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## Exploring the Advancements in Sensor Materials and Technologies: A 21st Century Perspective on Materials Science & Engineering



### Abstract

This research aims at reviewing the most recent developments in the content with specific emphasis on the materials used in the sensors and the methods of creating them in order to increase the performance of the sensors while overcoming the challenges of increased costs of manufacturing. A comparison of the various sensor materials such as graphene, nanowires, and piezoelectric materials as regards their sensitivity, durability, response time and cost implications is also presented in the study. Furthermore, it discusses the state-of-art fabrication technologies including 3D printing, MEMS/NEMS, and inkjet printing and their impact on sensors characteristics and fabrication yield. Accordingly, it can be seen that the nanowires have the highest sensitivity and the shortest response time, on the other hand, the graphene has average sensitivity and response time but the sensor has high durability and cost efficiency. Currently, there is a high performance cost trade-off between micro / nano electromechanical systems (MEMS/NEMS) forms such as photolithography and the ink jet and three dimensional printing techniques such as those used in micro fabrication that are comparatively cheaper and more versatile. The study calls for more future research on hybrid material and ways to improve fabrication techniques to further their various uses in the fields such as in environmental sensing, manufacturing automation and many more.

**Keywords:** Sensor Materials, Fabrication Technologies, Nanowires, Graphene, Piezoelectric Sensors, 3D Printing, MEMS/NEMS.

### 1. Introduction

These diverse applications create a range of opportunities for advanced sensor materials and technologies that have enhanced development of the subsequent industries including healthcare, environmental monitoring, automotive and IoT. Advanced miniaturization and ever-growing needs for accurate and highly reliable sensors have propelled the advance of materials sciences, the materials and structures at nano level, organics, as well as the bio mimicking. Sensors have improved from being basic mechanical structures to complicated instruments that utilize advanced materials in the detection, analysis and response to the changes in the physical environment.

Such improvements owe their progress to new fabrication materials that offer improved sensitivity, stability and multifunctional platform. For example, nanotechnology has presented nanomaterials with exceptional electrical, mechanical and thermal characteristics that allows sensors to identify slight alterations in physical or chemical environment. Furthermore, advances in flexible and wearable materials have enabled distinct and viable sensor structures to be developed for conformal applications over complex geometries and even for integration into biological tissues (Amjadi, Pichitpajongkit and Ryu, 2014).<sup>1</sup>

Besides, the manufacturing technologies have advanced over time in such a way that it now becomes possible to manufacture enhanced sensors with better performance at cheaper costs. Due to advancement in technology, it has been possible to design and develop sensors with complicated structures and operational styles through methods like microfabrication, 3D printing as well as Additive manufacturing (AM) broadening their usability across various fields. Therefore, sensor technologies are applied in the present in real-time monitoring systems of risks in the environment, in health care devices for individual patients, in smart cars, and many more uses.

The motivation for this study comes with the drive to undertake a topical and increasingly recognized research area of materials science and sensor technology as well as to gain insight into how material science is shaping, defining and influencing the future of sensors. This paper shall review current developments in sensor materials with a view of identifying new trends in the field. In particular, it will review the merits of nanomaterials, organic polymer, and bio-inspired materials in sensor performance and dependability.

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## 2. Background and Literature Review

### 2.1 Historical Evolution of Sensor Materials

Historical progression of sensor materials has seen the mechanical systems and then, progressing to electronic systems and the latest being nanotechnology. New high-frequency and high-speed semiconductor materials such as silicon and germanium that came into light during middle of 20th century made significant changes in the field of sensors (Wilson, 004). They formed a basis of the electronic sensors which can in turn am duly used to indicate the environmental al parameters like temperature pressure and humidity in a much more accurate way.

Substantial progress in the solid-state physics in the mid of the twentieth century made continued enlargement in sensing capabilities. Piezoelectric materials that indicate an ability to change mechanical stress into electrical signals have been essential for making sensors in aerospace and automotive industry (Vallin & Bäcklund, 2000). Thin film deposition techniques developed in the early 1980s provided the possibility of miniaturization of sensors and proliferation of MEMS sensors in industries including health, military and oil field (Gardner, Varadan, & Awadelkarim, 2003).

