DEVELOPMENT OF REPLACEABLE SENSING ELEMENT TESTER FOR OPTICAL-BASED HUMIDITY SENSOR

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

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DEDICATION

Alhamdullilah prays to Allah because of favor and grace from Allah, this work is dedicated to Universiti Teknikal Malaysia Melaka (UTeM) who's without their requirement's this final year project wouldn't be possibly conducted. Besides that, this work is dedicated to my parents who have pass on love of giving and respect on the education that has demanded me to become a responsible and educated student. Never forget to my lecturer, I would like to thanks to my supervisor, Ir. Dr. Haziezol Helmi bin Mohd Yusof from Faculty of Electronics and Computer Technology and Engineering (FTKEK) who has given I courage, support, and guidance along my final year project. Also, thanks for giving me the knowledge and ideas on improvising this project. By all the above who has contributed support and courage to who's without this courage's dedicating it's over and over. I would doubtfully have a lot of confidence and wouldn't be brave enough to end this project perfectly and smoothly.

ABSTRACT

The project is about the development of a sensing element tester on optical -based humidity sensor device. There were many research studies on the optimization of ZnO nanorods growth condition such as ZnO growth durations, ZnO nanorods coating area or growth process parameters towards optimum sensing response for humidity detection. However, researchers faced inconsistency issues when they had to re-setup the device for testing every sample they tested which cause variations in the measurements and difficult to conclude the optimized parameter for the best sensing response. Therefore, a sensing device with the capability of a replaceable sensing material was needed to ensure the consistency of the sensing setup. This project utilized a glass substrate as the light medium, with a commercial Light-Emitting Diode (LED) as the light source and a photodiode as the photodetector placed at both ends of the glass so that the light travels from the LED towards the photodiode through the glass substrate. ZnO nanorods were fabricated on the surface of several thin microscope cover glasses with variations in growth duration. This enables the ZnO-coated thin cover glass easily replaced on the glass substrate without affecting the sensor setup. The fabricated samples were then characterized against humidity sensing and analyzed the impact of growth durations. It was found that the sample with 9 h of growth time exhibited higher output voltage reading as compared to 3 h sample during initial characterization without humidity sensing. In humidity sensing, it was observed that the 9 h sample produced higher sensing response towards humidity detection with the sensitivity of -6.77 mV/%. This project helps researchers streamline the optimization process of sensing performance and enhanced the consistency of measurement.

ABSTRAK

Projek ini adalah mengenai pembangunan ujian elemen sensor pada peranti pengesan kelembapan berasaskan optik. Terdapat banyak kajian penyelidikan mengenai pengoptimuman syarat tumbesaran nanorod ZnO seperti tempoh tumbesaran ZnO, kawasan pemercikan nanorod ZnO, atau parameter-proses tumbesaran ke arah tindak balas pengesan kelembapan yang optimum. Walau bagaimanapun, para penyelidik menghadapi isu ketidakseragaman apabila mereka perlu menyusun semula peranti untuk menguji setiap sampel yang mereka uji, yang menyebabkan variasi dalam pengukuran dan sukar untuk membuat kesimpulan mengenai parameter yang dioptimumkan untuk tindak balas pengesan terbaik. Oleh itu, diperlukan satu peranti pengesan dengan keupayaan menggunakan bahan pengesan yang boleh digantikan untuk memastikan konsistensi penyusunan pengesan. Projek ini menggunakan substrat kaca sebagai medium cahaya, dengan Light-Emitting Diode (LED) komersial sebagai sumber cahaya dan fotodiod sebagai fotodetektor diletakkan di kedua hujung kaca agar cahaya bergerak dari LED ke fotodiod melalui substrat kaca. Nanorod ZnO telah difabrikasi di permukaan beberapa gelas mikroskop nipis dengan variasi dalam tempoh pertumbuhan. Ini membolehkan gelas nipis yang dilapisi ZnO digantikan dengan mudah pada substrat *kaca tanpa mempengaruhi penyusunan sensor. Sampel yang difabrikasi kemudian dicirikan terhadap pengesan kelembapan dan analisis kesan tempoh pertumbuhan. Ditemui bahawa sampel dengan tempoh pertumbuhan 9 jam menunjukkan bacaan voltan keluaran yang lebih tinggi berbanding sampel 3 jam semasa pencirian awal tanpa pengesan kelembapan. Dalam pengesan kelembapan, diperhatikan bahawa sampel 9 jam menghasilkan tindak balas pengesan yang lebih tinggi terhadap pengesan kelembapan dengan kepekaan -6.77 mV/%. Projek ini membantu para penyelidik menyusun proses pengoptimuman prestasi pengesan dan meningkatkan konsistensi pengukuran..*

