A BRIEF NOTE ON PRINCIPLE, MECHANISM AND APPLICATIONS OF PIEZOELECTRIC MATERIALS

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Abstract

Smart materials have gained popularity during the past three decades. Piezoelectric materials have demonstrated essential properties for engineering uses, such as in industrial sensors and actuators. Today, piezoelectric materials serve as the foundation for a multi-billion-dollar global market and are essential to many applications and products that take advantage of this phenomenon. The brief review article will focus on the basic aspects of piezoelectricity and its applications in various fields. This will act as first-hand information for those who want to gain information on piezoelectricity and the new researches being carried out for the generation of green source of energy. This article also creates awareness among the readers for conjugate source of electricity which is the piezoelectricity. Knowing about the other sources of energy apart from the conventional sources of energy will also help us in creating a healthy world.

INTRODUCTION

The hunt for the green source of energy has come a long way, in this modern era there is a surge in the demand for electricity which can only be gratified by creating a source of energy that is elixir of life. With the evolution of time there are many sources of green energy that have come into force starting from wind energy, biomass, geothermal energy, solar energy and many more. A compelling name which is also the part of this list is "***Piezoelectricity"*** which simply portents generating electricity by applying pressure. Now the question arises applying pressure on what? And the answer to this question is applying pressure on ***piezoelectric materials***. Materials which engender electricity on applying pressure on them are known as piezoelectric materials. There is plentiful piezoelectric material, each having different properties and area of use. There are distinctive strategies for changing over mechanical vitality from vibrating or moving objects into the electrical vitality required by electronic gadgets, counting electromagnetic acceptance, electrostatic acceptance and piezoelectric impact.

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As compared to the other methods piezoelectric materials offer higher energy density and greater flexibility of integration into a system, and has therefore been most studied **[1]**. These materials have variety of applications which make them different from other materials. The practical application of piezoelectricity can have probably significant impact on the reduction of the cost of electricity consumption. Also, the reciprocal energy transformation features of piezoelectric materials enable them to function as sensor, actuators, or transducers.

The piezoelectric effect is a unique effect, which leads to the generation of electricity which is termed as piezoelectricity, due to the deformation caused by mechanical energy/force when acted upon it. The generation of piezoelectricity from mechanical energy is the resultant of its crystal structure deformation leading to development of a potential. This potential could provide a clean and green source of energy. This clean and green generation of electricity through phenomena known as piezoelectricity has motivated us to pen down this brief review article. Nonetheless, this phenomenon has attracted the attention of scientists as it can cater to the ever-growing demand of energy without affecting our atmosphere and environment. We have provided the basic principle by which the piezoelectric effect takes place.

The type of the crystals based on the effect is also discussed in detail. The applications mentioned in the manuscript are not exhaustive but can provide potential information on the most crucial aspects including the applications of piezoelectricity.

PRINCIPLE/METHODOLOGY OF PIEZOELECTRIC MATERIALS

As discussed earlier piezoelectric materials generate electricity when an external pressure is applied on them, but do all materials or crystals generate electricity on applying pressure? No, there is a certain class of crystals that show this unique property of piezoelectric effect. Crystal arrangement is described by their organized and imitating structure of atoms that are adhered together by bonds; this is called a unit cell. Crystals which are symmetric are of no use for piezoelectric purpose. So, the most important and essential condition for a crystal to be piezoelectric is that it should have a non centrosymertical arrangement. When some pressure is applied on such crystals their structure defaces and opposite charges appear on the surface of the crystal, which gives rise to the potential difference and hence electricity is generated on squeezing the crystal.

