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Experimental analysis and optimization of a photo resist coating process for photolithography in wafer fabrication

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Abstract

This investigation is applied the Taguchi method and combination the analysis of variance (ANOVA) to the photo resist (PR) coating process for photolithography in wafer manufacturing. Plans of experiments via nine experimental runs are based on the orthogonal arrays. In this study, the thickness mean and the uniformity of thickness of the PR are adopted as the quality targets of the PR coating process. This partial factorial design of the Taguchi method provides an economical and systematic method for determining the applicable process parameters. Furthermore, the ANOVA prediction of the thickness mean and the uniformity of thickness for the PR has been applied in terms of the PR temperature, chamber humidity, spinning rate, and dispensation rate by means of the designs of experiments (DOE) method. The PR temperature and the chamber humidity are found to be the most significant factors in both the thickness mean and the uniformity of thickness for a PR coating process. Finally, the sensitivity study of optimum process parameters was also discussed.

Keywords: Photo resist; Spin coating; Taguchi method; Optimization; ANOVA

1. Introduction

Photolithography is the patterning process that transfers a design from a mask or reticle to the photo resist (PR) on the wafer surface. Photolithography was first used in the printing industry, and is fundamental to printed circuit board manufacture. Photolithography was adapted in the semiconductor industry for transistor and integrated circuit manufacture in the 1950s. It is the most crucial process steps in IC fabrication, since the device and circuit designs are transferred to the wafer by etching or ion implantation through the pattern defined on the PR on the wafer surface via the photolithography process [1–8].

The photolithography process can be subdivided into three main operations: PR coating, alignment and exposure, and PR developing. First the wafer is coated with a thin layer of photosensitive material, called PR, which is exposed by ultraviolet (UV) light through a mask or reticle with the pattern of clear and dark areas generated by the plotter, based on IC design. The chemistry of the exposed PR is changed by the photochemical reactions under the clear areas through which the UV light can pass.

PR is the photosensitive material used to temporarily coat the wafer and transfer the optical image of the chip design on the mask or reticule to the wafer surface. PR coating is the most important process in photolithography. PR coating, PR solutions, PR temperature, chamber humidity, spinning rate, dispensing rate, ventilate quantity, spinning time and acceleration rate affect the thickness quality of PR film, which involves difference of thickness mean and difference of thickness uniformity. The process parameters of PR coating setup and alignment are in terms of kind of PR. Moreover, trial-and-error was used, and acquaintances with engineers were used to find suitable combinations of process parameters. However, this approach is time-consuming and cannot obtain the best process condition.

Many industries have employed the Taguchi method [9,10] over the years to improve product and process performance. This method is powerful and effective in helping manufacturers to design their products and processes as well as to solve troublesome quality problems.

Actually, the Taguchi method has been used quite successfully in several industrial applications, including manufacturing processes, mechanical component design, and process optimization. Satisfactory experimental results were achieved [11–13], etc.

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Additionally, the DOE method have been widely applied to various fields such as Chao and Hwang [14] proposing an improved Tagchui's method for milling CFRP composite, Sun al et. [15] developing a DOE-based measurement performance to integrate critical measurement strategy factors, and Lin and Chananda [16] improving injection-molding quality by four-factor full-factorial design, and so on.

Therefore, this study is applied the Taguchi method to determining the applicable process parameters of the PR coating. The four factors of PR temperature, chamber humidity, spinning rate and dispensing rate were to recommend by operation manual of the TOKYO Electron Limited Co. as control conditions [17]. Three levels of experiment were selected in every control condition. The thickness mean and uniformity of thickness of PR are adopted as the quality targets of the PR coating process. Furthermore, analysis of variance (ANOVA) is applied to investigate which parameters most significant influence the PR coating process. Finally, the sensitivity studies of optimum process parameters were also discussed.

