Paper

A Study on the Sub-Micron LIGA Process

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Summary

Microstructures with sub-micron widths and gaps (lines and spaces) can be applied to practical and high performance MEMS devices. In the sub-micron LIGA process, one of the most crucial considerations is the fabrication of an X-ray mask with thick X-ray absorbers having sub-micron width. An X-ray mask, which is composed of 1 μm-thick Au with a 0.6 μm line width and a 0.2 μm space as absorbers, 2 μm-thick SiC with 240 MPa of tensile stress as a membrane and 625 μm-thick Si as a frame, was fabricated. As a result of the sub-micron LIGA process, a sub-micron PMMA structure with a maximum aspect ratio of 85, corresponding to 0.2 μm minimum width, 6 μm length and 17 μm height, and sub-micron Ni structures with a maximum aspect ratio of 75, corresponding to 0.2 μm minimum width and 15 μm height, were fabricated.

Keywords: *sub-micron LIGA process, sub-micron structures, high aspect ratio, deep X-ray lithography and X-ray mask*

1 INTRODUCTION

With the advance, precision and complication of industrial systems, micromachining is attracting attention as a fabrication technology of micro devices with intelligence and high performance, because the micro devices can be applied to various fields, such as the mechanical, medical, optical, biological and so on. Especially, in order to fabricate a mechanical system with anisotropic rigidity, fabrication technologies of microstructures with a high aspect ratio have been researched [1, 2, 3].

A typical fabrication technology for these microstructures with a high aspect ratio is the LIGA process using deep X-ray lithography, electroforming and molding [4, 5]. The LIGA process can fabricate microstructures with a high aspect ratio of more than 100, corresponding to less than several microns in width and more than several hundred microns in height. The microstructures fabricated by the LIGA process can obtain a minimum resolution of sub-microns and precise surface roughness of several tens of nano-meters. Therefore, the microstructures are expected to be applied to micro devices with high precise accuracy, such as microparts, microsensors, microactuators, and so on. In particular, there are great expectations in applying microstructures for optical devices in the rapidly progressing optronics field, as these optical devices require high accuracy structures of nano-meter order, which are difficult to obtain using conventional mechanical processes [6].

In this paper, we present the fabrication of sub-micron structures with high aspect ratio using the sub-micron LIGA process.

2 X-RAY MASK

2.1 Design

In order to fabricate sub-micron structures, one of the most crucial considerations is the fabrication of an X-ray mask with thick X-ray absorbers for deep X-ray lithography. As shown in Fig. 1, an X-ray mask for deep X-ray lithography is composed of an X-ray absorber, a membrane and a frame. The X-ray absorbers are required to have a high absorption to X-rays, high accuracy of the pattern and so on. The membrane is required to have a high transparency to X-rays, moderate tensile stress, high Young's modulus and so on. The Frame is required to have high mechanical strength, be easy to handle and have a simple forming process. Based on these requirements, Au, SiC and Si were selected as the X-ray absorber, membrane and frame respectively. The thicknesses of SiC and Si were decided at 2 μm and 625 μm. The thickness of Au X-ray absorbers was decided in the following procedure [7].

One of important items for evaluation of an X-ray mask is contrast, C, which is defined as the ratio of transmitted energy of the X-rays through the membrane, E_M, to transmitted energy of the X-rays through the membrane and the absorber, E_A;

$$C = \frac{E_M}{E_A} \cdot \quad (1)$$

The thickness of the Au absorbers is decided by the trade-

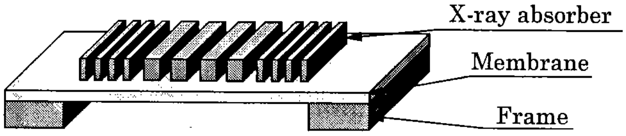


Fig. 1 Basic structure of an X-ray mask for deep X-ray lithography.

