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Microfabrication and Application of Series-Connected PZT Elements

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Abstract

This paper presents series-connected PZT elements that yield high output voltage, and also shows complete establishment in the fabrication process. Series-connected PZT elements are realized by connecting the upper electrode of a PZT element with the lower electrode of another PZT element. Sputtered PZT thin-film has perovskite crystalline structure and piezoelectric coefficients up to 40 pC/N. To avoid troublesome wet etching, the PZT films, the electrodes, and insulation layers are dry-etched. The all dry-etching process performs multilayer wiring of the electrodes. Evaluations for the PZT elements validates that the output voltage is the sum output voltage of each single element.

Keywords: Microfabrication; Series-connected PZT elements; Multilayer wiring; High output voltage

1. Motivations

Recently, PZT (Lead Zirconate Titanate) thin film has widely been used for the integration of sensors, actuators, and energy harvesting devises because of its great piezoelectric characteristics that include high response rate, low energy consumption, and large displacement. The application of PZT to MEMS is still difficult, although PZT is a promised material in MEMS fields. The reason is mainly that reproducible and stable PZT deposition is difficult and that PZT is generally wet-etched (e.g. it leads to degrading piezoelectric characteristics and undercut etching of the structure). On the other hand, the miniaturization of sensors leads to poor intensity and signal-to-noise ratio of the output signal. Realization of integrated sensor generating high output voltage must allow the flexible circuit design and improves the signal-to-noise ratio. The output voltage obtained from PZT on a deformed cantilever is proportional to the in-plane stress of the PZT thin-film. If the PZT thin-film is separated to some areas and series-connected, the obtained output voltage becomes the total summation of the output voltages of the each element. The summation of the local in-plane stress in each separated area is much larger than the averaged one in the net PZT area. Therefore the high output voltage is obtained from series-connected PZT elements. Figure 1 shows the conceptual diagram of the amplification of the output voltage of series-connected PZT elements. Itoh et al. have

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reported digital accelerometer using PZT elements, which is series-connected and laterally arrayed on a cantilever, and CMOS switches (Fig. 2)[1]. They successfully fabricated the accelerometer with series-connected PZT elements using sol-gel PZT deposition and wet etching. For the further integration, dry-etching process would be preferred. In addition, the obtained output voltage of the sensor did not corresponded to the summation of the output voltages of each element. In this research, we focus on the amplification of the output voltage using longitudinally series-connected PZT element. The fabrication process utilizing dry-etching process is established and it is validated that the output voltage is a summation of the each one for series-connected PZT. A longitudinal series-connection of PZT elements also enhances the amplification of the output voltage.

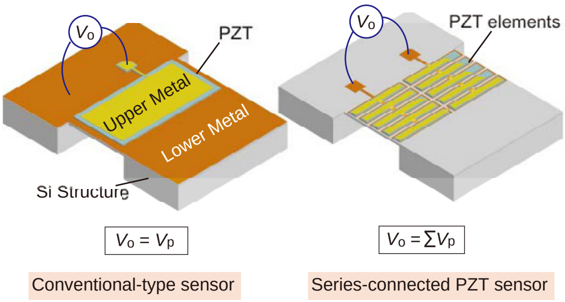

Fig. 1 Conceptual diagram of series-connected PZT elements.

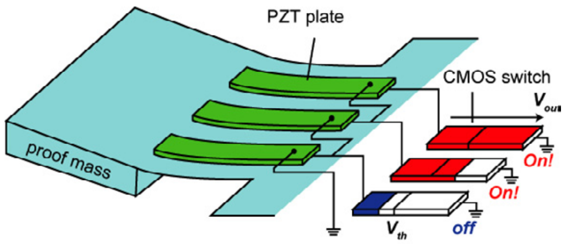

Fig.2 Digital output accelerometer reported by Itoh et al.[1].

