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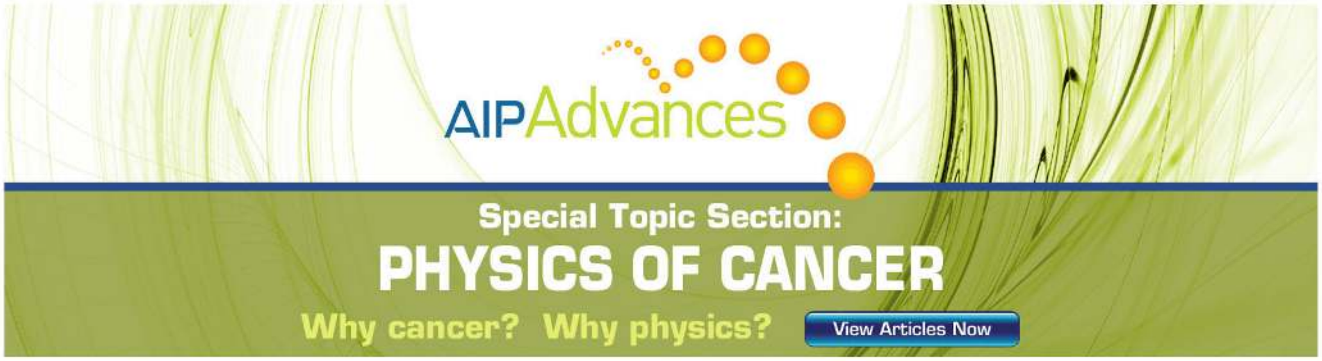

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Development of piezoelectric microcantilever flow sensor with wind-driven energy harvesting capability

Huicong Liu,[1] Songsong Zhang,[1] Ramprakash Kathiresan,[1] Takeshi Kobayashi,[2] and Chengkuo Lee[1,a)]
[1]*Department of Electrical and Computer Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576*
[2]*National Institute of Advanced Industrial Science and Technology (AIST), 1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, Japan*

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We have developed a piezoelectric (PZT) microcantilever as an air flow sensor and a wind-driven energy harvester for a self-sustained flow-sensing microsystem. A flow sensing sensitivity of 0.9 mV/(m/s) is obtained. The output voltage and optimized power regarding to the load resistance of 100 kΩ are measured as 18.1 mV and 3.3 nW at flow velocity of 15.6 m/s, respectively. The corresponding power density is as large as 0.36 mW/cm^3. The experimental results have elucidated the smart function of using PZT microcantilevers as flow-sensors and wind-driven energy harvesters simultaneously. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4723846]

At present, the development of ultra low-power microelectronics and circuits has opened a promising research direction to self-sustained wireless microsensor nodes without using battery.[1] An interesting preliminary concept has been demonstrated such as a self-powered system using a nano-power-generator for long distance wireless data transmission.[2] Aiming at a self-sustained flow-sensing microsystem as a wireless sensor node for future applications including smart home, factory automation, and environmental monitoring in rural field or agricultural land, it requires not only the micro-scale flow sensors and control circuits with the capabilities of sensing, monitoring, and communicating but also a renewable micro-scale power source by scavenging energy from environment.

Piezoelectric materials are widely adopted in microsensors for characterization of regimes including pressure, acceleration, strain, or force by converting them into electrical charge based on piezoelectric effect.[3] In particular, Seo and Kim[4] have reported a piezoelectric micro flow sensor by measuring the resonant frequency changes with respect to different flow velocities. We have proposed a flow-sensing approach by measuring the output voltage of the piezoelectric microcantilever from air flow-induced vibrations. Comparing with conventional micro flow sensors, piezoelectric-based micro flow sensors do not require additional power to measure mechanical strain,[5] Coriolis force,[6] or thermal flux[7] and have not been reported until our study. On the other hand, wind energy regarded as a renewable energy source is present everywhere in open environments. So far, a few large scale wind-driven energy harvesters[8,9] have been reported but are less developed at micro-scales. We thus aim to investigate MEMS energy harvesting from wind flow using a flexible piezoelectric microcantilever. The significance of this concept is that it does not require an external vibration source eliminating the bandwidth issue of traditional vibration-driven energy harvesters[10–13] and combines aerodynamics with vibrations to generate necessary power.

