Design and Analysis of ZnO Nanowires-Based Piezoelectric Accelerometer for Haptic Tactile Displays

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THESIS ACCEPTANCE CERTIFICATE

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DEDICATION

I dedicate my thesis to my beloved family, especially my parents and sisters for their unwavering support, encouragement, prayers, and belief in my abilities. Your love and guidance have been the foundation of my success.

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ABSTRACT

This thesis presents the proposed design and analysis of a Zinc Oxide (ZnO) nanowire-based accelerometer with a novel capability to measure acceleration in three directions. The piezoelectric properties of ZnO compose a self-powered acceleration sensing method by eliminating the power biasing requirement. The higher aspect ratio property of the ZnO-based accelerometer enables larger deformation and higher piezoelectric response output. A mathematical model is derived to analyze the ZnO nanowire fundamental properties for its use in accelerometer applications. The model and design of the tri-axis accelerometer are further validated by using the finite element method (FEM) based numerical simulations. The key parameters of the accelerometer such as mechanical deformation, frequency response for displacement and voltage, and sensitivity are evaluated while applying the dynamic acceleration of 0.1 g and the static acceleration up to 50 g. The simulation results show a sensitivity of 0.25 V/g for an applied acceleration in the x and y axes (Shear acceleration) and 1.40 V/g sensitivity is achieved in the z-axis (Normal acceleration). The effect of different parameters, including varying nanowire aspect ratio, and nanowire array sizes are also evaluated to optimize the accelerometer's performance. The tri-axis acceleration sensing and self-powered capability of the proposed accelerometer make it a good choice for tactile haptic displays in biomedical applications.

Keywords: Accelerometer, MEMS, Piezoelectric, Nanowires, Zinc Oxide, Tri-Axis, Self-Powered

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

MEMS	Micro Electromechanical Systems
NWs	Nanowires
ZnO	Zinc Oxide
$BaTiO_3$	Barium Titanate
GaN	Gallium Nitride
PVDF	Polyvinylidene fluoride
AlN	Aluminum Nitride
PZT	Lead Zirconate Titanate

CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

MEMS stands for Micro-Electro-Mechanical Systems. MEMS technology has had an impact everywhere in the past decade such as in medical instruments, haptics, cars, mobile phones, consumer electronics, and beyond [1-4]. It is a small machine that combines electrical and mechanical components on a single chip. These MEMS devices help the technology to work more efficiently and more precisely.

The most used MEMS device worldwide is the MEMS accelerometer [5-7]. Accelerometers are used to measure shocks, vibrations, or static and dynamic motion. The basic functionality of MEMS Accelerometers is to convert mechanical force into electrical signals through which the accurate vibration or motion and its orientation can be detected easily. Due to their versatility, MEMS accelerometers have become an integral part of modern technology, they have applications in automotive, aerospace, biomedical devices, and consumer electronics [1], [4], [8-9].

The performance of the accelerometer mainly depends on the transduction mechanism, which is used to convert the mechanical energy into electrical signals. There is various transduction mechanisms used to convert acceleration into an electrical signal. The Piezoelectric materials have gained more attention than other reported transduction mechanisms because they can generate charge when the sensor is subjected to force. Due to this characteristic of piezoelectric materials, they can detect low mechanical energy, and the response time of the piezoelectric devices is very high.

In recent years, the inclusion of nanotechnology into MEMS devices has further increased their performance. The nanowires have a one-dimensional nanostructure due to which they have a high surface-to-volume ratio, they offer significant advantages over bulk materials. Due to these advantages of nanowires, ZnO NWs have emerged as a promising material in the field of MEMS accelerometers, and they also offer exceptional piezoelectric properties. They have high piezoelectric constant and, they have excellent electromechanical coupling efficiency, which makes them ideal for use in converting mechanical energy into electrical signals. Additionally, ZnO is biocompatible, making it suitable for biomedical applications.

The motivation for this research is the growing demand for highly sensitive and highly accurate MEMS accelerometers, which can measure the acceleration in all axes. In the literature, mostly reported accelerometers are limited to measuring acceleration in one axis, which restricts their use in multiple applications like robotics, biomechanics, biomedical, and structural health monitoring. The capability of multi-axis accelerometers to measure acceleration in all three dimensions makes them a complete package that can measure and provide accurate representations of an object's motion and orientation.

Despite the technological advancements in MEMS accelerometers, there is still a need for devices that have the properties of high sensitivity, high accuracy, and reliability. The ZnO nanowires offer unique properties through which they can counter all these problems. Due to their integration into the MEMS accelerometers, an opportunity arises that can overcome the limitations of traditional accelerometers by providing high sensitivity and high accuracy.

The interdisciplinary nature of research and its integration into the various aspects of materials science, mechanical engineering, nanotechnology, and microfabrication, adds to the motivation. Understanding the piezoelectric properties of ZnO nanowires and their potential applications in MEMS accelerometers not only contributes to the advancement of MEMS technology but also opens new possibilities for the development of high-performance sensors in various domains.

The result of this research has an impact on a wide range of applications in industries such as consumer electronics, biomedicals, automotive, and many other industries [1], [4]. In consumer electronics, more sensitive and accurate accelerometers are required to enhance motion sensing in wearables and smartphones. In the biomedical field, accurate and sensitive accelerometers are important because of the requirements for precise monitoring of physical activities.

Overall, the motivation for this research is to increase and enhance the properties of MEMS accelerometers and also explore the unique and unutilized potential impact of ZnO nanowires in the next generation of devices that can meet our demands and needs in the future.

1.2 MEMS

MEMS is the technology that has transformed industries through the integration of micro-level sensors and actuators on a single chip. The miniaturization of components and their microfabrication techniques has enabled the concept of compact, high-performance, and cost-effective devices that can perform complex tasks. MEMS devices are characterized by their small size, low power consumption, and ability to operate in a wide range of environments. These devices are typically in a range of a few micrometers to several millimeters, which allows the device integration of devices into the various systems. Due to this miniaturization achieved through MEMS technology the footprint of the devices has been reduced as well as their power requirements are also reduced.

MEMS devices are found in a variety of applications, like consumer electronics, automotive safety systems, aerospace, and healthcare. They play an important part in the industry and serve as sensors such as accelerometers, gyroscopes, tactile sensors, force sensors, and pressure sensors [10-15] and as actuators such as micromirrors, microswitches, and micropumps [16-18]. MEMS sensors and actuators can monitor, control, and respond to changes happening in the system. Their small size and the ability to integrate multiple functions have made MEMS devices an essential component in the development of smart and interconnected systems, contributing to the growth of the Internet of Things (IoT) and other technological devices.

1.3 MEMS Accelerometers

MEMS accelerometers are one of the most critical and widely used sensors in MEMS devices. A MEMS accelerometer is used to measure acceleration which can be produced by shock, vibration, or motion and this acceleration can either be static or be dynamic. The MEMS accelerometers convert mechanical energy into electrical signals. They can enable the accurate measurement of motion, orientation, and impact, making them an integral part of a wide range of applications.

MEMS accelerometers are an integral part of consumer electronics as they are used in smartphones, tablets, and wearable devices [3], [19]. They enable features such as screen rotation, motion-based gaming, fitness tracking, and fall detection. They can also play an important role in the automotive industry by being used in airbag deployment systems and navigation systems. In aerospace, they can be used for vibration monitoring and navigation. They are also playing an important role in the biomedical field having used real-time feedback to the patients, monitoring physical activities, and healthcare providers [1], [20].

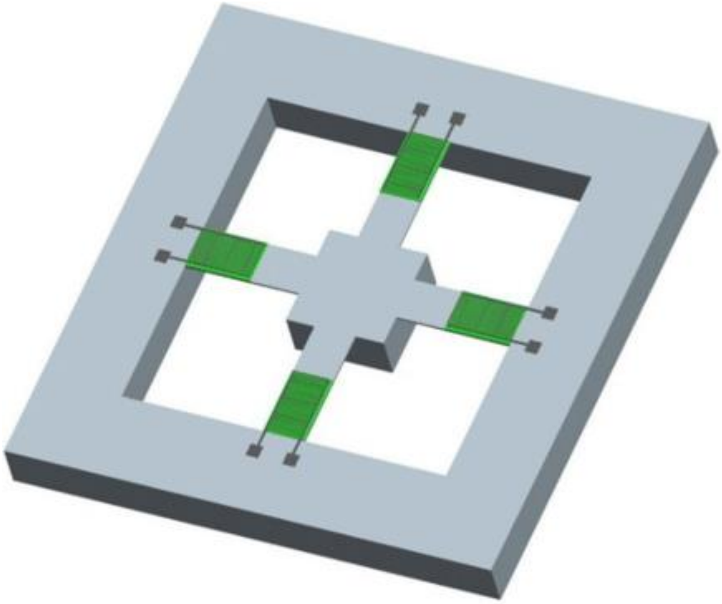

Fig. 1.1 MEMS Piezoelectric Accelerometer using PZT [7]

1.4 Transduction Mechanism in MEMS

The performance of the MEMS sensors is highly dependent on the transduction mechanisms. Various transduction mechanisms are reported in the literature i.e. capacitive, inductive, optical, magnetic, piezoresistive, and piezoelectric[5-7], [21-24]. Each transduction mechanism has some pros and cons. Capacitive sensors can measure changes in acceleration by the change in capacitance when the sensor changes some mechanical change in the environment. They offer high sensitivity and a large range, but their main issue is stray capacitance and complex read-out circuitry [5]. Inductive transduction mechanisms also offer some advantages, which is their high dynamic range, but they are very rarely used in industries because of their low-frequency response and low reliability. Like Inductive sensors, optical MEMS sensors are used very little. Although they have several advantages in that they offer good reliability and a wide sensing range, the main issue is that they are non-conformable and bulky in size [22]. Magnetic sensors sense the mechanical change in the form of a change in magnetic force. They are also used in MEMS industries because they offer several advantages i.e., they have a linear output and a high sensitivity. Contrary to that, the main issue that comes with their reliability is they are not reliable, and their frequency response is also poor. Piezoelectric transduction mechanism is widely used in MEMS industries, as they offer a change in resistance when there is any mechanical change detected in the environment. Like other transduction mechanisms, they also have some advantages and disadvantages. The piezoresistive sensors have a simple construction, low cost and have a spatial resolution. But the main issue in this type of transduction mechanism is that they consume high power and have hysteresis issues with them [23]. The piezoelectric transduction mechanism is one of the most popular transduction mechanisms used in MEMS sensors. Piezoelectric sensors are equipped with piezoelectric materials. The piezoelectric materials generate voltage when it is subjected to some mechanical stress or force. The generated voltage can be used to measure the physical quantity that is affecting the MEMS sensors. They offer high accuracy, high sensitivity, high frequency as well as high dynamic range. The only issue with them is the charge leakages. Due to these several advantages of the piezoelectric transduction mechanism, it is particularly effective in the use of sensing applications due to its direct conversion of mechanical energy into electrical signals.

