Fabrication of the photo-resist mask onto 3D non-planar wafer for micro abrasive jet machining

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***Abstract*—** This paper presents a novel fabrication technique of a photo-resist mask onto 3D curved wafer for micro-abrasive jet machining (AJM) process. The photo-resist mask structure selectively blocks the abrasive jet at the portion of the surface that is not supposed to be machined. Previous studies on the photo-resist mask fabrication process were mainly focused on planar wafers and it was difficult to adapt the fabrication technology directly to materials with 3D curved surfaces because besides UV power and scanning speed, the solidifying action is strongly affected by the beam size as well as hatching size. In this research work, a modeling algorithm that uses images obtained from 3D CAD or no CAD mask models of the wafer has been developed and validated through a number of experiments. SU-8 a negative, epoxy-type, near-UV photo-resist based on EPON SU-8 epoxy resin has been used for the photo-resist mask fabrication. Even though, the SU-8 photo-resist is highly sensitive epoxy resin to UV light, existing fabrication process onto the wafer surface is still an ill-defined problem relying on heuristic methods because of the lack of adequate knowledge on the sensitivity variation. The UV laser limits the SU-8 photo-resist mask to 300µm thickness where photo-resist is most sensitive; therefore a spin coating technique is desired to allow the resist to acquire uniform thickness. For 3D non-planar, the spinning technique is very much demanding and sometimes unfeasible depending on the wafer shape. In this study, the spinning issue has been consciously analyzed and worked out through dilute, at defined ratio, of the concentrated SU-8 epoxy resin with Cyclopentanone (C_5H_8O). Through Taguchi method, the most effective controlling parameters for fabrication of the mask with appropriate hardness and surface quality as vital conditions for micro-AJM process have been ranked and reported in this paper.

***Keywords*—** EPON SU-8 epoxy resin, micro-stereolithography, photo-resist mask, 3D non-planar wafer

I. Introduction

SU-8 is a negative, epoxy based, near-UV photo-resist designed for MEMS and other microelectronic applications. It was originally developed and patented by IBM [1, 2, 3]. Initially, the SU-8 was processed by using standard lithograph techniques simply because when SU-8 is exposed to UV light its molecular chains cross-link, causing the SU-8 to solidify. The SU-8 is highly transparent in the ultraviolet region, allowing fabrication of relatively thick (hundreds of micrometers) structures with nearly vertical side walls.

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However, the SU-8 is highly sensitive epoxy resin to UV light, R. Yang et al [2] revealed that, when coated the SU-8 on planar wafer, the UV range limits the thickness to 300µm for the 365nm-wavelength where the photo-resist is the most sensitive as demonstrated by standard lithography equipments. The SU-8 negative photo-resist absorbs much more at 320 nm than at 365 nm thus 320 nm UV lasers should not be used for the SU-8 exposure, unless it is for very thin layers (less than 250µm).

D. Stumbo et al [3] added that, after coating the SU-8 photo-resist on the planar wafer surface, spinning is desired to allow the resist to acquire uniform thickness. 3-4 ml of the SU-8 photo-resist is initially spin coated at 500 rpm for 10sec, followed by ramped up to 1000 rpm and spun for another 20 sec to obtain 250 µm thick resist layer. The coated substrate is then soft baked on a hotplate at 65°C for 7 min and ramped to 95°C and baked again for 30 min. The substrate is then allowed to cool down for thermal relaxation for about 10 min.

Previous researchers were mainly focused on planar workpieces; for 3D non-planar, both spinning and soft baking are very much demanding and sometimes impossible depending on the wafer shape. Firstly, the non-uniformity of the wafer surface can not to allow the concentrated epoxy resin to acquire nearly uniform thickness as applied to the planar wafer. Secondly, it is not viable to distribute nearly same amount of heat in all the coated points of 3D curved wafer, which makes soft baking useless process. This research work, deliberately analyzed the above mentioned challenges and the proposed solutions are reported in this paper.

Actually, the fabrication technology known as micro-stereolithography uses a focused laser beam with a diameter of a few microns as a light source and a complex optical system for the beam delivery. By scanning the laser beam over the surface of a UV-curable photopolymer, a cross section of the wafer surface can be solidified [4]. Even though the process is simpler than micro-mask fabrication based on semiconductor technology, the approach needed always preparation for each next layer to be fabricated.

