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A Feasibility Study on the Micro Electro-Discharge Machining Process for Photomask Fabrication

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A feasibility study of micro electro-discharge machining (micro-EDM) technology has been conducted for its possible contribution in the photomask industry. A series of experimental runs was performed on three specimens using a micro-EDM system with built-in wire electro-discharge grinding. Different thicknesses of chromium films were coated on borosilicate glass substrates. Unwanted chromium metal was machined through to the transparent glass substrate, leaving behind the desired pattern. In this study, lines were machined at different voltages, using electrodes of 20 μm in diameter, and no significant wear of electrodes was observed.

The machined regions on the specimens were quantified in terms of linewidth deviation and light transmission. The experimental results showed that the linewidth deviations for all three specimens are below the 10% cut-off threshold. The best average light transmission obtained from this experiment was 75.8% at 90 V. The results gathered so far, suggests that the application of micro-EDM to produce a photomask is an acceptable process.

Keywords: Micro electro-discharge machining; Photomask; Rapid prototyping

1. Introduction

Micro electro-discharge machining (micro-EDM) has shown that it possesses the capability of machining a micro hole and a micro shaft as small as 5 μm in diameter, and also a variety of complex microstructures by minimising the discharging pulse energy to the 10^{-7} J level and by using a precise mechanism providing submicron accuracy. In special applications, surface roughness values better than 0.1 μm were reported [1]. Micro-EDM offers a flexible and cost-saving alternative for many applications that do not require ultra-high precision. This is of special importance in the case of rapid prototyping. Cost-effective methods based on pulse plasma vaporisation or electro-etching for fine line scribing have been reported [2]. With sufficiently thin surface films (or sufficiently high pulse energies) and an insulating substrate, the surface geometry is electrically self-limiting. This work investigates the feasibility of micro-EDM in photomask fabrication.

In the IC industry, finer and finer geometries are required, and batch processes are a prerequiste. However, with micromachining, batch fabrication is not always a prerequisite [3]. Although conventional mask fabrication techniques can create photomasks with very good pattern definition, with vertical sidewalls and small feature sizes for use in the IC industry, these techniques require complex processes and equipment, namely lithography, electron-beam and laser technologies.

Many microstructures and components such as micro sensors and actuators used in micro electromechanical system (MEMS) do not require the level of quality that these techniques can provide, permitting a lower resolution and, hence, a lower-cost mask. Furthermore, if a single set of patterns is needed quickly or some modifications or variations to a particular pattern are needed for concept development or prototyping, the conventional mask fabrication processes can be complicated and not cost-effective. Hence, if a simple, direct and inexpensive mask fabrication technique using micro-EDM could achieve results comparable to the conventional mask fabrication techniques for microstructures with dimensions of a few millimetres and minimum feature size down to 5 μm, a variety of uses for that electro-machining technology could be immediately envisaged. In past work, it has been shown that many applications of the LIGA process for creating high aspect ratio microstructures have minimum linewidths in the 5–10 μm range [4], thus, the LIGA process is within the operating range of micro-EDM technology. Some typical dimensions of microactuators employed in MEMS are summarised in Table 1. Table 2 gives details of photomasks.

In this paper, a feasibility study of the micro-EDM process was conducted as an alternative technique for producing photomasks for use in a MEMS environment. The effects and characteristics of machining thin conductive films coated on a non-conductive substrate using micro-EDM were examined.

A comparison of conventional mask fabrication and the proposed micro-EDM technique is made. Figure 1 shows the

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Table 1. Examples of microactuators [5].

