THREE D FLEXIBLE VIBRATION STRUCTURE DESIGN AND ITS FABRICATION FOR MICRO ENERGY HARVESTING

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Abstract: In this paper we propose a design and fabrication method for three dimensional vibration structures for micro energy harvesting. Since many of actual ambient vibration energy sources vibrate in random directions, desirable vibration-driven harvesters should be designed to utilize the three dimensional vibration. PDMS micro flexible structures are employed for this purpose and the free-standing PDMS casting method using a SU-8 casting mold was applied. It is also demonstrated that characteristics of the PDMS cantilever fabricated by our casting method were appropriate for vibration sources of low frequencies and wideband width.

Keywords: MEMS, PDMS, Energy harvesting, Molding

1. INTRODUCTION

Environmental energy harvesting is a technology that efficiently converts environmental energy sources to electrical energy. In recent years, demands for environmental energy harvesters have been rising. A representative application is power supply for the monitoring node of a sensor network system. Some example of environmental energy sources are vibration, heat gradient, and light, generated by machines, humans and etc. Conventional micro vibration energy harvesters are designed for adapting a particular direction of the vibration energy sources. Since many of actual ambient vibration energy sources are vibrating in random directions, desirable vibration energy harvesters should be designed to utilize the three dimensional vibration.

The environmental energy harvester is required to be small enough as the power supply of the sensor network system, though the small vibration energy harvesters tend to have high resonance frequency. However, environmental vibration generated by machines and humans consist of relatively low frequency band. Moreover, available frequencies of the actual vibration sources are broad. Therefore wideband characteristics have advantages for the vibration energy harvester.

In low frequency environment, electrostatic energy harvesters are better option, since mechanical design can be optimized separately from electric part.

In this paper, only mechanical design is discussed, and a PDMS free-standing cantilever structure is proposed to efficiently utilize three dimensional vibrations. It is also demonstrated that the PDMS cantilever fabricated by our casting method had low and wideband frequency characteristics

2. THEORY AND DESIGN
2.1. DESIGN FOR 3D VIBRATIONS

In this chapter, we describe a concept of the vibration energy harvester using an electret. An electret can hold the electric field for a long period of time. Fig.1 shows the outline of the energy harvesting concept. An electret is put between the upper electrode and the lower electrode. The cantilever vibration causes gap changes between the electrodes, and alters the strength of the electric field. As a result, the electron moves back and forth, which results in electric current in the external load. When the upper electrode vibrates in a parallel direction to the electret as shown in Fig.2, the strength of electric field also changes, and the electric current is caused.
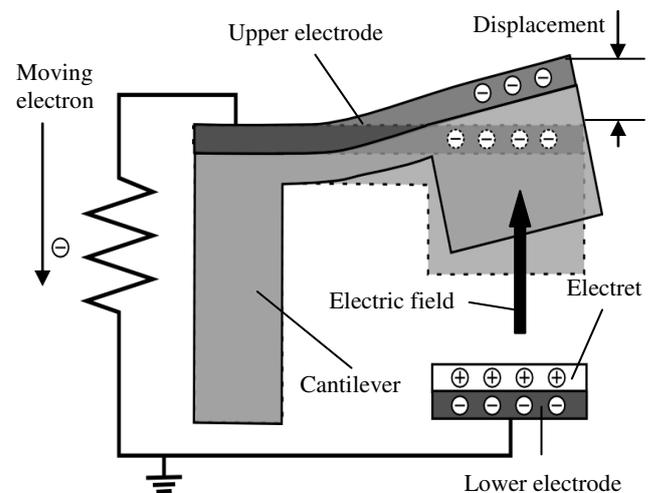

Fig.1. Concept of a electret energy hervesting device (Vertical direction).
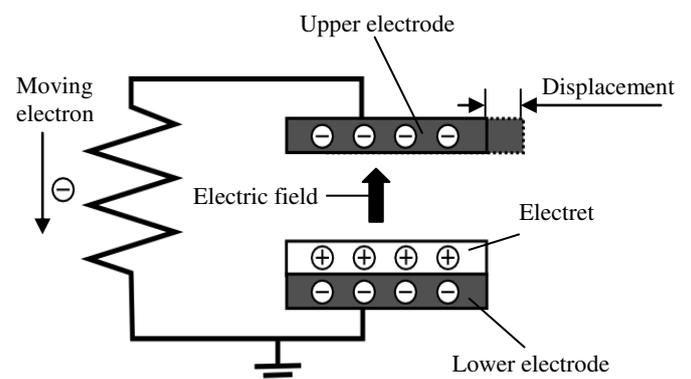

Fig.2. Concept of a electret energy hervesting device (Parallel direction).

