ZnO thin film piezoelectric MEMS vibration energy harvesters with two piezoelectric elements for higher output performance

Wang, Peihong; Du, Hejun

2015

Wang, P., & Du, H. (2015). ZnO thin film piezoelectric MEMS vibration energy harvesters with two piezoelectric elements for higher output performance. Review of Scientific Instruments, 86(7), 075002-.

<https://hdl.handle.net/10356/83659>

<https://doi.org/10.1063/1.4923456>

© 2015 AIP Publishing LLC. This paper was published in Review of Scientific Instruments and is made available as an electronic reprint (preprint) with permission of AIP Publishing LLC. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1063/1.4923456>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 19:29:29 SGT

ZnO thin film piezoelectric MEMS vibration energy harvesters with two piezoelectric elements for higher output performance

Peihong Wang and Hejun Du

Citation: *Review of Scientific Instruments* **86**, 075002 (2015); doi: 10.1063/1.4923456

View online: <http://dx.doi.org/10.1063/1.4923456>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/rsi/86/7?ver=pdfcov>

Published by the AIP Publishing

Articles you may be interested in

[Harvesting vibration energy using two modal vibrations of a folded piezoelectric device](#)

Appl. Phys. Lett. **107**, 033904 (2015); 10.1063/1.4927331

[Characteristics of piezoelectric ZnO/AlN-stacked flexible nanogenerators for energy harvesting applications](#)

Appl. Phys. Lett. **106**, 023901 (2015); 10.1063/1.4904270

[Energy harvester array using piezoelectric circular diaphragm for broadband vibration](#)

Appl. Phys. Lett. **104**, 223904 (2014); 10.1063/1.4878537

[Nonlinear output properties of cantilever driving low frequency piezoelectric energy harvester](#)

Appl. Phys. Lett. **101**, 223503 (2012); 10.1063/1.4768219

[Measured efficiency of a ZnO nanostructured diode piezoelectric energy harvesting device](#)

Appl. Phys. Lett. **101**, 093902 (2012); 10.1063/1.4749279

ZnO thin film piezoelectric MEMS vibration energy harvesters with two piezoelectric elements for higher output performance

Peihong Wang^{1,2,a)} and Hejun Du³

¹Key Laboratory of Opto-Electronic Information Acquisition and Manipulation of Ministry of Education, Anhui University, Hefei 230601, China

²School of Physics and Material Science, Anhui University, Hefei 230601, China

³School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

(Received 24 January 2015; accepted 22 June 2015; published online 9 July 2015)

Zinc oxide (ZnO) thin film piezoelectric microelectromechanical systems (MEMS) based vibration energy harvesters with two different designs are presented. These harvesters consist of a silicon cantilever, a silicon proof mass, and a ZnO piezoelectric layer. Design I has a large ZnO piezoelectric element and Design II has two smaller and equally sized ZnO piezoelectric elements; however, the total area of ZnO thin film in two designs is equal. The ZnO thin film is deposited by means of radio-frequency magnetron sputtering method and is characterized by means of XRD and SEM techniques. These ZnO energy harvesters are fabricated by using MEMS micromachining. The natural frequencies of the fabricated ZnO energy harvesters are simulated and tested. The test results show that these two energy harvesters with different designs have almost the same natural frequency. Then, the output performance of different ZnO energy harvesters is tested in detail. The effects of series connection and parallel connection of two ZnO elements on the load voltage and power are also analyzed. The experimental results show that the energy harvester with two ZnO piezoelectric elements in parallel connection in Design II has higher load voltage and higher load power than the fabricated energy harvesters with other designs. Its load voltage is 2.06 V under load resistance of 1 M Ω and its maximal load power is 1.25 μ W under load resistance of 0.6 M Ω , when it is excited by an external vibration with frequency of 1300.1 Hz and acceleration of 10 m/s². By contrast, the load voltage of the energy harvester of Design I is 1.77 V under 1 M Ω resistance and its maximal load power is 0.98 μ W under 0.38 M Ω load resistance when it is excited by the same vibration. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4923456>]