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ZnO	:	Zinc Oxide
SnO2	:	Tin Dioxide
WO3	:	Tungsten Trioxide
TiO2	:	Titanium Dioxide
LED	:	light-emitting diode
IM/DD	:	intensity-modulated/direct-detection
3D	:	3-Dimentional
PLA	:	Polylactic Acid
GPS	:	Global Positioning System
FOS	:	Fiber Optical Sensing
RH	:	Relative Humidity
AH	:	Absolute Humidity
APDs	:	Avalanche Photodiodes
P	:	Positive
N	:	Negative
AM	:	Amplitude Modulation
FM	:	Frequency Modulation
UV	:	Ultraviolet

c	:	Speed of light
v	:	Frequency
λ	:	Wavelength
σ	:	Sigma
n	:	Refractive Index
I	:	Intensity
CAD	:	Computer Aided Design
TIA	:	Transimpedance Amplifier
Rf	:	Feedback Resistor
Cf	:	Feedback Capacitor
Op - Amp	:	Operational Amplifier
PCB	:	Printed Circuit Board
$(CH_3)_2CO$	:	Acetone
CH_3CH_2OH	:	Ethanol
NaOH	:	Sodium Hydroxide
$Zn(CH_3COO)_2(H_2O)_2$	:	Zinc Acetate Dihydrate
$C_6H_{12}N_2$	:	Hexamethylenetetramine (HMT)
$Zn(NO_3)_2 \cdot 6H_2O$	:	Zinc Nitrate Hexahydrate
DI Water	:	Deionized water
PTFE	:	Polytetrafluoroethylene
L	:	Length
W	:	Width
C	:	Celsius

CHAPTER 1

INTRODUCTION

This chapter briefly explains about the background project, problem statement, objectives of the project, the scope of the project and report structure.

1.1 Background Project

Humidity sensors are crucial in various sectors, including industrial, agricultural, environmental, and medical fields [1]. Electronic humidity sensors, commonly used in modern automatic systems, are best suited for their impedance or resistance and capacitance detection schemes. However, optical humidity sensors offer several advantages over electronic sensors. The use of light rays instead of electrical current, providing immunity to electromagnetic interference and ensuring safety when working with flammable substances. Optical sensors are sensitive, inexpensive, nondestructive, and versatile [2]. It requires nanomaterials as sensing elements, with Zinc Oxide (ZnO), Tin Dioxide (SnO_2), and Tungsten Trioxide (WO_3) being commonly used due to their effective light absorption characteristics [3].

In this research, Zinc Oxide (ZnO) was chosen as the sensing element due to its high sensitivity to gases, including humidity, and its ability to perform well across a wide temperature range. The hydrothermal synthesis [4] [5] method was employed for ZnO nanorods growth, offering a cost-effective and simpler alternative to other coating techniques. ZnO nanorods were fabricated on a thin cover glass, which serves as a replaceable sensing element. The thin cover glass has minimal impact and is cost-effective compared to using thicker substrates [6]. The sensor device consists of a commercial light-emitting diode (LED) [7] as the light source, a standard microscope glass substrate to carry light, and a photodiode placed at the edge of the sensor body setup that closer to the glass substrate as the photodetector. A visible light with a central wavelength of 525nm (green LED) [8] was used in the sensor system. An Arduino platform was utilized for signal processing and display, providing a simpler alternative to more complex options. The humidity sensing device is based on the intensity-modulated/direct-detection (IM/DD) method [7], which utilizes the output light's intensity to measure humidity levels. This cost-effective optical communication strategy finds wide applications in fiber communication, free-space optical communication, and indoor visible light communication. Addressing that, the aim of this project is to develop an effectiveness of replaceable sensing tester device on sensing medium, as well as can enhance the consistency of measurement, while this research requires to create a user-friendly, cost-effective optical sensing tester device.