1.5 Piezoelectric Mechanism and its Significance

The piezoelectric mechanism is a key focus of this thesis due to its unique ability to generate an electric charge in response to mechanical stress. The piezoelectric mechanism is ideal for accelerometers because of their high sensitivity, fast response time, and excellent working under conditions. Whenever a stress is applied it generates voltage and during dynamic acceleration it continuously generates voltage until the force is removed. The generated voltage is proportional to the applied mechanical stress, making it a precise vibration and motion-measuring sensor. They are particularly valuable in several environments where other transduction mechanisms may struggle, such as in high-temperature or high-pressure conditions.

Piezoelectric materials are used in both thin films and nanowires to measure acceleration. Piezoelectric thin films have some pros and cons. As they are versatile, they can be deposited on various substrates, they are easily scalable, and have a compact size. But the main issue with them is that they have limited mechanical durability, their performance is affected by temperature changes, and they have low piezoelectric coefficients compared to bulk materials. The other option is piezoelectric nanowires, as they also offer several unique advantages.

1.6 Nanowires in MEMS Devices

The primary focus of this thesis is on piezoelectric nanowires. The piezoelectric nanowires are used in MEMS sensors to sense the change the acceleration by generating voltage. Nanowires with their one-dimensional structure offer several advantages over traditional bulky materials. Due to their high surface-to-volume ratio, high piezoelectric coefficients, and unique electrical and mechanical properties, nanowires have the potential to improve the sensitivity, accuracy, and miniaturization of MEMS devices [25].

Nanowires can be fabricated from various materials such as PZT, AlN, $BaTiO_3$, GaN, PVDF, and ZnO [14], [26-31]. Each piezoelectric nanowire offers distinct properties and that can be useful for specific applications. In the context of MEMS accelerometers, nanowires provide enhanced piezoelectric response, making them ideal for sensing applications that require high precision. The lead-based piezoelectric accelerometer has a very high piezoelectric coefficient, but the main issue is that they are toxic to the environment and biomedical applications [32]. The other reported piezoelectric materials in the literature are bio-friendly but their piezoelectric constant is low. ZnO nanowires are biocompatible and have a high piezoelectric coefficient.

1.7 ZnO Nanowires

The focus of the thesis is on the ZnO nanowires piezoelectric accelerometers [14], [24], [33]. Due to their unique piezoelectric properties, they have emerged as a promising material for MEMS accelerometers. ZnO nanowires exhibit high piezoelectric coefficients and excellent electromechanical coupling efficiency, which are essential for converting mechanical energy into electrical signals with high fidelity. The one-dimensional structure of ZnO nanowires enhances their piezoelectric response, allowing for greater sensitivity and accuracy in sensing applications. Additionally, ZnO is biocompatible, making it suitable for biomedical applications where safe and reliable materials are required.

The ZnO nanowires can be fabricated very easily by using various methods, i.e. Chemical Vapor Deposition (CVD) and hydrothermal growth [31], [34]. By using these methods of fabrication, the dimensions and the properties of the nanowires are precisely controlled, which is very crucial in optimizing the properties of the accelerometer. The ability to tailor the properties of ZnO nanowires makes them a versatile material for a wide range of sensing applications.

1.8 Overview

The primary focus of the thesis is to design and analysis of a ZnO nanowires-based piezoelectric accelerometer having a capability of measuring acceleration in tri-axis. The novelty of this work lies in its ability to measure acceleration in three axes with high sensitivity and a wide range.

The research presented in this thesis involves extensive Finite Element Method (FEM) simulations to analyze the performance of the ZnO nanowire-based accelerometer under different conditions. Both static and dynamic accelerations are applied to assess the device's sensitivity and responsiveness. The study also explores the variation in sensitivity when acceleration is applied in-plane and out-of-plane, providing valuable insights into the device's behavior.

The following chapters will detail the literature review, design and working principle of the sensor, mathematical modeling, FEM simulation, results and discussions, and conclusions drawn from this study, highlighting the significance of ZnO nanowires in advancing MEMS accelerometer technology.

CHAPTER 2: LITERATURE REVIEW

The development of MEMS accelerometers has been a significant focus of research due to their wide applications in various fields such as consumer electronics, automotive systems, aerospace, and biomedical devices. Over the past few decades, efforts have been done to improve the performance, sensitivity, and reliability of these devices, particularly using advanced materials and nanotechnology.

2.1: Traditional MEMS Accelerometers and Piezoelectric Materials

MEMS accelerometers are devices that measure acceleration forces, which can be static or dynamic motion or vibrations. The basic working principle of these devices involves converting mechanical energy into electrical signals, which can then be measured and analyzed. Early MEMS accelerometers primarily relied on capacitive and piezoelectric transduction mechanisms. Capacitive accelerometers, while accurate and stable, often face challenges in miniaturization and sensitivity when compared to piezoelectric-based devices [35].

Due to their high sensitivity and fast response times, piezoelectric materials, which generate an electrical charge in response to mechanical stress, have been widely used in MEMS accelerometers. Traditional bulk piezoelectric materials, such as PZT, have been the choice for many years [26]. However, these materials have limitations regarding their size, weight, and the complexity of integrating them into MEMS structures. This has led researchers to explore alternative piezoelectric materials that can perform better in miniaturized devices.

2.2: Advances in Nanotechnology and the Rise of Nanowires

The advent of nanotechnology has revolutionized MEMS devices, enabling the fabrication of structures at the nanoscale, which has led to significant improvements in performance. Among the various nanomaterials explored, nanowires have attracted considerable attention due to their unique one-dimensional structure. The high surface-to-volume ratio of nanowires results in enhanced mechanical and electrical properties, making them highly efficient in converting mechanical energy into electrical signals.

Nanowires possess several advantages over traditional bulk materials. Their small size allows for greater flexibility in device design, while their high surface area improves interaction with external forces, thereby increasing sensitivity. Among the various types of nanowires studied, Zinc Oxide (ZnO) nanowires have emerged as a particularly promising candidate for MEMS accelerometers. ZnO is a wide-bandgap semiconductor with strong piezoelectric properties, making it suitable for sensing applications where high sensitivity is essential [36].

Research has demonstrated that ZnO nanowires exhibit superior piezoelectric coefficients compared to bulk materials. The experiments on the piezoelectric properties of ZnO nanowires and found that their one-dimensional structure enables them to generate stronger electrical signals under mechanical stress [37]. This characteristic makes ZnO nanowires an attractive option for MEMS devices, particularly in applications that require precise motion detection, such as in aerospace, robotics, and biomedical devices [1], [38-39].

2.3: Zinc Oxide (ZnO) Nanowires in MEMS Accelerometers

The application of ZnO nanowires in MEMS accelerometers has gained significant traction in recent years, owing to their exceptional piezoelectric properties and compatibility with microfabrication processes. ZnO nanowires have been shown to enhance the performance of MEMS accelerometers by providing higher sensitivity, improved response times, and greater accuracy in detecting acceleration forces.

One of the key advantages of ZnO nanowires is their ability to generate a substantial electrical response to even small mechanical deformations. This is particularly important in applications where detecting minute changes in motion is critical. For instance, [Author5, Year] explored the use of ZnO nanowires in MEMS accelerometers designed for inertial navigation systems. The study demonstrated that the ZnO nanowire-based accelerometer exhibited higher sensitivity and lower noise levels compared to traditional accelerometers, making it ideal for applications requiring precise motion tracking.

Additionally, ZnO nanowires are biocompatible, which has led to their adoption in biomedical devices. The biocompatibility of ZnO makes it suitable for wearable health monitoring systems, where sensors must be in close contact with the human body for extended periods. Ghazali et al. investigated the integration of ZnO nanowires into MEMS accelerometers for wearable devices, finding that their high sensitivity and biocompatibility made them ideal for tracking physical activity, monitoring vital signs, and detecting falls in elderly individuals [20].

2.4: Fabrication Techniques for ZnO Nanowires

The successful integration of ZnO nanowires into MEMS accelerometers requires precise fabrication techniques that ensure the nanowires possess the desired dimensions, alignment, and material properties. Over the years, various fabrication methods have been developed to produce high-quality ZnO nanowires for MEMS applications.

Hydrothermal growth is one of the most widely used techniques for fabricating ZnO nanowires. This method involves the chemical reaction of zinc salts in an aqueous solution at elevated temperatures, leading to the growth of ZnO nanowires on a substrate. Hydrothermal growth is favored for its simplicity, low cost, and ability to produce nanowires with uniform dimensions. A hydrothermal growth process that produced ZnO nanowires with precise control over their diameter and length, which is crucial for achieving consistent performance in MEMS accelerometers [31].

Another popular method for fabricating ZnO nanowires is vapor-phase deposition, which involves the condensation of vaporized zinc and oxygen precursors onto a substrate to form nanowires. Vapor-phase deposition offers advantages in terms of producing nanowires with high crystallinity and fewer defects, which can enhance the performance of MEMS devices [34].

In addition to these methods, researchers have explored other techniques, such as electrochemical deposition and template-assisted growth, to produce ZnO nanowires with tailored properties. The choice of fabrication technique depends on factors such as the desired nanowire characteristics, the intended application, and the compatibility with existing MEMS fabrication processes.

2.5: Challenges and Future Directions

Despite the promising results, there are still challenges associated with the use of ZnO nanowires in MEMS accelerometers. Issues such as long-term stability, scalability of fabrication methods, and integration with existing technologies need to be addressed. Future research should also focus on improving the scalability of ZnO nanowire fabrication techniques to enable mass production of MEMS accelerometers for commercial applications. Additionally, exploring hybrid materials that combine ZnO nanowires with other nanostructures could lead to further improvements in performance.

CHAPTER 3: DESIGN AND WORKING PRINCIPLE

3.1: Design of the Accelerometer

The schematic of the proposed design of the ZnO nanowire-based accelerometer is illustrated in Fig. 3.1. This accelerometer utilizes the unique piezoelectric properties of ZnO nanowires to achieve high sensitivity, accurate measurement and an ability to measure acceleration in all three axes. The structure of the accelerometer is layer by layer such that each layer has some specific function and serves as an important part of the sensor to increase its sensitivity.

