

Investigation on Nanogenerators for Wearable Electronic Applications

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Abstract: A novel nanogenerator combining triboelectric and piezoelectric mechanisms is developed in this study. In addition to the conventional hybrid type nanogenerators, the addition of piezoelectric content in the triboelectric layer remarkably increases responsiveness. The nanogenerators are successfully used as wearable power sources for hydrothermometers and self-powered motion detectors. This research has provided a novel approach to enhancing the performance of nanogenerators while maintaining their high flexibility and compactness, thereby breaking the bottleneck for their use in wearable electronics.

Keywords: Wearable electronics, Energy harvesting, Nanogenerators, Piezoelectricity.

1. Introduction

In recent years, the search for a sustainable and reliable power source for wearable or implantable electronic devices has become increasingly crucial. Pacemakers, for example, play a vital role in maintaining the heart's rhythm for millions of patients worldwide; however, pacemakers typically rely on batteries that require periodic replacement, subjecting patients to reoccurring surgical interventions. Similarly, smartwatches and smartphones have become a vital part of our daily lives, yet their functionalities are still subjected to daily recharging due to the limited battery capacity. Developing a portable energy source that can power these electronic devices can alleviate the "low battery anxiety," which would be a revolutionary breakthrough.

The emerging energy harvesting technology has become a promising solution for portable power sources by converting the dissipated energies in the ambient environment, such as solar power, thermoelectric energy, mechanical vibration, and microwave radiation, into electric power. Among these different types of energy sources, mechanical vibration energy has the advantages of environmental abundance, easy accessibility, and intermittent existence, making it an ideal energy source for ambient energy harvesting. Two strategies are typically used to convert vibration energy into electric energy: taking advantage of the triboelectricity and piezoelectricity of materials and forming either triboelectric nanogenerators (TENGs) or piezoelectric nanogenerators (PENGs).

Ever since their first proposal, the TENGs and PENGs have drawn intensive research interest, with tens of thousands of research papers having been published, revealing their working principles and optimizing their performance. However, most of the existing PENGs and TENGs tend to be inflexible and bulky, making them unsuitable for wearable applications. Moreover, existing PENGs tend to be inefficient at converting energy from mechanical to electrical, requiring further research and

development to optimize their performance for medical devices like pacemakers. Furthermore, integrating energy storage capabilities into nanogenerators could enhance their usability in wearable applications by providing a more reliable power source for continuous operation.

To facilitate the real-world application of TENGs or PENGs in various scenarios, including batteries for implantable devices like pacemakers and wearable electronic devices, a few adjustments must be made. Notably, these adjustments should focus on decreasing the size, increasing elasticity, and improving energy conversion efficiency.

The goal is achieved through the development of a hybrid nanogenerator with a combined energy-conversion mechanism. This involves the piezoelectricity within poly(vinylidene fluoride) (PVDF) and ZnO, as well as the triboelectricity at the heterointerface. A comparison between the hybrid device and the individual PENGs and TENGs revealed the advantageous performance of this novel device type. Subsequently, a rectifier circuit and an energy storage unit were developed, enabling its application in powering portable electronic devices, such as a thermohydrometer and a light-emitting diode. This work is the first report of a hybrid nanogenerator with two types of piezoelectric layers. The notable compactness, high flexibility, and superior performance of the fabricated nanogenerators show great promise in future portable power sources.

2. Theoretical background

TENGs and PENGs are two types of nanogenerators that convert mechanical energy into electricity through contact electrification and piezoelectricity, as schematically shown in Figure 1[1].

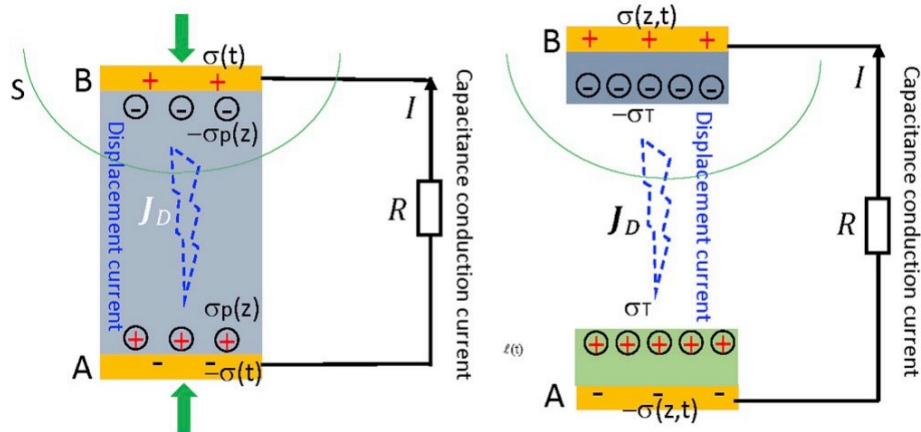


Figure 1: Schematic of (a) PENGs and (b) TENGs [1].

2.1. Working Principles of TENGs

The functionality of TENGs relies on tribonegalelectrification or contact-electrification [2]. One well-known triboelectrification phenomenon is the act of rubbing a plastic rod against a piece of cloth. One will find the rod negatively charged and have gained the ability to attract small pieces of hair or paper. Charge transfer occurs when materials with different electric potentials are in contact. Mechanical friction is not a prerequisite but can still promote charge transfer.

