A micro membrane vibrator with thermally driven bimorph cantilever beams

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ABSTRACT

A micro membrane vibrator consisting of bimorph cantilever beams and a membrane is designed, fabricated, and tested here. Due to the discrepancy of thermal expansion coefficients between different layers, the membrane moves with temperature change. The four-layer structure including SiO2-polysilicon-insulated SiO2-aluminum is fabricated with four masks. The numerical finite element program ANSYS 51 is used to investigate the behavior of different designs to have larger displacement and force. According to the testing results, we observe that our designs can induce the maximum Z-axis displacement up to 117 μm when input power is 6.98 W. The working frequency is about 40 Hz when the amplitude is kept between 2 and 5 μm approximately.

Keywords: bimorph, membrane vibrator, micromachining

1. INTRODUCTION

In order to allow large volume stroke, two important components of micropumps including membrane vibrators and chamber structures are developed progressively. In the part of membrane vibrators, choosing the driving types such as magnetic, electrostatic, piezoelectric and thermal forces is the most important issue to induce a larger volume stroke.

The development of miniaturized fluid pumping systems started in 1980 with the work of Smits and Wallmark using piezoelectric bimorphs. In 1988, H. T. G. Van Lintel et al. presented the micropumps which have a thin glass pump membrane actuated by a piezoelectric disc with a diameter of 12.5 mm.[2] In 1989, Masayshi Esashi et al. presented a piezoelectric micropump with the smaller pumping area of 2x2 mm^2 on a silicon wafer.[3] In 1990, the new actuating principle of an electro-thermopneumatic liquid pump was presented by F. C. M. Van De Dol et al..[4] The pump membrane is driven from gas contained in a cavity controlled by resistive heating. In 1992, a bulk micromachined pump with electrostatic actuation which can be operated with high frequencies up to 100 Hz was presented by R. Zengerle et al.[1] In 1995, R. Zengerle et al. presented a bi-directional silicon electrostatic micropump which can be operated with higher frequencies from 2 kHz to 6 kHz.[5]

According to the correlating research, electrostatic and piezoelectric forces are unstable to deliver the large force. Piezoelectric drives are difficult to manufacture if the needed size is below 4mm.[1] Magnetic materials are not compatible with the standard IC technology. Therefore, the bimorph effect that is a kind of electro-thermo-mechanical behavior is adopted to be the primary driving principle for its large force and high compatibility with IC fabrication. Here, a micro membrane vibrator with four layers including SiO_2 - polysilicon- SiO_2 - aluminum will be designed and fabricated to act as the driving component of micropumps.

2. DESIGN PRINCIPLE OF MICRO MEMBRANE VIBRATORS

As shown in Figure 2.1, two designed bimorph beams consist of aluminum film on top and two layers below：SiO2 and polysilicon in sequence. Aluminum and SiO2 are chosen because of the large discrepancy of their thermal expansion coefficients. Polysilicon layer provides the source of heaters. After applying electric current to the polysilicon layer, the

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temperature rises and the bimorph beam bends downward along negative Z-axis. The curvature, k=1/r, is expressed for rectangular cross sections as following.

$$k = 1/r = \frac{6 \cdot b1 \cdot b2 \cdot E1 \cdot E2 \cdot t1 \cdot t2 \cdot (t1 + t2) \cdot (\alpha_2 - \alpha_1) \cdot \Delta T}{(b1 \cdot E1 \cdot t1^2)^2 + (b2 \cdot E2 \cdot t2^2)^2 + 2 \cdot b1 \cdot b2 \cdot E1 \cdot E2 \cdot t1 \cdot t2 \cdot (2t1^2 + 3t1 \cdot t2 + 2t2^2)}, \quad (1)$$

r : the radius of curvature of the beam
ΔT : the change in temperature
E1,E2 : Young's modulus
α_1, α_2 : the thermal expansion coefficients
t1, t2 : the thickness of different layers
b1, b2 : the width of different layers

The deflection d at the free end of the bimorph beam from the constant curvature k introduced by thermal strain is :

$$d = \frac{kL^2}{2} \quad \text{for } L << r, \quad (2)$$

Figure 2.2 shows the simulation of the tip displacement along Z-axis for the rectangular and trapezoidal bimorph beams from top view heated at $200^0 C$ uniformly by Ansys 5.1. The thicknesses of aluminum, SiO2 and polysilicon films are 1.0, 0.5 and 0.3 μm respectively. Figure 2.3 shows the finite element analysis results and the tip deflection calculated by using analytical model. The maximum difference between the analytic model and Ansys 5.1 is 1.409 %. Furthermore, changing the shapes of polysilicon layers is also simulated that the design (b) enables to have larger displacement along Z axis than design (a) in Figure 2.4.

