A Miniaturization Strategy for Harvesting Vibration Energy Utilizing Helmholtz Resonance and Vortex Shedding Effect

Chengliang Sun, Xiaojing Mu, Li Yan Siow, Wei Mong Tsang, Hongmiao Ji, Hyun Kee Chang, Qingxin Zhang, Yuandong Gu, and Dim-Lee Kwong

***Abstract*— In this letter, we report a miniaturization strategy for harvesting a low-frequency random vibration energy with a piezoelectric energy harvesting (EH) system utilizing coupled Helmholtz resonance and vortex shedding effect. This is made possible by transferring the low-frequency vibration energy into a pressurized fluid, which is in turn converted into predefined, pressure-independent high-frequency energy harvested by the device. The vibration-pressurized fluid conversion extends the device sampling frequency band; enables efficient harvesting of broadband low vibration frequencies with small form factor. Proof of concept of the proposed strategy has been demonstrated with an AlN-based MEMS EH, which delivered an output power density of 95.5 mW/cm^3 under a constant input airflow at 4.2 lbf/in^2 pressure.**

***Index Terms*— Piezoelectric energy harvester, flow induced vibration, vortex shedding, Helmholtz resonating.**

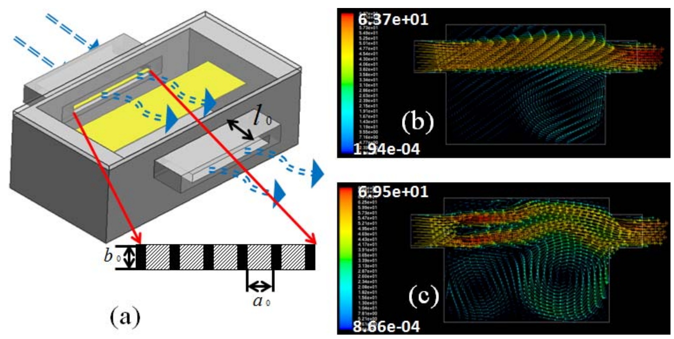

Fig. 1. (a) Illustration of the structure of the proposed flow-induced EH and fluid behaviors in the EH's cavity (b) without bluff body, no vortex shedding effect and (c) with bluff body, Helmholtz resonance is enhanced by vortex shedding effect.

I. INTRODUCTION

As THE society goes mobile and highly distributed, smart, smaller and wireless become the natural resort of solutions. A dramatic trend is the rapid growth of the self-powered wireless sensor network for industrial, environmental and healthcare applications. This emerging trend of self-powered electronic systems creates great demand for new energy solutions – highly efficient, eco-friendly, environment friendly, health friendly and miniature EHs [1], [2]. In some applications, the wireless smart node must be imbedded in the structure or body or standalone in certain environments, where no physical connection to the outside world exits. This needs miniaturize sensor nodes and deeply miniaturized EHs. Piezoelectric energy harvesting devices have been extensively used in vibration systems. However, besides the electromechanical properties of the piezoelectric material and the structure of the device, the power generation capability of the piezoelectric energy harvesting devices highly depends on the vibration source, especially its frequency, from which the energy is extracted. The key challenge of this capability is the frequency matching between the EHs and ambient vibration source. Current piezoelectric vibratory EH strategies, although showing some commercial tractions, are inherently bulky and inefficient for low frequency applications (10ths$\sim$100s Hz) [3], [4]. Some other research efforts have been demonstrated to harvest energy from fluid flow at the devices scale of centimeters and above [5]–[7]. The frequency vs. size contradiction and non-robust fabrication limit the practical use of current EHs.

In this letter, we propose a novel vibration-fluid-vibration energy harvesting strategy that eliminates this contradiction. In this strategy, we transfer the low frequency vibration energy into a pressurized fluid, which in turn drives a pre-defined high frequency piezoelectric energy harvesting structure. This results in a high efficiency, miniature EH for a wide spectrum of low frequency applications. To prove the concept of this strategy, in this letter, we demonstrated the first successful implementation of an aluminum nitride (AlN)-based MEMS EH utilizing coupled Helmholtz resonance and Vortex shedding effect.