As is known, the nucleus of atoms is surrounded by electron shells, or electron clouds, to be more specific. The energy landscape of electrons in the electron cloud forms a potential well centered in the nucleus (Figure 2a). The electrons are thus trapped in these potential wells, where the closer to the nucleus, the lower energy they possess, i.e., being more stable. Some halogens or chalcogens have a stronger willingness to grab electrons from their neighborhoods, presenting higher electronegativity and larger potential well depth. When the two materials are in contact, the electron clouds overlap.

An asymmetric double-well is formed, and the energy barrier between the two wells is lowered (Figure 2b). The electrons can thus transfer from one material to another, causing a charge imbalance on both sides after separation.

In the case of TENGs, the exterior of the heterostructure of two materials with distinct electronegativity is encapsulated with metallic electrodes. After each contact, the localized charges are generated on both sides of the heterosurface, inducing an electric field across the polymer layer. The electric field will thus cause an electric displacement at the polymer-metal interface:

$$D = \varepsilon_0 E + P + P_s = \varepsilon E + P_s = D' + P_s \quad (1)$$

where ε_0 is the dielectric constant in vacuum, E is the electric field, P is the induced polarization in the polymer, and P_s is the surface polarization generated at the hetero surface.

By repeatedly contacting and separating the two materials, a displacement current can thus be obtained as:

$$J_D = \frac{\partial D'}{\partial t} + \frac{\partial P_s}{\partial t} = \varepsilon \frac{\partial E}{\partial t} + \frac{\partial P_s}{\partial t} \quad (2)$$

where J_D is the displacement current density.

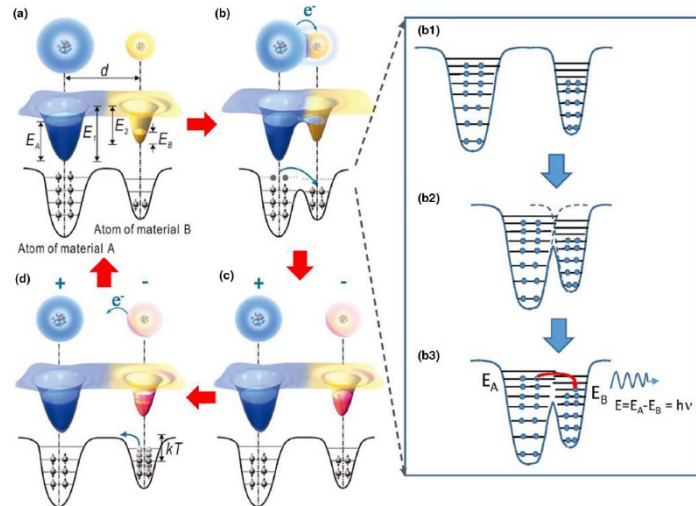


Figure 2: A schematic of the electron-cloud potential well to explain contact-electrification and charge transfer between two matters with different electronegativity. (a) before contact, (b) in contact, (c) after contact, showing electron transfer from one atom to the other after being forced to have electron cloud overlap, and (d) charge release at an elevated temperature [3].

2.2. Working Principles of PENGs

Unlike TENGs, which require two different materials for electrification, the PENGs rely on the piezoelectricity of one single material. The term piezoelectricity originates from the Greek word “piezein,” which means to press or squeeze, which is the process of generating electricity through mechanical stress. A schematic of the piezoelectric effect is shown in Figure 3.

The compound molecules typically possess dipolar charges due to the difference in electronegativity between the constituent atoms. In the absence of pressure, these dipoles in the piezoelectric materials are spread out randomly, which means that there are no net electric dipole moments. The application of external pressure will induce a rearrangement of the dipolar charges; a net electric polarization is then generated, creating a voltage across its opposite sides.

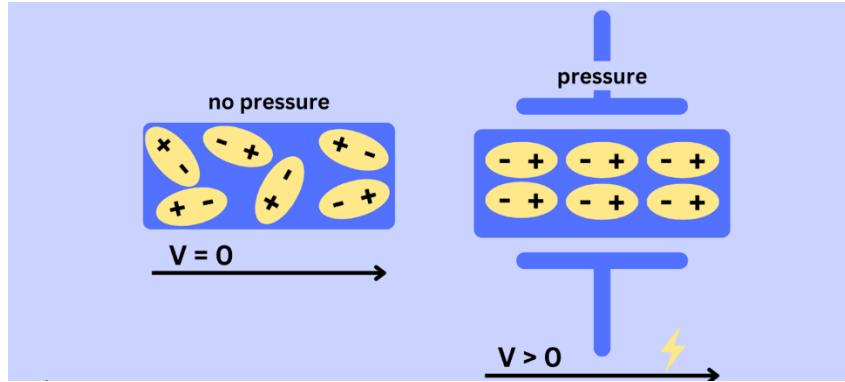


Figure 3: A schematic of the ordering of polar atoms within a piezoelectric material with or without an external pressure.

Piezoelectric materials are around us everywhere: bones, quartz crystals, some ceramics, and polymers. The quartz watch is a good example of the application of the piezoelectricity of quartz crystals. Beyond this application, the piezoelectric materials can also be used to generate electricity from mechanical energy.

