DESIGN AND FABRICATION OF PDMS ZNO BASED PIEZOELECTRIC DEVICE

A project report
submitted in partial fulfilment of the requirements for the award of the degree of

Bachelor of Technology
in
Electronics and Communication

By

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CANDIDATE'S DECLARATION

I, Shivam, hereby certify that the work, which is being presented in the report, entitled "Design and fabrication of pdms - zno based piezoelectric device" , in partial fulfillment of the requirement for the award of the Degree of Bachelor of Technology and submitted to the institution is an authentic record of my own work carried out during the period Dec-2024 to May-*2025* under the supervision of Dr. Monoj Kumar Singha at the Department of Electronics and Communication, University of Allahabad. The matter presented in this report has not been submitted elsewhere for the award of any other degree or diploma from any Institutions.

I declare that I have cited the reference about the text(s) /figure(s) /table(s) /equation(s) from where they have been taken. I further declare that I have not willfully lifted up some other's work, para, text, data, results, etc. reported in the journals, books, magazines, reports, dissertations, theses, etc., or available at web-sites and included them in this report and cited as my own work.

Date:

Shivam

CERTIFICATE FROM THE SUPERVISOR

This is to certify that the Mr. Shivam has carried out this project entitled “Design and fabrication of pdms zno based piezoelectric device” under my supervision.

Date:

Dr. Monoj kumar singha
(Supervisor)

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ABSTRACT

This paper presents the design, fabrication, and performance evaluation of a flexible piezoelectric device based on a ZnO–PDMS nanocomposite. The device leverages the piezoelectric properties of zinc oxide (ZnO) and the mechanical flexibility of polydimethylsiloxane (PDMS) to convert mechanical deformations into usable electrical energy.

ZnO nanoparticles were synthesized via a chemical precipitation method and incorporated into a PDMS matrix prepared with a 10:1 ratio of elastomer base to curing agent. A uniform dispersion of 20 wt% ZnO was achieved through manual stirring, followed by spin coating and microwave-assisted curing at 90°C.

The resulting nanocomposite is soft, stretchable, and suitable for various wearable and energy-harvesting applications. To evaluate performance across different active areas, sensors were fabricated in three dimensions—3×3 cm^2, 5×5 cm^2, and 7×7 cm^2. The fabricated sensors exhibited excellent mechanical flexibility and durability under repeated mechanical stress. A maximum peak-to-peak voltage (Vpp) of 6–9 V was recorded from the 7×7 cm^2 sample under normal hand pressing conditions, whereas the smaller dimensions yielded proportionally lower outputs.

Compared to conventional rigid piezoelectric materials, the ZnO–PDMS composite offers enhanced flexibility, ease of fabrication, and cost-effectiveness. Furthermore, its compatibility with low-power IoT modules makes it a promising candidate for self-powered systems in health monitoring, biomechanics, and smart wearable applications such as smart footwear and muscle activity tracking.

Keywords:- Zinc Oxide (ZnO), PDMS, Piezoelectric Sensor, Flexible Electronics, Energy Harvesting, IoT.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Today, the demand for clean and renewable energy is greater than ever due to the rapid depletion of fossil fuels and the rise in carbon emissions [1]. To address these issues, researchers are exploring new ways to collect energy from the environment. One such method is the use of Piezoelectric Nanogenerators (PNGs), which can convert mechanical energy—such as walking, body movement, air flow, or sound—into electrical energy [2].

Piezoelectric materials are capable of generating an electrical charge in response to applied mechanical stress or pressure. When mechanical force is applied, the dipole moments within the crystal structure of the material align, leading to the generation of an electric field [3]. These materials include lead zirconate titanate (PZT), zinc oxide (ZnO), and polyvinylidene fluoride (PVDF), all of which can convert mechanical deformation directly into electrical energy [4]. However, among these, ZnO has attracted significant attention due to its low cost, ease of synthesis, biocompatibility, and eco-friendliness [5].

ZnO naturally forms a wurtzite crystal structure, which has a distorted tetrahedral geometry responsible for its strong piezoelectric behavior [6]. When ZnO is processed into nanostructures such as nanoparticles, nanorods, or nanowires, its surface area and piezoelectric efficiency improve considerably [7]. Studies have shown that ZnO-based piezoelectric devices have achieved significant increases in output voltage and energy harvesting performance in recent years [8].

While PZT exhibits excellent piezoelectric properties, it contains lead, making it toxic and difficult to handle or dispose of safely. Therefore, ZnO serves as a suitable lead-free alternative for piezoelectric applications, especially in biomedical and wearable electronics [5][6].