EVER GROWING DEMAND FOR CLEAN AND GREEN SOURCES OF ENERGY AND PIEZOELECTRICITY AS OPTION

The rapid rise in energy consumption has resulted in a greater reliance on fossil fuels resulting in an increased CO_2 emission each year. In order to solve this challenge, it is critical to transition from fossil fuel-based energy resources to renewable and sustainable energy resources. Over the time the replacement for fossil fuels have been developed which are solar energy, wind energy, biomass energy and many more. Apart from these sources of energy "piezoelectricity" is one such source which has emerged over the recent times **[2]**. Piezoelectricity is shown by piezoelectric materials, which are crystals with certain properties. Since the curie brothers discovered the phenomenon in 1880-1881, piezoelectric materials have been used in wide range of fields. In our day-to-day life processes which involve mechanical energy, a substantial quantity of this energy is lost in form of heat or kinetic energy and this remains neglected. So, to utilize this lost energy harvesting techniques using piezoelectric materials have shown a great success. This type of technology is already being used in highly developed countries. Apart from these piezoelectric materials also have other applications in many fields like medical, defence, industrial and many more. Also, the devices which use piezoelectric material are known to have high efficiency and greater life time. Many such applications of piezoelectric materials are listed further.

CLASSIFICATION OF PIEZOELECTRIC MATERIAL

The breed of piezoelectric material preferred for energy harvesting is very important as it influences harvester's performance and efficiency. Piezoelectric materials can mainly be classified into four main categories namely Single crystal (Rochelle salt, Lithium niobate, Quartz crystal), Ceramics (Barium titanate, Lead zirconate titanate, $KNbO_3$), Polymers (PLA, PVDF & Co- Polymers, Cellulose & derivates) and Polymer Composites (PVDF-ZnO, Cellulose- $BaTiO_3$ Polyamides-PZT). Among all these crystals **PZT** (Lead zirconate titanate) is widely used material for piezoelectric sensors and transducers due to its finest piezoelectric properties **[3]**.

CLASSIFICATION OF PIEZOELECTIRC DEVICES ON BASIS OF EFFECT SHOWN:

Generators, sensors, actuators, and transducer are the four broad kinds of piezoelectric devices, depending on the sort of physical effect used. Different types of fundamental functionalities exist for each of these basic devices. Now categorizing some devices based on the effect they show **[4]**.

- **DIRECT PIEZOELECTRIC EFFECT:** The direct piezoelectric effect is effect in which mechanical energy is converted into electrical energy. This effect is used in generators and sensors. This is measured as a charge or voltage signal between the two surfaces of the material.

  Sensors:Accelerometer and pressure/force sensor

  Generators: Energy harvesting and ignitors
- **INVERSE PIEZOELECTRIC EFFECT:** The inverse piezoelectric effect is in which the electrical energy is converted into mechanical energy. Actuators show inverse piezoelectric effect

  Actuators: Ultrasonic motors
- **BOTH EFFECTS:** Finally, both the effects which is direct and inverse piezoelectric effect are used in transducers.

  Transducer:Ultrasonic sonar devices

APPLICATIONS OF PIEZOELECTRIC MATERIALS:

Since the discovery of the piezoelectric effect which was in 1880-1881 by the Curie brothers have been used in variety of fields. Some of its applications are listed below.

1. **PIEZOELECTRIC IGNITORS:** The most basic application of piezoelectric material is a gas ignitor which is a widely used device in day-to-day life. Piezoelectric material is the heart of this type of ignitor. The piezoelectric material embedded in the ignitor produces an electric spark when a strong force is applied to it with a spring-loaded hammer. Although some gadgets employ wires to direct the spark to a specific spot, piezoelectricity does not require electrical connections. Piezoelectric devices have substantially longer lifespan. When struck by the little spring-loaded hammer, quarts is a tough substance that is barely damaged. Simultaneously this process generates enough energy to ignite a spark. Quarts may be struck thousand times