Since piezoelectric microcantilever is a promising candidate for a self-sustained flow-sensing microsystem due to its passive nature, i.e., detectable output charge is a function of flow rate, we have characterized the flow sensing and energy harvesting capabilities of a wind-driven piezoelectric (PZT) microcantilever. More specifically, a self-sustained flow-sensing microsystem with an array of similar PZT microcantilevers will be able to measure the flow rate of ambient wind by one microcantilever while the rest are used to scavenge wind energy.

Figure 1(a) shows a schematic illustration of a PZT microcantilever immersed in a wind flow along a parallel incidence direction (x-direction) with respect to the cantilever surface. The PZT microcantilever consists of a 3000-μm-long and 300-μm-wide PZT beam sandwiched by top and bottom electrodes and a 5-μm-thick Si supporting layer, as seen from the cross section view. The microfabrication process is started from a SOI wafer with 5 μm Si device layer, 1 μm buried oxide layer, and 400 μm Si handle layer. A thermal oxide layer of 0.3 μm is initially deposited on the Si device layer before bottom electrode of $LaNiO_3$ (0.2 μm)/Pt(0.2 μm)/Ti(0.05 μm) is deposited by RF (for $LaNiO_3$) and dc magnetron sputtering (for Pt/Ti). A 3-μm-thick PZT thin film is then deposited by sol-gel technique. This (100) crystallographic orientation helps in maximizing the dielectric constant and electrical properties of the PZT film. The deposited films are then pyrolyzed and crystallized by rapid thermal annealing. Finally, Pt/$LaNiO_3$ layers are sputtered on top of the PZT film to form a top electrode. The photograph of the final released PZT microcantilever is shown in the same figure. A bent cantilever design is utilized for achieving the maximum amount of momentum from the wind flow and hence obtaining maximum transduction from wind energy to mechanical vibration and eventually electrical energy.

The flow sensing capability of the PZT microcantilever is characterized by using an air flow testing system as shown in Fig. 1(b). A flow channel of diameter 3.5 mm connected

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[a)] Author to whom correspondence should be addressed. Electronic mail: elelc@nus.edu.sg. Tel.: (65)6516-5865. Fax: (65)6779-1103.

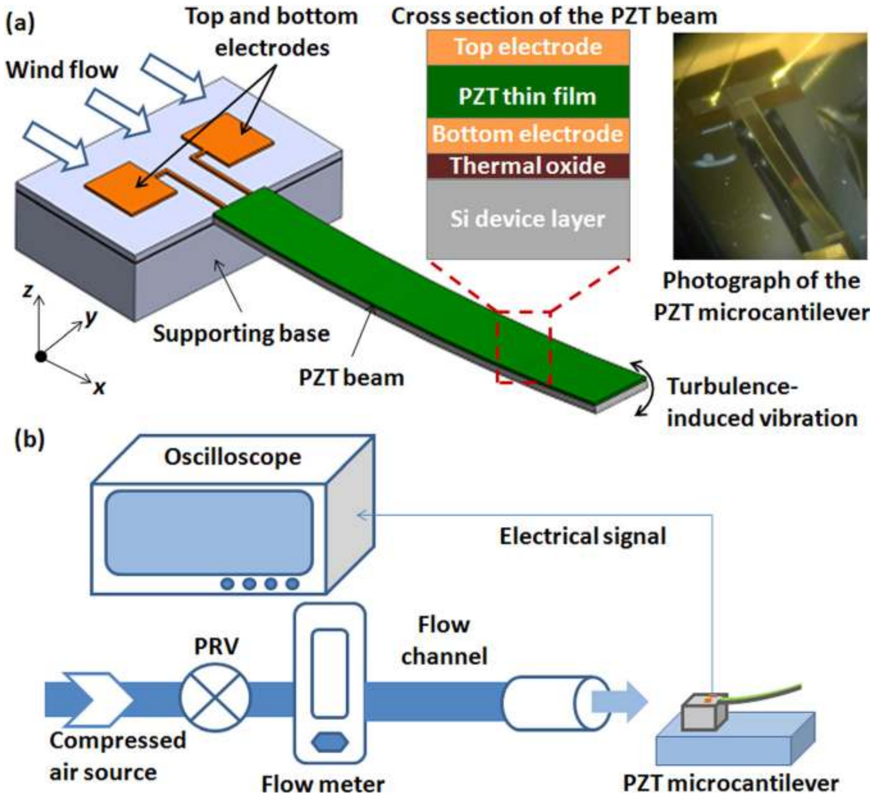


FIG. 1. (a) Schematic illustration of a PZT microcantilever immersed in a wind flow for flow sensing and energy harvesting; (b) schematic drawing of an air flow testing system.