I. INTRODUCTION

With the fast development of ultra low power VLSI (Very Large Scale Integration) design and microelectronics technology, WSNs (wireless sensor networks), micro sensors and transducers and MEMS (Microelectromechanical systems) devices are being widely used in industry, agriculture, medicine, biology, and even military. Correspondingly, their requirements for power source are becoming higher and higher. Conventional power sources including batteries and electric cables can no longer satisfy some rigorous demands such as being wireless, self-sustainable, and infinite lifetime. Energy harvesting technique can scavenge energy from the ambient environment and then convert it into electrical power automatically.^{1,2} So, it is a very promising alternative to conventional power sources. Piezoelectric vibration energy harvesters have attracted greater attention due to their higher energy density, no need of external power, and ease of integration with other micro devices, as compared with electromagnetic, electrostatic, or magnetoelectric energy

harvesters.^{3–8} Piezoelectric vibration energy harvesters based on PZT (lead zirconate titanate) or AlN (aluminum nitride) thin film have been studied widely,^{9–14} but there are a few reports about ZnO (zinc oxide) film-based energy harvesters, although piezoelectric ZnO thin film has many advantages over PZT or AlN such as no environmental pollution and no requirement for poling or post-annealing. In addition, the effect of ZnO piezoelectric elements in series and parallel connections on the output performance of ZnO energy harvesters has not been studied in the literature. Pan *et al.* designed and fabricated a flexible piezoelectric vibration energy harvester by depositing ZnO thin film on PET (polyethylene terephthalate) structures.^{15,16} Its operating frequency bandwidth arrives to 350 Hz after optimization of PET's thickness and a flash LED (Light emitting diode) is driven by this energy harvester. However, this energy harvester is not compatible with CMOS technique. Md Ralib *et al.* presented a piezoelectric energy harvester based on AZO (aluminum doped zinc oxide) piezoelectric thin film.¹⁷ This study, though using micromachining technique to fabricate the harvester and its output open circuit voltage is 1.61 V at 7.77 MHz resonance frequency, lacks enough data about output performance of the energy harvester. Liu *et al.* found that increasing the number of PZT piezoelectric elements on

^{a)}Author to whom correspondence should be addressed. Electronic mail: wangpeihong2002@ahu.edu.cn.

a same cantilever could increase the operation bandwidth and output power of piezoelectric energy harvesters when these PZT elements were connected in parallel, and the amplitude of the cantilever was limited.¹⁸ Dayou *et al.* investigated the performance of width-split piezoelectric energy harvester and found that its bandwidth can be increased by wider variation in natural frequency of each participating split beam and connecting them in parallel.¹⁹ The problem is that they did not give the fabrication process of the prototype in detail and also did not discuss the effect of electrical connection of split beams on the power and bandwidth of the output.

This paper first introduces two designs of piezoelectric MEMS vibration energy harvesters with ZnO thin film, with their device configurations and fabrication processes illustrated, respectively. Then, it explores the characterization of the ZnO thin film and the harvester prototypes, which is followed by simulating and measuring the resonant frequency of the harvester prototypes. Finally, this paper reports and discusses the experimental results, in particular, the output voltage and output power of ZnO energy harvesters of different designs and different connections of ZnO piezoelectric elements.

II. DESIGN

Fig. 1 gives the 2-D schematics of the ZnO piezoelectric energy harvesters with different designs. This harvester mainly consists of a silicon (Si) cantilever, a Si proof mass, and a ZnO piezoelectric layer. As seen in Fig. 1(a), the ZnO piezoelectric layer covers the full surface of the cantilever's root in Design I which is the same as the traditional design of piezoelectric energy harvesters. In Design II shown in Fig. 1(b), the ZnO piezoelectric layer is separated into two equal parts along the direction of length. These two piezoelectric elements in Design II can be connected in series or in parallel. Although

FIG. 1. 2-D schematics of ZnO piezoelectric vibration energy harvesters with Design I (a) and Design II (b). It is a top view and the vibration excitation occurs out of the page.

FIG. 2. Fabrication process flow of the ZnO thin film piezoelectric energy harvester. (a) Oxidation; (b) deposition of Au/Ti bottom electrode; (c) sputtering of ZnO thin film; (d) depositing Au/Ti top electrode; (e) etching SiO₂ and Si from the front side; (f) releasing the cantilever by etching Si and SiO₂ from back side.

these two designs have different piezoelectric elements, the total area of piezoelectric material in two designs is the same.

