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EVALUATING STRUCTURE AND POWER CONVERTING CIRCUITS FOR HYBRID TRIBOELECTRIC AND PIEZOELECTRIC NANOGENERATOR

A hybrid nanogenerator integrates both triboelectric and piezoelectric components into a single device. By doing so, it can harness energy from different types of mechanical inputs more efficiently. When the hybrid nanogenerator is subjected to mechanical motion, both triboelectric and piezoelectric effects are activated. For example, when pressing or sliding motions occur, the triboelectric layers produce a charge due to contact and separation, while the piezoelectric material generates a charge from the mechanical stress applied. The combined effect can produce higher electrical output and improve the efficiency of energy harvesting from a broader range of mechanical motions. In this paper, the novel structure of hybrid triboelectric and piezoelectric nano-generators have been merged to harvest abundant mechanical energy. Ecoflex and PVDF-based hybrid nanogenerator have been proposed to harvest mechanical energy. While Ecoflex synthesized with 0.5 % hexachlorofullerene (C60Cl6) is used for the triboelectric layer in the TENG part, 3wt% polymethyl methacrylate (PMMA) integrated with polyvinylidene fluoride (PVDF) matrix is utilized as a dielectric medium in piezoelectric part of the nanogenerator. Efficient hybrid nanogenerator structures were selected and appropriate power converters were used. The hybrid NG's performance in generating electrical microenergy was demonstrated experimentally.

Keywords: hybrid nanogenerator, triboelectric nanogenerator, piezoelectric nanogenerator, mechanical energy harvesting, dielectric medium, power converter circuit.

Introduction

With the swift expansion of the industrial economy and the global population, traditional energy sources like fossil fuels are increasingly inadequate to satisfy energy requirements. The adoption of renewable and sustainable energy sources, including light, heat, wind, wave, vibration, and rotational energy, emerges as a viable and promising strategy to address the worldwide energy crisis [1]. Over the past decade, extensive research and efforts have focused on environmental energy harvesting techniques. These sources generate large-scale electricity for industrial and household use, alleviating local power shortages. Simultaneously, microscale energy harvesting has gained global attention for replacing batteries in portable electronics and wireless sensor nodes, enabling self-charging devices and self-powering smart wireless sensor network systems [2].

These energy harvesters capture ambient renewable energy and convert it into electricity using various transduction mechanisms, including photovoltaic, thermoelectric, pyroelectric, piezoelectric, electromagnetic, and triboelectric methods, offering sustainable power solutions [3].

Most renewable energy sources in our environment are not consistently stable or available. Because a single harvester's energy output depends on the source's availability, it often cannot meet the power needs of electronic devices. Hybrid energy harvesting technology is emerging as a solution to the energy insufficiency of single harvesters. It involves collecting energy from multiple sources and converting it into electricity through various transduction mechanisms. This approach, using hybrid materials, structures, and mechanisms, enhances energy conversion efficiency and benefits from multiple energy sources simultaneously. Multi-source hybrid energy harvesters with diverse energy conversion materials and configurations have been consequently developed as integrated devices [4].

The output power increases significantly when multiple energy sources are available simultaneously or alternately. Despite this, the development of high-efficiency power conversion from single-source harvesters and various transduction mechanisms remains a primary research focus. Technical reviews on piezoelectric [5], electromagnetic [6], triboelectric [2], thermoelectric [7], pyroelectric, and hybrid mechanisms have covered materials, theories, configurations, and applications [8]. Due to their irregular high-voltage, low-current pulse output, TENGs typically have low energy supply efficiency when powering electronics or charging storage devices, limiting their practical use in self-powered microsystems. Therefore, effective power management is crucial to enhance the energy efficiency of TENGs [3]. Self-powered applications using NGs have grown rapidly, particularly in biomedical fields. Implantable TENGs have proven effective for human-machine interfaces and wearable devices for monitoring physical activities. Recent studies indicate that TENGs can generate electricity from various mechanical energies, including water waves, sound, and traffic noise. While TENGs generate high voltages and low currents, PENGs produce low voltages and medium currents [9]the high impedance of the TENG cannot meet the low impedance requirement of electronic devices. TENG devices need efficient and secure power management solutions to overcome the issue. Recently, different power management techniques with matched impedance and regulated output power have been proposed to efficiently utilize a TENG as a power source. These power management techniques include direct current (dc. Both have low power outputs and therefore require efficient power management circuits for hybrid TENG/PENG.