off of required lithography resolution and required X-ray mask contrast because high resolution of the lithography is obtained by thin absorbers, and high contrast of the X-ray mask for deep X-ray lithography is obtained by thick absorbers. In our experiments, deep X-ray lithography is carried out using the beamline for the LIGA process of the synchrotron radiation (SR) light source, "AURORA", at Ritsumeikan University [8]. The beamline, which is composed of a 200 μm thick layer of Be and a 50 μm thick layer of Kapton as band-pass filters, has a critical wavelength of 0.4 nm and wavelength range from 0.15 nm to 0.8 nm. In consideration of the critical wavelength and the wavelength range, required contrast, C, was calculated. Figure 2 shows the required contrast, C, versus a lithography depth using the X-ray mask with the combination of the Au X-ray absorber and the SiC membrane of 2 μm thickness. This result shows that C is required to be 5.5 for X-ray lithography of a 20 μm thick PMMA resist. Figure 3 shows the required Au thickness, which was obtained by conversion from C, versus a lithography depth using the X-ray mask. It was found that an Au X-ray absorber of 1 μm thickness is necessary for deep X-ray lithography of 20 μm thick PMMA.

2.2 Fabrication

The X-ray mask, which is composed of 1 μm thick Au as an X-ray absorber, 2 μm thick SiC as a membrane and 625 μm thick Si as a frame, was designed. The combination of the 1 μm thick Au absorber and the 2 μm thick SiC membrane of the X-ray mask gives a contrast of about 5.5 which is required for deep X-ray lithography of a 20 μm thick PMMA resist using the energy spectrum produced by AURORA.

Figure 4 shows a procedure for a fabrication process of an X-ray mask with Au absorbers having sub-micron widths and gaps. A membrane was formed by KOH etching after SiC etching on the reverse side by reactive ion etching (RIE) (a). By vacuum evaporation , a metal seed layer (Ni/Cr) for Au electroforming was formed on the upper side (b). Sub-micron structures of resist for electron beam (EB) lithography as molds were fabricated by lithography using EB direct writing (c). After Au electroforming (d), the EB resist structures and the metal seed layer were removed by wet etching using an organic solution and an acid solution (e). Figure 5 shows the fabricated X-ray mask with a membrane size of 10 mm × 30 mm. The membrane has 240 MPa of tensile stress.

3 LITHOGRAPHY ACCURACY

Typical important factors having influence on accuracy of deep X-ray lithography are Fresnel diffraction [4] and a deformation of the X-ray mask and resist due to heat generation under SR X-ray irradiation.

The influence of Fresnel diffraction relating to lithography resolution will be increased at longer wavelengths. The resolution limit caused by Fresnel diffraction, R_d, is given by

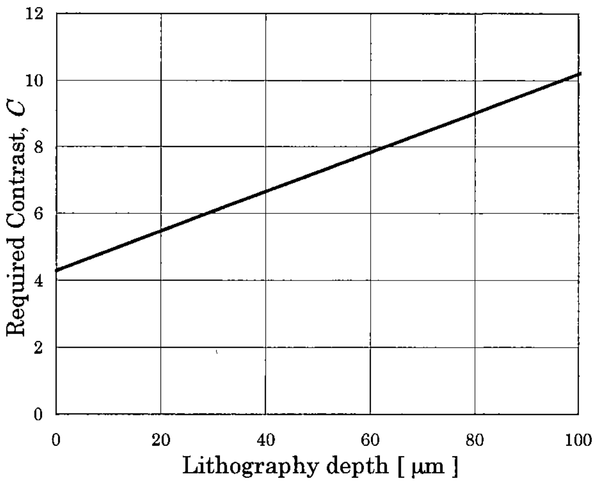


Fig. 2 Required Contrast, C, for lithography depth.

