Sensors and Actuators A 238 (2016) 71–79

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Multilayer piezoelectric haptic actuator with CuO-modified PZT-PZNN ceramics

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ARTICLE INFO

Article history:
Received 12 July 2015
Received in revised form 6 November 2015
Accepted 9 December 2015
Available online 11 December 2015

Keywords:
Piezoelectric
Actuator
Haptic
Multi-layer
PZT-based ceramics

ABSTRACT

A piezoelectric haptic actuator composed of a multilayered ceramic (MLC) of 0.5 mol% CuO-modified $0.69Pb(Zr_{0.47}Ti_{0.53})O_3$–$0.31[Pb(Zn_{0.4}Ni_{0.6})_{1/3}Nb_{2/3}]O_3$ (0.5CPZT-PZNN) ceramic was developed and characterized. The 0.5CPZT-PZNN ceramic was well-sintered at 900 °C. This ceramic showed a small $\varepsilon^T{}_{33}/\varepsilon_o$ of 1801 and a large d_{33} of 570 pC/N, necessary characteristics for high-performance actuators operating at low voltages. This ceramic also showed a high field-induced strain, maintained after 10^6 fatigue cycles. A three-layer MLC was synthesized at 900 °C using this ceramic. Ag metal was used as the electrode for the MLC actuator. No inter diffusion between the Ag electrode and the 0.5CPZT-PZNN ceramic layer was observed. The MLC actuator exhibited a high free stroke of ± 300 μm even after 10^6 bending cycles. The piezoelectric haptic actuator fabricated using this MLC showed a large vibration acceleration of 2.1 G with a low capacitance of 20 nF. This demonstrates the suitability of the 0.5CPZT-PZNN ceramic for applications in piezoelectric haptic actuator.

1. Introduction

Piezoelectric actuators have been used in many industrial applications, such as ink-jet printers, fuel-injection nozzles in automobile engines, and ultrasonic motors [1–3]. Recently, investigation on piezoelectric vibration actuators has increased in the interest of their applications in haptic devices for portable electronics [4–6]. Piezoelectric vibration actuators for haptic devices must have large vibration accelerations with low power consumption, to minimize the need for battery replacement. Multilayer ceramics (MLCs) are frequently used for the successful fabrication of piezoelectric vibration actuators; these possess a high strain (or vibration acceleration) at low operating voltages [1,7]. The strain of the actuator increases with increased layers in the MLC; however, the capacitance of the actuator also increases, resulting in increased power consumption. Since the dielectric constant of a material ($\varepsilon^T{}_{33}/\varepsilon_o$) is proportional to its capacitance, the piezoelectric ceramics used for the MLC must have small $\varepsilon^T{}_{33}/\varepsilon_o$ for applications to in low-power-consumption vibration actuators. Therefore, the ceramic comprising the vibration actuator ideally has a large piezoelectric strain constant (d_{ij}) as well as a small $\varepsilon^T{}_{33}/\varepsilon_o$ for simultaneous large vibration and low power consumption.

$Pb(Zr,Ti)O_3$-based piezoelectric ceramics with morphotropic phase boundary compositions are generally used for actuator devices because of their large d_{ij} value [8–12]. However, since these ceramics also show large $\varepsilon^T{}_{33}/\varepsilon_o$ values, they are unsuitable for low-power consumption actuators [8–12]. Recently, a rhombohedral $0.69Pb(Zr_{0.47}Ti_{0.53})O_3$–$0.31[Pb(Zn_{0.4}Ni_{0.6})_{1/3}Nb_{2/3}]O_3$ (PZT-PZNN) ceramic, sintered at 1100 °C, was shown to possess a large d_{33} value with a small $\varepsilon^T{}_{33}/\varepsilon_o$ [13,14]. This recommends the PZT-PZNN ceramic as a good candidate for piezoelectric vibration actuators. However, its sintering temperature is too high to fabricate MLCs with Ag electrodes. For MLCs with Ag electrodes, the ceramic must be sintered at 900 °C without degrading its piezoelectric properties. According to previous works, CuO was successfully used to decrease the sintering temperature of $0.65PZT$–$0.35Pb(Ni_{1/3}Nb_{2/3})O_3$ without losses to their piezoelectric properties [12]. Therefore, in this work, a small amount of CuO was

