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Study on increasing output current of piezoelectric energy harvester by fabrication of multilayer thick film

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ABSTRACT

Piezoelectric energy harvesting generally demonstrates low output power because its output current is low compared to its high output voltage. The low current and high impedance limit the applications of piezoelectric energy harvesting systems. Thus, it is necessary to increase the output current and reduce the internal impedance. This study presents the fabrication of multilayer piezoelectric thick films with high output currents. Single-layer and five-layer piezoelectric devices are prepared using the tape-casting process. The material properties of each lead zirconate titanate (PZT) ceramic are measured using an impedance analyzer and a d_{33} meter. The electrical properties of the piezoelectric devices were evaluated by a controllable strain module using vibration exciter. The capacitance of the single-layer device was 7.33 nF and that of the five-layer device was 241.04 nF, which was 32.88 times higher than that of the single-layer device. The open circuit voltage of the five-layer device decreased 6.09 times compared to the single-layer, but the short circuit current increased 5.30 times. The impedance matching load of the five layer device for maximum power transfer was averagely 34.05 times smaller than that of single-layer. Under maximum power transfer conditions, the current of the five-layer PZT device was 6.61 times larger than the single-layer, even though the output power of both devices was similar. Because of this capacitance and current increase, the energy stored in the 220 μF capacitor for 10 s using the five-layer device was 920% larger compared to the energy stored using a single-layer.

1. Introduction

The PEH(Piezoelectric Energy Harvesting) technologies used for converting mechanical energy into electrical energy are being studied worldwide [1–3]. The PEH technologies can be distinguished based on the vibration type [4,5] or the impact type [6,7], and the electrical power can be generated from water [8,9], wind [10,11], movement of people [12,13], vibrations in trains [14,15], and so on. As PEH generates power from the surrounding unutilized energy, it is suitable for WSNs, which often face troubles in battery replacement [16–18]. However, PEH has a low output current in contrast to a high output voltage. To drive the sensors used in the Internet of Things and WSNs, a high output current is required.

The purpose of this paper is to increase the output current of PEH system through the fabrication of multilayer piezoelectric device. In the meantime, multilayer piezoelectric device has been extensively studied in the field of actuators and transformers [19–21]. However, multilayer piezoelectric device research in the field of energy harvesting, especially the 'thick film' form, is relatively inadequate.

Xu et al. [22] investigated the 'bulk' multilayer piezoelectric stack in the form of a bulk using a '33′ mode. Shin et al. [23,24] analyzed the output power by stacking 'bulk' piezoelectric devices in single-, double- and triple-layers to increase the total thickness. The output power increased due to the increase in overall thickness, but it did not show the effect of increasing the current by multilayer device. Oh et al. [25] fabricated a multilayer 'thick film' to increase current. However, it was made of P(VDF-TrFE) polymer material and the current characteristics were not compared with the single-layer film. Song et al. [26] fabricated a multilayer 'thick film' which made of ceramic material. Unlike this study, the multilayer devices were fabricated using sheets of different thicknesses.

In this study, a sheet of the same thickness was made in one batch by the tape casting process (Fig. 1). Then, a multilayer device was fabricated by stacking different numbers of sheets. The tape-casting process, which was first described as a method

Abbreviations: PZT, lead zirconate titanate; PEH, piezoelectric energy harvesting; WSN, wireless sensor network.

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Table 1
Piezoelectric properties of pellets at the various sintering temperatures.

Sintering Temp. (°C)	Diameter (mm)	Thickness	Density (g/cm^3)	d_{33}($^{-12}$m/V)	C_p	tan delta	f_r	f_a	R	k_p (%)	e_r	g_{33}	Q_m	$d_{33}{}^{*}g_{33}$
1100	10.31	1.01	7.93	348	1.00	0.47	211	255	5.31	72.62	1,368	25.44	450	8854
1150	10.30	1.01	7.93	350	1.02	0.48	210	255	6.24	73.62	1,395	25.09	371	8781
1200	10.31	1.01	7.84	359	1.08	0.45	209	251	9.03	71.29	1,473	24.37	255	8749