By means of attaching four bimorph beams to the membrane, a micro membrane vibrator is shown in Figure 2.5. As heating four bimorph beams, the bottom membrane deflects due to the bending of the beams. Figure 2.3-3 shows the displacement of the micro membrane vibrator along Z-axis in simulation as four beams are heated to $200^0 C$ uniformly. The maximum displacement along negative Z-axis is 93.753 μm and the net volume stroke is 23.95×10^6 μm^3. Figure 2.7 shows the distribution of Von Mesis stress. The maximum Von Mesis stress is 0.56 GPa in the base of four bimorph beams. The stress also concentrates in the membrane obviously. The factor of safety is about 12.5. The maximum deflection is generally proportional to temperature as shown in Figure 2.8.

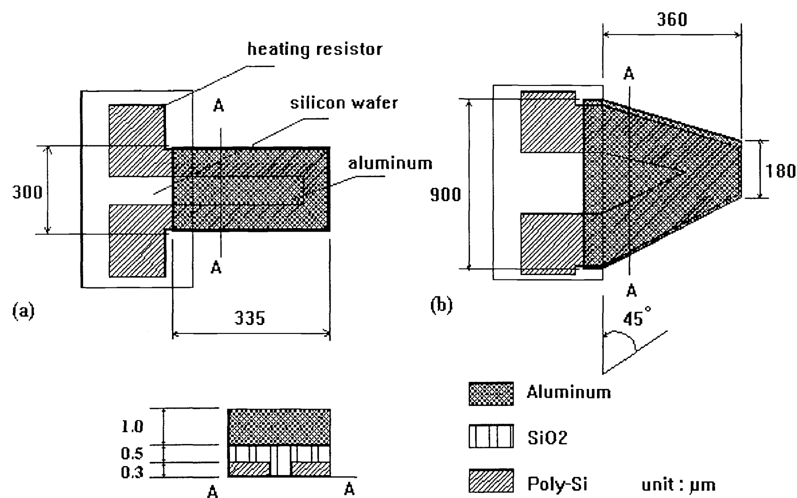

Figure 2.1 Materials of two bimorph beam structures

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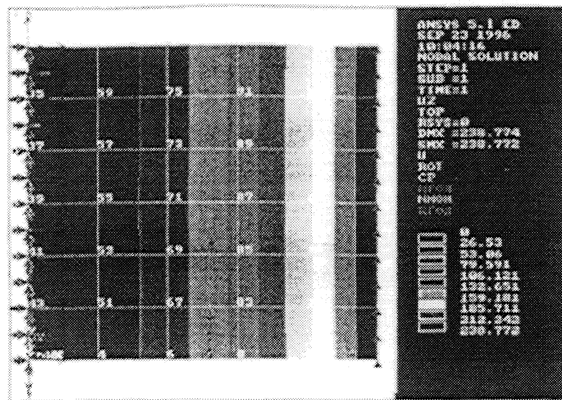
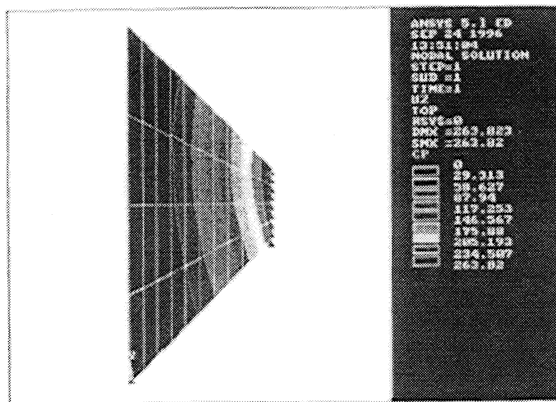


(a) Rectangular type (maximum deflection : 238.772 μm)



(b) Trapezoidal type (maximum deflection : 263.82 μm)