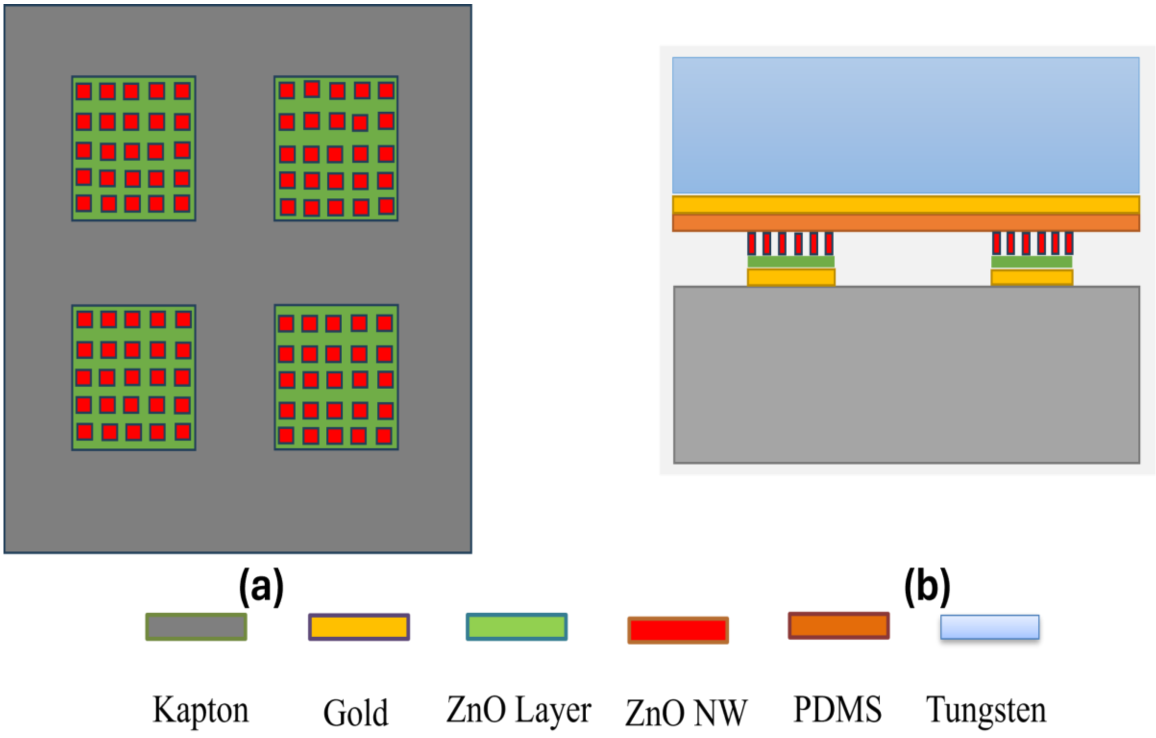

Fig. 3.1 Schematic of Proposed Accelerometer (a) Top View (b) Side View

The substrate of the accelerometer consists of a Kapton. Kapton is chosen as the substrate material due to its unique property of flexibility and durability. Other traditional substrates such as silicon are rigid and can be cracked when subjected to stress, Kapton offers a more flexible foundation to the sensors. This flexibility plays a crucial role in applications in which the accelerometers experience mechanical deformations. The use of Kapton as the substrate material is reported in several studies that demonstrate its effectiveness in flexible electronic devices [13-14], [40].

On top of the Kapton substrate, four gold electrodes are patterned. These gold electrodes serve as the electrodes for the device, playing a crucial role in the transduction of mechanical energy into electrical signals. Gold is used as an electrode because of its excellent electrical conductivity. The precise patterning of these electrodes on the Kapton substrate allows for optimal contact with the ZnO nanowires, which are responsible for generating the electrical signal in response to mechanical stress.

Then for the growth of ZnO nanowires, a ZnO seed layer is deposited on the top of the gold electrodes. The seed layer acts as a base for the nanowires, ensuring that they grow uniformly and in the desired orientation. The seed layer is very critical, as it directly influences the properties of the ZnO nanowires. By providing a well-defined base for the nanowire growth, the ZnO seed layer ensures that the piezoelectric properties of the nanowires are fully utilized, leading to enhanced sensitivity in the accelerometer.

The ZnO nanowires (NWs) are then grown on the surface of the ZnO seed layer. The growth process is carefully controlled to ensure that the nanowires are only deposited on the seed layer, preventing unwanted growth on other parts of the device. The ZnO nanowires serve as the primary sensing element of the accelerometer. When the accelerometer is subjected to mechanical stress, the nanowires deform, generating an electrical charge due to their piezoelectric nature. This electrical signal is then collected by the electrodes and used to measure the magnitude of the applied force.

To further improve the performance of the accelerometer, a dielectric layer is deposited on top of the ZnO nanowires. This dielectric layer plays a dual role in the device's design. First, it increases the sensitivity of the accelerometer by enhancing the electric field generated by the nanowires. Second, it acts as an adhesive layer that helps to bond the top electrode to the rest of the structure. PDMS (Polydimethylsiloxane) has been selected as the material for the dielectric layer due to its high dielectric constant. PDMS is also flexible and biocompatible, making it suitable for a wide range of applications, including those in biomedical devices.

Following the deposition of the PDMS layer, a thin layer of gold is patterned on top of it. This gold layer acts as the top electrode of the accelerometer, providing a contact point for the electrical signal generated by the ZnO nanowires. The top electrode must be carefully aligned with the underlying structure to ensure efficient signal collection and minimize any losses. The use of gold for the top electrode, like the bottom electrodes, ensures that the device maintains high electrical conductivity and stability over time.

On the top of the gold electrode, a proof mass is placed. The proof mass is an important part of the accelerometer, as it determines the device's sensitivity to acceleration. In this proposed design, tungsten has been used as the material for the proof mass due to its high density. The high density of tungsten allows the proof mass to generate significant force in response to acceleration which can enhance the sensitivity of the device. The positioning of the proof mass is carefully examined to ensure that the maximum force can be transferred to the ZnO nanowires.

Due to the layer-by-layer structure, the accelerometer achieves high sensitivity and accuracy, allowing it to detect acceleration in all three axes. The 3D model and exploded view of the proposed accelerometer, shown in Fig. 3.2, provide a clear visualization of how the different components fit together to form the final device. Each layer and component has been designed in such a way that it optimizes the performance of the accelerometer, making it suitable for a wide range of applications where precise motion detection is required.

In summary, the proposed accelerometer design is built upon the flexible Kapton substrate, with gold electrodes, a ZnO seed layer, ZnO nanowires, a PDMS dielectric layer, a gold top electrode, and a tungsten-proof mass. Each of these components has been selected and arranged to maximize the sensitivity and reliability of the device, leveraging the unique properties of ZnO nanowires to achieve superior performance in motion detection.

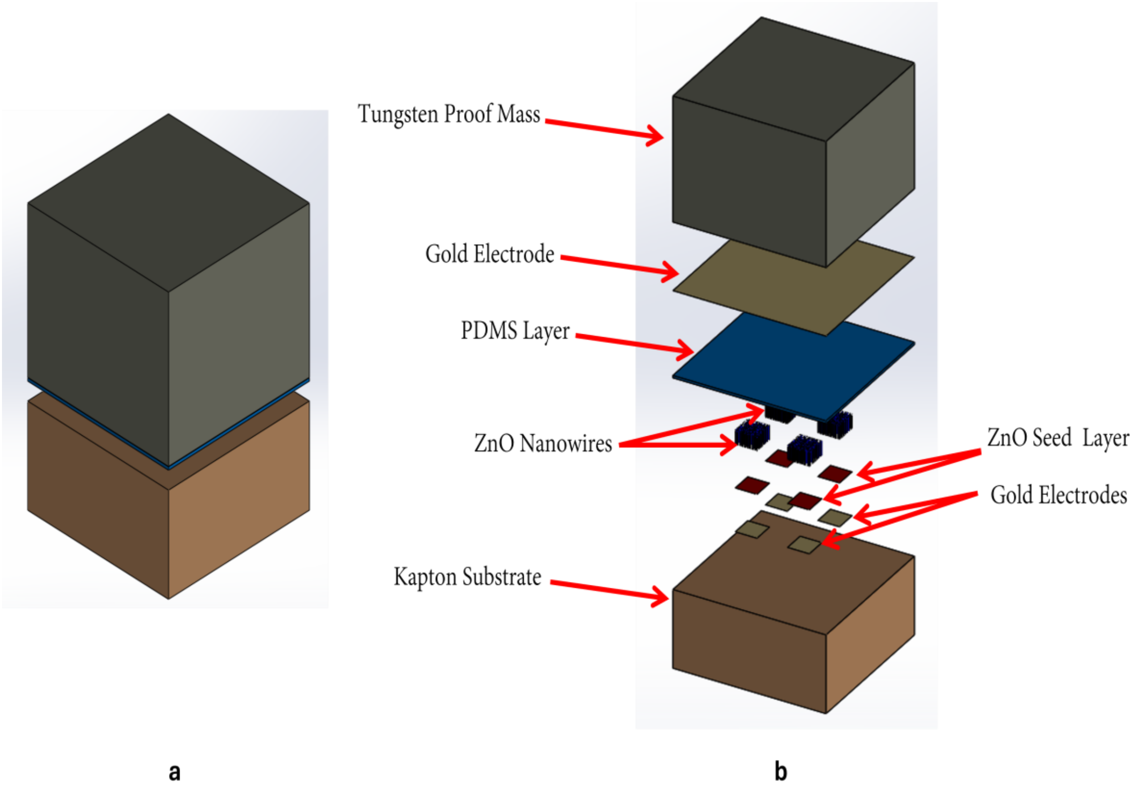

Fig. 3.2 Design of Proposed Accelerometer (a) 3d View (b) Exploded View

3.2: Working Principle

ZnO nanowires exhibit unique piezoelectric properties that make them highly suitable for various sensing applications. One of the most significant characteristics of ZnO nanowires is their ability to generate electrical voltage in response to mechanical stress. Specifically, when ZnO nanowires are subjected to compressive forces, they generate a negative voltage, and when they experience tensile forces, they generate a positive voltage. This unique behavior of producing both positive and negative voltages based on the type of mechanical stress allows ZnO nanowires to effectively measure acceleration across multiple axes, making them ideal for multi-axis accelerometers [36].

