SURFACE MICROMACHINABLE ACCELEROMETER USING FRINGE ELECTRICAL FIELD OF PENETRATING FERROELECTRIC SUBSTRATE AND ITS CHARACTERIZATION

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Abstract: This paper reports fabrication and characterization of a high sensitive surface micromachinable accelerometer using ferroelectric material having a large dielectric constant, such as bulk PZT (εr=2600). The measuring principle is based on detecting capacitance change with respect to the dielectric mass movement in the fringe electrical field. High sensitivity of several sub pF/g is confirmed, which is increased several hundreds times compared with author’s previous sensor using polymer Parylene (εr=3.15). It is proven that the accelerometer bandwidth is much lower than the mechanical resonant frequency of the Parylene structure by FEM simulation and experimental investigation, the reason of which is also discussed.

Keywords: ferroelectric substrate, PZT, Parylene, accelerometer, sensitivity, characterization

1. INTRODUCTION

Several types of capacitive accelerometers have been proposed and some have been developed commercially [1]. However, because many conventional sensors for vertical acceleration detection are composed of two facing electrodes, a wafer-bonding process is necessary [2]. For lateral detection, because the devices are normally composed of high-aspect ratio beams and comb fingers, a Deep Reactive Ion Etching (DRIE) process is necessary [3].

Contrary to these accelerometers, we have previously proposed a new type of accelerometer that consists of a dielectric proof mass made of Parylene and a comb-shaped planar capacitor below it (Fig. 1) [4]. The measurement principle is based on detecting capacitance change with respect to the dielectric mass movement in the fringe electrical field. Since this sensor utilizes the fringe electrical field instead of the normal electrical field, the technology is greatly simplified and only surface micromachining is required.

However, owing to a low dielectric constant of Parylene (εr = 3.15), the sensitivity was rather low. To increase the sensitivity, the author lowered mechanical stiffness using spiral beams [5]; however, this method has two problems. One is that the stiction between the mass and the substrate is liable to occur during fabrication. Another is that the measuring range of acceleration is narrowed. The allowable amplitude of mass is defined by the gap length between the mass and the substrate: however, if the stiffness is comparatively low, the mass easily touches down to the substrate when applied comparatively large acceleration.

Considering this situation, the author has proposed the concept of using ferroelectric material having a large dielectric constant, such as bulk PZT (εr=2600), instead of Parylene (Fig. 2) [6]. Considering practical fabrication, ferroelectric
material is used for the substrate instead of the suspended proof mass. The measurement principle was verified by both the theoretical calculation using an approximate model, and the finite element method (FEM) simulation [6].

Following the report of [6], in this paper, the sensor (Fig. 3) is practically fabricated and the performance of it is characterized. In this characterization, it is proven that the accelerometer bandwidth is much lower than the mechanical resonant frequency of the Parylene structure by FEM simulation and experimental investigation, the reason of which is also discussed.

2. FABRICATION AND CHARACTERIZATION

Fabrication process is shown in Figs. 4 and 5. The fabricated device is shown in Fig. 6. To avoid stiction, bumps are made, and the sacrificial layer of amorphous silicon is dry-etched by XeF$_2$ gas.

The sensitivity is characterized by an experimental setup (Fig. 7). The capacitance change is detected with the aid of a readout IC (MicroSensors Inc., MS3110), which converts capacitance change into voltage. A commercial accelerometer (EMIC Corp., 540-E) is used for reference. The gap length between the proof mass and the substrate is very small, approximately 1 µm, and no vent holes are set on the proof mass, which makes the squeezed film damping effect of the device too severe. Therefore, the fabricated sensor is shaken by a piezoelectric actuator in a vacuum chamber to remove air damping effect, considering hermetic packaging in future, whereas the commercial one is shaken in atmospheric pressure.
Example waveforms at 50, 700, 3000 Hz are shown in Fig. 8. At 50 Hz, although the commercial sensor cannot detect small acceleration, the fabricated sensor detects it with good S/N ratio. There is a phase lag between the output of the commercial sensor and the developed one at 700 and 3000 Hz. The frequency response of the gain is shown in Fig. 9. Seeing this figure, the frequency bandwidth is limited up to 650 Hz, which is the reason of the phase lag mentioned above. Over this frequency, the gain is decreased by -40 dB/dec, which implies that this sensor structure can be assumed as a second-order vibration system.

At 700 Hz, changing the amplitude of the shaker, the amplitude of the developed sensor’s output is compared with that of commercial one’s (Fig. 10). It is confirmed that linearity between the sensor output and the input acceleration is achieved. The sensitivity of the developed sensor is estimated as 0.4 pF/g at this frequency, which is increased several hundreds times compared with author’s previous sensor using polymer Parylene ($\varepsilon_r = 3.15$) [6]. The achieved sensitivity is comparable order with those of reported high-resolution types of microaccelerometers [1, 3].

### 3. DISCUSSION ON BANDWIDTH

Since the characterization was done in the atmospheric pressure at the earliest stage, the reason for the phase lag and the narrow bandwidth mentioned above was thought to be the air damping. Following this, to remove the air damping effect, the experiment is carried out in vacuum in this paper; however, the bandwidth is not improved, which is still narrow at 650 Hz.

In vacuum, the damping ratio $\zeta$ is apparently below 1, thus the electrical bandwidth is theoretically up to the mechanical resonant frequency of $f_r$. Taking account of the intrinsic tensile stress of Parylene (estimated as 10 MPa experimentally by using a rotational tip method, the detail is omitted for want of space), the $f_r$ of the fabricated structure is simulated by FEM (Fig. 11), which is proven to be 8.2 kHz. Using a vacuum chamber and a laser Doppler vibrometer (Fig. 12), the $f_r$ of the fabricated structure is experimentally investigated. Three samples of with/without aluminum electrodes are tested, to check the influence of aluminum coating on Parylene on $f_r$. The result is shown in Fig. 13. It is experimentally confirmed that $f_r$ is 7.9–8.8
kHz, which agrees with the FEM simulated result (see Fig. 11). It is also confirmed that the aluminum coating effect on \( f_r \) can be negligible.

The bandwidth of fabricated accelerometer including electrical circuitry, which is characterized as approximately 650 Hz (see previous chapter), is much lower than the mechanical \( f_r \). Considering these results totally, the reason for this difference may be caused by the issues related to the electrical measurement method. Checking the actual bandwidth of the employed CV converter IC is in progress. Employment of other CV converter circuitries is also ongoing.

5. CONCLUSIONS

Fabrication and characterization of a high sensitive surface micromachinable accelerometer is reported, which uses ferroelectric material having large dielectric constant, such as bulk PZT \( (\varepsilon_r = 2600) \). The high sensitivity of several sub pF/g, which is increased about several hundreds times compared with a sensor using polymer Parylene \( (\varepsilon_r = 3.15) \), is confirmed. The difference between the accelerometer bandwidth and the mechanical resonant frequency is investigated by the FEM simulation and the experimental method.

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