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## Modeling and Experimental Study of a Low-Frequency-Vibration-Based Power Generator Using ZnO Nanowire Arrays

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***Abstract*—A piezoelectric power generator based on ZnO nanowire arrays (NWAs) is proposed for scavenging energy from low-frequency ambient vibration. A low-temperature and low-cost hydrothermal method is employed to grow the uniform ZnO nanowires with the diameters of $\sim$70 nm and lengths of $\sim$2.5 $\mu$m. A theoretical model is derived to better understand piezoelectric-energy harvesting and to predict the output performance of cylindrical ZnO NWAs. The open-circuit output voltages of the resonant generators at normal and shear modes are 1.1 and 3.59 mV, respectively. [2012-0043]**

***Index Terms*—Hydrothermal method, low frequency, power generator, vibration, zinc oxide (ZnO) nanowires.**

### I. Introduction

Piezoelectric power generators have immense potential for applications such as self-powered nanoelectronic devices and systems [1]–[4]. Piezoelectric power generators based on aligned zinc oxide (ZnO) nanowires have been previously reported [5]. The output voltage of such nanowire generators has recently been improved to 10 mV under the driving of ultrasonic wave [2]. ZnO nanowires were grown on $c$-plane-oriented $\alpha$-$Al_2O_3$ substrate by vapor–liquid–solid process, using Au particles as a catalyst [6], [7]. Recently, p-doped ZnO nanowire arrays (NWAs) for generator application had also been grown on (001) silicon substrate using thermal vapor deposition [8]. The electric output of such a p-type generator is 10–15 mV in magnitude under a conductive atomic force of 5 nN. Besides using silicon substrate, well-aligned ZnO nanowires with an average length of $\sim$5 $\mu$m had also been grown on GaN/AlN substrate through a vapor–solid process [9]. The vapor-phase method, as compared to the low-cost and simple aqueous methods, usually employs vacuum, sophisticated equipment, and higher temperature which restricts the type of substrate used. Among the aqueous-grown methods, the hydrothermal method has emerged as a powerful method for the fabrication of 1-D nanostructures, offering significant advantages such as controllable structures and a cost-effective low-temperature substrate-independent technique that allows for easy integration. A theoretical model that predicts the electrical power generated by an array of vertically aligned ZnO nanoribbons is proposed [10]. Finite-element-method calculations for analyzing the bending of a semiconducting piezoelectric ZnO nanowire for generator are presented [11]. Vibration-based generators provide the maximum output power when such devices operate at their mechanical resonances. However, the vibration frequency of available ambient-vibration sources is random and varies from one case to another. For example, the vibration frequency of a laptop during normal operation is 90.2 Hz, but the one of a running compact disk read-only memory is 43.2 Hz [12]. Therefore, it is necessary to develop the generators with multiple modes to improve conversion efficiency.

In this letter, we propose a low-frequency-vibration-based power generator using ZnO cylindrical NWAs grown by hydrothermal method for process integration and low cost. This device can scavenge the vibration energy under normal and shear modes for improving its output power.

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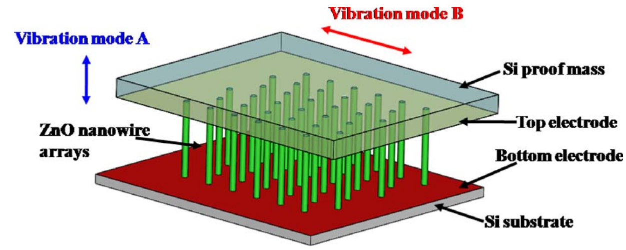


Fig. 1. Schematic diagram of the power generator, which consists of ZnO NWAs and Si proof mass for low-frequency-vibration harvesting. The generator is excited, and energy is scavenged by normal-mode A and shear-mode B.

### II. Experimental Results

Fig. 1 shows the cross-sectional drawing of the piezoelectric power generator, which includes the NWA deposited on silicon substrate, Cr/Au layer as the bottom electrode, and silicon proof mass with the top electrode. The proof mass helps to scavenge kinetic energy from low-frequency vibrations, hence allowing the generator to achieve better performance. The mass measures $1.1\ \text{cm} \times 1.1\ \text{cm} \times 0.07\ \text{cm}$ and is pasted on top of the NWA by epoxy. The generator is excited at two vibration resonant modes, i.e., normal-mode A and shear-mode B, so as to maximize the output voltage generated. In normal-mode A, the proof mass moves up and down along the longitudinal direction of the ZnO nanowires. In shear-mode B, the direction of the proof-mass movement is perpendicular to the length of the ZnO nanowires.