When the upper electrode moves both in a vertical direction and a parallel direction, the energy harvester converts vibration energy into electric energy more effectively. Therefore, we design the device shown in Fig.3. In this configuration, the vertical direction is Z, the parallel direction is X and Y. When the cantilever moves with larger amplitudes, the energy harvesting device outputs higher electric energy since the change of the electrical field increases. Though in the direction of Z and X the cantilever moves with large amplitudes by appropriately designing thickness and the width, it is difficult in the direction of Y. Therefore we designed the new structure as shown in Fig.4. The new structure moves with large amplitudes in all direction, X, Z and Y.

2.2. DESIGN FOR LOW RESONANT FREQUENCY

The frequency of vibration of machines and humans is about 1 kHz or less. The resonance frequency of the cantilever should be designed within the range of this frequency band for efficiently converting mechanical energy to electric energy. Resonant frequency f of the first mode is given by,

$$f = \frac{k_1}{2\pi}\sqrt{\frac{EI}{\rho Al^4}} , \qquad (1)$$

where l is the length of the cantilever, I is the geometrical moment of inertia, E is the Young's modulus, A is the cross-sectional area, ρ is the density and k_1 of 1.875 is the first eigen value, respectively. The vibration energy harvester is usually made of Si by using the micromachining techniques. However, Young's modulus E is as high as 130 GPa for Si in <100> crystal orientation. PDMS is the polymeric material which has a characteristic of relatively low Young's modulus at about 2.5 MPa. As a result, the resonant frequency can be lowered by using PDMS even with the small size device.

2.3. DESIGN FOR BROADBAND

Machines and humans generate the vibration of not only a certain specific frequency but also various frequencies. When the device has a broadband characteristic, it can efficiently convert vibrations of various frequencies into electrical energy. A quality factor Q is given by,

$$Q = \frac{\sqrt{mk}}{2c} , \qquad (2)$$

where m is the mass of a structure, k is the spring constant, c is the viscous damping coefficient, respectively. When Q becomes smaller, a structure has the broader frequency characteristic. PDMS has the low spring constant and the high viscous damping coefficient. Therefore, PDMS is expected to have low Q, and broadband characteristics.

3. FABRICATION TECHNIQUE
3.1. MOLDING METHOD

The free-standing PDMS cantilever is casted using a SU-8 casting mold [1]. For making the SU-8 casting mold, at first SU-8 is coated on the 3 inch Si wafer, and the casting mold is formed on that. The purpose of this first layer is to prevent the structure being damaged when PDMS is released from the mold. The complex multi-layer casting mold can be fabricated by repeating SU-8 spin-coating and UV exposing, as shown in Fig.5. The depth of the casting mold for the cantilever and the proof mass are 240 μm and 400 μm, respectively. Fig.6 shows a photomicrograph of the casting mold.

A method of making the PDMS structures by the SU-8 casting mold is shown in Fig.7. The PDMS is poured into the casting mold, and a Polyethylene terephthalate (PET) seat is put on the PDMS. Then an extra Si wafer and the rubber board are placed on the PET seat. The stack comprising the casting mold, PDMS, PET seat, the extra Si wafer and rubber sheet is placed between two aluminium plates and fixed with screw. The fixed stack is cured for 2 hours by 80 degree in a hot plate. When the curing is completed, PDMS structures are peeled from the master.
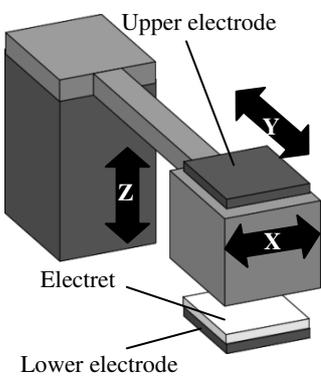

