measuring machine. The reader is referred to Ueda *et al.*,[10] who used an identical method, for complete details about the etching process.

3. Results and Discussion

3.1 Correlation between etching and spray characteristics

Fig. 2 shows a cross-section of the etched substrate. When etching a metal, dissolution of the surface results in the formation of a sidewall at the photoresist stencil edge. Once this sidewall has been formed, there is nothing to prevent the etchant from dissolving the metal under the stencil to form what is known as an undercut. This phenomenon causes serious problems in the micro-fabrication of lead -frames. Using a quantitative description of the shape of the etched recess, the etching factor can be evaluated from[3]

$$\text{Etching factor} = \text{Etching depth} / \text{Undercut} = 2D / (W_2 - W_1) \quad (1)$$

where W_1 is the width of the slot in the developed photoresist stencil, W_2 is the width of the slot at the metal surface after etching, and D is the depth of the etching measured when the process is stopped before it breaks through the metal sheet. Since it is desirable that the undercut is minimized, etching systems with large etching factors are required for precision etching in metallic substrates.[11]

The equation used to calculate the impact force can be written as

$$\text{Impact force} = \frac{\sum_{i=1}^{n} \frac{\pi}{6} d_i^3 \rho U_i}{\Delta t} \quad (2)$$

where ρ is the density of the droplet, d_i is the droplet size, U_i is the axial velocity, and t is the sampling time. Equation (2) gives the momentum in flux per unit time.

Fig. 3 shows the regression line and coefficient of determination between the etching factor and impact force. The equation can be written in a linearized form following Sdiahmed[ref]:

$$Y = \alpha + \beta X \quad (3)$$

where X is the independent variable (impact force), Y is the dependent variable (etching factor), α is the intercept, and β is the slope. The value of the parameters α and β were determined to be 2.030 and 0.258, respectively. The coefficient of determination (R^2) had a range of $0 \le R^2 \le 1$, and the regression equation was most significant when $R^2 = 1$. The significance of the regression was statistically evaluated by testing the hypothesis $\beta = 0$ using an F-test. The etching factor had a good positive correlation with the impact force. Since the etching factor depended strongly on the impact force, the impact force was used to predict the etching factor.

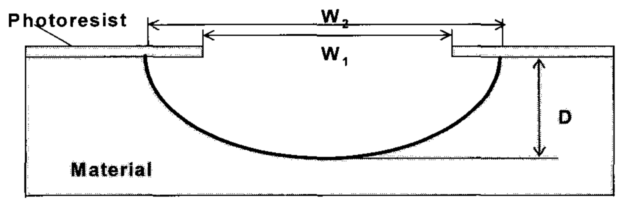


Fig. 2 Diagram of the etched material

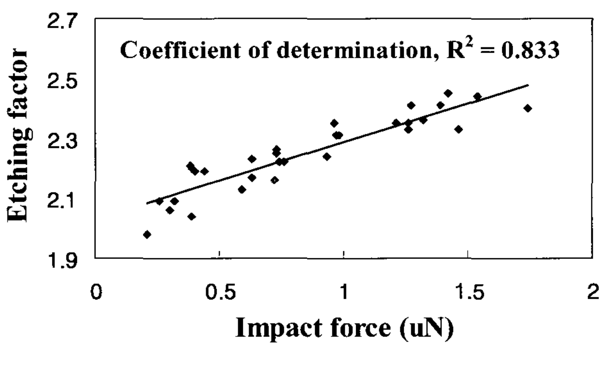


Fig. 3 Correlation between the etching factor and impact force

3.2 Modeling the spray distribution using a Monte-Carlo technique

A Monte-Carlo technique was used to examine the validity of the statistical closure schemes. This technique has wide applications in such fields as mathematics, statistics, science, and engineering.[12–14] The impact force measured for a given set of spray characteristics was calculated during the first step of our modeling process. The impact force was transformed into a spray distribution function. The substrate was divided into 10 × 10-mm cells and random coordinates were generated in unit cells. A total of 5000 drops was plotted in random coordinates for one injection. The etching factor and uniformity can be predicted from the average drop number and the uniformity of the drop number, respectively. The uniformity was determined from the coefficient of variation.

