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Ni Cantilever Fabrication by Transfer Process without Sacrificial Layer

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Nickel cantilevers, the beam lengths of which ranged from 100 μm to 1000 μm in 100 μm increments and the width of which was 100 μm, were fabricated on a glass substrate by the transfer process. The cantilevers were fabricated on a dummy substrate and transferred to a glass substrate using an epoxy resin as an adhesive layer. No sacrificial layer was used. Because a conventional aligner was used in the bonding process, the glass substrate could be aligned with the dummy substrate. The substrates were pressed together at atmospheric pressure during bonding by evacuating the sample bed. The glass substrate adhered to the dummy substrate after being pressed. The force required to separate the substrates was increased by the additional bond between the dummy and the glass substrates in most samples. Even when the separation was successful, all beams longer than 800 μm were fixed to the glass substrate and about 50% of the beams shorter than 700 μm acted as vibratory beams. The resonant frequencies were similar to those calculated using the parameters for bulk Ni. The vibratory beams bent upwards from the substrates.

1. Introduction

Overhang structures are often used in microelectromechanical systems. An overhang structure has to be fixed on a sacrificial layer during fabrication by the conventional process. The sacrificial layer is removed in the final step of the process to separate the overhang structure from the substrate. The overhang structure often adheres to the substrate due to capillary force during the separation process. This adhesion is one of the

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most serious problems for surface micromachining, and many processes have been proposed to avoid it.[1–3]

Recently, fine pattern fabrication processes utilizing the transfer process have been developed.[4–7] In these processes the desired pattern is fabricated on a dummy substrate and the pattern is transferred to the desired substrate (main substrate) using an adhesive layer. An overhang structure can be obtained on the main substrate without the use of a sacrificial layer. However, these processes require the samples to be cleaned by Ar-ion-beam sputtering and then pressed in an UHV chamber,[4] or pressed by a press machine during the bonding process.[6,7]

In this study, cantilevers are fabricated by the transfer process. An epoxy resin is used as the bonding adhesive layer. An epoxy film is coated onto the main substrate, and the cantilever on the dummy substrate is pressed onto the main substrate with an atmospheric pressure press by evacuating the sample bed. A conventional inexpensive aligner is necessary in the bonding process. The cantilever beams are vibrated by applying an AC voltage between the cantilever and the counter electrode on the main substrate. The resonant frequencies of the fabricated cantilever beams are measured.

2. Process and Materials

A schematic view of the cantilever structure is shown in Fig. 1. The Ni cantilever structure is fabricated on a glass substrate. The cantilever structure consists of cantilever beams, a support electrode and a base electrode. The cantilever beam lengths are from 100 μm to 1000 μm in 100 μm increments. The beam width is 100 μm. The cantilever has relatively long and wide beams. It is difficult to fabricate a cantilever with long and wide beams by a conventional process because the adhesion problem is serious for a cantilever with long beams, and a long etching time is required to remove the sacrificial layer for a cantilever with wide beams.

The fabrication process is as follows. First, the cantilever structure is placed onto the dummy substrate. The fabrication process is shown in Fig. 2. The starting substrate is a silicon wafer with a surface layer of approximately 0.5-μm-thick SiO_2 (Fig. 2(a)). A Cu film approximately 0.1 μm thick is evaporated onto the substrate to be used as a seed layer for Ni electroplating (Fig. 2(b)). A positive tone photoresist film (Tokyo Ohka, OFPR-800) approximately 3 μm thick is coated onto the substrate. Both the cantilever beams and the support electrode patterns are fabricated in the photoresist, and nickel is electroplated (Fig. 2(c)). A conventional nickel sulfamate bath is used. The Ni is approximately 2.0 μm thick. Before making the base electrode a thin Au film approximately 0.1 μm thick is coated onto the Ni patterns by electroless plating (Electroplating Engineers of Japan Ltd., IG7903) (Fig. 2(d)). The Au film is required to ensure a good adhesion between the support electrode and the base electrode. When an Au film is not present, the base electrode is often removed from the support electrode during the separation process. The patterned resist is removed and a new photoresist film is coated. The base electrode pattern is fabricated in the photoresist. The base electrode is also fabricated by Ni electroplating (Fig. 2(e)). The base electrode is approximately 2.5 μm thick. The gap between the cantilever beam and the substrate is defined by the thickness of the base electrode. Finally, both the patterned resist and the Cu[8] films are removed (Fig. 2(f)).