Devicer	Size	Movement application	Support	Speed response	Force, torque	Material	Input
Electrostatic micromotor	60–120 μm (diameter)	Rotation	Sliding	500 r.p.m.	A few pNm	Poly-Si	60–400 V
Electrostatic micromotor	100 μm (diameter)	Rotation	Sliding	15000 r.p.m.	10 pNm	Poly-Si	50–300 V
Electrostatic resonator	5×100×100 μm^3	10 μm	Elastic	10–100 kHz	2 μN	Poly-Si	40 V_{dc} +10 V_{ac}
Electrostatic valve	100×350× 390 μm^3	On–off valve	Elastic	NA	110 mmHg	Metal, Si_3N_3	30 V
Ultrasonic micromotor	2mm (diameter)	Rotation	Vibration	100–300 r.p.m.	25 pNm	PZT	4 V (100 kHz)

Table 2. Attributes and requirements of photomasks used in the IC industry [3].

Attributes	Typical photomask
Transmission, $\%T$	≥ 50%
Absorber thickness	±1 μm
Field size	50 × 50 mm^2
Radiation resistance	1
Surface roughness	< 0.1 μm
Waviness	< ±1 μm
Dimensional stability	< 0.05 μm
Residual membrane stress	10^8 Pa
Linewidth deviation*	< 10%

*Requirement of linewidth deviation < 10% [6].

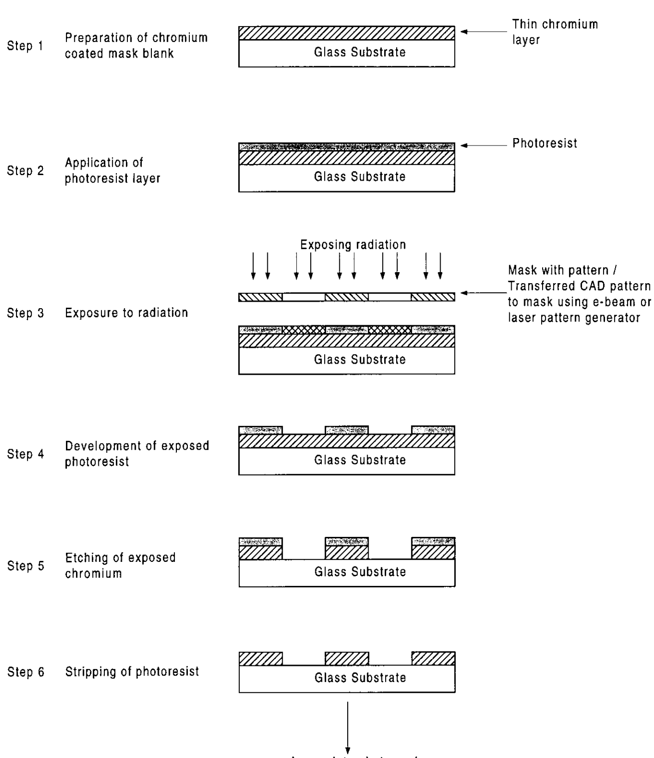

Fig. 1. Lithography using deep UV, electron beam or laser exposure.

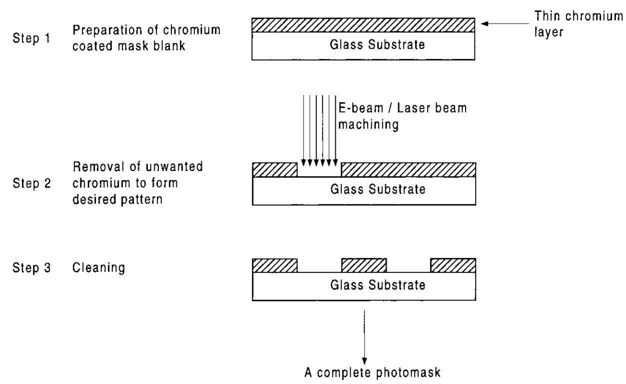

Fig. 2. Direct writing technology.