Manuscript received November 14, 2013; revised December 17, 2013; accepted December 17, 2013. This work was supported by the Agency for Science, Technology and Research through IME's RF MEMS Resonator Core Project. The review of this letter was arranged by Editor S. J. Koester.

The authors are with the Institute of Microelectronics, Agency for Science, Technology and Research, Singapore 117685 (e-mail: guyd@ime.a-star.edu.sg; sunc@ime.a-star.edu.sg).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2013.2295922

II. ENERGY HARVESTER DESIGN

Fig. 1(a) shows the schematic of the proposed AlN-based EH consisting of a Helmholtz resonate cavity with an orifice, a narrow beam shaped bluff body and a piezoelectric micro-belt. The orifice contains multiple parallel micro-channels to accelerate the input flow rate. When the fluid flows through the cavity, it will be partially trapped in the cavity and excited to resonate at the Helmholtz resonating frequency determined by cavity dimensions. This resonating fluid induces a force on the piezoelectric micro-belt, causing it to vibrate, thus generating the strain-dependent charge output. The bluff body is placed at the entrance of the cavity to enhance the Helmholtz resonance as well as the resultant charge output by the well-known vortex shedding effect, which can also lower the threshold input pressure. To validate this enhancement due to the bluff body on the resonating fluid, simulations were conducted under the same flow rate for the device without [Fig. 1(b)] and with [Fig. 1(c)] bluff body. From the simulation results, it can be seen that the resonating effect of the device with bluff body is much stronger than the one without bluff body.

Another distinct advantage of the proposed EH is that the operation frequency can be pre-defined and is independent of the input fluid flow. Generally, the resonant frequency of the Helmholtz resonator depends on the volume of the cavity and the size of the orifice. In our proposed EH, the orifice consists of multiple rectangular shaped micro-channels, and its resonant frequency can be defined as [8]:

$$f = \frac{c}{2\pi}\sqrt{\frac{na_0b_0}{V(l_0+1.7r_0)}}, \quad r_0 = \sqrt{\frac{na_0b_0}{\pi}} \tag{1}$$

where c is the speed of sound, n is the number of micro-channels, l_0 is the length of the orifice, V is the volume of the cavity and r_0 will be defined by a_0 and b_0 which are the width and height of the rectangular micro-channel, respectively. From equation (1), it can be seen that the resonant frequency is independent of input flow rate.

III. Device Fabrication

In order to validate the proposed EH concept, a series of EH designs were fabricated with CMOS compatible process by using AlN/SOI platform. Key process integration steps are shown in Fig. 2(a)–(h). The process start with a functional Al/AlN/Mo stacks [Fig. 2(a)] deposited on a SOI wafer; three masks [Fig. 2(b)–(d)] were used for top Al, bottom Mo electrodes patterning and backside release etching to define the device layer. Subsequently, one bare Si wafers [Fig. 2(e)] was bonded to the bottom of the device layer to form the bottom sealed cavity, which also acts as the support wafer for the front side release of the device layer. Another Si wafer [Fig. 2(f)] with a special cavity design was defined and bonded to the top side of the device layer to obtain the final EH device [Fig. 2(h)]. Fig. 2(i) shows the fabricated functional structure, including micro-machined channels which formed inlet and outlet of the Helmholtz resonator, the piezoelectric micro-belt and the bluff bodies [Fig. 2(j)]. Finally, the device is bonded on a PCB board also with a PDMS cap for testing [Fig. 2(k)].

IV. Measurement Results and Discussion

To evaluate the vortex shedding effects induced by the bluff bodies on the performance of the EHs, both the output voltage and output power of the two devices with and without the bluff body were measured. Both the EHs was driven using pressurized air flow monitored by a pressure meter and a flow meter.