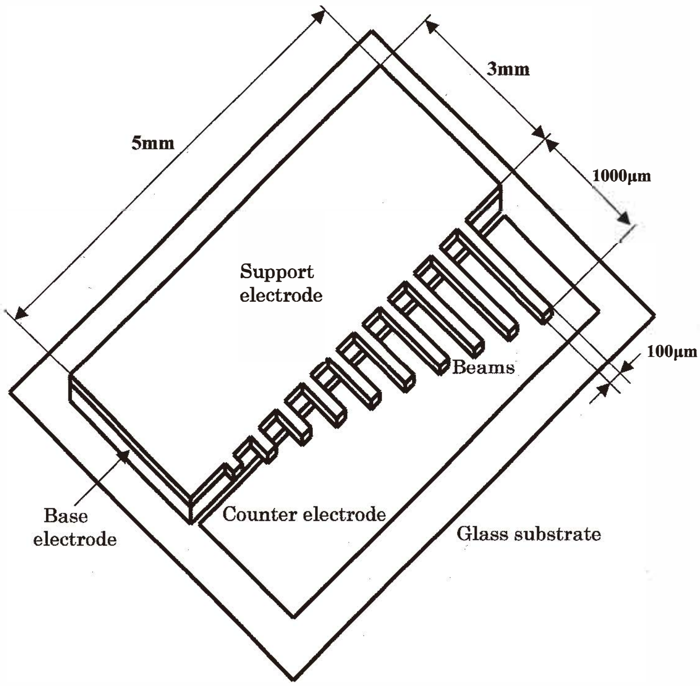


Fig. 1. Overview of fabricated cantilever structure.

The fabricated cantilever structure is transferred from the dummy substrate to the main substrate. The transfer process is shown in Fig. 3. A glass substrate is used as the main substrate. The Cr pattern for the counter electrode is fabricated on the glass substrate. A thin epoxy resin film is used as the adhesive layer (Fig. 3(a)). A commercial epoxy system (Blenny Co., GM-6600) is used. The system consists of an epoxy resin and a curing agent. The epoxy resin and the curing agent are diluted with cyclohexanone. The dilution ratio is defined as the ratio of the weight of the cyclohexanone to the weight of the epoxy resin. The diluted epoxy resin is coated onto the glass substrate by spin coating. The revolution speed is fixed at 3000 rpm. The epoxy resin film is baked at 130°C for 0–5 min on a hot plate (prebaking). The epoxy film thickness is measured after 3 min of prebaking. The relationship between the epoxy film thickness and the dilution ratio is shown in Fig. 4. A film with an almost uniform thickness can be obtained. We use an epoxy resin with a dilution ratio of 5 to achieve an epoxy film thickness of about 0.3 μm.

The main substrate is aligned with the dummy substrate (Fig. 3(b)). After the alignment, the main and dummy substrates are pressed together under atmospheric pressure at room temperature for 5 min by evacuating the sample bed. The contacted substrates are moved from the aligner to a conventional oven while the pressure is maintained. The samples are baked at 150°C for 25 min to cure the epoxy resin (cure baking) (Fig. 3(c)).

