Paper

Micromechanical Characterization of Self-Oscillating Microcantilever Using Piezoresistive Microsensors

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The flow-induced vibration of the microcantilever is investigated. In particular, to avoid flow disturbance resulting from size of measuring probe, we use the monolithic boron-doped piezoresistive microsensors. By characterizing the dynamic behavior of the microcantilever, the new micromechanics is experimentally determined, completely different from the conventional mechanics in the flow-induced vibration.

Keywords: flow-induced vibration, microcantilever, piezoresistive sensor, vortex shedding, natural frequency

1. Introduction

Micromachining has been developed into a hot research topic for four decades. Specifically, miniaturization of mechanical components for medical and biochemical fluid handling such as pumps, valves, sensors, and channels spurred growth of microfluidics quantitatively and qualitatively. Recent works did not present only miniaturization but also use of advantage of micro size. Tuckerman and Pease introduced a microchannel heat sink, having high heat transfer coefficient[1]. The experimental results showed that heat transfer coefficient was inversely proportional to the hydraulic diameter of the channel. Another application was the flow-through PCR device with fast thermal response basically resulting from small channel size[2][3]. Also, the microneedle using high capillary pressure was developed for blood sampling[4]. However, they are recognized still on the verge of making small since they can be governed by the Navier-Stokes equation and conventional heat transfer.

We for the first time challenge new micromechanics, completely different from conventional mechanics. In this paper, the flow-induced vibration of the microcantilever is compared with the conventional flow-induced vibration. Specifically, its dynamic behavior is experimentally characterized by using the monolithic piezoresistive sensors.

2. Theoretical Background

When an elastic bluff body is exposed to a steady flow, self-oscillation occurs[5][6]. The oscillation frequency is related to the vortex shedding around the structure. The vortex shedding frequency is expressed as:

$$f_s = S\frac{U}{D} \qquad (1)$$

where f_s indicates the dominant vortex shedding frequency, S Strouhal number, U free stream speed and D maximum width normal to the free stream. The Strouhal numbers for blunt bodies with circular and noncircular cross-section have been introduced[7]. The Strouhal number is generally a function of Reynolds number and geometry. Especially, in low Reynolds number, the Strouhal number increases with increasing Reynolds number. However, it is constant around 0.2 in higher Reynolds number.

Also, the previous works presents an experimentally evaluated correlation of Strouhal number for two-dimensional bluff body[8].

$$S = 0.028\left(\frac{D}{d}\right)\left(1-\frac{u}{U}\right) \qquad (2)$$

where d denotes the vortex street width and u vortex street velocity around the bluff body. However, as the width decreases, the ratio of the vortex street velocity to the free stream velocity approaches to unity since the vortex street width is closer to the width of the structure. As a result, it is impossible to evaluate the Strouhal number in the aspect of the conventional mechanics. In addition, there is no sensor to measure the vortex street velocity around the microstructure without disturbing the flow stream.

3. Microfabrication Process

To evaluate validity of conventional equation in microstructure, the microcantilever was fabricated. Fig. 1 illustrates the schematic diagram. It consists of two microbeams with initial deflection and piezoresistive sensors to characterize the dynamic behavior without disturbing the flow stream. Fig. 2 describes 5-masks fabrication process. The SOI wafer with 6 μ-thick n-type silicon/ 1μm-thick silicon dioxide was prepared. The fabrication starts with the thermal growth of 1000 Å-thick silicon dioxide (SiO_2), acting as a barrier for the subsequent deep boron diffusion process. The piezoresitive resistors were defined by patterning the silicon dioxide by using the first mask. In the process of Fig. 2(b), the boron diffusion process was performed at 1000 °C for 20 minutes. In the process of Fig. 2(c), the silicon dioxide was removed in buffered oxide etch solution (BOE) and thermally grown again to remove the boron glass layer. For electrical isolation, the 2000 Å-thick silicon dioxide was deposited. In the process of Fig. 2(d), the second mask generated contact windows for electrical interconnection. Fig. 2(e) depicted the aluminum sputtering process and patterning of the electrical lines by the third

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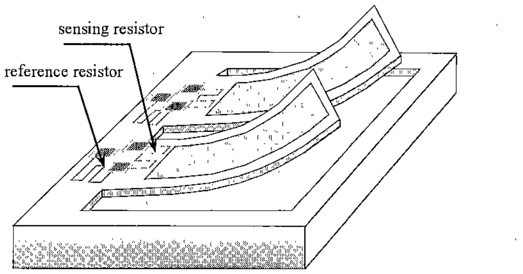


Fig. 1. Schematic view of the microcantilevers with sensors.