To enhance the flexibility and mechanical properties of piezoelectric devices, researchers have developed flexible piezoelectric composites by mixing piezoelectric fillers like ZnO with soft polymer matrices such as Polydimethylsiloxane (PDMS) [9]. PDMS is an inert non-toxic, flexible, and non-flammable silicone-based elastomer widely used in microfluidics, sensors, and biomedical devices [10].

Combining ZnO nanoparticles with PDMS results in a composite that can bend and stretch while still producing electrical signals when pressure is applied [11]. These composites can be integrated into portable or wearable energy-harvesting devices. When connected to an external circuit, the electric charges generated by mechanical movement are transferred, producing a continuous current flow to power small electronics like LEDs, sensors, and wireless modules [2][9].

In this project, PDMS–ZnO composite samples are fabricated to study their piezoelectric behavior. The focus is on investigating how the size, shape, and dispersion of ZnO nanoparticles affect the mechanical strength, flexibility, and piezoelectric output of the final material. The goal is to develop a low-cost, efficient, and environmentally friendly piezoelectric device suitable for energy harvesting in applications such as wearable electronics and biomedical sensors [11][12].

1.2 LITERATURE REVIEW

Many researchers have explored the use of piezoelectric materials for energy harvesting because of their ability to convert mechanical energy into electrical energy. Among them, Zinc Oxide (ZnO) has become a popular material due to its non-toxic nature, low cost, and ease of fabrication. It has a wurtzite crystal structure that allows strong piezoelectric effects when stress is applied [13].

Wang and Song (2006) were the first to demonstrate a ZnO nanowire-based nanogenerator, which produced electrical output from simple body movements and air flow [14]. Their work opened the door for using ZnO in flexible and wearable devices.

Later, researchers began mixing ZnO with flexible polymers like Polydimethylsiloxane (PDMS) to create composite piezoelectric materials. PDMS is stretchable, safe, and widely used in biomedical devices. These composites maintain good mechanical strength while still being soft and bendable.

Jugade and Kulkarni (2020) studied PDMS–ZnO composites for muscle activity sensing. They found that adding ZnO improved the piezoelectric response without making the material too stiff. Their device showed voltages up to a few volts during bending and pressing [15][16].

Another study by Kumar and Kim (2012) showed that ZnO nanostructures like nanorods and nanoparticles can increase the surface area, improving the electrical output of the composite. They also pointed out that ZnO can work in low-frequency and small-movement conditions, which makes it useful for real-life body movement harvesting .

Chang et al. (2010) developed a flexible nanogenerator using a ZnO-polymer composite, which successfully powered small electronics like LEDs. This showed the possibility of using such devices in self-powered systems [17][18].

In 2021, Yu and Tao reviewed various flexible piezoelectric materials and concluded that ZnO–PDMS is one of the best combinations for wearable and biomedical sensors due to its flexibility, stability, and good power output [19].

Most recently, researchers have focused on improving the output voltage and durability of the composites by optimizing ZnO particle size, distribution, and fabrication methods like spin coating, microwave curing, and multi-layer stacking [20].

These studies show that PDMS–ZnO composites are promising materials for energy harvesting, muscle monitoring, and wearable sensors. However, there is still room for improvement in terms of output efficiency, long-term durability, and large-scale fabrication. Our project aims to contribute to this field by designing an efficient ZnO–PDMS piezoelectric composite with better performance and low cost.

CHAPTER 2

DEVICE FABRICATION & WORKING MECHANISM

2.1. Working Principle

Piezoelectricity refers to the ability of certain materials to convert mechanical energy into electrical energy and vice versa. This phenomenon occurs when mechanical stress is applied to a piezoelectric material, leading to the generation of an electrical charge. The underlying principle is based on the behavior of the crystal lattice in the material.

1. Direct Piezoelectric Effect:
    a. When mechanical stress, such as pressure or tension, is applied to a piezoelectric material, it causes a shift in the positions of the material's internal electric charges.
    b. The shift in charge creates an electrical potential (voltage) on the surface of the material.
    c. The generated voltage is proportional to the amount of applied mechanical stress. For instance, if you press on a piezoelectric crystal, it produces a voltage proportional to the amount of pressure applied.
2. Converse Piezoelectric Effect:
    a. In contrast, the converse piezoelectric effect occurs when an external electric field is applied to the piezoelectric material.
    b. The applied electric field causes the internal charges within the material to move, resulting in deformation or a change in shape of the material.
    c. This deformation can lead to an expansion or contraction of the material depending on the direction of the applied electric field.

These two effects are utilized in various piezoelectric devices, enabling them to sense mechanical changes or produce mechanical work when an electrical charge is applied.

