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Piezoelectric energy harvesting using shear mode $0.71Pb(Mg_{1/3}Nb_{2/3})O_3-0.29PbTiO_3$ single crystal cantilever

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In this letter we presented a cantilever beam used for vibration energy harvesting based on shear mode $0.71Pb(Mg_{1/3}Nb_{2/3})O_3-0.29PbTiO_3$ single crystal. The working principle of the device was inferred and the factors influencing the output were obtained using an analytical method. The electrical properties under different conditions were studied systematically. Under a cyclic force of 0.05 N (peak value), a peak voltage of 91.23 V, maximum power of 4.16 mW were measured at 60 Hz with a proof mass of 0.5 g. The results demonstrate the potential of the device in energy harvesting applied to low-power portable electronics and wireless sensors. © *2010 American Institute of Physics*. [doi:10.1063/1.3327330]

During the past decade, energy harvesting from mechanical vibrations of ambient environments has been a hot research topic due to its potential to application in many fields. Hereinto, piezoelectric energy harvesting has attracted considerable attentions[1–5] for the outstanding advantages of simpler structure compared to other methods such as using electromagnetic and electrostatic effects.[6] In 2005, a study reported a piezoelectric cymbal transducer for energy harvesting. At 100 Hz the output power can reach 52 mW when connected with a load of 400 kΩ under an ac force of 70 N with a prestress load of 67 N.[7] Subsequently, another piezoelectric vibration energy scavenging generator using compressive axial preload was researched in 2006. The device can create 0.36–0.65 mW power output when subjected to a 12.2 g proof mass across a range of frequencies from 160 to 195 Hz.[8] In 2007, a drum transducer was studied as the energy harvesting device. Under a prestress of 0.15 N and a cyclic stress of 0.7 N, a power of 11 mW was generated at 590 Hz across an 18 kΩ resistor.[9]

In recent years, relaxor piezoelectric single crystal $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3-xPbTiO_3$ (PMN-*x*PT or PMN-PT) has attracted continuous attention due to the well-known ultrahigh electromechanical response (d_{33} and k_{33} could reach as high as 2500 pC/N and 0.94, respectively).[10,11] Besides, recent research discovers PMN-PT also has excellent thickness shear mode performance (d_{15} and k_{15} can reach the high values of 5980 pC/N and 97%, respectively).[12] However, the application based on the shear mode single crystal has been seldom reported. In this work, we proposed a unimorph bender as a cantilever beam structure for harvesting mechanical energy based on the shear mode of PMN-0.29PT single crystal. Under a cyclic force of 0.05 N (peak value), a high output peak voltage of 91.23 V, and output power of 4.16 mW were obtained at 60 Hz with a proof mass of 0.5 g.

The structure of the proposed device is shown in Fig. 1. The PMN-PT wafer (13.0 mm × 6.0 mm × 1.0 mm) and the brass shim (50.0 mm × 6.0 mm × 0.3 mm) were bonded together using a silver-loaded epoxy (Applied Products E-Solder 3021). The PMN-PT wafer was poled along the length direction (indicated by the arrow) and the driving electrodes were painted on the two surfaces perpendicular to the thickness direction.[12] The gross mass of the beam is 1.50 g.

The working principle of the device can be stated as follows (Fig. 1). The device is driven to shake by a vibration source. The piezoelectric constitutive equations for the wafer can be expressed as[13]

$$T_5 = c_{55}^D S_5 - h_{15} D_1, \quad (1)$$

$$E_1 = -h_{15} S_5 + \beta_{11}^S D_1, \quad (2)$$

where E_1 and D_1 are the electric field and electric displacement along the thickness direction, respectively; T_5 and S_5 are the shear stress and strain, respectively; c_{55}^D is the shear elastic stiffness coefficient at constant electric displacement and h_{15} is the shear mode piezoelectric stiffness constant; β_{11}^S is the dielectric impermittivity along the thickness direction at constant strain. E_1 and D_1 can be expressed as $E_1 = U/b$ and $D_1 = Q/A$, where U and Q are the induced voltage and charge, and b and A are the thickness of the wafer and the area of the electrode, respectively. S_5 can be expressed as $S_5 = (1/2)p/l$, where p is the vertical displacement of the wafer (Fig. 1) and l is the length of the wafer. Putting these