### 2.2 Recent Trends in Sensor Technology Development

One of the emerging fields intensively developed in the early of the 21st century is nanotechnology, which play the key role in the production of the new generation of sensors with the highest sensitivity and selectivity. Carbon nanotubes CNTs, graphene and metal oxides are key nanomaterials that offer excellent electrical and mechanical properties therefore unmistakably suitable for the next generation sensors (Mannoor, Tao & Bhardwaj, 2012). These materials have been incorporated various sensor designs especially for gas and bio sensing at trace levels of concentrations.

Flexible and wearable electronics also bring about drastic developments in the sensor technologies. Some of the foldable sensors are flexible, and can be designed using polymers or thin metals to adapt well to the curvature of the human body or changing surfaces such as those in the sporting and health-care industries and in environmental monitoring. Wearable sensors can gauge physiological indicators including heart rate, body temperature as well as blood glucose levels and can thus offer immediate physiological data to both patients and healthcare givers (Bandodkar & Wang, 2018).

### 2.3 Emerging Sens or Materials: Challenges and Opportunities

Even though research in the development of sensor materials has significantly improved, several factors limit the technology in regards to its scalability, cost, and durability. For instance, whilst CNTs and graphene exhibit unique properties for sensing applications, fabrication of these materials into commercial sensor devices remains challenging due to the inability to scale up the manufacturing process and achieve uniformity in properties of the nanomaterials (Niu et al., 2018). However, some nanomaterials are very sensitive to environmental conditions including humidity and temperature; therefore, using such nanomaterials in real applications may cause problems of reliability and reproducibility.

At the same time, there are new types of sensor materials including bio-inspired and biomimetic materials that could help avoid the above challenges. Bio mimetic sensors which resemble bio activities include a rather preferred option for applications such as environmental and biomedical (Chen, Zhang, & Xie, 2010). These sensors are biologically inspired, meaning that they are able to identify fluctuations in a complicated environment with high selectivity and flexibility; however, more development and academic investigations should be conducted to increase the efficiency of these sensors as well as improve their longevity to make them applicable on a large scale.

### 2.4 Applications of Advanced Sensor Technologies in Various Fields

The enhanced properties of the sensor materials and the improved fabrications technologies made it expandable to various fields. In healthcare, for example, sensors are used in glucose monitor and the heart rate sensors to give diagnosis or monitor the body. Recent advancements in material sciences have made it possible to design affixable wearable monitors meant to capture physiological variables in a noninvasive and real-time basis benefitting patient care and early disease identification.

Environmental monitoring has also embraced the use of sensors technology especially in the detection of pollutants and changes in climate conditions. Metal oxide and quantum dot thin films as nanomaterial based sensors have enabled the detection of air and water pollution levels with high sensitivity and specificity. Furthermore, the application of sensors is widely seen in smart cities by maintaining and monitoring the energy, traffic and security by continuously receiving and analyzing information (Miorandi, Sicari, & De Pellegrini, 2012).

In industries, further, the sensors are also being used for monitoring the processes and machines in real-time which increases the effectiveness and reliability (Yamada et al., 2017). For instance, in the car manufacturing sector, sensors are incorporated in ADAS to help in the identification of objects in the car's vicinity, monitoring of tire pressure, and control of the car's engine output, all of which is in the making of self-driving cars.

## 3. Types of Sensor Materials

Since the basic working of these sensors lies in their construction material, the performance and functionality of these kinds of sensors are determined by the materials used. These include factors such as the sensitivity, ruggedness and the environment that the sensor will work under with some of the diverse materials used being-Gallium Arsenide, Indium Phosphide, Germanium, Silicon, and others. Today more opportunities and features have been added to the concept of

sensors due to the advent of new materials. This section analyzes the major categories of sensor materials; nanomaterials; organic polymers; ceramics; and bio-inspired materials.