J.S.Choi et al [5] developed a novel type of micro-stereolithography technology using a UV lamp and optical fiber (Fig. 1 and Fig.2) because the UV lamps are reasonably priced vis-à-vis the UV lasers. Moreover, since the optical path of the UV light is confined in the optical fiber, unintended beam irradiation is not a problem. The focused UV light moves on the photopolymer in the x–y direction while the substrate moves in only the z-direction, and thus little possibility exists of the structure collapsing. Nonetheless the

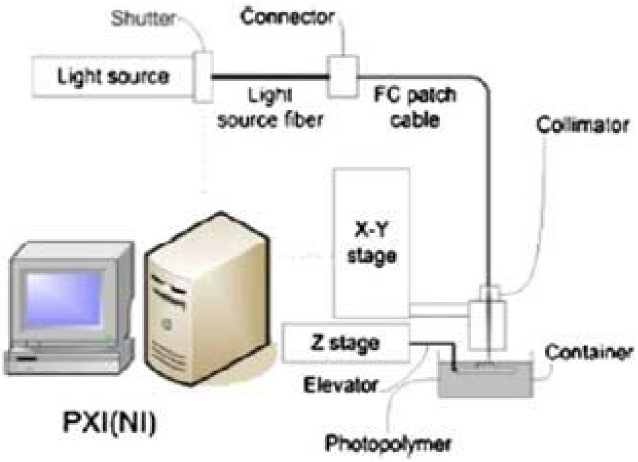

Fig.1 Schematic diagram of micro-stereolithography system

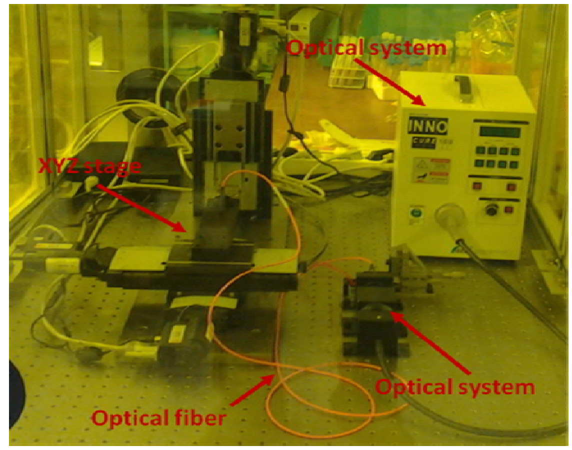

Fig.2 Actual micro-stereolithography system

developed micro-stereolithography is cost effective and superior for mass production, it was still difficult to adapt the fabrication technique directly to materials with 3D curved surfaces because besides the UV power intensity, scanning speed, baking process, spinning process etc.; the solidifying action is strongly affected by the beam size as well as hatching size. Furthermore, although, the SU-8 photo-resist is highly sensitive epoxy resin to UV light, existing fabrication process onto the wafer surface is still an ill-defined problem relying on heuristic methods. This is due to the lack of adequate knowledge on the sensitivity variation as well as ranks of the most effective controlling parameters for optimal photo-resist mask in term of hardness and surface quality required by micro-AJM process.

Recently, Kim et al [6] introduced a direct mask modeling algorithm that generates a 3D CAD mask model directly from cross-sectional images of an arbitrarily shaped wafer. The algorithm uses cross-sectional images obtained by computed tomography (CT) or magnetic resonance imaging (MRI) scanners; it is very accurate and efficient when there are no CAD models of the wafer or only inaccurate ones. Nevertheless the developed algorithm showed high potential in the simulation process, there was still a need to validate its applicability through experiment work. In this research work, the developed algorithm has been test and verified through a number of experiments.

Moreover, through Taguchi method the most effective controlling parameters for fabrication of the SU-8 photo-resist mask with appropriate hardness and surface quality as vital conditions for micro-AJM process have been ranked. 3D curved glass (BK57) and tungsten carbide (WC) have been used as workpiece samples and preliminary validating results of micro-AJM process [7] are also reported in this paper.

