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Piezoelectric Energy Harvesting Using PZT Bimorphs and Multilayered Stacks

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Piezoelectric materials have a unique ability to interchange electrical and mechanical energy. This property allows the absorption of mechanical energy such as ambient vibration and its transformation into electrical energy. The electrical energy generated can be used to power low-power electronic devices. In the present study, energy harvesting by lead zirconate titanate (PZT) multilayer (ML) stacks and bimorphs is presented. The devices were fabricated by a tape casting technique and were poled at 2 kV/mm for 30 min immersed in a silicone oil bath maintained at 60°C. The energy harvesting characteristics of the fabricated devices were measured in a suitably assembled test setup. The output voltage obtained from the PZT bimorphs and ML stacks was 450 mV and 125 mV, respectively. The higher output voltage from the bimorph is due to its low capacitance.

Key words: Piezoelectric, energy harvesting, multilayered stack, bimorph

INTRODUCTION

The process of acquiring energy from the surrounding system and converting into usable electrical energy is termed energy harvesting. Over the last few years, there has been a rapid increase in energy harvesting from vibrating bodies such as industrial machinery, the pressure exerted while walking, vehicles passing along roads and bridges, wind energy, etc.[1,2] Although the amount of energy harvested is very low, on the order of micro- to milliwatts, the energy is very useful and convenient for self-powering of low-power electronic equipment; For example, such power is sufficient for self-powering of wireless sensor networks used for passive and active monitoring applications. Therefore, the requirement for an external power source or periodic replacement of batteries is avoided. Similarly, the power harvested from walking or jogging by embedding lead zirconate titanate (PZT) devices into shoes is sufficient to power a mobile phone. This is very important for security personnel deployed in remote areas.

There are many novel ideas for vibration-based piezoelectric energy harvesters. Bimorphs are simple devices with potential for energy harvesting because they produce large deformations under vibration. Priya et al. demonstrated that usable levels of electric power can be generated from wind energy using piezoelectric bimorphs.[3] Wright et al. presented vibration energy harvesting using bimorphs for wireless electronics.[4] Shen et al. proposed a PZT cantilever with a micromachined silicon proof mass for a low-frequency vibration energy harvesting application.[5] Xu et al. studied energy harvesting using a PZT multilayer (ML) stack. While the energy harvested was 347 mW in resonance mode, it was nearly 321 mW in off-resonance mode.[6]

The major challenge of harvesting energy from PZT devices lies in the design and construction of an efficient power conversion circuit.[7] The internal impedance of piezoelectric generators is relatively high as compared with the low internal impedance

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of conventional power supplies and batteries. This high internal impedance of PZT restricts the amount of output current that can be driven by the PZT source to the microamp range. Another unique characteristic of this power source is that it generates relatively low output voltages, offering challenges to develop efficient rectifier circuits since many diode rectifiers require nonzero turn-on voltages to operate.[8,9] To obtain the maximum voltage from PZT devices, the design of electronic circuitry with various combinations of electronic components has been explored. In this study, in-house-fabricated PZT multilayered stacks as well as PZT bimorphs were used for comparative study of their energy harvesting ability. An energy harvesting test assembly with the best combination of electronic components in the circuit was used to extract the maximum voltage from the PZT devices.

EXPERIMENTAL PROCEDURES

Fabrication of PZT Devices

PZT multilayered stacks were fabricated using in-house-developed PZT powder.[10] An integrated fabrication facility consisting of a tape casting unit, screen printer, laminator, iso-press, etc. was used for fabrication of the ML stacks. The process consisted of preparation of homogeneous PZT slurry using required amounts of PZT powder, solvent, dispersant, binder, and plasticizers. This homogeneous slurry was poured onto the tape caster, and PZT tapes of 110 μm thickness were fabricated by changing parameters such as the doctor blade clearance, casting speed, slurry viscosity, etc. A process flowsheet for fabrication of the ML stacks by the tape casting technique is presented in Fig. 1. The dried PZT tapes were screen-printed with platinum (Pt) electrode paste, then PZT layers were stacked and laminated. The green stacks were cofired at 1250°C for 2 h. The cofired stacks were electroded and poled at 2 kV/mm. The detailed method of ML stack fabrication has been presented in previous publications.[11,12] Fabricated ML stacks are presented in Fig. 2. These stacks were characterized for their displacement and energy harvesting ability.