1.2 Problem Statement

In the field of humidity sensing, ZnO nanorods have been a significant technological advancement. To improve sensitivity and system performance, which reduces the complexity of signal detection and processing, it is crucial to optimize the growth process and the coating area. In spite of optimization work on the ZnO synthesis process exhibits that the most effective sensing response occurred when compared with their unique optimum growth parameters, there are still inconsistencies in terms of the ideal growth conditions connected to the performance between the sensor body devices [7]. However, researchers encountered inconsistency problems when they had to re-setup the sensor body for testing on several samples with different growth conditions such as durations or area. Therefore, a sensing device with capability of replaceable sensing material is needed to ensure the consistency of the sensing setup.

1.3 Objective

Concerning the problem statements outlined in the previous section, the objective is listed below:

1. To design and develop an integrated sensing tester device with a built-in amplifier circuit into a 3D printed sensor's body.
2. To fabricate Zinc Oxide nanorods on the thin cover glass surface for replaceable sensing element using hydrothermal method.
3. To analyze the performance of the developed sensing tester device towards humidity detection.

1.4 Scope of Work

The sensing medium used was a glass substrate. ZnO nanorods were fabricated via a hydrothermal method on several thin cover glasses with different growth durations (3h, 6 h, and 9 h). An LED (green) visible light with a central wavelength of 525nm was used as a light source. An amplifier chip of LT1884 was used in the project, and the sensor body setup was made of Polylactic Acid (PLA) filament, which was printed using a 3D printer. The photodiode model SFH203 was utilized as a photodetector for the project, and an Arduino microcontroller was used for signal processing.

1.5 Report Structure

This thesis consists of five chapters demonstrating the Development of Replaceable Sensing Elements Tester for Optical-based Humidity Sensor.

Chapter 1 focuses on the introduction regarding the research background and problem statements. The objectives and scope of works of the research are also highlighted in this chapter.

Chapter 2 a literature review on related research topics. This includes the role of sensors, thin glass substrate as sensing elements, types of optical sensors, nanomaterials material synthesis method and ZnO particles. .

Chapter 3 explains in detail the methodology briefly. This chapter discusses the implementation of hardware and software. It also includes a fabrication process of ZnO nanomaterials coating on thin glass substrates. The optical optimization on the effect of growth conditions of the fabricated ZnO nanorods.

Chapter 4 presents the outcomes of the proposed project based on the three objectives, as well as the associated costs.

Chapter 5 presents the overall accomplishments of the proposed project based on Chapter 1's three objectives. This chapter concludes with a number of ideas for future enhancements.

CHAPTER 2

LITERATURE REVIEW

This chapter covered the relevant findings and serve as the primary source of data, providing support and evidence for this project.

2.1 Background Study

Sensor technology has enhanced the daily lives of people through its applications across various fields. Sensors are devices or components designed to detect changes in the surrounding environment and collect signals, enabling appropriate responses. These sensors come in various types, such as those for light, temperature, motion, humidity, and pressure, and find applications in diverse areas, including lifestyle, healthcare, fitness, manufacturing, and daily routines [9]. Current industrial trends driving innovation involve technologies like ultrasound, radar, touchless optoelectronic solutions, and laser technology [10].

