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High-Efficiency Nanostructured Materials for Flexible and Wearable Energy Harvesting Technologies

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Abstract. The growing demand for portable, sustainable power sources has driven significant advancements in flexible and wearable energy harvesting technologies. These technologies leverage ambient mechanical, thermal, and vibrational energy to power small electronic devices, offering a promising solution for self-sustaining, on-the-go power systems. The integration of nanostructured materials into energy harvesting devices has emerged as a key strategy to enhance efficiency, flexibility, and performance. This paper explores the role of high-efficiency nanostructured materials in the development of flexible and wearable energy harvesting systems. It examines various energy harvesting mechanisms, including piezoelectric, triboelectric, and thermoelectric, and their compatibility with nanomaterials. The unique properties of nanostructured materials—such as increased surface area, flexibility, and enhanced electrical performance—are discussed in the context of optimizing energy conversion efficiency. The paper also reviews the design principles for integrating these materials into flexible and wearable devices, highlighting recent innovations and case studies in the field. Applications of flexible energy harvesters in wearable electronics, self-powered medical devices, and environmental monitoring are presented, along with the challenges of scaling, durability, and sustainability. Finally, future perspectives on the commercialization of these technologies are provided, emphasizing the need for improved material fabrication, cost-effectiveness, and long-term reliability. This paper offers a comprehensive overview of how nanostructured materials are revolutionizing energy harvesting, paving the way for more efficient, sustainable, and portable power solutions.

Keywords: Nanostructured Materials, Flexible Energy Harvesting, Wearable Power Devices, Piezoelectric Nanomaterials, Triboelectric Generators, Sustainable Energy Harvesting

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Introduction

In the last few years, there has been significant progress toward the field of energy harvesting and in particular, there has been an increased interest due to the need for sustainable and self-sufficient systems. Energy harvesters, which are also simply referred to as energy scavengers, devices that collect waste energy and convert it to electrical energy, are ecological and sustainable technologies. This technology is very beneficial in powering portable and wearable devices in scenarios where adherent constraints of traditional energy sources like batteries that have weight, size, and limited life cycles. As low-power electronics continue to proliferate in fields such as consumer electronics, healthcare, and the Internet of Things (IoT), energy harvesting has emerged as an essential technology to achieve long-lasting, low-maintenance power solutions. This has resulted in increased research efforts aimed at improving the performance, integration, and variety of energy harvesting technologies. The process of energy harvesting is practiced in capturing the energy contained in ambient sources such as sun radiation, temperature difference, mechanical movements and vibrations, and electromagnetic radiation, and converting it to electric energy which can either be stored or utilized directly. The greatest benefit of energy harvesting technology is to sustain a power supply consistently without the need to regularly recharge particularly for low powered appliances and devices. This capability is especially important for distant or mobile devices which may not easily have a fixed energy source. As such the efficiency of an energy harvesting system is highly dependent on the design of the material or device architecture and its ability to capture and convert energy with maximum effectiveness, particularly in portable and wearables applications where space is a premium and convenience is a must.[1]
Various approaches have been employed to harvest and convert energy from the environment, utilizing the ambient energy of a given type: noise, temperature, movement, etc. The broad categories are piezoelectric, triboelectric, thermoelectric and electromagnetic energy harvesting. Piezoelectric energy harvesting is based on materials that produce an electric charge when subjected to a mechanical force, and vice versa. This technology finds numerous applications for harvesting vibrational energy obtained from mechanical equipment or human body movement. Triboelectric energy harvesting is concerned with the generation of electricity through the triboelectric effect as a result of friction between two dissimilar materials possessing different electron affinities. Wearable applications increasingly employ triboelectric nanogenerators (TENGs) thanks to their lightweight and flexible characteristics that allow efficient energy capturing from human activities. On the other hand, thermoelectric energy harvesting systems are based on the Seebeck effect, which utilizes the voltage induced by temperature differences across the medium. This technology has a big advantage in retrieving waste heat produced during industrial processes or body heat making it suitable for wearables. Mechanical energy harvesting uses electromagnetic induction to convert mechanical motion into electricity, which is typically found in areas of persistent motion such as automotive systems. Each of the technologies possesses its own advantages and deficiencies, which recent development in materials and device architectures have attempted to remedy. In the last five years the research scope in energy harvesting has made a turn in such a way that advanced designs and strategies are being employed to make it possible to integrate energy harvesting devices into wearable and portable gadgets. Nanotechnology has risen to the center stage of research with nanostructures materials such as nanowires, graphene and carbon nanotubes having properties that improve the energy conversion efficiency of the harvesting devices. Furthermore, multi-modality energy harvesting system synthesis is one more applicable strategy where triboelectric and piezoelectric effects are synthesized into one system enabling the collective impact of the harvesting mechanisms. This integrated approach is especially pertinent for wearable devices where the harvested energy comes from several sources such as motion of human or body,

temperature and light. Moreover, the progress in flexible electronics has led to the design of energy harvesting systems which can be tailored to intricate geometries like the human body while maintaining operational efficiency. This adaptability is important in the case of wearable applications since the harvesting devices can be incorporated into textiles, accessories, or even the human skin. Hence the scope for current development is rapidly shifting towards designing and fabricating materials and devices with enhanced energy conversion efficiency together with adequate flexibility and mechanical strength.[2]