Fig.3. Concept of the energy hervester for moving in various directions.
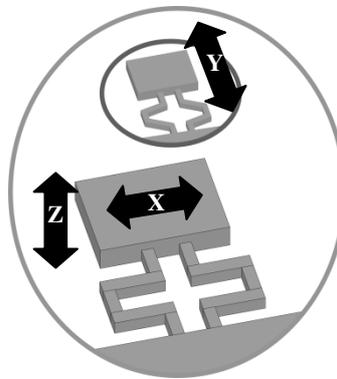
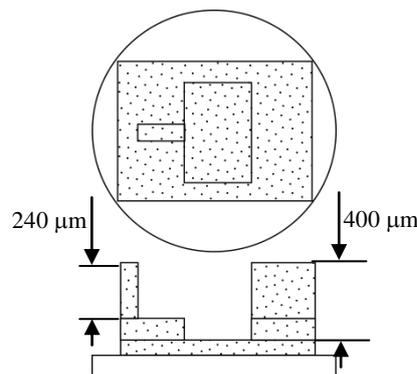Fig.4. The new structure for moving in various directions.
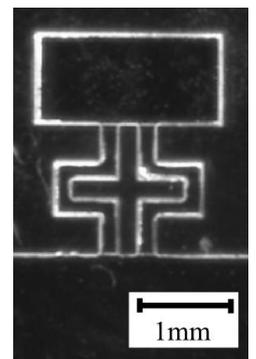

Fig.5. The casting mold for making cantilever.

Fig.6. A photomicrograph of the casting mold

3.2. FABRICATION RESULTS

Photomicrographs of PDMS cantilevers made by the casting mold are shown in Fig.8 (a). Unnecessary burrs existed around the cantilever [2]. Unnecessary burrs were caused by excess PDMS overflowing into narrow gap between the casting mold and the PET seat. It was not enough to eliminate unnecessary burrs by fixing two Al plates more tightly with s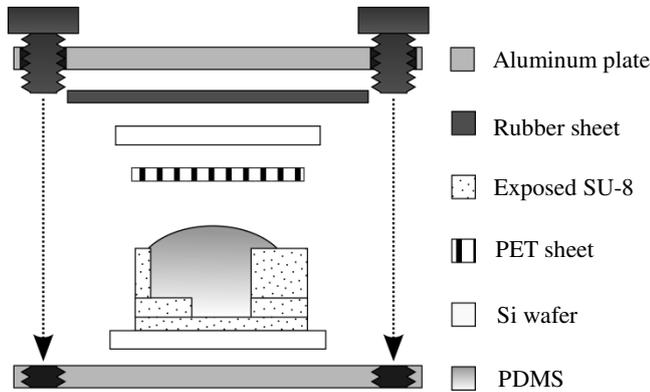crews. To avoid the burrs PDMS pools were located in the casting mold as shown in Fig.9. Since excess PDMS was absorbed by the pools, the PDMS free-standing structure was made without unnecessary burrs as shown in Fig.8 (b). The new structure for vibrating in various directions also was successfully fabricated without unnecessary burrs as shown in Fig.10.

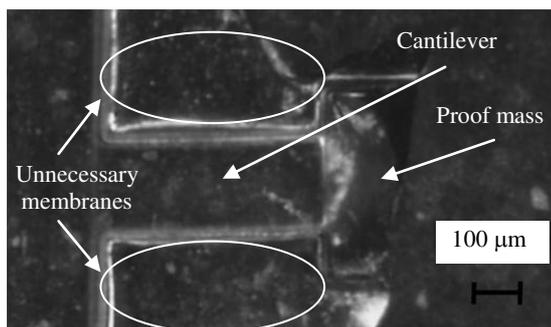Fig.7. The Free-standing PDMS casting method.