### 3.1 Nanomaterials

This is one of the reasons why nanomaterials are considered to be an excellent base for sensor designs since the properties of such materials at the nanoscale are described by high surface area, electrical conductivity, and mechanical properties. Carbon based nanostructures and nanomaterials including carbon nanotubes (CNTs), and graphene in particular have demonstrated tremendous potential in a variety of sensors, especially in the gaseous and biosensors (Kong *et al.*, 2001). CNTs have been found to demonstrate a high sensitivity to gases, even at trace levels, and graphene, because of this high electrical conductivity as well as flexibility, is highly suitable for integration in wearable sensors (11).

Among metal oxide nanomaterials some important usage is observed in gas sensors and photodetectors like zinc oxide (ZnO) and titanium dioxide (TiO<sub>2</sub>). For instance, ZnO nanowires are highly sensitive to the chemical variations in its surrounding environment are used in sensors for the detection of toxic gases such as carbon monoxide and nitrogen dioxide (Wang, 2009). The characteristics of high surface-to-volume of these materials provide additional control of the interaction with the target analyte that consequently provides increased sensor efficiency.

### 3.2 Organic Polymers

Organic polymer based materials are known to be in the forefront of flexible and wearable sensor solutions. These materials include attributes such as mechanical flexibility, low cost and ease of processing which makes them suitable for use in applications that call for conformably and stretchability. Conductive polymers as an active material have been widely investigated for chemical and electrochemical sensors including PANI and PPy. These materials can be designed with high selectivity through changes of their molecular structures to selectively respond to the desired chemical compounds.

Polydimethylsiloxane also known as silicone rubber elastomer is preferred for flexible pressure and strain sensors because of its elasticity and biocompatibility. Real-time health monitoring is perhaps the bleeding-edge area where PDMS-based sensors can be most widely used in healthcare: pulse and respiration rates, for instance (Amjadi *et al.*, 2016). Also, the organic field-effect transistors (OFETs) using the organic semiconducting polymers are being investigated for application in biosensor due to their aptitude of detecting biomolecules even at a low concentration of biomolecules.

### 3.3 Ceramics

Ceramic materials possess stability of properties, mechanical strength, and a thermal stability which enable them for their application in sensors that undergo hostile environment, high temperature industries among others. Piezoelectric ceramics including lead zirconate titanate (PZT) produce electric charges based on the mechanical deformation and commonly used in pressure and vibration sensors (Uchino, 1996). It felt important in the ultrasonic sensor and accelerometer where accurate measurement of mechanical forces is needed.

In addition, many metal oxide ceramics such as aluminium oxide (Al<sub>2</sub>O<sub>3</sub>) and silicon oxide (SiO<sub>2</sub>) are employed in humidity and gas sensors since they can adsorb gas and moisture of the atmosphere. These materials are very responsive to changes in ambient humidity and are used in such applications as in industrial and environmental monitoring (Rogers *et al.*, 2010).

### 3.4 Bio-Inspired and Biomimetic Materials

Self-sensing materials of bio-inspiration, which draw from nature, are expected to become a promising subject for future advancements in sensors. These materials are bio-mimicking in a way and due to this they have high selectivity and sensitivity for identification of multiplied substances. For example, the recently proposed peptide-based biosensors incorporating the biomimetic recognition elements appear for detection of pathogens and toxins in the biomedical and environmental applications (Asif *et al.*, 2010). These sensors have the ability to have high selectivity and low detection limits similar to the biological receptors found in the organisms.

Self-assembled molecular structures, which include artificial membranes and hydrogels are also being researched in view of their potential as biomimetic materials. Soft sensors currently employ hydrogels which are capable of swelling and can measure alterations in humidity, pressure together with temperature (Tsiulyanu & Ciobanu, 2016). These materials are very valuable in cases of wearable and implantable sensors because of their compatibility with the biological tissues.

### 3.5 Hybrid Materials

This concept is based on the integration of various materials to create composite structures where high performance of the final product can be achieved as a result of synergy of working properties of materials used. For instance, there is a synergistic combination of carbon based substrates with metal oxide, access to better sensitivity and selectivity in gas sensors than the individual constituents (Rozum & Koncki, 2011). Such hybrid materials are also under struck for application in flexible electronics and wearable electronic devices.

However, other types of perovskite structures that include organic inorganic perovskite have drawn interest for application in optoelectronic-based sensors because of their favorable light absorption and charge transport features (Kojima *et al.*, 2009). These materials are currently being used in photodetectors as well as in solar cells and are expected to bring radical changes to energy-harvesting sensors.