The equation used to calculate the uniformity was

$$Vc = \frac{\sigma}{\overline{N}} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(N_i - \overline{N})^2}}{\frac{1}{n}\sum_{i=1}^{n} N_i} \quad (4)$$

$$\text{Uniformity} = (1 - Vc) \times 100 \quad (5)$$

where σ is the standard deviation, $\overline{N}$ is the average drop number, N_i is the drop number per unit cell, and Vc is the coefficient of variation. The simulation modeled the spraying process using the Java object-oriented programming language. The fixed conditions and chamber conditions used in this study are listed in Tables 1 and 2.

Fig. 4 shows the simulated spray distribution as a function of the distance from the nozzle tip. The drop number per unit cell decreased as the radial distance and the distance from the nozzle tip increased.

3.3 Effect of feed speed and distance from the nozzle tip

Fig. 5 shows the average drop number as a function of the uniformity under different simulation conditions at a pipe pitch of 70 mm. In view of the undercut and the reaction of the etchant, we selected feed speeds of 1, 2, and 3 m/min. The average drop number was highest at a feed speed of 1 m/min. The uniformity was related to the distance from the nozzle tip. In particular, a spray pressure of 0.3 MPa yielded over 99% uniformity.

Table 1 Fixed simulation conditions

Conditions	Value
Material size (width × length, mm)	400 × 400
Injection pressure, P_i (MPa)	0.3, 0.4
Feed speed, V_F (m/min)	1, 2, 3
Reciprocating velocity, V_r (mm/s)	100
Pipe pitch, P_P (mm)	70
Nozzle pitch, N_P (mm)	200

Table 2 Composite chamber conditions used in the model

Conditions	Distance from nozzle tip (mm)	
	Front Chamber	Rear Chamber
A	150	150
B	150	200
C	150	250
D	200	200
E	200	250
F	250	250

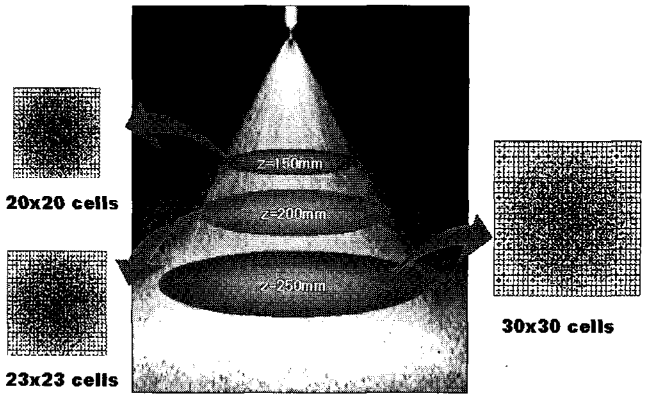
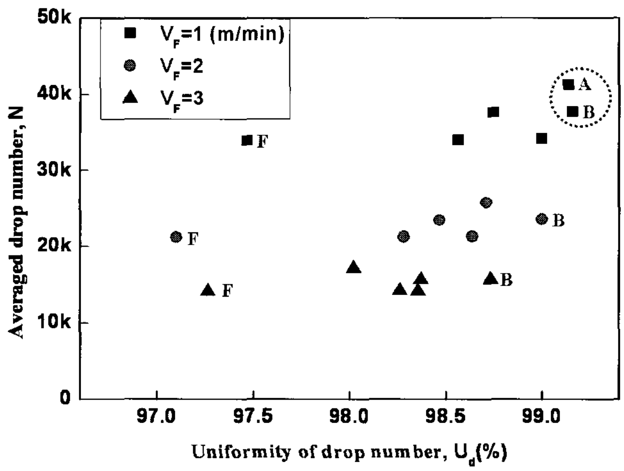