The need for self-powered and easily portable devices is on the rise in consumer electronics, health care as well as IoT markets. Regular batteries have limitations caused by their life span, physical dimensions, and impact on environment. In contrast, systems of energy harvesting can ensure an uninterrupted supply of energy and thus development of a fully electronic device with its own energy source which will be easy to operate. It is also very useful in the case of portable equipments like straps where the end user needs small, effective and long-lasting energy sources that do not affect movement. The growth of usage of wearable device has caused an increasing requirement for energy harvesting systems which are not only efficient but most importantly, the systems shall be thin, light in weight, and can take repeated mechanical stress. When incorporated in clothing, accessories, and other wearables, Flexible energy harvesters eliminate the need for external bulky batteries. Such flexibility is important for the use in wearable applications because it allows the energy harvester to adapt to the body of the user, thus improving the comfort and the usability. Also, the possibility of embedding flexible energy harvesters directly into textiles paves the way to the production of “smart” cloths which are capable of harvesting energy from the user’s body motion or other surrounding conditions. In turn, low-profile and wearable energy harvesting devices and systems have many opportunities for use in consumer electronics, health care and IoT systems. In the case of consumer electronics, energy harvesting systems are commonly used in wearables such as fitness bands, smart watches and AR devices which makes it possible to extend battery life and minimal recharging intervals. In the area of healthcare, self-powered biosensors and wearable health monitors can track patient vital signs as long as necessary since the non-invasive devices do not depend on external power sources. For IoT applications, energy harvesting systems can provide power for sensor networks and other devices in remote locations where supply of conventional power sources can be very difficult, thus lowering the operational costs and increasing the lifetime of such devices. Nanotechnology appears as a significant contributor to the progress of technologies related to energy harvesting materials with specific electrical, mechanical, thermal or other required properties. Such nanostructured materials including nanowires, graphene and carbon nanotubes exhibit higher surface area, better electrical conductivity and greater flexibility than bulk materials. Such properties help nanomaterials to enhance the energy conversion mechanisms such as piezoelectric and triboelectric effects, but also help design lightweight, strong and resilient energy harvesters. For energy harvesting applications, nanostructured materials offer significant advantages over the conventional materials. The large surface area of their volume increases the amount of charge that can be generated/stored which increases the efficiency of the harvesting device. Besides, their power and ductility enable their application in energy harvesting systems for wearable technology as these are able to withstand mechanical stresses due to motion and cycle loading. They also enable the design of hybrid architectures integrating several energy harvesting mechanisms, constructing devices with enhanced performance and wider applications at the same time.[3] [4]

The purpose of this paper is to provide details on the role of nanoscale structures for the energy harvesters which are intended to be worn or flexed however remain flexible. The aim of this paper is to illustrate nanotechnology as a key component in the emergence of self-powered, wearable electronics through the analysis of developments in materials, device structures, and hybrid systems. Finally, the report will address the prospects and limitations in extending this work, particularly exploring how nanomaterials can provide a breakthrough in the development of self-contained, environmentally friendly power sources for wearables and IoT based systems.

Fundamentals of Energy Harvesting

The energy harvesting domain includes several techniques that employ different mechanisms to gather energy available in the environment and transform it into electric energy. The major application of this process relates to the harvesting of vibration or motion induced energy from the environment. This phenomenon is commonly referred to as piezoelectricity, where certain solids generate an electric charge due to mechanical stress applied to them. There has been recent interest in lead zirconate titanate (PZT) and barium titanate materials, along with polyvinylidene fluoride (PVDF), all of which have shown high piezoelectric responses. To enhance energy conversion efficiency and compatibility with flexible substrates necessary for wearable applications, recent researches focus on flexible nanocomposite/doped ceramics. Hybrid piezoelectric systems that use both piezoelectric and tribo electric systems are also being studied to maximize output in low-frequency active human movements.11

Triboelectric energy harvesting is based on the triboelectric effect in which charges are generated from contact and separation of two or more materials with dissimilar electron affinities. Such devices known as TENGs are particularly attracting attention because they are lightweight, have an adaptable structure and also show efficiency in low force environments, all attractive features for wearable technology. TENGs rely on abundant materials such as PDMS and PTFE because these materials can produce a large charge density due to contact electrification. Recent research has investigated surface treatment and nano-coating for the purpose of increasing the charge retention and durability of TENGs, making them useful for wearables.[5]

Thermoelectric energy harvesting utilizes the thermoelectric effect called the Seebeck Effect which generates voltage and current from a temperature differential across the material. This technique, however, is particularly useful in applications where thermal gradients can be expected like industrial processes or wearables that utilize body heat. Of note, progress has been made to enhance key thermoelectric materials such as bismuth telluride or tin selenide using nanostructuring techniques. Focus has shifted towards developing flexible thermoelectric generators that can be used on the cylindrical shape of the human body as well as increasing ZT values thermoelectric efficiency while retaining mechanical flexibility.14

Besides the above-mentioned mechanisms, electro-magnetic and photovoltaic PV energy harvesting can also be utilized, particularly for flexible devices. Due to their size, electromagnetic harvesters are not commonly utilized in wearables but are useful in applications involving rotary or reciprocating motion. Solar photovoltaic energy harvesting primarily using organic solar cells to harness energy can be embedded in wearables as these materials tend to be lightweight and flexible, benefiting from utilizing polymer substrates.