Sensors play a crucial role in converting physical phenomena into measurable digital signals, which can then be displayed, read, or processed further. Various experts and researchers classify sensors in multiple ways. In one classification, sensors are categorized into Active and Passive types [10]. Active sensors require an external excitation signal or power source to operate, while passive sensors do not rely on external power and generate output responses independently. For instance, active sensors like GPS and radar require an external power source, while passive sensors, also known as self-generated sensors, produce their electrical signals and operate without external power this can be relate with illustration view on the working of sensor in Figure 2.1. These include thermal sensors, electric field sensors, and metal detectors. Sensors' detection methods serve as another basis for classification. These methods encompass electrical, biological, chemical, radioactive, and other approaches. Another classification focuses on conversion phenomena, distinguishing between input and output. Common conversion processes include thermoelectric, photoelectric, electrochemical, electromagnetic, thermo-optic, and others.

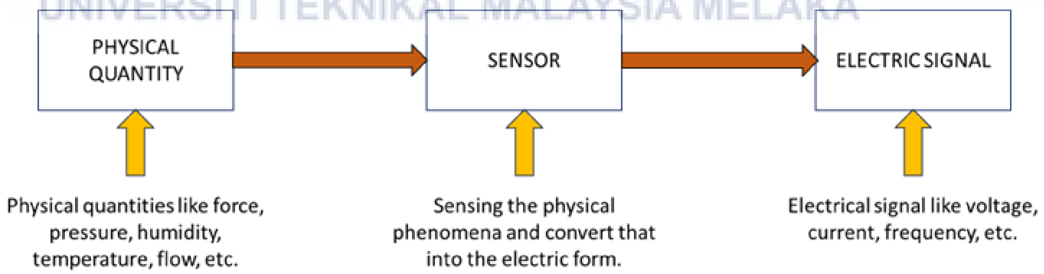


Figure 2.1 Illustration view on the working of sensor

Optical humidity sensors are a type of sensor that utilizes the light absorption or reflection capabilities of humidity-changing materials. To estimate humidity levels, to measure light intensity or spectral shifts. Depending on how the used of light, optical humidity sensors are classified into several sensors such as absorption-based sensors, fluorescence-based sensors, and light scattering sensors [11]. All of these optical humidity sensors are based on the interaction of light with humidity-sensitive materials. It gives a way to assess and quantify humidity levels in the surrounding environment by monitoring changes in light intensity, wavelength, or scattering pattern. These sensors have features such as durability to electromagnetic interference, quick reaction time, and accuracy, making an appropriate for a wide range of applications requiring precise humidity control. In the context of optical sensors, the concept of extrinsic and intrinsic terms refers to the properties of the detecting substance utilized in the sensor.

2.2 Optical Sensor

An optical sensor is a device that uses light to detect and measure physical or environmental properties. [12] It operates on the principle that certain materials or components respond to changes in light, whether in intensity, wavelength, or other optical properties, and converts these changes into measurable electrical signals. Optical sensors have a wide range of applications due to their sensitivity, precision, and immunity to electromagnetic interference [13]. It can be used to measure various parameters, including light intensity, color, motion, position, and environmental factors like humidity and gas concentrations.

Some common types of optical sensors include photodiodes for light detection, color sensors for identifying and classifying colors, and optical encoders for measuring position and movement. Optical sensors are widely used in industries such as manufacturing, automotive, telecommunications, healthcare, and environmental monitoring [13]. In the context of environmental monitoring, optical sensors are particularly useful for applications like humidity sensing, where it can provide high precision and resistance to electromagnetic interference [14]. Optical sensors have a diverse range of applications and are valued for their accuracy and versatility in measuring optical properties.