Figure 2.2 Simulations of the tip displacement along Z-axis from top view

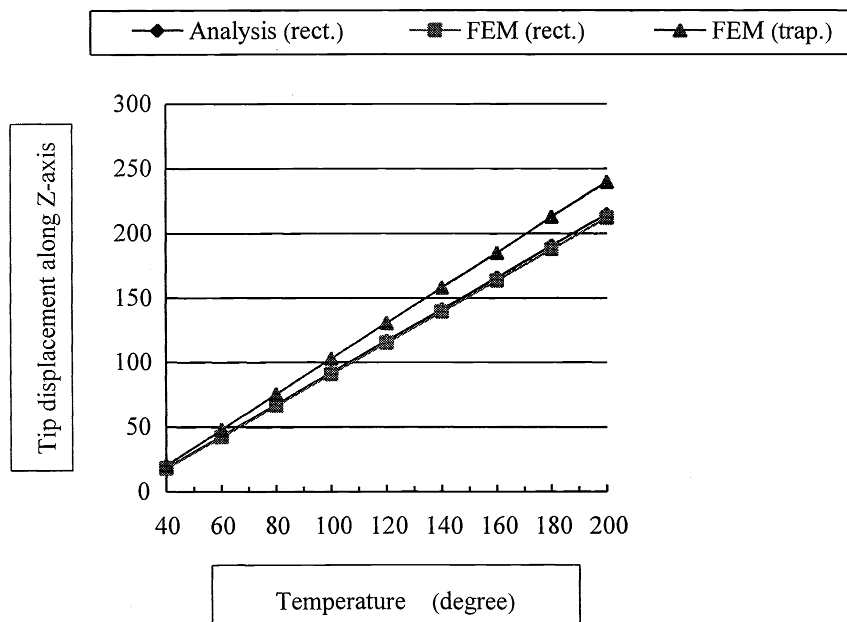


Figure 2.3 The results of finite element analysis and analytical model

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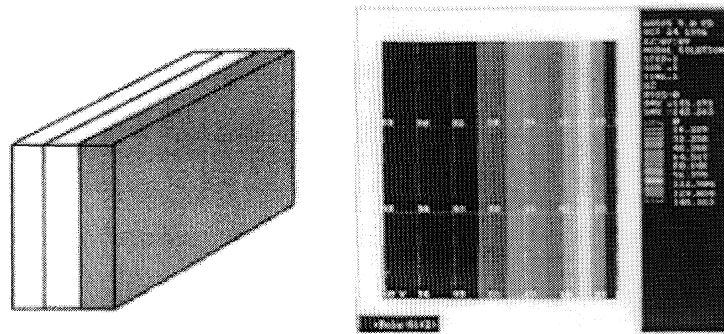
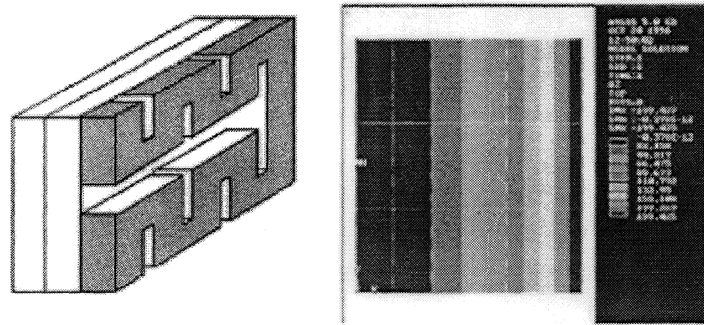


Design (a) Maximum deflection (145.163 μm)



Design (b) Maximum deflection (199.425 μm)

Figure 2.4 Two designs and the finite element results in polysilicon layer

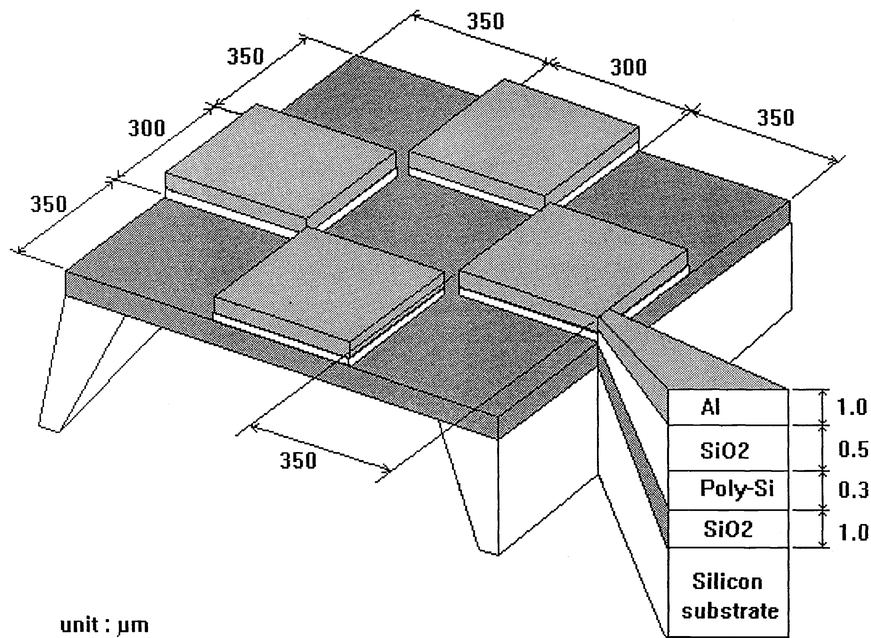


Figure 2.5 The dimensions of the micro membrane vibrator

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Figure 2.6 The displacement of the micro membrane vibrator along negative Z-axis ($200\,^{0}C$)