III. FABRICATION

The ZnO piezoelectric MEMS energy harvester is fabricated on a silicon wafer by means of the micromachining technique and the fabrication process flow is shown in Fig. 2. The fabrication process starts with the oxidation of a silicon wafer of 4 inch in diameter (Fig. 2(a)). The Au/Ti layer of 100 nm thickness is sputtered on the surface of SiO₂ layer and patterned as bottom electrode (Fig. 2(b)). Then, a 1.4 μm ZnO thin film is deposited by means of the radio-frequency (RF) magnetron sputtering method and patterned by wet etching technique which involves the use of diluted 5% HCl solution (Fig. 2(c)). After ZnO deposition, another 100 nm Au/Ti layer is sputtered and patterned as top electrode (Fig. 2(d)). Then, the silicon wafer undergoes deep reactive ion etching (DRIE) for two times. First, the pattern of the cantilever with desired thickness is defined by etching SiO₂ and Si from the front side (Fig. 2(e)). Second, the cantilever with proof mass is released after etching SiO₂ and Si from the back side (Fig. 2(f)). The photo of the array of fabricated ZnO piezoelectric energy harvesters on a silicon wafer is given in Fig. 3. In order to decrease the effect of variation of material properties on different substrates' region on the performance of device, two energy harvesters with Design I and Design II located in the center of the substrate are selected as prototypes in the following experiments.

IV. RESULTS AND DISCUSSION

The optical photos of the ZnO piezoelectric energy harvesters with Design I and Design II are given in Figs. 4(a) and 4(b). The SEM images of these two energy harvesters are given

FIG. 3. The picture of the array of ZnO thin film piezoelectric energy harvesters with different designs on a 4 in. silicon wafer.

in Figs. 4(c) and 4(d). The dimensions of the Si cantilever and the Si proof mass of the two designs are the same, namely, $2000 \times 5000 \mu\text{m}^2$ and $1500 \times 1000 \mu\text{m}^2$, respectively. The dimension of the ZnO element in Design I is $1000 \times 480 \times 1.4 \mu\text{m}^3$. The dimensions of the two ZnO elements in Design II are same and are $1000 \times 240 \times 1.4 \mu\text{m}^3$. Therefore, the areas of ZnO thin film in two designs are the same.

The XRD pattern of the ZnO thin film deposited on bottom electrode is inserted in Fig. 4(c) and it indicates that there is a very strong peak at 34.422° and it is just the ZnO(002) diffraction peak. So, the ZnO film has a highly c-axis-preferred orientation, which shows the ZnO film has high piezoelectric quality. The FE-SEM (Field Emission SEM) image of the cross section of the ZnO film with electrodes is shown in the inset in Fig. 4(d). It shows that the ZnO film has columnar texture and so is highly c-axis-oriented,

FIG. 5. The simulation result of the first order vibration mode of the Si cantilever.

which agrees with the XRD pattern as shown in Fig. 4(c). The other characterizations of the ZnO film can be found in our published literatures.^{20,21}

For an energy harvester, its resonant frequency is a very important parameter. So, the natural frequency of the ZnO energy harvester is first evaluated by simulation. As the ZnO layer and the Au/Ti electrode layer are much thinner than the silicon cantilever, they have little effect on the resonant frequency of the cantilever. So, the ZnO element and electrodes are ignored in the simulation and the result of the mode analysis of the Si cantilever is given in Fig. 5. It shows that the resonant frequency of the first mode of the Si cantilever is 1368.8 Hz.

Then, the vibration behavior of the fabricated ZnO energy harvesters is tested by a Laser Doppler Vibrometer

FIG. 4. The images of the fabricated ZnO energy harvesters. (a) and (b) are the optical photos of the energy harvesters with Design I and Design II, respectively. (c) and (d) are the SEM images of the energy harvesters with Design I and Design II, respectively. The inset in (c) is the XRD pattern of the ZnO film on Au/Ti bottom electrode and the inset in (d) is the cross-sectional view of ZnO piezoelectric layer.

FIG. 6. The relationship between the magnitude of velocity of the cantilever's tip in Design I and the input vibration frequency measured by LDV.

(LDV, Polytec PSV-300). The magnitude of velocity of the cantilever's tip in Design I versus the vibration frequency is given in Fig. 6. It shows that the resonant frequency is 1300.1 Hz. The resonant frequency of the fabricated ZnO energy harvester with Design II is 1313.4 Hz. So, the two ZnO energy harvester prototypes have almost the same resonant frequency. The difference of the resonant frequency between the simulation and the test may be caused by over etching of Si cantilever during DRIE progress.

The output performance of the fabricated ZnO piezoelectric energy harvesters is carried out by using the experimental setup shown in Fig. 7. A vibrator (B&K 4810) is used to supply mechanical vibration to the energy harvester. A waveform generator (Agilent 33120A) incorporated with a power amplifier (B&K 2718) is used to supply sine wave signal to the vibrator. An accelerometer (B&K 4374) and a conditioning amplifier (B&K 2692) are used to measure the acceleration of the vibration. An oscilloscope (Tektronix TDS 3014) with an impedance of 1 M Ω is used to measure the output voltage of the energy harvester. In the testing process, the frequency of the input vibration is set as the natural frequency of the energy harvester and the acceleration of the input vibration is fixed as 10 m/s².