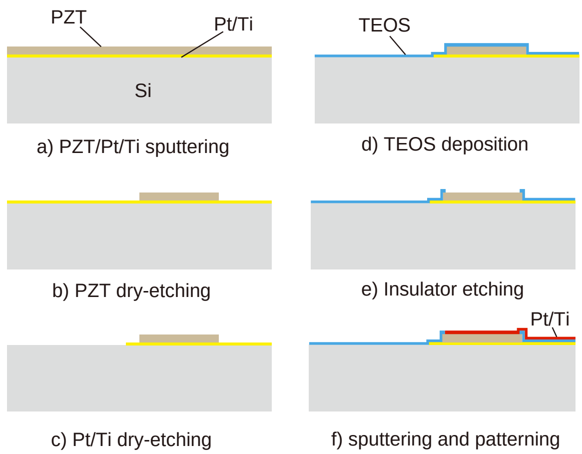

Fig.3 Fabrication process of series-connected PZT elements on Si substrates.

Table 1 Condition of PZT deposition using RF magnetron sputtering. Instrument: CS200Special (ULVAC, Inc., Japan) size of target PZT: ϕ300mm, sample: ϕ100mm.

	Ti	Pt	PZT
Substrate temperature (˚C)	530	530	475
RF power density (W/cm^2)	6.2	6.2	1.4
Gas rate (sccm)	Ar: 40	Ar: 40	Ar: 39 O_2: 0.5
Thickness (nm)	10	100	3000
Deposition rate (nm/min)	12.5	21.4	10.6

2. Fabrication and Evaluations

Figure 3 indicates the fabrication process of the cantilever with the series-connected PZT elements. At first, PZT and Pt/Ti lower electrode were deposited (a). Next, the PZT and Pt/Ti were individually dry-etched (b, c). A TEOS layer was deposited on PZT using chemical vapor deposition for insulating upper and lower electrodes (d), and was patterned by using CHF_3 plasma etching (e). At last, sputtering and dry-etching upper Pt/Ti electrodes (f) performed series-connected PZT elements.

2.1. Sputtering PZT and the Evaluations

Table 1 indicates the condition of PZT deposition. PZT thin-film with a thickness of 3μm was sputtered. The crystalline structure was evaluated using X-ray diffraction (XRD). The measurements clearly revealed that the PZT thin-films have a polycrystalline perovskite structure with a preferential (0 0 1) orientation (Fig. 4). An SEM image of the cross-section demonstrates that PZT was deposited without pores or cracks (Fig. 5). The polarization and electrical field (*P-E*) hysteresis loop was measured for evaluating the electrical properties. Obtained *P-E* curve indicated a typical ferroelectric behavior (Fig. 6). The remanent polarization and the coersive electric field of the PZT thin-film was -14, 16 μC/cm^2 and -70, 60 kV/cm, respectively. To evaluate the piezoelectric characteristics, a simple cantilever with the PZT thin-film and the upper metal electrode was fabricated, and a sinusoidal voltage was applied. From the tip displacement of the cantilever, the piezoelectric coefficients, d_{31}, was measured up to 40 pC/N.

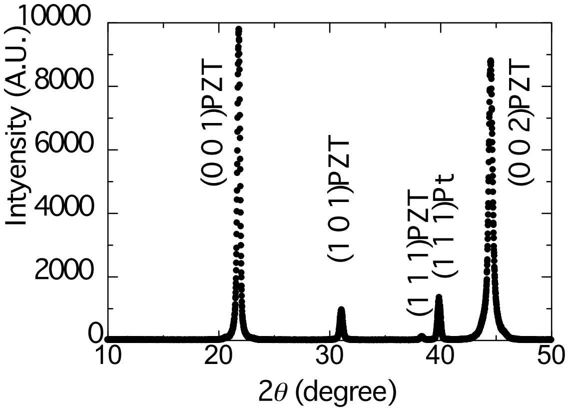

Fig. 4 XRD pattern of PZT thin-film. The PZT thin-film has perovskite crystalline structure with a (0 0 1) preferential orientation.