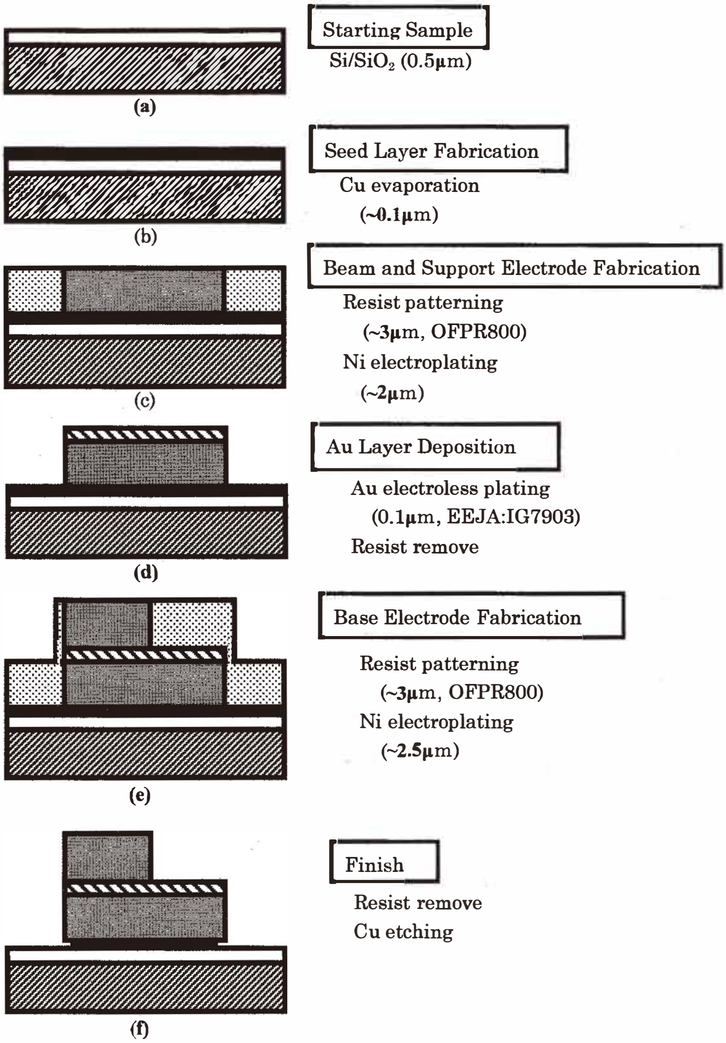


Fig. 2. Fabrication of cantilever structures on dummy substrate.

The main substrate usually adheres to the dummy substrate after baking. The dummy substrate is pulled from the main substrate to effect their separation (Fig. 3(d)).

The procedures for the pressing and the cure baking are described in detail with reference to Fig. 5. A sample bed is placed on a conventional aligner stage. The sample bed is made of aluminum and its weight is approximately 800 g. It is easy to move the sample bed. The mask holder and sample bed can be evacuated via valves V1 and V2,

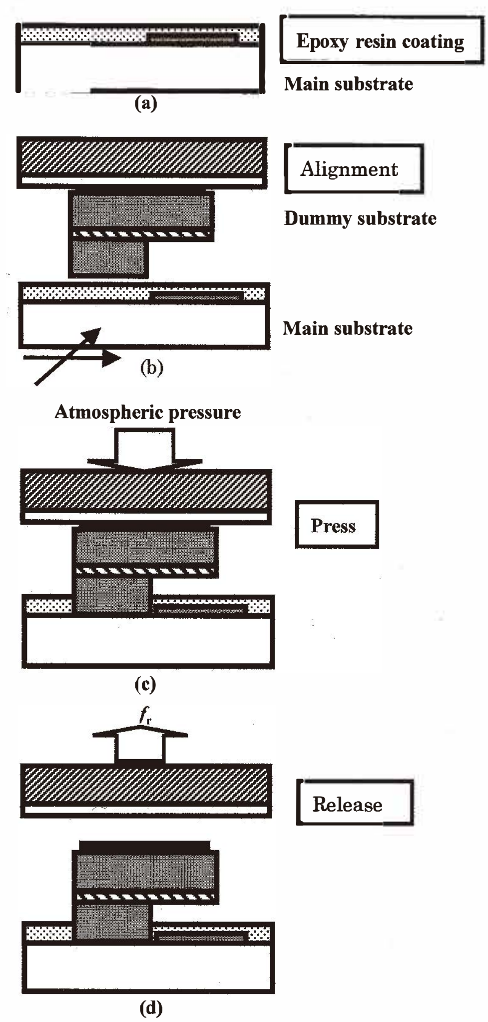


Fig. 3 Process flow of transfer.

respectively. Flexible teflon tubes are used for the vacuum piping. First, the main substrate is fixed to the mask holder, and the dummy substrate placed on the sample bed. The main substrate is separated from the dummy substrate by a small gap, and the main substrate is aligned with the dummy substrate (Fig. 5(a)). After the alignment, the aligner stage is elevated and the dummy substrate contacts the main substrate. When sufficient contact pressure is obtained, the sample bed is evacuated and the main substrate is pressed onto the dummy substrate under atmospheric pressure. The main substrate is fixed onto the sample bed (Fig. 5(b)). The sample bed can be moved to the oven while maintaining the pressure (Fig. 5(c)).