Fig. 8 indicates the relationship between the load voltage and load resistance of ZnO energy harvesters. It shows that the load voltage increases with the load resistance for all ZnO energy harvesters. The increasing rate of load voltage is large at first and then becomes slow. The load voltage for parallel connection in Design II is the biggest and the load voltage

FIG. 7. Schematic of the experimental setup.

FIG. 8. The load voltage versus load resistance for two kinds of energy harvester prototypes when the prototype is resonant and the input acceleration is 10 m/s².

for single ZnO element in Design II is the smallest under the same testing condition. Meanwhile, the load voltage for Design I is the second biggest. The maximum of the load voltage for parallel connection in Design II is 2.06 V under 1 M Ω resistance and that for Design I is 1.77 V under 1 M Ω resistance. For Design II, the load voltage for series connection is a little larger than that for single ZnO piezoelectric element; however, the load voltage for parallel connection is about twice that for single ZnO element in the resistance range of 0.1–1.0 M Ω , which agrees with the experimental results of Ref. 18 very well. If the resistance range is very large, the load voltage for parallel connection and series connection will have a new change, which can be found in Ref. 18.

The load power can be calculated by using the following equation: $P_{load} = \frac{V_{pp}^2}{4R_{load}}$, where V_{pp} is the peak-peak value of the load voltage and R_{load} is the load resistance. The calculated result is shown in Fig. 9, which suggests that the load power increases with the load resistance first and then decreases after it reaches a maximum for every ZnO energy harvester. Meanwhile, the load resistances corresponding to the maximal

FIG. 9. The load power versus load resistance for two kinds of energy harvester prototypes when the prototype is resonant and the input acceleration is 10 m/s².

load power vary with different energy harvesters. The load power for parallel connection in Design II is always larger than that for Design I. For Design II, the load power for series connection is a little larger than that for a single piezoelectric element and the load power for parallel connection is much larger than that for series connection and a single piezoelectric element, which agrees with the experimental results of Ref. 18. Hence, it is concluded that the piezoelectric elements in parallel connection in Design II can produce much higher load power in the resistance range of 0.1–1.0 M Ω . The maximal load power of parallel connection in Design II is 1.25 μ W under load resistance of 0.6 M Ω , while the maximum of the load power of Design I is 0.98 μ W under 0.38 M Ω load resistance.

V. CONCLUSIONS

Two different designs of piezoelectric MEMS vibration energy harvesters based on ZnO thin film are simulated, fabricated, and characterized. XRD pattern and SEM images of the ZnO thin film show that it is highly c-axis orientated and so has good piezoelectricity. The ZnO energy harvester prototypes are fabricated by means of MEMS micromachining. The tested result from LDV shows that the natural frequency of the ZnO energy harvester is 1300.1 Hz which is close to the simulation result of 1368.8 Hz. The experimental results show that the load voltage increases with the load resistance but the load power increases first and then decreases with the load resistance for all the energy harvesters. The ZnO energy harvester with two piezoelectric elements in parallel connection has the largest load voltage of 2.06 V under load resistance of 1 M Ω and the largest load power of 1.25 μ W under load resistance of 0.6 M Ω , when it is excited by an external vibration with frequency of 1300 Hz and acceleration of 10 m/s². The increase in load power generated from Design I to Design II comes from the reduction in mechanical damping by splitting the ZnO piezoelectric element.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No. 51007001), Anhui Provincial Natural Science Foundation of China (No. 1508085ME72), and the open foundation of Key Laboratory of Opto-electronic Information Acquisition and Manipulation of Ministry of Education, Anhui University, China (No. OEIAM201411).

¹S. Roundy, P. K. Wright, and J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes," *Comput. Commun.* **26**(11), 1131–1144 (2003).