II. CAD MODELING OF 3D CURVED WAFER

In this study, the developed modeling algorithm for planar

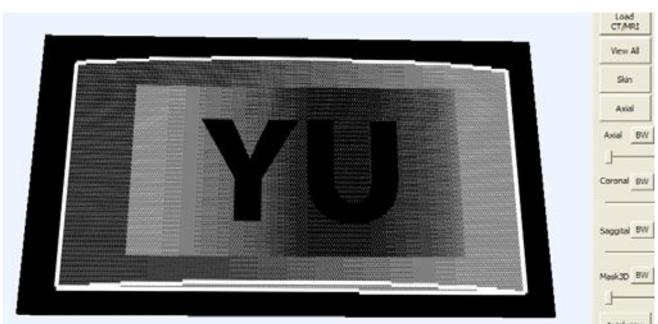

Fig.3 Image of the mask model onto 3D wafer

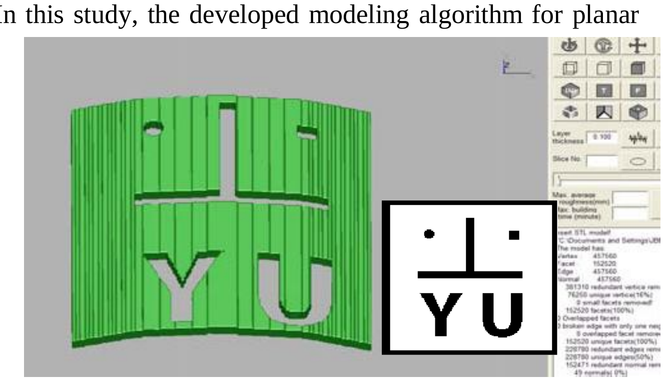

Fig.4 Structure of the mask model

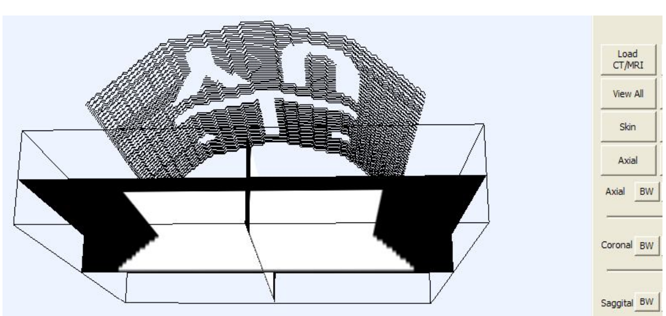

Fig.5 Image of the computerized mask model

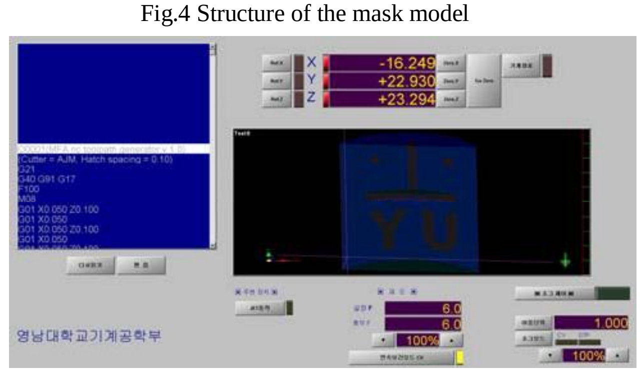

Fig.6 Simulation of the fabrication process

and non-planar mask models assisted in two ways; Firstly, visualization of the design and confront problems before putting the model into physical form as shown in Fig. 3 and Fig. 4. Secondly elaborate computerized models of objects (Fig.5) and generate numerical control (NC) codes required by micro-stereolithography as well as micro-AJM processes. The developed algorithm has been skillfully customized for making it compatible to each machine controller. The designed model has been simulated to put into picture the whole process before it is physically produced as shown in the Fig 6.

III. FABRICATION STEPS OF THE SU-8 PHOTORESIST MASK

As stated in many literatures and mentioned again in the introduction of this paper, the SU-8 photo-resist is highly sensitive epoxy resin to UV light. In this work, The UV light parameters such as spectrum, power intensity, and beam size have been cautiously analyzed.