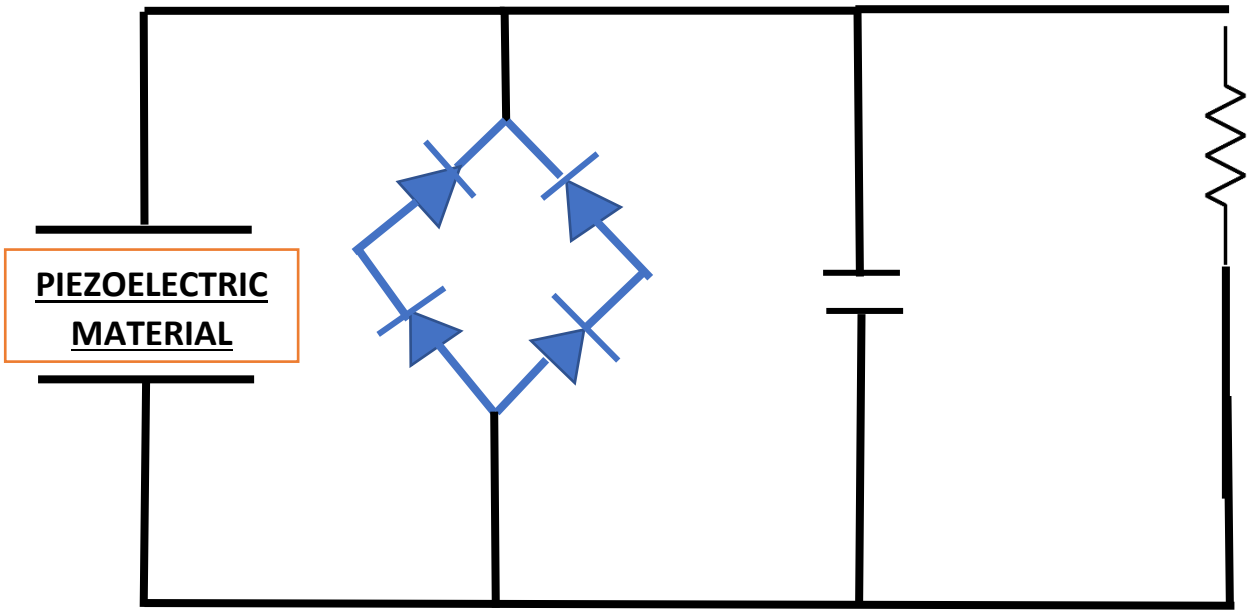
without displaying any signs of wear. These lighters are the most efficient and effective solution for frequent use. They will save money and time in the long term because they will consistently offer a steady spark. These lighters are perfect for variety of uses where a source of fire is required **[5]**.

2. ENERGY HARVESTING

2.1 ON ROADS: Energy harvesting is defined as conviction by which energy is seized, transformed, reserved and utilized using various sources, by making use of storage devices and other units **[6]**. Piezoelectric materials play a significant role because the pressure applied is directly proportional to the electrical energy generated. Using piezoelectric materials both vehicle pressure and vibrations generated on road pavement can be converted into electrical energy. Piezoelectric energy harvesting method has significant dominance over other sustainable energy sources.

Now to design a piezoelectric energy harvesting model we require an electrical circuit which is shown below.

Figure 01: Electric circuit with Piezo-electric material.



When a stress is applied on a piezoelectric material, this causes a mechanical strain to arise in the device which is transformed into electrical charge. PZT (Lead Zirconate titanate) is widely used piezoelectric material for generating power. The energy obtained from the piezoelectric material cannot directly be

used first it needs to be rectified so for that purpose we use full wave bridge rectifier in the circuit whose output is connect to a capacitor **[7]**.

Bridge rectifier is preferred here due its higher efficiency and lower peak inverse voltage as compared to full wave rectifier. Now since the street lights are required to work only during night so we need a device that stores the electrical energy. Also, the power generated determines the type of energy storage device to be used. There are mainly two types of energy storage devices which can be used for this purpose that are super-capacitor and rechargeable batteries. With the evolution in time, it was seen that super-capacitor is more reliable energy storage device as compared to the rechargeable batteries. The upper hand for using super-capacitors over batteries is that super-capacitor does not damage the diode, it has lesser charging time and it is less influenced by the temperature of environment.

