

Development of a Flexible CuO Nanogenerator for Sustainable Energy Harvesting from Biomechanical Motions

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Abstract:

As global energy demands surge and conventional resources dwindle, the search for sustainable alternatives intensifies. While bioenergy, hydropower, solar, and wind offer large-scale solutions, emerging technologies are essential for diversifying the energy landscape. Nanogenerators, leveraging nano energy principles, signify a pivotal advancement. By harnessing minute ambient energy, nanogenerators exploit piezo, tribo, and pyroelectric effects, with Wang et al.'s seminal 2006 breakthrough igniting this transformative journey. Lightweight, easily manufacturable, and eco-friendly, nanogenerators herald a paradigm shift in energy harvesting. This paper delivers an exhaustive exploration of nanogenerator fundamentals, performance metrics, and recent innovations. Ultimately, paper charts the future trajectory and confronts challenges, guiding the evolution of this groundbreaking technology.

Keywords — Nanogenerators, Nano energy principles, Piezoelectric, triboelectric, and pyroelectric nanogenerator, Sustainable power sources, Self-powered systems, Integration with solar photovoltaics.

I. INTRODUCTION

Energy is a fundamental need for day to day life and the sustainable progress of modernize society, essential across various sectors such as transportation, communication, aviation, and numerous electronic devices. Overuse of fossil fuels led to the exhaustion of these substances, as consumption of energy has skyrocketed due to the fast rate of industries, urban sprawl, and population development in the past few years. Sustainability energy sources have been the focus of intense study due to this development and the urgent problems of climate change, global warming, and diminishing energy supplies. According to 2018 BP Energy Outlook, renewable source is the rapid-growing power resource, contributing to 40% of the global rises in power consumption [1].Established renewable energy sources such as bioenergy,

hydropower, solar, and wind generate energy on scales ranging from megawatts to gigawatts. Conventional batteries, while widely used, have limited lifespans and pose environmental hazards, highlighting the need for alternative energy solutions. Ambient mechanical energy, abundantly available, offers a viable option for conversion into electrical energy [2]. Human movement has a great deal of potential that can be successfully transformed into electricity [3] (Table 1)

Table 1: Power potential during movement of the human body [3].

Body Motion	Mechanical Energy Available (Watts)	Electrical Energy Generated (Watts)	Electrical Energy Per Movement (Joule)
Blood Flow	1.92	1.14	1.15
Exhalation	2	1.15	2.01

Inhalation	1.81	1.12	1.82
Upper Limb Movement	2	1.50	1.23
Walking	65	20.36	19.92
Finger Typing	7.7–18	2.1–4.1	225–405 m

II. RELATED WORK

Lately, Particularly, the mechanical energy generated by human activities remains a significant, underutilized resource. Nanogenerators, which convert mechanical energy into electrical energy through piezoelectric represent a groundbreaking advancement in this domain. The pioneering work by Wang et al. in 2006, which introduced the first nanogenerator using ZnO nanowires with energy conversion efficiency of 17-30%, marked a pivotal moment in this field [3]. Since then, nanogenerators have evolved into lightweight, easily manufacturable, and sustainability power devices.

This review goal to offer a complete examination of nanogenerators, concentrate on their fundamental principles, performance metrics, recent technological advancements, and diverse applications. It traces the evolution and development of nanogenerators over the past decade, emphasizing the materials used improvements in electrical output, and their capability to harness various forms of ambient energy. The review also considers the integration of nanogenerators with other renewable technologies, such as solar photovoltaics, and discusses future prospects and challenges within this rapidly growing field [4].

More specifically, nanogenerators are remarkable for their capacity of converting mechanical energy into electrical energy from a wide range of sources, including human motion, vibrations, flowing water, rain, wind, and even waste heat through the pyroelectric effect. On the other hand, nanogenerators, by virtue of their nanotechnology structure, are able to effectively capture low-frequency mechanical vibrations [5]. Figure 1a demonstrates the important findings in mechanical energy harvesting research. Figure 1b displays the

energy needs of several devices at various energy scales. For instance, ZnO nanowires can be bent more than bulk ZnO without damage, enabling them to endure greater strain and produce high electricity [6].

