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Green Frontiers

Emerging Technologies for a Sustainable Future

Editors

Dr. Tanay Pramanik

Dr. Sayantan Sil

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Preface

In an age marked by rapid scientific progress and increasing global challenges, the integration of knowledge across disciplines has become essential for meaningful innovation and sustainable development. *Green Frontiers: Emerging Technologies for a Sustainable Future* is conceived as a comprehensive academic work that brings together diverse fields of study to present a unified perspective on contemporary scientific and technological advancements. The book seeks to highlight how evolving knowledge systems can address pressing environmental concerns, enhance technological capabilities, and contribute to the betterment of society.

The primary purpose of this volume is to provide a balanced understanding of both foundational concepts and emerging trends across multiple domains. It explores critical issues such as environmental degradation, renewable energy development, advanced materials, and intelligent systems, emphasizing their interconnected nature.

The scope of the book is intentionally broad, encompassing insights from environmental science, physics, engineering, biotechnology, and applied sciences. It reflects the growing need to move beyond isolated disciplinary frameworks and adopt integrated perspectives that foster innovation.

This volume is designed to serve as a valuable resource for students, researchers, and professionals alike. Students will find it particularly useful in building conceptual clarity and gaining exposure to emerging areas of study.

The relevance of *Green Frontiers: Emerging Technologies for a Sustainable Future* lies in its focus on the dynamic relationship between scientific advancement and societal needs. As the world faces challenges such as climate change, resource scarcity, and technological disruption, there is an increasing demand for knowledge that is both comprehensive and applicable. It is hoped that this work will encourage critical thinking, inspire innovation, and enable readers to contribute effectively to a sustainable and technologically advanced future.

— Editorial Board

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Table of Contents

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"Innovation and sustainability are not opposites—they are partners in shaping the future."

— Paul Polman

Former CEO, Unilever; Sustainability Leader

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CHAPTER 2

PIEZOELECTRIC MATERIALS: THE FUTURE OF PORTABLE POWER

Roney Ghosh[1], Rajdeep Bhandari[1], Samik Sarkar[1], Sayan Roy[1], Chandan Adhikari[2], Sayantan Sil[1*], Tanay Pramanik[1*]

[1]Institute of Engineering and management, Kolkata (Newtown Sector), University of Engineering and Management, Kolkata, University Area, Action Area III, B/5, New Town, Kolkata 700160, India

[2]Institute of Engineering and management, Kolkata (Salt Lake Sector), University of Engineering and Management, Kolkata, University Area, Action Area III, B/5, New Town, Kolkata 700160, India

Abstract:

The conversion of waste energy into usable electrical energy is known as energy harvesters. There are many reasons why traditional energy resources are limiting compared to new technologies. This research focuses on making flexible piezoelectric materials through combinations of lead zirconate titanate (PZT) powder, polydimethylsiloxane (PDMS) synthetic silicone, multiwalled carbon, and various solvents including tetrahydrofuran (THF) and chloroform. Each type was subjected to a variety of conditions in order to evaluate its maximum output potential, expected lifetime, and durability. The primary goal was to develop a source of energy capable of supplying enough current (power) to allow the usage of mobile phones, wireless devices, and microelectromechanical systems (MEMS).

Keywords:

Piezo electric material, Energy harvesting, Lead zirconate titanate, Flexural discs, PZT

Introduction:

With the rapid advancements in microelectronics (specifically the semiconductor industry), the modern electronic device continues to decrease in size and increase in integration. As a result, there is also a significant reduction in power consumption as these devices become smaller, and more integrated. This creates a pressing need for compact, lightweight, and sustainable energy sources that can be used independently of

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traditional power supplies (i.e., home electricity grids or coin-cell batteries). As a result, the demand for new ways of producing power that can work in remote/mobile environments continues to grow, as do the methods for converting different types of ambient energy to usable electrical energy.