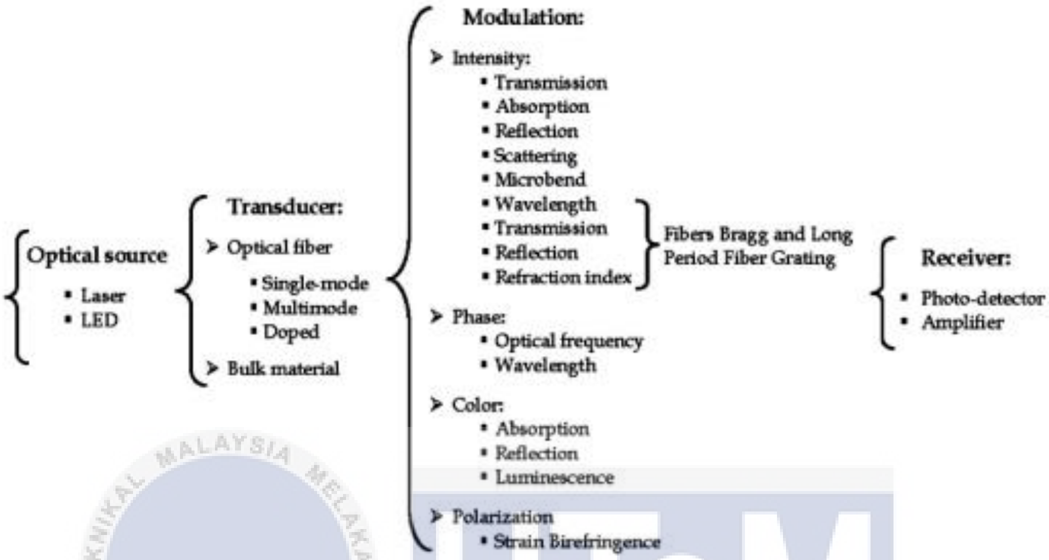


Figure 2.2 Basic Components of an Optical Sensor

Source: Naseer Sabri et al (DOI 10.1088/1742-6596/423/1/012064)

Figure 2.2 provides a detailed representation of the components of an optical source, which can be a laser, LED, or laser diode. The optical fiber used in Fiber Optic Sensing (FOS) devices can be either single-mode or multi-mode [15]. Additionally, there is a sensing or modulator element present, which serves to transduce the measured quantity into an optical signal. Furthermore, an optical detector and actuating circuitry are included, which consist of processing electronics, an oscilloscope, or an optical spectrum analyzer, to name a few examples. Amplitude, phase, color (spectral signal), and state of polarization are among the optical properties that can be manipulated in FOS devices [16]. The following are the optical modulation techniques used by the sensors shown in Figure 2.3.

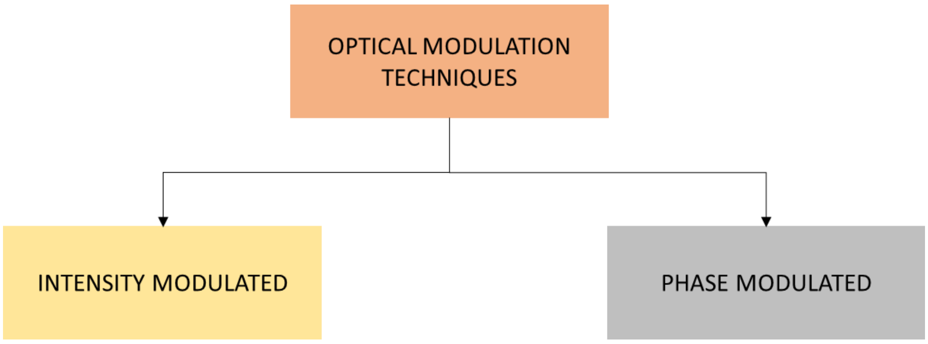


Figure 2.3 The Optical Modulation Techniques

Intensity-Modulated Sensors, the detection of variations in light intensity, which are proportional to the disturbances in the surrounding environment, can be achieved through the use of sensors. The fundamental concepts associated with intensity modulation include transmission, reflection, and micro bending. In order to incorporate these concepts into optical fibers, either a reflective or transmissive target can be utilized. Additionally, there are other mechanisms that can be employed independently or in combination with the primary concepts, such as absorption, scattering, fluorescence, and polarization [17]. Therefore, the intensity modulation serves as a valuable technique for the development of optical sensors, enabling the measurement of perturbations in the environment by monitoring variations in light intensity. Its versatility in utilizing different mechanisms and its compatibility with various types of fibers make it a powerful tool in the field of sensing technology.