Figure 2.7 The distribution of Von Mesis stress

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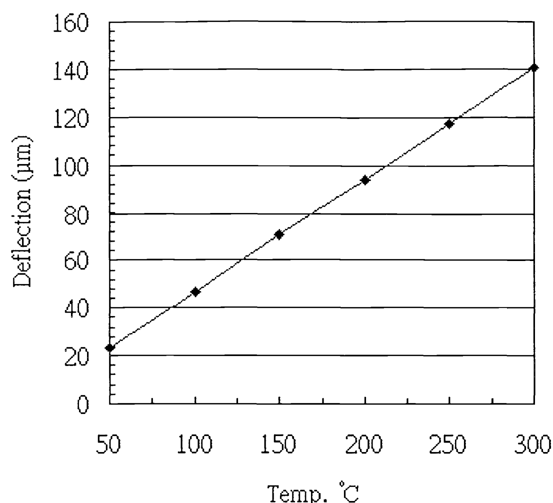


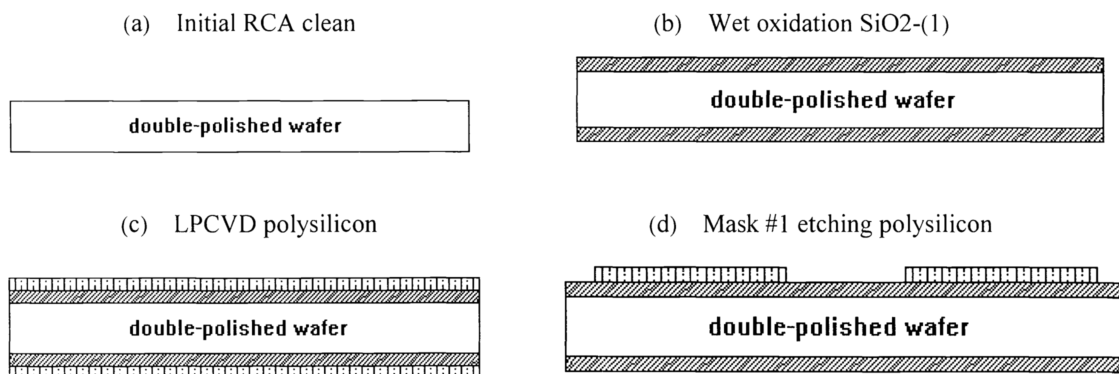
Figure 2.8 The maximum Z-axis deflection vs. Temperature

3. FABRICATION

A SiO_2 film of $1.0\,\mu m$ is oxidized firstly in a double-polished wafer that is regarded as the membrane of the microvibrator. By means of KOH etching selectivity between SiO_2 and Si, this film can also defend against KOH etching in the front side of wafers during KOH backside etching. In order to heat the bimorph beam, a layer of polysilicon with $POCl_3$ driven-in under the bimorph beam is deposited about $3000\,A^\circ$ to be the heating resistor. The temperature rises as electric current passes through polysilicon film. After patterning the polysilicon layers, heating resistors and electric contact pads are defined respectively. These steps are shown in Figure 3.1 (a)-(d).

Because of large discrepancy of thermal expansion coefficients and small Young's modulus, SiO_2 and Aluminum are chosen to be the bimorph materials. The second SiO_2 film is oxidized thermally about $5000\,A^\circ$ between polysilicon and aluminum layers, which not only constructs the bimorph beam but isolates polysilicon and aluminum films. After patterning the second SiO_2 film, aluminum is evaporated upon the second SiO_2 layer and patterned. The steps are illustrated in Figure 3.1 (e)-(h). Before patterning SiO_2 films in the back side of the wafer, photoresist are coated and baked in the front side to protect from etching SiO_2 films. The IR aligner is helpful to align the patterns in opposite side. The steps are shown in Figure 3.1 (i)-(k).

During the process of KOH backside etching , the devices in the front side are protected by the acrylic chuck as Figure 3.1 (l) shows. Until the silicon is etched appropriately, the membrane vibrators with four bimorph beams and a membrane are completed after removing the acrylic chuck as shown in Figure 3.1 (m).