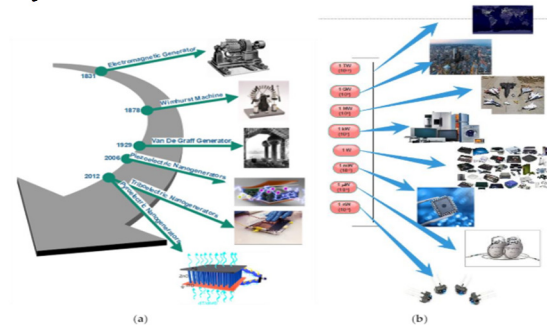


Figure 1. (a) The most important developments in mechanical energy harvesting technology history. (b)Power needed for different devices at different power levels

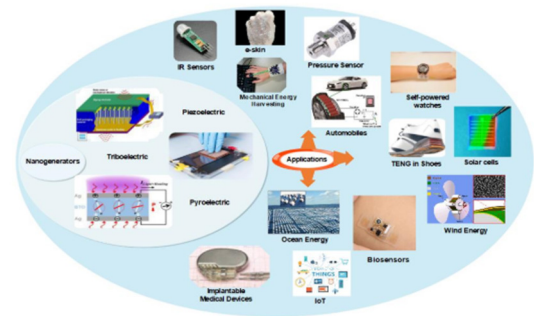


Figure 2. Various nanogenerator kinds and their uses in the Internet of Things era (IoT).

Figure 2 shows various nanogenerator kinds and their uses in the Internet of Things era (IoT). The technology's growth is evidenced by the increasing number of publications in the field, with around 469 papers published in 2018 alone, a 1.5-fold increase compared to 2017 [6]. This review aims to highlight the transformative potential of nanogenerators in providing sustainable energy solutions across a wide range of modern technological applications. The research on nanogenerators is growing steadily, as Figure 3 illustrates.

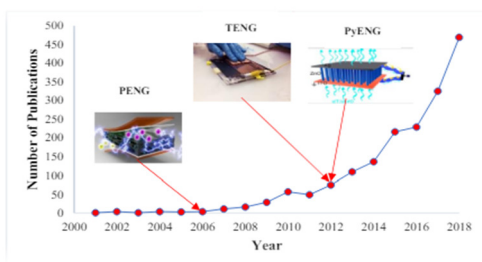


Figure 3. The overall quantity of publications made throughout time in the field of nanogenerators.

III. PROPOSED WORK

1. Piezoelectric Nanogenerators (PENG)

The piezoelectric effect, in which stress from mechanical action causes electric charges to be generated, is the mechanism by which PENGs create electricity. The greatest energy states that electrons may occupy both internally and externally Fermi levels are separated by a piezo potential disparity in PENGs, which is created when two electrodes on a piezoelectric material with balancing Fermi levels are subjected to external strain [2]. Till electrostatic equilibrium is achieved, charge carriers flow via an external load due to this potential disparity. On the flip side, mechanical strain may be induced in piezoelectric materials by use of an electric field. 2 main topologies are available for PENGs.

When the force is applied perpendicular to its axis, as shown in Figure 4a, PENG operates. In the initial setup, an electric field is generated by stretching a single nanostructure in a direction transverse to its development. Employing an atomic force microscope probing to apply force transverse to the axis of a nanostructure causes compression strain on one side and tension strain on the other [7]. A minimally current-reversed Schottky diode is formed when the positively-potentialized probing makes connection with the stretched surface. A bias positive voltage at the interfaces generates a rapid peak output current caused by the potential differences when the instrument touches the compression sides with negative potential. The electricity field at the tip of the nanostructure is balanced by current flowing through the ohmic contact at its base [8]. When the top electrodes come into touch with a negatively potential, conduction takes place; conversely, when it comes

into contact with a positively charged potential, no current is produced. This is the case in p-type semiconductors because of the movement of holes, while in n-type semiconductive nanostructures it is the inverse. As an alternate, consider Figure 4b, which shows the strain acting on the nanostructures in an orientation perpendicular to their formation.

