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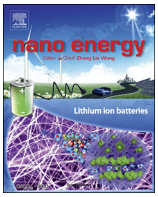

Full paper

Structural approaches for enhancing output power of piezoelectric polyvinylidene fluoride generator

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ABSTRACT

Flexible piezoelectric generators have attracted considerable attention in recent years on account of their potential applications in mechanical energy scavenging devices using portable, wearable, and implantable electronics. Key issues for realizing a flexible piezoelectric generator include insufficient output power generation and poor efficiency at low frequency. We therefore propose structural approaches to enhancing the output power of the flexible piezoelectric generator using polyvinylidene fluoride. Specifically, we propose the use of a substrate and curved structure, and optimization of the aspect ratio of the generator for maximizing output power density. Through these approaches, induced stress and output voltage of the generator are analyzed by finite element modeling and validated through experiments. Considering these results for generator optimization, we fabricate a multilayered flexible curved generator, which produces ~200 V of the peak output voltage and ~2.7 mA of the peak output current. The output power density of the generator reaches ~17 mW/cm^2, which is sufficient to drive various commercial electronics as a power source. Furthermore, it is demonstrated that this power source can illuminate 952 LED bulbs. This conceptual technology can provide the groundwork to enhancing the output power of conventional piezoelectric generators, thereby enabling novel approaches to realizing self-powered systems.

1. Introduction

With recent technological advances, portable, wearable, and implantable electronics are now widely used in daily life [1]. The application of energy harvesting devices as sustainable power sources for these electronics has been extensively studied to convert mechanical energy into electrical energy and avoid the large size, heavy weight, insufficient operating time, and explosive potential of the battery [2]. Researchers have strived to realize a sustainable energy supply source using triboelectricity [3–5], piezoelectricity [6,7], electromagnetics [8], electrowetting [9], and magneto-mechano-electrics [10]. Among them, the piezoelectric generator is one of the most attractive power sources in mechanical energy conversion. Two piezoelectric materials exist: ceramic and polymer-based materials. Ceramic materials have a large piezoelectric constant; however, it is too difficult and cumbersome to employ it in wearable applications. Moreover, it is too brittle to withstand the application of a strong external force. On the contrary, polymer-based materials are very flexible and have good durability; however, they have a low piezoelectric constant. Nevertheless, because of the widespread use of portable and wearable electronics, polymer-based materials have been recently attracting considerable research interest. Significant efforts have been made to implement flexible piezoelectric generators using PZT [11–13], ZnO [14–16], polyvinylidene fluoride (PVDF) [17–19], GaN [20], BaTiO3 [21], and ZnSnO3 [22]. Most flexible piezoelectric generators produce insufficient output power much less than 1 mW/cm^2 [23–27]. However, in practical applications such as wireless communications, consumer electronics, healthcare devices, biomedical devices and sensor networks a few mW of electrical power requires [28]. In recent, a few flexible generators show the possibility of power generation over mW/cm^2 level [29–32].

In our previous work, the flexible piezoelectric generator using PVDF film as an organic material was shown to be effective with high output power by generating 3.9 mW/cm^2 [33]. We demonstrated the possibility that the PVDF piezoelectric generator can be applied to wearable devices, such as shoe insoles and watch straps,

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and we showed its DC power generation in periodic vibrational environments through the electrical circuit connection. Two important factors exist in considering output power generation of piezoelectric materials: piezoelectric constant and applied strain. Although PVDF has a much lower piezoelectric constant than bulk ceramics, it can generate high output power if it can be subjected to higher induced stress by an external force. However, the previous works require further evidence and more clear analysis to prove the high output generation.

We herein introduce structural approaches and evidence to substantiate the high output power and efficiency of the piezoelectric PVDF film generator. Output power and power efficiency obtained by simulation and experimental results are compared in terms of three structural factors: substrate attachment; curved structure; and aspect ratio of PVDF film for power efficiency of the generator. In addition, we fabricated a flexible piezoelectric PVDF generator with an oval structure and generated ~17 mW/cm^2 of instantaneous power density at 30 Hz of vibrational conditions. This work represents an initial effort to increase output power of flexible piezoelectric generators with consideration of device geometry. By proposing approaches that involve enhancement and control of applied stresses, this work presents a novel framework for developing a thin, built-in power source in self-powered electronics.