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http://dx.doi.org/10.1016/j.sna.2015.12.012
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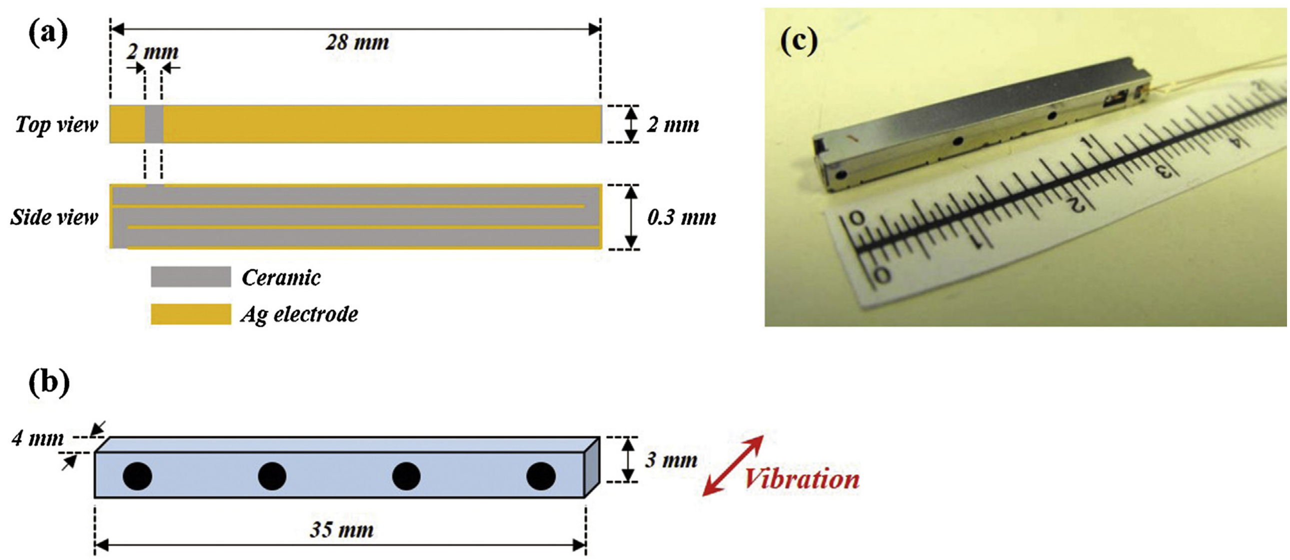

Fig. 1. Schematic of (a) the three-layer MLC and (b) the piezoelectric vibration haptic actuator; (c) photograph of the fabricated piezoelectric vibration haptic actuator.

used to permit sintering of PZT-PZNN at 900 °C; three-layer MLCs were successfully synthesized using the CuO-modified PZT-PZNN ceramic. Finally, piezoelectric actuators were produced using this MLC; their vibrational properties were carefully investigated.