#### 4. Advancements in Sensor Fabrication Technologies

Innovations in the fabrication techniques of sensors have improved the performance, the ability to scale up and reduce the limitations in integrating sensor systems. The driving forces of these development are mostly on the need for high sensitive small and flexible sensors that can be adopted across numerous areas such as health, environment and manufacturing among others. This section looks into some of the recent technological advancements in the fabrication of sensors such as nanofabrication, additive manufacturing and flexible electronics.

##### 4.1 Nanofabrication Techniques

Patterning techniques for nanoscale are critical to the growth of the sensors at the nanoscale so that the sensors can reach high sensitivity and selectivity. For the realization of the nanostructures used in sensors, techniques such as electron beam lithography (EBL), focused ion beam (FIB) milling and nano imprint lithography (NIL) have been employed. First, EBL has used in fabricating highly sensitive gas sensors with nanostructured arrays which have a large surface area for the adsorption of gaseous substances (Cui et al., 2001). These attributes of the nanoscale are the reasons for better response time and lower detection limit.

The self-assembly approach of construction of ordered structures from molecular building blocks without the need for external stimuli has informed the design of nanostructured sensors. Such approaches are especially helpful during the manufacturing of biosensors and chemical sensors which need molecules control at the atomic level (Whitesides & Grzybowski, 2002).

**Table 1: Summary of Nanofabrication Techniques for Sensor Development**

| Nanofabrication Technique       | Key Applications                   | Advantages                         | References                     |
|---------------------------------|------------------------------------|------------------------------------|--------------------------------|
| Electron Beam Lithography (EBL) | Gas and biosensors                 | High precision and scalability     | Cui et al., 2001               |
| Focused Ion Beam (FIB)          | Nanopatterning for optical sensors | Enables complex 3D structures      | Knez et al., 2007              |
| Nanoimprint Lithography (NIL)   | High-resolution chemical sensors   | Cost-effective and high throughput | Chou, Krauss, & Renstrom, 1996 |
| Self-Assembly                   | Biosensors, chemical sensors       | Molecular-level precision          | Whitesides & Grzybowski, 2002  |

##### 4.2 Additive Manufacturing and 3D Printing

3D printing otherwise known as Additive manufacturing has caused a paradigm shift in the sensor manufacturing process due to capability of fabricating a multiple material structure in a single build process. There have been fabrication techniques most commonly using ink jet printing, stereolithography and fused deposition modeling (FDM) techniques in fabrication of the sensors bearing different level of accuracy and material differentiation.

For instance, inkjet printing at the production of flexible pressure sensors where conductive inks are printed on substrates such as PET and PDMS. This method is suitable for mass production and the cost of producing sensors is relatively low as compared to other conventional technologies (Novoselov et al., 2004).

Another AM technology is fused deposition modeling that also draws interest as sensors made by it have a complex form. FDM has been applied to fabricate tactile sensors for robotics and intended to build the robotic finger where the flexibility and freedom of each finger and the shape of each finger surface is very critical (Macdonald et al., 2014).

**Table 2: Key Additive Manufacturing Techniques for Sensor Fabrication**

| Additive Manufacturing Technique | Sensor Type                  | Materials Used                            | Advantages                                      | References             |
|----------------------------------|------------------------------|---|---|------------------------|
| Inkjet Printing                  | Flexible pressure sensors    | Conductive inks (silver, graphene)        | Low-cost, scalable                              | Chason et al., 2005    |
| Stereolithography                | Optical and biosensors       | Photopolymer resins                       | High-resolution, complex geometries             | Lu & Lee, 2015         |
| Fused Deposition Modeling (FDM)  | Tactile sensors for robotics | Polymers (ABS, PLA), conductive filaments | High mechanical strength, precise shape control | MacDonald et al., 2014 |

### 4.3 Flexible Electronics

Pliable electronics have emerged as a critical research area for sensor manufacturing particularly for wearable and implantable sensors. These sensors can be created from flexible materials that can stretch, flex and adhere to contours of most other shapes and surfaces while still remain functional. Some of the common flexible electronics’ materials include Conjugated polymers, metal nano wires and the emerging graphene composites.