A Cr/Au (100 nm/10 nm) layer was deposited on a $SiO_2$/Si substrate by thermal evaporation. A seed solution of 0.01-M zinc acetate (ZnAc) in 10-mL absolute ethanol is then spin coated on the substrate at 1000 r/min for 1 min repeated for three times. The sample is then annealed at 250°C for 30 min, causing ZnAc to be thermally decomposed to become ZnO nanocrystals. The well-dispersed ZnO nanocrystals act as nucleation sites for the growth of ZnO nanowires. The growth precursor, which consists of an aqueous 25-mM zinc nitrate hexahydrate and hexamethylenetetramine solution, is prepared after which 0.1 g of polyethyleneimine is added to 50 mL of aqueous precursor. Seeded substrates are suspended upside down in the growth precursor and left to stand for 6 h at 90°C. Fig. 2(a) shows a cross-sectional SEM of the growing ZnO NWA with an average length of 2.5 $\mu$m. The diameter of the ZnO nanowires varies from

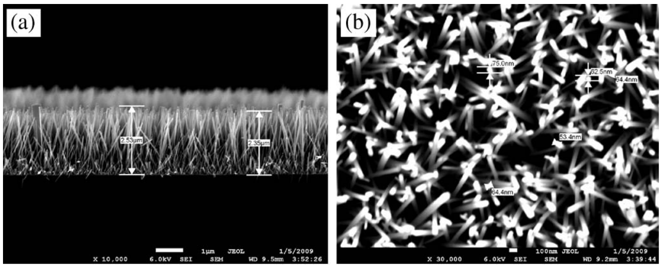


Fig. 2. (a) Cross-sectional SEM image of the self-aligned ZnO NWA grown by a chemical approach and having a length of 2.5 $\mu$m. (b) SEM image viewed from the top of the self-aligned ZnO nanowire and having a single ZnO-nanowire diameter that varies from 53 to 75 nm.

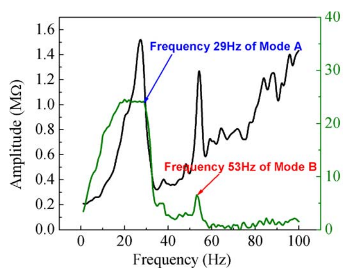


Fig. 3. Impedance–frequency testing results for the piezoelectric generator.

53 to 75 nm as shown in Fig. 2(b), with an average diameter of 70 nm. The nanowires have hexagonal wurtzite structures and present a preferential orientation along the $c$-axis. The growth area of the ZnO NWA is about 1 $cm^2$, with a number density of $30/\mu m^2$. As such, the total number of nanowires in an area of 1 $cm^2$ for the piezoelectric generator is calculated as about $3 \times 10^9$.

The impedance–frequency relationship of the ZnO generator, which is measured by the HP 4194A impedance analyzer, is shown in Fig. 3. The result shows that the resonant frequencies for modes A and B are 29 and 53 Hz, respectively. The corresponding impedances for modes A and B are 1.53 and 1.35 MΩ, respectively.

The interfacial shear strength is expected to be controlled by a combination of friction and adhesion [10]. The friction will be limited by the coefficient of friction $\mu$ and the maximum axial load $F_0$, which is defined as the force that can be applied on the cylindrical nanowire prior to buckling. This corresponds to an interfacial force as

$$V_f = \mu F_0 = \mu \frac{\pi^3 Y d^4}{256 T^2} \tag{1}$$

where $\mu$ is the coefficient of friction between the ZnO tip and silicon proof mass, $Y = C_{11} - C_{13}^2/C_{33}$ is the Young's modulus for plane stress, $C$ is the fourth-rank stiffness tensor, and $d$ and $T$ are the diameter and length of the ZnO nanowire, respectively. For ZnO, the values of $C_{11}$, $C_{13}$, and $C_{33}$ are 210, 105, and 210 GPa, respectively. For the values of $\mu = 0.3$, $d = 70$ nm, and $T = 2.5$ $\mu$m, the interfacial force $V_f$ is derived to be 15.39 nN.

The total electrostatic energy stored in a ZnO nanowire is

$$E = \frac{\varepsilon_{11}\pi\left(\frac{d}{2}\right)^2 \Delta\phi^2}{2T} = \frac{\varepsilon_{11} T V_f^2}{2\pi\left(\frac{d}{2}\right)^2}\left\{e_{15} + \frac{\varepsilon_{11} C_{44}}{e_{15}}\right\}^{-2} \tag{2}$$

where $e$ is the third-rank stress constant tensor and $\varepsilon$ is the second-rank electric permittivity tensor.

Substituting (1) into (2)

$$\begin{aligned} E &= \frac{\pi^5 \mu^2 \varepsilon_{11} Y^2 d^6}{32\,768 T^3}\left\{e_{15} + \frac{\varepsilon_{11} C_{44}}{e_{15}}\right\}^{-2} \\ &= 0.0093\, \mu^2 \frac{\varepsilon_{11} Y^2 d^6}{T^3}\left\{e_{15} + \frac{\varepsilon_{11} C_{44}}{e_{15}}\right\}^{-2}. \end{aligned} \tag{3}$$