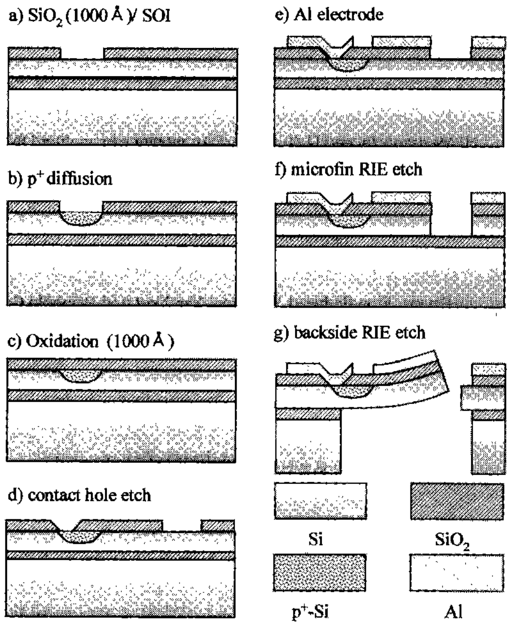


Fig. 2. Fabrication process of the microcantilever.

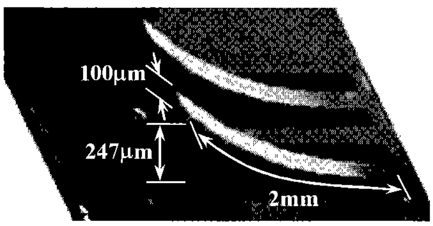


Fig. 3. Microcantilevers with upward initial deflection.

mask. In order to obtain the ohmic contact, alloy process was performed at 450 °C for 30 minutes. Fig. 2(f) included the dry etch to make the microcantilever by using the fourth mask. The fabrication process was completed by etching the backside of the silicon substrate using deep-RIE-etch in the step of Fig. 2(g). Due to built-in residual stress in bimorph, the microcantilever was initially deflected upward. Fig. 3 shows the fabricated microcantilevers. Based on the fabricated sizes, the natural frequencies were estimated to be 1.17, 7.34 and 20.54 kHz, respectively.

4. Experiment and Discussion

To measure the sheet resistance of the diffused resistors accurately, a Greek-cross pattern was used. The van der Pauw resistivity measurement can estimate the sheet resistance of the Greek-cross resistor within 0.1 % error for $L_G/w_G > 1.02$[9]. The

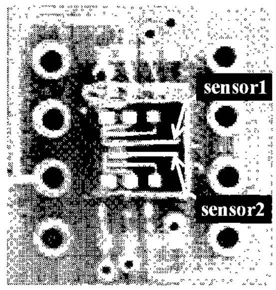
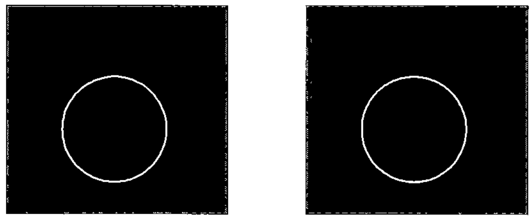


Fig. 4. Electrically wired microcantilevers with PCB.



(a) before air blowing (b) after air blowing

Fig. 5. Visualization of Flow-induced vibration of microcantilever.

sheet resistance was measured to be 43 Ω/□.

For signal processing, the electrodes on the silicon substrate were wired to the PCB electrodes as shown in Fig. 4. The measured electrical resistances of the sensing resistors were 2.33 and 2.30 kΩ, respectively. The resistances of the reference resistors were also measured to be 2.36 and 2.38 kΩ, respectively. Based on the measured resistors, a Wheatstone bridge circuit was instrumented to measure the vibration of the microcantilever. When the microcantilever vibrates, the built-in stress at the fixed end is changed. This results in the change of piezoresistivity and finally the voltage output is read.

The flow-induced vibration of the microcantilever was examined for air velocities of 3, 4, 5 and 6 m/s in the wind tunnel. The dynamic motion of the microcantilever was measured. The dynamic signal analyzer (HP, 35670A) determined the dominant vibrating frequency of the microcantilever by measuring the power spectral density. Also, by reading the voltage outputs from an oscilloscope (Tektronix, TDS 784A), the vibrating amplitude was obtained. An anemometer (KANOMAX, 6631) was also placed to calibrate inlet air velocity.