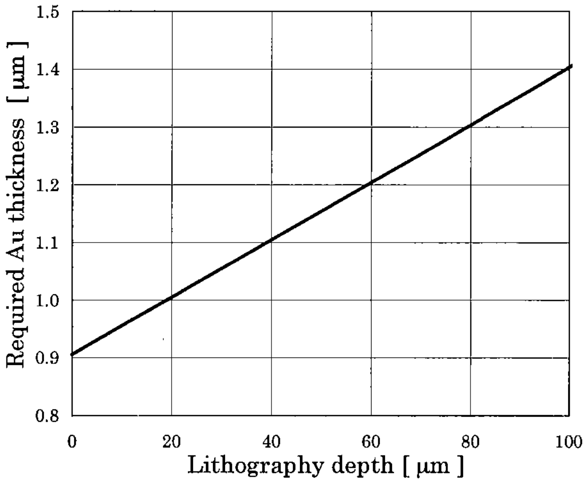
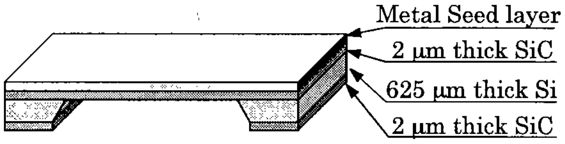
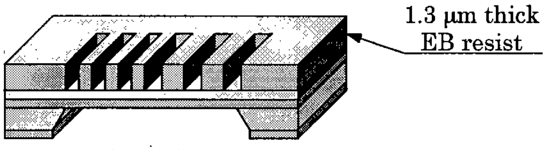


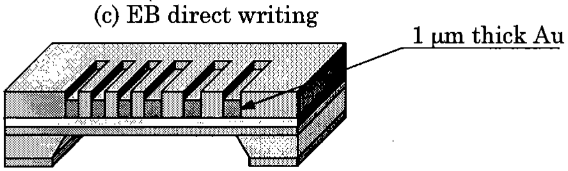
Fig. 3 Required Au thickness for lithography depth.



(a) SiC and Si etching
(b) Seed layer forming



(c) EB direct writing



(d) Au electroforming

(e) Resist and seed layer removing

Fig. 4 Procedure for fabrication process of an X-ray mask with thick Au absorber having sub-micron resolution.

$$R_d = 1.5(\lambda \cdot G/2)^{1/2}, \quad \cdots\cdots\cdots\cdots (2)$$

where λ and G are wavelength and the gap between the X-ray absorber and the PMMA resist [4]. In order to fabricate sub-micron structures, reduction of the value of G is an effective means, because λ is given by the beamline structure used in experiments. Figure 6 shows the PMMA microstructures fabricated by deep X-ray lithography setting the gaps at 40 μm and 100 μm respectively. Some deviations caused by the influence of Fresnel diffraction were confirmed in top parts, but the PMMA structures had vertical side-walls. Figure 7 shows deviation length versus the influence of Fresnel diffraction under different gaps between the X-ray mask and the PMMA resist. The deviation length was about 1/3 of the calculation results given by Eq. (2). It is thought that the difference in these values is influenced by exposure dosage, the dissolving ability of the developer, developing time, and so on.

These results show that the gap is enough to be set at several tens of microns in order to fabricate the sub-micron structures with 20 μm height using deep X-ray lithography. However, there is a problem in actuality where a gap with non-uniformity is formed by a warp in a sample of a PMMA resist with residual stress on a Si substrate. In order to control the gap precisely, a PMMA resist must be polymerized without residual stress, which was the main cause of the warp in the sample. The residual stress is generated by a high polymerization temperature and a difference of thermal expansion coefficients between Si (3.6 × 10^{-6}/℃) and PMMA (75.0 × 10^{-6}/℃).