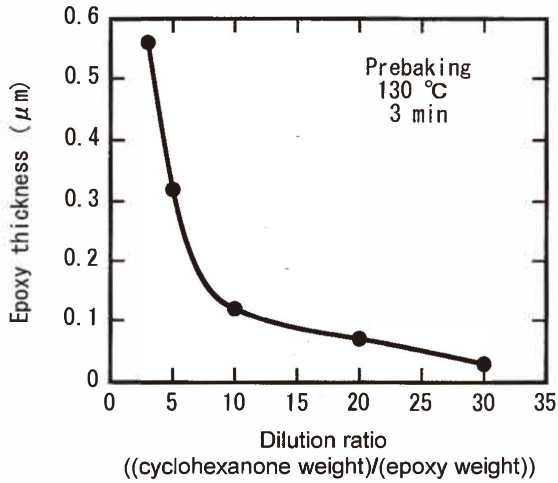


Fig. 4. Relationship between dilution ratio and epoxy film thickness.

The force required to effect the separation is measured. The main substrate is fixed onto a container and the dummy substrate is pulled by a force gauge. The pulling force is increased gradually and the force, f_r, is measured just before the dummy substrate is separated from the main substrate. The cantilever structures is always removed at the boundary of the Cu film and the SiO_2 surface when the transfer is successful. The adhesion force between the Cu film and the SiO_2 surface is very important. If the adhesion force is strong, it is difficult to remove the cantilever structure from the dummy substrate. If the adhesion force is weak, the cantilever structure may be removed during the fabrication of the dummy substrate. Before the transfer experiment, the adhesion force between the cantilever structure and the dummy substrate is measured. The force gauge is directly connected to the base electrode. The force required to remove the cantilever structures is approximately 200 gf. The force required for the separation must be equal to 200 gf.

3. Results and Discussion

The sizes of the dummy and main substrates are approximately 70 mm^2 and 1 in^2, respectively. The experimental conditions and results are summarized in Table 1. The evacuation required for the atmospheric pressure press is stopped just after placing the contacted substrates into the oven for some experiments. The samples without the atmospheric pressure press during baking are indicated by the symbol × in the third column. The forth column shows the values of f_r. Although f_r is increased up to 1100 gf, somc samples cannot be separated. These unsuccessful samples are marked with an ×. Because the epoxy film thickness is less than the gap between the cantilever beam and the main substrate surface, only the base electrode is adhered to the main substrate and f_r

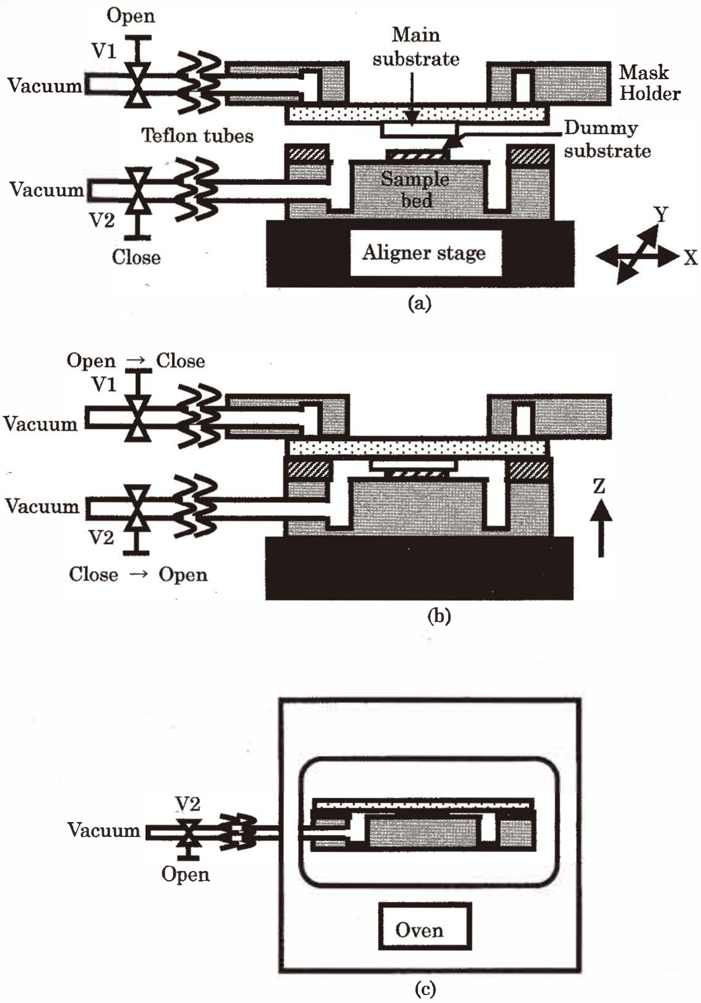


Fig. 5. Procedures for pressing and cure baking.