In Fig. 5, the flow-induced vibration of the microcantilever was visualized using a high-speed motion analyzer. In the absence of airflow, the microcantilever did not oscillate. As soon as air was blown over the microcantilever, it started to vibrate.

For quantitative evaluation, the power spectral densities for four different air velocities were measured as shown in Fig. 6. It was determined that the vibrating frequency of the microcantilever was fixed to be 1.17 kHz, independent of the inlet air velocity. Also, the second mode of vibration was shown up at 7.35 kHz for an air velocity of 6 m/s. By comparing the measured vibrating frequencies to the analytical natural frequencies, it was determined that the flow-induced microcantilever vibrates at the fundamental natural frequencies regardless of air velocity. This is completely different from the conventional flow-induced vibration.

For four different air velocities, the voltage outputs during 10 milliseconds were read for observing the long-term vibration behavior of the microcantilever (Fig. 7). Also, the peak-to-peak

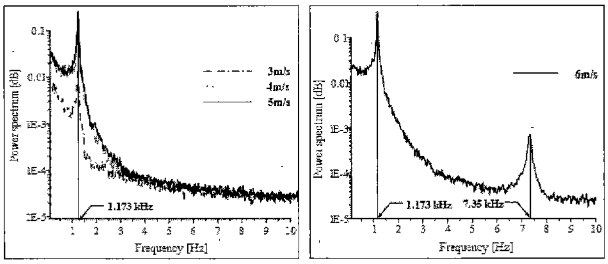
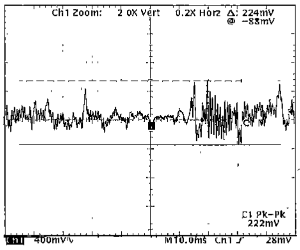
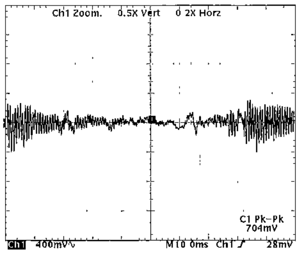
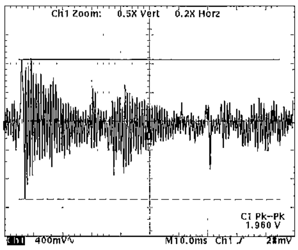


Fig. 6. Power spectrum analysis for four different air velocities.


(a) air velocity of 3 m/s


(b) air velocity of 4 m/s


(c) air velocity of 5 m/s

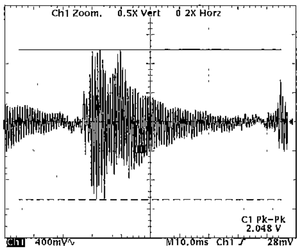

(d) air velocity of 6 m/s

Fig. 7. Voltage outputs of the microcantilever for 10 milliseconds.

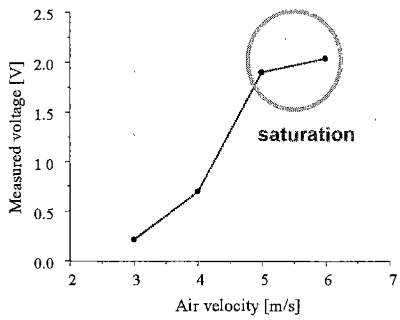


Fig. 8. Measured peak-to-peak voltage outputs of microcantilever.

voltage outputs of the microcantilever were illustrated in Fig. 8. The measured voltages tended to saturate with increasing air velocity as experimentally investigated in the torsional vibration of a plate[10]. It was reasoned that the saturation of the vibrating displacement was resulted from the occurrence of the second mode vibration. However, based on histogram of the microcantilever vibration, the microcantilever did not vibrate with a constant vibrating displacement. Besides, even though the microcantilever vibrated at the fundamental frequency, the destructive lock-in phenomenon resulting from matching of the vibrating frequency and the natural frequency did not occur.

5. Conclusion

In this paper, several new findings were experimentally obtained in the flow-induced vibration of the microcantilever. Firstly, the microcantilever vibrates at the fundamental frequency, independently of the flow velocity. Secondly, the destructive lock-in phenomenon does not occur in spite of vibration at the fundamental frequency. Finally, the amplitude tends to saturate due to appearance of the second mode vibration. They are completely different from the conventional mechanics on flow-induced vibration.

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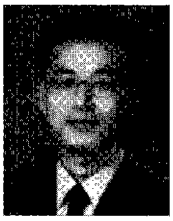

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