2.2. Piezo-electric materials

Some naturally piezoelectric occurring materials include Berlinite (structurally identical to quartz), cane sugar, quartz, Rochelle salt, topaz, tourmaline, and bone (dry bone exhibits some piezoelectric properties due to the apatite crystals, and the piezoelectric effect is generally thought to act as a biological force sensor).

An example of man-made piezoelectric materials includes barium titanate and lead zirconate titanate. These materials can generate an electric charge in response to applied mechanical stress. For weak electric fields, this effect can be approximated to be linear and the quantities are governed by the following constitutive equations:

$S = sE \cdot T + d\,t \cdot E$

$D = d \cdot T + \mathrm{T} \cdot E$

- S = Strain; T = Stress;
- D = charge-density displacement; E = Electric field;
- d = piezo-electric co-efficients; T = permittivity

We will be working with two such piezo-electric materials, namely PZT-5A (*Lead zirconate titanate*) and PVDF (Polyvinylidene fluoride)

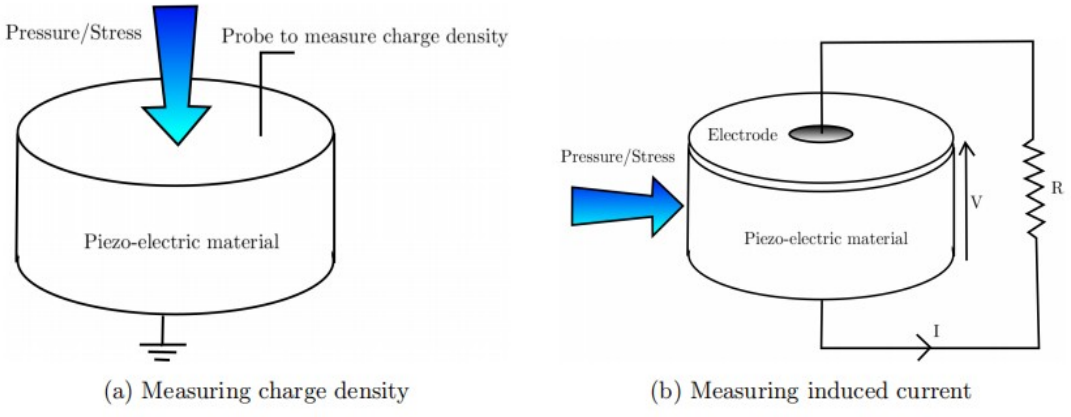


Fig 2.2.a - PiezoElectric Material Working Mechanism

2.3. Materials and Chemicals Required

To fabricate the ZnO–PDMS-based piezoelectric device, the following chemicals, materials, and equipment were used:

Chemicals:-

Zinc Acetate Dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$): Used as the precursor for synthesizing ZnO nanoparticles.

Potassium Hydroxide (KOH): Acts as a precipitating agent in ZnO synthesis.

Polydimethylsiloxane (PDMS): Used as a flexible polymer matrix for the composite.

PDMS Curing Agent: Mixed with PDMS in a 10:1 ratio to cure and solidify the composite.

Materials:-

Aluminium Foil: Used as electrode material and a base during curing.

Distilled Water and Ethanol: Used for washing and cleaning during ZnO synthesis and device fabrication.

Equipment:-

Digital Weighing Machine: For accurate measurement of chemicals and materials.

Magnetic Stirrer with Hot Plate: For uniform mixing of chemical solutions during ZnO synthesis.

Programmable Muffle Furnace: Used for calcining the ZnO nanoparticles at high temperatures.

Vacuum Desiccator: To remove moisture and store samples in a moisture-free environment.

Spin Coating Machine: Used for uniform spreading of PDMS–ZnO composite onto substrates.

Laboratory Oven: For drying and curing the fabricated layers.

Digital Storage Oscilloscope (DSO): For measuring the output voltage generated from the fabricated piezoelectric device.

2.4. Zno Synthesis -

Zinc oxide (ZnO) nanoparticles were synthesized using a chemical precipitation method. To begin, 4.39 grams of zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$) was accurately measured using a laboratory precision balance and dissolved in 100 mL of distilled water to prepare a 0.2 M solution. In a separate beaker, 2.24 grams of potassium hydroxide (KOH) was dissolved in 100 mL of distilled water to form a 0.4 M solution. The KOH solution was then added slowly, dropwise, into the zinc acetate solution under constant stirring using a magnetic stirrer. The mixture was stirred for 20–30 minutes at room temperature to allow complete reaction. After stirring, the solution was kept undisturbed for 24 hours, during which a white precipitate of zinc hydroxide ($Zn(OH)_2$) formed. The precipitate was then collected through filtration and washed multiple times with distilled water followed by ethanol to eliminate any residual impurities. The washed precipitate was dried in a laboratory oven at 80°C for 3 to 6 hours. Once dried, the solid was manually ground into a fine powder using a mortar and pestle. Finally, the powder was annealed at 500°C for 1 to 2 hours in a programmable muffle furnace to obtain crystalline ZnO nanoparticles. The resulting ZnO powder was then stored in clean, airtight containers for further use in the composite film fabrication process.