Phase-Modulated Sensor [17], an interferometer is a device that compares the phase of light in a detecting fiber to a reference fiber. Two single-mode fibers and a coherent laser light source are used in these sensors. After splitting, the light passes into the sensing and reference fibers. A phase shift happens between them if the light in the detecting fiber is subjected to the perturbing environment. The interferometer detects the phase shift. Compared to intensity-modulated sensors, phase-modulated sensors have substantially higher accuracy. While polarization is correlated with strain birefringence, color variations are proportionate to changes in the optical signal's absorption, transmission, reflection, or luminescence.

2.3 Types of Optical Sensor

2.3.1 Intrinsic Optical Sensor

An intrinsic optical sensor is a type of optical sensor that utilizes the intrinsic properties of the sensing material to measure the target parameter, such as humidity [12]. It operates based on the changes in the optical properties of the material itself, such as absorption, reflectance, or fluorescence, in response to the target parameter. In an intrinsic optical humidity sensor, the sensing material is selected or engineered to exhibit a specific optical response to changes in humidity. When the humidity level changes, it affects the interactions between the water molecules in the air and the sensing material, leading to variations in the material's optical properties. These variations are then detected and quantified to determine the humidity level. The advantage of intrinsic optical sensors is that can offers a high sensitivity and selectivity to the target parameter. By tailoring the properties of the sensing material, it is possible to optimize the sensor's response and accuracy [12]. However, intrinsic sensors may require careful calibration and compensation for environmental factors, such as temperature changes, to ensure accurate measurements.

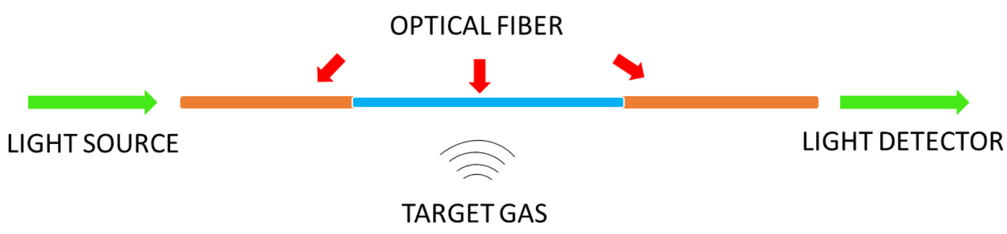


Figure 2.4 Diagram of Intrinsic Optical Sensor

2.3.2 Extrinsic Optical Sensor

An extrinsic optical sensor, also known as an indirect optical sensor, relies on an external element or probe to interact with the target parameter and then measures the resulting optical signal. In the case of humidity sensing, the external element may be a material that changes its optical properties in response to humidity, and the sensor detects the changes in the optical signal. For example, in an extrinsic optical humidity sensor, a material with humidity-sensitive properties, such as a polymer coating, may be applied to an optical fiber [12]. The moisture in the surrounding environment interacts with the coating, causing changes in its refractive index or light scattering characteristics. These changes can be measured by analyzing the changes in the intensity, wavelength, or phase of the light transmitted through the fiber. Extrinsic optical sensors offer advantages such as flexibility and remote sensing capabilities. The use of optical fibers allows for easy integration into complex systems, and the measurement can be performed at a distance from the sensing element. However, extrinsic sensors may require additional components and signal processing techniques to interpret the optical signals accurately.