with a compressed air source is used to mimic the ambient wind flow. A flow meter is used to change the air flow velocity in the flow channel. The nozzle of the flow channel is placed at close proximity to the PZT microcantilever so as to avoid any loss due to wind scattering. The electrical signal of the device is monitored by a digital signal oscilloscope. In the case when the PZT microcantilever is completely immersed within the air flow boundary layer, it will oscillate in a turbulence-induced vibration mode[14] and exhibit a modulated response nearby its resonant frequency.[4]

Figure 2 shows the output rms voltage of the PZT microcantilever against flow velocity varying from 0 to 19.5 m/s. According to fluid dynamics,[15] the viscous flow induced dragging force (F_d) acting on the PZT beam increases with air flow velocity (V_{flow}), and the governing equation is changed under different Reynolds number conditions (Re).

$$F_d = \frac{1}{2} C_d \rho V_{flow}^2 A \quad (\text{for Re} > 10^3), \tag{1}$$

$$F_d = C_d \mu V_{flow} l \quad (\text{for Re} < 1), \tag{2}$$

where C_d, ρ, μ, A, and l are the coefficient of the drag force, fluid density, fluid viscosity, base area, and characteristic length, respectively. Therefore, as we expected, the output voltage of the flow sensor increases steadily as the flow velocity increases. The mean sensitivity of the flow sensor is observed as 0.9 mV per unit change of flow velocity (1 m/s) by determining the slope of the voltage output. The error bar indicates the maximum and minimum rms voltages obtained from the flow sensor at a specific flow velocity. Figures 2(a) and 2(b) show the instantaneous output waveforms of the PZT microcantilever at flow velocities of 3.9 and 15.6 m/s, respectively. Due to the turbulence-induced vibration, the output spectrum of the flow sensor at a specific flow velocity shows a similar modulated oscillation nearby its own resonant frequency (around 650 Hz) but with irregular oscillation amplitudes.

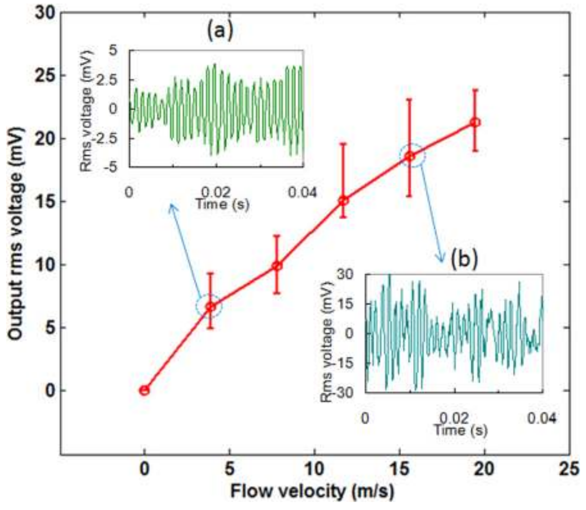


FIG. 2. Output rms voltages of the PZT microcantilever against flow velocities varying from 0 to 19.5 m/s. Inset (a) instantaneous output waveform at flow velocity of 3.9 m/s; (b) instantaneous output waveform at flow velocity of 15.6 m/s.

To be characterized as an energy harvester, the PZT microcantilever is initially measured by a conventional vibration testing system, including an electromagnetic shaker, an amplifier, and a dynamic signal analyzer. Figure 3 inset shows the output rms voltage against excitation frequency sweeping at input acceleration of 1.0 g. The peak rms voltage is 16 mV at the resonant frequency of 650 Hz. Such output value is equivalent with the one derived from the air flow testing at the flow velocity of 11.7 m/s (in Fig. 2). For an excitation frequency of 650 Hz and input acceleration of 1.0 g, the output rms voltage and power against external load resistance are measured and shown in Fig. 3. It is observed that the load rms