2. Photo resist coating

PR coating is a deposition process in which a thin layer of photo resist is applied on the wafer surface. The wafer is positioned on a spindle using a vacuum chuck that can hold the wafer during high-speed rotation. Liquid PR is applied on the wafer surface, and centrifugal force from the wafer rotation spreads the liquid over the whole wafer. After the evaporation of the solvents in the PR, the wafer is coated with a thin layer of PR. The PR thickness is related to both PR viscosity and wafer spinning rate. As spinning rate increases the PR layer becomes thinner and more uniform. The PR thickness is inversely proportional to the square root of the spin rate. Since PR has high viscosity and very high surface tension, very high spin rate is required for uniform PR spinning coating. The typical PR thickness in photolithography is between 5000 and 30,000 Å.

The PR can be dispensed using either static or dynamic methods. In the static method, the PR is dispensed onto a stationary wafer surface, and is permitted to spread over part of the wafer surface. When the PR puddle spreads to a certain diameter, the wafer is spun rapidly, with a spin rate up to 7000 rpm, to distribute the PR evenly across the entire wafer surface. The PR thickness is related to the PR viscosity, surface tension, PR drying characteristics, spinning rate, acceleration rate, and spinning time.

For dynamic dispensing, the PR is applied at the center of the wafer while it is rotated at a low spinning rate, approximately 500 rpm. After PR dispensing, wafer spinning is accelerated to 7000 rpm, to spread the PR uniformly across the wafer surface. The dynamic dispensing method uses less PR, whereas static dispensing can achieve uniform PR coating. In this study, the experiment work was used the type of dynamic dispensing.

2.1. Photo resist property

Presently, most advanced semiconductor fabs use positive PR because it achieves the high resolution required for submicron feature size. PR has four basic component: polymer, sensitizer, solvent, and additives.

Polymer is the organic solid material that sticks on the wafer surface and withstands etch and ion-implantation processes for masking the pattern transfer process. Polymer is formed by organic compounds, namely carbonhydrogen molecules (C_xH_y) with complicated chain and ring structures. The most commonly used positive PR polymer is phenol–formaldehyde or novolac resin. Additionally, the most commonly used negative photoresist polymer is polyisoprene rubber.

The sensitizer is an organic compound with high photo-activity, which controls and modifies the photochemical reaction of the PR during exposure. The sensitizer for the positive PR is a dissolution inhibitor, which is cross-linked within the resin. During exposure, the light energy dissociates the sensitizer and breaks down the cross-links, making the exposed resin soluble in an aqueous developer solution. The sensitizer for the negative PR is an organic molecule containing the N_3 group. Exposure to UV light liberates N_3 gas, forming the free radicals that help to cross-link the rubber molecules. The chain reaction of the cross-links then polymerizes the exposed areas, which have greater bonding strength and higher chemical resistance.

The solvent dissolves the polymer and sensitizer, and suspends them in the liquid PR. The solvent thus facilitates the application of PR on a wafer surface at a thickness of 0.5-μm–3-μm. The solvent thins the PR to allow the application of thin layers via spinning, analogous to paint. Before the spin coating process, approximately 75% of PR is solvent. Positive PR generally use acetate-type solvents, and negative PR normally use xylene (C_8H_{10}).

Additives control and modify the photochemical reaction of PR during exposure to achieve the optimal lithography resolution. Dye is additive for both positive and negative PR.

To achieve completed pattern transfer, the PR needs to have good resolution, high etch resistance, and good adhesion. High resolution is the key to achieve successful pattern transfer. Without high etch resistance and good adhesion of the PR, the next etch or ion implantation processes will most likely fail to meet process requirements and will cause intolerable error. However, the thinner the PR film, the lower the etching and ion- implantation resistance. It is always a trade-off between these two conflicting requirements.

The PR grade AZ DX5106 from Taiwan/Clariant (Japan) K.K. is used in this study. The property of propylene glycol monomethyl ether acetate, water content, and kinematic viscosity are 97.9, 0.06 wt% and 5.7 cSt, respectively.