In PENGs, a thin piezoelectric layer is encapsulated by two metallic electrodes on opposite sides. Upon pressing, the electric displacement can be numerically described by [1]:

$$\begin{cases} \sigma_p = C_{pq}\varepsilon_q - e_{kp}E_k \\ D_i = e_{iq}\varepsilon_q + \kappa_{ik}E_k \end{cases} \quad (3)$$

where E_k is the electric field, D_i is the electric displacement, σ_p is the stress tensor, ε_p is the strain tensor, C_{pq} is the elastic modulus tensor, e_{kp} is the piezoelectric tensor, κ_{ik} is the dielectric tensor. A solution to this equation gives the body charge ρ^R and surface charge Σ^R of the piezoelectric material:

$$\begin{cases} \rho^R = -\frac{\partial D_{Ri}}{\partial x_i} \\ \Sigma^R = n_i D_{Ri} \end{cases} \quad (4)$$

In the case of nonconductive piezoelectric materials, the PENGs can be considered as capacitors, and the generated voltage is given as:

$$V_O = \frac{e_{ip}\varepsilon_p}{C_p} \quad (5)$$

where C_p is the equivalent capacitance of the PENG. If a PENG is connected to a load, the displacement current density can be described as:

$$J = \frac{\partial D_R}{\partial t} = e_{ip} \frac{\partial \varepsilon_p}{\partial t} \quad (6)$$

2.3. Literature review

Up to present, most of the scientific efforts have been devoted to refining the fabrication procedures to either elevate the device's performance or to improve environmental friendliness. The functionality of TENGs relies on contact electrification; by increasing the area of friction layers, the generation of electrostatic charges will be promoted [4]. The conventional surface treatment methods are either complicated or costly. A facile fabrication technique of micro-nano structured TENGs was developed by preparing micro-nano patterned polyformaldehyde (POM) film using electrospinning and using a polytetrafluoroethylene (PTFE) film as another friction layer [5].

Polydimethylsiloxane (PDMS) is a frequently used friction material in TENGs due to its features such as good flexibility, transparency, non-toxicity, and biocompatibility [6–7].

PDMS that possess both high elasticity and low stickiness are favored for surface charge generation, despite these two features being contradictory. Zhang et al. developed a hybrid bilayer PDMS composed of a low-sticky home-made PDMS (elastomer and curing agent: 5:1) and a high elastic commercial PDMS (elastomer and curing agent: 10:1), which showed significant improvement in device output [8].

The field of piezoelectric nanogenerators has also witnessed significant advancements, such as improvements in the piezoelectric properties of nanomaterials by developing new composites. The lead zirconate titanate [$\text{Pb}(\text{Zr,Ti})\text{O}_3$ or PZT] is a well-established piezoelectric ceramic for PENG applications [9]. By forming the gradient porous structure in the PZT thin films, the ability to transfer stress is improved, and the efficiency of electromechanical conversion can be greatly enhanced [10]. When developing flexible PENGs, piezoelectric powders are frequently dispersed into a polymer matrix, resulting in suboptimal piezoelectric output performance due to a low piezoelectric phase ratio.

Niu et al. developed a different mixing technique to promote uniform PZT powder dispersion and refine filler composition. A more compact particle distribution induces greater stress, bringing about higher output performance. [11] Besides, the low current density of PENGs limits their applications. A new design with a three-dimensional intercalation electrode was proposed in PENGs based on Samarium-doped $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - PbTiO_3 (Sm-PMN-PT) polycrystalline nanowires. A record-high current density of approximately $290 \mu\text{A}\cdot\text{cm}^{-2}$ was achieved due to the large amounts of induced surface polarization charges [12]. Although the improved performance, this research uses toxic compounds and requires poling processes to create a higher piezoelectric effect. Recently, a series of research has highlighted the use of novel piezoelectric material systems, like PVDF copolymers, and some inorganic compounds (such as BaTiO_3 and KNaNbO_3) that can support the development of flexible and multifunctional nanogenerators [13]. PVDF exhibits poor stretchability due to plastic deformations.

Additionally, PVDF generates a nonpolar α phase during processing, making fabricating high performing piezoelectric generators hard. Poling PVDF is also time consuming and energy intensive. To address these issues, Pei et al. integrate metamaterials and use 3D printing to induce higher crystallinity and high polar phase composition [14].

Another promising strategy to increase the efficiency of nanogenerators is by hybridizing piezoelectric nanogenerators with triboelectric ones. A fiber-structured hybrid nanogenerator with a structure of PET core/PDMS: Carbon black electrode/ ZnO /PVDF/ PDMS: Carbon black electrode was demonstrated to show an open-circuit voltage of 5 V [15]. The structures of the majority of hybrid nanogenerators make it complicated to incorporate both mechanisms into the film stacks. Instead, a composite film simultaneously achieving the coupling of piezoelectric charge generation and triboelectrification may be used. In a recent study, Chen et al. achieved this implication by embedding electrospun PVDF nanofibers in the surface of the PDMS film. The hybrid nanogenerator can generate much higher electrical outputs than individual TENG and PENG devices [16].

The nanogenerators have great application prospects in wearable electronics. They can not only convert the biomechanical energy generated by daily activities into electricity but also be applied as a self-powered sensor to precisely and accurately monitor cardiovascular status or joint motions [17].

3. Experimental Procedures

3.1. Device Fabrication

PDMS (Polydimethylsiloxane) is a widely used silicon-based organic polymer with numerous applications in various fields, including microfluidics, electronics, and biomedicine. It is a transparent, flexible, and biocompatible material with low surface tension and chemical stability. In this study, the PDMS (Dow Corning SYLGARD 184) was first mixed to the standard 10:1 ratio (base: curing agent) in a 100-ml (about 3.38 oz) beaker with a stirring rod, which was then poured into a petri dish with a syringe, each section containing 2 ml (about 0.07 oz) more than the last, allowing each piece to be approximately 1 mm (about 0.04 in) thicker than the last.