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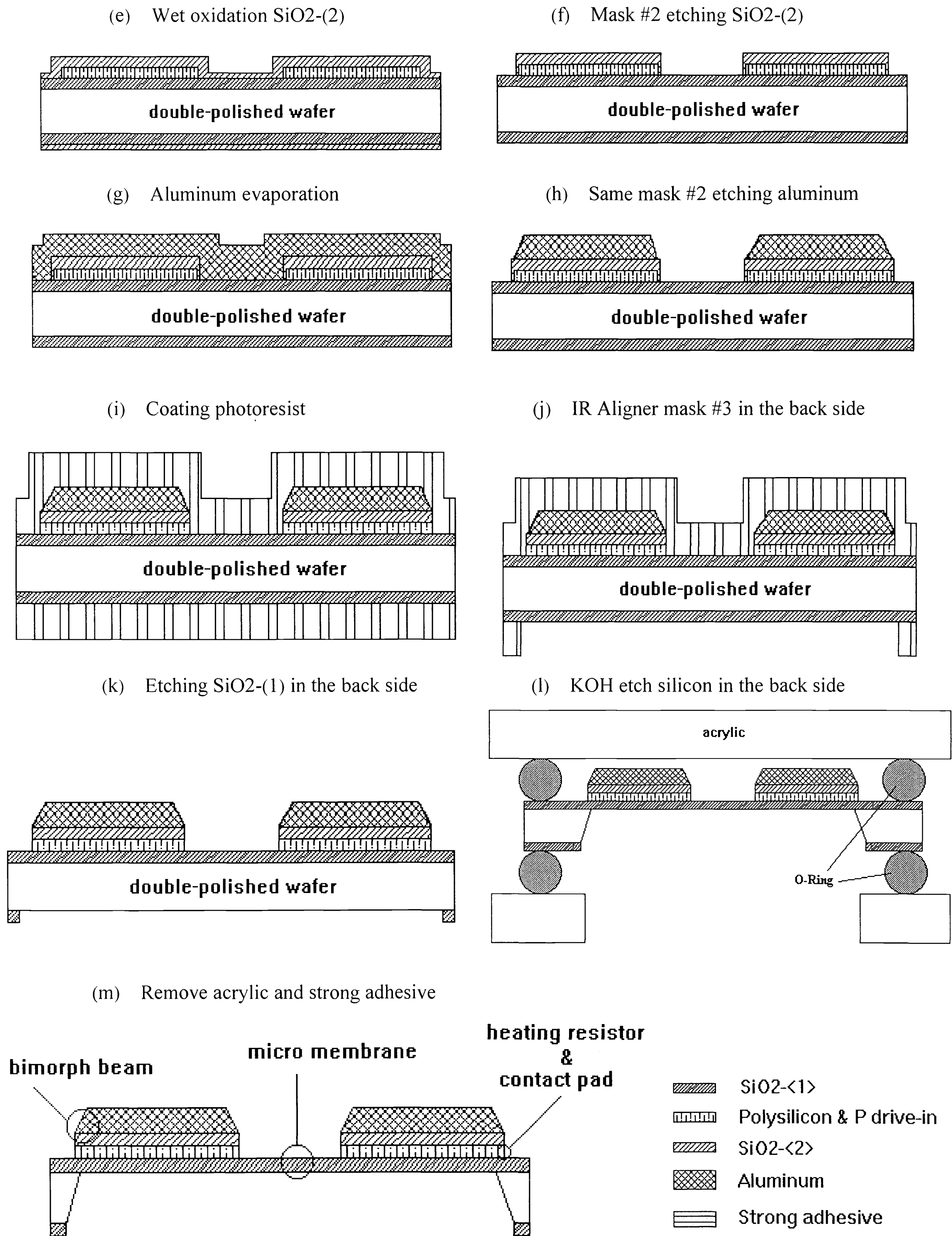

Figure 3.2-1 Fabrication process

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4. RESULTS

The thickness of first thermal SiO2, polysilicon, second thermal SiO2 and aluminum films are 1.1854 μm, 0.3 μm, 0.462 μm, and 1.0066 μm respectively. The total thickness of the beam is 2.954 μm. Figure 4.1 shows different designs of micro membrane vibrators under optical microscope. As Figure 4.2 shows, each layer of the bimorph beam can be observed and measured under SEM. Figure 4.3 shows some successful devices which the remaining SiO2 film is about 1.2~1.5 μm. Generally, the remaining film wrinkles owing to the thermal residual stress between the four-layer structure. According to the experiment results, the wrinkling SiO2 films in the designs of A-2, B-2, C-2, and D-2 are more irregular than the designs of A-1,B-1, C-1, and D-1. Annealing during the process of the SiO2 oxidization is adopted to improve the defect. Sometimes, as Figure 4.4 shows, the SiO2 film ruptured because of the non-uniform KOH etching.