A. Measurement: UV spectrum

It is believed that, UV laser beam should not be used for the SU-8 exposure, unless it is for very thin layers [2]. Even though, in this work, the UV lamp has been used instead of UV laser, it is imperative to ensure the recommended sensitivity range [2]. Following that, UV spectrum was measured and plotted (Table I and Fig.7). The interpretation of the plot for the UV spectrum shows that with the developed micro-sterolithography, the high percentage of UV light matches with the wavelength between 360nm and 600nm which proved the optimal conditions.

TABLE I
DATA OF THE UV SPECTRUM

S/N	Wavelength (nm)	% of the corresponding data
1	345.42	0.457
2	345.63	0.457
.....	.....	…..
.....	.....	…..
300	409.75	1.664
301	409.96	1.536
…..	…..	…..
…..	…..	…..
3580	1028.94	0.046
3581	1029.1	-0.192

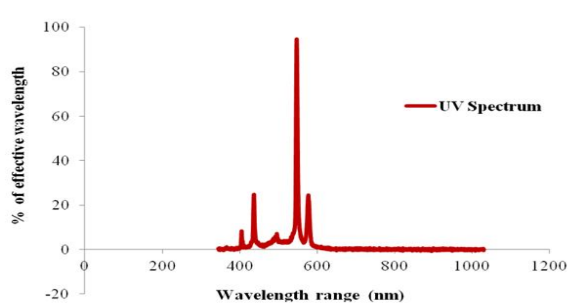

Figure 7: UV spectrum for the wavelength

B. Measurement: Spot size and UV light power intensity

As mentioned before, besides scanning speed, baking process etc., the photo-resist mask hardness and surface quality is strongly affected by the UV power as well as beam size; therefore, in this work, laser beam profiler (Newport: LBP Series) and laser power meter (FieldMaxII-Coherent) were used to provide graphical representations and parameter range of the developed micro- stereolithography system.

Moreover, it is well-known that for a converging lens of thickness (d) as shown in Fig.8, a focal length (f) is a positive distance at which a beam of collimated light will be focused to a single point. Following that, the convex lens has been put at the end point of the optical system of the developed micro-stereolithography system (UV lamp and fiber optic). Consequently, in this research, a number of measurements were conducted to locate the focal point and figure out the beam width (Table II and Fig.9). Systematic precaution was taken in the measurement process to prevent the extreme UV power intensity at focus which could damage the lens of the beam profiler.

The LBP series indicated minimum spot size was found to be 321.84 μm and 324.19 μm in the vertical and horizontal direction respectively with a nearly circular shape (Fig.10).

The SU-8 manufacturers and users [2,3] proposed the exposure dose versus thickness at UV wavelength 350 - 450 nm (150 - 1400 mJ/cm2 for 10 - 450 μm respectively) Following that, the laser power meter (FieldMaxll -Coherent) has been used to measure the scanning energy. The results demonstrated that the developed micro-streolithography system delivers the UV power which is in the recommended range (Fig.11) and maximum power delivery is 27.5μW.

C. Fabrication process

The renowned SU-8 manufacturer (MicroChem) recommended SU-8 2100 as a high contrast, epoxy based photo-resist designed for micromachining and other

TABLE II
SYSTEMATIC MEASUREMENT OF THE SPOT POINT

Focal distance (mm)	**Beam width (13.5%)**		**Correlation (%)**	
	Horizontal (µm)	**Vertical (µm)**	**Horizontal**	**Vertical**
10	777.86	780.67	88.05	89.73
15	494.16	506.13	84.36	86.09
17	357.6	362.68	82.54	82.34
18	324.19	321.84	82.94	89.95
19	332.75	328.78	84.66	84.36
20	394.00	394.22	86.85	86.63
22	502.90	505.49	87.48	87.77
27	795.69	801.20	93.07	93.06