There have been several studies devoted for designing of the hybrid triboelectric and piezoelectric nanogenerators to harvest mechanical energy. The flexible nanogenerator using P(VDF-TrFE) nanofibers and a PDMS/MWCNT composite membrane, operating through separate triboelectric and piezoelectric hybrid mechanisms has been proposed [10]. P(VDF-TrFE) nanofibers, created via electrospinning, serve as both a piezoelectric functional layer and a triboelectric friction layer. Multiwall carbon nanotubes (MWCNTs) were added to PDMS films to enhance the triboelectric generator's performance by increasing initial capacitance. The nanogenerator was fabricated using low-cost MEMS processes. Another study suggests that a hybridized triboelectric-piezoelectric-electromagnetic nanogenerator may efficiently harvest vibration energy [11]. The device integrates three energy harvesting modes into a single unit, with a magnetic levitation structure as its core component. This design might potentially offer higher sensitivity compared to conventional spring or cantilever systems, due to reduced energy loss, making it suitable for capturing small vibrations, such as those from a slapping desk or a running car. Additionally, the design may help prevent mechanical fatigue or damage, although further validation is necessary to confirm these benefits. A hybrid piezo/triboelectric nanogenerator (H/P-TENG) was designed for mechanical energy harvesting using polymer ceramic composite films, specifically PDMS/BZT–BCT and PVA. The H/P-TENG, incorporating 15 wt% forward-poled BZT–BCT in PDMS, showed a 190 % performance increase over a TENG made from pure PDMS [12]. Finally, Hybrid nanofiber mats were created using poly(vinylidene fluoride) and thermoplastic polyurethane as piezoelectric and triboelectric materials through simultaneous electrospinning [13]. When subjected to periodic compression, these hybrid nanogenerators showed a 75.0% increase in voltage density and a 169.23 % increase in current density due to surface roughening. Additionally, the decoration with rGO NPs and ZnO NWs further boosted voltage density by 271.80 % and current density by 230.77 %. A piezoelectric/triboelectric hybrid nanogenerator (PT-NG) was developed using a composite film of electrospun PVDF nanofibers embedded in PDMS [14]. This design enhances mechanical-to-electrical energy conversion while protecting the PVDF during compression. The PT-NG efficiently charges capacitors and performs well as a self-powered wearable sensor, capable of detecting finger movements, recognizing gestures, and monitoring respiration.

The power management module must match the impedance of electronic devices with a hybrid TENG/PENG and regulate its output for steady power. DC buck conversion, capacitive transformation, rectification, electromagnetic transformation, IC switches, voltage trigger switches, travel switches, and transistor switches have been adopted for efficient power conversion, the techniques are not efficient and straightforward though [2].

Recent studies have been devoted on polymer-based TENG and PENG, highlighting their use as both energy harvesters and self-powered sensors [15]. Generally, TENGs convert mechanical energy into electrical energy through the combined effects of contact electrification and electrostatic induction. This mechanism allows TENGs to harvest energy from various mechanical motions in the environment. On other hand, PENGs utilize the piezoelectric effect to convert mechanical energy into electrical energy, serving as energy harvesters, and detect mechanical stimuli to generate electrical signals, functioning as self-powered sensors [16]. Both devices can be combined to improve the power density of the sources.

