Multilayer piezoelectric energy scavenger for large current generation

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Abstract Piezoelectric energy harvesting system is promising to the energy source of wireless sensor nodes for ubiquitous sensor networks. The piezoelectric material has been usually considered as a high voltage and low current source. When charging current into the thin film battery or supercapacitor, a larger current is needed to shorten the charging time. In order to increase the current in the piezoelectric energy harvesting, multilayer ceramics were fabricated. N-layer multilayer ceramics decreased the voltage but increased the current N times. The impedance of the multilayer ceramics are matched to 1 kΩ which is similar to the impedance of general electrical devices. The multilayer piezoelectric generator could be directly employed for electrical device without the additional electrical circuit to improve efficiency.

1 Introduction

In recent years, ubiquitous sensor networks (USN) of wireless sensors and communication nodes have been of great interest because of the potential to create a large market and significantly impact society. For realizing

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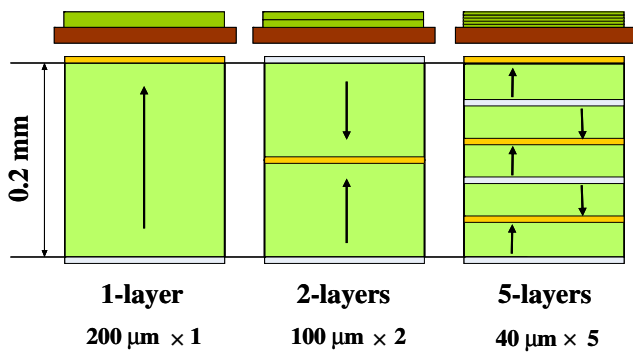Department of Materials Sci. & Eng.,
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USNs, however, the practical solutions for self-powering these sensors and electronic devices should be suggested. The fixed energy sources such as batteries and fuel cells have serious drawbacks like as replacing and re-charging them due to their short life time.

There are several power generating methods using ambient environment energy, including thermal gradient, solar energy and vibration energy. In particular, the piezoelectric energy harvesting from ambient vibration sources has been attracted much attention because it has a high power density compare to other energy scavenging methods [1–5]. Nevertheless, the piezoelectric energy harvesting also have some improvements. While the standard electronic circuitry requires a high current at a low voltage, piezoelectric materials generally produce from several tens to hundreds voltages at micro scale current. In addition, storage devices for sensor node operation also need the larger current to shorten the storage time. Since normal battery voltage capacity is about 3 V, further higher voltage is unnecessary to recharge. So it is necessary to reduce the voltage and increase the current of the piezoelectric generator.

As piezoelectrics have a high impedance and electrical device has several hundreds ohms of resistance, the impedance is not matched each other. In this reason, several studies have examined an optimization of piezoelectric energy harvesting by modifying the electrical circuit used [6–7].

In this study, to increase the generating current, we made multilayer ceramics and characterized the energy harvesting properties. We also examined the impedance matching for the multilayer by modifying the capacitance of piezoelectric generator.

2 Experimental

The composition of piezoelectric ceramics used in this study was 0.01 Pb(Mg$_{1/2}$W$_{1/2}$)O$_3$− 0.41 Pb(Ni$_{1/3}$Nb$_{2/3}$)O$_3$− 0.35

Fig. 1 Illustration of the piezoelectric multilayer ceramic structure

$PbTiO_3 - 0.23 \, PbZrO_3 + 0.1$ wt.% $Y_2O_3 + 2.0$ wt.% ZnO. Properties of the piezoelectric material are $d_{33}=550$ pC/N, $g_{33}=16.1$ Vm/N and $k_p=56.5\%$ [8]. The powder was prepared by a conventional solid-state synthesis and then multilayer ceramics was made according to the general multilayer device fabrication process. In this work, three types of multilayer ceramics were prepared: one-, two- and five-layer ceramics which have the same total thickness of 200 µm (Fig. 1). The geometrical dimension of the multilayer ceramics was $35 \times 10 \times 0.2$ mm. All piezoelectric multilayer ceramics were attached on the flexible substrate, Fiber Reinforced Plastic (FRP; Young's modulus=17 GPa, Poisson's ratio=0.285), using super glue and cured for 1 h at 80 °C. The detailed schematic of fabricated cantilever is shown in Fig. 2.

