X-ray Mask with SiC Membrane for LIGA Process

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Summary

In order to develop a practical LIGA process, a high contrast X-ray mask with a SiC membrane was produced. The X-ray mask was composed of a 3 µm thick Au as an absorber, a 2 µm thick SiC as a membrane of dimensions 10 mm x 30 mm and a 2 mm thick Si of dimensions 3 inch as a frame. A feature of the X-ray mask is the application of a SiC membrane, which has high permeability to X-rays, high thermal conductivity and moderate tensile stress. As a result, Ni microstructures with a maximum aspect ratio of 100, corresponding to 2 µm width and 200 µm height, were fabricated by the LIGA process.

Keywords: X-ray mask, SiC membrane, LIGA process, high aspect ratio microstructure

1 INTRODUCTION

In order to fabricate high aspect ratio microstructures, LIGA (German acronym for Lithographie, Galvanoformung, Abformung) process [1-3] using synchrotron radiation (SR) is one of the most promising techniques. The LIGA process is a technique which is a combination of deep X-ray lithography, electroforming, and molding. In the LIGA process, X-ray lithography can fabricate higher aspect ratio microstructures than photo lithography using ultraviolet (UV) rays, and various materials such as metals, plastic and ceramics can be applied. The LIGA process in combination with surface micromachining is expected to produce microactuators with high power, microsensors with high sensitivity and micro electro mechanical systems (MEMS) with high performance.

X-ray lithography in the LIGA process needs an X-ray mask with high resolution in order to fabricate microstructures which have dimensional accuracy in the submicron range. X-ray lithography also needs a mask with high contrast because long time exposure is required for the fabrication of resist microstructures more than 1 mm thick.

In this paper, we present the structure and performance of an X-ray mask for the practical LIGA process using a SiC membrane which has high permeability to X-rays, high thermal conductivity and moderate tensile stress [4]. We also report on fabrication of Ni microstructures by the LIGA process applying the X-ray mask.

2 BEAMLINE FOR LIGA

X-ray lithography in the LIGA process was carried out at a beamline for LIGA of AURORA at the SR center of Ritsumeikan University [5]. Figure 1 shows spectra of AURORA and the beamline for LIGA composed of a 200 µm thick layer of Be and a 50 µm thick layer of Kapton as band pass filters. Critical wavelength is 4 Å. A PMMA (Polymethylmethacrylate) resist for the X-ray lithography was used. The investigations described hereafter were all carried out in the above conditions.

Fig.1 Spectra of AURORA and the beamline for LIGA.
3 MASK DESIGN

3.1 Contrast

As shown in Fig. 2, an X-ray mask for the LIGA process is composed of an X-ray absorber, a membrane and a frame. Table 1. shows important requirements for an X-ray mask for the LIGA process [1-4]. Au was used as an X-ray absorber for the following reasons: 1) Au is quite opaque to X-rays because of its high atomic number; 2) An Au X-ray absorber can be made by electroforming. SiC was used as a membrane, because of its high permeability to X-rays, high thermal conductivity, high Young's modulus, moderate tensile stress which can support an absorber, and optical transparency which is suitable for multi-layer alignment. Si was used as a frame because it is easy to form.

It is desirable that the X-ray absorber be formed into the minimum thickness required for the fabrication of PMMA resist by X-ray lithography, because the accuracy of the photoresist pattern which is used as a mold for electroforming of the X-ray absorber becomes lower with increasing thickness of the photo resist. To manufacture high aspect ratio MEMS with high performance [5,6], we wanted to achieve the maximum lithography depth. From the above mentioned consideration, we paid attention to one parameter to decide on the thickness of the X-ray absorber.