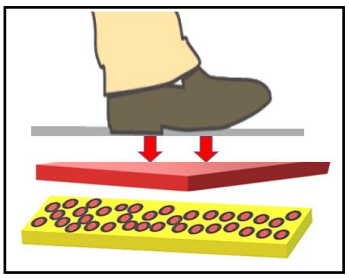
Many urban and rural square kilometers of road pavements are exposed to various sources of energy on a regular basis among which vibrational energy is something about which we are interested in, as this vibrational energy can be converted to electrical energy and then this electricity generated can be used to light up the street lights.

2.2 <u>BY WALKING</u>: Piezoelectric materials can be designed in many different ways that are very apt to be used for power harvesting applications. The design of the power harvesting device can be modified through alteration of piezoelectric materials, changing the electrode arrangement and by changing the direction of stress applied on the material. Energy harvesting has recently been recognized due to its ability to power portable electronic devices. There are many different kinds that appears around us but amongst all those motions walking is the primary and the most basic motion in normal human lives, so this vibration due to walking motion can be used as energy harvesting. As the human body is subjected to grievous acceleration and deceleration during walking, the inertial mechanism is most appropriate for energy harvesting. When researches were carried out about this mode of energy harvesting it was estimated that $1mW/cm^3$ power could be generated from human walking. For this purpose, piezoelectric tiles were made and then

energy was harvested from those tiles. To test the voltage produced using the piezo tile, people of different weights mainly in the range of 40 kg to 70kg were made to walk on those tiles **[8]**. When the relation between the weight of the person and power generated was seen the variation was a linear increase which simply implies that more is the weight of the person, larger is the voltage generated. Hence it was found out that a piezo-tile is capable of generating 40V. The basic circuit for energy harvesting is same the only difference is the type of material used and amount of pressure applied on the material.

2.3 FROM SHOES: Apart from the other two ways of energy harvesting using piezoelectric materials there is a newly emerging technology which is energy harvesting from piezoelectric shoes. There are recent researches being carried about the same which depicts the feasibility and practicality of the piezoelectric shoes **[9]**. Many ideas about the design and fabrication of such types of shoes has been presented till now and it is a topic of great interest. The basic electrical circuit for energy harvesting remains the same the only difference here is about the placement of piezoelectric material and about the utilization of energy obtained from the shoes. Due to the dynamic nature of piezoelectricity, the material should be placed where more changeable and higher pressure is exerted when walking, this is due to the fact that the amount energy extracted depends directly on the amount of pressure applied on the material. Now as the energy generated by shoes is a little less in amount so it can only be used on a small scale, for example I this case the energy generated can be utilized to charge the mobile phones and other small-scale activities which basically require less energy to function.

Figure 02: A shoe making stress through force, induces polarization, and charges thus gets rearranged to produce electric energy.



3. MEDICAL APPLICATIONS:

3.1 ULTRASOUND IMAGING: Ultrasonic is a cyclic sound pressure wave whose frequency exceeds the frequency of human hearing. Most signal generators emit signals in electric form because that is most convenient way to modify and produce the signal. So, a device such as piezoelectric crystal is necessary for converting electrical power into acoustic power **[10]**. Ultrasound transducer is a probe which is used in ultrasound imaging consists of piezoelectric material. Ultrasound waves are released rapidly from the transducer. These sound waves pass through tissues and fluids. A number of sound waves are reflected back onto the transducer. By investigating the reflected sound waves, the ultrasound machine creates a picture of the tissue. The piezoelectric material embedded in the ultrasound probe gives rise to the ultrasound waves. Large number of piezoelectric crystals are attached to the front of the probe. When electric current is applied to the probe the piezoelectric crystal inside it starts to vibrate and these vibrations give rise to the sound waves with the frequency range of 1.5 and 8 MHz Both direct and inverse piezoelectric effects are taking place in the transducer **[11]**. Ultrasound imaging is the most widely used procedure in the medical field as it is the safest procedure.

3.2 ULTRASONIC DENTAL SCALER: A piezoelectric dental scaler is device that breaks down the calculus and plaque formed on the tooth's enamel surface. Dental scanner has piezoelectric ceramic rings inside it for inducing axial vibrations, and it operates at ultrasound frequencies. They operate in the range of 25-50 kHz and oscillate parallel to the tooth's plane **[12]**.