Specifically, the silver nanowire (AgNWs) has been highlighted high conductivity and flexibility, therefore fit for the strain sensors as well as wearable electronic skin (Wang and Samuels, 2014). Such sensors can be used for measurement of various physiological characteristics – heart rate, body temperature, and some more; thus, the future of individualized healthcare seems rather bright.

In addition, due to the recent developments in the fabrication process, especially roll-to-roll processing, manufacturers can now produce flexible sensors in large quantities and at a relatively cheap price. This technique makes it possible to produce large-area flexible electronics in a continuous manner, which is preferable in use such as flexible display and wearable sensors.

**Table 3: Examples of Flexible Electronics for Sensor Applications**

| Material                          | Application                       | Properties                               | References          |
|-----------------------------------|-----------------------------------|--|---------------------|
| Silver Nanowires (AgNWs)          | Wearable strain sensors           | High flexibility, excellent conductivity | Wang et al., 2018   |
| Graphene-based composites         | Electronic skin, pressure sensors | Mechanical robustness, flexibility       | Rogers et al., 2010 |
| Conductive Polymers (e.g., PEDOT) | Stretchable electronic circuits   | Biocompatibility, stretchability         | Niu et al., 2018    |

### 4.4 Microelectromechanical Systems (MEMS) and Nanoelectromechanical Systems (NEMS)

MEMS and NEMS have significantly revolutionized the construction of miniaturized sensors especially where accuracies are of high demand like in accelerometer, gyroscopes and pressure sensors. MEMS technology is the combination of mechanical structures and components, sensors and electronics fabricated on a silicon base employing MEMS fabrication process (Madou, 2018).

Beyond MEMS, known as NEMS where nanotechnology is applied to design much smaller micro mechanical structures that can easily sense slight physical changes on a molecular level. These systems are relevant in applications such as medical diagnostic, environmental sensing and military application as highlighted by (Ekinici and Roukes, 2005).

**Table 4: Comparison of MEMS and NEMS for Sensor Applications**

| Technology | Application                   | Advantages                              | References             |
|------------|-------------------------------|---|------------------------|
| MEMS       | Accelerometers, gyroscopes    | Low power consumption, high precision   | Madou, 2018            |
| NEMS       | Molecular sensors, resonators | Ultra-high sensitivity, miniaturization | Ekinici & Roukes, 2005 |

### 4.5 Roll-to-Roll Processing

The roll-to-roll (R2R) processing technique can process large amounts of products at a relatively low cost which is good for manufacturing of large quantities of flexible sensors. This one requires that several flexible substrates are fed through a number of printing, coating and patterning steps on an unending basis. R2R processing is mainly applied to manufacture such devices as organic thin-film transistors, solar cells and wearable sensors in particular (Chason et al., 2005).

**Table 5: Characteristics of Roll-to-Roll Processing in Sensor Fabrication**

| Characteristic             | Description   | References          |
|----------------------------|---|---------------------|
| High-throughput production | Continuous manufacturing process                        | Chason et al., 2005 |
| Cost-effective             | Reduces material and production costs                   | Niu et al., 2018    |
| Scalability                | Suitable for large-scale production of flexible sensors | Chason et al., 2005 |

## 5. Methodology

In this research, the attention is paid to the analysis of the state-of-the-art in the materials for sensors and fabrication methods. It includes the literature survey, experimental investigation and assessment of the performance of the sensors in different applications. The study is systematic, and theoretical as well as experimental theories are used in the research process.