A curvature radius, κ, of the warp in the sample are given by

$$\frac{1}{\kappa} = \frac{(E_p t_p^{\,3} + E_{Si} t_{Si}^{\,3})(E_p t_p + E_{Si} t_{Si})}{6E_p E_{Si} t_p t_{Si} t(\alpha_p - \alpha_{Si}) \times \Delta T} + \frac{3E_p E_{Si} t_p t_{Si} t^2}{6E_p E_{Si} t_p t_{Si} t(\alpha_p - \alpha_{Si}) \times \Delta T}, \quad \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where E_P and E_{Si} are Young's modulus of PMMA and Si, t is the total thickness of Si and PMMA resist, t_P and t_{Si} are the thicknesses of PMMA resist and Si, α_P and α_{Si} are the thermal expansion coefficients of PMMA and Si, and ΔT is temperature change. The residual stress of the PMMA resist, σ_P, are given by

$$\sigma_P \cong -\frac{E_p t_p^{\,3} + E_{Si} t_{Si}^{\,3}}{6t_p t} \times \kappa . \quad \cdots\cdots\cdots (4)$$

Figure 8 shows the residual stress of PMMA versus different polymerization temperatures. These experimental values are similar to the calculated results. Based on these results, a PMMA resist was polymerized without residual stress, which was the main cause of the warp in the sample, by controlling the polymerization temperature at near room temperature in an air conditioned chamber.

The deformation of the X-ray absorber, the membrane and the resist due to heat generation under SR X-ray irradiation was investigated. Surface temperature of a PMMA resist, a SiC membrane and an Au X-ray absorber in He at 1

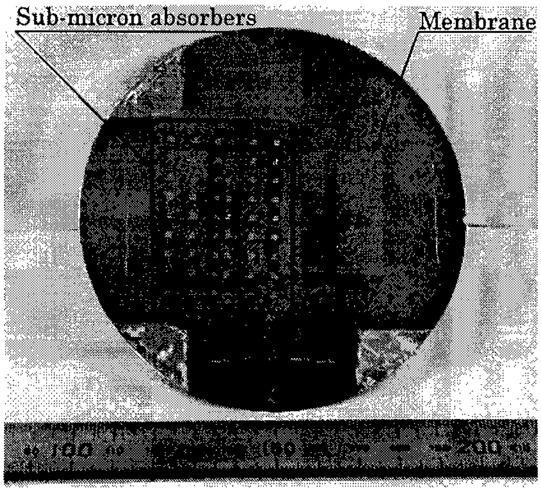
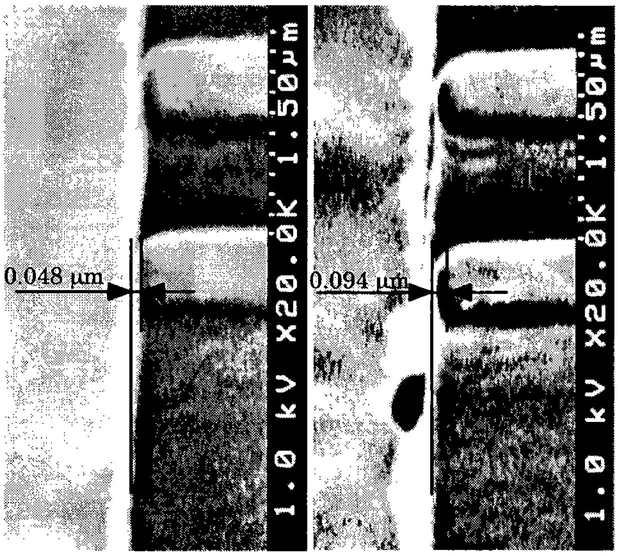


Fig. 5 A fabricated X-ray mask with thick Au absorber having sub-micron resolution.



Exposure gap = 40 μm　　Exposure gap = 100 μm

Fig. 6 PMMA microstructures fabricated by deep X-ray lithography under the different gaps.