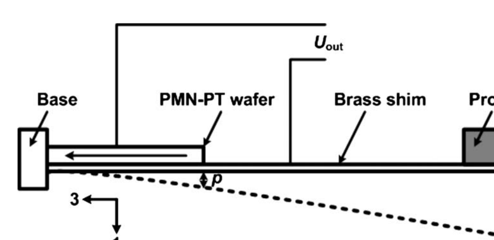

FIG. 1. The structure and working principle of the proposed device. The poling direction of the wafer is indicated by the arrow.

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TABLE I. The performances of the PMN-PT wafer used in this work.

l (mm)	A (mm^2)	b (mm)	C^T (nF)	C^S (nF)	f_r (kHz)	f_a (kHz)	k_{15}
13.0	13.0×6.0	1.0	5.18	0.67	472	1200	0.932
c_{55}^D (10^9 Pa)	c_{55}^E (10^9 Pa)	β_{11}^T ($10^{-4}/\varepsilon_0$)	β_{11}^S ($10^{-4}/\varepsilon_0$)	d_{15} (pC/N)	e_{15} (C/m^2)	g_{15} (10^{-3} V m/N)	h_{15} (10^8 V/m)
46.6	6.09	1.33	10.30	3080	18.75	46.4	21.8

equations into Eq. (2), the current generated under a load resistance can be obtained as follows:

$$I = \frac{dQ}{dt} = \frac{A}{b\beta_{11}^S}\frac{dU}{dt} + \frac{Ah_{15}}{2l\beta_{11}^S}\frac{dp}{dt}. \quad (3)$$

The voltage is expressed by

$$U = R_L I = \frac{R_L A}{b\beta_{11}^S}\frac{dU}{dt} + \frac{R_L A h_{15}}{2l\beta_{11}^S}\frac{dp}{dt}, \quad (4)$$

where R_L is the load resistance. Assuming that p is expressed by $p=p_0e^{j\omega t}$, and therefore, U can be expressed by $U=U_0e^{j(\omega t+\theta)}$. Putting these two equations into Eq. (4) and solving it, then we can yield the output peak voltage (U_p) as,

$$U_p = U_0 = \frac{\omega R_L A h_{15}}{2l} p_0 \Big/ \left[(\beta_{11}^S)^2 + \left(\frac{\omega R_L A}{b}\right)^2 \right]^{1/2}. \quad (5)$$

The power dissipated in the load resistance is

$$P = U_0^2/2R_L = \frac{R_L A^2 h_{15}^2 p_0^2}{8l^2} \Big/ \left[\frac{(\beta_{11}^S)^2}{\omega^2} + \frac{R_L^2 A^2}{b^2} \right]. \quad (6)$$

Equations (5) and (6) show that the voltage is proportional to h_{15} and p_0, and the power is proportional to h_{15}^2 and p_0^2. Hence, if the piezoelectric material with a high piezoelectric constant is used, the generated voltage and energy would improve greatly. Due to the flexible performance of the structure, the vertical displacement of the wafer can get a large value, which is also an advantage for enhancing the output.

In the experiment, the crystal was grown by a modified Bridgman technique[11,14] and then cut into wafers as the orientations of $[111]^L/[11\bar{2}]^W/[1\bar{1}0]^T$ and the dimensions shown in Table I. The performances of the wafer used in this work are listed in Table I. C^T and β_{11}^T are the capacitance and impermittivity at free stress; C^S and β_{11}^S are the capacitance and impermittivity at free strain; f_r and f_a are the resonance and antiresonance frequencies, respectively; c_{55}^D and c_{55}^E are the elastic stiffness coefficients at constant electric displacement and electric field, respectively; k_{15}, d_{15}, e_{15}, g_{15}, and h_{15} are the electromechanical coupling coefficient, piezoelectric strain constant, piezoelectric stress constant, piezoelectric voltage constant and piezoelectric stiffness constant, respectively. Compared to the PMN-0.30PT wafer with the orientations of $[100]^L/[010]^W/[001]^T$,[15] the piezoelectric constants (d_{15}, e_{15}, g_{15}, and h_{15}) and electromechanical coupling coefficient (k_{15}) are significantly excellent, which is the advantage for the energy harvesting device to obtain high performance.