The petri dish was then placed onto a heating plate for it to cure after it was stabilized for 1 hour.

This process was repeated with different concentrations of the curing agent but with the same thickness (1 mm). To add zinc oxide into the PDMS base, different mass percentages of zinc oxide powders were measured, then mixed into the 5:1 PDMS and carefully stirred to ensure their uniform distribution.

The piezoelectric PVDF thin films with thicknesses of 119 μm were purchased from TE connectivity and then cut into uniform squares. The PENGs were fabricated by encapsulating the PVDF thin film with aluminum electrodes on both sides. The hybrid nanogenerators were developed by stacking PVDF over the PDMS layer, with aluminum and copper electrodes attached to each side, respectively. The schematics and photos of both types of nanogenerators are shown in Figure 4.

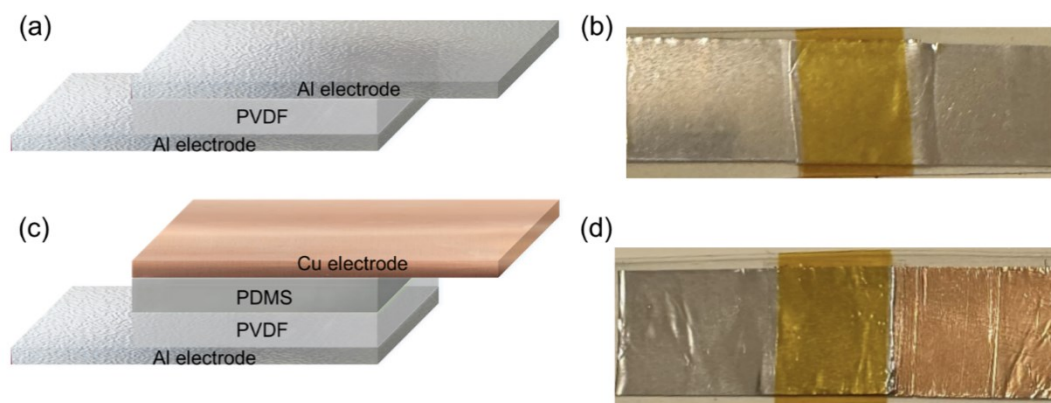


Figure 4: The schematics and photos of nanogenerators (a) and (b) PENGs, and (c) and (d) hybrid nanogenerators.

3.2. Device Characterization

The voltage output from the nanogenerators is measured using a Keithley 2450 source meter. Four groups of samples were compared: PENGs with different PVDF thickness, hybrid nanogenerators with different PDMS thickness, hybrid nanogenerators with different PDMS ratios, hybrid nanogenerators with different ZnO concentrations, and hybrid nanogenerators with different AlN concentrations.

4. Experimental Results

I started the research from a typical PENG with 119 μm thick PVDF as the active layer. Figure 5 (a)–(e) shows the open circuit voltage (OCV) produced by bending at various frequencies. Under each bending cycle, a voltage burst emerges, a result of the accumulation of surface charge due to

piezoelectricity. After releasing, the surface charge is relieved, and the voltage dips indicate the current flows reversely. Under very low bending frequencies, a moderate peak-to-valley voltage amplitude of less than 0.2 V is observed. The voltage amplitude increases at higher bending frequencies since the larger changing rate of electric displacement generates a higher displacement current, according to Eq. (6). At a maximum bending frequency of 110 BPM (1.83 Hz) (frequency was recorded in BPM as I bent the nanogenerators on the beat of a metronome to ensure constant frequency), an unexpected reduction in OCV is witnessed. This is presumably explained as the piezoelectric PVDF does not have sufficient time to respond to the mechanical deformation, which substantially reduces the output. The maximum OCV achieved in the PENG is ~ 0.6 V (Figure 5(e)), with a short circuit current of ~ 0.16 μ A. Such performance proves the functionality of PENGs.

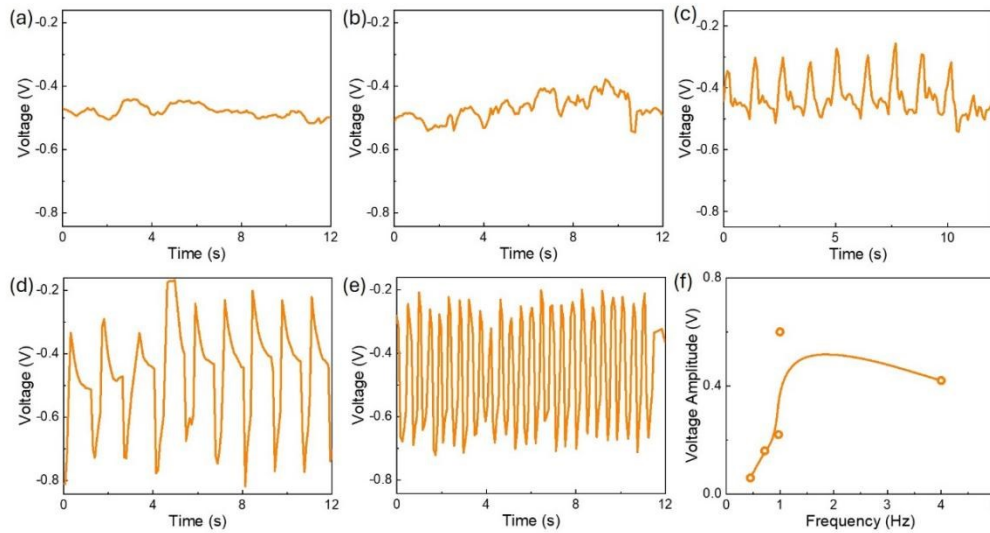


Figure 5: Characterization of PENGs. (a)-(e) the voltage response under bending at frequencies ranging from 0.45 to 4 Hz. (f) the dependence of net voltage amplitude on bending frequencies.