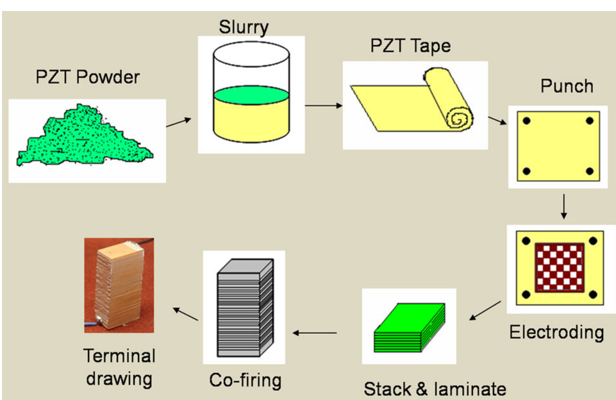

Fig. 1. Fabrication procedure for ML stacks.

Fabrication of Bimorphs

PZT bimorphs were also fabricated using the tape casting technique. PZT tapes of thickness 200 μm to 300 μm were prepared using a laboratory tape caster. PZT tape was cut into rectangular pieces with dimensions of 40 mm × 15 mm (10 numbers) and sintered at 1250°C for 2 h. The sintered tapes were leveled, electroded, and poled at 2 kV/mm for 30 min in a silicone oil bath maintained at 60°C to facilitate domain wall motion during poling. A parallel bimorph was prepared by using two such sintered and poled pieces with aluminum foil in the middle. The fabricated bimorphs are presented in Fig. 3.

CHARACTERIZATION OF PZT ML STACKS

The displacement of the fabricated ML stacks was measured using a simple strain gauge. For displacement measurement, the ML stack was placed on a plane rigid support and the tip of the strain

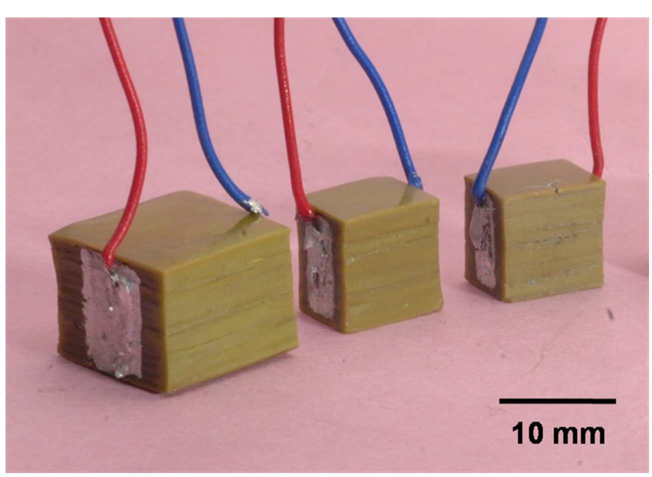

Fig. 2. Fabricated PZT ML stacks.

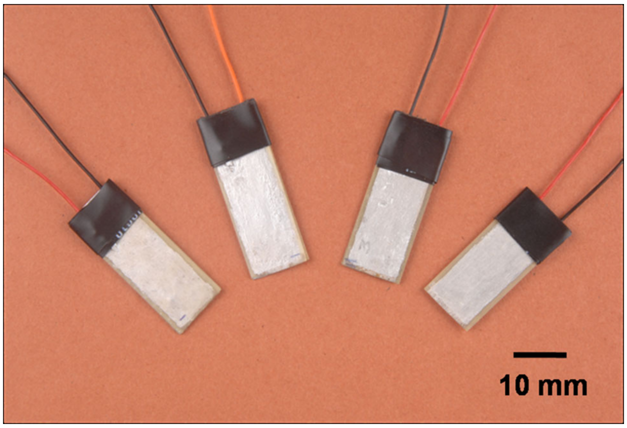

Fig. 3. Fabricated PZT bimorphs.

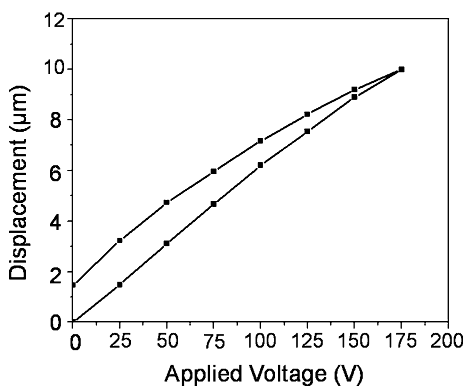

Fig. 4. Typical plot of displacement versus voltage for PZT ML stack.