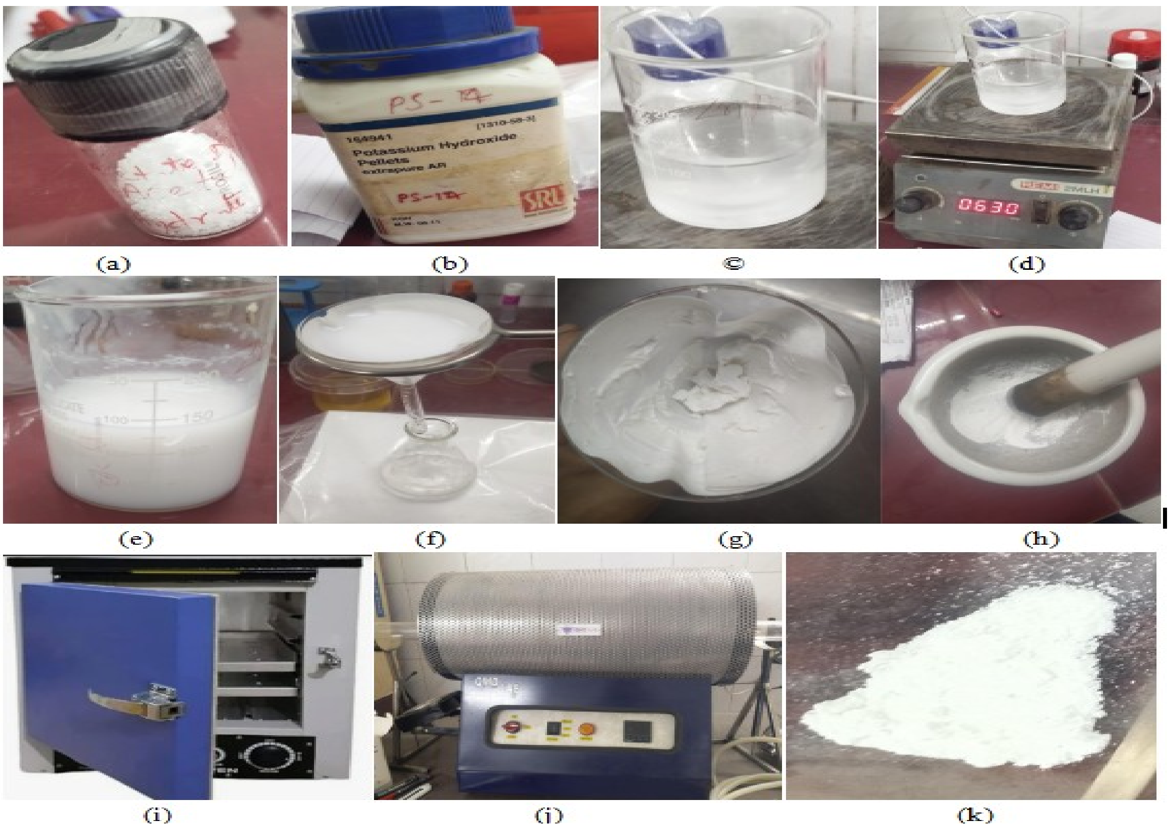


Fig 2.4.a - (a) Zinc Acetate (b) KoH (c) Solution of 0.4M KoH in100ml water (d) Magnetic stirring (e) Precipitate solution (f) Filter the Solution (g)Precipitate form (h) motar&Pastle (i)Oven (j) prog.Muffle Furnace (k) Zno forms

2.5. Composite Preparation

The fabrication process began with the preparation of both pristine PDMS and ZnO–PDMS composite films. For all samples, the polydimethylsiloxane (PDMS) elastomer base and curing agent were mixed thoroughly in a 10:1 weight ratio. For the composite film, 20 wt% of microcrystalline ZnO powder was added to the PDMS mixture. The mixture was stirred vigorously for 5–10 minutes using a glass rod to ensure uniform dispersion of ZnO particles and to minimize the formation of large agglomerates. Once the mixture appeared homogeneous, it was poured onto a clean, flat aluminum sheet or glass slide mold. To remove air bubbles introduced during mixing, the prepared mixture was placed in a vacuum desiccator and degassed for 10–40 minutes. For achieving uniform film thickness, the degassed paste was spin-coated on a glass slide at 1000 rpm for 1–2 minutes. Alternatively, the solution could be directly spread and flattened on the glass slide using a squeezing method. All samples, including the pure PDMS films, were then cured in a laboratory oven at 80°C for 30–40 minutes. After curing, the films were cooled to room temperature and gently peeled off from the substrate for further testing.