I have subsequently introduced triboelectricity into PVDF-based PENGs, forming a hybrid nanogenerator. In this attempt, a commercially available PDMS film (Gelpek) with a thickness of 0.165 mm is used, and the OCV with different bending frequencies are shown in Figure 6. The hybrid nanogenerators exhibit a similar frequency dependence to the case of PENGs, with the maximum output at a medium bending frequency. On the other hand, the hybrid ones typically favor lower frequencies and show smaller voltage output. The slower frequency characteristics are attributed to the protracted charge transfer in triboelectricity compared with piezoelectricity[18]. Possible explanations for the smaller output are (1) the high stickiness of the commercial PDMS surface impedes charge transfer upon separation, which substantially suppresses triboelectricity, and (2) the insertion of the PDMS layer weakens the surface electric field generated by the piezoelectric player, thereby reducing piezoelectricity. Explorations on how to resolve the above two problems are thus conducted.

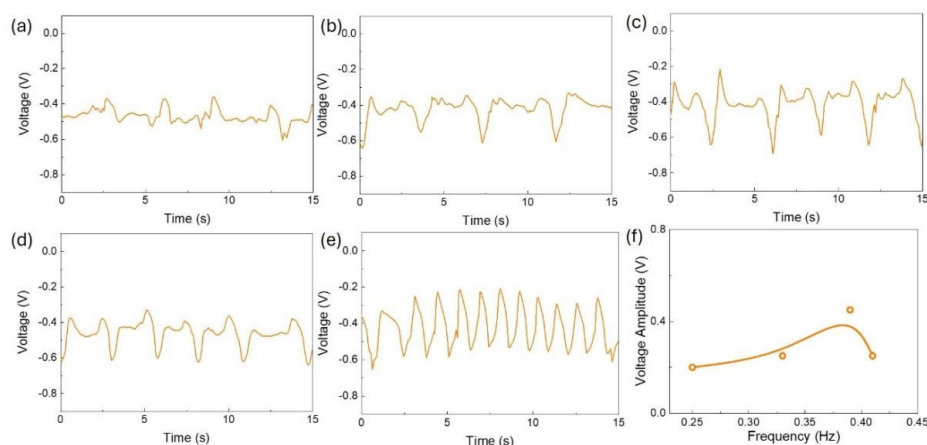


Figure 6: Characterization of hybrid nanogenerators based on commercial PDMS/PVDF. (a)-(e) the voltage response under bending at frequencies ranging from 0.25 to 0.73 Hz. (f) The dependence of net voltage amplitude on bending frequencies.

Firstly, I try to modify the surface stickiness of PDMS by preparing homemade PMDS films. This can be done by changing the ratio between the base and the curing agent in Dow Corning SYLGARD 184. In the experiment, the PDMS gels with base: curing agent ratios ranging from 20:2 to 20:3.4.5 are placed in a petri dish and then cured on a hotplate at 53 °C, as shown in Figure 7(a). Four hybrid nanogenerators are then made based on the homemade PDMS films and 119 μm -thick PVDF layer (Figure 7(b)), and the measurement results are shown in Figure 7(c)-(f), respectively. With increasing concentrations of curing agents, a gradual improvement in OCV is observed. An increased OCV of >0.6 V is achieved. Such an improvement is explained as the use of low sticky PDMS facilitating fast separation between the two aberration layers. The transferred charges are thus localized in the opposite layers and induce stronger electric fields. Consequently, we have successfully addressed the stickiness by using home-made low sticky PDMS films.

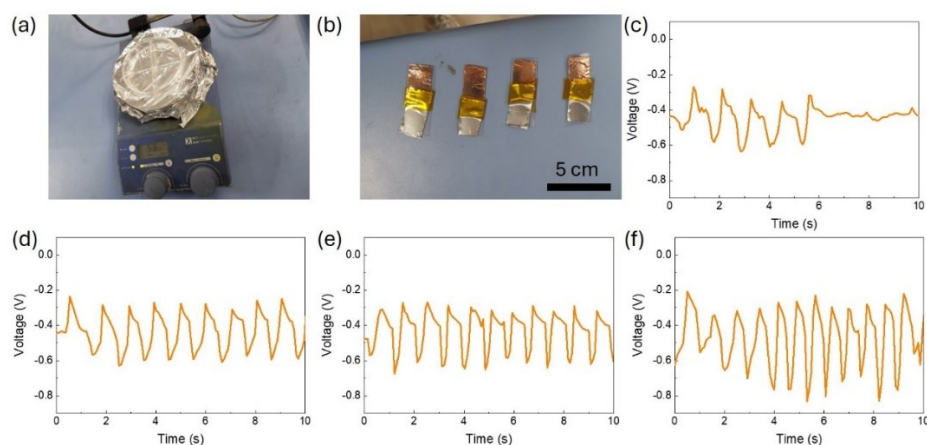


Figure 7: Fabrication and characterization of hybrid nanogenerators based on homemade PDMS/PVDF. (a) The photograph of homemade PDMS prepared with a different base: curing agent ratios. (b) The photograph of hybrid nanogenerators. (c)-(f) the voltage response of hybrid nanogenerators based on homemade PDMS with base: curing agent ratios ranging from 20:2 to 20:3.4.5. The bending frequency is maintained at approximately 1.1 Hz.