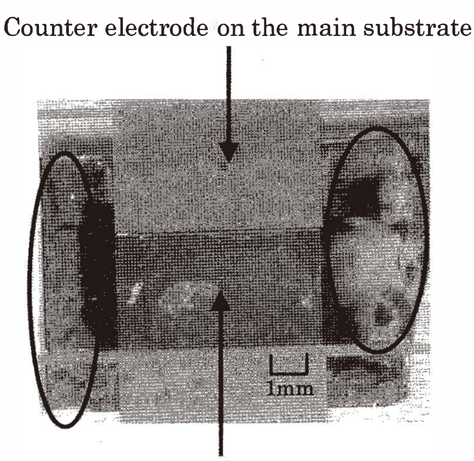
Table 1
Summarize of experimental conditions of transfer and results of separation.

Sample No.	Prebaking	Pressure during cure baking	f_r(gf)
1	No	1 atm	500
2	130°C, 3 min	1 atm	○*
3	130°C, 3 min	1 atm	500
4	130°C, 3 min	×	×
5	130°C, 5 min	1 atm	900
6	130°C, 5 min	1 atm	200
7	130°C, 5 min	×	×

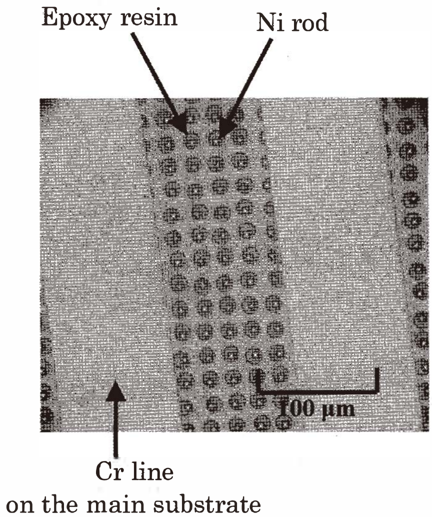
* not measured

becomes approximately 200 gf. For sample 6 the cantilever structure can be separated from the Cu and SiO_2 surface. However, other samples have large f_r values. The transfer experiments are performed under various prebaking conditions, but it is hard to determine a relationship between the prebaking conditions and the separation results. Because the glass substrate is used as the main substrate, the contact surface can be seen through the glass substrate before separation. A photograph of the unseparated sample is shown in Fig. 6(a). The dummy substrate is adhered to the main substrate at the edges of the dummy substrate (marked by circles). The epoxy resin is condensed at the edge of the dummy substrate. Although the fabrication process is not described in this paper, the transfer of small Ni rods, whose size and thickness are 5 μm^2 and 2 μm, respectively, was also attempted by virtually the same process. A photograph of the small Ni rods on the contact surface is shown in Fig. 6(b). It can be clearly seen that the epoxy resin is condensed around the Ni rods. Although the condensation cannot be controlled at present, it is important to control the condensation to avoid adhesion between the dummy substrate and the main substrate.

Figure 7 shows the fabricated cantilever structure on the main substrate for sample 1. The cantilever structure is successfully transferred to the main substrate. An AC voltage is applied between the cantilever structures and the counter electrode. A laser beam irradiates the top of the cantilever beams and the reflected laser beam intensity is measured by a position sensitive detector (PSD, Hamamatsu, S3932). The 1000-μm-long cantilever beam has an electric contact with the counter electrode. If the epoxy resin is uniformly



(a)



(b)

Fig. 6. Photograph of contact surface through the glass substrate: (a) cantilever structure, (b) small Ni rods.