2.2. Schematic of a PR spin coater

Fig. 1 schematically illustrates a PR spin coater, which applied to the PR coating process for Photolithography in the 8-inch wafer fabrication. The PR is brought into the dispensing

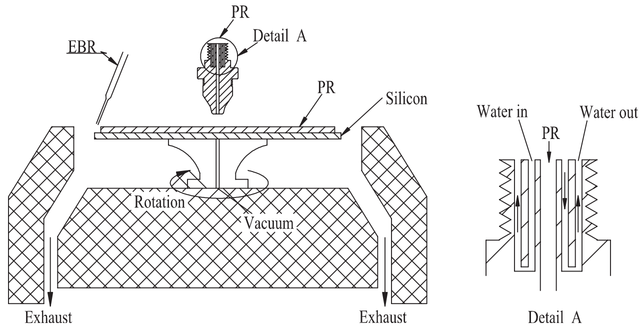

Fig. 1. Schematic of a PR spin coater.

nozzle via a tube with a water sleeve, in which water from a heat exchanger is used to maintain a constant PR temperature since the viscosity is related to the PR temperature. The spin rate and spin rate ramp are precisely controlled, as are the air flow temperature and air flow rate in the coater, since they can affect the drying characteristics of the PR. The spindle is either nitrogen- or water-cooled to avoid wafer temperature no uniformity caused by the center heating, since the spindle can become very hot during the high-speed spinning if not properly cooled. The excess PR and edge-bead removal (EBR) solution are collected and drained from the bottom of the station, and the vaporized solvent is evacuated from the exhaust. The PR thickness mean and uniformity of thickness are also related to the exhaust gas temperature and gas flow rate, since they can affect the PR-drying characteristics. In fact, the best PR thickness uniformity can be achieved without exhaust flow. However, without exhaust, the accumulation of the solvent vapor fumes can endanger health and safety. Generally, increasing exhaust flow rate leads to an edge-thick PR thickness profile, owing to the faster drying of PR near the edge, increasing the viscosity of PR and its thickness there.

Following the PR spin coating, the PR covers both sides of the wafer near the edge. Edge-bead removal (EBR) is necessary to get rid of the PR buildup on the edge, because in the following etch or ion implantation process, mechanical wafer handlers such as robot fingers or wafer clamps can crack the PR buildup at the edge of the wafer and cause particulate contamination. The thick edge bead may also cause focus problems during the exposure process at the wafer edge. Both chemical and optical methods are used to remove the edge bead.

3. Experimental procedures and test results

3.1. Taguchi method

The Taguchi method has been successfully applied for designing experiments in recent years. Depending on the objective, there are three different mean square deviations for the signal–noise ratios that can be defined including nominal-the-better, larger-the-better, and smaller-the-better. The mean square deviation can be considered to be the average performance characteristic values for each experiment. The different signal–noise ratios, corresponding to n experiments, are presented below:

Nominal-the-better

$$\frac{S}{N} = -10\log\left(\frac{1}{nS}\sum_{i=1}^{n} y_i^2\right) = -10\log\left(\frac{\bar{y}^2}{S^2}\right) \tag{1}$$

Larger-the-better

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{2}$$

Smaller-the-better

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) = -10\log(\bar{y}^2) \tag{3}$$

Where S denotes the standard deviation, y_i is the data obtained from the on-line experiments, and n represents the number of times the experiments were performed. The above equations yield the S/N ratio of the thickness and thickness uniformity. Typically, lower thickness and thickness uniformity on the wafer surface during the PR coating process is preferred. Therefore, the smaller-the-better S/N ratio formula is chosen here, after the optimal parameters combination is obtained.

3.2. Experimental design

PR coating product quality is influenced by process parameters that include PR solutions, PR temperature, chamber humidity, spinning rate, dispensing rate, ventilation quantity, spinning time and acceleration rate, and so on. In this study, we were selected the PR temperature, the chamber humidity, the spinning rate, and the dispensation rate for controllable parameter in the PR coating process. The controllable parameter is based on operation manual of the TOKYO Electron Limited Co. Accordingly, this study performed the experiment work using four controllable 3-level factors and two response variables. Table 1 lists the four factors of PR temperature (i.e. A/°C), chamber humidity (i.e. B/%), spinning rate (i.e. C/rpm), and dispensation rate (i.e. D/ml/s) with three levels in this study. Namely, the experiment work in this study is based on the orthogonal array $L_9(3^4)$.