3.3 BONE REPAIRING: Piezoelectric materials have been studied extensively for energy generation and harvesting, structural health monitoring and biomedical device applications. They also have ability to deform in response to physiological movements, delivering electrical stimulation to cells or injured tissue without requiring an external power source. Because bone is piezoelectric, the charges or potential it creates in response to mechanical action

have the potential to promote bone development. So, because of their ability to generate charges or potential in reaction to mechanical deformations, piezoelectric materials have shown significant promise for creating devices which are to be used for bone repairing. Hence piezoelectric materials play an important function in promoting regeneration and repair **[13]**.

4. E-TEXTILE APPLICATIONS

Electronic textiles (e-textiles), are the fabrics that accommodate electronic or computational devices. The primary challenge in electronic textiles is to seek out materials and devices that provide the specified functionality and that are often easily meshed into hybrid materials. Piezoelectric materials offer remarkable promise for e-textile applications by offering low power consumption. The differentiating property of piezoelectric material is their capability to produce a wide range of voltages, from tens of millivolts to many volts supported the sort and magnitude of the applied pressure. From the previous researches done, the technology of e-textile was used in designing a glove. The purpose of designing the glove was to detect and differentiate between tap and flex moments of the hands without effecting the flexibility of the glove, in short, the desire was to sense the movement of hands **[14]**.

5. PIEZOELECTRIC MATERIALS USED IN PRINTERS

5.1 DOT MATRIX PRINTER: In a piezoelectric dot matrix printer, piezoelectric actuators in the printer head move needle like spindles which poke across a band of ink ribbon against a sheet of paper with various motifs to form characters. A dot matrix printer is the only printing technology that can generate triplicate copies and carbon copies **[15]**.

5.2 INKJET PRINTER: There are two main ways of ejecting ink from a printer. The primary is thermal technology, which uses heating to warm the ink from bubbles that causes the ink to eject. The other is the modern-day technology that is the piezo technology, which applies a voltage to modify the shape of the piezoelectric element, the mechanical movement from which the ink ejects. Piezoelectric printing heads used in in jet printers are incredibly

durable as they are not exposed to heat-induces functional deterioration. These types of printers can use a good sort of inks, including dye and pigment inks **[16]**.

6. **PIEZOELECTRIC SPEAKER:** Piezoelectric speaker are speakers that uses piezo-electric effect to produce sound. By applying voltage to piezoelectric material, it generates initial mechanical motion. Later on, this motion is converted to an audible sound using resonators and diaphragms. These kinds of speaker are mainly used in digital quartz watches and other electronic devices. Piezoelectric speaker is more concerned with the amplitude and pitch of sound rather than the quality of sound **[17]**. Piezoelectric speakers create sound by the disturbance produced in the atoms which are present inside the material. An uncountable number of atoms and molecules surround us and they are in constant motion. These particles movie in straight lines until they collide with other atoms and their direction changes. When an electric field is applied across the piezoelectric material a potential difference is created at its ends, due to which the piezoelectric material inside the speaker starts to vibrate resulting in the collision of atoms inside it and hence generating a sound **[18]**.

7. PIEZOELECTRIC MATERIALS FOR OCEAN ENERGY

As we know that Piezoelectric materials directly convert strain energy into electric energy and the other way around so they are commonly used in sensing and actuating applications. There have been recent developments on the application of piezoelectric effect in ocean fields**[19]**. There are significant research projects on extracting ocean energy with the help of piezoelectric materials. Also, there are various harvesting techniques in an ocean environment**[20]**. Technology for extraction of energy from the ocean using piezoelectric materials is still on its ongoing stage.Of late, many ideas were proposed for the same which were based on very wide ranging and different concepts. There are mainly three sources of energy in the ocean from which energy can be extracted.The water current, wave motion and wave's impact forces on the material.For each of these sources there are different methods employed for energy extraction **[21]**.