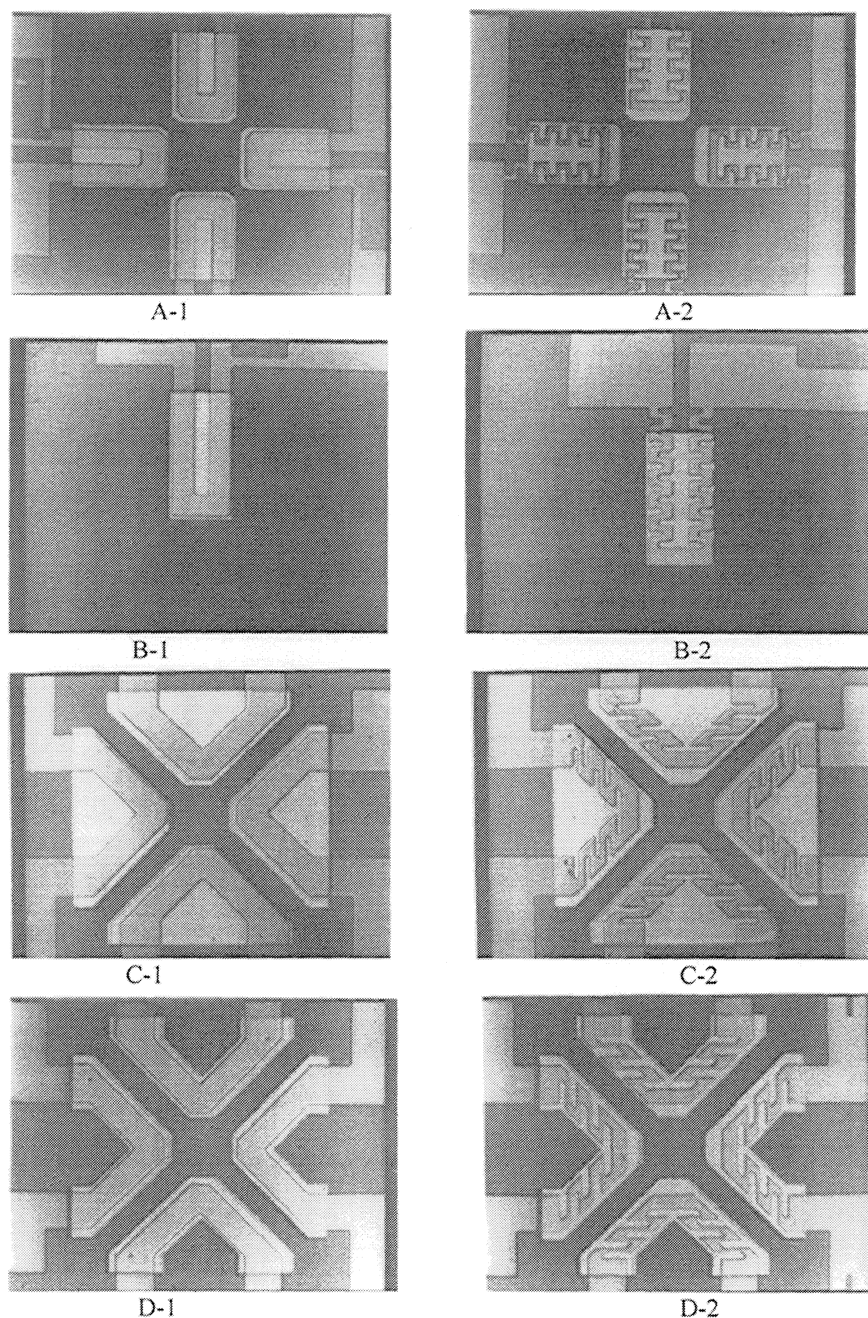

Figure 4.1 Top-view of different micro membrane vibrators (OM)

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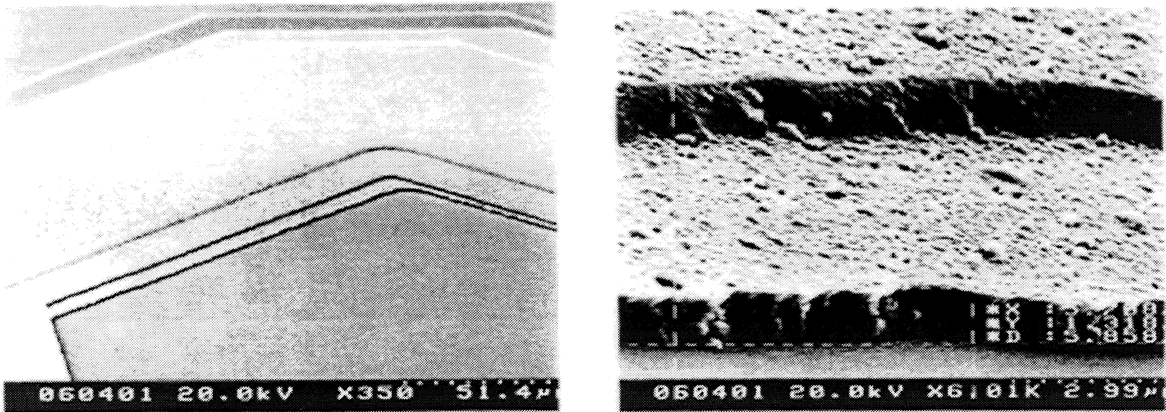