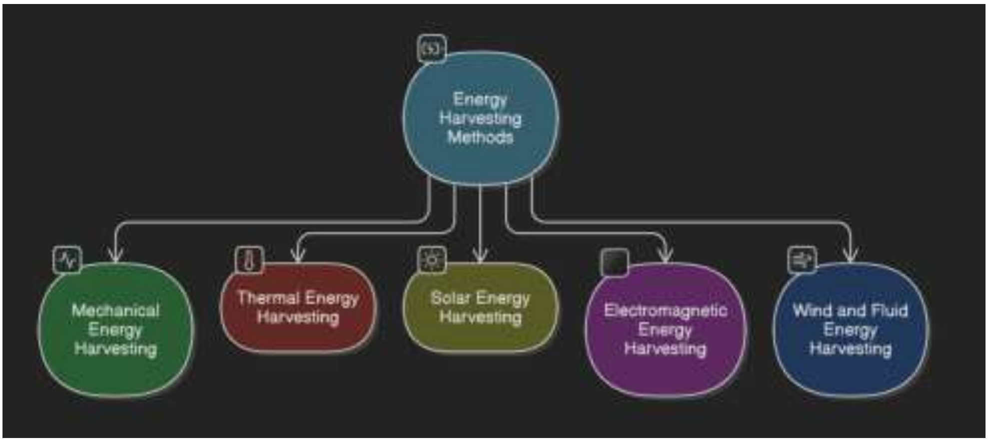

Figure 1 : Different energy harvesting methods

High-Efficiency Nanostructured Materials for Energy Harvesting

The emergence of nanomaterials with very high-efficiency materials may provide the critical advancement for the field of energy harvesting particularly in wearables and flexible applications where high power density and flexibility is a requirement that cannot be achieved with bulk materials. The incorporation of nanomaterials into energy harvesting devices has led to an enhanced efficiency and output due to the distinct structural, electrical and thermal properties of the materials. Current studies have recently set their sights on the composition, surface area, and architecture of nanostructured materials for optimum electricity generation through piezoelectric, triboelectric, thermoelectric and other means.16
In the last five years, piezoelectric nanomaterials have been highly sought due to their ability to produce electricity when subjected to mechanical stress, which is suitable for output from the human body wearables. It has been shown that environmental friendly lead-free materials such as barium titanate ($BaTiO_3$) as well as potassium sodium niobate (KNN) are good alternatives to lead based piezoelectric ceramics. Barium titanate ($BaTiO_3$) nanoparticles for instance are known to possess enhanced piezoelectric properties when doped with transition metals or when incorporated into polymer matrices to form nanocomposites with high energy output and flexibility. Polyvinylidene fluoride (PVDF) and poly(vinylidene fluoride-trifluoroethylene) (PVDF-TrFE) and their co-polymers have also been regarded as good candidates for piezoelectric materials. Furthermore, studies of piezoelectric nanowires, for example ZnO and GaN ones, have revealed that their morphology structure (one-dimensional) can be engineered to yield higher output. ZnO nanowires, especially those arranged into vertical arrays which improves contact area as well as piezoelectric response under compressive forces, have displayed remarkable performance.[6 7]
Triboelectric energy harvesting, which is based on contact electrification between two disparate materials, has seen a radical transformation with the introduction of nanostructures on its surface that enhance the contact area and hence generation of charge. Last developments in triboelectric nanomaterials concentrated on developing nanostructures that are conveniently incorporated in flexible substrates. Typical materials include polydimethylsiloxane (PDMS), poly(tetrafluoroethylene) (PTFE) and Kapton, which have high charge affinity. A number of researchers have attempted various surface treatments so as to enhance the triboelectric output of these materials. For example, utilizing exposure of surfaces materials to nanoscale structures, such as nanohole, nanopillar, or nanograss

structures, enhances the surface roughness and therefore, the contact and triboelectric performance. The combination of both nanostructured metals and polymers has shown enhanced charge separation properties. Incorporation of aluminium-coated PDMS films leads to enhanced triboelectric effect due to metal-polymer interaction and increased effective surface area.[8 9]

Thermoelectric nanomaterials are quite beneficial for converting harvested waste heat into electric energy especially in situations where such devices have a need for heat dissipation, for example in industrial applications or wearables. Materials with a great thermoelectric performance have a figure of merit (ZT) value that is greater than one, representing a balance between electrical conductivity, Seebeck coefficient and thermal conductivity of the material. The perforation at the nano scales has been a commonly used technique in the optimization of these parameters through the reduction of the thermal conductivity without affecting the electrical properties of the material. Thermoelectric materials with bismuth telluride (Bi_2Te_3) can operate efficiently in room-temperature applications and are the most popular materials. However, Bi_2Te_3 is usually rarely used in its bulk form because, at the nanoscale, these structures have a high ZT value due to the effects of phonon scattering on lattice thermal conductivity. Lead telluride (PbTe) and tin selenide (SnSe) have also displayed significant promise as potential nanomaterials for thermoelectric devices operating at elevated temperatures. SnSe has earned particular attention as it has set impressive high ZT peaks in nanostructured forms due to a low thermal conductivity alongside a high Seebeck coefficient.

Nanostructures offer the ability to directly design the features that are important for efficiency in enhancing energy harvesting. Nanomaterials have been adapted for use in energy harvesting through techniques such as doping, and compositional layering as well as surface patterning. For instance, ZnMgO nanowires can be doped with magnesium to improve their piezoelectric responses whereas triboelectric energy output can be increased by layering materials with complementary charge affinities. In addition to this, atomic layer deposition (ALD) and molecular beam epitaxy (MBE) enhance the surface properties that are the key determinations for energy harvesting performance.[10]

Adopting various nanomaterials into hybrid structures can exploit their properties in more than one way thereby improving energy harvesting capabilities. For instance, in hybrid piezoelectric-triboelectric devices two mechanisms are employed such that the energy conversion from mechanical motions is maximized. Carbon-based nanomaterials, especially graphene/ carbon nanotubes (CNTs) are usually part of the hybrids due to their conductivity and flexibility properties. Recently, it was reported that composites made from PVDF-TrFE and CNTs could serve as better candidates than conventional piezoelectrics in both mode of operation due to their flexibility; this makes them suitable for wearable applications.[11 12]

Surprisingly, surface modification has turned out to be a crucial tool for enhancing the efficiency of applications involving nanostructured materials. An example is the modification of surfaces of thermoelectric materials with organic molecules to enable charge transfer that is much more efficient than in the case of unmodified surfaces; in consequence, there would be more efficient conversion from any input energy into useful power. Furthermore, the addition of polar molecules on triboelectric materials through functionalization increases the charge carrier density and thus enhances the triboelectric effect. With higher performance combining durability and stability of nanomaterials at different environmental conditions, there is a better progress in the chemical functionalization. At present, PVDF based nanocomposite containing BaTiO3 nanoparticles has been developed achieving a notable improvement in piezoelectric coefficient than pure PVDF. Such composite has shown relatively high flexibility and strength, suitable for usage in low power wearable devices. Since BaTiO3 ions had the ability to improve energy generation, greater conversion efficiency was achieved toward flexible electrical usage. Enhancement in power output of TENGs has been witnessed in nanostructured PDMS-PTFE triboelectric due to the nanopatterned surfaces. When nanograss was placed on PDMS Surface, the area in contact increased thus improving the amount of charge separated in motion. The TENG system has been used to power tiny wearable sensors thus proving its practicality for self-powered wearable devices. Recently, tin selenide (SnSe) nanostructures have emerged as high benchmarks of thermoelectric efficiency surpassing a ZT of 2.8 at elevated temperatures. Researchers reported enhancement of the Seebeck coefficient whilst controlling the structure of the nanostructures to minimize thermal conductivity. This thermoelectric material with high conversion efficiency is suitable for use in wearable devices operating on body heat and in sectors where temperature differences are on in rapid motion.