Researchers are investigating the methods used for converting various forms of energy into usable power. Some of the most popular methods of harvesting energy, or scavenging energy, are through the use of electromagnetic work, electrostatic work, and piezoelectric work. In the last decade, researchers have been developing their knowledge of how to capture human-based energy through physiological and physical movements, i.e., walking, breathing, and dissipating body heat; some research has shown that low-power electronic devices (e.g., portable computers, sensors) can operate using energy that results from biological processes.

The method of piezoelectric energy harvesting stands out amongst many choices as an increasingly viable option because of its high efficiency levels and adaptability. Piezoelectric materials are distinguished from others by their ability to transform mechanical deformation (or vibration) directly into electrical energy through what is referred to as the 'Piezoelectric Effect'. The potential generated by these materials is based on their internal crystalline structure which, when placed under stress and/or strain, has the ability to produce a voltage. Natural materials such as Quartz and Rochelle Salt naturally possess piezoelectric characteristics. However, manmade materials like Lead Zirconate Titanate (PZT) and Polyvinylidene Fluoride (PVDF) have been specially designed to maximize performance and provide more flexibility than natural materials.

Piezoelectric materials are versatile in their use as they demonstrate excellent electromechanical coupling efficiency, high-energy density and are mechanically robust. Their flexibility allows them to easily be integrated into many wearable electronics or compact devices without sacrificing functionality, or altering the design. For these reasons, piezoelectric materials are widely used in many types of technology from common items such as gas lighters and Ultrasonic Sensors, to the more advanced uses of Biomedical Implants, Autonomous Sensors and Guided Missile Systems.

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Continuous research in this area continues to further improve the composition of piezoelectric materials, the structural design of these materials, as well as the efficiency of converting mechanical energy into electrical energy to produce self-powered, maintenance-free electronic systems for the next wave of smart devices and Wearable Technology.

Review of literature:

The need for piezoelectric materials:

Piezoelectric materials have the potential to generate electricity in places where traditional energy resources are not available. For example, many Indian soldiers stationed in high elevation areas of Himachal Pradesh and Kashmir have little or no access to the type of electrical power we are accustomed to. These regions have very low pressure, sub-zero temperatures and lower amounts of oxygen than normal atmospheric conditions, which causes the temperature in winter to drop below -50 degrees Celsius. Soldiers in these extremely cold environments must wear clothing that keeps them protected from the elements, and sometimes they require supplemental oxygen tanks to breathe adequately.

As a result of the severity of the environment, soldiers may experience frostbite and snow blindness, along with fevers. Thus, a critical challenge is the need for a reliable, lightweight power source that would enable the soldier to charge a number of electronic devices commonly used for communication and other purposes. This could be accomplished through the development of a portable piezoelectric generator that captures the mechanical energy produced from the heel strikes of walking, and converts that mechanical energy into usable electrical energy that could power microelectronic devices. Of all types of human-generated energy, walking has been the focus of extensive study in the area of energy harvesting. Scientific studies indicate that a normal heel strike produces approximately 67 watts of mechanical energy and that there is the potential to convert an approximate 5 watts of this energy to electrical energy with the use of a well-designed piezoelectric transducer.

History of piezoelectric materials:

In 1995, piezoelectric powered materials were first studied as a means of utilizing the energy created by a person walking, by Antaki et al. Next, the MIT researchers led by Paradiso built a shoe that contained two types of piezoelectric material: polyvinylidene fluoride (PVDF) and lead zirconate titanate (PZT). The PVDF was placed in the insole of the shoe and the PZT was placed in the sole in a unimorph architecture. When someone walked in the shoe, the PVDF produced approximately 1mW of power and the PZT produced approximately 2mW. Together, they created enough power to drive an RF encoder to send location information to be used to track personnel.

While there were ongoing development and research on piezoelectric materials during that same time frame, there was also ongoing research with electroactive polymers (sometimes referred to as dielectric elastomers), which also provided energy conversion capabilities, similar to piezoelectric materials, however, through different mechanisms. An example of this is a shoe generator using electroactive polymers that produced 800 milliwatts of power output at a walking speed (two steps per second) with only 3 mm of heel compression. This device had an energy density of 0.4 J/g. Additionally, the UK Ministry of Defence created a prototype piezoelectric shoe generator that was tested and used on a 100-mile journey across the Namibian desert by British inventor Trevor Baylis, producing about 150 milliwatts of continuous power.