- ²S. Priya and D. J. Inman, *Energy Harvesting Technologies* (Springer Science+Business Media, New York, 2009).
- ³S. Saadon and O. Sidek, "A review of vibration-based MEMS piezoelectric energy harvesters," *Energy Convers. Manage.* **52**(1), 500–504 (2011).
- ⁴M. Rezaei, J. Lueke, D. Raboud, and W. Moussa, "Challenges in fabrication and testing of piezoelectric MEMS with a particular focus on energy harvesters," *Microsyst. Technol.* **19**, 1195–1219 (2013).
- ⁵A. Toprak and O. Tigli, "Piezoelectric energy harvesting: State of the art and challenges," *Appl. Phys. Rev.* **1**, 031104 (2014).
- ⁶P. Wang, K. Tanaka, S. Sugiyama, X. Dai, X. Zhao, and J. Liu, "A micro electromagnetic low level vibration energy harvester based on MEMS technology," *Microsyst. Technol.* **15**(6), 941–951 (2009).
- ⁷K. Tao, S. Liu, S. W. Lye, J. M. Miao, and X. Hu, "A three-dimensional electret-based micro power generator for low-level ambient vibrational energy harvesting," *J. Micromech. Microeng.* **24**, 065022 (2014).
- ⁸J. Yang, Y. Wen, P. Li, X. Yue, Q. Yu, and X. Bai, "A two-dimensional broadband vibration energy harvester using magnetoelectric transducer," *Appl. Phys. Lett.* **103**, 243903 (2013).
- ⁹S. R. Platt, S. Farritor, and H. Haider, "On low-frequency electric power generation with PZT ceramics," *IEEE/ASME Trans. Mechatronics* **10**(2), 240–252 (2005).
- ¹⁰B. Yang, J. Liu, G. Tang, J. Luo, and C. Yang, "A generator with nonlinear spring oscillator to provide vibrations of multi-frequency," *Appl. Phys. Lett.* **99**, 223505 (2011).
- ¹¹P. Janphuang, R. Lockhart, N. Uffer, D. Briand, and N. F. de Rooij, "Vibrational piezoelectric energy harvesters based on thinned bulk PZT sheets fabricated at the wafer level," *Sens. Actuators, A* **210**, 1–9 (2014).
- ¹²R. Elfrink, T. M. Kamel, M. Goedbloed, S. Matova, D. Hohlfield, Y. van Anel, and R. van Schaijk, "Vibration energy harvesting with aluminum nitride-based piezoelectric devices," *J. Micromech. Microeng.* **19**, 094005 (2009).
- ¹³Z. P. Cao, J. Y. Zhang, and H. Kuwano, "A piezoelectric generator fabricated from the structure of AlN/SUS," in *Proceedings of the 11th Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications* (Cell Bench Research Center, KAIST, 2011), pp. 118–121.
- ¹⁴R. Andosca, T. G. McDonald, V. Genova, S. Rosenberg, J. Keating, C. Benedixen, and J. Wu, "Experimental and theoretical studies on MEMS piezoelectric vibrational energy harvesters with mass loading," *Sens. Actuators, A* **178**, 76–87 (2012).
- ¹⁵C. T. Pan, Z. H. Liu, Y. C. Chen *et al.*, "Design and fabrication of flexible piezo-microgenerator by depositing ZnO thin films on PET substrates," *Sens. Actuators, A* **159**(1), 96–104 (2010).
- ¹⁶C. T. Pan, Z. H. Liu, and Y. C. Chen, "Study of broad bandwidth vibrational energy harvesting system with optimum thickness of PET substrate," *Curr. Appl. Phys.* **12**(3), 684–696 (2012).
- ¹⁷A. A. Md Ralib, A. N. Nordin, H. Salleh, and R. Othman, "Fabrication of aluminium doped zinc oxide piezoelectric thin film on a silicon substrate for piezoelectric MEMS energy harvesters," *Microsyst. Technol.* **18**, 1761–1769 (2012).
- ¹⁸L. Huicong, T. C. Jui, Q. Chenggen, K. Takeshi, and L. Chengkuo, "Piezo-electric MEMS energy harvester for low-frequency vibrations with wide-band operation range and steadily increased output power," *J. Microelectromech. Syst.* **20**(5), 1131–1142 (2011).
- ¹⁹D. Jedol, W. Y. H. Liew, and C. Man-Sang, "Increasing the bandwidth of the width-split piezoelectric energy harvester," *Microelectron. J.* **43**, 484–491 (2012).
- ²⁰P. Wang, H. Du, S. Shen, M. Zhang, and B. Liu, "Deposition, characterization and optimization of zinc oxide thin film for piezoelectric cantilevers," *Appl. Surf. Sci.* **258**(24), 9510–9517 (2012).
- ²¹P. Wang, H. Du, S. Shen, M. Zhang, and B. Liu, "Preparation and characterization of ZnO microcantilever for nanoactuation," *Nanoscale Res. Lett.* **7**(3), 176 (2012).