(a) (b) (c) (d)

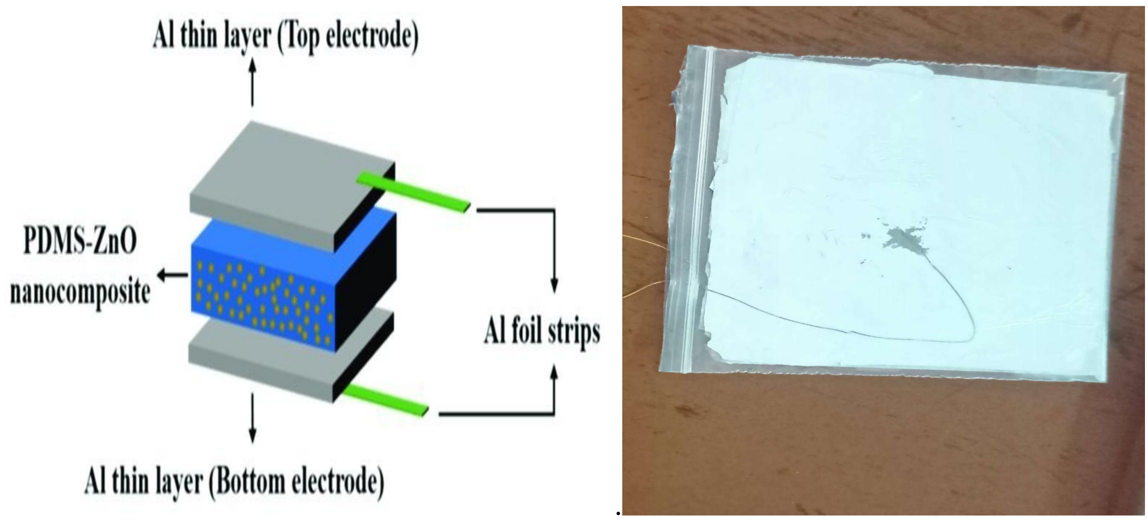
(e) (f) (g) (h)

Fig 2.5.a - (a) PDMS and Curing agent (b) Zno (c)weighing pdms and curing agent in 10:1 ratio (d) mixing solution (e)Add zno by 20% w/w (f) vaccum desiccator (g) spin coating (h) Poured solution On Al foil

2.6 Device Fabrication

After curing and peeling off the flexible PDMS–ZnO composite film (containing 20 wt% ZnO) from the substrate, the films were cut into three different square dimensions: 4×4 cm^2, 5×5 cm^2, and 6×6 cm^2, to study the effect of size on output performance. Each film was assembled into a sensor structure by placing it onto a sheet of aluminum foil, which served as the bottom electrode. Another layer of aluminum foil was applied on the top side of the film to act as the top electrode, ensuring good contact across the surface. Both aluminum electrodes were attached securely using conductive silver paste to ensure stable electrical contact. Copper wires were then soldered onto the aluminum electrodes to allow external electrical connections.

This sandwich-like structure, where the ZnO–PDMS composite film is placed between two aluminum electrodes, forms a flexible piezoelectric device capable of generating voltage under mechanical stress or tapping. The sensor was connected to a full-wave bridge rectifier to convert the alternating piezoelectric signals into direct current (DC), and a capacitor was used to store the rectified voltage. The device's electrical response to mechanical pressure was monitored using a Digital Storage Oscilloscope (DSO). Testing showed that all sensor sizes generated measurable voltage outputs, with larger dimensions generally producing higher voltages. The enhanced performance of the ZnO–PDMS composite sensors, compared to pristine PDMS, confirmed the effectiveness of 20 wt% ZnO for low-power sensing and energy harvesting applications.



(a) (b)

Fig 2.6.a - (a)Proposed Structure Of Zno-PDMS With Electrode (b) PiezoDevice after Spin coating process

CHAPTER 3

RESULT AND DISCUSSION

3.1 Physical Observation of Fabricated Sensors

Description of the appearance, flexibility, and thickness of the fabricated ZnO–PDMS films (20 wt%).. Differences in films of different sizes: 3×3 cm², 5×5 cm², and 7×7 cm².