The experimental setup is presented as follows. A Mechanical Shaker (LDS Ltd., model type V406) which can supply a maximum force of 89 N (5–9000 Hz) was used to excite the vibration. The base of the device was fixed on the shaker with screws. The shaker was driven by an Arbitrary Function Generator (Sony Tektronix AFG 320) and Power Amplifier (LDS Ltd., model type PA 100E) to supply a sinusoidal force of the desired magnitude and frequency. The output voltage from the device was monitored by a Tektronix Digital Oscilloscope (HP 54645A). The whole experimental setup was put on a spongy cushion to avoid any interference from the surroundings. Various load resistances were used in order to characterize the performances of the device. The powers under different load resistances R_L were calculated using the formula $P=U_p^2/2R_L$, where U_p is the output peak voltage.

Figure 2 shows the measured impedance spectrums of the device with 0 and 0.5 g proof mass within the frequency range of 40–600 Hz, for the frequency of the vibration energy is usually low. From the curves it could be observed the device has two resonance frequencies with 0 g proof mass, corresponding to the first two bending modes. The resonance frequencies were shifted to lower frequencies under 0.5 g proof mass condition.

Figure 3 shows the outputs of the device with 0 g proof mass as a function of the excitation frequency. The results were measured under a cyclic force of 0.05 N. A maximum output power of about 1.53 mW can be obtained from the device at 150 Hz with a matching load resistance of 667 kΩ which approximates the impedance of the device at 150 Hz shown in Fig. 2, and the peak voltage reaches 50.9 V at the same condition. When the load resistance is further increased, the voltage increases but the power decreases. At the other resonance frequency, 400 Hz, a maximum power of 0.37 mW can be obtained and the peak voltage is 16.9 V with a load resistance of 231 kΩ.

When bonding a proof mass of 0.5 g at the end of the brass shim, the resonance frequencies of the device were shifted to lower frequencies (Fig. 4). The peak value of the

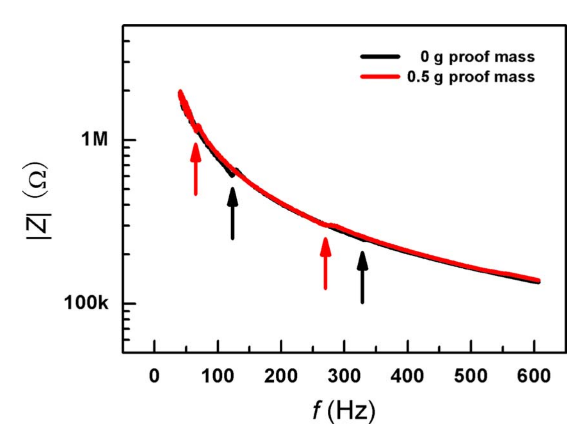

FIG. 2. (Color online) The impedance spectrums of the fabricated device under different proof mass conditions.