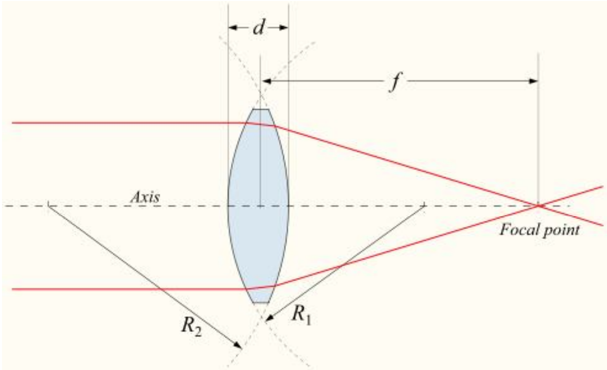

Fig.8 Ideal schematic diagram of converging lens

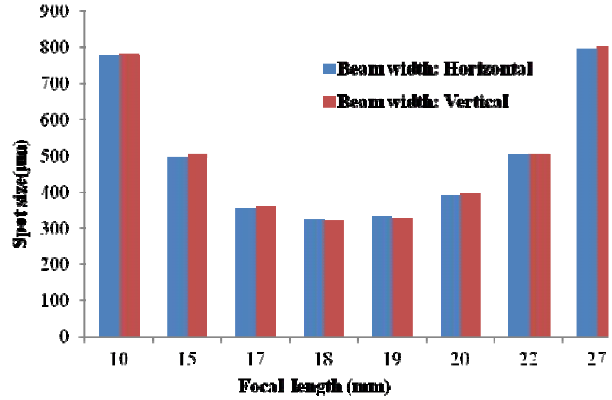

Fig.9 Plot of actual beam profile

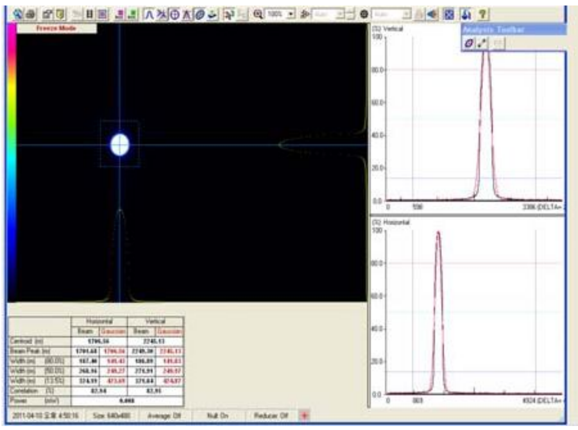

Fig.10 Measured smallest beam size

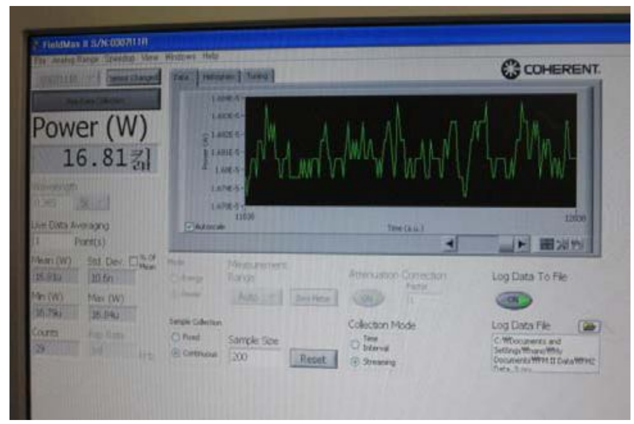

Fig.11 Measurement of UV power

microelectronic applications, where a thick, chemically and thermally stable image is desired [2].