In the design of the proposed accelerometer, we have used this unique property by growing four unique structures of ZnO nanowires. Each of these structures is strategically positioned to measure acceleration in three axes.

When acceleration is applied in the normal direction, along the z-axis, all four structures of ZnO nanowires experience compressive stress simultaneously. Due to the piezoelectric nature of ZnO, each of these four nanowire structures generates a voltage in response to this stress. Since all the nanowires are being compressed in the same manner, the voltage generated by each structure is identical. This uniform voltage output from all four structures allows the accelerometer to accurately detect the acceleration in the z-axis direction [41].

However, the behavior of the structures of ZnO nanowires becomes changed when acceleration is applied in the x or y directions. In these cases, the nanowire structures are subjected to both compressive and tensile stresses, depending on their orientation relative to the applied force. When acceleration is applied along the x-axis, structures 1 and 2 experience compressive stress, while at the same time, structures 3 and 4 experience tensile stress. Due to this opposite stress behavior between the two pairs of ZnO nanowire structures, the direction and magnitude of the acceleration can easily be determined [41].

Similarly, when acceleration is applied in the y-axis direction, the nanowire structures respond similarly. In this scenario, structures 1 and 4 experience tensile stress, while structures 2 and 3 are subjected to compressive stress. Similarly, the ZnO nanowires exhibit the opposite voltages based on the type of mechanical stress they encounter. This opposing voltage output in response to x-axis and y-axis accelerations allows the accelerometer to distinguish between different directions of movement.

The multi-axis sensing capability of the accelerometer is achieved by analyzing the voltage outputs from each of the four ZnO nanowire structures. By comparing the magnitudes and polarities of the voltages generated by these structures, the accelerometer can accurately determine the direction and magnitude of the applied acceleration. For instance, when the voltages from structures 1 and 2 are negative, and the voltages from structures 3 and 4 are positive, the accelerometer can conclude that the acceleration is occurring in the x-direction. Similarly, when structures 1 and 4 produce positive voltages, and structures 2 and 3 produce negative voltages, the acceleration is identified as occurring in the y-direction [13].

The design of the accelerometer ensures that it can effectively measure acceleration in all three dimensions (x, y, and z) by using the piezoelectric properties of ZnO nanowires. The ability to produce opposite voltages under compressive and tensile stresses is a key feature that enables the device to perform accurate multi-axis measurements. This makes the accelerometer particularly suitable for applications where precise detection of movement in multiple directions is critical, such as in robotics, navigation systems, and wearable devices [19], [39].

In summary, the working principle of the proposed ZnO nanowire-based accelerometer is based on the unique piezoelectric response of ZnO nanowires to compressive and tensile forces. By strategically arranging four nanowire structures and utilizing their voltage outputs, the accelerometer can accurately measure acceleration along the x, y, and z axes. Due to this capability, it can be used in various applications that require high precision and multi-axis sensing.

CHAPTER 4: MATHEMATICAL MODELING

An analytical model has been developed to describe the behavior of the proposed ZnO nanowire-based accelerometer. This mathematical model plays a crucial role in understanding the piezoelectric response of ZnO nanowires and the resulting voltage generated under applied acceleration. By comparing the results of both analytical modeling and FEM simulations, the performance of the accelerometer is evaluated.

Firstly, convert the applied acceleration into force. This conversion is done by first calculating the mass of the proof mass using the following equation:

$$m = \rho \mathrm{V} \qquad \text{(i)}$$

where m is the mass, ρ is the density, and V is the volume of the proof mass

In this case, tungsten is used as the material for the proof mass due to its high density. The calculation of mass is important for determining the force applied to the ZnO nanowires.

Next, Newton's second law is applied to convert the mass and acceleration into force, using the equation:

$$F = \mathrm{ma} \qquad \text{(ii)}$$

where F is the force and a is the applied acceleration.

The calculated force is crucial for the evaluation of the mechanical deformation of the ZnO nanowires, which directly influences their piezoelectric response.

The ZnO nanowire is modeled as a cantilever beam, with one end fixed and the other end is free on which the load is applied. This configuration leads to deformation along the length of the nanowire. The moment of inertia of the nanowire is the measure of its resistance to bending, and is calculated using the following equation (iii)

$$I = \frac{bh^3}{12} \qquad \text{(iii)}$$

where b is the width of the nanowire and h is its height of the nanowire

The moment of inertia is a key factor that affects the stress and strain distribution along the nanowire. To further analyze the mechanical behavior of the ZnO nanowires, the spring constant k is calculated by using Hooke's law. The spring constant tells us the stiffness of the nanowire and is determined by the following equation:

$$k = \frac{3EI}{h^3} \qquad \text{(iv)}$$

where E is Young's modulus of the ZnO nanowires

The spring constant directly influences the displacement of the nanowire under the applied force. The displacement of the nanowire, which is important for determining the strain experienced by the nanowire, is calculated using the following equation:

$$x = \frac{F}{k} \qquad \text{(v)}$$

where k is the spring constant

This displacement affects the amount of charge generated by the nanowire due to the piezoelectric effect. Another important factor in the piezoelectric response of ZnO nanowires is the bending moment, which is calculated using the equation:

$$M = \mathrm{Fh} \qquad \text{(vi)}$$

where h is the height of the nanowire and M is the bending Moment

The bending moment creates axial stress along the nanowire, with the maximum stress occurring at the fixed end. The stress experienced by the nanowire is calculated by using eq (vii) [42]

$$\sigma = \frac{Mc}{I} = \frac{Mh}{2I} \qquad \text{(vii)}$$

where $c = \frac{h}{2}$

where σ is the stress and h/2 represent the distance from the neutral axis. Stress is a critical parameter as it directly affects the piezoelectric voltage generated by the nanowire.

Once the stress is determined, the electrical displacement D is calculated using the equation:

$$D = d_{33}\sigma \qquad \text{(viii)}$$

where d_{33} is the piezoelectric constant of the ZnO nanowires

The electrical displacement represents the amount of electric charge generated per unit area due to stress. The next step is to calculate the electric field, which is directly proportional to the electrical displacement:

$$E = \frac{D}{\epsilon_0 \epsilon_{pdms}} \qquad \text{(ix)}$$

where ϵ_0 is the absolute permittivity and ϵ_{PDMS} is the permittivity of the PDMS layer.

The PDMS layer's presence between the ZnO nanowires and the top electrode plays a significant role in determining the overall permittivity of the system. Finally, the generated voltage VV across the ZnO nanowires is calculated using the equation:

$$V = \mathrm{Eh} \qquad \text{(x)}$$

This voltage is the key output of the accelerometer and corresponds to the applied acceleration.

The analytical model provides a detailed understanding of the stress distribution, displacement, and generated electrical output of the accelerometer, thereby demonstrating its sensing capabilities. By comparing this analytical model with FEM simulations, valuable insights into the performance of the accelerometer are gained, and the generated voltage is validated for sensing applications.

To validate the accelerometer's performance, a detailed analysis of the generated voltage along the z-axis is conducted when acceleration was applied in the z-direction. The model predicts a sensitivity of 1.59 V/g for the proposed accelerometer when a static acceleration of up to 50g is applied. Fig. 4.1 illustrates the calculated voltage as a function of the applied acceleration. Due to the compression of the nanowires, the generated voltage is negative, and therefore it is also considered negative in the mathematical model.

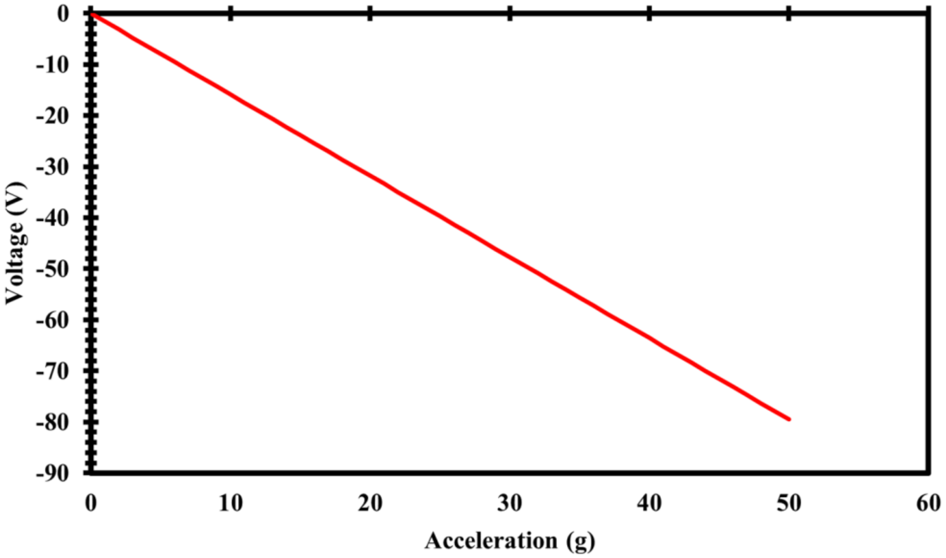

Fig. 4.1 Calculated Generated Voltage vs Applied Acceleration by using Mathematical Modelling

By combining the analytical model with FEM simulations, a comprehensive evaluation of the accelerometer's performance is achieved, ensuring that the proposed design is optimized for accurate and high-sensitivity acceleration measurement.

CHAPTER 5: FEM SIMULATION

5.1: Mode Shapes

Mode shapes play an important role in understanding the performance and behavior of piezoelectric accelerometers. These shapes tell us about how the structure deforms at specific frequencies which can directly impact the distribution of stress and the generated voltage in nanowires. Analyzing the first six mode shapes of the proposed accelerometer offers a deeper understanding of its operational characteristics, though only the 4th, 5th, and 6th modes are utilized for practical measurement, while the 1st, 2nd, and 3rd modes are excluded.

The first three mode shapes occur at lower frequencies, but they are not considered useful for accurate measurements. This is because these modes involve twisting and diagonal flexure, which lead to uneven stress distribution across the nanowires. The non-uniform stress results in insufficient piezoelectric voltage generation, making these lower modes ineffective for precise sensing applications. For instance, in the twisting mode, the nanowires do not experience consistent compressive or tensile stress, which is necessary for generating a reliable voltage signal.

Contrary to that, the 4th, 5th, and 6th mode shapes are selected due to their ability to produce more uniform stress distribution and maximize the voltage output in the nanowires. These modes occur at higher frequencies, where the deformation patterns align more closely with the desired directional measurements of acceleration.