Figure 4.2 SEM shows the bimorph beam structures

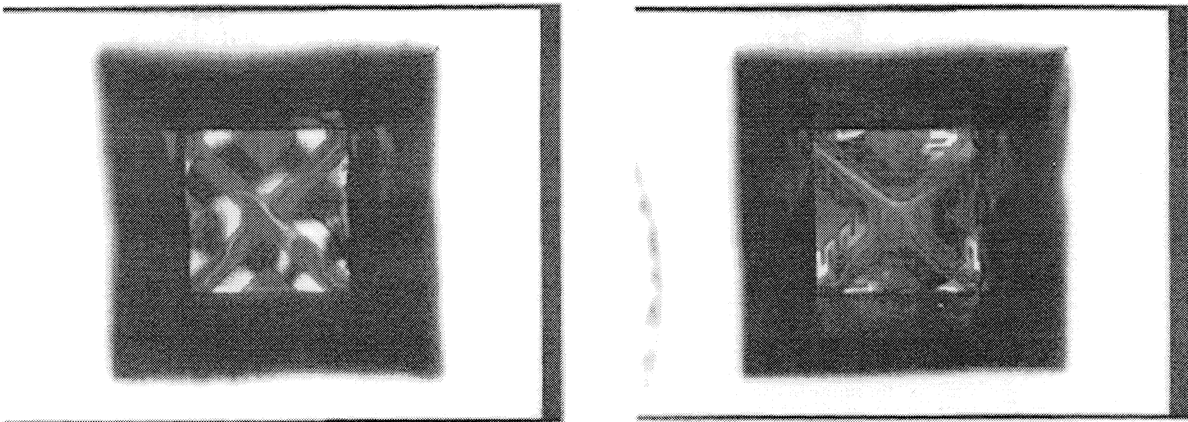

Figure 4.3 Top view of successful devices from the backside (C-1, C-2)

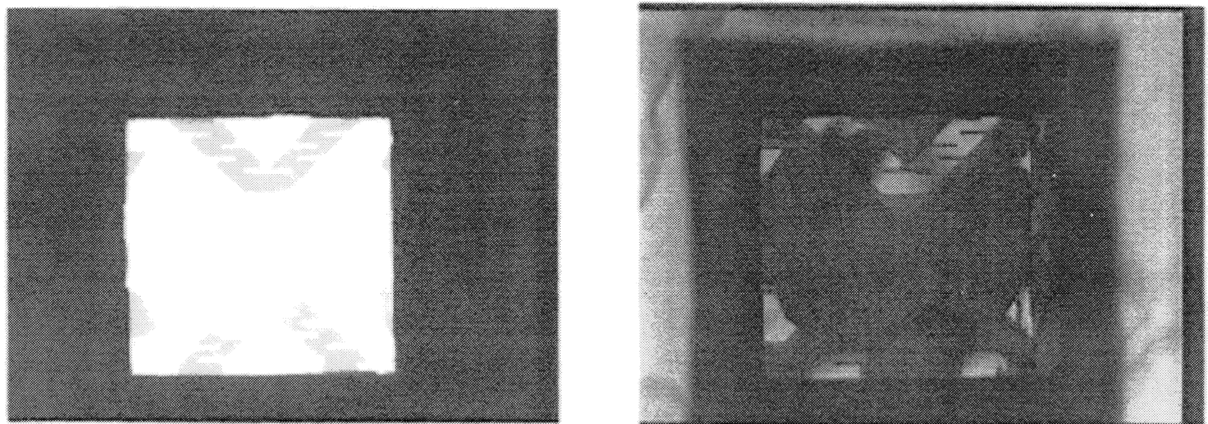

Figure 4.4 The remaining ruptured films owing to non-uniform KOH etching

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The preliminary testing results including input power versus displacements and working frequency. The displacement along negative Z-axis at the center of micro membrane vibrators is measured in different input voltages and constant current as illustrated in Figure 4.5. We observe that the membrane vibrator with the area of 1000 μm x 1000 μm can induce the maximum Z-axis displacement up to 117 μm before the aluminum film melting when input power is 6.98 W. The working frequency is about 40 Hz when the amplitude is kept between 2 and 5 μm. According to the measured data, the four-beam vibrators have larger displacement about 5-8 μm than one-beam vibrators like the design of B-1. But, the one-beam vibrators are allowed to input larger power because of the lower resistance in the polysilicon layers. The heating resistors of the four-beam vibrators are broken sometimes when input power is larger than 5W. Furthermore, the aluminum films begin melting when input power is over 15 W. Melting is always happening in the critical points such as the corner and the thinner linewidth of the heating resistor as shown in Figure 4.6.