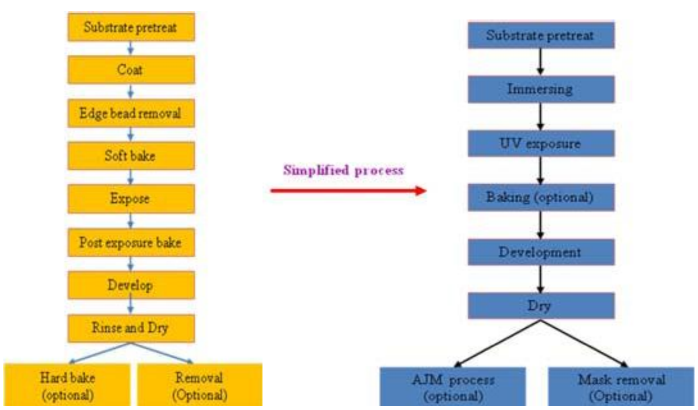

Fig. 12 Old and new proposed overflowing fabrication steps

Since the spin coating for the 3D non-planar wafer is very much challenging and sometimes unfeasible depending on the wafer shape, in this research, the issue of spinning has been consciously analyzed and worked-out through dilute of the concentrated SU-8 2100 with another chemical product known as Cyclopentanone (C_5H_8O). Table III and Table IV shows some of the dilute factor used in this work.

The scanning process consisted of overflowing fabrication steps and each step was believed to affect the mask hardness as well as surface quality. From many literature reports, the imperative steps as well as the effect of each step is still not well-known. This is due to the lack of adequate knowledge in the mask fabrication mechanism. Some of the recommended fabrication steps are awkward and sometimes not viable; therefore, through the author's intuition the most vital fabrication steps have been proposed as shown in the Fig. 12.

IV. EXPERIMENTAL RESULTS AND TAGUCHI ANALYSIS

The design of experiment (DOE) using Taguchi approach can economically satisfy the needs of process design optimization and significantly reduce the time required for experimental investigations [8].

In this study, the Taguchi approach has been used to set the values of the controlling variables for fabrication of the suitable mask in term of hardness and surface quality required by micro-AJM process. A number of experiments have been carried out to fabricate SU-8 photo-resist mask onto 3D curved wafer as shown in the Fig.13.

A. Analysis of the SU-8 photo-resist mask properties

Initially, the main function of the mask structure during micro-AJM process is to selectively block the abrasive jet at the portion of the surface that is not supposed to be machined [6]. Preliminary experimental results in this research work

Fig. 13 Fabricated SU-8 photoresist mask (Smallest channel/hole is 500μm)

demonstrated that micro-AJM action is strongly affected by the mask hardness and surface quality. Following that, the SU-8 mask hardness and surface quality have been measured by using micro-Vickers and Non-contact surface roughness instruments respectively. The design of experiment setup through Taguchi approach as well as measured results for both mask hardness and surface roughness are shown in the Table III and Table IV respectively.

TABLE III
TAGUCHI APPROACH (L9) FOR MASK HARDNESS

Dilute factor	UV Power (μW)	Scanning speed (μm/s)	Area factor	**Mask Hardness (HV)**
1	19	5.0	3.2	**6.62**
1	22	7.5	4.3	**6.77**
1	25	10	5.4	**7.50**
2	19	7.5	5.4	**7.71**
2	22	10	3.2	**6.63**
2	25	5	4.3	**6.36**
3	19	10	4.3	**7.70**
3	22	5	5.4	**2.39**
3	25	7.5	3.2	**5.77**

TABLE IV
TAGUCHI APPROACH (L16) FOR SURFACE HARDNESS

Dilute factor	UV Power (μW)	Scan speed (μm/s)	Area Factor	Hard baking (min)	**Surface roughness (Ra_ μm)**
1	16	5	3.2	10	**0.27**
1	19	7	3.6	15	**1.01**
1	22	9	4	20	**2.17**
1	25	11	4.4	25	**0.55**
1.5	16	7	4	25	**0.498**
1.5	19	5	4.4	20	**0.25**
1.5	22	11	3.2	15	**0.78**
1.5	25	9	3.6	10	**0.9**
2	16	9	4.4	15	**1.05**
2	19	11	4	10	**1.38**
2	22	5	3.6	25	**0.57**
2	25	7	3.2	20	**1.23**
2.5	16	11	3.6	20	**0.82**
2.5	19	9	3.2	25	**1.87**
2.5	22	7	4.4	10	**2.67**
2.5	25	5	4	15	**0.174**

Through Taguchi analysis, the scanning speed and UV exposure power have been ranked as the most effective factors to the mask hardness as well as surface quality as shown in the main effects plot for the Means (Fig 13 and Fig.15) as well as main effects plots for Signal to Noise ratios (Fig.14 and Fig.16).