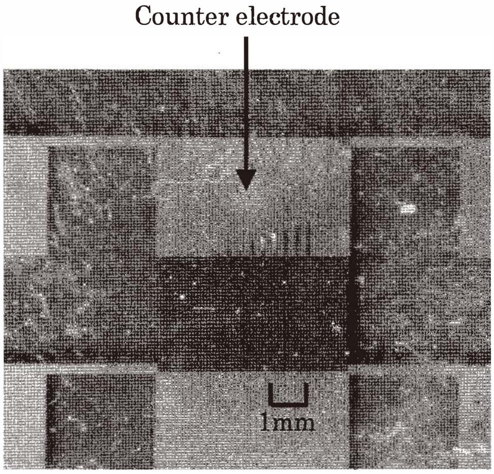
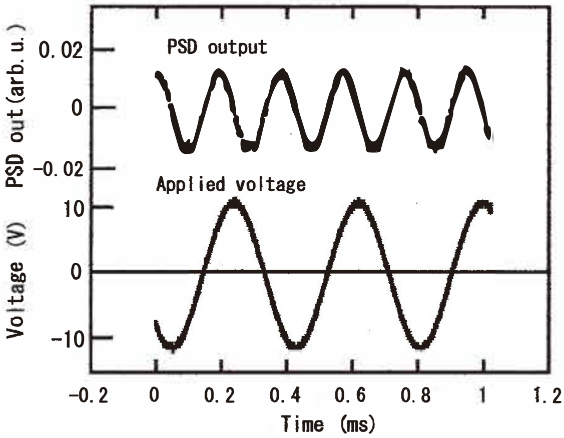
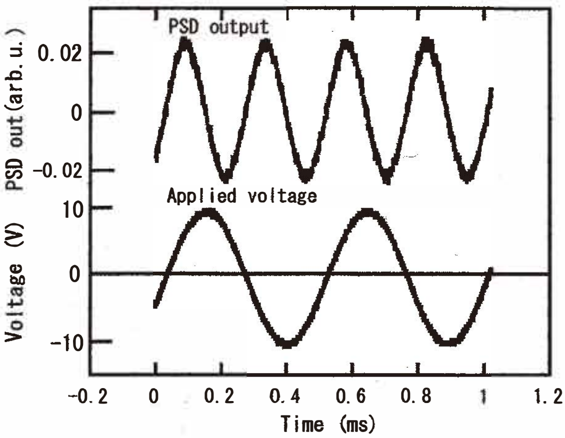


Fig. 7. Photograph of fabricated cantilever structure on main substrate.

coated over the main substrate, no electric contact is produced between the cantilever structure and the counter electrode. In our experiments the thickness of the epoxy resin film is not uniform due to condensation, and a Cr surface may partially appear. Even when only one cantilever beam touches the counter electrode, the cantilever structure is electrically shorted. The 1000-μm-long cantilever beam is removed before applying the AC voltage. Although the 900- and 800-μm-long cantilever beams are electrically isolated from the counter electrode, no vibration can be detected. The cantilever beams must be bonded to the main substrate with epoxy resin. For 700- and 600-μm-long cantilever beams, vibrations can be detected. The 500-μm-long cantilever beam is fixed to the substrate. The beams shorter than 400 μm act as vibratory beams when an AC voltage is applied. The vibrations around the resonant frequency are shown in Figs. 8(a) and 8(b) for the 700- and 600-μm-long cantilever beams. Because the AC voltage is applied between the cantilever structures and the counter electrode, the cantilever beams are pulled to the counter electrode during both the positive and negative cycles of the AC voltage. Therefore, the beam vibration frequency is double that of the applied AC voltage. The resonant frequencies are 5.3 kHz and 4.1 kHz for the 700- and 600-μm-long cantilever beams, respectively. The resonant frequency is calculated assuming a simple rectangular beam.(9) The Young's modulus and the density used are 200 GPa and 8.9 g/cm^3, respectively, which are the values for bulk Ni. The calculated resonant frequencies for the 700- and 600-μm-long cantilever beams are 3.1 kHz and 4.2 kHz, respectively. For the 600-μm-long cantilever beam the calculated resonant frequency is almost equal to that obtained from the experiment. However, the resonant frequency obtained from the experiment is higher than the calculated one for the 700-μm-long cantilever beam. The 700-μm-long cantilever beam may be fixed to the substrate at some intermediate point by the condensed epoxy resin. In that case, the cantilever beam is free to vibrate from the point fixed by the



(a) 700 μm



(b) 600 μm

Fig. 8. Waveforms of applied voltage and beam oscillation detected by PSD: (a) 700-μm-long beam, (b) 600-μm-long beam.