The two response variables include thickness mean (t_{m}, Å) and thickness uniformity (t_{u}, Å) on the wafer surface after coating process. The thickness mean and thickness uniformity can be 5300 ± 30 Å. 5300 Å represents the mean value of the PR coating thickness; a mean value of thickness permits a little

Table 1
Experimental factors and factor levels

Levels of experimental factor	Experimental factors			
	A (°C)	B (%)	C (rpm)	D (ml/s)
1	22	37	2900	0.75
2	22.5	40	3100	1.0
3	23	45	3300	1.5

Table 2
Orthogonal array $L_9(3^4)$ of the experimental runs and results

L9	A	B	C	D	t_m (Å)	t_u (Å)
1	1	1	1	1	5312.4	20.60
2	1	2	2	2	5314.9	20.63
3	1	3	3	3	5300.3	41.22
4	2	1	2	3	5308.2	27.57
5	2	2	3	1	5310.9	12.84
6	2	3	1	2	5296.4	25.04
7	3	1	3	2	5308.7	13.48
8	3	2	1	3	5301.5	26.91
9	3	3	2	1	5296.2	18.68

tolerance in the upper and lower limits. The tolerance closer to 5300 Å means coating film quality is better. The value of $\pm$ 30 Å shows the PR thickness uniformity values, that is the maximum and minimum deviation values of the coating film surface. The upper and lower limits of the mean value of thickness and the deviation of the thickness uniformity value are both smaller-the-better. The value both of thickness mean and thickness uniformity was to recommend by operation manual of the TOKYO Electron Limited Co. on the PR coating process of the 8-inch wafer fabrication.

3.3. Measurement of thickness

PR coating of the 8-inch wafer was performed according to the experiment design. The thickness mean and the thickness uniformity were measured using an OPTI-PROBE analyzer of the Therma-Wave Co. The thickness mean measured as average value of the 49 point on wafer surface in polar direction. The valve of the thickness uniformity is maximum and minimum deviation values of the 49-point on wafer surface. The measured results of the thickness mean and the thickness uniformity are listed in Table 2.

4. Results and discussion

4.1. Best experimental run

Two qualities were selected as the target qualities in this study, that is, the two response variables include thickness mean and thickness uniformity on the wafer surface. Typically, lower values of the thickness mean and thickness uniformity on the wafer surface in the PR coating process are desirable. Therefore, the smaller-the-better *S/N* ratio formula is selected in this investigation.

Table 3
S/N ratios of taguchi experimental results

Experimental run	*S/N*		Normalized		η (Normalized) tol
	t_m (Å)	t_u (Å)	ηt_m	ηt_u	
1	12.44	20.60	0.048	0.5947	0.6428
2	14.92	20.63	0.000	0.5935	0.5935
3	0.34	41.22	1.000	0.0000	1.0000
4	8.19	27.57	0.159	0.3448	0.5034
5	10.94	12.84	0.082	1.0000	1.0821
6	3.61	25.04	0.375	0.4274	0.8026
7	8.74	13.48	0.141	0.9583	1.0997
8	1.45	26.91	0.617	0.3656	0.9821
9	3.79	18.68	0.362	0.6786	1.0410

Table 4
The response table for *S/N* ratio

	A	B	C	D
Level 1	0.7454	0.7486	0.8091	0.9219
Level 2	0.7960	0.8859	0.7126	0.8319
Level 3	1.0409	0.9479	1.0606	0.8285

The Taguchi method can be employed to obtain the optimal level/factor combination of PR coating process parameters. The Taguchi method uses the signal–noise to represent the quality characteristic, and the largest *S/N* ratio is demanded. Table 3 shows the *S/N* ratios obtained using the Taguchi method, while Table 4 lists the responses for the *S/N* ratios. In Table 4, A_3, B_3, C_3, and D_1 illustrate the largest values of *S/N* ratios for factors A, B, C, and D, respectively. Consequently, $A_3B_3C_3D_1$ is the condition for the optimal parameter combination of the PR coating process. Restated, the PR temperature is 23 °C, chamber humidity is 45%, spinning rate is 3300 rpm, and dispensation rate is 0.75 ml/s.

4.2. AVOVA results

The analysis of variance (ANOVA) of the DOE method [18] was conducted and the results are shown in Table 5 and Table 6.