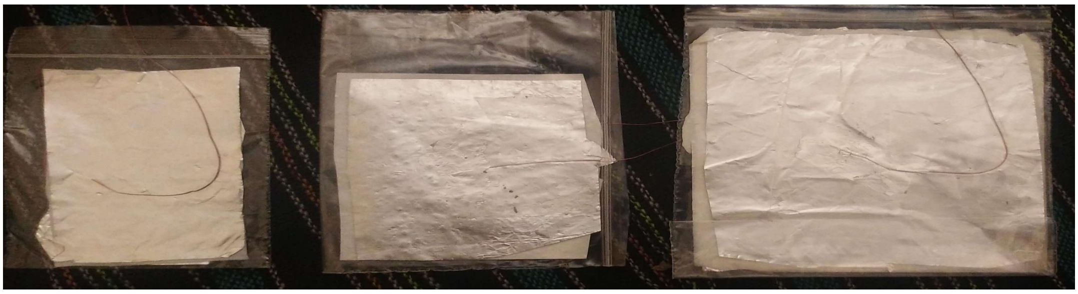


Fig 3.1.a - Different dimension Of PiezoSensor

Comparison of output voltages at different sensor sizes-

3×3 cm² → Voltage range ~1–2 V and 5×5 cm² → Voltage range ~3-4 V and 7×7 cm² → Voltage range ~6–9 V

The output voltage increases with sensor size because a larger area can absorb more mechanical energy and more ZnO particles contribute to the charge generation.A larger contact area leads to greater deformation and better dipole alignment, enhancing the piezoelectric effect.

Observation Method:

Output waveforms observed using a Digital Storage Oscilloscope (DSO).Waveform nature was sinusoidal or spiked depending on tapping frequency and force.

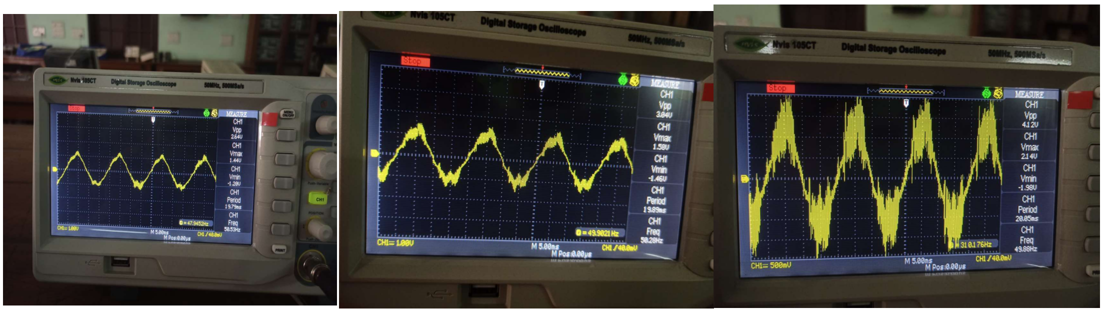


Fig 3.2.b - DSO waveform Vpp observed for different dimensions

3.2 Rectification and Capacitor Charging Circuit

To convert the AC signal from the sensor into usable DC voltage, a **full-wave bridge rectifier circuit** was implemented using four **1N4007 diodes**. A **capacitor** was added to smooth and store the voltage.

Circuit Description:

Input: Output from the sensor (AC)

Rectifier: Full-wave bridge (1N4007 ×4)

Output: DC across capacitors of varying values: 100 µF, 470 µF, 1000 µF

Working:

The rectifier converted the piezoelectric AC output to **pulsating DC**.

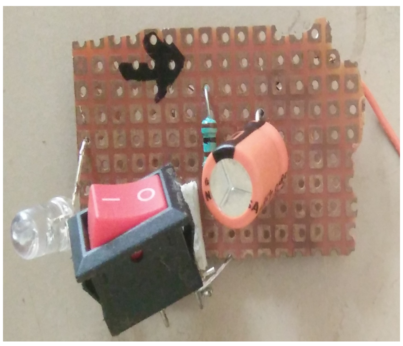
The capacitor acted as a **filter and storage unit**, charging up with repeated mechanical input.

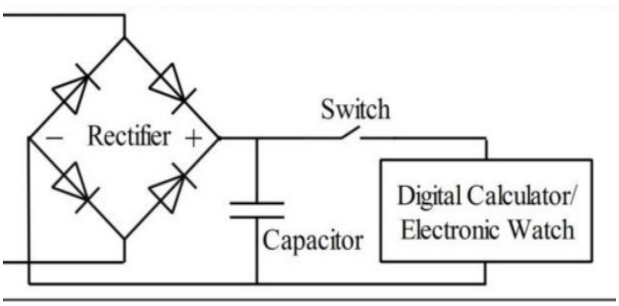
Observations:

The **capacitor voltage increased gradually** with repeated tapping.