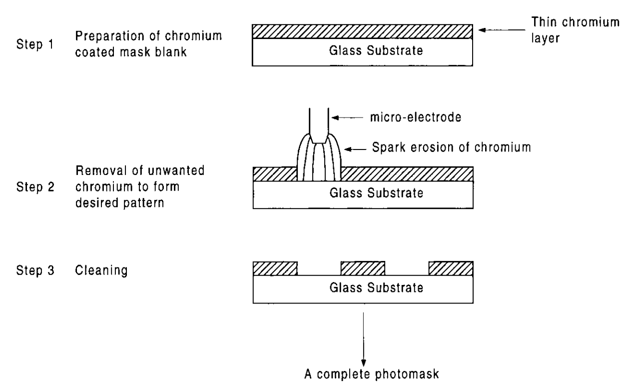

Fig. 3. Proposed micro-EDM technique.

lithography method using either a deep UV, electron beam or laser exposure.

This method has the following advantages:

It has the ability to produce good pattern definition, vertical sidewalls, and small feature sizes.
It yields excellent fine linewidths (well under 1 μm with e-beam technology, and 3 μm with laser technology) [2].

The disadvantages are:

It requires complex processes and equipment.
It is time consuming.

It is expensive, with a very high capital cost [7].

E-beam and laser direct write technologies, as shown in Fig. 2, have the ability to produce excellent small features and can remove material directly. However, they suffer from a small heat-affected zone [3] and high capital cost [7].

The proposed micro-EDM technique (see Fig. 3) has the following advantages.

It has the ability to produce complex features.

There is simple and direct material removal.

It has the ability to reconstuct and repair opaque defects in photomasks.

Machining can be performed without the problems of tool wear, since there is no contact between the electrode and the workpiece.

It is low cost, and relatively cheaper when compared to e-beam/laser.

However, the limitations are:

The smallest feature sizes which can be produced are not comparable to those produced by conventional techniques, since the smallest feature size produced so far is 5 μm.

Like other thermal removing techniques, micro-EDM machining leaves behind a small heat-affected zone on the workpiece.

There are interior corner radii which is an inherent characteristic of micro-EDM machining features.

2. Experimental Work

Figure 4 shows the micro-EDM system, MG-ED72W used for the feasibility study of machining fine lines on thin chromium coated glass substrate, and its application in photomask fabrication.

In order to measure the effect of spark erosion of chromium on the borosilicate glass surface, a preliminary experiment was performed to quantify the transmission of light through the machined chromium regions (transparency). This experiment was performed using the set-up shown in Fig. 5, to make transmission measurements. This simple set-up uses a 632 nm helium-neon laser as a light source, with a focused spot size of 20 μm.

The 632 nm laser beam from a helium–neon source was first directed into a prism, which bent the beam at a 90° angle. The emerging beam was next directed into an aperture for sizing. It was then passed through a collimating lens and subsequently through a focusing lens, the focused beam was then ready for use. Each scribed line to be measured was placed at the focal point of the laser beam. Two readings from a power meter were taken from positions 1 and 2 separately. At

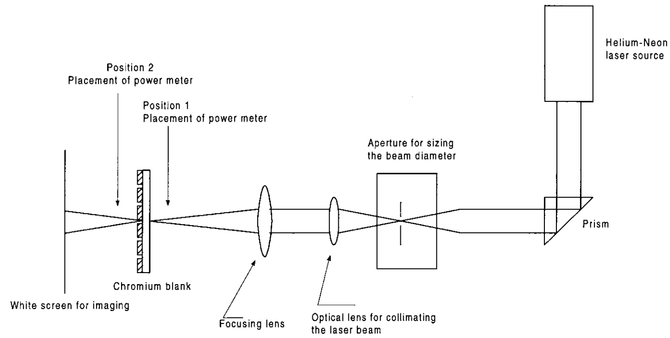

Fig. 5. A laser assisted light transmission measurement system.