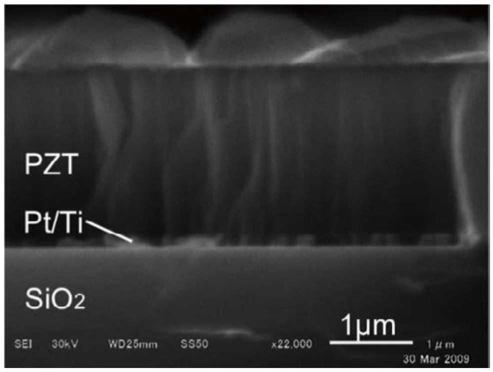

Fig. 5 SEM image of cross-section of the PZT thin-film.

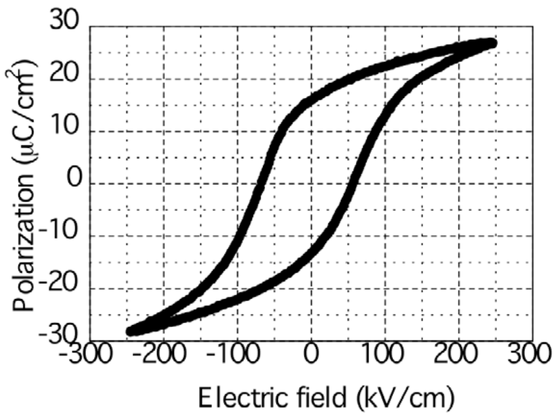

Fig. 6 *P-E* hysteresis curve of the PZT thin-film at a frequency of 1 kHz.

2.2. Dry-etching process

For the fabrication of the series-connected PZT element, all etching process was conducted using plasma dry-etching. Especially for the thick PZT (compared with other materials) etching, not only etch rates, but the selectivity to metals and photoresist materials are important. Four dry-etching conditions were optimized in this study; 1) high PZT etch rate and high selectivity to photoresist, 2) PZT etching, highly selective to the lower metal of Pt, 3) Pt/Ti etching, 4) TEOS etching. These etching conditions are shown in Table 2. A well-established selective dry-etching process for PZT patterning and multilayer wiring of PZT electrodes yielded etching selectivity to Pt/Ti beyond 71, which is the highest value in our best knowledge. For the insulation of multilayer wiring, TEOS layer was patterned by using CHF_3 dry-etching. After sputtering and dry-etching the upper electrode-metal, Pt/Ti, multilayer wiring was performed. Figure 7 shows the SEM image of the series-connected PZT elements with multilayer wiring. These images clearly indicate successful multilayer wiring and selective dry-etching of PZT to Pt/Ti.

Table 2 Dry-etching conditions. A: PZT etching of high-rate and selective to photo-photoresist (selectivity: 1.25), B: PZT etching of highly selective to Pt/Ti (selectivity >71), C: Pt/Ti etching. Instrument: RIE-101iPH, (Samco, Inc., Japan), D: TEOS etching.

	A	B	C	D
Pressure (Pa)	0.65	1.0	1.5	5.0
ICP power (W)	500	500	200	200
Bias power (W)	200	50	50	20
Gas rate (sccm)	Cl_2: 5	Cl_2: 5	Cl_2: 7	CHF_3: 50
	BCl_3: 50	BCl_3: 50	Ar: 21	
	CH_4: 2.4	CH_4: 2.4		

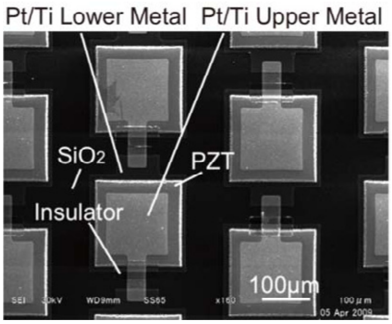

Fig. 7 SEM image of multilayer wiring.