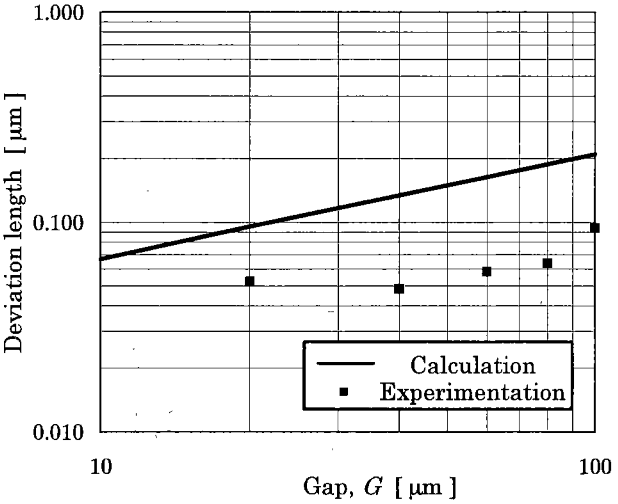


Fig. 7 Deviation length versus the influence of Fresnel diffraction under different gaps.

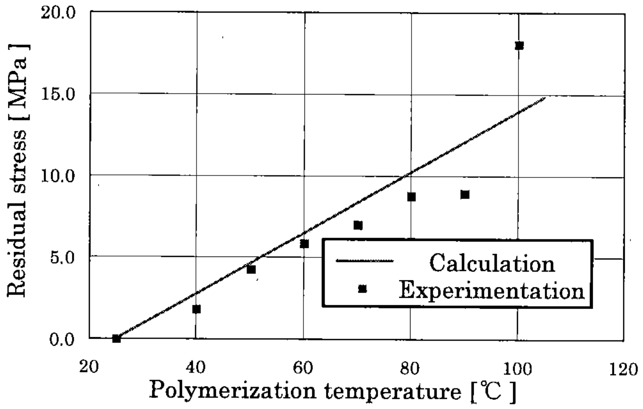


Fig. 8 Residual stress in a PMMA resist versus different polymerization temperatures.

atm under SR X-ray irradiation were measured. A diameter of the measurement target area was 2.8 mm. Figure 9 shows the profiles of the measured surface temperature. The surface temperature of the PMMA resist indicated an increase of 25 ℃ under mask-less SR X-ray irradiation. In a calculated result, the PMMA resist generates a maximum compressive stress of 6 MPa. However, this stress can be reduced by cooling down the sample using scanning exposure, a water cooling system and so on. On the other hand, an increase of 5 ℃ of the surface temperature of the Au X-ray absorber (100 % of the membrane was covered by Au X-ray absorber) and the SiC membrane (0 % of the membrane was covered by Au X-ray absorber) was indicated. In a calculated result, the Au X-ray absorber and the SiC membrane generate a maximum compressive stress of 5 MPa. However, this is not a problem as the stress is compensated by the tensile stress of 240 MPa in the SiC membrane.

4 SUB-MICRON LIGA PROCESS

As shown in Fig. 10, PMMA structures with sub-micron width were fabricated by deep X-ray lithography under the following conditions: an exposure gap between X-ray mask and resist surface of 60 μm, and an exposure dose of 9 mA min / mm2. As shown in Fig. 11, the PMMA structure with a maximum aspect ratio of 85, corresponding to a 0.2 μm minimum width, 6 μm length and 17 μm height, was fabricated.

The value of the taper ratio is one of the important factors in evaluating fabricated microstructures with a high aspect ratio. Figure 12 shows a microstructure with a taper ratio of 0.168 / 100. Moreover, Fig. 13 shows the top and bottom parts of the microstructure with deviation from the vertical. In the top part, the deviation of 0.17 μm has been influenced by Fresnel diffraction because the value of the deviation gave good agreement with the value obtained by Eq. (2). In the bottom part, the deviation of 0.15 μm has been influenced by secondary electrons from the Si substrate and the metal seed layer (Ni/Cr) [9]. In order to reduce the influence of secondary electrons, it might be necessary to select an element with a lower atomic number