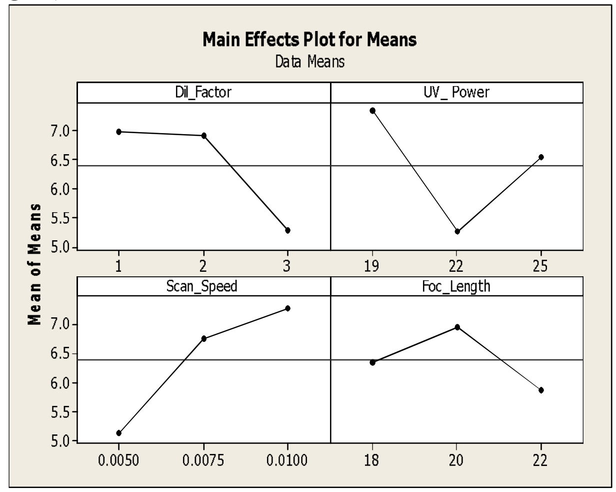

Fig.13 Plot for Means (Mask hardness)

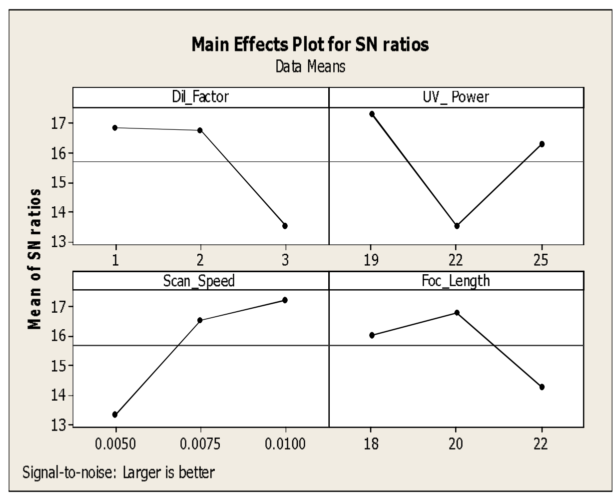

Fig.14 Plot for SN ratios (Mask hardness)

In the analysis of the mask hardness as well as the surface roughness, the larger-is-better methodology was selected for the machining variables against process response because this characteristic involves continuously measurable results. The ranks of the controlling parameters are plotted in Fig. 17 and Fig.18.

B. Preliminarily results for validation of the SU-8 mask

In this research, the effectiveness of the mask hardness as well as the surface quality has been validated through micro-AJM process as shown in the Fig.19. Nevertheless, the preliminarily micro-AJM results are promising, there are still some challenges to sort out with awareness such as scaling down to micro size the carved shape onto 3D non-planar wafer, improving the straightness of the carved mathematical

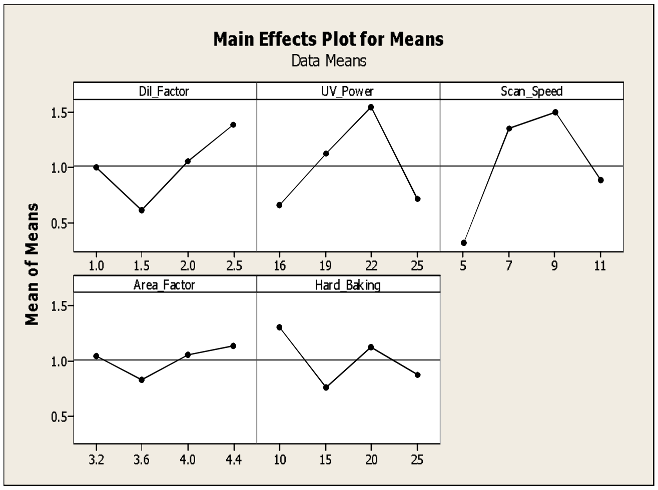

Fig.15 Plot for Means (Surface roughness)