Subsequently, I have attempted to explore the impact of PDMS thickness to find a solution to enhance the piezoelectric response. In this experiment, the thickness of homemade PDMS varied

from 0.7 to 4 mm (about 0.08 in). The photographs of the fabricated hybrid nanogenerators are shown in Figure 8a. The thickness dependence of the output voltage amplitude infers an increasing trend with decreasing thickness (Figure 8b-h).

We also note that the voltage amplitude also increases dramatically at higher bending frequencies (Figure 8i). This result confirms our assumption that inserting thick PDMS layers inside the hybrid nanogenerator will adversely impact energy harvesting efficiency. The piezo response can thus be restored by reducing the thickness of the PDMS layer.

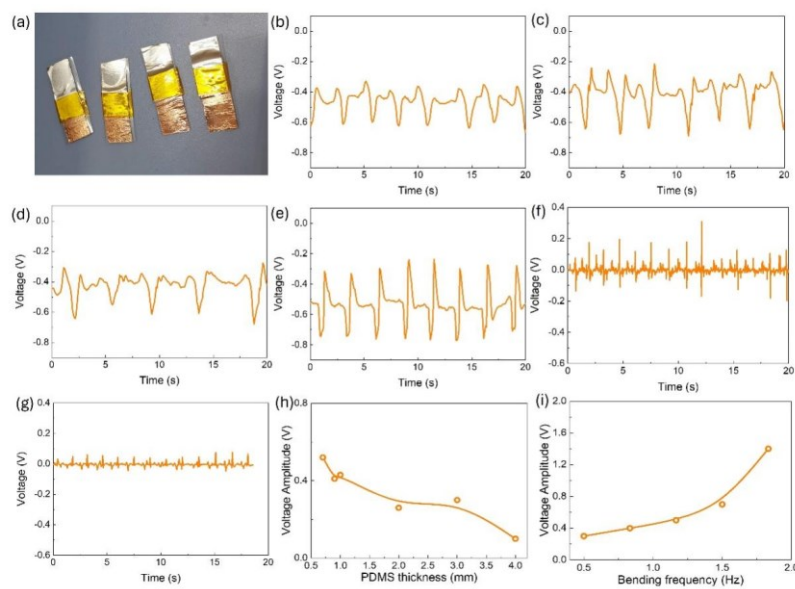


Figure 8: Fabrication and characterization of hybrid nanogenerators based on homemade PDMS/PVDF. (a) The photograph of hybrid nanogenerators with different PDMS thickness ranging from 0.7 to 2 mm. (b)-(g) the voltage response of hybrid nanogenerators based on homemade PDMS with thicknesses ranging from 0.7 to 4 mm. The bending frequency is maintained at approximately 0.4 Hz. (h) The dependence of net voltage amplitude on PDMS thickness. (i) the voltage response as a function of bending frequency for PDMS thickness of 3 mm.

The above experimental results have shown that the effect of a PDMS friction layer on the performance of nanogenerators is two-faced. On one hand, it introduces the triboelectricity mechanism, which contributes to higher voltage output. On the other hand, the insertion of a PDMS space between the piezo layer and the electrode attenuates the displacement electric field, which reduces piezoelectricity. Questions thus arise on how to take advantage of additional triboelectricity without hampering the piezoelectricity. To solve this problem, I propose converting PDMS into a piezoelectric one by adding piezoelectric nanopowders inside. The piezoelectric PDMS layer will then send the strong displacement electric field straight to the metal electrodes, adding to the piezoelectricity while keeping the triboelectricity at the interface and the piezoelectricity of the PVDF.

Two piezoelectric materials, AlN and ZnO, are chosen for the experiment due to their easy availability and high piezoelectric constant. To do this, the optimal ratio of the PDMS mixture was first made. The powders were weighed to match the mass percentage of 4, 6, 8, and 10% of the PDMS and then left on a heating plate to cure (Figure 9a). It is notable that the resulting material has a lower fracture toughness and was more brittle than the mixture without the nanopowders. This homemade ZnO:PDMS layer was then used to fabricate hybrid nanogenerators, as shown in Figure 9b. Compared with the hybrid nanogenerators fabricated with pure PDMS, the introduction of piezoelectric ZnO powders into PDMS has resulted in an overall increase in the voltage output upon bending (Figure 9-

f). This phenomenon confirms my assumption that additional piezoelectricity can promote energy harvesting efficiency. When the concentration of ZnO increased to 8%, a maximum voltage amplitude of 1.32 V was measured. The value represents a new record in the flexible hybrid nanogenerators. The voltage amplitude is sufficient to power a number of low-power portable electric devices.