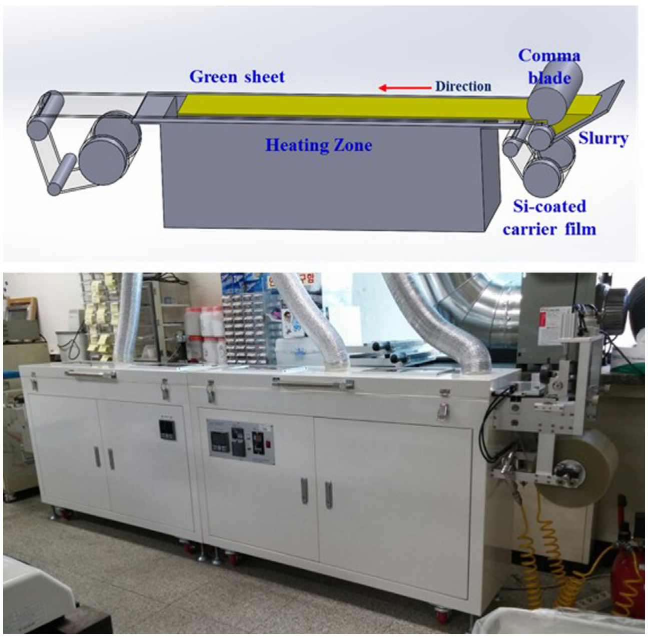

Fig. 1. Schematic diagram and photograph of tape-casting M/C.

to mass-produce capacitors, was used to fabricate the multilayer piezoelectric devices [27]. The tape-casting process is advantageous for the mass production of piezoelectric devices, and the thickness of the ceramics can be controlled easily by changing the thickness of the green sheets and the number of laminated sheets [28].

In this study, single-layer and five-layer piezoelectric devices were fabricated, and their output currents were compared. A controllable strain module was used to evaluate the power generation characteristics of the piezoelectric device. In the conventional vibration module of cantilever type, it is impossible to separately control the vibration frequency and strain applied to the piezoelectric device. Moreover, the resonant frequency changes even if the thickness of the cantilever beam is slightly different. Therefore, the strain applied to the piezoelectric thick film is changed, and the power generation characteristic is greatly changed. In contrast, the controllable strain module can control strain and vibration frequency independently. Therefore, it was possible to evaluate the power generation characteristics while applying the same amount of strain and vibration frequency to the multilayer piezoelectric device.

2. Fabrication of multilayer piezoelectric thick film

In this study, multilayer piezoelectric devices were fabricated to increase the output current. The following equations show the relationships between the output current and the number of piezoelectric device layers:

$$i = C \times \frac{dV}{dt} \tag{1}$$

$$\frac{dV}{dt} = \frac{d \times l}{\varepsilon \times A} \times \frac{dP}{dt} \tag{2}$$

$$\frac{dP}{dt} = \frac{3 \times E_p \times I_x}{L^3} \times \frac{d\delta}{dt} \tag{3}$$

$$C = N \times \varepsilon \times \frac{A}{l} \tag{4}$$

$$i = N \times d_{31} \times \frac{3 \times E_p \times I_x}{L^3} \times \frac{d\delta}{dt} \tag{5}$$

C is the capacitance, d is the piezoelectric strain coefficient, ε is the dielectric constant, A and l are the area of the electrode and thickness of the piezoelectric device, respectively, P is the applied force, E_p is the elastic modulus, I_x is the geometric moment of inertia, L is the length of the cantilever, δ is the displacement of the cantilever free end, and N is the number of layers. From the above equations, it can be inferred that the output current increases when the number of piezoelectric layers increases.

Lead zirconate titanate(PZT) powder (DPZ-HQ, Daiko, Japan) was prepared for manufacturing the multilayer piezoelectric thick films. First, to evaluate the material properties, pellets with diameters of 10 mm were fabricated. The piezoelectric charge constant d_{33} was determined using a d_{33} meter (Channel Product DT-3300, Micro-Epsilon, USA), and the piezoelectric voltage constant g_{33}, dielectric constant ε_r, electromechanical coupling coefficient k_p, and mechanical quality factor Q_m were measured using an

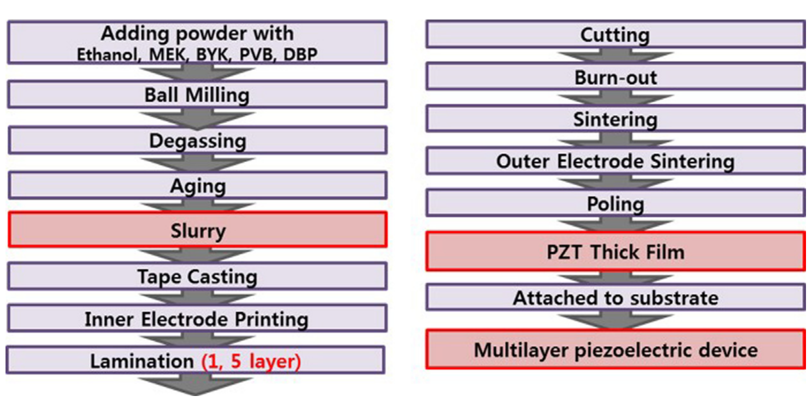

Fig. 2. Experimental procedure for multilayer piezoelectric device fabrication.