Table I. Properties of in-house-fabricated multilayered (ML) stacks

	MLS-1	MLS-2	MLS-3
No. of active layers	96	110	100
Layer thickness (μm)	110	100	90
Height (mm)	10	10	9
Area (mm^2)	120	48	48
Dimensions (mm^3)	12 × 10 × 10	8 × 6 × 10	8 × 6 × 9
Displacement (μm)	10	9	8
Block force (N)	4500	1700	1550
Voltage applied (V)	175	160	150

gauge was placed on the ML stack under prestressed condition. The terminals of the ML stacks were connected to appropriate terminals of a direct-current (DC) source, and the voltage was gradually increased. A typical plot of displacement versus voltage for an ML stack is presented in Fig. 4. The properties of the fabricated ML stacks are presented in Table I.

The block force of the ML stack was characterized using a block force measurement unit (TF Analyzer 2000, M/s aixACCT Systems GmbH, Germany). The ML stack was placed inside the sample holder, and its positive and negative terminals were suitably connected to the voltage source. The ML stack was prestressed by a spring-loaded mechanism with springs of different stiffness. The displacement and force generated by the ML stack for all the springs at a particular voltage are plotted. It was observed that the block force was a maximum of 4500 N at 175 V.

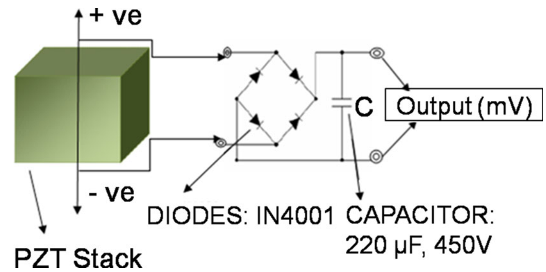

Fig. 5. Energy harvesting circuit diagram for PZT stack.

ENERGY HARVESTING STUDY

A piezoelectric harvester is usually represented electrically as a current source in parallel with a capacitor and resistor. The current source provides current proportional to the input vibration amplitude. Experiments were conducted on piezoelectric bimorphs and ML stacks with an in-house-developed circuit to convert the random charge generated by the devices into a stable, rectified DC voltage. The circuit designed for energy harvesting is shown in Fig. 5, where the positive and negative terminals of the piezoelectric bimorphs/stacks are connected to the in-house-developed circuit consisting of a full-wave bridge rectifier (four diodes, specification IN 4001 in bridge configuration) which converts the random charge generated by the piezoelectric bimorphs and ML stacks into a stable, rectified DC voltage. The rectified DC voltage is accumulated across the capacitor and measured using a multimeter.

Description of Measurement Setup

The measurement assembly setup consisted of an electrodynamic exciter and a power amplifier with 50 N capacity, a force transducer with a signal conditioner with capacity of 2 kN (M/s Bruel & Kjaer), and a function generator (1 μHz to 20 MHz; M/s Agilent). The piezoelectric bimorphs/ML stacks were bonded onto the aluminum sheet using adhesive tape with their positive (+ve) and negative (−ve) terminals connected to the rectifier circuit. The aluminum sheet was clamped onto the base structure as shown in Fig. 6a. The force transducer was connected to the electrodynamic exciter plunger; the other end of the transducer