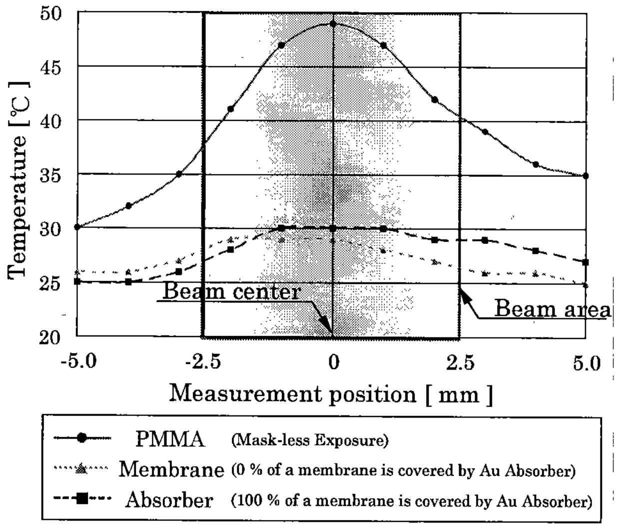


Fig. 9 Profiles of surface temperature of a PMMA resist, a SiC membrane and an Au absorber under SR X-ray irradiation.

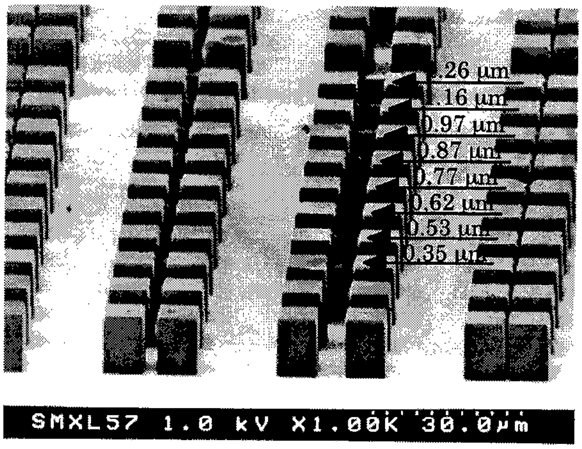


Fig. 10 PMMA structures with sub-micron width fabricated by deep X-ray lithography.

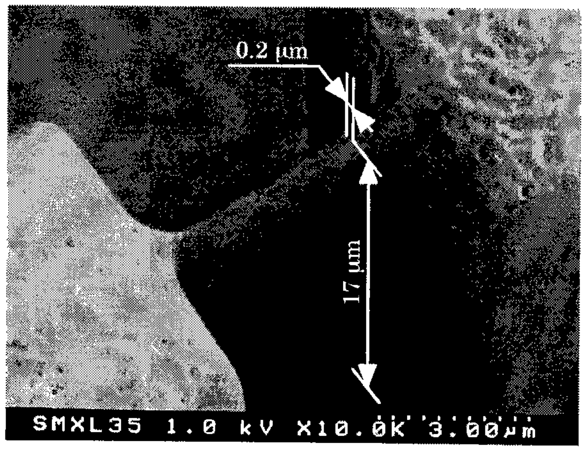


Fig. 11 A sub-micron PMMA structure with a maximum aspect ratio of 85.

for the substrate and the seed layer.

As shown in Fig. 14, Ni structures with sub-micron width were fabricated by Ni electroforming using sub-micron PMMA structures as molds. An electrolyte containing 350 g/l of nickel sulfamate and 30 g/l of boric acid at 37 ℃ was used for the Ni electroforming. The pH and current density were 4.0 and 0.1 A/dm2 respectively. The Ni structures had a maximum aspect ratio of 75, corresponding to a 0.2 µm minimum width and 15 µm height.