8. PIEZOELECTRIC ULTRASONIC MOTORS

Inthe field of piezoelectric materials, the creation of ultrasonic motors is a highlight. Ultrasonic motors use the reverse piezoelectric effect of piezoelectric materials to transfer electrical energy into mechanical output.The piezoelectric effect is used in these motors in the ultrasonic frequency range, which is between 20 kHz and 10 MHz and is inaudible to humans. The most widely used material in these kinds of motors is PZT and quarts **[22]**. Ultrasonic waves are used to rotate a rotor in an ultrasonic motor. The piezoelectric material used in ultrasonic motors is used to generate ultrasonic waves, whereas conventional motors use permanent magnets or coils to move a rotor. The piezoelectric element swells and contracts in response to a difference in electrical potential between two terminals, and the ultrasonic waves are generated by this repeated swelling and contracting **[23]**.

9. PIEZOELECTRIC MICROPHONE

Microphones are device like phones and computers which are used on a daily basis, but they also have a variety of specialized applications including studio recording and laboratory testing**[24]**. The majority of these microphones use capacitive transduction to transform sound into an electrical signal. On the other hand, Piezoelectric transdution has certain advantages over capacitance transduction, including ease of manufacturing**[25]**. Certain crystalline material is used in the microphone which is the piezoelectric crystal, this crystal develops voltage when bent or distorted. This crystal used in microphones is cut and then positioned to provide the proper output voltage for the microphone **[26]**.

10. PIEZOELECTRIC MATERIAL FOR AIRCRAFT APPLICATIONS

The aerospace industry is evaluating structural health monitoring as a way to improve the safety and reliability of aircraft structures while also lowering operational costs. Sensor networks built inside aircraft structures can offer critical information about the structure's condition and damage state. Piezoelectric materials are commonly used among the numerous types of transducers. They are used in structural health monitoring because they can be used as actuators or sensors and vice versa due to their piezoelectric action. This technology not only intends to detect structural breakdowns but also provides an early warning of physical damage. In this

technology a sensor network is used, which is generally made of PZT, which plays an important role in performance of this system and a large PZT sensor network offers high reliability **[27].**

11. SONAR TECHNOLOGY

Sonar (sound navigation and ranging) is a technology that detects the location of objects in the ocean using acoustic waves. The simplest sonar devices emit a sound pulse from the transducer and then measure the time it takes for the sound pulses to return to the transducer. This time difference, along with the speed of sound in water, can be used to compute the distance to an object. Advanced sonar system can provide additional range and direction information. The transducer used in the sonar is made of a piezoelectric materials which are used due to their attractive properties.

Active and passive sonar are the two forms of sonar. Passive sonar is listening device that receives and converts sound waves from another source into electrical signals for display on monitor. On the other hand, active sonar, sends out sound waves in pulses, which scientist then use to measure the time it takes for these pulses to travel through the water which in turn reflect off the object and return to the ship. Both the sonars use piezoelectric material to generate the sound wave **[28]**.

12. PIEZOELECTRIC MATERIAL AND OPTICAL FIBRE SENSOR FOR ELECTRIC FIELD DETECTION

The use of fiber optic sensors to monitor strain, temperature and pressure has been studied extensively for many years. There has been significantly less research into using these sensors to measure electric and magnetic field. So, in the recent researches it was seen that piezoelectric material with fiber optic sensor can be used to detect the electric field. In this case piezoelectric materials are used as sensors which detect electric fields without the use of electrical contact.An attached fiber optic sensor detects material deformation in the presence of an electric field, allowing the magnitude of the applied field to be computed from the sensor output **[29]**.

13. ACCLEROMETER

An accelerometer is a technology that senses the vibration or acceleration of motion of a structure. The bulk constricted the piezoelectric materials as a result of which there is production of electrical charge which is proportional to the force exerted upon it **[30]**. These sensors are employed in a variety of applications, ranging from space stations to mobile devices. Vibration measurement is commonly used to diagnose the operation of high stress devices, equipment or structures such as steel structures, bridges or buildings. Accelerometers are also used in healthcare and athletic equipment, cameras and video recorders, telephones, remote controls, and mapping system among other applications **[31]**.