condensed epoxy resin to the end of the beam. The beam acts as a vibratory beam the length of which is shorter than 700 μm. Figure 9 shows an SEM photograph of the 700- and 600-μm-long cantilever beams. The cantilever beams are bent upwards. For the 600-μm-long beam the deviation of the beam top from the substrate is approximately 30 μm. The 700-μm-long beam seems to be bonded to the substrate at the position marked by the circle. Beam vibrations are measured for other samples. All beams longer than 800 μm are fixed to the substrate. For other length beams, approximate 50% of the fabricated beams act as

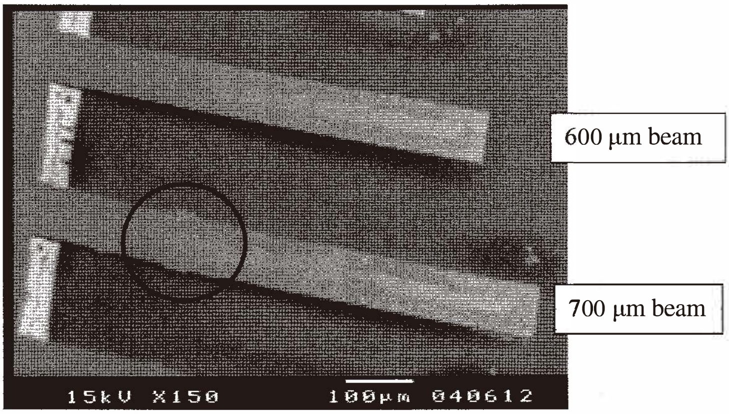


Fig. 9. SEM picture of 700- and 600-μm-long beams.

vibratory beams. The beam length cannot be related to the yield. For example, the 500-μm-long beam acts as a vibratory beam but the 400-μm-long beam is fixed to the substrate in the sample 6. Because the position of the epoxy resin condensation is not controlled, it is difficult to discuss the yield in detail. The vibratory beams bent upwards.

In previous work, the same size Ni cantilever structures were fabricated using a sacrificial layer.[10,11] The Ni film was deposited by electroplating from a bath with the same composition. No bend was observed for any of the beams. Therefore, the bend must be produced during separation. The maximum stress, σ_{max}, is estimated using the theory of a simple rectangular cantilever. It is assumed that a uniform pressure is applied to the support electrode and the cantilever beams, and the total force is equal to the separation force of 200 gf. The calculated value of σ_{max} is 46 GPa for the 600-μm-long beam. This value is very large and the beam is undoubtedly broken at the boundary of the cantilever beam and the support electrode. However, no cantilever beams are broken in our experiments. Because the cantilever beam is free in the calculation, a very large bending moment is produced at the fixed end of the cantilever beam. In the experiment both the cantilever beam and the support electrode are fixed on the dummy substrate and no bending moment is produced in the cantilever beams until the cantilever structure is separated from the dummy substrate. A bending moment may be produced just before the separation is completed. However, it is difficult to estimate the bending moment produced just before the separation is completed. One of the practical ways to obtain a straight cantilever beam is as follows. A Cu film between the base electrode and the dummy substrate is etched before the separation process. The etching time of the Cu film can be controlled in order that the Cu film under the cantilever beam is removed completely but that under the support electrode remains. It is easy because the support electrode is much larger than the cantilever beam width. Because the cantilever structure is adhered to the dummy substrate only at the support electrode, no force is applied to the cantilever beam during the separation.

4. Conclusions

A Ni cantilever structure with beams of various lengths is fabricated by the transfer process without the use of a sacrificial layer. The cantilever structure is fabricated on a glass substrate. The vibrations of cantilever beams are observed by applying an AC voltage between the cantilever structure and the counter electrode.

Additional adhesion due to the epoxy resin is observed for most samples, and the force required for separation is larger than expected (–200 gf). Two of the seven samples could not be separated, and half of the beams remained fixed to the substrate by the epoxy resin even when the separation was successful. For the successfully separated samples, all the beams longer than 800 μm remain fixed to the substrate, and of the other beams, approximately 50% act as vibratory beams. The yield is not good at present. Moreover, the successful cantilever beams are bent upward after the separation. Two important techniques have to be developed in order to improve the process; 1. the control of the epoxy resin condensation, and 2. the control of the adhesion force between the cantilever structure and the dummy substrate.

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