In this paper, the Ecoflex and PVDF-based hybrid nanogenerator has been proposed to harvest mechanical energy. While Ecoflex synthesized with 0.5 % hexachlorofullerene (C60Cl6) is used for the triboelectric layer in the TENG part, 3wt % polymethyl methacrylate (PMMA) integrated with polyvinylidene fluoride (PVDF) matrix is utilized as a dielectric medium in piezoelectric part of the nanogenerator. Efficient hybrid nanogenerator structures were selected and appropriate power converters were used. The hybrid NG's performance in generating electrical microenergy was demonstrated experimentally.

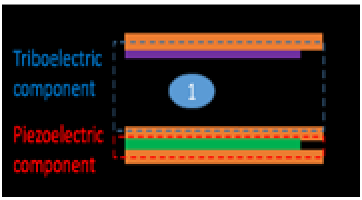
Materials and methods

A.Hybrid NG structures

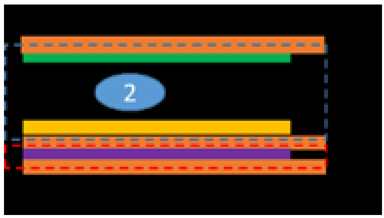
The structures for hybrid nanogenerators are fabricated with synthesized dielectric materials with improved triboelectric properties and their chemical and electrical characteristics have been presented in previous studies [15], [16]. Four structures of the hybrid nanogenerators (NG) as well as PENG and TENG have been presented below (Figure 1). The hybrid NG consists of triboelectric and piezoelectric components. The structure-1 was fabricated such that Ecoflex/

flurelene 5 wt% was attached to the top electrode (N1) while PVDF/PMMA 3 wt% was placed between electrodes N2 and N3 (Figure 1a). The contact and separation of electrodes N1 and N2 represent a triboelectric component, and the deformation of dielectric material between N2 and N3 operates as a piezoelectric component. Similarly, the structure-2 of the hybrid NG is fabricated such that in triboelectric component PVDF/PMMA 3 wt% is attached to N1 and polyvinyl alcohol (PVA) 15 wt% is attached to N2 (Figure 1b). In the piezoelectric component, Ecoflex/flurelene 5 wt% is placed between the electrodes N2 and N3. The structure -3 of hybrid NG is fabricated such that the triboelectric component's electrode N1 is attached with Ecoflex/flurelene 5 wt% and N2 attached with PVA 15 wt % (Figure 1c). The piezoelectric component's electrodes have Ecoflex/flurelene 5 wt% between N2 and N3. Structure-4 of the hybrid NG is fabricated similarly to structure-1 but N2 is attached with PVA 15 wt% in the triboelectric component (Figure 1d). The structure of TENG consists of the electrode N1 attached with PVA 15 wt%, and Ecoflex/flurelene 5 wt% attached to N2 (Figure 1e). The structure of PENG consists of PVDF/PMMA 3 wt% placed between the electrodes N1 and N2.

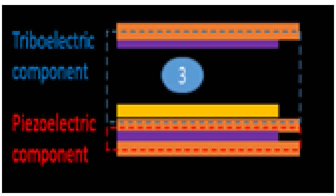
(a)



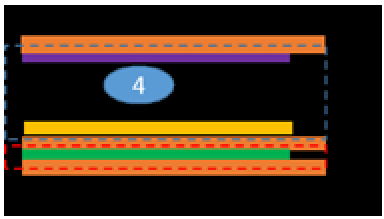
(b)



(c)



(d)



(e) (f)