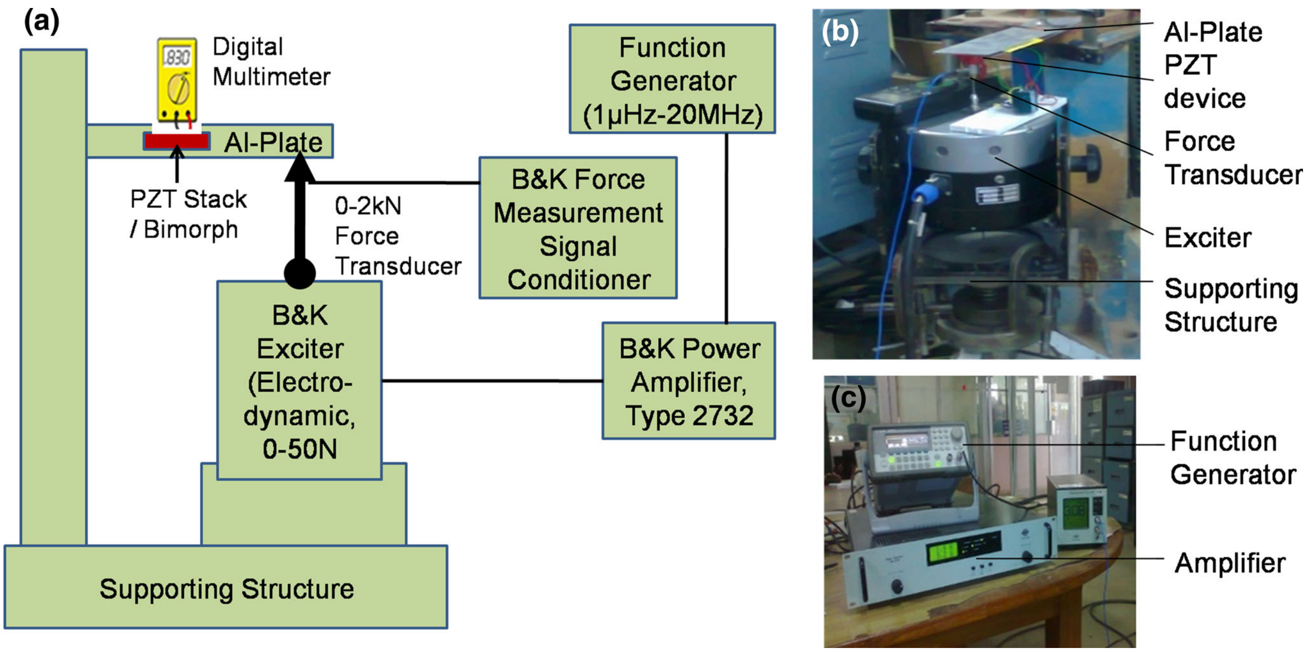

Fig. 6. (a) Schematic diagram of energy harvesting measurement setup. (b) Mechanical setup for energy harvesting. (c) Instrumentation setup for energy harvesting.

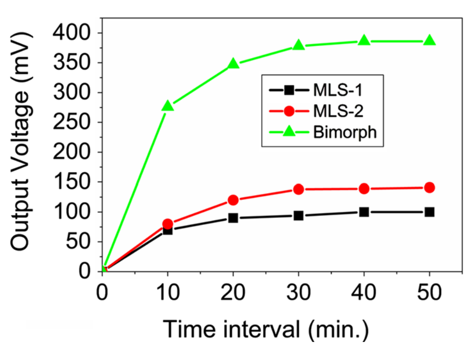

Fig. 7. Comparison graph of output voltage for ML stack and bimorph.

was bonded onto the opposite face of the aluminum plate which had the piezoelectric bimorphs/ML stacks. A function generator was used to input a sinusoidal waveform to the electrodynamic exciter to generate the vibration and force. The force was measured using a force transducer. The signal to the shaker was kept at constant amplitude of 200 mV_{p-p}, equivalent to a 3 N force at a fixed frequency of 24 Hz from the function generator. The shaker plunger was attached to the force transducer to measure the input force acting on the PZT bimorphs/ML stacks. The voltage accumulated across the capacitor was measured. A 10-min period was allowed for each cycle of operation. The voltage accumulated across the capacitor was noted using a digital multimeter (M/s Mitsubishi). The actual experimental setup is shown in Fig. 6b and c.

RESULTS AND DISCUSSION

Various combinations of capacitors were explored to obtain the best capacitor value. The experiments were conducted with 1700 μF/100 V, 4.7 μF/400 V, 4.7 μF/100 V, and 220 μF/450 V capacitors on a trial basis using a PZT-1 ML stack of 96 layers with thickness of 110 μm each and area of 12 mm $\times$ 10 mm. From these experiments, it was observed that the charge retention with the 220 μF/450 V capacitor yielded better results as compared with the other capacitors. Hence, this capacitor was used for measurement of the output voltages from all the PZT stacks and bimorphs. The output voltage produced by the ML stacks and bimorphs is presented in Fig. 7. It was observed that the bimorph produced a higher output voltage compared with the PZT ML stacks. This is attributed to the high capacitance of the ML stack compared with the bimorph, as presented in Ref. 13. Those authors compared the performance of bimorph piezoelectric energy harvesters with one, two, and three PZT layers, concluding that: (i) the overall capacitance of an n-layer generator is n^2 times greater than that of a single-layer generator, and (ii) the open-circuit voltage of a single-layer generator is n times greater than that of an n-layer generator. Based on the above, the output voltage for the bimorph is higher compared with that for the ML stack.

CONCLUSIONS

A study of energy harvesting using PZT bimorphs and PZT ML stacks was carried out using a suitable test setup assembly. To obtain the maximum voltage from the PZT devices, the design of electronic circuitry with various combinations of electronic components was explored. It was concluded that the PZT bimorphs generated a higher output voltage (450 mV) compared with the ML stacks (125 mV), probably due to their low capacitance.

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