As shown in Fig. 3, $E_M (J/\text{mA s mm}^2)$ is the energy of the X-rays transmitted through the membrane and $E_A (J/\text{mA s mm}^2)$ is the energy of the X-rays transmitted through the absorber. The ratio of $E_M$ to $E_A$ is the contrast $C$ for the transmitted energy of the X-rays:

$$C = \frac{E_M}{E_A}$$

In order to fabricate microstructures with a high aspect ratio, a large value of $C$ is required. The membrane used throughout this work was 2 μm thick SiC, so that $E_M$ was constant, while $E_A$ depends on the thickness of the X-ray absorber. The required thickness of the X-ray absorber is obtained from the value of $C$. In the next section, we describe the calculation of absorbed energy of the PMMA.
3.2 Absorbed energy of PMMA

As shown in Fig. 3, to obtain the required value of \( C \), we investigated the absorbed energy quantity of the X-rays between the surface and the bottom of the PMMA resist. At the bottom, the PMMA resist must absorb more than the minimum energy quantity \( P_{\text{min}} \) (\( \text{J/cm}^3 \)) which is required for development. On the other hand, on the surface of the PMMA resist under the absorber of the mask, the PMMA resist must absorb less than the threshold energy quantity \( P_{\text{th}} \) (\( \text{J/cm}^3 \)) to which would produce changes in quality during the development process. \( P_{\text{min}} \) and \( P_{\text{th}} \) were obtained by the following procedure, appropriate for the wavelength range for X-ray lithography in the LIGA process using AURORA, which is mainly less than 7.3 Å [5]. The beam spectrum of AURORA is converted into the exposure energy spectrum per unit time \( E_{\text{ex}} \) (\( \text{J} / \text{mA s mm}^2 \)). The exposure energy spectrum at the terminal of the beamline for LIGA \( E_{\text{ex}} \) (\( \text{J} / \text{mA s mm}^2 \)) is

\[
E_{\text{ex}} = E_{\text{x}} \times \exp \left( -\left( x_{\text{Be}} \mu_{\text{Be}} + x_{\text{Kap}} \mu_{\text{Kap}} \right) \right), \quad (2)
\]

where \( x_{\text{Be}} \) (\( \text{µm} \)) and \( x_{\text{Kap}} \) (\( \text{µm} \)) are the thickness of Be and Kapton, which are 200 µm and 50 µm. \( \mu_{\text{Be}} \) (\( \text{µm}^{-1} \)) and \( \mu_{\text{Kap}} \) (\( \text{µm}^{-1} \)) are the absorption coefficient of Be and Kapton [7], and are given roughly by

\[
\mu_{\text{Be}} = 4.25 \times 10^{-5} \lambda^{1.0}, \quad (3)
\]

\[
\mu_{\text{Kap}} = 2.00 \times 10^{-5} \lambda^{1.0}, \quad (4)
\]

where \( \lambda \) is the wavelength in Angstroms. The transmitted energies of the X-rays through the membrane \( E_{\text{m}} \) and through the absorber \( E_{\text{a}} \) can be expressed as

\[
E_{\text{m}} = E_{\text{ex}} \times \exp \left( -x_{\text{SiC}} \mu_{\text{SiC}} \right), \quad (5)
\]

\[
E_{\text{a}} = E_{\text{ex}} \times \exp \left( -x_{\text{Au}} \mu_{\text{Au}} \right), \quad (6)
\]

where \( x_{\text{SiC}} \) (\( \text{µm} \)) and \( x_{\text{Au}} \) (\( \text{µm} \)) are the thicknesses of SiC and Au. \( \mu_{\text{SiC}} \) (\( \text{µm}^{-1} \)) and \( \mu_{\text{Au}} \) (\( \text{µm}^{-1} \)) are the absorption coefficients of SiC and Au [7], and are given roughly by

\[
\mu_{\text{SiC}} = \begin{cases} 3.90 \times 10^{-7} \lambda^{4.0} & (1.00 \sim 6.64 \text{Å}) \\ 3.57 \times 10^{-3} \lambda^{5.0} & (6.64 \sim 10.0 \text{Å}) \end{cases} \quad (7)
\]

\[
\mu_{\text{Au}} = \begin{cases} 130 \times 10^{-7} \lambda^{2.0} & (1.00 \sim 5.58 \text{Å}) \\ 320 \times 10^{-7} \lambda^{0.7} & (5.58 \sim 10.0 \text{Å}) \end{cases} \quad (8)
\]