The 4th mode shape, occurring at a frequency of 3883 Hz, exhibits shear deformation along the Y-axis. This mode is used for measuring acceleration in the Y-axis because the deformation results in structures 1 and 4 experiencing tensile stress, while structures 2 and 3 undergo compressive stress. This differential stress across the nanowires creates an optimal condition for voltage generation, making the 4th mode ideal for Y-axis acceleration measurements.

At 3902 Hz, the 5th mode shape exhibits shear deformation along the X-axis, making it suitable for X-axis acceleration measurements. In this mode, a similar behavior is observed as in the 4th mode, with structures 1 and 2 experiencing compressive stress and structures 3 and 4 undergoing tensile stress. This consistent stress distribution ensures that the generated voltage accurately reflects the applied acceleration along the X-axis, reinforcing the importance of this mode shape for X-axis sensing.

The 6th mode shape, occurring at 6647 Hz, is associated with normal deformation along the Z-axis. This mode is critical for Z-axis acceleration measurements because the deformation pattern at this frequency causes all four nanowire structures to experience identical stress. As a result, the voltage generated by each structure is uniform, providing a reliable and consistent output for Z-axis acceleration. The synchronous movement of the sensor at this frequency ensures that the accelerometer can effectively measure vertical acceleration with high accuracy.

Overall, the 4th, 5th, and 6th mode shapes are selected for their ability to maximize the performance of the piezoelectric accelerometer. By focusing on these modes, the accelerometer can achieve accurate, high-sensitivity measurements across the X, Y, and Z axes. The exclusion of the first three modes, due to their inadequate stress distribution and insufficient voltage generation, further highlights the importance of mode shape selection in optimizing the device's performance. This detailed analysis of mode shapes contributes to a better understanding of how the accelerometer functions under different conditions and provides valuable insights for its application in various sensing environments.

As a result, the 4th, 5th, and 6th mode shapes are considered due to their superior stress distribution and voltage generation capabilities, which played a key role in the accurate measurement of multi-axis acceleration.

5.2: FEM Simulation

Finite Element Method (FEM) simulations were conducted to thoroughly evaluate the performance of ZnO nanowires in measuring multi-axis acceleration. These simulations are performed to analyze the response of the accelerometer under conditions of static and dynamic acceleration. To evaluate the sensor behavior, the proposed piezoelectric accelerometer design is numerically modeled using COMSOL Multiphysics software. These simulations provided valuable insights into how applied acceleration affects stress distribution, deformation, and the voltage generated by the ZnO nanowires.

A 3D representation of the meshed accelerometer model is depicted in Fig. 5.1. The sensor design includes a Kapton substrate with dimensions of 290 x 290 µm and a thickness of 150 µm. On top of this substrate, four gold electrodes are patterned, each of 77.5 x 77.5 µm with a thickness of 0.5 µm. The distance between the electrodes is 45 µm from each other. These gold layers act as the bottom electrodes, forming the basis for electrical connectivity in the device. Next, ZnO seed layers are deposited directly on top of the gold electrodes. These seed layers have the same area as the gold electrodes but have a thickness of 0.1 µm. The purpose of these seed layers is to facilitate the growth of ZnO nanowires, which are the key sensing elements of the accelerometer. Four arrays of ZnO nanowires, each arranged in a 15 x 15 grid, are grown on top of the seed layers. Each nanowire has a height of 40 µm, a width of 2.5 µm, and a spacing of 2.5 µm between adjacent nanowires. The chosen spacing of 2.5 µm allows sufficient freedom of movement for the nanowires, as recommended by Wood et al. [14]. A layer of PDMS (Polydimethylsiloxane) with a thickness of 8 µm is then placed on top of the ZnO nanowires. This PDMS layer covers the entire sensor area, measuring 290 x 290 µm, and serves as a dielectric layer, providing an insulation layer between the nanowires and the top electrode. On top of the PDMS layer, a thin gold electrode with a thickness of 0.5 µm is patterned, having the same area as PDMS. This gold layer acts as the top electrode, completing the electrical circuit for the sensor. Finally, a tungsten-proof mass, with dimensions of 290 x 290 x 290 µm, is positioned on top of the gold electrode. The high density of tungsten ensures that the proof mass contributes significantly to the sensitivity of the accelerometer.

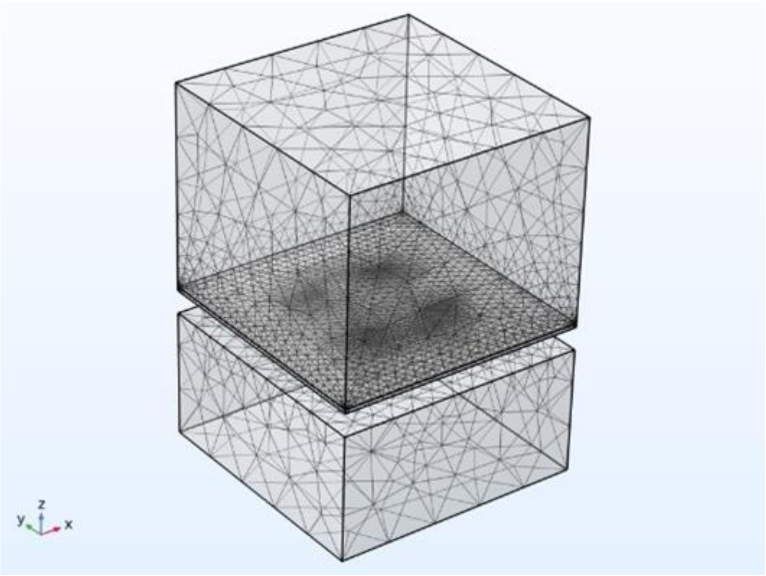

Fig. 5.1 3d Meshed Model of Proposed Accelerometer

To assess the performance of the accelerometer, the accelerometers are tested under both dynamic and static acceleration. Dynamic acceleration tests is performed by applying an acceleration of 0.1g across a various range of frequencies along all three axes (x, y, and z). This dynamic testing allowed for the observation of how the sensor responds to varying frequencies, providing insight into its behavior under real-world conditions. Additionally, static acceleration tests are performed by applying a constant acceleration of up to 50g along each axis with a step of 1g.

Throughout these simulations, key performance parameters such as stress distribution, mechanical deformation, and the voltage generated by the ZnO nanowires are carefully analyzed. The stress analysis provided information on how the applied forces were distributed across the nanowires, Deformation analysis is performed to analyze the bending of the nanowires. The primary focus is on the analysis of voltage generation on the nanowires subject to acceleration. The generated voltage is found to be proportional to the applied acceleration, validating the piezoelectric properties of the ZnO nanowires and their suitability for multi-axis sensing applications.

CHAPTER 6: RESULTS AND DISCUSSION

The performance of the proposed ZnO nanowire-based piezoelectric accelerometer was evaluated by applying dynamic and static acceleration. By using FEM simulations to analyze stress distribution, deformation, and voltage generation across the nanowires. The main aim of these analyses is that the effectiveness of the multi-axis acceleration measurement is demonstrated.

6.1 Dynamic Acceleration Testing

Dynamic acceleration is applied with an input of 0.1g applied across all three axes to assess the stress output of the sensor. Since the modal frequencies differ along each axis, the performance of the accelerometer is analyzed across various frequency ranges. This approach allowed for a detailed understanding of how stress impacts the ZnO nanowires under acceleration, which is crucial for accurately predicting the generated voltage.

Figures 6.1a, 6.2b, and 6.3c present the FEM simulation results, showing the stress distribution on the nanowires when a 0.1g acceleration is applied along the x-axis, y-axis, and z-axis, respectively. The stress distribution is a key factor in determining the piezoelectric response of the nanowires, as uneven stress can lead to inconsistent voltage output.

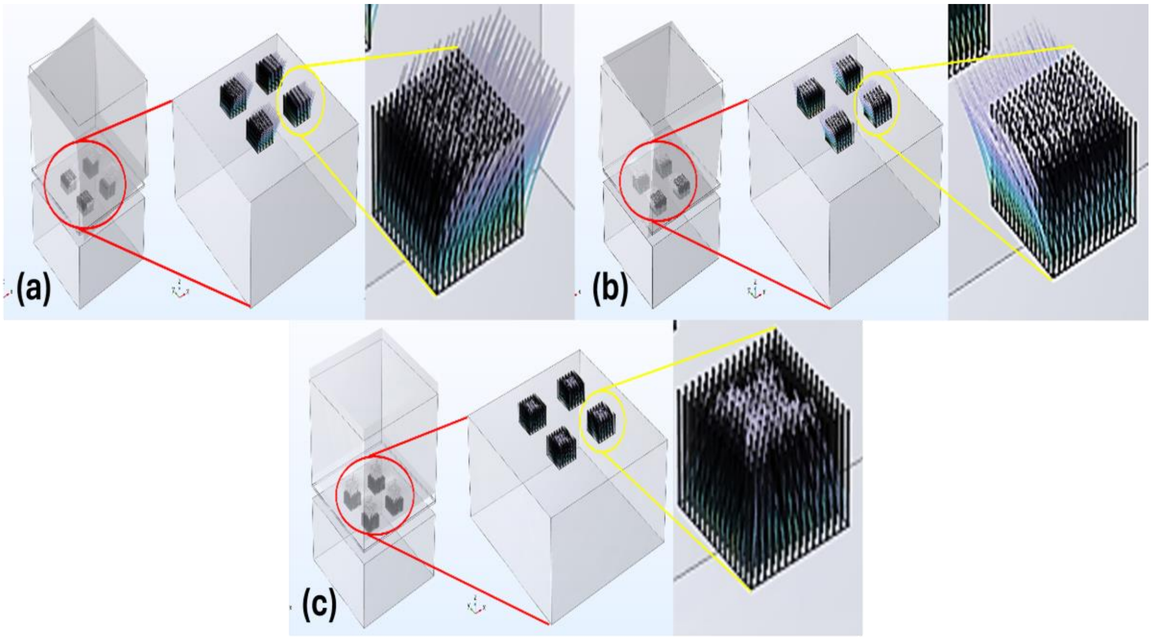

Fig. 6.1 Stress Distribution on ZnO Nanowires when an Acceleration of 0.1g is applied in the direction of X-Axis (b) Y-Axis (c) Z-Axis

The frequency vs. stress response for each axis is shown in Figures 6.2a, 6.2b, and 6.2c. In the x-axis, the maximum stress occurs at the modal frequency of 3902 Hz. Similarly, the y-axis shows peak stress at 3882 Hz, which is the modal frequency for that axis. For the z-axis, the highest stress is observed at 6648 Hz. These frequencies represent the points at which the sensor experiences the greatest stress, which directly correlates with the voltage output.