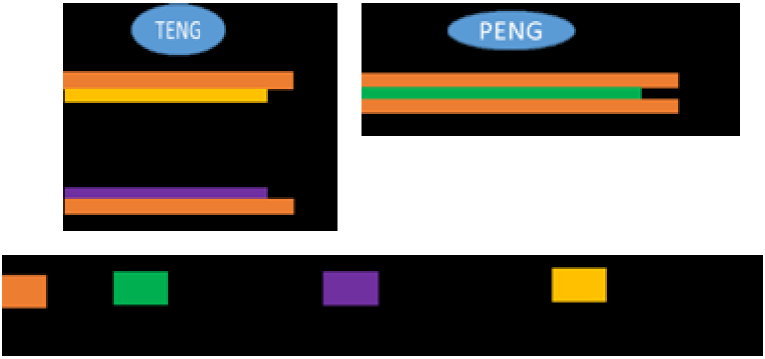


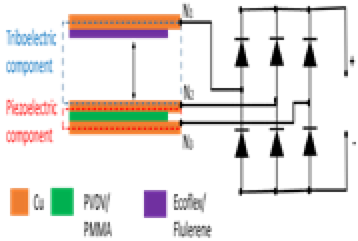
Figure 1 –The fabrication structures of the hybrid NGs (a) structure -1, (b) structure -2, (c) structure – 3, (d) structure -4, (e) TENG structure, (f) PENG structure

Deriving and applying electromechanical equations for a hybrid NG is complex, especially when the components' motions are closely linked. A general system of equations for a hybrid NG combines piezoelectric and triboelectric principles, particularly applying Maxwell's law of displacement current, but varies across the piezoelectric and triboelectric domains [17]:

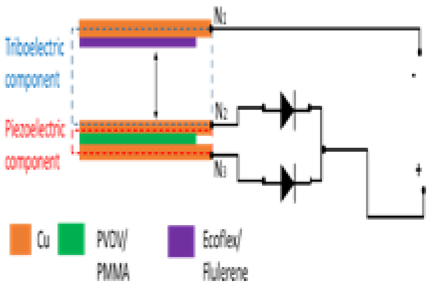
where is the separation distance between the triboelectric layers or the distance inside the piezoelectric material; is the surface polarization charge density on the piezoelectric material; is the surface density of free electrons accumulated in the electrodes of the triboelectric material; are the thickness and dielectric constants of two dielectrics of the triboelectric pair; are the output voltage downstream of the piezoelectric and the triboelectric device; is a function that involves the output voltages and currents of the piezoelectric and triboelectric components and which depend on the specific configuration and electrode connections.

B.Power converters circuits for hybrid NG

The power converters' topologies are presented and assessed according to their performances measured from the output side. The first converter's topology (connection-1) represented a three-phase full-bridge rectifier connected to N1, N2 and N3 electrodes (Figure 2a). The second topology (connection-2) represents half-wave rectification with two diodes, anode sides connected to N2 and N3 (Figure 2b). The third topology (connection-3) has two full-bridge rectifiers connected in parallel (Figure 2c). The final topology (connection-4) has two full-bridge rectifiers connected in series (Figure 2d). Inputs of the first full-bridge connected to N1 and N2, and the second full-bridge rectifier's inputs connected to N2 and N3. It should be noted converter's topology for TENG and PENG consists one full bridge rectifier as it utilized in [15] and [16].



(a)



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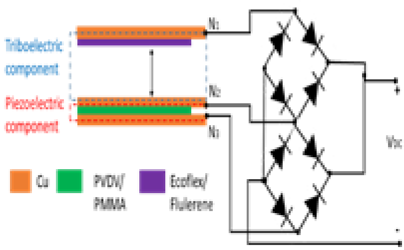

(c)

(d)

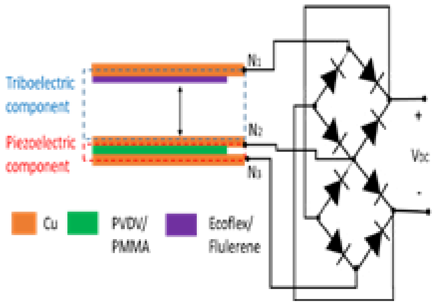

Figure 2 – Power converters connections: (a) connection – 1, (b) connection- 2, (c) connection -3, (d) connection- 4