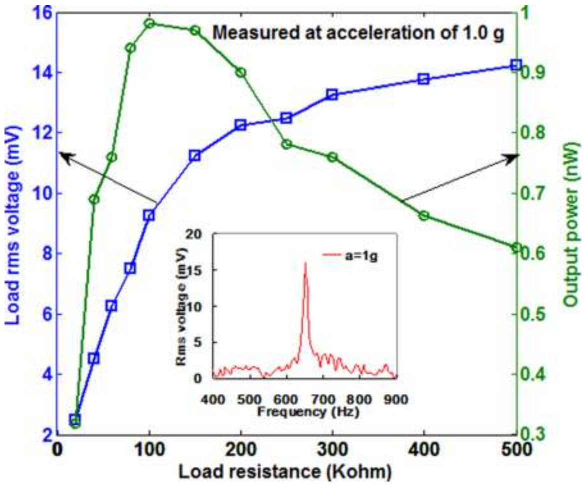
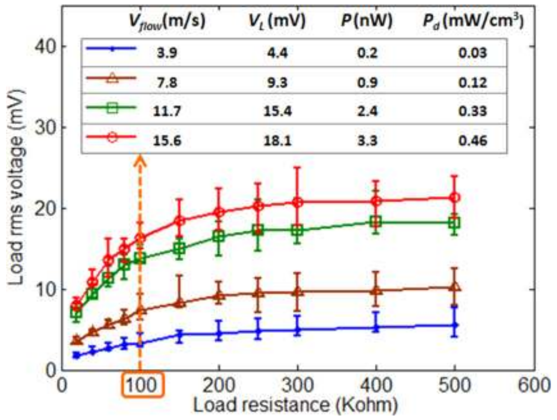


FIG. 3. Output rms voltage and power against load resistance for an excitation frequency of 650 Hz and input acceleration of 1.0 g. Inset figure shows the output rms voltage against excitation frequency at input acceleration of 1.0 g.

voltage increases monotonically as the load resistance increases. Nevertheless, the power output reaches the optimized value of 0.98 nW with a matched resistance of 100 kΩ.

For characterization of the wind-driven energy harvesting capability, the load rms voltages against load resistance with respect to different flow velocities are measured by using the air flow testing system. As shown in Fig. 4, the load rms voltage increases gradually with the increment of the load resistance. This is in accordance with the vibration testing results as shown in Fig. 3. Meanwhile, the maximum load voltage (V_L) and power (P) delivered to the matched load resistance of 100 kΩ are summarized in the inset table with respect to flow velocities varying from 3.9 to 15.6 m/s. The corresponding power densities (P_d) are shown in the inset table (when normalized by the PZT beam size of $3000\,\mu\text{m} \times 300\,\mu\text{m} \times 8\,\mu\text{m}$). At flow velocities of 11.7 and 15.6 m/s, which are ubiquitous in outdoor environment as wind levels 6 and 7 of beaufort scale, the power densities of 0.33 and 0.46 mW/cm^3 have been achieved, respectively, which are actually comparable with other vibration-driven MEMS piezoelectric energy harvesters. In addition, our proposed wind-driven energy harvester completely eliminates the operating bandwidth issue that a traditional vibration-driven energy harvester achieves the maximum power at only a particular resonant frequency.



V_{flow}(m/s)	V_L (mV)	P(nW)	P_d (mW/cm^3)
3.9	4.4	0.2	0.03
7.8	9.3	0.9	0.12
11.7	15.4	2.4	0.33
15.6	18.1	3.3	0.46

FIG. 4. Load rms voltages against load resistance with respect to different flow velocities. Inset table summarizes the maximum load rms voltages, optimized power, and power densities at different flow velocities regarding to a matched load resistance of 100 kΩ.

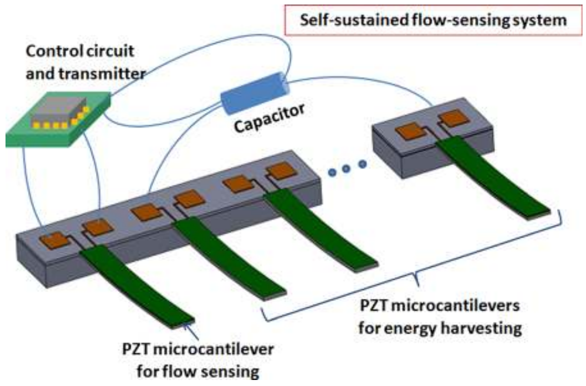


FIG. 5. A self-sustained flow-sensing microsystem by utilizing PZT microcantilevers.

In this paper, a piezoelectric PZT microcantilever is characterized in terms of flow sensing and energy harvesting capability. As shown in Fig. 5, a self-sustained flow-sensing autonomous microsystem for applications in outdoor environment is possible by employing one PZT microcantilever for flow sensing and integrating an array of PZT microcantilevers for energy harvesting from wind-driven vibrations. With further research effort in the system optimization, an efficient remote sensing system operated autonomously can be realized in a low power consumption manner since the piezoelectric sensing mechanism is a passive approach.

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