Flexible and Wearable Energy Harvesting Devices

The increasing popularity of portable electronics has also increased interest in the development of flexible energy harvesting systems that can harness energy from sources such as motion, temperature differences, and triboelectric effects. Flexible and more so, wearable energy harvesting devices (EHDs) can present a better option to the norm of batteries due since it makes it possible for wearable devices to be self-powered and compatible with movement around the human body systems. This part provides an overview of the key trends in design, materials, and processes that were recently employed in EHD customization to increase their flexibility, effectiveness, and strength.29 In response to this need, the development of power density EHDs devices that can endure everyday usage A vicious circle of low durability and power density EHDs devices that incorporate native EHD materials.29 There are three major parameters that affect the design of wearable EHDs: the need to have enough power output, mechanical flexibility, and the ability to resist the wear strain. To increase the output power, attention of researchers was turned to the possibility of enlarging the effective surface area and manipulating the properties of the active materials at the nanoscale . In parallel, flexibility is enhanced by utilizing materials that are mechanically flexible like polymers and elastomers and combining them with nanomaterials such as silver nanowires and other carbon-based nanomaterials. In a recent advancement, however, the efficient piezoelectric nanocomposite was created by embedding barium titanate nanoparticles in a stretchable silicone matrix which greatly increased power output owing to the synergistic forces of elastic and piezoelectric. Waterproofing methods using biocompatible materials such as polydimethylsiloxane (PDMS) or ecoflex elastomers ensure the durability of such devices as they offer protection against environmental conditions. Repeated deformation introduces mechanical stresses that can be detrimental to the longevity of a device, especially the wearables. To mitigate this, stress is usually evenly distributed across the devices using parts made of conductive polymers, nanowires, graphene, and other two-dimensional (2D) materials that offer superior mechanical properties. For instance, a TENG recently incorporated graphene oxide nanoflakes with a PDMS matrix enabling the TENG to endure over 10,000 bending cycles without a loss of output.[3] [13]

Techniques such as microstructuring and patterning can also be used with the aim of reducing stress rather than strain concentration. Thin film materials are known to potentially crack when put under stretch, therefore, wrinkling and buckling strategies are utilized to induce extra stretchability. The proposed design which integrates “island-bridges” constructions with thin active materials allows to reduce the strain of the available energy harvesting materials or components while still in achieving the expected functionality. The use of nanomaterials in the fabrication of wearable devices has increased their scope in flexible energy harvesting due to improved conductivity, stretchability, and power density. These nanomaterials are integrated into fabrics, patches, and bands that make the devices wearable. Inkjet and screen printing and roll-to-roll coating have been used for nanomaterials deposition in flexible substrates for wearable devices. For instance inkjet printing of silver nanowires and carbon nanotubes have developed stretchable high-conductive circuits on fibrils and elastomers for flexible electrodes essential for TENGs and piezoelectric generators (PEGs). PENGs' electrospinning technique has been utilized in the production of nanofibers to elicit improvement of the mechanical properties and flexibility. A case in point is that PVDF nanofibers doped with CNTs have been electrospun, these led to a flexible PEG that achieved a favorable piezoelectric response even when bent. Other nanofabrication approaches such as atomic layer deposition (ALD) allow layer to layer materials to be evenly placed on top of each other to provide uniformity and control of atomic levels which is beneficial in improving thermoelectric and piezoelectric characteristics for ultrathin film applications. Direct integration of nanomaterials into textile has been focused on for wearable applications. TENGs supported by conductive fibers such as silver nanowires or carbon nanotubes can be built into fabrics and used as energy harvesters suitable for smart clothing. Advances include recent efforts to tackle this critical barrier through embedding graphene and copper nanowires into yarns to improve the electrical conductivity and endurance to stretching for these fabrics.[14]

In flexible patches, nanosphere structured PDMS based TENGs have been applied using skin patches for harvesting human motion energies. Most recently, a PDMS patch with nanostructured ZnO nanowires was demonstrated, which made it possible to harvest energy from both movement of the human body and the heat emitted by the human body, which was a demonstration of the flexibility of wearable TENGs. Among the wearable applications, triboelectric nanogenerators have gained much popularity owing to their lightweight structure and high versatility. The current trend aims to enhance the power density of TENGs through expanded use of material and increased surface area of TENGs. Among the outstanding advances in this area was the development of a PDMS based TENG with a micrograted substrate coated with MXene nanosheets which significantly increased output through enhanced charge density. Also recently, PTFE-based TENGs were introduced into flexible and breathable fabrics by layering nanofiber coated PTFE films onto conducting silver coated fabrics. The textile based TENG was able to generate energy from movements and walking of the arms and lower legs in order to run sensors and LEDs. Last year, the creation of multi-layered TENGs facilitated the generation of high output power because of the increase in the number of friction layers. Another study employed a three-layer TENG, PDMS/PVDF/polyurethane, and reported that higher power output performance was achieved due to frictional charge accumulation across the different triboelectric layers. This multi-layered TENG structure can be configured into clothes for harvesting energy from routine body motions. Flexible PEGs are an essential feature of wearable devices where repeated and small deformations such as those caused by walking or stretching can be exploited. Areas of research have sought eco-friendly, lead-free material options for use in PEGs such as potassium sodium niobate (KNN) and PVDF based composites.[15] [16]