Results and discussion

This section presents the electrical characteristics for harvesting mechanical energy by hybrid NG for analysis. The performance of the designed hybrid NG (structure-1) has been measured with an oscilloscope in contact separation mode (5 Hz and 10 N) and compared with PENG and TENG performance. The connection-1 power converter's topology was utilized in this test. The open-circuit voltage and short-circuit current diagrams are shown in Figure 3 and Figure 4. The maximum values of the PENG, TENG, and Hybrid NG output voltages reach 10.8 V, 5.28 V, and 6 V respectively. However, the mean value of the voltage of Hybrid NG is the highest, 0.5905 V which is higher by 23% and 22.3% from TENG and PENG voltages respectively. The maximum values of the PENG, TENG, and Hybrid NG currents reach 1.24 μA, 0.536 μA, and 0.42 μA respectively. However, the mean value of the current of Hybrid NG is the highest, 0.0534 μA which is higher by 72.8% and 13.9% from TENG and PENG voltages respectively (Table 1). Moreover, the Hybrid NG demonstrates the maximum charge transfer compared to PENG and TENG (Figure 5). For example, the Hybrid NG has generated 1.84 μC which is higher by 8.65% and 291.4% than TENG and PENG respectively. Similarly, the performance of the Hybrid NGs has been analyzed by considering their structures which are presented in the previous section. The output voltages of the Hybrid NGs are presented in Figure 6. Structure-4 has the best performance than other structures. For example, it has reached 45 V with 5.9579 μC charge transfer which is improved by 61.4%, 879.6%, and 8.52% than structure-1, structure-2, and structure-3 respectively (Table 2). This has shown that Structure-4 is a better configuration for power generation. Next, the power converters have been tested for efficiency and minimal losses. The maximum output voltage has reached 67 V with 2 half-bridge rectifiers whereas 25 V with a three-phase rectifier which is higher by 38.9% and 108.3% than with connections 3 and 4 (Figure 7).

Table 1 – The output voltages and currents of the Hybrid NG

Type of NG	, V	, V	, өA	, өA
TENG	5.28	0.48	0.536	0.0309
PENG	10.2	0.483	1.24	0.0469
Hybrid NG	6	0.591	0.42	0.0534

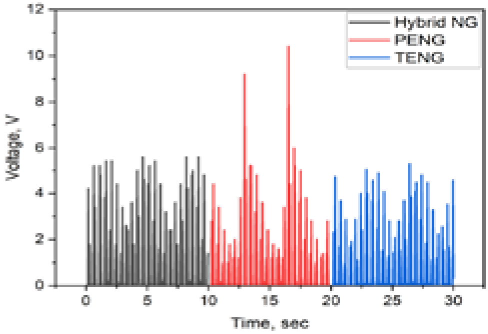

Figure 3 – Hybrid NG's output voltage after full-wave rectification at 5 Hz and 10 N

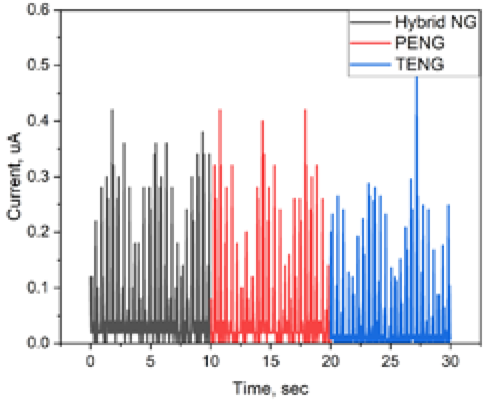

Figure 4 – Hybrid NG's output current after full-wave rectification at 5 Hz and 10 N