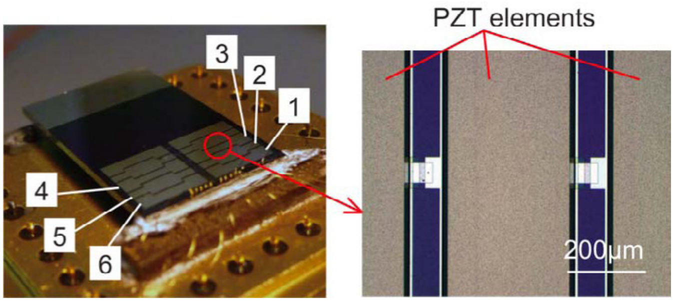

Fig. 8 Optical image of the device wired on a can-package. Six PZT elements connected serially were evaluated.

3. Measurements of Output Voltage

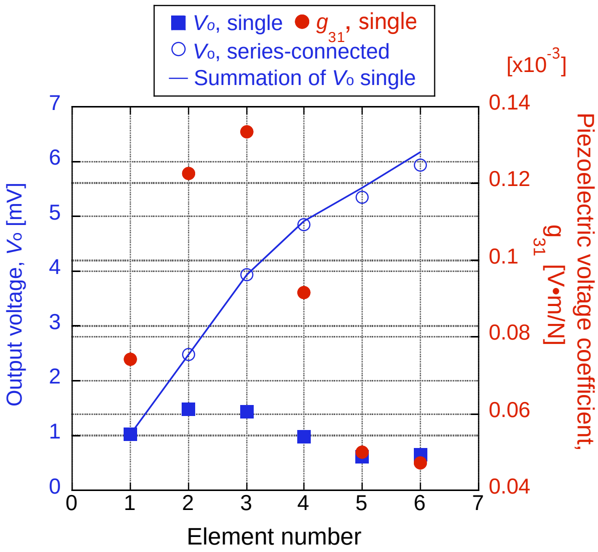

Fig. 9 The output voltage and piezoelectric voltage coefficient, g_{31} measured using a Doppler vibrometer.

To confirm that series-connected PZT elements yields high output voltage, cantilever with series-connected PZT elements was diced and the output voltage was measured. A packaged device image is shown in Fig. 8. The size of the cantilever is 16.5mm x 10mm x 0.5mm. The output voltages of series-connected six PZT elements on the cantilever were measured. The cantilever was vibrated at a resonant frequency of 2174 Hz using a stacked bulk PZT actuator. The peak-to-peak amplitude was 19.3μm. Figure 9 shows the relationship between connected element number and output voltage. The output voltage obtained from the each element (hollow-circle dots) and the calculated values of the piezoelectric voltage coefficient, g_{31} (circle dots) are also plotted. The line indicates the summation of the output voltage of each element. The results clearly demonstrate that the output voltage obtained from the series-connected PZT elements corresponds to the summation of the output voltage of each element. The calculated g_{31} values were very small (the corresponding piezoelectric coefficients, d_{31}, are about 1.2 pC/N). However, the PZT elements did not experience any poling treatments. Actually, other experiments with a poling treatment of 200 kV/cm for 10 minuets exhibit the values of g_{31} of 2.7 ~ 4.1 x 10^{-3} V·m/N. The optimization of the poling treatments is a future work.

4. Conclusions

For amplifying output voltages of sensors, longitudinally series-connected PZT elements is proposed and the test device was fabricated. Sputtered PZT thin-film showed ferroelectric characteristics with piezoelectric coefficients, d_{31} of up to 40 pC/N. Well-established PZT processing techniques performed selective-etchings of PZT and electrode metals, Pt/Ti, resulting in the realizations of multilayer wiring and series-connected PZT elements. Oscillation measurements of the series-connected PZT elements validated that the output voltage of the device is the summation of that of each single element.

References

1. Itoh T, Kobayashi T, Okada H, Masuda T, Suga T. A Digital Output Piezoelectric Accelerometer for Ultra-low Power Wireless Sensor Node. *Proc IEEE Sensors 2008 Conf*: 544-47.