In 2010, researchers at McAlpine's lab discovered how to fabricate flexible nanogenerators. Their method included synthesizing PZT (lead-zirconate-titanate) nanofibers and assembling them onto silicon substrates to develop very flexible nanogenerators that are able to be used in medical devices, i.e. pacemakers and any other devices used to sustain life, since they can also be used in conjunction with implants. Furthermore, this method was the first to overcome the limitations of rigidity and fragility associated with conventional PZT sheets.

The result of the collaboration between Dr. Zhong Lin Wang from Georgia Institute of Technology and Korea Advanced Institute of Science and Technology is additional advancements in flexible nanogenerator technology. Dr. Wang's group was studying how the piezoelectric and semiconducting properties of zinc oxide (ZnO) work and was also producing several different nanostructures, such as ZnO nanowires and ZnO nanobelts. They were also performing in vivo test by implanting these nanowires into the lungs (diaphragm) and cardiopulmonary region (heart) of laboratory rats. The results showed that the nanowires produced 4 picoamperes at 2 millivolts for the diaphragm and 30 picoamperes at 3 millivolts for the heart.

Finally, Wang and his team recently published in Advanced Materials their fabricated device called a nanocomposite generator (NCG). The research team created the NCG using a straightforward and inexpensive fabrication method, consisting of multiple components including multiwalled carbon nanotubes, barium titanate nanoparticles and silicon. This fabrication method allows them to keep the costs of manufacturing low and produce generators over large areas without fluctuations in performance. Testing of the NCG showed that its output was 150 nanoamperes at 1.5 volts with foot compression and 4 nanoamperes at 150 millivolts with finger pressure. It was demonstrated that the NCG could charge a capacitor bank that was used to power an LED and achieve practical energy storage and utilization.

Development of piezoelectric materials:

Over the last several years, there have been advances in our knowledge of how to harness the energy of Piezoelectric Materials. Some of the most recent studies reveal that piezoelectric materials can be used to produce electricity. The research outlined in this paper used three types of piezoelectric materials; commercially available piezoelectric composite flexural discs, in-house fabricated piezocomposites (which are also known as piezoelectric composites), and piezoelectric rings. Each type of piezoelectric material utilized for the research provided a means of converting mechanical vibrations into electrical energy via a mechanical-to-electrical conversion mechanism. The two types of piezoelectric transducers (made from soft-grade SP-5H PZT) were specifically designed to be used in low-power applications such as (sensors and transducers). The discs (which were obtained from a common electronic buzzer) were assembled into stacks of four discs; two of the discs had a diameter of 3.2 cm and two had a diameter of 4.0 cm. All the discs were connected together (in an electrical parallel configuration), so that when vibration occurred on the discs, they could produce an electric current. The highest output current measured across a 100KΩ resistor was 380 µA; and the highest voltage measured across the 100KΩ resistor was approximately

20 V (prior to the resistive losses).

The materials used to produce a PZT-based composite were polydimethylsiloxane (PDMS), PZT-5H powder, multiwalled carbon nanotubes (MWCNTs), synthetic silicone rubber, and organic solvents including tetrahydrofuran (THF) and chloroform. Two forms of composite test specimens were made; the first was only PZT with PDMS added for binding, the second included MWCNTs as well as PDMS and PZT. The PZT-PDMS composites were first made by means of a shear mixing process where one gram of PZT powder was mixed with ten grams of PDMS at a speed of one hundred revolutions per minute (rpm). Then a curing agent was mixed into the composite at a 10-to-1 ratio, which resulted in a cured film after twenty-four hours which solidified into an elastomer/rubber-like material.

The particle size of PZT powder was then reduced using a planetary ball mill as follows: the PZT powder was combined with zirconia balls at a weight ratio of four to 1, and two to one, and diluted in propanol, then the mixture was kept in the mill for twenty-four hours. Results of particle size analyses from a BCDN-Z analyzer indicated that the diameter of the powder particles was reduced from three microns to one micron, but no further size reduction was accomplished.