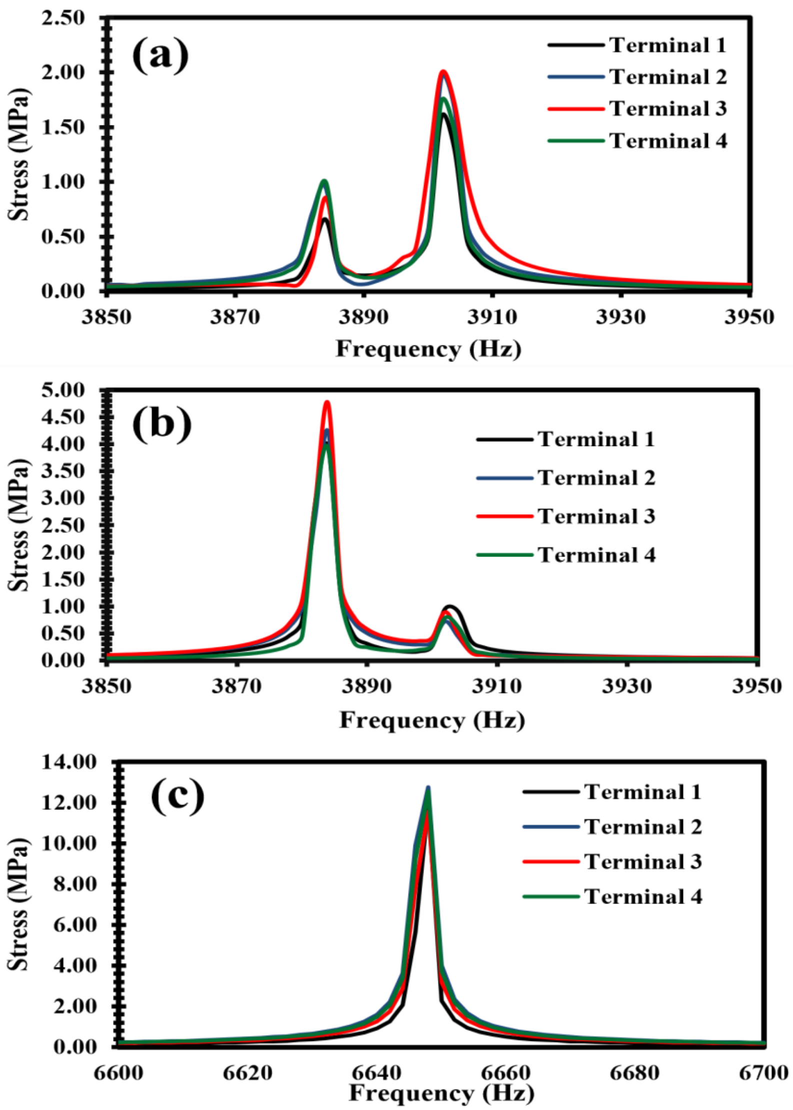

Fig. 6.2 Stress vs Frequency Response Graph of ZnO Nanowires when an Acceleration of 0.1g is applied in the direction of (a)X-Axis (b) Y-Axis (c) Z-Axis

Dynamic acceleration was also applied to evaluate the voltage generated by the ZnO nanowires under different frequencies. For the x-axis, a frequency range of 3850-3950 Hz with a step size of 2 Hz was used. Structures 1 and 2 experienced compressive stress, resulting in a negative voltage output, while structures 3 and 4 experienced tensile stress, generating a positive voltage. The highest voltage output was recorded at 3902 Hz, as shown in Figure 6.3a.

A similar analysis was conducted for the y-axis, where the applied frequency range was also 3850-3950 Hz. Structures 1 and 4 experienced compressive stress, while structures 2 and 3 were subjected to tensile stress, leading to opposite voltage polarities. The maximum voltage was observed at 3882 Hz Figure 6.3b.

For the z-axis, the frequency range tested was 6600-6700 Hz. In this case, all four nanowire structures experienced compressive stress, generating a uniform voltage output. The peak voltage was recorded at 6648 Hz Figure 6.3c. These results illustrate the accelerometer's sensitivity within the specified frequency ranges and confirm the sensor's ability to measure acceleration accurately along all three axes.

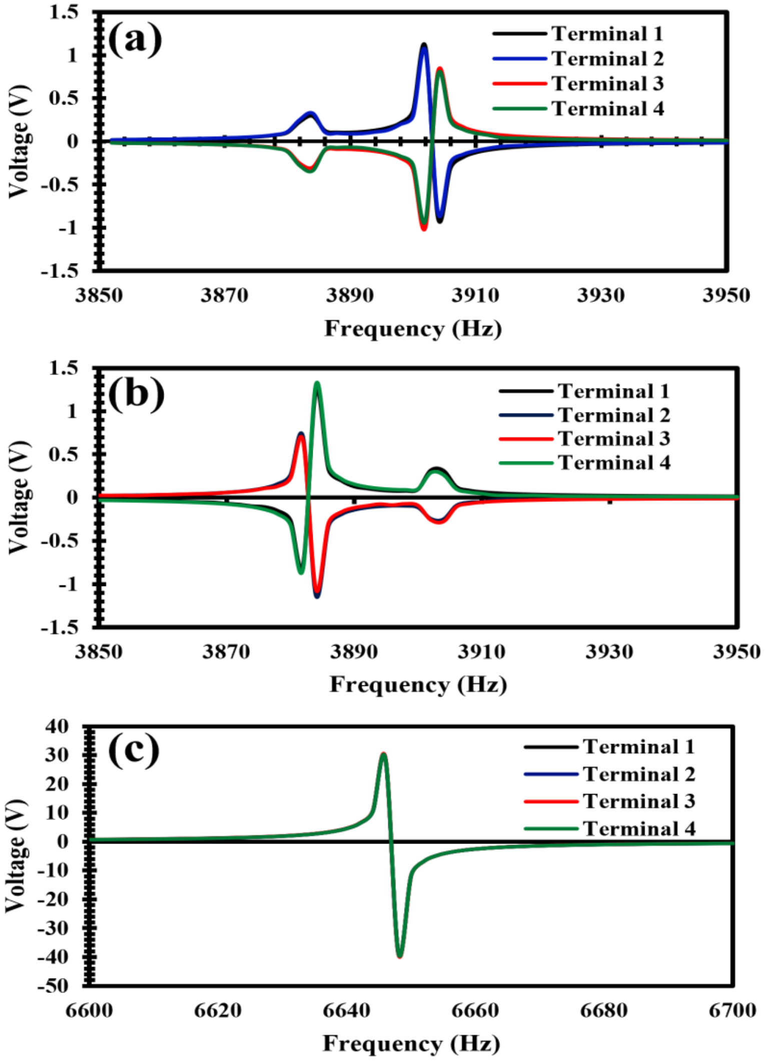

Fig. 6.3 Frequency vs Generated Voltage Graph of ZnO Nanowires when an Acceleration of 0.1g is applied in the direction of (a) X-Axis (b) Y-Axis (c) Z-Axis

In addition to stress and voltage, the deformation behavior of the nanowires was also analyzed under dynamic acceleration. Figures 6.4a, 6.4b, and 6.4c show the deformed image of the accelerometer when a 0.1g acceleration is applied along the x-axis, y-axis, and z-axis, respectively. The corresponding frequency vs. deformation graphs are shown in Figures 6.5a, 6.5b, and 6.5c. The maximum deformation in the x-axis occurs at 3902 Hz, in the y-axis at 3882 Hz, and in the z-axis at 6648 Hz. These results demonstrate how the nanowires deform under different frequencies, which directly impacts their piezoelectric response.

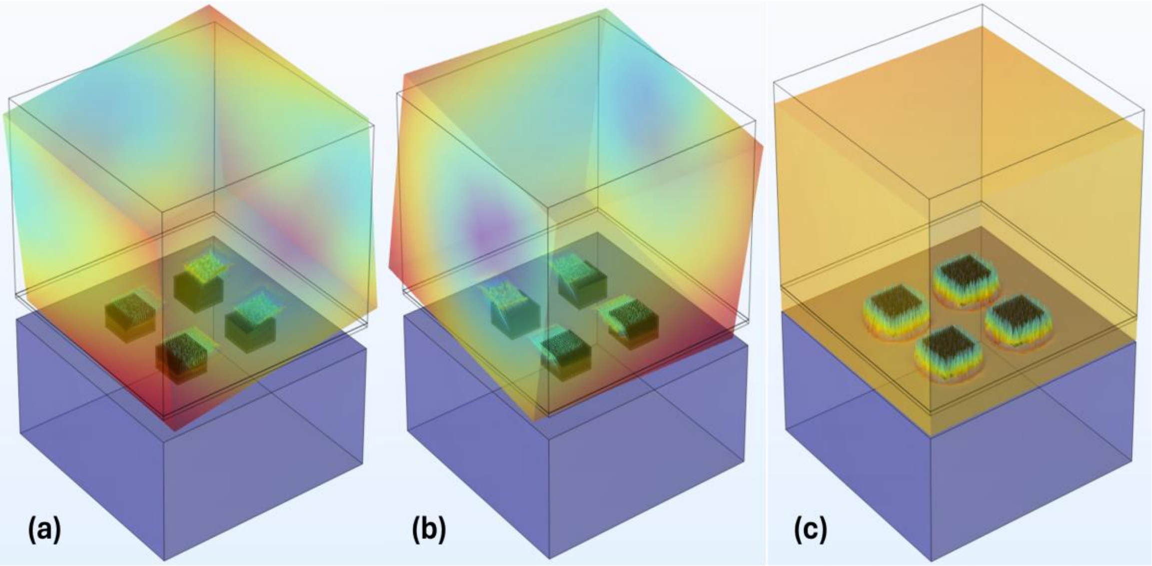

Fig. 6.4 Deformation of Accelerometer subjected to Acceleration of 0.1g applied in the direction of (a) X-Axis (b) Y-Axis (c) Z-Axis