Larger capacitors stored more energy but charged at a slower rate due to higher capacitance.

Example: A **470 µF capacitor** connected to a **7 × 7 cm²** sensor achieved approximately **4.5 V** after **10–15 seconds** of continuous tapping.





(a) (b)

Fig 3.2.a - Rectifier Circuit with capacitor for storing charge

3.3Pratical Application -

A. Muscle Activity Monitoring

The flexibility, biocompatibility, and sensitivity of the ZnO–PDMS composite films make them ideal candidates for wearable biomedical sensors, particularly for muscle activity monitoring. When attached to the skin over a muscle group (e.g., biceps or calf), the sensor can detect subtle mechanical deformations caused by muscle contractions.

Working Principle:

Muscle contraction creates a mechanical strain on the film.

This strain induces a piezoelectric response, generating an output voltage signal.

The voltage pattern can be correlated with the intensity and frequency of muscle movement, providing insights into muscular health and activity levels.

Uses -

Physiotherapy and Rehabilitation Monitoring

Wearable Fitness Trackers

Biomedical Diagnostics

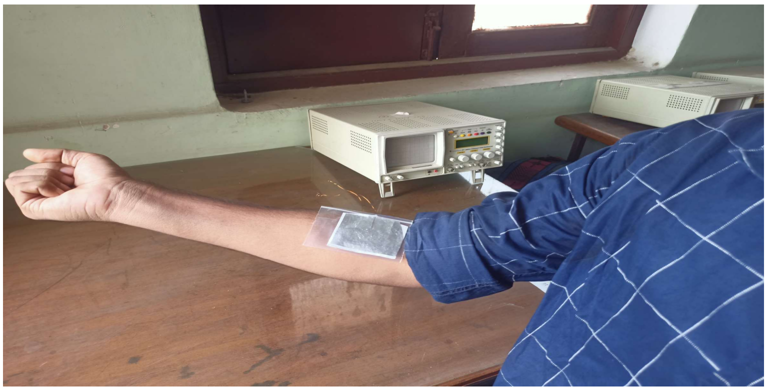


Fig 3.3.a Muscle Activity detection

B. Footstep Voltage Generation and Monitoring

ZnO–PDMS films were also tested for their ability to generate voltage under foot pressure, simulating a **self-powered footstep sensor**. When placed inside shoes or under floor mats, the sensor responds to the pressure of each step.

Working Principle:

Each footstep applies **mechanical force** on the sensor.

This generates a **voltage spike**, which can be captured and recorded.

Repeated steps result in a periodic signal that can be used for energy harvesting or movement tracking.

Applications

Energy harvesting floor tiles in smart buildings.

Gait analysis systems for medical diagnostics

Fig 3.3 b - Footstep voltage generation

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1. Conclusions

This project focused on combining triboelectric and piezoelectric effects for energy harvesting applications. In this work, a flexible and efficient hybrid energy harvesting device was developed by integrating both piezoelectric (ZnO–PDMS composite) and triboelectric mechanisms into a single platform. The synergistic operation of these two transduction methods enables enhanced energy output from a wide range of mechanical stimuli, including bending, pressing, and vibrations, which are commonly encountered in daily human motion.

The ZnO–PDMS piezoelectric layer, synthesized using a cost-effective and scalable method, provided reliable and stable electrical output under mechanical strain, while the triboelectric layer, fabricated using eco-friendly or recycled materials, contributed additional voltage through contact electrification and electrostatic induction. The resulting hybrid device exhibited improved voltage and current performance compared to individual mechanisms alone, demonstrating its potential for powering small electronics and sensors.

This hybrid approach offers a promising pathway toward self-powered wearable systems, biomechanical sensors, and green energy solutions. Its lightweight, flexible, and environmentally conscious design makes it particularly suitable for integration into health monitoring devices, smart textiles, and Internet of Things (IoT) platforms. Future work may involve optimizing the structural design, improving energy storage integration, and exploring the real-time application of the harvested energy in powering microelectronic systems.

4.2. Future Work

The results from this project open several avenues for further research and improvement in triboelectric and piezoelectric energy harvesting systems:

1. Material Optimization: Future work can explore advanced materials with improved triboelectric and piezoelectric properties, enhancing energy conversion efficiency and output.
2. Device Scaling: The scalability of hybrid devices for large-scale energy harvesting applications, such as wearable electronics or environmental monitoring, should be investigated.
3. Integration with Wireless Systems: Combining energy harvesting devices with wireless communication systems could create self-sustaining networks for Internet of Things (IoT) applications.
4. Real-World Testing: While simulations provide valuable insights, physical prototypes must be tested under real-world conditions to validate the performance and long-term reliability of the devices.
5. Multi-Effect Energy Harvesting: Exploring the potential of combining other energy harvesting mechanisms, like thermoelectric or electromagnetic effects, alongside triboelectric and piezoelectric systems.