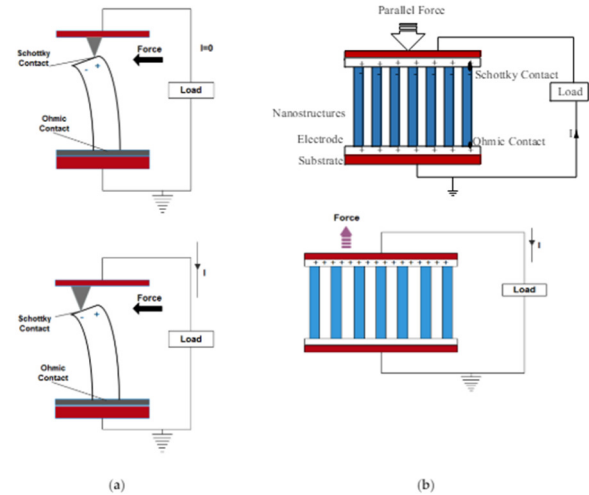


Figure 4. (a) Force exerts transverse to the growth of the nanowire. (b) Force exerts parallelly to the growth of the nanowire.

Figure 4b shows the subsequent possible arrangement, which makes use of externally strain running along to the direction of formation of the nanostructure. A lateralized nanowire with Schottky and ohmic connections may be subjected to a unidirectional compression force when a force exerted to its tip. This force produces a negative potential at the nanowire's tip and, as a result of the piezoelectric effect, raises the Fermi level. A positive potential is created at the tip of the nanowire when electrons go downward via an external circuit. Instead of electrons flowing through the nanowires, the Schottky contact channels them into the outside circuit. The removal of force stops the piezoelectric effect, which causes an inverse voltage peak as electrons migrate from the bottom electrode to the top, canceling out the positive potential at the tip [6]. The Schottky contact produces a direct current output due to its in-situ rectification action. To prevent charges from building up, Zhu et al. [10] substituted a PMMA layer for the Schottky contact. In this nanogenerator,

a piezopotential field is generated along the nanowires by compression force, which leads to an accumulation of inductive charges on the electrodes. This arrangement is analogous to a capacitive one, in which strained nanowires function as polarizing dipole moments in a dielectric-filled plate capacitor [11]. Relaxation of stress causes the piezopotential to vanish and electrons to flows return to the external circuit, producing alternating current (AC) in the case of a capacitive setup or a Schottky diode with series resistance.

Stacking several nanowires in such a way that their voltage output is adequately synchronized increases the power output of PENG. 2 successful integrating techniques were devised by Wang et al. (2007) [7]: vertical-nanowire-integrated nanogenerators (Figure 5a) and lateral-nanowire-integrated nanogenerators (Figure 5b), in which nanowires grown in parallelly are layered. The nanowires in PENGs that are connected vertically flex laterally and compressed vertically. Lateral incorporated PENGs use radial forces or surface bending to cause nanowire distortion via laterally bending [9]. Because 1D nanostructures have an extremely large dimension ratio, circumferential strain dispersion is ignored while uniformly bending the sides of nanowires, which may be thought of as extending. Research evaluating the capacity of energy conversion with nanowires that were bent lateral and those that were crushed vertically indicated that the latter produced a greater voltage [12].

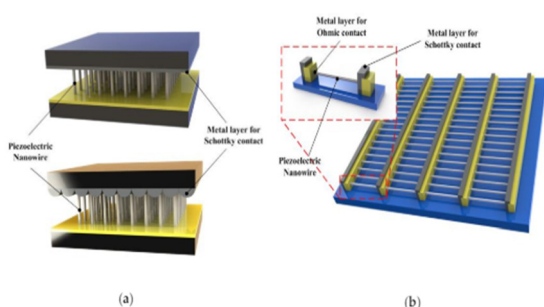


Figure 5: The piezoelectric nanogenerator's geometric configuration (PENG). (a) The vertically integrate nanogenerator's basic construction. (b) The laterally integrate nanogenerator's fundamental structure

2. Development and Optimizing Output Power in PENGs

An early nanogenerator that made use of ZnO nanowires was developed in 2006 [6]. A conductivity atomic microscope in contact mode was used with a silicon tip coated with platinum to bend parallel nanowires. The energy generated per discharge from a single ZnO nanowire (NW) was 0.05 fJ, while the power and output voltage were around 8 mV and 0.5 pW, correspondingly. Approximately 10 pW/ μm^2 was the output power density at a nanowire density of 20/ μm^2 . A productivity of 17-30% in power conversion was attained by means of the Schottky barrier that was created among the nanowires and the metal tip of the microscope. The piezoelectric potential distribution in a 50 nm diameter and 600 nm long nanowire was estimated to be about 0.3 V by Gao and Wang (2007) using perturbation theory [9]. According to their research, the surface piezoelectric potential of a nanowire increases as its translation along its length-to-diameter axis increases, whereas the opposite relationship holds true for its dimension ratio. A microfiber-based PENG was developed by Qin et al. in 2008 utilizing a ZnO thin film electrode and a hydrothermal method.