2. Theory of curved piezoelectric generator with d$_{31}$ mode

Piezoelectricity is a form of coupling between the mechanical and electrical behaviors of ceramics and crystals belonging to certain classes. These materials exhibit the piezoelectric effect, which is historically divided into the two phenomena of the direct and converse piezoelectric effects. In simple terms, when a piezoelectric material is mechanically strained, electric polarization proportional to the applied strain is produced. This is called the direct piezoelectric effect. On the other hand, when the same material is subjected to electric polarization, it becomes strained and the amount of strain is proportional to the polarizing field. This is called the inverse piezoelectric effect. These two effects can be written as:

$$S = S^E \cdot T + d^t \cdot E \tag{1-1}$$

$$D = d \cdot T + \varepsilon^T \cdot E \tag{1-2}$$

where S, S^E, T, E, ε^T, and D are the mechanical strain, compliance matrix, mechanical stress, electrical field, dielectric permittivity, and charge density, respectively. Here, the superscripts E, T represent measurements obtained at a constant electric field and constant stress. Additionally, d and d^t indicate the matrices for direct and reverse piezoelectric effects, respectively. The above equations can be rewritten in the following form to obtain the electrical potential from an energy harvesting device, which is often used for applications involving sensing:

$$S = S^D \cdot T + g \cdot D \tag{2-1}$$

$$E = -g \cdot T + \beta^T \cdot D \tag{2-2}$$

where g and β^T are the voltage coefficient matrix and inverse dielectric permittivity, respectively. The superscript D indicates constant electric displacement.

Fig. 1 shows the curved piezoelectric energy harvesting device using the d$_{31}$ mode. When the piezoelectric energy harvesting device is pressed by external force in the middle of the device, the PVDF and substrate are subjected to compressive and tensile stresses, respectively, thereby generating electric potential. From Eq. (4), it can be estimated by the following:

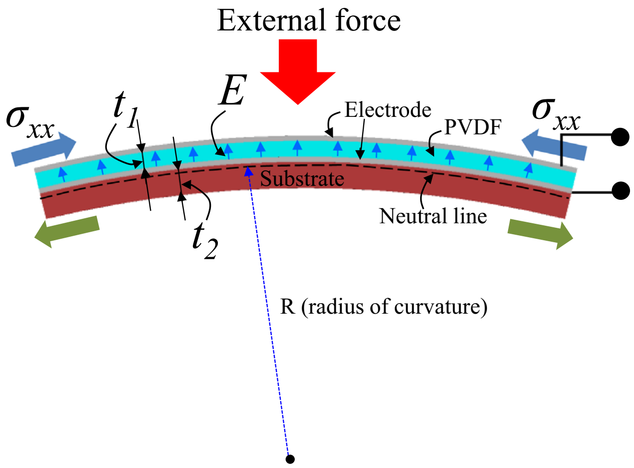

Fig. 1. Curved piezoelectric generator with the d$_{31}$ mode.

$$V_{31} = \sigma_{xx} \cdot g_{31} \cdot t \tag{3}$$

where $\boldsymbol{t}$ is the thickness of the piezoelectric material, as shown in Fig. 1. Thus, we can easily estimate the output voltage of the d$_{31}$ mode piezoelectric generator. The PVDF we employ has the material properties shown in Fig. 1.

Furthermore, we can estimate the electric charge from the curved piezoelectric generator using mechanical strain and electrical displacement. The charge developed on the surface of the piezoelectric material, q, can be expressed as the integral of electrical displacement over the effective surface area of the electrodes [34].

$$q = \int_A D_3 \cdot dA \tag{4}$$

Using the piezoelectric effect with the d$_{31}$ mode, Eq. (1), it can be also written as:

$$q = d_{31} \cdot c_{11}^E \int_A S_1 \cdot dA \tag{5}$$

where c_{11}^E is the stiffness matrix component, and A is the effective area of the electrode. The charge generated on the surface is described as a function of the strain induced in the generator. Therefore, the electric charge is deeply related to the strain induced in the device. The strain-applied force relationship in the bending-stretching mode can be derived by the membrane strain, bending strain, and displacement of the neutral surface. However, in this curved structure case, because there is no external force applied in the x-direction, it is assumed that the membrane strain of the neutral surface can be negligible compared to the bending strain. In addition, for such an impact-type generator, the quasi-static analysis is considered appropriate. Thus, the curved generator generates the following charge equation.

$$q = -b \cdot d_{31} \cdot c_{11}^E \cdot \left(\frac{t_1 + t_2}{2}\right) \int_0^l \frac{\partial^2 w}{\partial x^2} \cdot dx \tag{6}$$

where b, w are the width of the device and the component of the displacement vector of a point on the neutral surface in z-directions. Consequently, the output voltage and output current of the generator depend on the thickness of the piezoelectric material and the width of the electrode on it.

3. FEM modeling for enhancing output potential of flexible curved generator

Here, we introduce two structural approaches to enhancing the output power of the curved PVDF generator: (1) use of a substrate