In Table 5 shows AVOVA for thickness mean (t_m), the value of 'probability > *F*-Value' is 0.0057, which is less than 0.0500, indicating that a model term A (i.e. PR temperature, °C) and term B (i.e. chamber humidity, %) are significant. The model *F*-value of 13.81 implies the selected model is significant. There is only a 0.57% chance that a 'model *F*-value' could occur due to noise.

Similarly, in Table 6 shows AVOVA for thickness uniformity (t_u), the value of 'probability > *F*' is 0.0034, which is less than 0.0500, indicating that a model term A (i.e. PR temperature, °C), term B (i.e. chamber humidity, %), and term D (i.e. dispensation rate, ml/s) are significant. The model *F*-value of 19.70 implies the selected model is significant. There is less than a 0.34% chance that a 'model *F*-value' could occur due to noise.

Table 5
ANOVA for t_m

Source	Sum of squares	DOF	Mean square	*F* value	*P* value
Model	324.51	2	162.25	13.81	0.0057
A	74.91	1	74.91	6.38	0.0450
B	249.60	1	249.60	21.25	0.0037
Residual	70.49	6	11.75	–	–
Total	395.00	8	–	–	–

Table 6
ANOVA for t_u

Source	Sum of Squares	DOF	Mean square	*F* value	*P* value
Model	549.70	3	183.23	19.70	0.0034
A	91.10	1	91.10	9.80	0.0260
B	105.69	1	105.69	11.36	0.0199
D	352.91	1	352.91	37.94	0.0016
Residual	46.50	5	9.30	–	–
Total	596.20	8	–	–	–

4.3. Confirmation tests

4.3.1. Optimal parameter combination

The $A_3B_3C_3D_1$ is the condition for the applicable parameter combination of the PR coating process. Under the condition $A_3B_3C_3D_1$ of the applicable parameter combination of the PR coating process was via the confirmation tests. The quality product has a mean value of thickness is 5296.2 Å, while a uniformity of thickness is 13.6 Å.

4.3.2. Sensitivity study

Following the optimal parameter of the $A_3B_3C_3D_1$, the experiment is analyzed sensitivity. Namely, the experiment changes one optimal parameter only and the other three are fixed in turn proceeding. The thickness mean and thickness uniformity of the quality product results are shown in Figs. 2–5.

Fig. 2 shows the variation of the thickness mean and thickness uniformity versus the PR temperature (that is, factor A: 21–24 °C) under the condition $B_3C_3D_1$. From Fig. 2, the thickness mean decreases with increasing PR temperature. However, the thickness uniformity decreased rapidly when the PR temperature ranged between 21–22.5 °C. However, when the PR temperature exceeded 22.5 °C the thickness uniformity increased rapidly.

Fig. 3 illustrates the relation of the thickness mean and thickness uniformity with the chamber humidity (that is, factor B: 37–46%) under the condition $A_3C_3D_1$. Fig. 3 indicates that the thickness mean increases with increasing chamber humidity. At the same time, the thickness uniformity decreased rapidly when chamber humidity ranged between 37–40%. Meanwhile, when the chamber humidity exceeded 40% the thickness uniformity increased rapidly.

Fig. 4 shows the variation of the thickness mean and thickness uniformity versus spinning rate (that is, factor C: 2800–3400 rpm) under the condition $A_3B_3D_1$. Fig. 4 indicates that, the thickness mean and thickness uniformity values vary little under different spinning rates.

Fig. 5 displays the relation of the thickness mean and thickness uniformity with the dispensing rate (that is, factor D: 0.6–1.5 ml/s) under the condition $A_3B_3C_3$. Fig. 5 reveals that

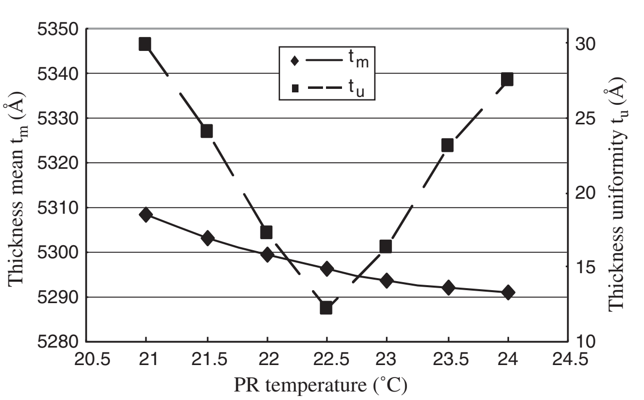

Fig. 2. Variations of thickness mean and thickness uniformity versus PR temperature.