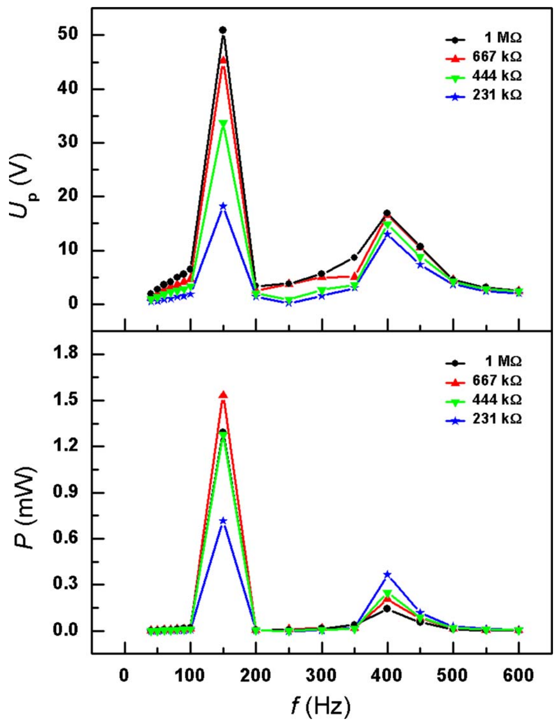

FIG. 3. (Color online) Frequency dependence of output peak voltage (U_p) and output power (P) with 0 g proof mass and various load resistances under a cyclic force of 0.05 N (peak value).

cyclic excitation force is also 0.05 N. A maximum output power of 4.16 mW can be obtained from the device at 60 Hz with a matching load resistance of 1 MΩ. A peak voltage of 91.2 V was measured at the same condition. The maximum outputs were remarkably enhanced compared with the device without proof mass. A maximum power of 0.22 mW and a

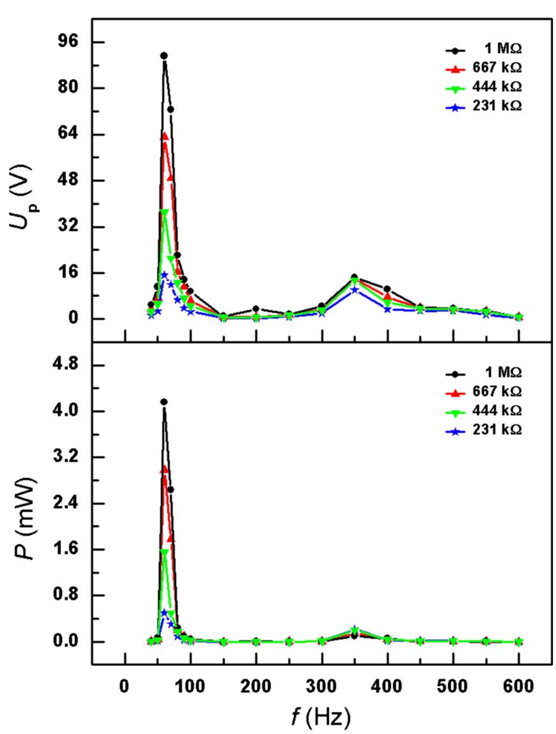

FIG. 4. (Color online) Frequency dependence of output peak voltage (U_p) and output power (P) with 0.5 g proof mass and various load resistances under a cyclic force of 0.05 N (peak value).

peak voltage of 10.1 V were measured at the other resonance frequency, 350 Hz.

Compared with the cantilever device based on the transverse mode (31-mode) PMN-PT single crystal,[16] the volume of the wafer is only a half ($13.0\times6.0\times1.0$–$25.0\times12.45\times0.5\ \mathrm{mm}^3$) and the proof mass is only two fifths (0.5–1.25 g), while the maximum power output is much higher (4.16 mW at 60 Hz to 0.586 mW at 174 Hz).

In summary, a vibration energy harvesting device using the cantilever bender based on the shear mode of PMN-PT single crystal has been designed and fabricated. The working principle of the device was inferred and the electrical properties under different frequencies, load resistances, and proof masses were studied systematically. The device can give large output voltage and power due to the high piezoelectric constant of the material and the flexible performance of the structure. Also, the flexible structure makes the resonance frequency very low. Under the cyclic force of 0.05 N (peak value), the device with 0.5 g proof mass can generate a peak voltage of 91.2 V and a maximum power of 4.16 mW at 60 Hz with a matching load resistance of 1 MΩ. This proposed device has the potential to be applied to low-power portable electronics and wireless sensors.

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