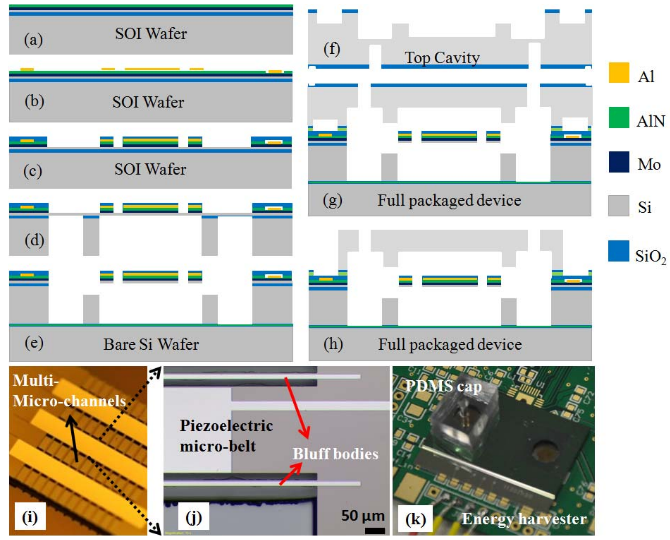

Fig. 2. Major process integration steps and integrated EH device. (a) The piezoelectric AlN/Mo stack was consecutively deposit on a SOI wafer. (b) Pattern the top and bottom Al electrodes (c) Pattern the piezoelectric stack; (d) Device layer release etch from backside; (e) bonding device wafer with bottom cap wafer and further release etch from front side; (f) Top cap wafer fabrication; (g) bonding top cap wafer with the device wafer, inlet and outlet hole forming by DRIE; (h) partial dicing to expose top electrodes; (i) interior function structures; (j) bluff body and AlN micro-belt and (k) fully integrated EH device.

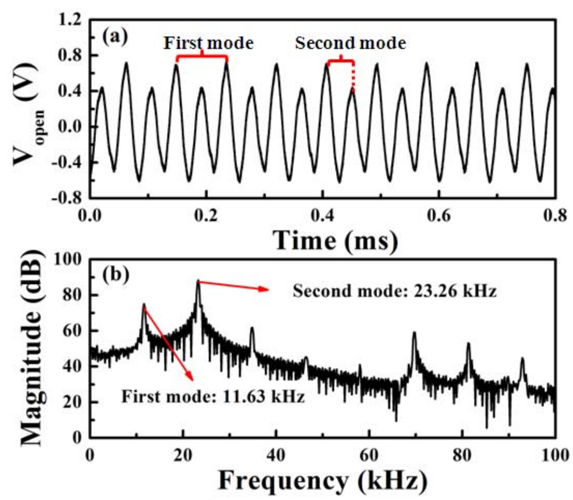

Fig. 3. (a) Time domain open circuit output voltage and (b) the corresponding frequency spectra.

In the output voltage measurements, the device without bluff body starts to resonate when the input air flow is higher than 7.6 lbf/in^2 with a flow rate of 8 liters/min. Whereas, for the EH with the same geometry and dimensions but equipped with bluff body, the threshold resonating condition of the input air pressure was dramatically reduced to 3 lbf/in^2 with a flow rate of 3.5 liters/min. Fig. 3 shows the output open-circuit voltage (V_{open}) and its corresponding frequency spectra of the device with bluff body under a constant air flow at the pressure of 4.2 lbf/in^2 (i.e. the flow rate of 4 liters/min, where the generated voltage reaches maximum with a peak to peak value of 1.4 V). These experimental results agree well with the simulation predictions [Fig. 1(b) and (c)] on the vortex shedding effect of the fluid behavior in the resonating cavity.

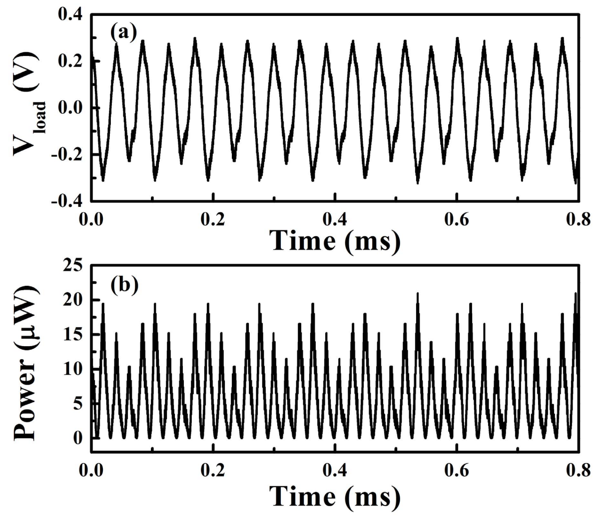

Fig. 4. Output power measurement with a 5 kΩ resistor load, (a) the voltage loaded on the resistor; and (b) the corresponding output power spectra with the peak output power of 21 μW.