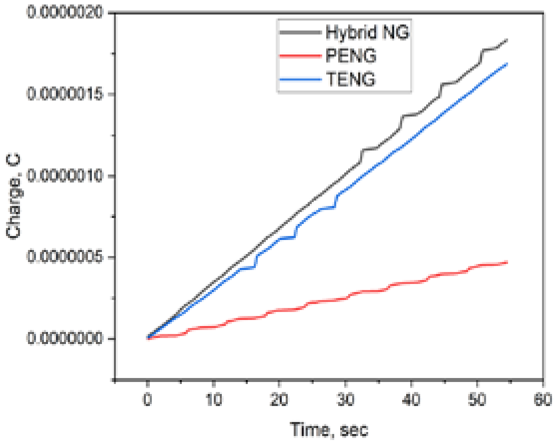

Figure 5 – Hybrid NG's charge generation within 55 sec at 5 Hz and 10 N

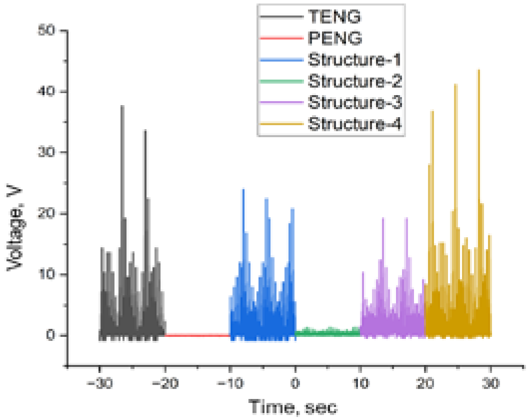

Figure 6 – Hybrid NG's output voltages with structures 1, 2, 3, and 4

Table 2 – Hybrid NG's maximum output voltages and maximum charges with structures 1, 2, 3, and 4

Parameter	TENG	PENG	Structure -1	Structure -2	Structure -3	Structure -4
Maximum output voltage, V	39.2	0.18	24	1.44	21.6	46.8
Maximum Charge, өC	5.222	0.033216	3.6912	0.60819	5.4902	5.9579

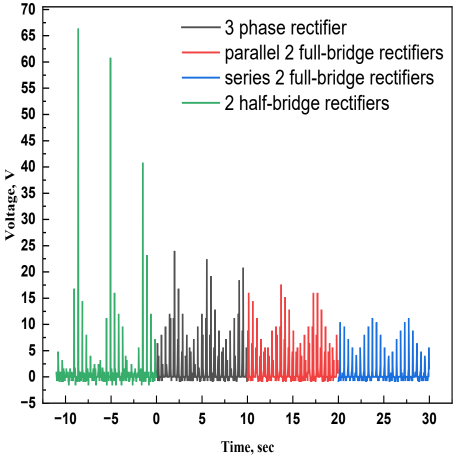

Figure 7 – Hybrid NG's output voltages with power converter connections 1, 2, 3, and 4 types

Conclusions

In this paper, a novel hybrid structure combining triboelectric and piezoelectric nanogenerators was developed to harvest abundant mechanical energy. Polymers-based hybrid nanogenerators were proposed for this purpose. Specifically, Ecoflex with 0.5 % hexachlorofullerene was used for the TENG's triboelectric layer, while a 3wt% polymethyl methacrylate integrated with a polyvinylidene fluoride matrix served as the dielectric medium for the piezoelectric part. Efficient hybrid nanogenerator structures were selected by evaluating performance with varying dielectric layers attached to the designated electrodes and appropriate power converters were utilized. The maximum power generation of the hybrid nanogenerator as well as demonstration of its practical application are planned as the future steps and will be presented in upcoming study.