PVDF with $BaTiO_3$ nanoparticles in a nanocomposite configuration has shown improvement in piezoelectric effect along with crosslinking enhancement as evidenced in recent filings. Coupled with flexible substrates, this composite had an impressive piezoelectric output even with moderate mechanical force and is conducive for small wearables. In another illustration, ZnO nanowires oriented on a stretchable backbone created a bio-mechanical PEG that can effectively extract energy from human breath. Flexible PEGs have also been integrated in insoles for energy absorption from contact with the ground, and recent trends have shown more success by using layered piezoelectric & conductive materials. One example showed insoles from a PVDF-ZnO nanocomposite. Hybrid devices are consisting of a mix of piezoelectric, triboelectric and thermoelectric energy generators and these devices have been making a lot of noise in the market due to their use for sutainable & reliable power generation for wearables devices. Hybrid systems tend to be more reliable than single mechanisms as they can draw on multiple available energy sources to power wearables. One promising example in the second half of 2021 is the work at University of Kisangani that created a car with a hybrid peg-teng which is the combination of a peg-teng and piezoelectric generation. This device was able to harvest sparks from weak human movements and as an added bonus the device also powered health monitoring and wireless transmission systems. Such sort of devices seem to be very useful indeed they could produce a constant stream of energy. There have also been some investigation into piezoelectric-thermoelectric hybrids. New developments in using nanostructured Bi2Te3 for thermoelectric and PVDF for piezoelectric generation. These devices were able to use the body heat and the movement of a body for producing a sufficient amount of energy to power small medical devices which required continuous power supply like heart rate and glucose monitors. The recent advancements in flexible and wearable energy harvesting devices reflect the growing importance of the wearable technology in personal electronics, health monitoring, and IoT applications. Advances in fabrication methods along with unique characteristics of nanomaterials has made it possible to develop devices with increased flexibility, mechanical strength, and power density. Looking ahead the research is expected to be directed at further enhancing the integration of energy storage, optimising hybrid components design and environmental stability which will lead to development of energy harvesting technologies which can be integrated into everyday tasks.[17]

Applications of Flexible and Wearable Energy Harvesting Technologies

Wearable products are getting smaller and lighter with the help of overcoming the limitations of flexible energy harvesting technologies. With these technologies, the wearable devices demand standalone power which includes energy generation from the motion of the human body. This section covers the recent changes that cut across various areas such as the use of nanoscale material and composite technologies as a means to provide power for wearable devices, medical sensors, smart textiles and fabrics. Additionally, it discusses the opportunities for market development as well as the obstacles that are present in the area. In conclusion there is a great demand for market tailoring and commercialization in this sector. The number of smartwatch users has increased multifold and the applications include regular wellness monitoring and augmented reality. The use of self charging wearables will reduce reliance on conventional batteries which can facilitate constant data acquisition for analysis. The application of energy harvesting technologies has greatly assisted the development of smart watches and fit bands as wearable devices. These devices have the potential to utilize piezoelectric, triboelectric and thermoelectric materials which in turn will facilitate power generation and self charging from the motion and body heat of the user. One such example is in the wristband space. Few researchers have created triboelectric nanogenerator (TENG) which is integrated with PTFE heating layer which converts hand motions into energy enough to drive a small LED light or small sensors such as accelerometers. Likewise, bismuth telluride (Bi_2Te_3) nanostructure based thermoelectric generators (TEG) have also been embedded into bracelets where sensors and screen's chips in smart watches use the temperature difference between wearer's skin and surrounding region. Energy harvesting is an important function in augmented reality glasses as visual and sensory functions are resource hungry. Integrating piezoelectric and triboelectric materials on the AR glasses' temples appears to be an effective design for generating power from head rotation and movements. TENGs coupled with lithium ion micro batteries are able to provide constant power to AR systems resulting in enhanced independence of operation of the devices.

In long-term observation of patients with devices like electrocardiograms (ECG) and electroencephalograms (EEG), there is need of constant and steady sources of energy. Materials like PVDF and ZnO nanowires have been utilized to make wearable TENGs and

PEGs that are able to harvest energy from minute movements of the skin and thus are able to make ECG and EEG sensors autonomous. An ECG patch made from PVDF nanofibers embedded into a flexible substrate that adheres to the skin was demonstrated in a recent investigation, which could record cardiac signals without the use of external batteries. This is the latest achievement in patient satisfaction and operating devices with autonomy.[18]