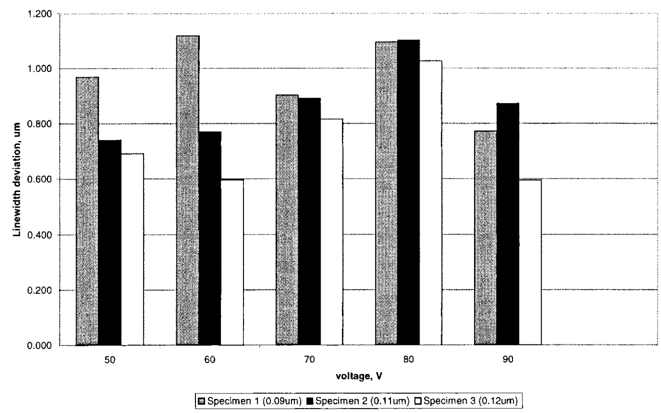

Fig. 6. Linewidth deviation vs. voltage for various specimens.

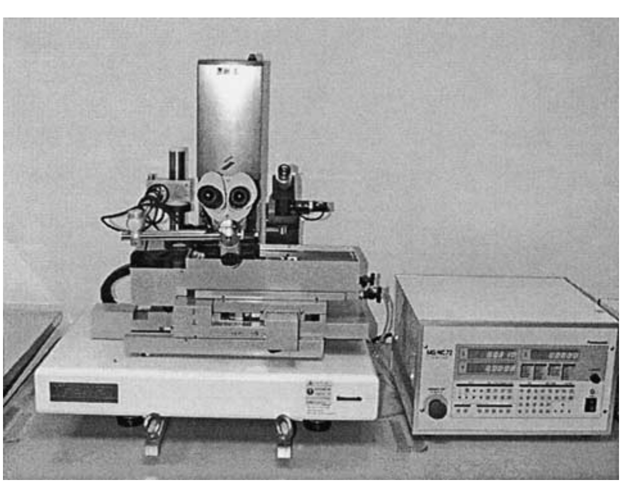

Fig. 4. The micro-EDM system.

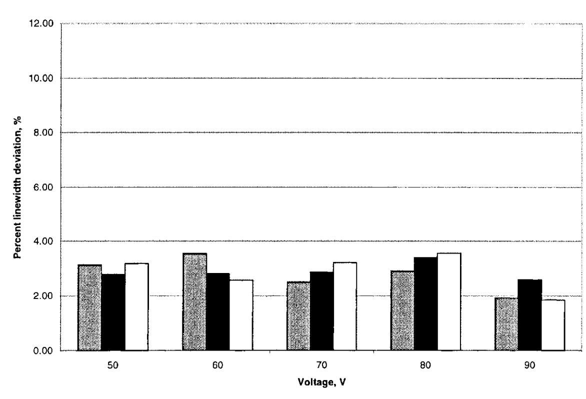

Fig. 7. Percentage linewidth deviation vs. voltage for various specimens.

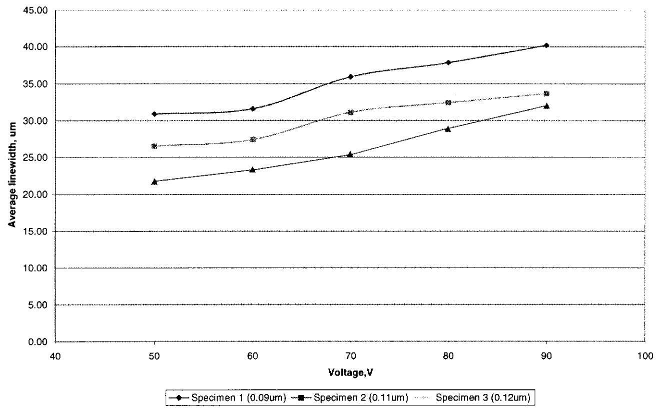

Fig. 8. Average linewidth vs. voltage for various specimens.