5 CONCLUSIONS

An X-ray mask, composed of 1 µm thick Au with 0.6 µm line widths and 0.2 µm minimum gaps as absorbers, 2 µm thick SiC with a tensile stress of 240 MPa as a membrane and 625 µm thick Si as a frame, was fabricated. In order to fabricate thick X-ray absorbers with sub-micron resolution, EB direct writing was used in the fabrication process of the X-ray mask. The sub-micron LIGA process using the X-ray mask was carried out under the optimum conditions based on investigations into typically important factors having influence on process accuracy, such as Fresnel diffraction and deformation due to heat generation under SR X-ray irradiation. As a result, a sub-micron PMMA structure with 0.2 µm minimum width, 6 µm length and 17 µm height and sub-micron Ni structures with 0.2 mm minimum width and 15 mm height were fabricated.

From these results, it is expected that sub-micron structures will be applied to practical and high performance MEMS devices. In particular, sub-micron structures fabricated by the sub-micron LIGA process are expected to be applicable to optical devices, which demands high process accuracy of nano-meter order. In future work, we intend to develop optimum conditions for the sub-micron LIGA process and to fabricate practical and high performance MEMS devices.

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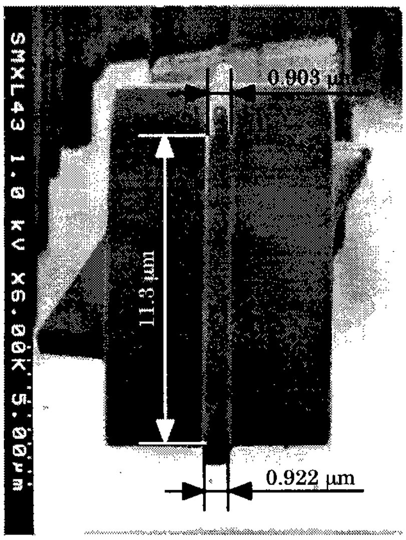
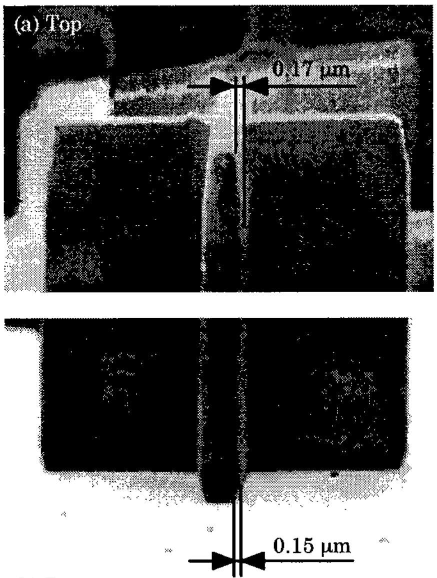


Fig. 12 A PMMA structure with taper ratio of 0.168/100.



(b) Bottom

Fig. 13 Reduced of definition of a PMMA structure.

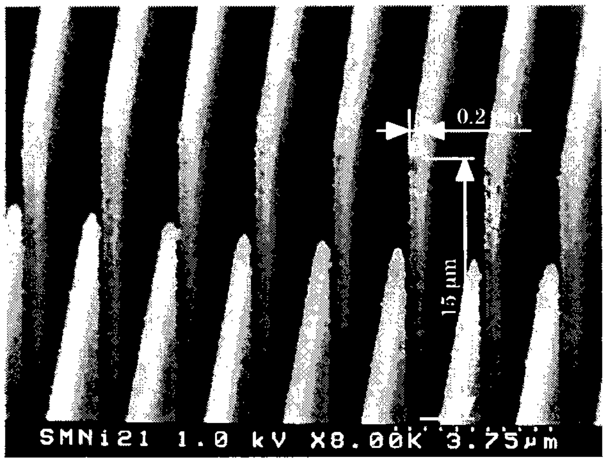


Fig. 14 Sub-micron Ni structures with a maximum aspect ratio of 75.

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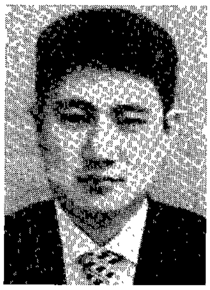

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