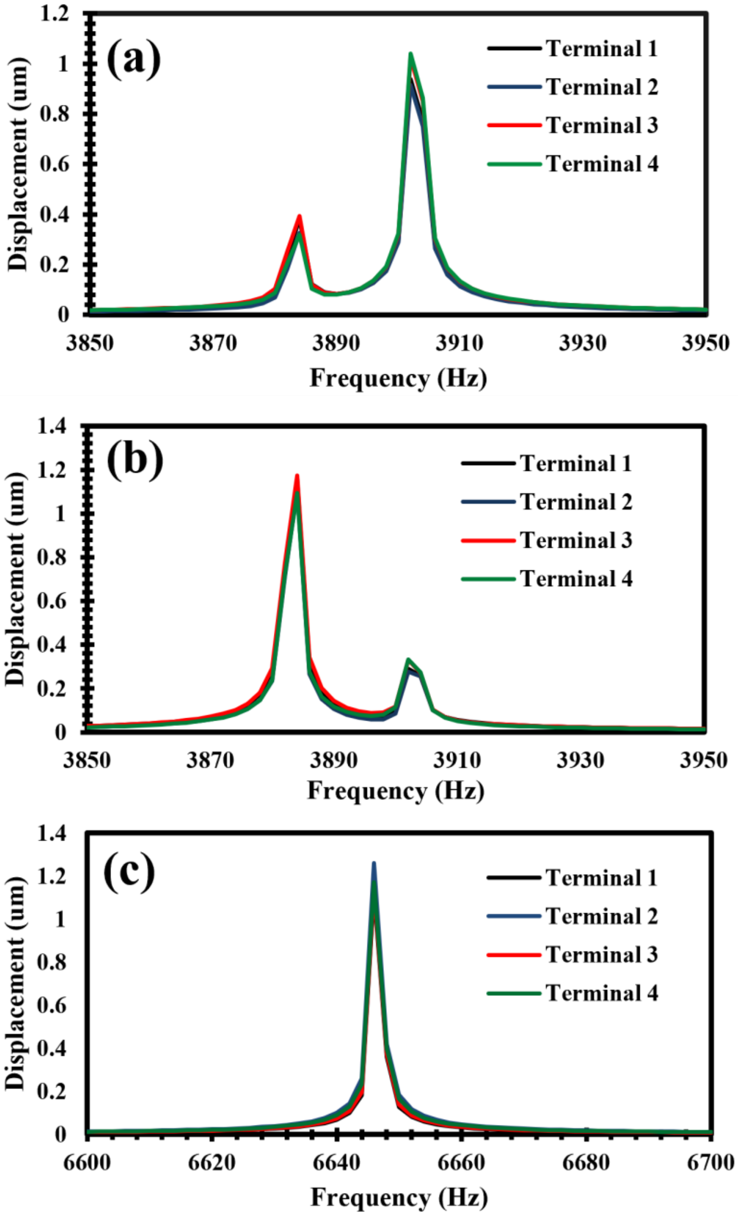

Fig. 6.5 Frequency vs Displacement Graph of ZnO Nanowires when an Acceleration of 0.1g is applied in the direction of (a) X-Axis (b) Y-Axis (c) Z-Axis

6.2 Static Acceleration Testing

To further evaluate the performance of the accelerometer, static acceleration tests were conducted across all three axes, with acceleration ranging up to 50g and a step size of 1g. The figures 6.6a, 6.6b, and 6.6c shows the direction of acceleration with the help of arrow heads.

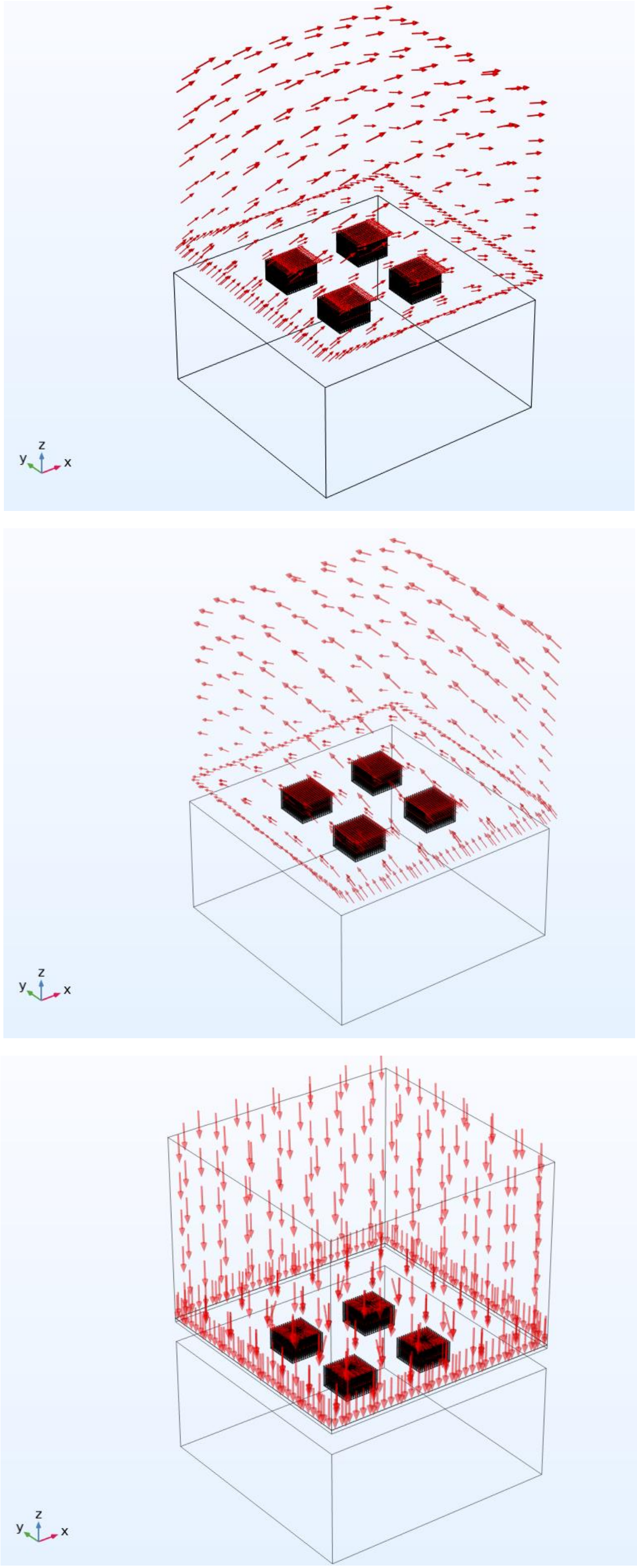

Fig. 6.6 Direction of Acceleration (a) X-Axis (b) Y-Axis (c) Z-Axis

The relationship between applied acceleration and resulting stress is presented in Figures 6.7a, 6.7b, and 6.7c for the x-axis, y-axis, and z-axis, respectively. The results reveal a linear relationship between acceleration and stress, indicating a stable and predictable response from the ZnO nanowires under static loading conditions. This linear behavior is crucial for ensuring the reliability of the sensor in various applications.

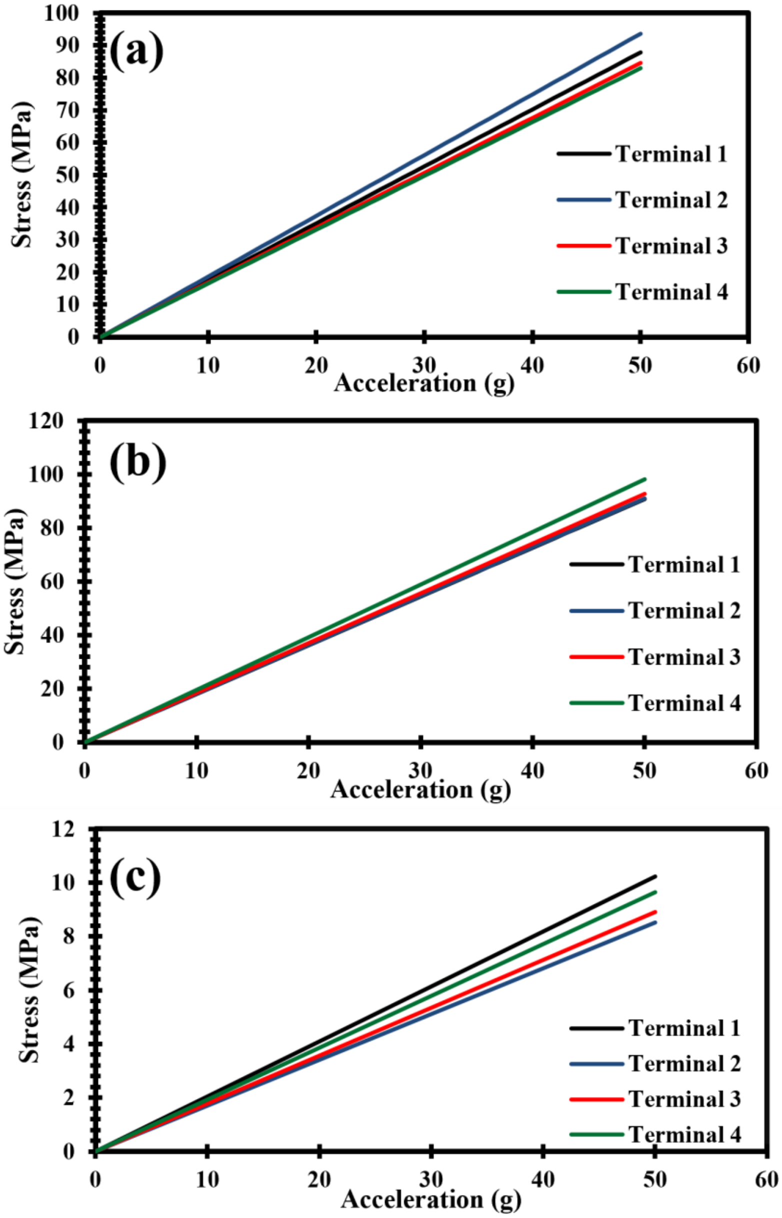

Fig. 6.7 Acceleration vs Stress Graph of ZnO Nanowires when a Static Acceleration up to 50g is applied in the direction of (a) X-Axis (b) Y-Axis (c) Z-Axis

The sensitivity of the accelerometer under static acceleration was calculated as 1.8 MPa per g for both the x-axis and y-axis, and 0.21 MPa per g for the z-axis. These values highlight the sensor's ability to detect small changes in acceleration, particularly in the shear axes (x and y), where the sensitivity is highest.

Static acceleration tests also focused on analyzing the generated voltage. For the x-axis, when an acceleration of up to 50g was applied, structures 1 and 2 experienced compressive forces, leading to a negative voltage output. Conversely, structures 3 and 4 experienced tensile forces, generating a positive voltage. Despite the opposite polarities, the magnitudes of the voltages were identical for both sets of structures. Figure 6.8aa illustrates the relationship between applied acceleration and generated voltage along the x-axis.