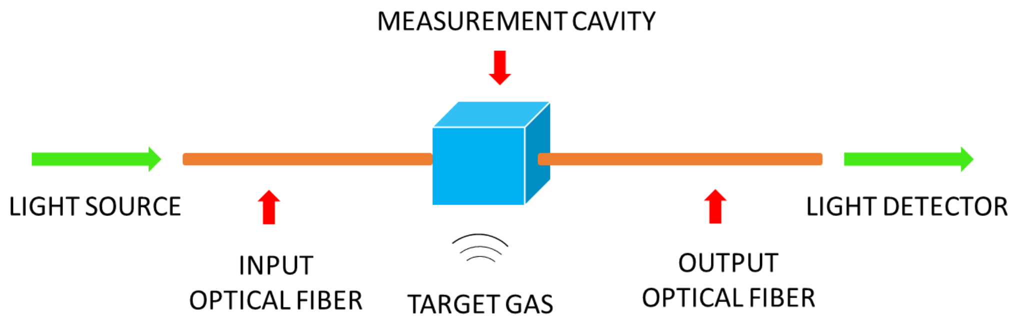


Figure 2.5 Diagram of Extrinsic Optical Sensor.

2.4 Humidity Sensor

Humidity is a very common component in our environment, and humidity measurements and control are essential not just for human comfort but also for a wide range of industries and technology [18]. Humidity sensors operate on the principle that certain materials change their electrical, mechanical, or optical properties in response to humidity variations [18]. These variations are then monitored and transferred into a readable output signal indicating the humidity levels. Humidity sensors can be categorized into two groups based on the method to measure humidity: relative humidity (RH) sensors and absolute humidity (AH) sensors. Relative humidity sensors determine humidity by comparing the current humidity reading at a specific temperature to the maximum humidity that can be present in the air at that temperature. To calculate relative humidity accurately, these sensors also need to measure temperature. On the other hand, absolute humidity sensors directly measure humidity without considering the temperature [19]. It is classified into four types: resistive humidity sensors, capacitive humidity sensors, thermal conductivity humidity sensors, and optical humidity sensors [20] [21]. Each humidity sensor type has advantages and disadvantages as well. Optical sensors give better precision, immunity to electromagnetic interference, and quick response time, but more expensive. The humidity sensor to be used is determined by the application's specific needs, such as accuracy, response time, cost, ambient conditions, and required maintenance.

2.5 Nanomaterials Synthesis Methods

The unique class of materials known as nanomaterials appeared into existence. It includes a wide range of materials with at least one dimension between 1 and 100 nm. Designed nanomaterials may have exceptionally vast surfaces. Outstanding magnetic, electrical, optical, mechanical, and catalytic capabilities that differ significantly from their bulk counterparts can be produced from nanomaterials. It is possible to accurately manage the size, shape, synthesis conditions, and proper functionalization of nanomaterials to optimize their desired characteristics.