Fig.8 (a). PDMS cantilever without PDMS pool.
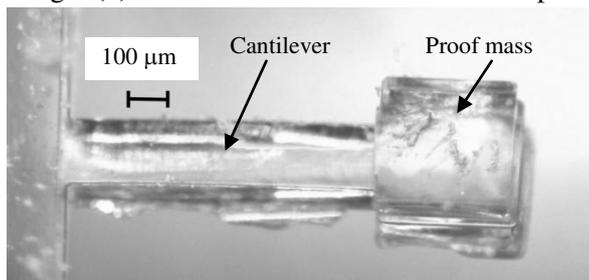
Fig.8 (b). PDMS cantilever with PDMS pool.

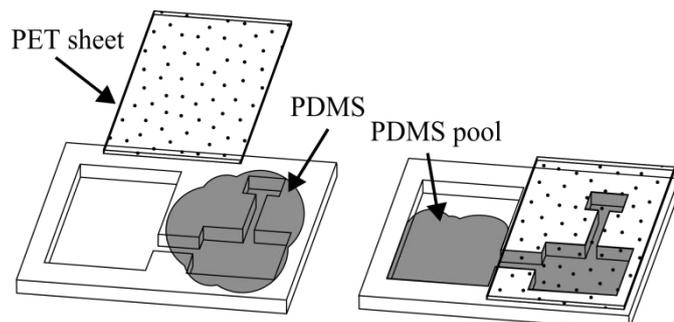Fig.9. PDMS pool made in the casting mold for remain membranes

4. OSCILLATION CHARACTERISTICS OF THE NEW STRUCTURE

Frequency characteristics of the PDMS new structure for vibrating in various directions are measured in an experimental set up shown in Fig.11. The oscillation amplitude of the shaker (PET-05-05A, IMV) and the PDMS structure are measured by the laser vibrometer (LV-1710, Ono Sokki). Moreover, when the amplitude is not able to be measured by he laser vibrometer, the amplitude is measured by the high speed camera recording and video analyses (VW-6000, KEYENCE) though resolution is inferior.

To demonstrate wideband characteristics, frequency characteristics of the PDMS cantilever is compared to a stainless wire cantilever (SUS304) having the same resonant frequency at 295 Hz. The PDMS cantilever has dimensions of 900 μm long, 200 μm wide and 230 μm thick. The length of stainless wire cantilever is 6.8 mm with 0.1 mm diameter. We set the PDMS proof mass with the same size of 400 × 400 × 350 μm at the tip of both cantilevers. The oscillation amplitude of these two cantilevers at the tip are measured by the laser vibrometer and normalized with maximum amplitudes as shown in Fig.12. The full width at half maximum of the PDMS and wire cantilevers are 150 Hz, 10 Hz, respectively. Therefore, the frequency characteristic of PDMS cantilever is broader than that of the wire cantilever.

Three dimensional characteristics of the cantilever are tested with the oscillation amplitude of the shaker at 20 μm_{p-p} in each three directions (X, Y and Z). The frequency characteristics are shown in Fig. 13, and the resonant frequencies are shown in Tab.1. In this experiment, the amplitude in X and Y were measured by the high speed camera recording and video analyses, and the amplitude in Z direction is measured by the laser vibrometer. The graph in Fig. 13 shows that the fabricated PDMS structure vibrates in various directions, X, Y and Z, though the amplitude in Y direction is relatively small. Peaks of the amplitude in each three directions were between about 160 Hz and 210 Hz. Therefore the PDMS cantilever has relatively low resonant frequencies. The full widths at half maximum in each three directions are between 40 and 90 Hz. Thus, it is demonstrated that the PDMS structure has a broader characteristic in the all three directions than the stainless wire cantilever.

5. CONCLUSION

The PDMS free-standing cantilever structures are successfully fabricated by the SU-8 casting mold with PDMS pool to eliminate unnecessary burrs. The maximum amplitude of 149µm in the Z direction is obtained at the resonant frequency of 160 Hz. The resonant frequencies in the all three directions are designed as low as 160 Hz to 210 Hz by talking an advantage of the low Young's modulus of PDMS. Wideband frequency characteristics of the PDMS cantilever are also demonstrated which is desirable for the low frequency environmental vibration sources.