Similar behavior was observed in the y-axis as shown in 6.8b, where structures 1 and 4 produced negative voltage due to compression, while structures 2 and 3 generated positive voltage due to tensile stress. In the z-axis 6.8c, all four structures experienced compressive stress, resulting in a uniform negative voltage output across the nanowires. The results show a linear relationship between acceleration and voltage, with sensitivities of 0.25 mV/g in the x and y-axes, and 1.40 mV/g in the z-axis. The high sensitivity values indicate that the accelerometer is highly responsive to changes in acceleration, making it suitable for applications requiring precise measurements.

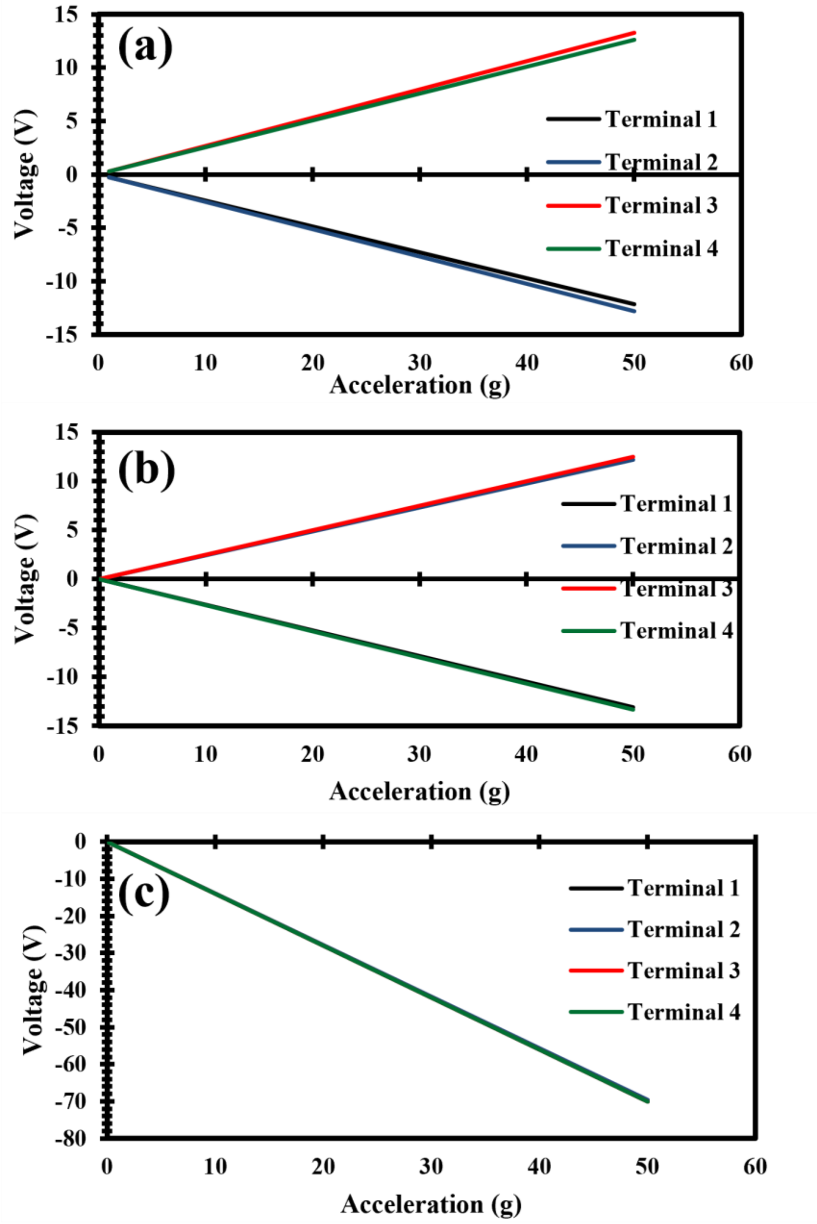

Fig. 6.8 Applied Acceleration vs Generated Voltage of ZnO Nanowires when a Static Acceleration up to 50g is applied in the direction of (a) X-Axis (b) Y-Axis (c) Z-Axis

Furthermore, the deformation of the nanowires under static acceleration was analyzed. The deformed images of the sensors shown in Figures a, b and c. The graphs of deformation vs acceleration is shown in Figures 6.9a, 6.9b, and 6.9c for the x, y, and z-axes, respectively. The deformation increased linearly with the applied acceleration, indicating a uniform mechanical response across all axes. The sensitivity of the accelerometer in terms of deformation was found to be 12 nm per g for the x and y-axes, and 21 nm per g for the z-axis. These results suggest that the sensor is capable of detecting minimal deformations, which is essential for applications that require high precision.

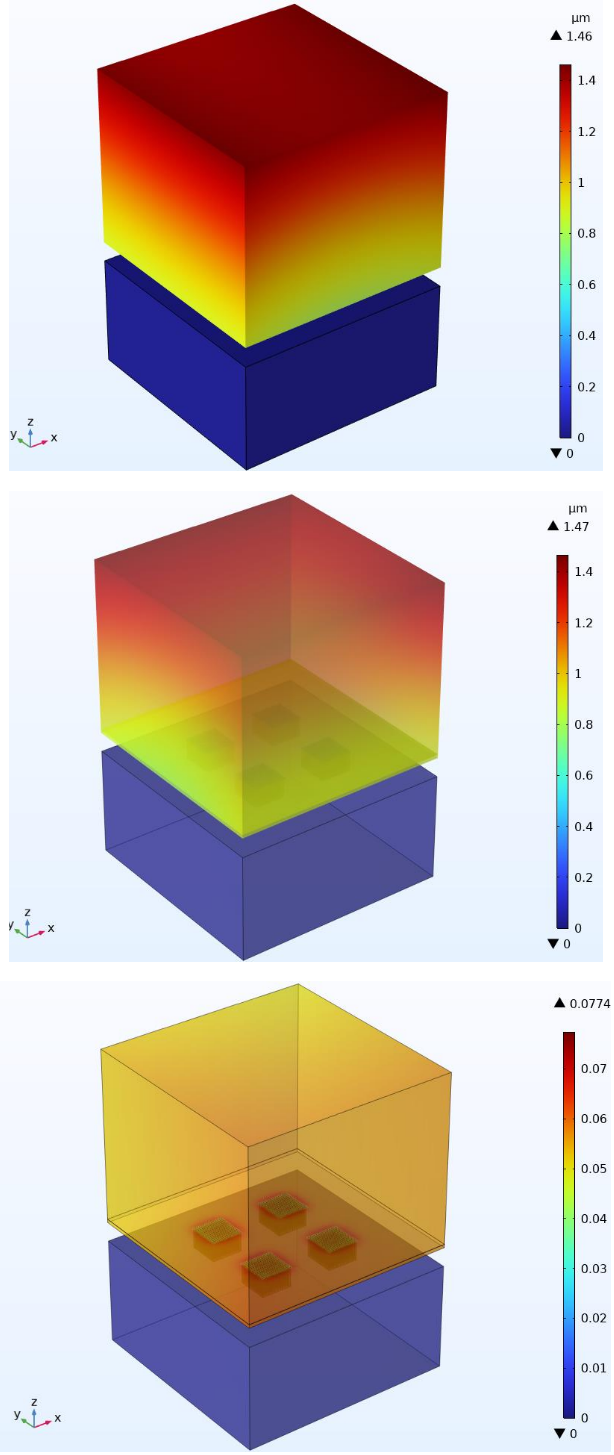

Fig. 6.9 Deformation of Accelerometer under applied Acceleration in the direction of(a) X-Axis (b) Y-Axis (c) Z-Axis

6.3 Comparative Analysis

Piezoelectric accelerometers based on nanowires, as reported in existing literature, are typically limited to measuring acceleration along a single axis, primarily in the normal direction (z-axis). However, the proposed design of this accelerometer extends the capability to measure acceleration along all three axes, including the shear axes (x and y). Table 6.1 provides a comparative analysis between the proposed accelerometer and previously reported designs, highlighting the advancements in sensitivity, measurement range, and multi-axis capability. The proposed sensor offers higher sensitivity, and a broader measurement range compared to earlier designs, making it a significant improvement over existing technology.

In conclusion, the FEM simulations and experimental analyses demonstrate the effectiveness of the proposed ZnO nanowire-based accelerometer in multi-axis acceleration measurement. The sensor exhibits high sensitivity, reliable performance, and consistent linear responses across all three axes, making it suitable for a wide range of applications, from industrial monitoring to consumer electronics. The ability to measure acceleration in both shear and normal axes sets this design apart from traditional accelerometers, offering a more versatile and accurate sensing solution.

Table 6.1: Example of a table

Reference	Axis	Material	Thickness	Range	Sensitivity
Kim et al. [31]	Single Axis	ZnO	8 µm	0-1g	15.1 pA/g
Koka et al. [28]	Single Axis	$BaTiO_3$	45 µm	-	50 mV/g
Wang et al. [24]	Single Axis	ZnO	-	-	16.3 mV/g
Ramanay et al. [43]	Single Axis	ZnO	1.3 µm	0-1g	6.9 V/g
Ramanay et al. [33]	Single Axis	ZnO	-	0-1g	1.93 V/g
Song et al. [2]	Single Axis	ZnO	12 µm	0-1g	37.7 pA/g
Proposed Sensor	Tri-Axis	ZnO	40 µm	0-50g	Shear: 0.25 V/g Normal: 1.40 V/g

CHAPTER 7: CONCLUSION

This study has presented a design and analysis of a piezoelectric accelerometer based on ZnO nanowires, highlighting its ability to measure acceleration across all three axes. An analytical model of the accelerometer was developed, and FEM simulations have been performed to examine the sensor's behavior under various conditions. The accelerometer is evaluated by applying both static and dynamic acceleration. The FEM simulations identified the resonance frequencies of the accelerometer as 3902 Hz, 3883 Hz, and 6647 Hz along the x-axis, y-axis, and z-axis, respectively. The results show that the accelerometer output is linear, and its sensitivity is high when subjected to static acceleration. The sensor demonstrated a sensitivity of 0.25 V/g for in-plane acceleration and 1.40 V/g for out-of-plane acceleration. The unique properties of ZnO nanowires contribute to the enhanced sensitivity of the sensor and allow it to operate as a self-powered device. Furthermore, the sensor's highly linear response under static acceleration makes it an ideal candidate for integration into haptic devices and biomedical applications.

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