When the PMMA resist is exposed, the energy spectrum of the X-rays transmitted through the membrane
and through the absorber, \( E_{\text{abs}} \) (J / mA s mm\(^2\)) and \( E_{\text{ta}} \) (J / mA s mm\(^2\)) are respectively

\[
E_{\text{abs}} = E_{\lambda} \times \exp \left( -x_{\lambda} \mu_{\lambda} \right),
\]

\( E_{\text{ta}} = E_{\lambda} \times \exp \left( -x_{\lambda} \mu_{\lambda} \right) \),

where \( x_{\lambda} \) (\( \mu \)) is the depth in the PMMA resist and \( \mu_{\lambda} \) (\( \mu \)) is the absorption coefficient of PMMA [7], which is roughly given by

\[
\mu_{\lambda} = 2.10 \times 10^{-4} \lambda^{1.4}.
\]

The energy quantity spectrum absorbed in PMMA behind the membrane \( E_{\text{abs}} \) (J / mA s mm\(^2\)) is given by

\[
E_{\text{abs}} = \frac{dE_{\text{ta}}}{dx_{\lambda}},
\]

where \( D \) is the exposure dose in Ampere-minutes given by the product of exposure time and beam current of the SR light source, for example, the exposure dose is 6 Amin when a sample is exposed for 30 minute by X-rays from the SR light source at a beam current of 0.2 A. Similarly the energy quantity spectrum absorbed in PMMA behind the absorber, \( E_{\text{ta}} \) (J / mA s mm\(^2\)), is given by

\[
E_{\text{ta}} = \frac{dE_{\text{ta}}}{dx_{\lambda}}.
\]

\( E_{\text{ta}} \) and \( E_{\text{abs}} \) are functions of \( \lambda \), so the energy quantities absorbed in the PMMA behind the membrane \( E_{\text{abs}} \) (J / cm\(^3\)) and the absorber \( E_{\text{ta}} \) (J / cm\(^3\)) are obtained by integration of \( E_{\text{ta}} \) and \( E_{\text{abs}} \) in the range of wavelengths less than 7.3\( \lambda \). \( C \) is given by fitting \( P_{\text{abs}} \) at the required lithography depth to

\[
P_{\text{abs}} = 1 \text{ kJ/cm}^3\text{ found from previous work of AURORA [5,6] and } P_{\text{ta}} \text{ at the surface of the PMMA resist to } P_{\text{ta}} = 0.1 \text{ kJ/cm}^3 [1,2].

3.3 Mask performance

Figure 4 shows the required versus a given lithography depth. This result shows that \( C \) is required to be about 15 for X-ray lithography of a 200 \( \mu \)m thick PMMA resist. The required thickness of the Au X-ray absorber is then obtained from \( C \) by Eq. (1). Figure 5 shows the required Au thickness for a given lithography depth. It is found that an Au X-ray absorber of above 2 \( \mu \)m thickness is required to fabricate a 200 \( \mu \)m thick PMMA resist. Figure 6 shows the distribution of transmitted energy along the beamline, X-ray mask which is composed of 3 \( \mu \)m thick Au and 2 \( \mu \)m thick SiC and PMMA resist at the beamline for LIGA of the AURORA. It was found that \( C \) was about 65 at the surface of the PMMA resist.

The thickness of the frame was 2 mm which was enough to prevent the frame from fracture during its fabrication and handling in the LIGA process.