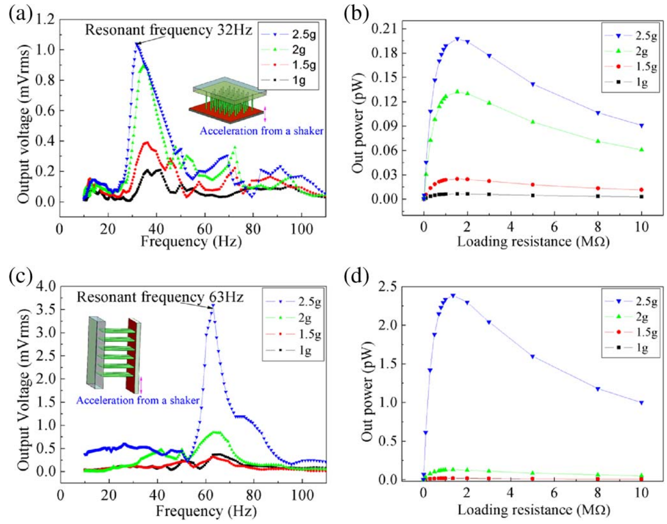


Fig. 4. (a) The output voltages of the generator when it is excited under different accelerations during normal-mode A. (b) The output power at 2.5-g acceleration and resonant frequency of 32 Hz under normal-mode A. (c) The output voltage of the generator when it is excited by different accelerations under shear-mode B. (d) The output power at 2.5-g acceleration and resonant frequency of 63 Hz under shear-mode B.

For ZnO, $C_{44} = 42.5$ GPa, $e_{31} = -0.61$ $C \cdot m^{-2}$, $e_{33} = 1.14$ $C \cdot m^{-2}$, $e_{15} = -0.59$ $C \cdot m^{-2}$, and $\varepsilon_{11} = \varepsilon_{33} = 7.38 \times 10^{-11}$ $F \cdot m^{-1}$ [13].

The dimension of our integrated power generator is 1.2 cm $\times$ 1.2 cm $\times$ 0.12 cm. For the experimental setup to investigate vibration-mode A, the generator is placed vertically on a shaker holder, with the gravitational pull acting on the silicon proof mass being parallel with the longitudinal direction of the NWA. Upon excitation from the shaker, the NWA contracts along its longitudinal direction and generates an output voltage between the top and bottom electrodes. This operation mode is denoted as normal-mode A. The vibration amplitude and frequency of the shaker are controlled by the dynamic signal analyzer, while the acceleration of the shaker is monitored by a microelectromechanical systems (MEMS) accelerometer placed on the holder. The open-circuit voltages of the generator and the voltages for different load resistances are recorded by the dynamic signal analyzer. Fig. 4(a) shows the output voltages of the ZnO NWA from 10 to 110 Hz at different accelerations. The measured open-circuit output voltages are 0.2, 0.39, 0.9, and 1.1 mV at 1-, 1.5-, 2-, and 2.5-g accelerations, respectively. For normal-mode A operation, the resonant frequency at 2.5-g vibration is 32 Hz, which is pretty close to the result of the first mode obtained through impedance testing. In addition, it is observed that the resonant frequency shifts toward lower frequencies with increasing shaker accelerations. This may be attributed to an increase in damping coefficient at larger accelerations. As the acceleration level increases from 1 to 2.5 g, the output power increases by 35 times, as shown in Fig. 4(b), which results from the nonlinear response of piezoelectric materials under large stress [14]. When the applied acceleration arrives at a certain value, some shorter nanowires (their length less than 2.5 $\mu$m) will be excited and deflected, which is further attributed to the increasing piezoelectric constant and output power. When the loading resistance matches the internal resistance of ZnO NWA, the maximum output power is 0.2 pW at 2.5 g.

In order to optimize the vibration mode and output performance, the generator is rotated by 90° and fixed on the shaker. The silicon proof mass now moves perpendicularly to the longitudinal direction of the ZnO NWA, resulting in shear-mode excitation. The maximum output voltage is obtained at a resonant frequency of 63 Hz, which agrees well with the second resonant frequency derived in Fig. 3. As shown in Fig. 4(c), the maximum output voltage is 3.59 mV at an acceleration of 2.5 g, i.e., a corresponding vibration velocity of about $0.063\ \mathrm{m \cdot s^{-1}}$. Based on (3), the total electrostatic energy during shear-mode B operation for an area of 1 $\mathrm{cm}^2$ is $4.7 \times 10^{-11}$ J. In order to improve the electrostatic energy further, the diameter of the growing ZnO nanowires should be increased, and their length will be reduced. Fig. 4(d) shows a measured output power of 2.39 pW for the 2.5-g acceleration when the loading resistance matches the internal resistance of 1.35 MΩ.

## III. Conclusion

In summary, a low-frequency piezoelectric energy generator based on ZnO NWA has been demonstrated by a proof-of-concept device. The normal and shear modes are excited, and their resonant frequencies obtained through impedance testing are 29 and 53 Hz, respectively. For an acceleration of 2.5 g, the maximum output power obtained from normal and shear resonant modes are 0.2 and 2.39 pW, respectively. A theoretical comprehensive model for shear mode is created and is used to predict the stored electrostatic energy for cylindrical ZnO NWA.

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