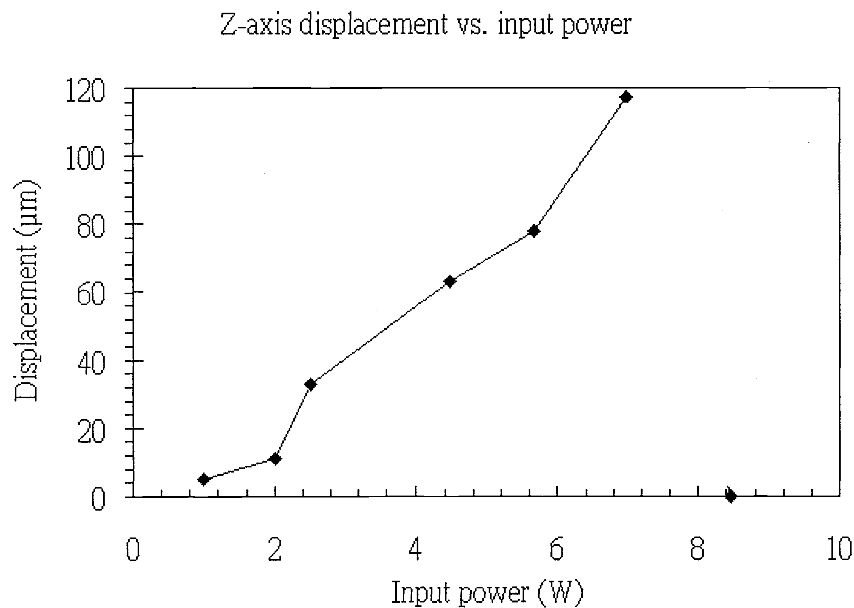

Figure 4.5 The maximum displacement vs. Input power

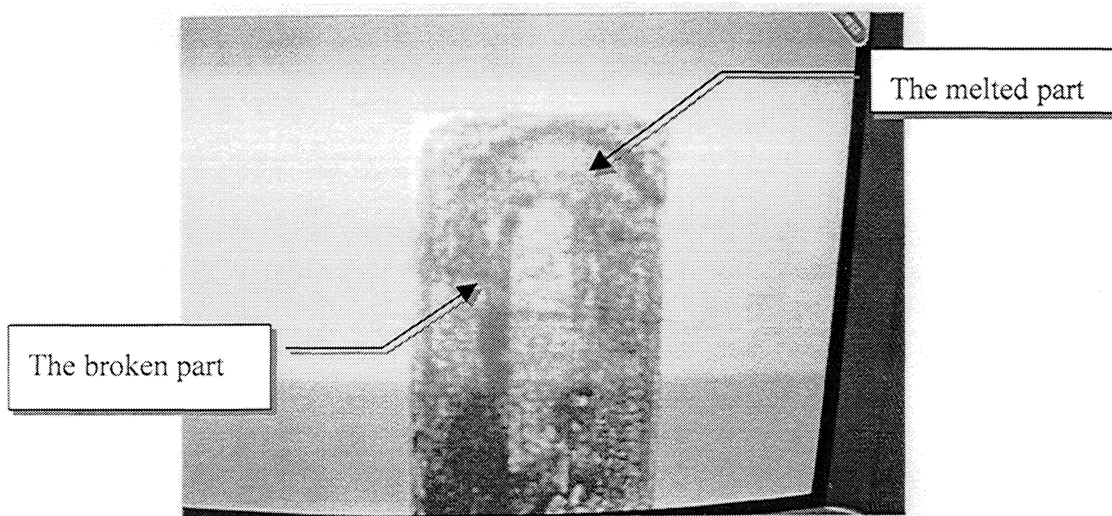

Figure 4.6 Three operating conditions in acting micro membrane vibrator

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5. CONCLUSIONS

The preliminary micro membrane vibrator has been designed, fabricated and tested. Our designs can induce the large deflection up to 117 μm. Although the driving frequency of the thermally driven membrane has to be low, the devices can work properly at 40 Hz when the amplitude is kept between 2 and 5 μm. The improved and simplified fabrication process is under way.

6. ACKNOWLEDGMENTS

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