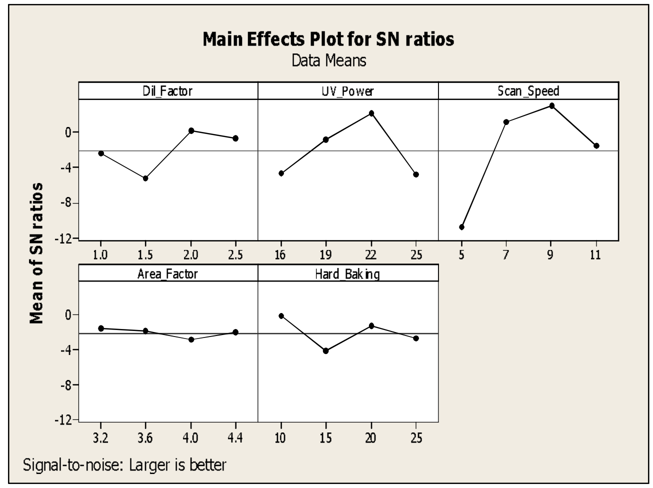

Fig.16 Plot for SN ratios (Surface roughness)

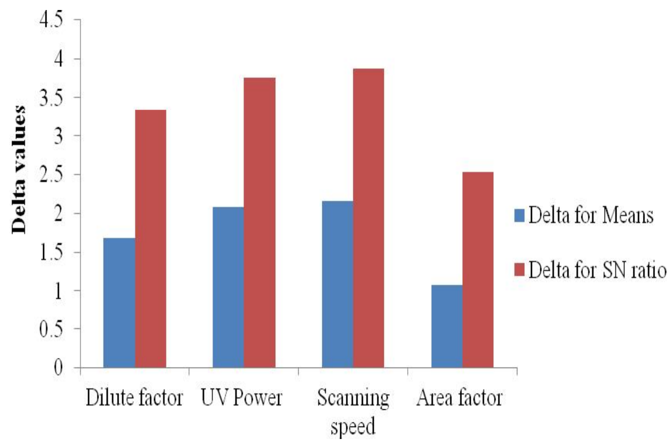

Fig.17 Hardness parameter's ranks

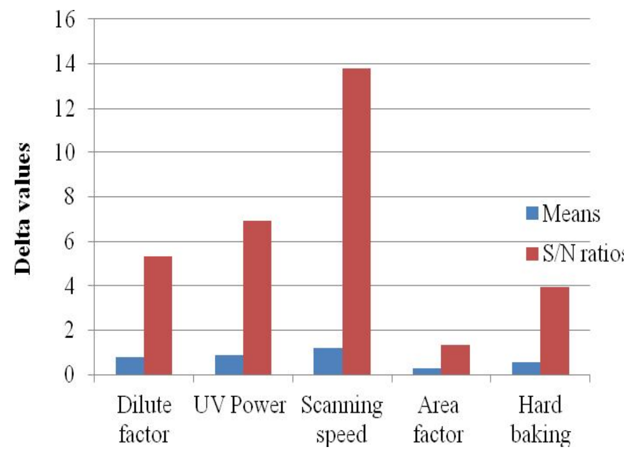

Fig.18 Surface roughness parameter's ranks

shape (rectangular/circular), optimizing all the controlling parameters that strongly affect micro-AJM process as well as expending range of application materials.

Fig.19 Carved shapes onto 3D non-planar wafer

V. CONCLUSION

In the previous work, an algorithm modeling photo-resist mask that required for micro-AJM process has been developed. It was expected to be subjected the developed algorithm to testing and verification through fabrication experiments. This paper reported the current results for verification of the algorithm. By using a proposed simplified fabrication process, various sizes of the SU-8 photo-resist masks have been effectively fabricated. Furthermore, through Taguchi analysis, the scanning speed and UV power have been ranked as the most effective factors to the mask hardness as well as the surface quality. In this research, the effectiveness of the mask hardness as well as the surface quality have been validated through micro-AJM process and successfully various shapes have been carved onto 3D non-planar glass (BK57) as well as tungsten carbide (WC). Nevertheless, the preliminarily micro-AJM results are very much promising, there are still some challenges to sort out with awareness; such as scaling down to micro size and improving the straightness of the carved mathematical (rectangular/circular) shapes, optimization of the controlling parameters that strongly affect micro-AJM process as well as expending range of application materials. In the future work, the authors are planning to cautiously fix all the above specified issues.

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