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ГИБРИДТІ ТРИБОЭЛЕКТРЛІК ЖӘНЕ ПЬЕЗОЭЛЕКТРЛІК НАНОГЕНЕРАТОРЛАРҒА АРНАЛҒАН ҚҰРЫЛЫМДЫ ЖӘНЕ ҚУАТТЫ ТҮРЛЕНДІРЕТІН СҰЛБАЛАРДЫ БАҒАЛАУ

Гибридті наногенератор трибоэлектрлік және пьезоэлектрлік компоненттерді бір құрылғыға біріктіреді. Осылайша, ол механикалық кірістердің әртүрлі түрлерінен энергияны тиімдірек пайдалана алады. Гибридті наногенератор механикалық қозғалысқа ұшыраған кезде трибоэлектрлік және пьезоэлектрлік әсерлер белсендіріледі. Мысалы, басу немесе сырғанау қозғалыстары пайда болғанда, трибоэлектрлік қабаттар жанасу және бөлу салдарынан заряд жасайды, ал *пьезоэлектрлік материал қолданылған механикалық кернеуден заряд жасайды. Біріктірілген әсер электр қуатын жоғарылатып, механикалық қозғалыстардың кең ауқымынан энергия жинау тиімділігін арттырады. Бұл мақалада гибридті трибоэлектрлік және пьезоэлектрлік наногенераторлардың жаңа құрылымы механикалық энергияны жинау үшін біріктірілді. Механикалық энергияны жинау үшін Ecoflex және поливинилиденді фторидпен (PVDF) негізіндегі гибридті наногенератор ұсынылды. TENG бөлігіндегі трибоэлектрлік қабат үшін 0,5% гексахлорфуллеренмен (C60Cl6) синтезделген Ecoflex пайдаланылса, диэлектриктік ортаның диэлектрлік ортасы ретінде PVDF біріктірілген массалық 3% полиметилметакрилат (PMMA) қолданылады. Тиімді гибридті наногенератор құрылымдары таңдалып, сәйкес қуат түрлендіргіштері пайдаланылды. Гибридті наногенераторының электрлік микроэнергияны өндірудегі өнімділігі эксперименталды түрде көрсетілді.*

Кілтті сөздер: гибридті наногенератор, трибоэлектрлік наногенератор, пьезоэлектрлік наногенератор, механикалық энергия жинау, диэлектрлік орта, қуат түрлендіргіш тізбегі.

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ОЦЕНКА СТРУКТУРЫ И СХЕМ ПРЕОБРАЗОВАТЕЛЕЙ ЭНЕРГИИ ДЛЯ ГИБРИДНОГО ТРИБОЭЛЕКТРИЧЕСКОГО И ПЬЕЗОЭЛЕКТРИЧЕСКОГО НАНОГЕНЕРАТОРА

Гибридный наногенератор объединяет трибоэлектрические и пьезоэлектрические компоненты в одном устройстве. Благодаря этому он может более эффективно генерировать энергию от различных типов механических входов. Когда гибридный наногенератор подвергается механическому воздействию движения, активизируются как трибоэлектрические, так и пьезоэлектрические эффекты. Например, когда происходят движения нажатия или скольжения, трибоэлектрические слои производят заряд из-за контакта и разделения, в то время как пьезоэлектрический *материал производит заряд из-за приложенного механического напряжения. Совместный эффект может производить более высокий электрический выход и повышение эффективности сбора энергии из более широкого диапазона механических движений. В этой статье новая структура гибридных трибоэлектрических и пьезоэлектрических наногенераторов была объединена для сбора обильной механической энергии. Гибридный наногенератор на основе Ecoflex и поливинилиденфторида (PVDF) было предложено собирать механическую энергию. В то время как Ecoflex, синтезированный с 0,5 % гексахлорфуллерена (C60Cl6), используется для трибоэлектрического слоя в части TENG, 3 % полиметилметакрилата (PMMA), интегрированного с матрицей PVDF, используется в качестве диэлектрической слоя в пьезоэлектрической части наногенератора. Были выбраны эффективная конструкция гибридного наногенератора и использованы соответствующие преобразователи мощности. Экспериментально продемонстрирована эффективность гибридного наногенератора для получения электрической микроэнергии.*

Ключевые слова: гибридный наногенератор, трибоэлектрический наногенератор, пьезоэлектрический наногенератор, сбор механической энергии, диэлектрический слой, схема преобразователя мощности.

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