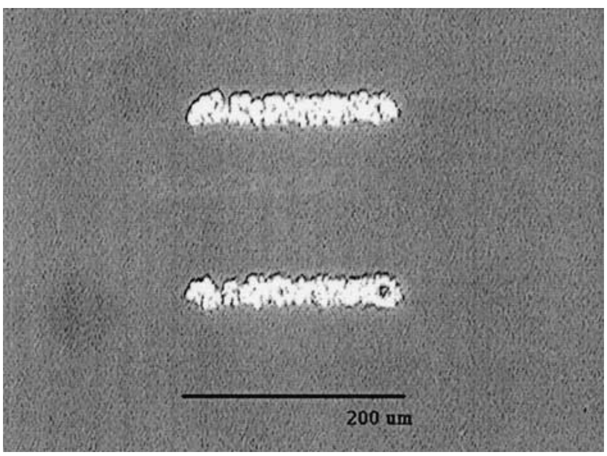

Fig. 9. Lines machined by micro-EDM.

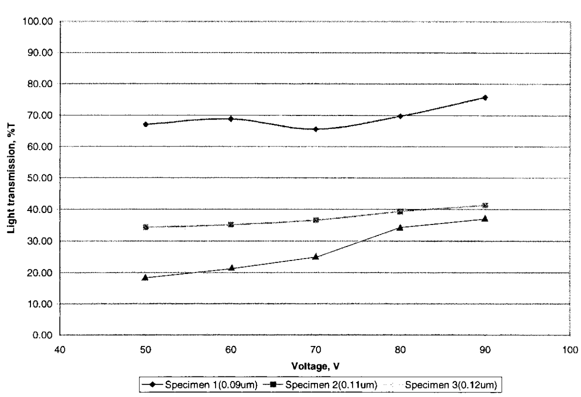

Fig. 10. Light transmission vs. voltage for various specimens.

position 1, the power meter registered the maximum intensity of the laser beam before passing through the etched chromium region, whereas at position 2, the power meter registered the amount of light that passed through the etched chromium region.

$$\text{Transmission, } \%\ T = \frac{O}{I} \times 100\%$$

where I = voltage before beam enters the etched chromium area

O = voltage after beam enters the etched chromium area

The power meter used consists of a probe, a multimeter (Fluke 79 series II multimeter) and a converter (Thor Labs model 520 mm converter).

The materials used in the experiment include:

1. ϕ 123 μm tungsten carbide electrode wires.
2. Chromium blanks:

   Thickness of ϕ 2" borosilicate glass wafer : 1.1 mm ± 0.1 mm

   Roughness of borosilicate glass wafer: ≤ ± 25 Å

   Thickness of chromium film: 900Å ~ 1200Å ± 100Å

An electrode of 20 μm diameter was first fabricated using the built-in wire electro-discharge grinding unit. The electrode was then made to translate linearly with respect to the work table to scribe lines on chromium blanks. The horizontal translation of the electrode during the scribing process of each line was 200 μm. A set of five lines 20 μm apart was scribed. Three chromium blanks with different thickness of chromium film were used:

Sample A ~ 900Å thick of chromium film
Sample B ~ 1100Å thick of chromium film
Sample C ~ 1200Å thick of chromium film

All three samples were treated with different voltages in the range of 50~ 90 V, while the condenser parameter was held constant at Con 4 (10 pF). After scribing, the samples were cleaned using ultrasonics for 45 min and measurements were then taken.

The reason for varying the voltage rather than the condenser parameter is that machining thin chromium film is very different from machining conventional conducting materials, as the former is very much less conductive and a low voltage results in an unstable pulse discharge. Hence, in order to determine the stable operating voltage range for machining this type of material configuration, varying of the voltage is essential. Once the operating voltage range is determined, the condenser parameter can then be used to control the discharge pulse energy, primarily for optimisation purposes.

Table 3. Transmissivity comparison between electron beam lithography technique and the proposed MEDM technique.