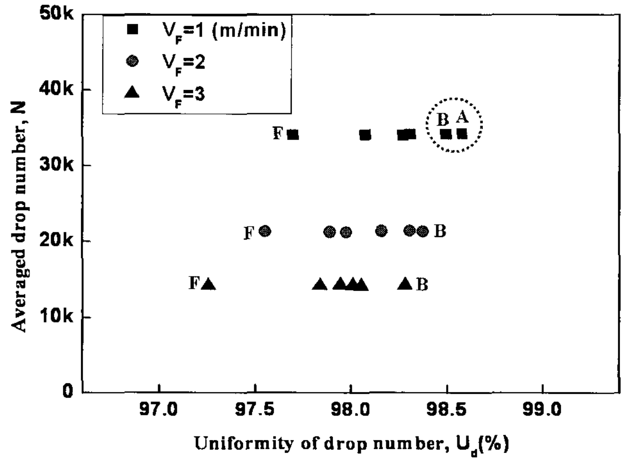
Fig. 4 Modeled impact force distribution with distance from the nozzle tip

3.4 Effect of feed speed and pipe pitch

Table 3 lists the modeled process conditions. The pipe pitch was 60, 70, and 80 mm. Fig. 6 shows the average drop number and uniformity for each set of conditions at a spray pressure of 0.3 MPa. For a feed speed of 1 m/min, the averaged drop number and uniformity were highest for conditions N1 and N4 when the pipe pitch was 60 mm. For the other feed speeds, higher results were obtained for conditions N4 and N6.



(a) Spray pressure of 0.3 MPa

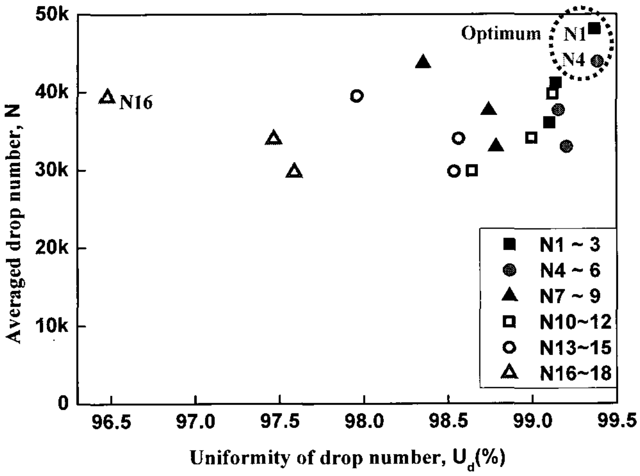


(b) Spray pressure of 0.4 MPa

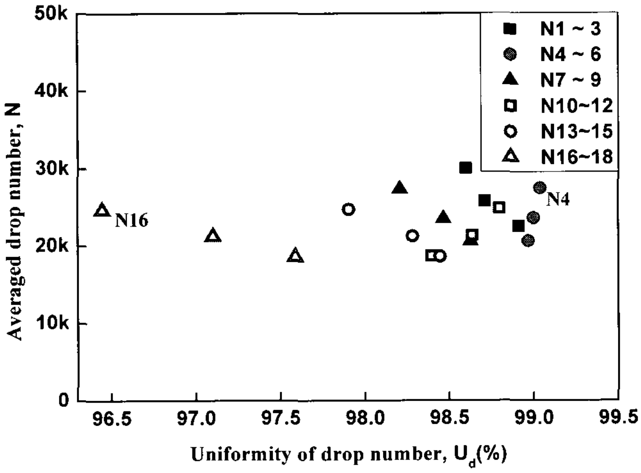
Fig. 5 Modeled impact force distribution with distance from the nozzle tip

Table 3 Conditions used for the pipe pitch simulations

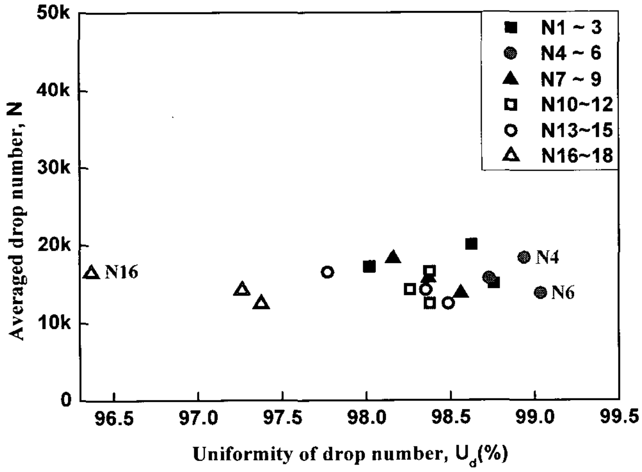
Pp (mm)	A	B	C	D	E	F
60	N1	N4	N7	N10	N13	N16
70	2	5	8	11	14	17
80	3	6	9	12	15	18