From Fig. 3(b), the first two modes (with the frequencies of 11.63 kHz and 23.26 kHz) of the voltage spectra dominate the energy harvesting capability of the device. The frequency of the first mode agrees well with the Helmholtz resonant frequency of 11.2 kHz as predicted by equation (1).

In the output power measurements, the power generated by the EH device with bluff body on a 5 kΩ resistor was measured along with the output voltage [as shown in Fig. 4(a) and (b)]. A peak output power of $\sim$21 μW with a power density of 95.5 mW/cm^3 at the fundamental resonance frequency under 4.2 lbf/in^2 input air pressure was achieved. While for the device without bluff body, the output power is $\sim$25 μW under a 7.6 lbf/in^2 input air pressure. According to the basis formulas of the pneumatic fluid energy and the volume of fluid which loaded on the piezoelectric micro belt, the energy harvesting efficiency of the device with bluff body is calculated to be 0.037%, which is 4.1 times high than that of the device without bluff body (0.009%).

V. Conclusion

In summary, a novel miniaturization strategy for harvesting low frequency vibration energy is implemented in a MEMS format. It eliminates the size vs. frequency contradiction faced by most current EH technology. In this letter, the prototype of AlN based MEMS EHs were developed to proof this strategy. Two key characteristics can be observed from the measurement results: 1) the operating frequency of the EH is determined by the physical sizes of the cavity and orifice and is independent of the input fluid flow rate, which greatly simplifies the ASIC design and simultaneously improves the energy storage efficiency; 2) the bluff body enhances the Helmholtz resonance and lowers the threshold of input fluid pressure. These observations are in good agreement with the theoretical and simulation prediction. Furthermore, both AlN and Si have a very high Q factor, this result in low dielectric and mechanical loss inside the EHs which definitely increases the life time of the EHs. This letter also provides a new direction for building high performance, broadband, miniature EH for implantable biomedical devices, automotive sensing, and wireless communication applications.

Acknowledgment

The authors would like to thank Dr. H. Campanella Pineda and Dr. H. Yu for helpful discussions.

References

[1] Z. L. Wang and W. Wu, "Nanotechnology-enabled energy harvesting for self-powered micro-/nanosystems," *Angew. Chem. Int. Ed.*, vol. 51, no. 47, pp. 2–24, 2012.

[2] S. R. Anton and H. A. Sodano, "A review of power harvesting using piezoelectric materials (2003–2006)," *Smart Mater. Struct.*, vol. 16, no. 3, pp. R1–R21, 2007.

[3] R. Elfrink, S. Matova, C. de Nooijer, *et al.*, "Shock induced energy harvesting with a MEMS harvester for automotive applications," in *Proc. IEEE IEDM*, Dec. 2011, pp. 677–680.

[4] L. Tang, Y. Yang, and C. K. Soh, "Toword broadband vibration-based energy harvesting," *J. Intell. Mater. Syst. Struct.*, vol. 21, no. 18, pp. 1867–1897, 2010.

[5] L. A. Weinstein, M. R. Cacan, P. M. So, *et al.*, "Vortex shedding induced energy harvesting from piezoelectric materials in heating, ventilation and air conditioning flows," *Smart Mater. Struct.*, vol. 21, no. 4, pp. 045003-1–045003-10, 2012.

[6] C. Sun, J. Shi, D. J. Bayerla, *et al.*, "PVDF microbelts for harvesting energy from respiration," *Energy Environ. Sci.*, vol. 4, pp. 4508–4512, Aug. 2011.

[7] S. P. Matova, R. Elfrink, R. J. M. Vullers, *et al.*, "Harvesting energy from airflow with a michromachined piezoelectric harvester inside a Helmholtz resonator," *J. Micromech. Microeng.*, vol. 21, no. 10, pp. 104001-1–104001-6, 2011.

[8] R. C. Chanaud, "Effects of geometry on the resonance frequency of Helmholtz resonators," *J. Sound Vibrat.*, vol. 178, no. 3, pp. 337–348, 1994.