A power density ranging from 20 to 80 mW/cm² was achieved by this hybrid structure, which generated an output voltage of 1-3 mV and a current of 4 nA [13]. In a similar vein cadmium sulfide (CdS) nanowires generated by physical vapor deposition and hydrothermal methods were used in a nanogenerator model shown by Lin et al. (2008) [14].

In comparison with nanowires made using hydrothermal techniques, those made via physical vapor deposition generated a greater voltage. A flexible surface without sliding connections was used to create a laterally integrated PENG that could generate alternating current [15] by Yang et al. (2008). Under strains ranging from 0.05 to 0.1%, this PENG produced an oscillating output voltage (AC) of up to about 50 mV for a single nanowire. To boost power production, these flexible PENGs may be linked in series on a shared substrate. For the operation of a commercial LED, the produced

electricity was held in capacitors. A peak output power density of around 0.44 mW/cm² and a volume density of 1.1 W/cm³ were accomplished by combining 20 layers of nanowires and regulating their density using nanowires [16]. Lin et al. used light to adjust the output performance of nanogenerators based on CdS nanowires in a different work published in 2008 [17]. A positive voltage output was achieved because the light lowered the nanowires' Schottky barrier height.

3. PENGs' Applications

Powering self-operating nano/microsensors, electronics, wearable/flexible gadgets, and biomedical apparatus are just a few of the many cutting-edge uses for piezoelectric nanogenerators (PENGs) [2]. Nanogenerators and nanobatteries are perfect applications for PZT nanofibers due to their higher piezoelectric voltage and dielectric properties. An important milestone for the advancement of biosensing technology was reached in 2014 with the creation of biosensors based on ZnO nanowires. Implanted electrical nerve generators (PENGs) are a great way to power medical equipment like pacemakers, cardioverter-defibrillators, and brain stimulants, as well as for tracking your health. Nanogenerators constructed of ZnO nanowires, indium tin oxide (ITO), and PZT sheets are transparent and flexible, allowing them to capture energy from motions such as finger typing. Because of their higher output voltage and remarkable flexibility, PENGs have enormous potential as electronic device power sources.

For the purpose of improving power conversion efficiency and enabling omnipresent power production, hybrid energy harvesting equipment have been created that integrate PENGs with other energy harvesting techniques as triboelectric nanogenerators (TENGs) and pyroelectric nanogenerators (PyENGs). To further improve the efficacy of power conversion, PENGs have also been included into solar photovoltaic cells. For instance, a PVDF nanogenerator and a silicon nanopillar solar cell were combined to form a tandem nanogenerator, which can generate electricity from both the sun and sound waves. A full-wave bridge rectifier can convert the highest AC voltage of 65 V produced by chemical

reinforced composite-based PENGs to DC output, which can then be used to charge capacitors and power LEDs. This shows that these devices have promise as self-powered wearable and portable electronics.

A composite piezoelectric nanogenerator made of electrospun polyvinylidene fluoride (PVDF) and zinc sulfide nanorods has a resonance frequency of around 86 ± 3 Hz, an acoustic sensitivity of around 3 V/Pa, and a wind energy conversion efficiency of around 58%. Because of this feature, it may be used for self-powered sensors, security monitoring, wind energy harvesting, and noise detection. Several security systems may benefit from sensors based on PENG technology, such as those that monitor transportation, those that are wireless, and those that are biological.

IV. CONCLUSION

To harness mechanical and biomechanical energy, we have created a piezoelectric nanogenerator (PNG) out of Cu-TA-PVDF and CuO-TA-PVDF polymer nanocomposites. The instrument's PDMS encapsulation improves its functioning and adaptability in harsh environments. A variety of hand tap techniques were used to generate electrical energy. The gadget could charge and discharge capacitance quickly and efficiently, which allowed it to power several electrical equipment. The PNG can detect and use the energy from a wide range of biomechanical actions, including breathing, swallowing, syllable identification, and finger compression/relaxation. The CuO-TA PNG was also used to measure arterial pulses, and it worked quite well. We anticipate that CuO-TA will prove to be an effective piezoelectric material for the fabrication of PNGs and may one day serve as a self-sufficient biomedical device for use in health monitoring

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