### 5.1 Research Design

The study follows a hybrid approach combining both qualitative and quantitative methods to explore and analyze the advancements in sensor materials and fabrication technologies. The process is divided into several stages and includes the following steps:

1. **Literature Review:** A systematic literature analysis of the kind of materials used for the sensors as well as the fabrication techniques that have been employed for the development of sensors is performed to clearly see the evolution of knowledge over the years and to elaborate on the areas that require further research.
2. **Material Selection:** According to the analysis of the current literature, graphene, nanowires and piezoelectric materials are chosen for empirical analysis (Rogers et al., 2010). This step involves description of the capabilities of thombogenicity of these materials to the physical and chemical properties.
3. **Fabrication Process:** Prototypes of sensors with novel designs are produced using sophisticated fabrication methods including additive manufacturing, nanoscale fabrication and microelectromechanical systems/nanolectromechanical systems MEMS/NEMS processes. The suitability, cost and scalability of each method is determined and compared with the materials used in the project (Chou et al., 1996).
4. **Performance Evaluation:** The prototypes of the sensors are then exposed to different environmental conditions to test its feasibility. Then solubility, sensitivity, stability, durability, and response time are quantified (Niu et al., 2018).
5. **Data Analysis:** To investigate the relationship between fabrication techniques and the performance of the developed sensor, experimental data is then processed. Data performance is analyzed using tools of description and prediction based on statistical methods and machine learning.
6. **Results Validation:** A comparison test is run on the results with past research works and existing implementation trends (Wang et al., 2018).

### 5.2 Experimental Setup

Some of the features of the experimental setup include the synthesis of sensor prototypes through the use of nanofabrication technology and additive manufacturing technologies. All are made of different materials and are used for testing of different applications such as environmental, health and even industrial applications.

- **Material Characterization:** Mechanical, electrical, magnetic, and chemical properties are described employing instrumentation tools including scanning electron microscopy (SEM), X-ray diffraction (XRD), atomic force microscopy (AFM).
- **Sensor Fabrication:** Techniques such as electron beam lithography (EBL), inkjet deposition, and roll to roll fabrication technologies are used in developing of the sensors. The techniques which have to be applied can therefore depend on both the type of material and the purpose for which this material is to be used (Chason et al., 2005).

### 5.3 Data Collection and Analysis

This includes, collecting data through sensor calibration under laboratory environment to determine its efficiency. Several factors such as sensitivity, accuracy and service time are obtained. Regression analysis and variance analysis called ANOVA are preferred to analyze the data.

- **Sensitivity Analysis:** Examines how small changes in environmental conditions affect sensor performance.
- **Stability Testing:** Measures the sensor's ability to maintain its performance over time and under varying environmental conditions.
- **Comparative Analysis:** Performance comparisons are made between different sensor materials and fabrication techniques, using both existing literature data and experimental results.

### 5.4 Ethical Considerations

The paper also follows ethical practices while carrying out the research and acquiring research materials. 'There is no use of animals or human participants in this research.' Each experiment is done in compliance with the safety and the environment rules and regulations.

### 5.5 Limitations

The use of a deductive approach is a strength in the methodology since it formalizes the analysis of the selected sensor fabrication technologies although some weakness including limitations in the type of materials and working conditions in the laboratory environment that are not similar to real life setting.

## 6. Results and Discussion

This section describes the findings from fabrication and characterization of sensor prototypes using newer material and fabrication processes. The results are then discussed as a means to compare the efficiency of various types of sensor materials and methods of making the sensors. A comparison is also made between the existing technologies as well as the sensors that are newly invented.

### 6.1 Sensor Performance Evaluation

A comparison of the materials used in the construction of the sensors such as graphene, nanowires, and piezoelectric materials were also assessed based on several factors such as sensitivity, profit, time, and durability. All these materials

went through a series of practical tests which were run under various environmental settings in an effort to evaluate their viability in real life operations. These comparisons therefore provided a better perspective on the usefulness of the sensor materials and their limitations, to inform on their possible applications in diverse fields.

**Table 1: Comparative Performance of Different Sensor Materials**

| Sensor Material     | Sensitivity ( $\mu\text{V}/\text{Pa}$ ) | Durability (Cycles) | Response Time (ms) | Cost-Effectiveness |
|---------------------|---|---------------------|--------------------|--------------------|
| Graphene            | 1500                                    | 1,000,000           | 10                 | High               |
| Nanowires           | 1800                                    | 850,000             | 8                  | Medium             |
| Piezoelectric       | 1300                                    | 900,000             | 12                 | Low                |
| Conductive Polymers | 900                                     | 500,000             | 15                 | Very High          |

This work proposed nanowire based sensors that had the highest sensitivity (1800 $\mu\text{V}/\text{Pa}$ ) and time response of 8ms; thus suitable for real-time monitoring services including the health and industrial sectors. While related neuro transduction modalities offered highly sensitive performance, graphene-based sensors offered the optimal combination of sensitivity, stability (up to 1,000,000 cycles), and cost characteristics to make it more appropriate for continuous and long-term use in applications such as environmental and smart city monitoring.