The constant weight (240 g) was applied on the end of the cantilever as shown in Fig. 1 and the mass was suddenly removed and then the maximum output voltage was measured by the digital oscilloscope (Tektronix, TDS3014B). The electric power of each multilayer cantilever also measured with changing the electric circuit resistance and electrical matching point was also checked. Schematic of the measurement system of the piezoelectric generator with resistive load is shown in Fig. 3.
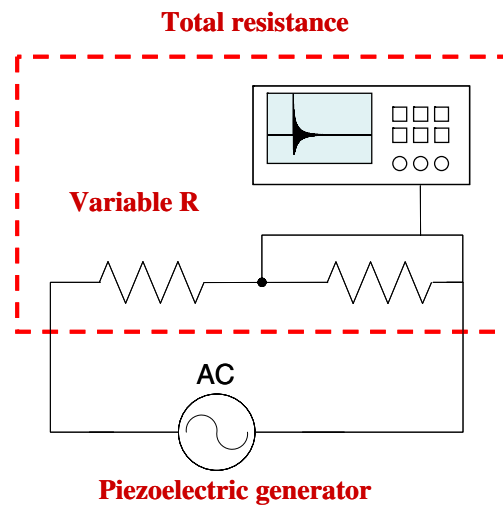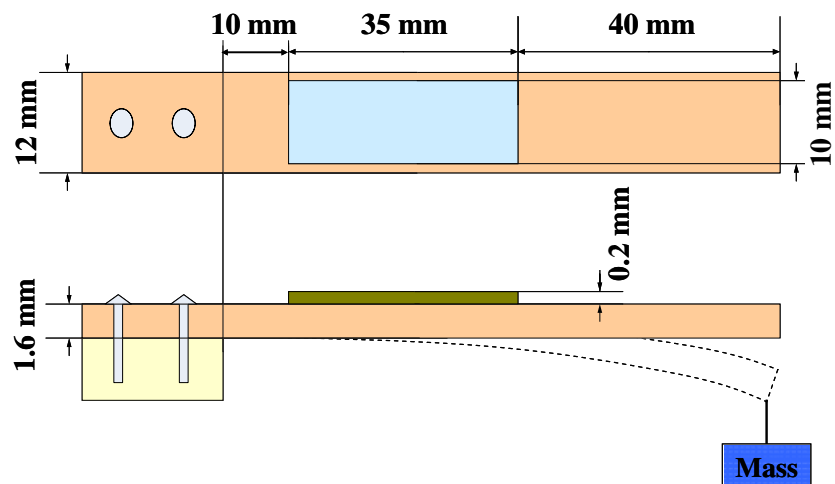

Fig. 3 Schematics of the measurement system of the piezoelectric generator with resistive load

3 Results and discussions

Figure 4 shows the output voltage of the cantilevers for the various external resistances. The output voltage increased with external resistance and saturated at the large resistance. The output voltage at the large resistance, which is similar condition to the voltage in an open circuit, increases with the thickness of each layer. For example, one-, two-, and five-layer samples had 200, 100, and 50 µm thickness of each layer and showed the about 100, 50, and 20 V, respectively. When the same amount of force was applied on the cantilevers, which were made of the same materials, Eq. (1) showed that the generated voltage should be linearly proportional to the thickness of each layer.

$$E = \frac{V}{l} = \frac{d_{31}}{\varepsilon_0 K} \cdot \frac{F}{A}, \qquad (1)$$

where E is the generated electric field, V is the voltage, l is thickness of each layer, d_{31} is the piezoelectric constant, ε_0

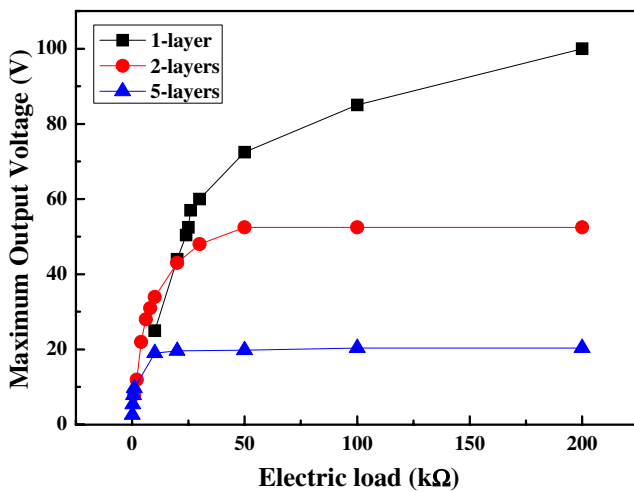Fig. 2 Schematics of the multilayer ceramic generator