2. Experimental procedures

Powdered PbO, ZrO_2, TiO_2, ZnO, NiO, and Nb_2O_5 (>99%, High Purity Chemicals, Saitama, Japan) were mixed for 24 h in a nylon jar with zirconia balls in ethanol with a composition of $0.69Pb(Zr_{0.47}Ti_{0.53})O_3$–$0.31[Pb(Zn_{0.4}Ni_{0.6})_{1/3}Nb_{2/3}]O_3$ (PZT-PZNN). After drying the powders mixture, it was calcined at 850 °*C* for 4 h. The calcined powder was re-milled with CuO additives at levels of x mol%, where $0.0 \leq x \leq 5.0$, for 24 h. The x mol% CuO-modified PZT-PZNN (xCPZT-PZNN) powders were pressed into discs at a pressure of 100 kgf/cm^2 and sintered at 900 or 925 °C for 4 h. Three-layer MLCs were synthesized using the 0.5CPZT-PZNN ceramic by tape-casting. The Ag electrode was screen-printed on the 150 μm—thick green sheets, prior to laminating the MLCs with three ceramic layers. The three-layer MLCs were burned out at 500 °C for 10 h and subsequently sintered at 900 °C for 4 h . The schematic structure of the three-layer xCPZT-PZNN MLC is depicted in Fig. 1(a). Moreover, both a schematic and a photograph of the piezoelectric vibration actuator module are presented in Fig. 1(b) and (c), respectively. The structural properties of the specimens were investigated by X-ray diffraction (XRD; D/max-RC, Rigaku, Tokyo, Japan) and scanning electron microscopy (SEM; S-4300, Hitachi, Osaka, Japan). The compositions of the specimens were identified by an energy-dispersive X-ray spectroscope (EDX: EMAX, Horiba, Kyoto, Japan) attached to the SEM. The densities of the sintered ceramics were measured by the water-immersion method. The average grain size of the specimens was obtained by the linear intercept method, using SEM images of the specimens. More than 100 grains from each specimen were measured to determine the average grain size of a specimen. The ceramics and MLCs were poled in silicone oil at 120 °C by applying a DC field of 3.0 kV/mm for 60 min ; the oil was then cooled to room temperature while maintaining the applied voltage. The piezoelectric and dielectric properties of the ceramics were determined using a d_{33} meter (eddyNCDT-3300, Micro-Epsilon, Raleigh, NC, USA) and an impedance analyzer (HP 4294A, Agilent Technologies, Santa Clara, CA, USA) according to IEEE standards. Electric field-induced strain (S-E) loops of the ceramics and the free stroke of the MLCs were obtained using a laser displacement sensor (LK-G10, Keyence Co., Tokyo, Japan) with a resolution of 10 nm and a spot size of 20 μm. The vibration acceleration of the actuator was measured using Accelerometer 8762 (KISTLER), PULSE Data Acquisition Unit 3560c (Brüel & Kjaer, Vibration analyzer), and Multi-functional synthesizer 1943 A (nF). An input signal following a sinusoidal function with a maximum voltage of 150 V was used to measure the vibration acceleration of the actuator. The input signal was applied to the actuator with frequencies sweeping from 100 and 300 Hz. A mass of 2.1 g was attached to the actuator; thus, the total mass of the module including the actuator, mass, actuator case, and supporter was approximately 3.0 g.

3. Results and discussion

Fig. 2(a)–(g) show the XRD patterns of xCPZT-PZNN ceramics with $0.0 \leq x \leq 5.0$ sintered at 900 °C for 4 h. A homogeneous rhombohedral perovskite structure (JCPDS #86-1712) is observed to be well-formed in all specimens, without secondary phases. In order to calculate the lattice parameters of the xCPZT-PZNN ceramics with $0.0 \leq x \leq 5.0$ sintered at 900 °C for 4 h, Si metal was used as a reference material, as shown in Fig. 2. The lattice parameters and the inter-axial angle of all specimens are $a = b = c = 4.045$ Å and $\alpha = 89.8°$, respectively. Fig. 3(a) shows the (1 1 1) peak of the

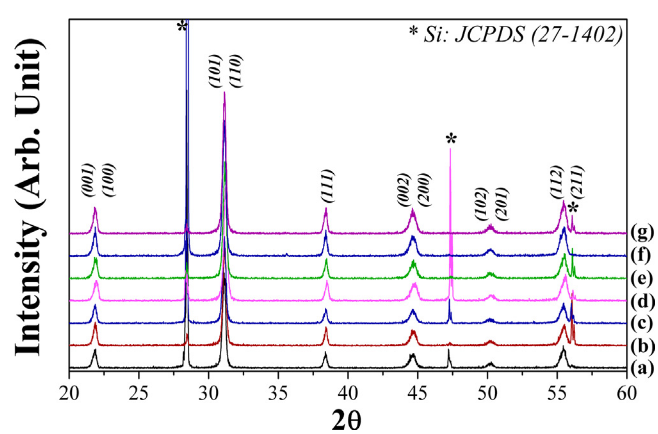

Fig. 2. XRD patterns of PZT-PZNN + x mol% CuO ceramics sintered at 900 °C for 4 h : (a) x = 0.0, (b) x = 0.5, (c) x = 1.0, (d) x = 1.5, (e) x = 2.0, (f) x = 3.0, and (g) x = 5.0. Si metal was used as a reference material.