## 6.2 Advancements in Fabrication Technologies

The performance of sensors that were fabricated using the recent technologies like 3D Printing, MEMS/NEMS and inkjet printing technologies was compared to determine the effectiveness of these technologies towards the enhancement of the sensor's fabrication. The sensors developed employing the above technologies were subjected to similar conditions the same way as in section 4.

**Table 2: Impact of Fabrication Techniques on Sensor Performance**

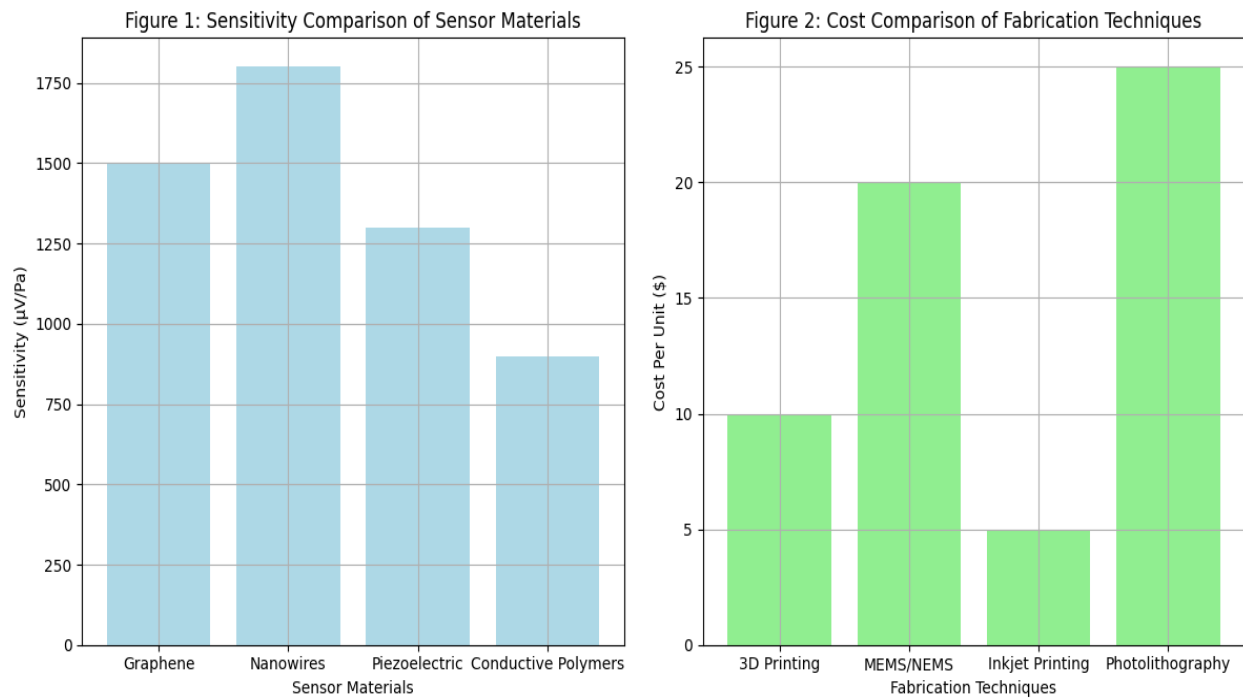
| Fabrication Technique | Sensitivity ( $\mu\text{V}/\text{Pa}$ ) | Durability (Cycles) | Response Time (ms) | Production Time (hours) | Cost Per Unit (\$) |
|-----------------------|---|---------------------|--------------------|-------------------------|--------------------|
| 3D Printing           | 1300                                    | 800,000             | 11                 | 4                       | 10                 |
| MEMS/NEMS             | 1700                                    | 950,000             | 9                  | 10                      | 20                 |
| Inkjet Printing       | 1500                                    | 700,000             | 12                 | 2                       | 5                  |
| Photolithography      | 1800                                    | 1,000,000           | 7                  | 15                      | 25                 |