(a) Feed speed of 1 m/min

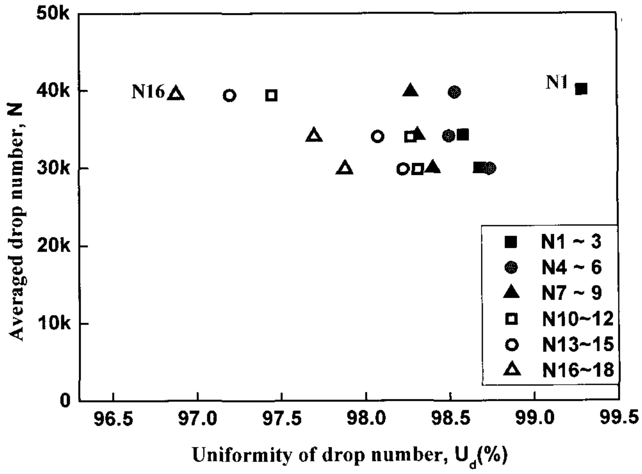


(b) Feed speed of 2 m/min

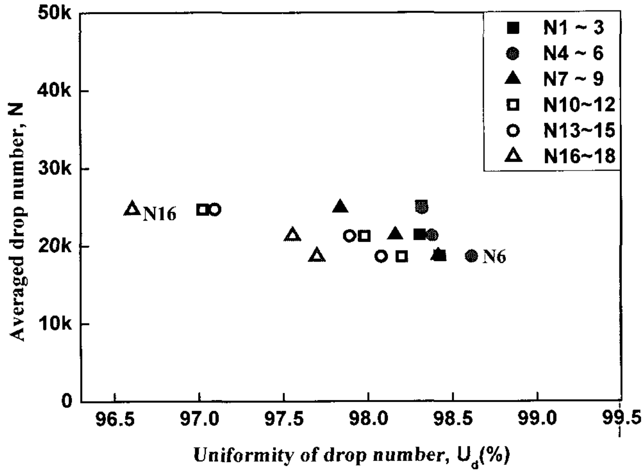


(c) Feed speed of 3 m/min

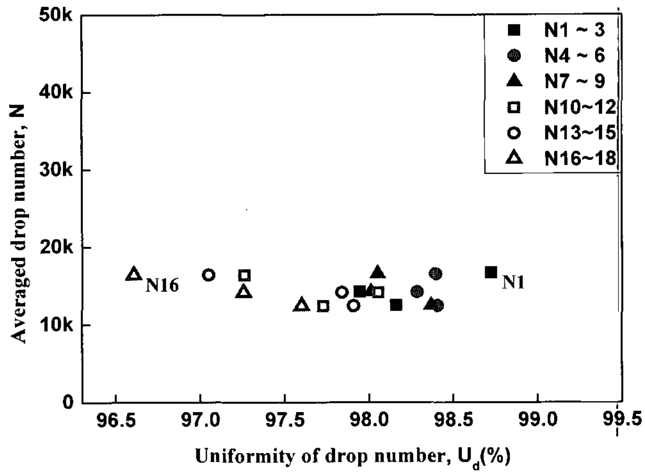
Fig. 6 Simulated distance from the nozzle tip with an injection pressure of $P = 0.3$ MPa



(a) Feed speed of 1 m/min



(b) Feed speed of 2 m/min



(c) Feed speed of 2 m/min

Fig. 7 Simulated distance from nozzle tip with an injection pressure of $P = 0.4$ MPa

Fig. 7 shows the average drop number and the uniformity under each set of conditions at a spray pressure of 0.4 MPa. For a feed speed of 1 m/min, the average drop number and uniformity were highest for N1 when the pipe pitch was 60 mm. The distance from the nozzle tip under condition B had over 98.5% uniformity. Lower uniformities were obtained for other feed speeds.