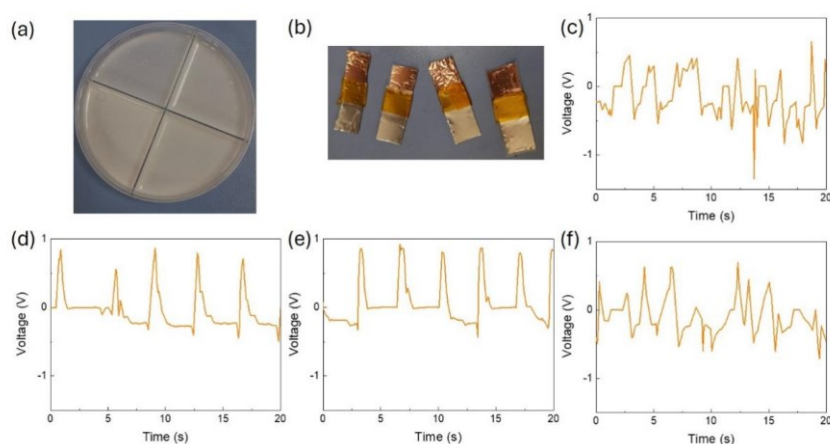


Figure 9: Fabrication and characterization of hybrid nanogenerators based on homemade PDMS mixed with ZnO nanopowders with ZnO concentrations of 2%–10%. (a) Photograph of the PDMS mixed with ZnO nanopowders curing on the hotplate. (b) Photograph of the hybrid nanogenerators with different ZnO:PDMS concentrations. (c)-(f) the voltage response of hybrid nanogenerators based on homemade PDMS with different ZnO concentrations. The bending frequency is maintained at approximately 0.3 Hz.

In addition to the success in nanogenerators based on ZnO:PDMS, another piezoelectric material, AlN, is also tested, as shown in Figure 10. AlN:PDMS tends to be yellow due to the different energy band structure of AlN compared with ZNO (Figure 10a). Disappointingly, the nanogenerators exhibit poor piezoelectricity lower than 0.1 V (Figure 10b-d). The comparison with ZnO:PDMS indicates that ZnO is more suited for hybrid nanogenerator development.

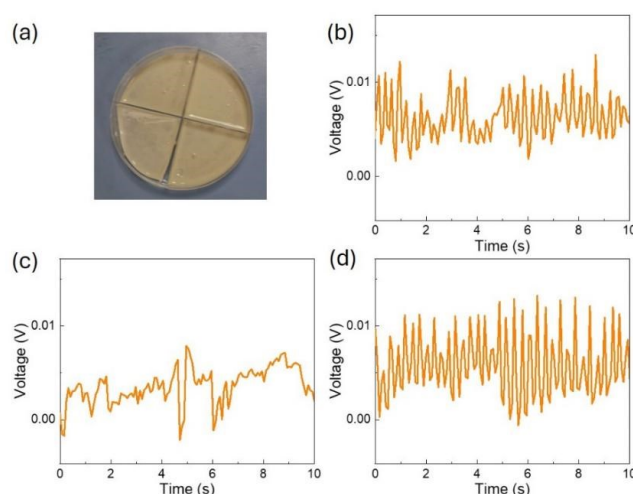


Figure 10: Fabrication and characterization of hybrid nanogenerators based on homemade PDMS mixed with AlN nanopowders with AlN concentrations of 4%–10%. (a) Photograph of the PDMS mixed with AlN nanopowders curing on the hotplate. (b)-(d) the voltage response of hybrid nanogenerators based on homemade PDMS with AlN.

The high flexibility of the nanogenerators positions them as promising options for wearable electronics. Figure 11 shows the voltage output of the wearable nanogenerator upon bending the wrist. The high output voltage indicates that they can readily be used in wearable power generators. I have also developed a rectification and energy storage circuit to convert the alternating voltage output from the nanogenerators into a potable direct current (DC) power source.

The voltage rectification is achieved using a home-made two-stage charge pump to maintain high voltage output in a relatively low input power scenario (Figure 12 a). The charge pump contains two Schottky diodes (packaged in a HSMS-2822-TR1G chip) and two capacitors (100 pF). The charge pump circuit is built on a circuit board with the components attached using surface mounting technology. The output performance of the nanogenerator circuit is then tested. A DC output voltage of 1.13 V is measured using a multimeter after the high flexibility of fabricated nanogenerators are promising candidates for wearable electronics. Figure 11 shows the voltage output of the wearable nanogenerator upon bending the wrist.

The high output voltage indicates that they can readily be used in wearable power generators. Meanwhile, the nanogenerator can also be used as self-powered motion detectors when attached to body joints (Figure 12). I have also developed a rectification and energy storage circuit to convert the alternating voltage output from the nanogenerators into a potable direct current (DC) power source. The voltage rectification is achieved using a home-made two-stage charge pump to maintain high voltage output in a relatively low input power scenario (Figure 13 a). The charge pump contains two Schottky diodes (packaged in a HSMS-2822-TR1G chip) and two capacitors (100 pF). The charge pump circuit is built on a circuit board with the components attached using surface mounting technology. The output performance of the nanogenerator circuit is then tested. A DC output voltage of 1.13 V is measured using a multimeter after bending the nanogenerators about 10 times (Figure 13 c). Such an output is sufficient to power a portable thermohydrometer (Figure 13 d). This success demonstrates that the nanogenerators, with high compactness and flexibility, can function as portable energy sources for electronic devices.