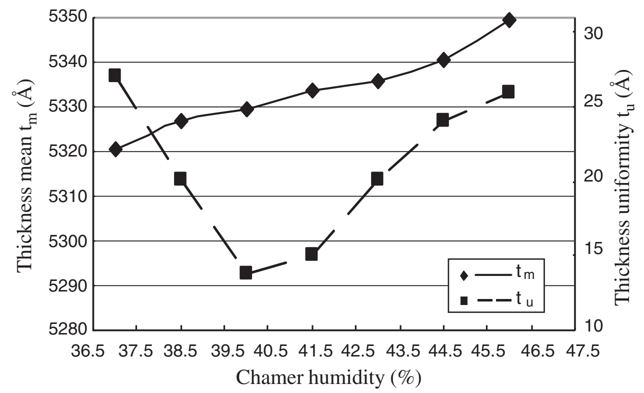

Fig. 3. Variations of thickness mean and thickness uniformity versus chamber humidity.

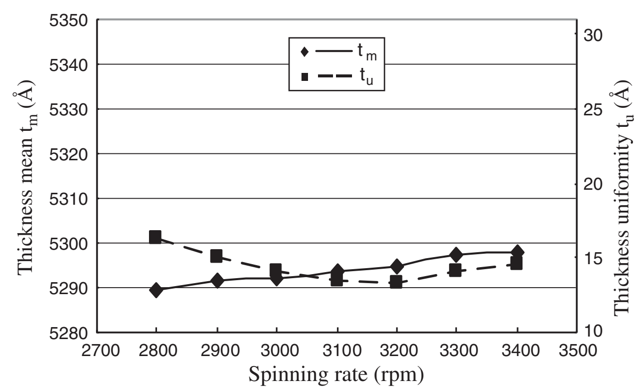

Fig. 4. Variations of thickness mean and thickness uniformity versus spinning rate.

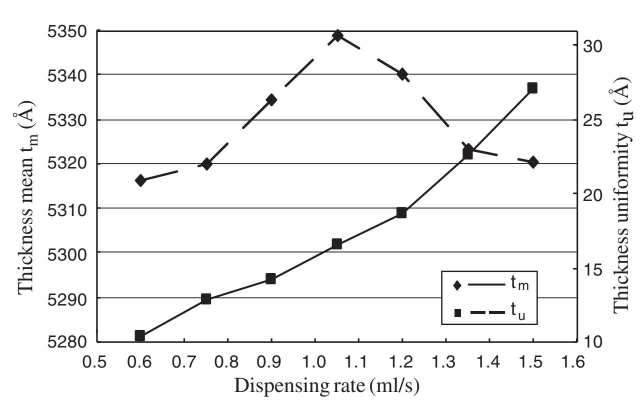

Fig. 5. Variations of thickness mean and thickness uniformity versus dispensing rate.

increased dispensing rate increases the thickness mean. The thickness uniformity increased rapidly when the dispensing rate ranged between 0.6–1.05 ml/s. However, when the dispensing rate goes above 1.05 ml/s the thickness uniformity decreased rapidly.

5. Conclusions

This study investigated the optimization of PR coating process factor and levels using the Taguchi method. Additionally, the ANOVA is used to examine how parameters most significant the PR coating process. Finally, the sensitivity studies of optimum process parameters were also discussed. The analytical results are summarized as follows.