Fig. 4 Variations of the maximum output voltage of multilayer ceramic generators with the different electric loads
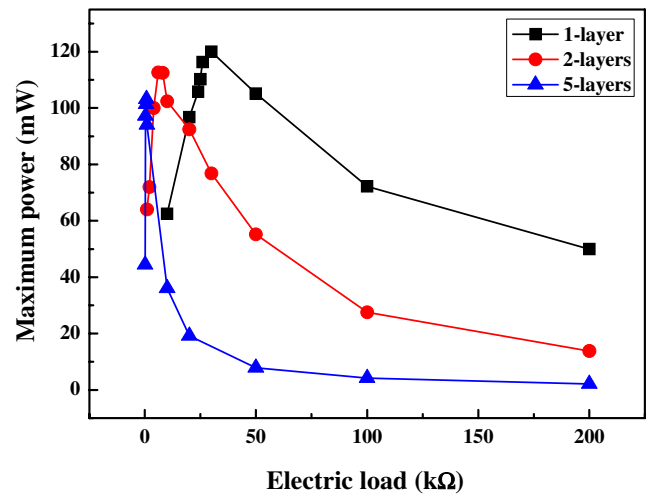

Fig. 5 Variations of the maximum power of multilayer ceramic generators with the different electric loads

is the vacuum permittivity, K is dielectric constant of material, F is the applied force and A is the area of the electrode of the piezoelectrics.

The output voltages are different, though, as three cantilevers are mechanically in the same condition, the totally generated power should be same to satisfy the principle of the energy conservation. However, as we used different electrical boundary condition, for example, N layer ceramics has N^2 times capacitance of one layer sample, the output energy should have different electrical quantities, though the total energy is same. In detail, as electrical power p can be expressed like $p = i \times V$, the higher voltage sample should have the lower generated current. Following equations shows the relationship between the generated current and the properties of cantilevers.

$$i = C \times \frac{dV}{dt} \tag{2}$$

$$C = N \times \varepsilon_0 \times K \times \frac{A}{l} \tag{3}$$

Substituting Eq. (3) into Eq. (2), we obtain

$$\frac{dV}{dt} = \frac{d_{31} \times l}{\varepsilon_0 KA} \times \frac{dF}{dt} \tag{4}$$

Table 1 Variations of the capacitance, measured resistance, calculated resistance and electric current of multilayer ceramics with the number of layers.

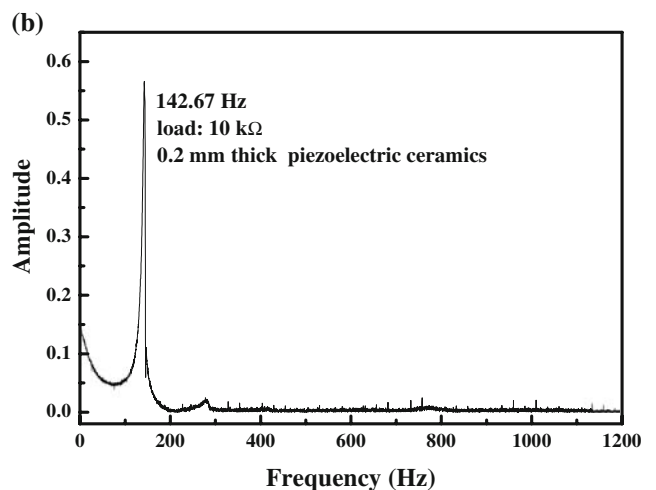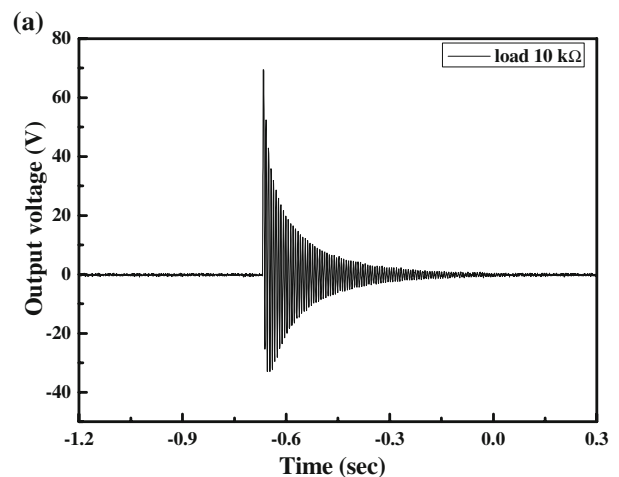|	One layer	Two layers	Five layers
Capacitance (nF)	40	164	998
Measured R (kΩ)	26	6	1
Calculated R (kΩ)	27.9	6.8	1.1
Electric current (mA)	2.1	4.6	9.7