LATEST ADVANCEMENTS AND RESEARCHES

1.<u>PIEZOELECTRIC MATERIALS FOR SOFT ELECTRONICS:</u> Piezoelectric materials that are flexible and soft have important applications in developing industries like soft robots and wearable electronics. Piezoelectric elastomers are becoming more and more common, however the current approaches for their fabrication mostly involve mixing elastomers with piezoelectric ceramic or polymer fillers. There is essentially no mechanical flexibility in traditional piezoelectric ceramics like lead zirconate titanate and barium titanate. Traditional piezoelectric polymers, such polyvinylidendifluoride (PVDF), lack elasticity but are mechanically flexible. It is difficult to create organic materials that are naturally piezoelectric along with excellent mechanical elasticity. But in this research, it was concluded that Polyacrylonitrile (PAN), amorphous piezoelectric polymer possesses cyano (-CN) side groups on each of its repeating units, making it ideal for this use**[32]**.

2. <u>PIEZOELECTRIC MATERIALS FOR POSTPANDAMIC ERA:</u>The number of patients who urgently require the monitoring of biological data is growing considering the COVID-19 pandemic. So, with the recognition that wearable monitors are desirable, the transition from obedient medical care to health management and preventative medical care has become a significant challenge. To overcome this obstacle researchers have developed new ways for sensing the biological motion of human body using the piezoelectric materials. They focused on piezoelectric materials

and composites that produce electrical energy from kinetic energy to provide wearable monitoring devices that are self-powered**[33].**

3. PIEZOCATALYTIC INACTIVATION OF WATER BACTERIUM AND HETEROPHISM: In order to reduce the risks to humans, it is necessary to search for cutting-edge methods to combat new pollutants. This issue was resolved using piezoelectric materials, which also enabled a more sophisticated oxidation process. In the past few years, piezocatalysis, which may generate reactive oxygen species in reaction to applied stress, has made remarkable progress in the degradation of organic contaminants and pathogens. Numerous industrial applications already use piezoelectric materials. Utilizing it as catalysis has been successful in recent years. In recent researches, researchers concluded that piezo catalysis appears to be useful for removing water pollutants, such as organic debris and microorganisms, as it is an advanced oxidation approach**[34].**

4. PIEZOELECTRIC ENERGY HARVESTERS FOR BRADBAND FREQUENCY APPLICATIONS: At the natural frequency, conventional piezoelectric energy harvesters only display a sharp peak power i.e., they exhibit very small bandwidth. These harvesters have a low harvesting effectiveness for wideband natural frequency environmental vibrations. To increase the bandwidth of the natural frequency, three graded cantilevers with six masses are suggested in the recent experimentations. The unused ambient vibration is converted into electrical power by these piezoelectric harvester cantilevers, which power sensors and microprocessors. The results in this research paper are satisfying and the desired output i.e., increased output power is achieved **[35].**

CONCLUSION

We here have provided a brief review of the principle, mechanism and latest advancements in the field of piezoelectricity with emphasis on the applications of piezoelectric materials. The piezoelectric materials exhibit a very unique property that, the pressure applied on the material is directly proportional to the amount of energy obtained due to which its many applications come into existence. Being a green source of energy also adds on to the purpose of using piezoelectric materials. Apart from the fact that the greed for electricity is never ending and that too with a source which is eco-friendly is always in demand. So, piezoelectric

materials very aptly satisfy this need. Over the time everything requires modifications so using piezoelectric materials in the modern-day devices have led us to a healthy change. So, the applications of these materials now could be seen in variety of fields. In this review article, we have showcased the basis and fundamental characteristics of piezoelectric materials along with their classifications. In all, in this brief review article, we have provided a basic and useful information regarding the wide range of applications of piezoelectric materials, including its exceptionally beneficial role in medical physics. Hence piezoelectricity can be used to make a better tomorrow by creating a healthy environment. This brief review article may provide beneficial information to the scientific community in this regard.

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