By expanding on these areas, the efficiency and applicability of energy harvesting systems can be significantly improved, leading to more sustainable, self-powered technologies.

REFERENCES

1.Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. Renewable and Sustainable Energy Reviews, 15(3), 1513–1524. https://doi.org/10.1016/j.rser.2010.11.037

2.Wang, Z. L., & Song, J. (2006). Piezoelectric Nanogenerators Based on Zinc Oxide Nanowire Arrays. Science, 312(5771), 242–246. https://doi.org/10.1126/science.1124005

3.Safari, A., & Akdogan, E. K. (2008). Piezoelectric and Acoustic Materials for Transducer Applications. Springer.

4.Uchino, K. (1996). Piezoelectric Actuators and Ultrasonic Motors. Springer US.Jugade, S. S., & Kulkarni, S. M. (2020). PDMS–ZnO flexible piezoelectric composites for measurement of muscle activity. Materials Today: Proceedings, 28, 961–966. https://doi.org/10.1016/j.matpr.2019.12.271

5.Wang, Z. L. (2009). Zinc oxide nanostructures: growth, properties and applications. Journal of Physics: Condensed Matter, 16(25), R829–R858. https://doi.org/10.1088/0953-8984/16/25/R01

6.Wang, Z. L. (2004). Nanostructures of zinc oxide. Materials Today, 7(6), 26–33. https://doi.org/10.1016/S1369-7021(04)00286-X

7.Chang, C., Tran, V. H., Wang, J., Fuh, Y.-K., & Lin, L. (2010). Direct-Write Piezoelectric Polymeric Nanogenerator with High Energy Conversion Efficiency. Nano Letters, 10(2), 726–731. https://doi.org/10.1021/nl903377u

8.Kumar, B., & Kim, S.-W. (2012). Energy harvesting based on semiconducting piezoelectric ZnO nanostructures. Nano Energy, 1(3), 342–355. https://doi.org/10.1016/j.nanoen.2012.01.002

9.Mata, A., Fleischman, A. J., & Roy, S. (2005). Characterization of Polydimethylsiloxane (PDMS) Properties for Biomedical Micro/Nanosystems. Biomedical Microdevices, 7, 281–293. https://doi.org/10.1007/s10544-005-6070-2

10.Lee, M., Bae, J., Lee, J., Lee, C. S., Hong, S., Wang, Z. L., & Kim, S. (2011). Self-powered environmental sensor system driven by nanogenerators. Energy & Environmental Science, 4(8), 3359–3363. https://doi.org/10.1039/C1EE01204A

11.Yu, A., & Tao, T. (2021). A review on recent progress of flexible piezoelectric devices for energy harvesting and biomedical applications. Materials, 14(8), 1916. https://doi.org/10.3390/ma14081916

13.Wang, Z. L. (2009). *Zinc oxide nanostructures: growth, properties and applications*. Journal of Physics: Condensed Matter, 16(25), R829–R858.

14.Wang, Z. L., & Song, J. (2006). *Piezoelectric Nanogenerators Based on Zinc Oxide Nanowire Arrays*. Science, 312(5771), 242–246.

15.Mata, A., Fleischman, A. J., & Roy, S. (2005). *Characterization of PDMS Properties for Biomedical Applications*. Biomedical Microdevices, 7(4), 281–293.

16.Jugade, S. S., & Kulkarni, S. M. (2020). *PDMS–ZnO flexible piezoelectric composites for measurement of muscle activity*. Materials Today: Proceedings, 28, 961–966.

17.Kumar, B., & Kim, S.-W. (2012). *Energy harvesting based on semiconducting piezoelectric ZnO nanostructures*. Nano Energy, 1(3), 342–355.

18.Chang, C., Tran, V. H., Wang, J., Fuh, Y.-K., & Lin, L. (2010). *Direct-Write Piezoelectric Polymeric Nanogenerator with High Energy Conversion Efficiency*. Nano Letters, 10(2), 726–731.

19.Yu, A., & Tao, T. (2021). *A review on recent progress of flexible piezoelectric devices for energy harvesting and biomedical applications*. Materials, 14(8), 1916.

20.Lee, M., et al. (2011). *Self-powered environmental sensor system driven by nanogenerators*. Energy & Environmental Science, 4(8), 3359–3363.