As a result of the incorporation of energy harvesting systems into the medical devices, battery dependence is reduced which increases the safety of patients and the devices last longer. This is especially important for devices that are implanted in the body because it is difficult and traumatizing to change the batteries or recharge them. Self-powering characteristic makes a great difference to devices like pacemakers, glucose monitors, and drug delivery systems. A construction of new biocompatible device based on PEG featuring energy harvester made of non-toxic KNN and polymer composites to generate energy from body motion is here in patenting. This system has enough energy to power on low energy pacemakers with less frequent battery replacement. To enhance self-powered technologies, wearable health monitors like heart rate, blood oxygen, and blood pressure monitors can be supplemented. A new hybrid device known as PEG-TENG has recently been created which is flexible and sticky. It has the ability to capture energy from skin deformation for providing power to blood pressure and heart rate monitors. This device embedded ZnO nanowires into a PDMS matrix which enables it to have high efficiency and durability even during motions on the human body. Long-distance patient monitoring relies heavily on energy harvesting. This involves the use of wearable patches with biosensors attached to them to detect biomarkers such as glucose, lactic acid, and hydration. The latest achievement used a TENG-TEG system that uses sweat to power a biosensor. It consisted of a TENG that was attached to a Bi_2Te_3-based TEG and used nanostructured carbon cloth as an electrode. This system makes use of body temperature and sweat movement to power glucose sensors which are important in managing diabetes in people that are far from hospitals. Moreover, Wearable EEG and EMG which are essential in checking muscle and nerve activity have been improved using flexible PVDF-TrFe and carbon nanotube composites to make PEGs. Such sensors provide real time data on muscle and neural activity and do not require an external power source which makes them useful for neurorehabilitation and controlling prosthesis devices. The approach of employing smart textiles and environmental monitoring devices is being transformed with the adoption of flexible energy harvesting devices. These applications demonstrate the potential and usefulness of nanostructured materials and energy harvesters in extracting energy from ambient sources, which makes them suitable for uninterrupted operation in various settings. Energy Harvesting Smart Textiles have been developed to harvest energy from the movement of the wearer, body heat and heat in the environment. For example, a recent work reported the combination of a multi-layered TENG structure with a piezoelectric PEG into a textile which is capable of harvesting motion and temperature. Enough energy was generated from the textile composed of silver diboride-coated fibers and PVDF-TrFE nanocomposites to power small light-emitting diodes and temperature sensors. Recently developed environmental monitoring systems need off-grid power supply especially in harsh outer environments. A good example is a hybrid TEG-TENG device located in external jackets where thermoelectric materials like Bi_2Te_3 are integrated together with micro patterned silicone-based TENG layers. This one captures temperature differences caused by sunlight and movements of the wind to power micro sensors for monitoring air pollution, UV levels, and environmental temperature. Smart fabrics are a new emerging area in which textiles are combined with energy harvesters and made into garments. The recent innovation includes pi cobbling piezoelectric yarns made of poly-L-lactic acid (PLLA) fibers and\ conductive graphene flakes into garments that can generate energy from human motion. Likewise, there was a nanotechnology based research that displayed a laminated structure of bendable fabric of PVDF and ZnO nanowires that could provide energy for low power electronics like a body worn pulse oximeter and body temperature indicators. These types of fabrics are very attractive for devices requiring constant health monitoring, in which sensors built into the garment can function gloom out assistance from an external power. In order to improve the life span and use of these methods, encapsulation techniques have been applied to prevent energy harvesting components from friction and environmental damage. The latest advancement in the production of fully waterproof and stretchable TENGs based on PDMS-coated conductive fabrics enhanced the prospects of development of smart fabrics that are able to generate energy in harsh conditions like rain, sweat or other temperature changes under TENGs. The market for flexible and wearable energy harvesting devices is substantial and it can be used in modern portable devices, health care technologies, or environment integrators. Several steps must, however, be taken in order for these technologies to become available. The market for wearable electronics is still on the increase fueled by the demand for smart watches, fitness trackers and health devices monitoring. This development is likely to boost the market penetration of flexible energy harvesters with promises of longer battery life and cleaner energy solutions. A recent report on the global market for wearable electronics forecasts that global revenues could exceed USD 80 billion by 2028 with a substantial chunk of investment on energy harvesting technologies. In the healthcare space, the demand for remote patient management systems is growing, where self-powered biosensors can add value by enhancing healthcare services and minimizing hospital visits. We can expect the use of wearable sensors for chronic diseases to grow, in which case energy harvesting technologies will be crucial for reliable and maintenance free devices.[19]

While promising, the deployment of flexible energy harvesters is faced with commercial challenges of efficiency, scale up and price affordability. A basic challenge is to generate sufficient power to run high consumption equipment, for instance, bio monitors and Augmented Reality displays. Energy harvesting systems as they stand may still be inadequate for such use cases which warrant enhancement in material efficiencies and novel hybrid systems. The other issue which is a major concern is scale up as a number of the low power energy harvesting components utilize nanomaterials and advanced methods of fabrication that are expensive and time consuming, This was recently addressed in a study where researchers aimed at using CNT composites and low temperature methods suitable for integration with roll to roll systems. Moreover, in the case of medical wearables, it is important to note also biocompatibility and environmental stability. Materials used in implantable or skin-contact devices should be safe, effective, and not biodegradable. However, integrating with energy storage devices such as flexible supercapacitors and microbatteries still requires enhancement. Energy harvesting devices such as thin film microbatteries may be of use in the future however these have challenges around weight and flexibility. New technologies for power storage, like flexible lithium-ion microbatteries, have just been developed, and they are suitable for TENG and PEG devices. Self-powered systems that enhance the longevity of electronic devices while reducing reliance on traditional batteries are now possible thanks to new energy harvesting technologies for portable electronics. The use of biomaterials has advanced energy harvesting applications in consumer electronics, medical devices, environmental monitoring, and smart textiles. However, applying the full potential of these devices in commercial markets need defeating substantial challenges, including power efficiency, biocompatibility, durability, and scalable manufacturing. As research continues, flexible energy harvesting systems are poised to play a transformative role in the growing fields of wearable electronics and autonomous medical devices, marking a significant advancement toward sustainable and self-powered technologies.[20]

Challenges and Future Perspectives

Enhancements of increasingly flexible and wearable energy harvesting devices are made but there still are several big challenges that discourage the mass integration and commercialization of these devices. These promises very large scale fabrication, effective lifetime, techno economic viability and ecological instability are main concerns. This section analyzes existing challenges and the scopes, with an emphasis on the scalability issues of nano-enabled materials, the lifetime of flexible devices, and the sustainable manufacture of cost-effective energy harvesting devices.[21]

The scalability of affordable energy collecting devices has to be thoroughly investigated which represents one of the major concerns. The energy conversion efficiency of nanostructured devices is improved but their costs and complexity of fabrication techniques greatly affect mass production. Existing strategies for the synthesis and integration of nanomaterials into energy harvesting devices are chemical vapour deposition, sol-gel processing and hydrothermal synthesis. But, alternate methods would however seem to prove useful as it is seen that these techniques have limitations in volumes as well as cost-effectiveness, making such methods less ideal for mass production. CVD is still the favored method to manufacture nanostructures for graphene and transition metal dichalcogenides (TMDs) which are used in energy harvesters. In a more recent study it has been established that MoS_2, a type of TMD, grown by chemical vapor deposition CVD has exceptional electrical conductivity and easy mechanical fabrication and thus can be applied in flexible thermoelectric devices. CVD processes on the other hand, require expensive environmental conditions needed for a successful synthesis and fabrication. A more common synthesis technique is the sol gel for metal oxide nanostructures such as ZnO and TiO_2 which are incorporated piezzoelectrically and photovoltaically. Because of the limits of a sol gel process, it is quite inexpensive and also helps control some aspects of the material properties but mass production while maintaining the same quality is the greater challenge.