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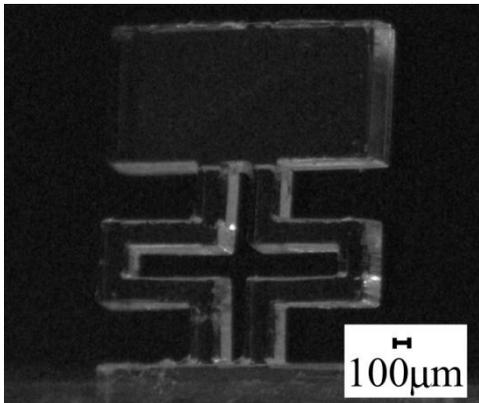
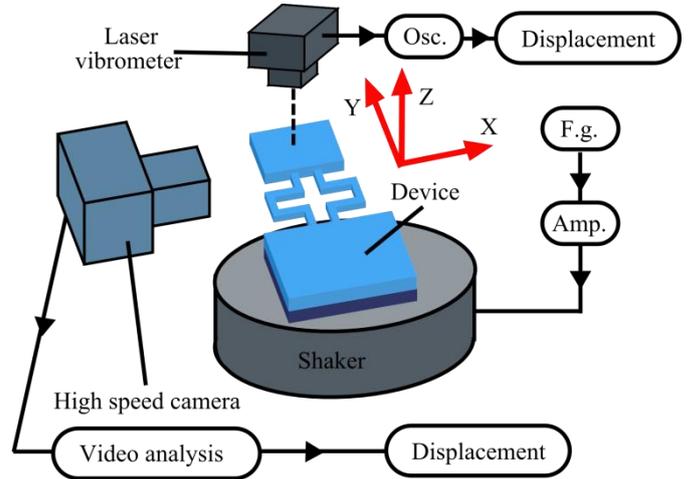Fig.10.The new PDMS structure made by casting mold.

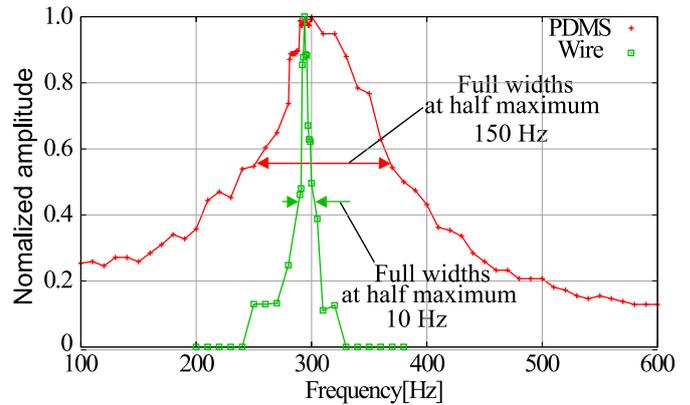Fig.11. Experimental setup for frequency characteristics.

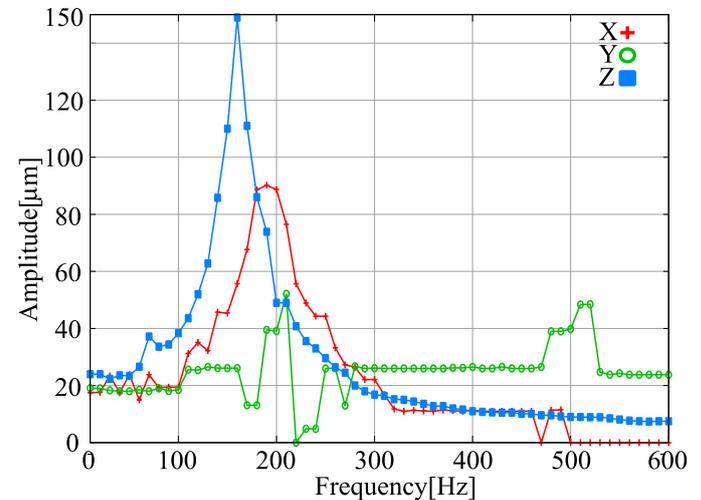Fig.12. PDMS has broad characteristics.

Fig.13. The PDMS structure vibrating in various directions.

Tab.1. Resonant frequency and amplitude of the PDMS structure.

Direction	Resonant frequency (Hz)	Amplitude (µm)
X	190	90.2
Y	210	52.1
Y	520	48.5
Z	160	149