Abstract

Vibration modes of MEMS piezoelectric diaphragms responding to an ultrasound pulse were investigated and influence of top electrodes to the vibration modes was discussed. The top electrode has a centrosymmetric shape divided into inner part for ultrasonic sensing and outer part for resonant frequency tuning. Piezoelectric output signal is generated in the inner electrode by centrosymmetric vibrations. The piezoelectric diaphragms were fabricated in flat or buckled shape and the top electrodes of various thickness were formed on them. Pulse-induced vibration modes were evaluated by using scanning laser Doppler vibrometry. The buckled diaphragms showed resonant peaks in a narrower frequency range compared to the flat diaphragm. The top electrode showed an influence on the vibration modes so that vibrations with a large amplitude spontaneously concentrated in the sensing electrode area, even in the case of a thin electrode film around 10 nm.

Keywords: resonant mode, vibration mode, diaphragm, piezoelectric, ultrasonic sensor

1. Introduction

Piezoelectric micromachined ultrasonic sensors have been developed [1–3] to utilize for three-dimensional measurement in applications to under water or medical imaging, or gesture recognition using airborne ultrasound. The authors have been developing two-dimensional array sensors on silicon-micromachined diaphragm structures with lead-zirconate-titanate (PZT) films for three-dimensional airborne ultrasonic measurement [4,5]. Figure 1 illustrates a structure of a single element of the array sensor. A PZT capacitor is formed on a thermally oxidized silicon (SiO2) diaphragm. The top electrode of the capacitor is divided into two parts of the inner electrode for ultrasonic sensing and the outer electrode for resonant frequency tuning [6]. The array sensor is used as a phased array in the three-dimensional measurement to detect the incident angles of the reflecting ultrasound, that is, the output signals from the
sensor elements of the array are processed with delay-and-summation technique. The summed-up signal is strongly affected by frequency scattering of each signal [5], and the outer tuning electrode of the sensor shown in Fig. 1 resolves this issue through resonant frequency tuning on each sensor element. On the other hand, the third dimension of radial distance is determined by time-of-flight of the ultrasound, and a short pulse waveform is used from the viewpoint of distance resolution. However, the short ultrasound pulse has a broad frequency spectrum beyond the designed fundamental resonant frequency of the sensor, and might cause higher order vibration modes on the sensor diaphragm. Previously the authors reported that vibration modes in impulse response of piezoelectric diaphragms without top electrode [7]. In this work, we investigated the influence of the top electrode to the vibration modes of the piezoelectric diaphragms.

2. Experimental

2.1. Fabrication of piezoelectric diaphragms

A 2-inch silicon wafer with 1 μm-thick SiO₂ was used as the starting substrate. Bottom electrode of platinum and titanium films were deposited on the substrate by using rf magnetron sputtering. Piezoelectric PZT film was then formed through sol-gel method up to 950 nm-thick (Mitsubishi Materials, type E1, 15wt% in 1-butanol, Pb/Zr/Ti=115/52/48). Next, the top electrode of gold film was deposited by using rf magnetron sputtering and patterned to form the double top electrode shape by etching with I₂+KI solution. Finally the SiO₂ on the backside was etched with buffered hydrofluoric acid to form windows, and silicon substrate was vertically etched through the windows by using ICP-RIE (SAMCO, RIE-400iPB) with conventional Bosch process to complete the diaphragm structures.

Buckled diaphragms were fabricated for a comparison to flat diaphragms because upward bucked diaphragms yield higher sensitivity than flat or downward ones [8]. The buckling behavior was controlled by residual stress of PZT through sol-gel preparation condition [9]. Thickness of the top electrode was controlled simply by the sputtering time. A normal sensor has the top electrode with 50 nm-thick gold film deposited for 2 minutes at 40 W. We also prepared top electrodes with the deposition time of 1 minute and 30 s. These thickness are referred to as 25 nm and 12.5 nm for convenience, although the thickness of these thin films were not precisely confirmed. Figure 2 shows three-dimensional profiles of the flat and the buckled diaphragms, and top view photographs of the buckled diaphragms having the top electrodes with the various thickness.

2.2. Evaluation of pulse induced vibration modes

An ultrasound pulse was generated by using a spark discharge sound source [7]. A pair of needles is set to face each other and parallelly connected to a capacitor which is being charged from a battery. When air between the
needles electrically breaks down with a spark discharge, a short ultrasound pulse is generated. The pulse has typically a duration around 25 $\mu$s and a broad spectrum centered at 80 kHz in the range from audible frequencies to 150 kHz, which were confirmed with a calibrated microphone (Brüel & Kjær, Type 4138). Vibration modes of the diaphragms responding to the pulse were measured by using a scanning laser Doppler vibrometer (Polytec, PVS-400) [7].

Fig. 3. Evaluation results of the pulse response of the diaphragms. (a) flat diaphragm without top electrode, and buckled diaphragms having (b) no top electrode and (c) 12.5 nm-thick, (d) 25 nm-thick and (e) 50 nm-thick top electrode. (i) major vibration modes of measured results and corresponding theoretical modes derived from a flat, no-stressed plate without an electrode (if available), (ii) frequency spectra at the center of the diaphragm, and (iii) time course vibration waveforms at the center of the diaphragm.
3. Results and Discussion

Typical examples of major vibration modes on the whole diaphragm, and frequency spectra and vibration waveforms at the center of diaphragms are shown in Fig. 3. Diaphragms without top electrode showed three major centrosymmetric vibration modes corresponding to theoretical ones, but resonant peaks of the buckled diaphragm distributed in a narrower frequency range than that of the flat one. In both cases, all these modes have a large amplitude and the vibration waveforms showed distorted damping oscillation due to interference of the vibrations with different frequencies. On the other hand, the diaphragms with top electrode showed no corresponding theoretical vibration modes, and one of the centrosymmetric mode has a dominant amplitude. Since the side peaks have much smaller amplitude, the damping oscillation of the vibration waveform showed almost no distortion.

Vibration on the diaphragms with the top electrode was concentrated into the inner sensing electrode region in all electrode thickness of 50, 25 and 12.5 nm, and each vibration mode showed much more similar patterns among them compared to the difference of those between the diaphragms with and without the electrode. The gold film with the thickness 12.5 nm of the top electrode has a mass component of only 2.5% to the whole diaphragm, which might have no enough mechanical influence to the vibrations. On the other hand, the electrode can have a large electrical influence by homogenizing the electric field in the piezoelectric layer under the electrode, even with a very thin gold film. Under the homogenized electric field, piezoelectric polarization can not distribute according to only the mechanical vibration, and converse piezoelectric stress would be generated from the difference between the free mechanical polarization distribution and the restricted distribution under the homogeneous field. This might cause the concentration of the vibration into the central electrode region.

4. Conclusions

Vibration modes of micromachined piezoelectric diaphragms responding to an ultrasound pulse were investigated. The piezoelectric diaphragms were fabricated in flat or buckled shape and the top electrodes of various thickness were formed on them. The buckled diaphragms showed resonant peaks in a concentrated narrow frequency range compared to the flat diaphragm. The top electrode showed influence on the centrosymmetric vibration modes to spontaneously concentrate on the sensing electrode, which might be caused through homogenized electric field by the electrode.

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