Hydrothermal synthesis and electrospinning are a few of the techniques that have been used to fabricate nanowires and nanofibers targeting energy harvesting. The bottleneck remains the same, scalability issues, uniformity and high purity in large-scale production of nanostructured material has always been a target as well as a technical challenge. For example, producing loads of graphene or MoS_2 nanoparticles of a set number of layers without any defects is still a huge challenge. Roll to roll processing is one of the methods that have been set to circumvent most of these problems, particularly thin film ones used to target energy harvesting sectors. Still more work needs to be done to improve the methods and bring down the cost of production. In a recent breakthrough, scientists invented a technique that involves continuous printing of TENG devices on flexible substrates using conductive ink made of silver nanowires. This technique is promising but has inherent disadvantages such as instability of materials as well as the conductivity issue during extended use. One of the methods includes nano-patterning by laser ablating polymers which could be ideal for scale up but is rather expensive. It is however true that price remains a hurdle but without the aforementioned key materials which include Nanomaterials and their derivatives such as TMDs and carbon nanotubes it is rather impossible to make good energy conversion devices. Currently, the goal for researchers is to find cheaper materials, like organic nanomaterials and composite materials, which can perform as well as the expensive ones. For example, hybrid materials based on graphene and bio-derived polymers have become promising also in harvesting energy due to their reduced fabrication cost. They are also investigating the possibility of additive printing and 3D printing processes that may reduce material use and provide control of nanostructures. The reliability of the energy harvesting devices depends strongly on their stability and durability in real-life employments. For instance, flexible devices can be strained mechanically, heated/cool ed, or placed in particular environments which can lead the devices to be less effective and reliable with time. To achieve this kind of performance, physics and materials have to be robust enough to tolerate such impact without any significant performance degradation.

Bending, stretching, and twisting, mechanical strain serves as a limitation for flexible devices. It has been a common practice to make the inner core of piezoelectric energy harvesters out of materials like PVDF and ZnO, however such structures are very strain sensitive and microstructure may be damaged during endemic load. Lately, they have begun researching the potential of nano-patterning and encapsulation for improving tolerance to this strain. For example, stretchable TENGs with PDMS encapsulating layers have been able to withstand repeated bending without damage and thus are ideal for applications in wearable technology. The stability of flexible devices is also controlled by environmental conditions such as the ambient temperature, humidity and UV exposure. Moisture can inhibit the Molysulfide and polyvinylidene fluoride materials, temperature changes lead to heat expansion and contraction and this can lead to cracks or even delaminations. During these prior stages of the processes, protective coatings including though not limited to encapsulating layers of parylene or PDMS are used to insulate the devices from such external aggressions. Although these coatings protect but they also add weight and cost to the device. Another idea that is gaining traction is the use of self-healing materials which enable the device to be able to repair itself from minute structural damage increasing the longevity of this device.

As for the testing procedures for the flexible energy harvesters, these are still being formulated as the rigid devises test protocols do not cater for the stresses which the flexible devices experience. They are now in the process of determining the standardized tests that would depict performance under conditions of bending, stretching and twisting your standard application. For example, More recent investigations undertook the evaluation of TENG and PEG devices after 10,000 bending cycles and recorded the performance decline by as much as 20%, thus such materials should have improved endurance. Powerful computational modeling and simulation techniques are also being used to understand the failure mechanisms which in turn will inform better material development. Recently, more and more flexible and wearable energy harvesting devices are being introduced, which also affect the design solutions - eco-friendliness is taking the central stage. The presence of hazardous materials , energy demanding manufacturing processes and non-recyclable elements raises the eco-column of these technologies. To deal with such issues, researchers are investigating biologically compatible and environmentally acceptable substrates such as biodegradable polymers and cellulose. The recent studies showed the introduction of cellulose nanofibers to TENG devices which were flexible and eco-friendly owing to the fact they were biodegradable. Another example includes the development of PEGs using lead free KNN (potassium sodium niobate), thereby enhancing the environmental character of these devices which were previously based on lead. In the area of manufacturing, to cut back the carbon emissions of nanomaterials synthesizing, low-energy techniques like solution processing and low temperature annealing are under investigation. For instance, in the previous research, a solution-processed vertically-aligned ZnO nanowire TENG with good efficiency was accomplished without a sintering step at high temperature which economically consumes energy. Researchers aim at performing up-scaling of energy harvesting devices through the use of eco-friendly processes and materials without sacrificing performance.[22] [23]

The evaluation of priciest materials in relation to its return on investment considers the likelihood of commercializing this material on a larger scale. While cutting-edge materials like graphene and carbon nanotubes demonstrate wide energy conversion, their growth can be impeded by cost. Nanocomposites, conductive polymers, and even bio inspired materials have created new avenues for low cost devices. For instance, you could use polyaniline or PEDOT–a polymer that is conductive, for TENG or PEG applications, achieving moderate energy conversion while still substantially cutting on cost compared to graphene. It would be an understatement to say the developments we have witnessed in the past couple of years in nanotechnology have been exciting. The development curve appears to only be getting steeper with the recent discoveries which provide a fair shot towards increasing efficiency for energy harvesting devices. Bio-Inspired types, smart nanomaterials and two-dimensional materials are paving the way in the flexible and wearable energy harvesting technologies space. Graphene and other transition metal dichalcogenides which include molybdenum sulfide and tungsten disulfide, are regarded as nanotechnology owing to their amazing mechanical, thermal and electrical properties. These materials have shown great promise in energy harvesting applications, particularly for thermoelectric and triboelectric devices. For example, TENGs that were enhanced with graphene have also been reported to lead to better electrical output owing to the high surface area as well as its high conductivity. MoS_2 based thermoelectric generators have had their efficiencies improved through certain unique bandgap properties of the material.[24]