Fig. 6 (**a**) Variation of the output voltages when the constant force was applied on the end of the one-layer cantilever and (**b**) Fourier transformed spectrum of the output voltages of one-layer cantilever

$$i = N \times d_{31} \times \frac{dF}{dt}, \qquad (5)$$

where t is time. From Eq. (5), it can be also known that the generated current is linearly proportional to the number of layer, piezoelectric constant of material, and mechanical vibration condition. If we consider that the piezoelectric constant of material can be increased by searching the new composition, which is a time consuming task, and that the mechanical vibration condition is also determined by the vibration source, we believe that multilayer approach is very effective to increase the generated current (see Table 1).

Figure 5 shows the electric power according to external electric resistance, which was calculated using $p = V^2/R$, where R is the resistive load. Three cantilevers showed similar maximum output powers at the different resistive loads. The resistive load, that is, electrical impedance matching condition, can be determined by Eq. (6)

$$R = \frac{1}{2\pi \times f \times C}, \qquad (6)$$

where f is the resonance frequency of the cantilever. As we use the mechanically same cantilever, f should be same. To calculate the impedance at the maximum output power, we first measured the natural frequency of the cantilevers. All three samples showed almost same natural frequency. Figure 6(a) and (b) showed one example of the output voltage in time domain and Fourier transformed spectrum of the one-layer cantilever. Natural frequency was around 142.7 Hz. When ceramic/metal cantilever structure actuator was used for energy harvester, as both ceramic and metal have large Young's modulus, the natural frequency was order of kHz range, which is far higher frequency than the vibration frequency in our environment. To obtain lower the frequency of order of hundred Hz, which is the usual frequency of vibration source found in our surrounding, a heavy mass was usually added on the end of the cantilever causing the easy mechanical failure on ceramics. However, as we made the cantilever by gluing the ceramics on the relatively flexible FRP substrate, we could get the natural frequency at the low frequency without adding the heavy mass and increase the safety factor of cantilever.

Using the measured natural frequency, impedances for the maximum output power were calculated and presented in Table 1. Measured values are similar to the calculated values. It should also be noticed that five-layer cantilever has maximum output at the 25 times smaller impedance than that of one-layer. Interestingly is that five-layer ceramic in our experiment has max power at near 1 kΩ. If we think that most electrical devices have several hundred Ohms internal impedance, the multilayer energy generator could be directly employed for electrical device without the additional electrical circuit. This may increase the efficiency of piezoelectric energy generator.

4 Conclusion

The piezoelectric material can generate a low current and high voltage. But a high electronic current is required for self-powered wireless sensor nodes. To increase electric current, multilayer ceramics were fabricated and characterized. Compared with the bulk ceramics, thin multilayer ceramics generated the large current by scarifying the voltage and the electric current was increased with proportion to the number of layer. The impedance of piezoelectric generator was decreased as increasing the number of layer. As a result, the impedance of the multilayer piezoelectric generator comes to be similar to that of the general electronic devices. So the multilayer energy harvester could be directly used for electrical device without the additional electrical circuit. It is promising to use multilayer ceramics to charge the battery and to power a wireless sensor node.

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