The second composite formulation comprised fine PZT (1 µm: Particle size 1 micrometer.), multi-wall carbon nanotubes (MWCNTs) nor a polymeric solution (PDMS) combined together using different weight fractions (i.e., percentage by weight). The two composite samples had the following compositions: a) 09% PZT and 0.5% MWCNTs; b) 16% PZT, 1% MWCNTs. The PZT, MWCNTs, and PDMS were initially mixed with each other using a roller mill with a ZrO2 jar for about 24 hours, followed by manual mixing with a curing agent using a ratio of 10 parts of curing agent per 1 part of mixture, and then poured into a square Teflon container for curing at room temperature for 24 hours. Certain samples were subjected to heating treatment for research purposes to examine how processing affected the mechanical properties of the composite material. Subsequently, the elastomeric films with thicknesses between 1 and 2 mm were cut into squares measuring 1 inch (25 mm) per side. A layer of conductive silver paste was then applied to the surface of each square film to form an electrical external-facing electrode layer and cured at ambient temperature for 24 hrs. before they were tested.

Post-curing, the samples were treated via corona poling, utilizing the silver-plated face as a ground electrode for the poling setup, which held a constant 70°C while an applied electric field strength was maintained at an average value of 50-80 kV for 30 mins. During this period, the heating plate was turned off after 20 mins, with the electric field maintained through to the end of the procedure. The samples were subsequently allowed to cool, before the opposite face was silver-coated and cured for an additional 24 hours. Measurement of the piezoelectric constant using a Piezo test PM300 d33 meter showed no substantial increase in piezoelectricity. Electrical contacts were formed using copper tape (50 μm thick) applied to both sides. Results from subsequent evaluation using a digital storage oscilloscope indicated insignificant output signals. However, use of a digital multimeter yielded peaks of 0.3 V, confirming the presence of natural piezoelectric activity within the sample material.

Conclusion:

Composite piezoelectric materials have a potential use as an alternative energy source to power ultra-low power microelectronic devices. Previous studies on composite piezoelectric materials have looked at using piezoelectric components in shoes to generate electric energy for military personnel in extreme climates in order to supply energy to essential communication devices. Although our current experiments have not yet produced the results we desire, research is being conducted to increase the knowledge of piezoelectric materials and develop better fabrication techniques for flexible piezoelectric harvesters and their performance. Research is also underway to produce energy harvesters from flexural composite piezo discs that show much promise for small power generation applications.

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Emerging Technologies for a Sustainable Future

Dr. Tanay Pramanik

Dr. Tanay Pramanik is a Professor of Organic Chemistry with over 13 years of academic, research, and administrative experience at institutions such as the National University of Singapore, Lovely Professional University, and the University of Engineering and Management, Kolkata. A university silver medalist, he qualified CSIR-NET with SPM Fellowship nomination and secured top ranks in GATE and JAM. He earned his PhD from NUS and specializes in organic electronics, conjugated polymers, green synthesis, and sustainable water purification. He has over 55 SCI/Scopus publications, 20 patents, and several books and chapters. His work has received international recognition, including awards at the Geneva Inventions Exhibition. He has also held key leadership roles and contributed significantly to teaching, research mentoring, and academic development.

Dr. Sayantan Sil

Dr. Sayantan Sil is currently working as an Associate Professor in the department of Basic Science and Humanities at Institute of Engineering & Management, University of Engineering and Management, Kolkata 700160. He qualified UGC NET with Junior Research Fellowship (JRF) and Lectureship (LS) awarded by the University Grants Commission (UGC). He completed his Ph.D. in Materials Science from Jadavpur University (JU), Kolkata in 2020, with research in collaboration with Variable Energy Cyclotron Centre (VECC), Kolkata. He is the author and co-author with over 45 publications in peer reviewed high reputed international journals. His research interests focus on synthesis and defect analysis of semiconducting nanoparticles as well as their applications in photovoltaic. Dr. Sil actively serves as a reviewer for leading journals published by Springer Nature and Elsevier.

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editor@edulearninghub.com www.edulearninghub.com

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