Natural materials most simply work. New energy harvesting structures are made by bio-inspiration with focus on accuracy and strength. For example, TENGs made of spider silk have shown remarkable deformation and recovery when subjected to oscillating strain. There is also a benefit in hybrid nanomaterials that have both organic and inorganic constituents. A recent case involves TENGS using cellulose nanofibers to enhance graphene, thus obtaining greater elasticity and joint energy output of both materials. Next-generation TENGs are smart nanomaterials that can self-repair and respond to environmental changes. Self-repairing polymers with microcapsules containing repairing elements can repair microcracks formed due to mechanical forces. For instance, a self-healing TENG based on urethane with PDMS microcapsules can restore almost 90 % of its functionality mechanically damaged. Also, it is possible to use adaptive nanosized materials in areas with varying temperatures or humidity since they respond to external stimuli. These materials enable devices to operate at relatively more effective states by changing their conductivity or flexibility depending on environmental factors. Hopefully, research on easily and cheaply manufactured energy harvesting technologies which are tunable and sturdy does not go in vain, for they certainly will push the boundaries in the technology space. Barring the manufacturing limits, new environmentally safe raw materials and advanced smart nanomaterials present great breadth for the flexible and wearable energy harvesting technologies to permeate vital facets of the market. Additionally, wearable technologies are becoming more important for sustainable devices of the future and this type of systems may be installed on the body, or even worn as a tattoo. Moreover, as research of bio-inspired, self-healing, and adaptive nanomaterials improves, the devices become more flexible, which further allows energy harvesters to become commercial, thus increasing life and performance of the devices significantly.[25]

Conclusion

Flexible and wearable energy harvesting technologies have recently become popular because they can power a wide range of applications without interruption. This article focused on the mechanostructured materials and devices that are valuable for piezoelectric, triboelectric and thermoelectric energy harvesting systems. New options for wearable electronics, medical devices, and consumer electronics have been created by the incorporation of nanomaterials into pliant substrates due to their better efficiency, flexibility, and longevity. The development and employment of nanostructured materials in energy harvesting technologies have greatly enhanced their performance. Notably, piezoelectric nanowires, particularly zinc oxide nanowires and polyvinylidene fluoride PVDF have been observed to exhibit higher energy conversion efficiency when ferroelectric polymers are used to coat flexible substrates. Likewise triboelectric Nags with materials like graphene and PTFE have shown promise for energy harvesting from human motion. BaTiO3 alloys and MoS2 have also increased the efficiency of thermoelectric materials which are applied onto the top of thermoelectric materials like BaTiO3 due to material development and nano engineering approaches. What can be noted from the latest work done is the fact that nanostructured materials should be preferred over traditional bulk materials owing to their superior performance in energy conversion, mechanical flexibility and efficient scaling.

The integration of nanomaterials in flexible devices not only improves their energy generation kinetics but also allows them to be incorporated in wearable devices smoothly. Nanostructured materials used in energy harvesting devices can be broadly classified into three categories: piezoelectric, triboelectric, and thermoelectric. Piezoelectric energy harvesting has advanced significantly in materials such as ZnO nanowires, PVDF nanofibers and $BaTiO_3$ nanoparticles which have proven better mechanotransduction efficiency. For Triboelectric Nanogenerators (TENGs), the likes of graphene, PTFE and nylon have been harnessed in a bid to fully exploit the triboelectric effect with graphene being hailed for its surface area and high conductivity. Thermoelectrics has also identified a number of materials such as Bi_2Te_3, Sb_2Te_3 and MoS_2 with MoS_2 appearing good due to enhancement of its Seebeck coefficient and certain thermoelectric characteristics at the nanoscale. The application of these materials is found in several fields such as in wearable sensors, medical monitoring devices, and even in smart textiles. For instance, TENGs are utilized to harness energy from the movement of the body while piezoelectric nanomaterials are used in sensors for health monitoring. Thermoelectric devices are gaining interest in the areas of wearable applications for harvesting heat from the body to operate small sensors or medical devices. Nanostructured materials have played a role in the increase in efficiency of energy harvesting systems. In piezoelectric devices, the incorporation of nanamaterials like ZnO and PVDF nanowires with a high surface to volume ratio enhances the charge confinement and increases the conversion of mechanical energy. With the case of TENGs, the enhancement of power that is produced as a result of mechanical movement is due to the increase in the contact area between materials brought about by the use of nanostructured materials. In thermoelectric devices, nanostructuring and the enhancement of the properties of the electron transport have resulted in decreased thermal conductivity which has resulted in higher emphasizes the thermoelectric figure of merit (ZT) which improved conversion efficiency.

Flexible devices, especially in energy harvesting technologies, hold great potential and can be anticipated as gaining traction in both consumer electronics and medical devices. On the flank of nanostructured materials further research as outlined is expected to enhance energy conversion efficiency, scalability, and durability features. For instance, the manufacturing, large area nanomaterials, roll-to-roll printing, and laser ablation are likely to improve the business potentials of these devices. Moreover, hybrid nanomaterials including piezoelectric and triboelectric materials integration could provide greater sustainability to energy harvesting systems. Within the next decade, we foresee a great deal of revolution in material science which will improve energy harvesting efficiency in energy harvesting systems considering the portability and durability. Today's research focuses on promising materials, such as 2D materials (graphene and MoS2 - TMDs), and organic polymers which are cost effective and have high focus processing ease. There are also other new processing methods that allow simple energy harvester designs with complex nanostructures to be mass produced. In brief, all these technological progress can lead to mass production of efficient and low-cost energy harvesting devices.

Flexible and wearable energy harvesting devices stand to benefit the most from applications in consumer electronics and medical sectors. Within those consumer electronics, such devices may be able to replace batteries or external power supplies for wearables such as smartwatches, fitness centers and augmented reality glasses. For medical devices, energy harvesting might be able to power implantable sensors (i.e. devices that are placed under the skin), ECGs and EEGs allowing remote monitoring to be self-sufficient. The combination of energy harvesting and wireless communication technologies could also enable fully self powered medical systems for remote monitoring of patients. To summarize, nano technologies have unlock new possibilities for developing flexible and wearable energy harvesting technologies but important barriers remain in terms of scalability, durability and cost. That said these devices once perfected could be among the most used devices in our everyday life as they are easier to fabricate and allow sustainable energy solutions for many applications.

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