Nano Energy (2015) 13, 174–181

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/nanoenergy

RAPID COMMUNICATION

Powerful curved piezoelectric generator for wearable applications

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Received 24 November 2014; received in revised form 31 December 2014; accepted 22 January 2015
Available online 24 February 2015

KEYWORDS
Energy harvester;
Piezoelectric;
Wearable

Abstract
With the widespread use of wearable electronics, the flexible piezoelectric energy harvesting devices have been extensively studied to efficiently convert the physical motion of the human body into electrical energy. The major obstacles for realizing a flexible piezoelectric generator include the insufficient output power generation and the poor efficiency at the low-frequency regime. Here, we demonstrate a curved piezoelectric generator favorable for wearable applications, generating a high output power. The curved structure plays a key role to improve the power generation, by effectively distributing the applied force across the piezoelectric layer, as well as to allow operation at the low frequency vibration range. Accordingly, this generator produces ~120 V of peak output voltage and ~700 μA of peak output current during a cycle. Furthermore, our generator can operate at low frequencies below 50 Hz, generating ~55 V of output voltage and 250 μA of output current at 35 Hz, and it even works at frequencies as low as 1 Hz. With this generator, we successfully lit up 476 commercial LED bulbs. In addition, we experimentally demonstrate the possibility that the generator can be used in shoes, watches, and clothes as a power source. Our results will provide a framework to enhance the output power of conventional piezoelectric generators, and open a new avenue for realization of self-powered systems, such as wearable electronic devices.

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http://dx.doi.org/10.1016/j.nanoen.2015.01.051
2211-2855/

Introduction

With recent advances in electronic technology, miniaturization, flexibility, and low power consumption have become the developmental trend of electronic devices and portable electronics that are commonly and essentially used in our daily lives, including (among others) smart phones, electronic watches, smart glasses, and wireless headsets.[1-3] However, the use of a battery in such devices has been one of their major implementation problems due to its large size, the insufficient capacity, the danger of explosion, and the inconvenience of recharging.[4,5] For mobile electronics, the integration of a wearable piezoelectric energy harvesting device, where the physical motion of the body can be transformed into electrical power, would be the most promising way to solve these issues, realizing the nature of the sustainable and portable energy source. However, the output power of the energy harvesters still needs to be further improved for such applications. The performance of the piezoelectric energy harvesters is determined mainly by two factors: (1) the electromechanical coupling property of the piezoelectric material, and (2) the device geometry for the efficient conversion of the mechanical energy into electrical energy. The most distinct features of the mechanical motion of the human body are its low frequency nature and the large displacements associated with it. To effectively utilize such mechanical energy, the wearable energy harvester should be equipped with the polymer-based, flexible materials, such as polyvinylidene difluoride (PVDF) [6-8], rather than the rigid ceramic-based materials, such as ZnO, [9,10] $BaTiO_3$, [11,12] and PZT [13-16]. They have been attempted to apply to wearable applications such as a backpack and shoes, using PVDF [17,18]. However, the piezoelectric properties of PVDF are much poorer compared with that of the conventional ceramic-based materials, albeit PVDF is the best piezoelectric material among all polymers, due to its overall performance characteristics. Therefore, using PVDF requires more critical for the design of the high-performance, wearable piezoelectric energy harvester. The key aspect to the design of the structure of the piezoelectric generators is to maximize the developed stress/strain in the piezoelectric layer due to the externally applied force. This is especially critical for the flexible piezoelectric generator where the strain/stress response may be localized due to the intrinsic softness of the material that can, in turn, limit the amount of electricity generated by the piezoelectric material. Therefore, it is highly desirable to design the structure of the flexible piezoelectric generator in a way that the external force can be well-distributed across the entire piezoelectric layer to maximize the total power generation.

Here, we propose a curved, flexible piezoelectric generator to improve the stress/strain distribution across the piezoelectric layer using computational simulations, and to demonstrate the high-power generation of the curved piezoelectric energy harvester. As a model system, we used the PVDF as the piezoelectric layer, integrated on the curved polyimide (PI) platform. The output signal of the generator is rectified by a full-wave bridge diode, and we obtained peak output voltage, output current density, and power density values of $\sim$155 V, $\sim$700 μA, and $\sim$3.9 mW/cm^2, respectively, using finger tapping. Moreover, the curved structure enables the generator to operate, harnessing low frequency vibrations below 50 Hz. We implement our curved piezoelectric generator in insoles and a watch-strap to demonstrate feasibility for wearable applications. In addition, we also examined the generator attaching on elbow to directly harvest electrical energy from body movements and on chest around heart as a heartbeat sensor. In the proposed design, the curved structure plays an important role in enhancing output power because of an effective applied stress distribution. The experimental output performances demonstrated that this work may lead to an innovative way in which wearable technology harvests energy from the physical activity of living creatures.

Working mechanism and experimental

Figure 1 shows the structure and working mechanism of the curved piezoelectric generator. It consists of two separate curved piezoelectric generators connected back-to-back, where each generator comprises a curved PI substrate and two piezoelectric materials. As shown in Figure 1(a), piezo 1 and piezo 2 are made of PVDF with electrodes attached on both sides of the curved PI substrate, labeled as 'curved piezoelectric generator 1', whereas the 'curved piezoelectric generator 2' with piezo 3 and piezo 4 is located on the other side. Here, the curved piezoelectric generator with top/bottom electrodes uses the d_{31} mode, also extensively used for other piezoelectric applications. In this mode, the direction of the induced electric field is perpendicular to the direction of the applied stress/strain. Therefore, the induced voltage of the curved piezoelectric generator can be computed in accordance to Eq (1), [19]

$$V_{3j} = \sigma_j g_{3j} L_j [\mathrm{V}] \tag{1}$$

where σ_j is the mechanical stress, g_{3j} is the piezoelectric voltage coefficient, and L_j is the distance between electrodes. Notation V_{3j} is the induced voltage in the 3-direction caused by a stress in the j-direction. In case of the curved piezoelectric generator, it uses d_{31} mode, thus L_1 is the thickness of the PVDF and dominant direction is 1 direction (x). Additionally, g_{3j} is defined by Eq. (2),

$$g_{3j} = d_{3j}/\varepsilon_0 \varepsilon^{\mathrm{T}} \left[\mathrm{Vm/N}\right] \tag{2}$$

where ε_0 is the permittivity of free space and ε^{T} indicates the permittivity under a constant strain.

In the structure of the curved piezoelectric generator, the curved PI substrate plays two important roles. First, it acts as a passive layer to be effectively subjected to the vertical force to the PVDF layer because the PVDF is too thin to receive it as well as has a low Young's modulus. Therefore, the thickness of the PI substrate should be thick enough to shift the neutral plane of the structure out of the piezoelectric layer (Supporting information, Figure S1). However, if it is too thick, it becomes more rigid, so it requires a larger force to generate the electric power. Second, it acts as an active layer that turns the deformed piezoelectric layer into its original shape, much like a spring. Also, it enables the piezoelectric material to be subject to only tensile or compressive stress in a whole volume during pressing and releasing (Supporting information, Figure S1), which results in an enhancement of the output power. This is because the proper thickness of the substrate makes the neutral plane move from PVDF to its inside.