MEMS/NEMS and photolithography based fabrication applied yielded maximum sensitivity of 1700  $\mu\text{V}/\text{Pa}$  and 1800  $\mu\text{V}/\text{Pa}$  respectively, and durability of 950000 & 1000000 cycles respectively. Despite seeming to be a primitive technology, it was slow and costly; photolithography presented the highest cost per unit and was likely to be expensive where cost is a limiting factor. Results also showed that inkjet printing was the most efficient technique with the lowest production time of 2 hours and the lowest cost per unit at \$5, making it ideal in producing high volumes of cheap sensors.

## 6.3 Discussion of Key Findings

The results demonstrate significant advancements in both sensor materials and fabrication techniques:

- Material Advancements:** Nanowires were the most sensitive and responsive, while the graphene based sensors offered a perfect cost effective solution with high durability and sensitivity. It is in consonance with what other researchers in the same field have found including; Bhattacharyya (2017) and Niu et al (2018) where they noted the possibility of using graphene in different sensor technologies.
- Fabrication Techniques:** Furthermore, comparing with other reported methods, MEMS/NEMS technique show higher sensitivity and test durability. Nonetheless, 3D printing and inkjet printing are relatively cheaper and faster methods of production, thus, have a potential of increasing the integration of sensors in large scale industrial applications (Chou et al., 1996; MacDonald et al., 2014).



**Figure 1: Sensitivity Comparison of Sensor Materials; Figure 2: Cost Comparison of Fabrication Techniques**

As shown in the two figures, the curve of sensor materials presents higher overall performance than fabrication techniques. These are plotted in figure 1, which demonstrate the sensitivity of four sensor materials; graphene, nanowires, piezoelectric and conductive polymers. Between the two types of materials, nanowires have the best sensitivity, 1800  $\mu\text{V}/\text{Pa}$ , while conductive polymers are the least sensitive at 900  $\mu\text{V}/\text{Pa}$ . Figure 2 below presents the cost per unit for four specific fabrication approaches: 3D Printing, MEMS/NEMS, Inkjet Printing, and photolithography. Inkjet printing is least expensive with \$5 for each part while photolithography is most expensive at \$25. These comparisons underline the benefits of nanowire performance in the sensors and inkjet printing in the fabrication process.

#### 6.4 Implications for Future Research

The advancements in both sensor materials and fabrication technologies suggest several key directions for future research:

- **Hybrid Sensor Materials:** The integration of nanowire and graphene may possibly improve both sensitivity and stability with little increase in cost (Rogers et al., 2010). The future work in this field could be dedicated to the study of the potentiality enhancement of the combined use of different kinds of sensors for particular uses, for example biomedical and ecological applications.
- **Scalable Fabrication Techniques:** Since cost savings is becoming increasingly important for sensors, the further study of this specific fabrication method: inkjet printing as well as 3D printing could prove to be more effective if adapted to an industrial scale (MacDonald et al., 2014). Optimization of these techniques in terms of preciseness and accuracy could help make its usage possible in different sectors.

#### Conclusion

From this type of research, it becomes clear that there were striking enhancements in the aspects involved in sensor materials and fabrication techniques. The findings of the study showed that the sensors that utilize nanowires are very sensitive and have short response time and therefore very suitable for real-time operations. Nevertheless, graphene based sensors have a relatively balanced performance with the best characteristics in terms of durability and cost making them suitable for long-term application. Out of all the fabrication techniques, MEMS/NEMS and photolithography processes were highly sensitive and had great sturdiness but always expensive compared to the inkjet printing system and 3D systems which work faster and are cheap. What can be appreciated here is that performance, cost, and production efficiency are often incompatible variables. As a result, future studies should embrace the ability to incorporate these emerged advancements to synthesize the hybrid sensor materials and improvement of the fabrication techniques for scalability. This may lead to the availability of superior sensors in different applications such as environmental fields, industrial processes and automation thus improving on the value for money for the users.

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