1. The optimal parameter combination of the PR coating process corresponded to a PR temperature of 23 °C, chamber humidity of 45%, spinning rate of 3300 rpm, and dispense rate of 0.75 ml/s. Therefore, $A_3B_3C_3D_1$ is recommended on the PR coating process parameters.
2. The coating parameter, PR temperature and chamber humidity are the most significant factor to attain a better mean thickness. Simultaneously, the PR temperature, the chamber humidity and the dispensation rate are the most significant factor to attain a better uniformity of thickness based on based on the AVOVA results.
3. Via sensitivity studies experiment analysis, the thickness mean were increased at chamber humidity, spinning rate and dispense rate increasing, respectively. But the thickness mean was decreased when PR temperature increasing. However, the thickness uniformity from decreased to increasing when PR temperature and chamber humidity increasing, respectively. But the thickness uniformity from increased to decreasing when dispensing rate increasing.
4. Under the condition of optimal parameter combination of PR temperature, chamber humidity and dispensing rate (i.e. $A_3B_3D_{1.}$), the thickness mean and thickness uniformity values vary little under different spinning rates.

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References

[1] T. Leslie, W. Arden, J. Ben-Jacob, D. Coleman, J. Polimeni, F. Prein, Photolithography overview for 64 megabit production, Microelectron. Eng. 25 (1994) 67–74.

[2] P.V. Zant, Microchip Fabrication, A Practical Quide to Semiconductor Processes, third ed., McGraw-Hill, New York, 1997.

[3] Hong, Introduction to Semiconductor Manufacturing Technology, Prentice-Hall, New Jersey, 2001.

[4] O.V. Balachova, M.A.R. Alves, J.W. Swart, E.S. Braga, L. Cescato, CF_4 plasma etching of materials used in microelectronics manufacturing, Microelectron. J. 31 (3) (2000) 213–215.

[5] Y.Z. He, Y.L. Han, Y.G. Zhao, B.S. Cao, Investigation into the flange problem of resist along the edge of substrate caused by spin coating, Microelectron. Eng. 63 (2002) 347–352.

[6] Y.K. Kuo, C.G. Chao, Y. Lin, Analysis of instability line width and white wall created by the photolithography process, Microelectron. J. 35 (11) (2004) 915–922.

[7] Y.K. Kuo, C.G. Chao, Analysis of the effects of reflectance and refraction generated by wafers made from fused silica, ALO_xN_y and $TiSi_xN_y$ under different light sources on pattern length and best focus, Microelectron. J. 36 (1) (2005) 35–39.

[8] B. Torbiéro, M.L. Pourciel-Gouzy, I. Humenyuk, J.B. Doucet, A. Martinez, P. Temple-Boyer, Mass patterning of polysiloxane layers using spin coating and photolithography techniques, Microelectron. J. (2005) (Available online 13 June).

[9] G. Taguchi, Introduction to quality engineering, Asian Productivity Organization, 1990, Japan.

[10] P.J. Ross, Taguchi Techniques for Quality Engineering, second ed., McGraw-Hill, New York, 1996.

[11] S.H. Hsiang, J.L. Kuo, An investigation on the hot extrusion process of magnesium alloy sheet, J. Mater. Process. Technol. 140 (2003) 6–12.

[12] A. Manna, B. Bhattacharyya, Investigation for optimal parametric combination for achieving better surface finish during turning of Al/SiC-MMC, Int. J. Adv. Manu. Technol. 23 (2004) 658–665.

[13] N. Tosun, L. Ozler, Optimization for hot turning operations with multiple performance characteristics, Int. J. Adv. Manu. Technol. 23 (2004) 777–782.

[14] P.Y. Chao, Y.D. Hwang, An improved Taguchi's method in design of experiments for milling CFRP composite, Int. J. Prod. Res. 35 (1997) 1–66.

[15] A.Y.T. Sun, S.J. Anand, S.Y. Tang, Comprehensive design of experiments-based framework for optimal CMM inspection and uncertainty analysis of form tolerances, Int. J. Prod. Res. 40 (9) (2002) 2097–2123.

[16] T. Lin, B. Chananda, Quality improvement of an injection-molded product using design of experiments: a case study, Qual. Eng. 16 (1) (2004) 99–104.

[17] Equipment Operation Manual: Tokyo Electron Limited Co., Model: CLEAN TRACK ACT8, 2000.

[18] C.M. Douglas, Design and Analysis of Experiments, fourth ed., Wiley, New York, 1997. pp. 243–245.