3.5 Correlation between experiment and simulations

The correlations between the actual etching characteristics and the simulated average drop number and uniformity were analyzed and are shown in Figs. 7 and 8. The regression curves can be expressed as

$$E_F = 1.436 \times 10^{-8} N^2 - 4.38 \times 10^{-4} N + 5.731 \quad (6)$$

$$E_U = 1.93 U_d^3 - 572.57 U_d^2 + 56479.76 U_d - 1.857 \times 10^6 \quad (7)$$

where E_F is the etching factor and E_u is the etching uniformity. The coefficient of determination for both was between 0.99 and 1.0.

The lead frame etching characteristics had good positive correlations with the simulated results. Thus the etching characteristics could be predicted using the simulations described in this study.

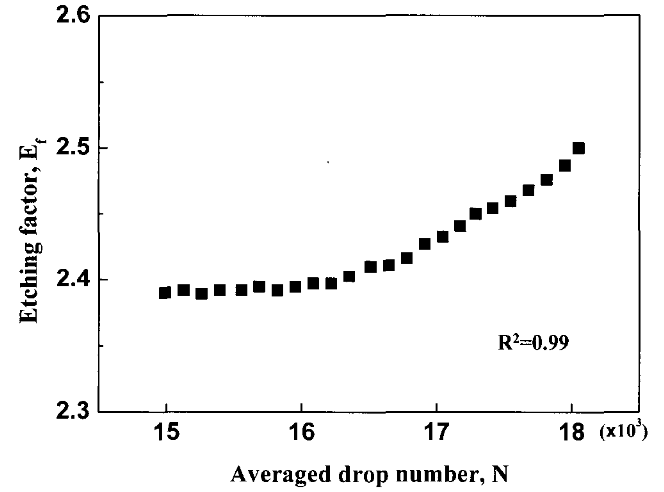


Fig. 8 Correlation between etching factor and average drop number

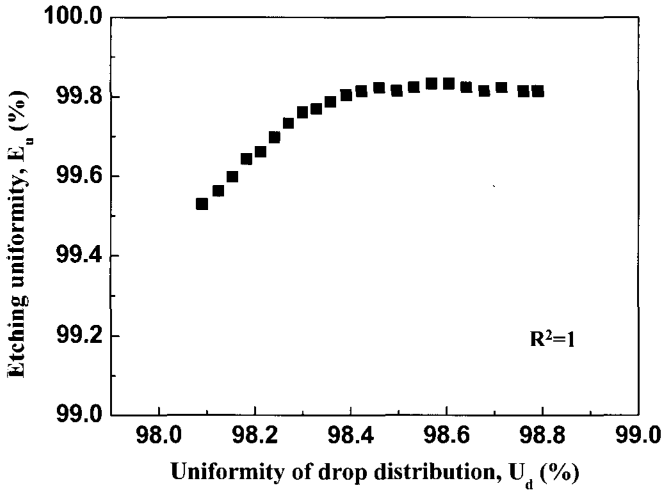


Fig. 9 Correlation between etching uniformity and uniformity of drop number

4. Conclusions

The correlations between spray and wet etching characteristics were investigated and analyzed. Etching processes were simulated for various process conditions. The results may be summarized as follows.

(1) The spray distribution simulated using a Monte-Carlo technique increased with the distance from the nozzle tip. At the same time, the drop number per unit cell decreased. The simulated results agreed well with the measured spray characteristics.

(2) For a pipe pitch of 60 mm, the average drop number was highest at a feed speed of 1 m/mm. The uniformity decreased with increasing distance from the nozzle tip. Compared to other conditions, Condition B gave high uniformity irrespective of the feed speed.

(3) The average drop number and uniformity were highest at a feed speed of 1 m/min. In particular, the spray pressure at 0.3 MPa and at distances from the nozzle tip corresponding to Conditions A and B indicated over 99% uniformity.

(4) The optimum process condition was a spray pressure of 0.3 MPa, a distance from the nozzle tip corresponding to Condition B, feed speed of 1 m/min, and a pipe pitch of 60 mm.

(5) The etching characteristics could be predicted by the simulations.

The results presented in this study may be used to expand and optimize etching processes. Further research is planned in which more data will be analyzed to improve the simulations.

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