Light transmission, %T	
Conventional technique (E-beam)	Micro-EDM technique
98% (QZ/Cr)	75.8% at 90 V specimen 1 (LE-30/Cr) 41.3% at 90 V specimen 2 (LE-30/Cr) 36.9% at 90 V specimen 3 (LE-30/Cr)

3. Results and Discussion

3.1 Linewidth Measurements

Observation of the chromium blank with the OMIS II optical system provides a method for evaluating linewidths. Obtaining measurements from the chromium blank was straightforward. Each line was optically measured at 10 points along the length. It can be observed that the average linewidths obtained from the three specimens fall in the range of 21 ~ 41 μm. These linewidths are greater than the size of the electrode used to machine them. This observation is expected and can be explained by the fact that it is the electric conditions chosen which determine the spatial resolution of the process, rather than the electrode geometry. As a result, these linewidths are appreciably larger than the diameter of the electrode.

From Fig. 6 for Specimen 1, the standard deviations for the different voltages are in the range 0.77–1.12 μm. For Specimen 2, the standard deviations are in the range 0.74–1.1 μm. Lastly, for Specimen 3, the standard deviations are in the range 0.59–1.1 μm. From Fig. 7, it can be observed that, the linewidth deviations for all three specimens are below the 10% cut-off threshold, that is, anything above the 10% threshold will not be accepted. Thus, MEDM is capable of machining lines on chromium blanks with linewidth deviations below 10%, which satisfied one of the requirements.

From Fig. 8, a direct relationship between the voltage parameter and the linewidth parameter can be observed, that is, as the voltage increases, the linewidth also increases, and vice versa. Therefore, similar to the case of machining conductive materials by micro-EDM, it is the pulse energy that determines the amount of material removal, as in this case of machining very thin chromium film coated on non-conductive substrate.

However, during this work, owing to the very thin chromium film coated on the non-conductive borosilicate substrate, the chromium blank as a whole was not very conductive and machining was difficult, resulting in the breaking of numerous electrodes. However, small pieces of copper foil were later placed between the chromium blank and the aluminum clamps to improve the conductivity. After the introduction of the copper foil, no electrodes were broken owing to the poor conductivity of the chromium blanks.

3.2 Light Transmission Measurements

A comparison of the transmissivity was made between a conventional photomask made by electron beam lithography and a photomask made by the proposed technique, which produced the data shown in Table 3. LE-30 and QZ represent low-expansion borosilicate and quartz substrates, respectively. Cr represents chromium film.

The regions machined by the proposed micro-EDM technique on all three specimens show a decrease in transmissivity. The best light transmission, $\%T$, was obtained from Specimen 1 with an average of 75.8% at 90 V. This observation of decrease in transmissivity might be due to the resolidified materials known as remelts being left on the surface. Figure 9 shows the linewidths produced. The existence of remelts can be observed and it is seen that these lines have corner radii similar to the radius of the electrode.

From Fig. 10, it can be observed that, in general, there is an increase in transmissivity for all the three specimens as the voltage increases. However, only Specimen 1 gives a better set of transmission data ranging from 65.5%–75.8% as compared to the other two specimens.

Hence it is found that machining relatively thinner chromium-plated blanks generally gives better transmissivity. This demonstrates the sensitivity of the pulse energy in the removal of the chromium film. However, it should be noted that machining at high voltages would generally result in producing larger linewidths. In addition, at a higher working voltage, the accuracy is lower owing to a larger spark-gap width, but is independent of the spatial resolution.

4. Conclusion

In this project, a feasibility study on using micro-EDM for photomask fabrication was conducted. The results obtained are comparable to those of a typical photomask process in terms of linewidth deviation (10% threshold) and light transmission ($\%T > 50\%$). In contrast to the relatively expensive fine-line lithographic technologies and direct write techniques developed for photomask fabrication, micro-EDM technology has far lower capital and operating costs. If feature sizes can be in the range of several μm such as required for microactuators and micromotors, the process can be advantageous. In addition, the process may well be cost effective and acceptable if it can produce photomasks for use in prototyping and concept development.

It should be noted that the micro-EDM parameters used have yet to be optimised. Further work is also required to investigate the effect of the HAZ on both the chromium features and the corresponding exposed pattern in the photoresist.

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