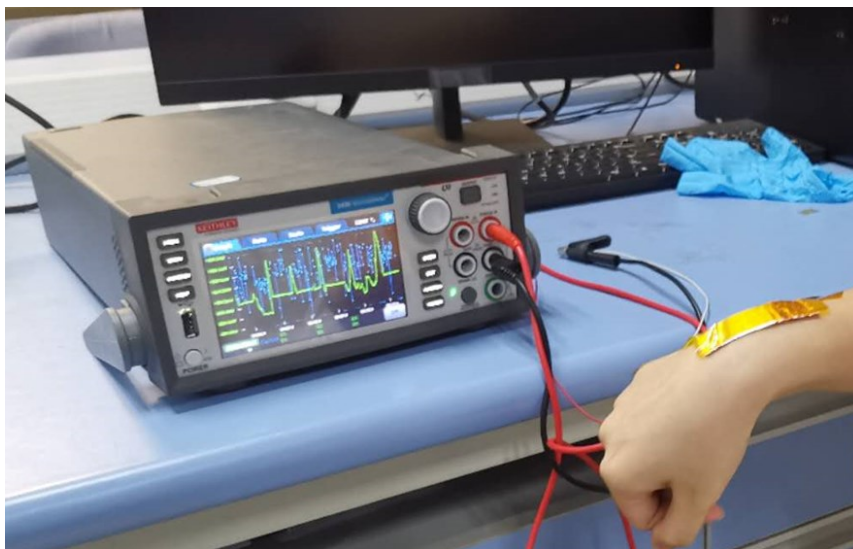


Figure 11: Measurement of the output voltage when the flexible nanogenerators are attached to the human wrist.



Figure 12: Demonstration of the nanogenerator as motion sensors to detect the motion of finger joints.

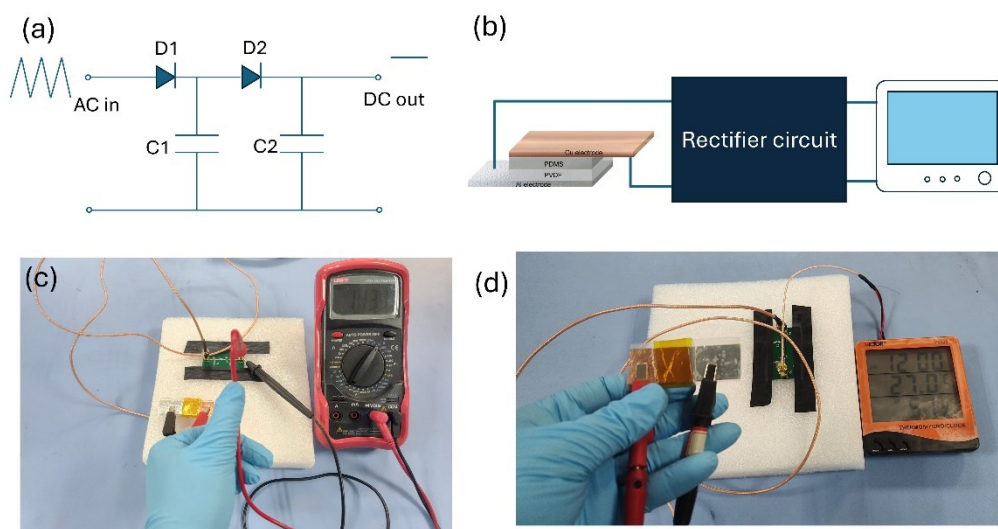


Figure 13: (a) The circuit diagram of a two-level charge pump for voltage rectifying and energy storage. (b) The schematic of the application and measurement of the wearable nanogenerator circuit. (c) The DC output of the nanogenerator circuit measured by a multimeter. (d) Demonstration of a thermohydrometer powered by the wearable nanogenerator.

5. Conclusions and Outlooks

In summary, I have developed a novel hybrid type nanogenerator by introducing additional piezoelectricity into PDMS and demonstrated their application prospect in wearable power generators. PVDF-based PENGs and PDMS/PVDF-based hybrid nanogenerators are first developed, and their frequency dependencies are studied. Home-made PDMS with higher curing agent content (which

makes it more rigid and less adhesive) and smaller thickness is beneficial for improving the voltage output of the PDMS/PVDF-based hybrid nanogenerators. Additional piezoelectric contents are added into the PDMS base, and I found a higher ZnO content (up 10%) further increases the output. By integrating the novel hybrid nanogenerators with a rectification circuit, the formed potable power source can output power to a thermohydrometer.

This work significantly contributes to nanogenerator research in two key aspects. I have proposed and realized a novel hybrid nanogenerator with two piezoelectric layers for the first time. The addition of a new piezoelectric layer effectively solves the existing problem of decayed piezoelectric field due to the spacing of a friction layer in conventional hybrid nanogenerators. Such findings provide new physical insights for the working principles of various types of nanogenerators. From the viewpoint of applications, I have demonstrated the flexible nanogenerators can power portable electronic devices. The intriguing features, including high compactness, flexibility, and biocompatibility, promise their application prospects in wearable electronics. This research has the potential to bridge the gap between scientific exploration and practical applications.

Future work will concentrate on applying the developed nanogenerators in practical scenarios. For example, a prototype for a portable power source with the rectifier circuit integrated on the flexible nanogenerators can be developed empowered by the flexible printed circuit technology. Subsequently, efforts will be devoted to extending its application scenario in the broader scope of the Internet of Things. For instance, such power sources can serve as energy harvesters for wireless sensors and edge computing nodes where kinetic energies are available.

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