4 X-RAY MASK FABRICATION

The fabricated X-ray mask used in manufacturing of semiconductors process for the LIGA process was composed of 3 \( \mu \)m thick Au as an absorber, 2 \( \mu \)m thick SiC as a membrane and 2 mm thick Si as a frame [8]. Figure 7 shows the process used for the fabrication of the X-ray mask. First, using a 2 mm thick Si of dimensions 3 inch substrate with 2 \( \mu \)m thick SiC formed by CVD on both sides, the reverse side windows were etched by RIE for anisotropic etching, then 20 nm thick Cr and 80 nm thick Au layers were formed in the upper side by vacuum evaporation to act as a seed layer for electroforming (a). Mask patterns were formed on the Si substrate by UV lithography, using a 3.2 \( \mu \)m thick spin-coated photo resist (AZP4620) (b). A 3 \( \mu \)m thick Au absorber was formed in the photo resist patterns by electroforming (c). The photo resist and seed layer were removed by \( O_2 \) ashing (d). As the final process, the mask frame was formed by anisotropic etching from the reverse side by soaking the structure in KOH (33%, 120\( ^\circ \mathrm{C} \)) (e). Specifications of the fabricated mask are as follows: the window size of the membrane is 10 mm x 30 mm. 50% of the mem-
brane is covered with absorber patterns. The tensile stress of the membrane is 240 MPa. The X-ray mask with a minimum line width of about 2 μm for the LIGA process was fabricated.

5 FABRICATION OF MICROSTRUCTURES

Microstructures of PMMA and Ni were fabricated by the LIGA process using the X-ray mask just described. A 200 μm thick PMMA sheet was glued by MMA resin with PMMA at 35 °C on a Si substrate with a spattered 0.1 μm thick Ti layer as a seed layer for electroforming. The X-ray mask was set in front of the PMMA resist with a gap of several hundred μm. The PMMA resist was exposed to 1 Am per unit length (1 mm) using the AURORA. PMMA microstructures were developed with a GG developer at 37 °C. Figure 8 shows SEM photograph of the PMMA microstructures. The diameter and line width of the smallest structures are 10 μm and 2 μm. It has been reported that 200 μm high PMMA structures were fabricated by exposure to 1 - 1.5 Am per unit length using a membrane-free mask [9]. In this experiment, 200 μm high PMMA structures could be fabricated under the same conditions using X-ray mask with SiC membrane. This result confirm that due to its high permeability SiC is a suitable material for an X-ray mask already discussed in great detail in 3.2. Using these PMMA microstructures as molds, Ni was electroformed using an electrolyte containing 350 g/l of nickel sulfamate and 30 g/l of boric acid at 37 °C. The pH and current density were 4.0 and 0.2 A/dm². PMMA molds on the substrate were removed by using GG-developer after a second X-ray exposure without a mask. Figure 9 and Fig. 10 show SEM photographs of the Ni microstructures. It has been reported that PMMA microstructures with aspect ratios of 80-100 have been fabricated by LIGA process [10]. In this experiment, Ni microstructures with a maximum aspect ratio of 100, corresponding to 2 μm width and 200 μm height, were fabricated.

6 CONCLUSION

An X-ray mask with a SiC membrane for the LIGA process was designed. The X-ray mask was composed of 3 μm thick Au as an absorber, 2 μm thick SiC as a membrane of dimensions 10 mm x 30 mm and 2 mm thick Si of dimensions 3 inch as a frame.
The combination of the absorber of 3 µm thick Au and membrane of 2 µm thick SiC gave a contrast of about 65 which was enough for the X-ray lithography of a 200 µm thick PMMA resist in the LIGA process using the energy spectrum produces by AURORA. An X-ray mask with a minimum line width of about 2 µm was fabricated. Using this X-ray mask, the LIGA process was carried out. Ni microstructures with a maximum aspect ratio of 100, corresponding to 2 µm width and 200 µm height, were fabricated by electroforming using PMMA molds.

These results are expected to be applicable to manufacturing MEMS with high performance.

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SiC薄膜を用いたLIGA用マスク

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