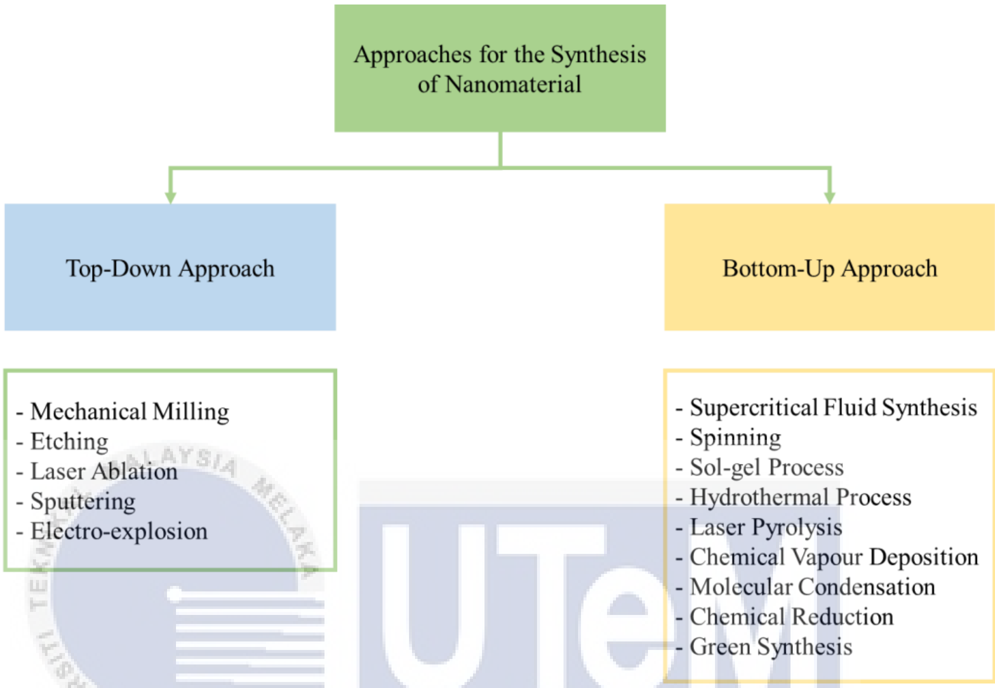


Figure 2.6 The synthesis of nanomaterials; Top-down and Bottom-down approaches.

2.6 Hydrothermal Synthesis Method

The hydrothermal process is one of the most widely used techniques for synthesizing nanostructured materials [22]. Hydrothermal synthesis offers several advantages, such as the ability to produce high-purity materials with controlled properties. It's also a versatile method for tailoring the size, shape, and structure of synthesized materials. While hydrothermal processes are valuable for materials synthesis, the high-temperature and high-pressure conditions can be energy-intensive and potentially have environmental impacts [23]. Examples of hydrothermal processes include the growth of nanomaterials like ZnO nanorods, the synthesis of zeolites for catalysis and adsorption, and the formation of certain minerals in geological settings.

These processes are vital in both scientific research and industrial applications to produce advanced materials.

2.7 Zinc Oxide Nanoparticles

There are numerous nanomaterials from semiconducting material oxides that have been used for the fabrication of gas sensors such as Zinc Oxide (ZnO), Titanium Dioxide (TiO2), Tin Oxide (SnO2) and Tungsten (VI) Oxide (WO3) [7]. These materials served as gas sensitive elements in which their properties such as conductance change upon the adsorption of gas molecules on their surface. ZnO is one of the most widely used materials for gas sensing applications due to its advantages in terms of good chemical stability, electrical compatibility, biocompatibility, and high electron transfer properties [24]. ZnO is a n-type semiconductor which has direct and wide band gap energy of 3.37 eV and a large exciton binding energy of 60mV [25]. The simple, low cost and environmental friendly fabrication process of ZnO makes it one of the popular choices among researchers. It also has a good optical transparency in visible spectrum which makes it useful for short wavelength optoelectronic application, resonators, biosensors, and medical devices.

2.8 Photodiode/Photodetectors

A photodiode is a semiconductor device that converts light into an electrical current through the photoelectric effect, where incident photons generate electron-hole pairs in the semiconductor material. This current allows photodiodes to detect and quantify light intensity [7]. Silicon photodiodes, a common example, are sensitive to a wide range of wavelengths, including visible and near-infrared light, making them versatile for various applications [26]. It is utilized as photodetectors in light meters, solar cells, and exposure meters for photography. In optical communication systems, silicon photodiodes play a critical role by converting modulated light signals into electrical ones, facilitating data transmission in fiber optic networks. Additionally, it can find application in spectrophotometers and spectrometers for material analysis and used in remote sensing and environmental monitoring to measure light across the visible and near-infrared spectrum. Furthermore, in scientific research and medical diagnostics, silicon photodiodes are essential for detecting and quantifying fluorescence emissions, supporting a wide array of laboratory experiments [27]. These photodiodes are available in different types, such as PIN photodiodes and avalanche photodiodes (APDs), each tailored to specific applications, renowned for their rapid response times, high sensitivity, and dependable light-to-electrical signal conversion.

Figure 2.7 Symbol for photodiode

Source: Photodiode (Arbind Kumar Malik)

2.8.1 Types of Photodiodes

a. PIN Photodiode

PIN photodiodes feature an additional intrinsic (I) layer between the P and N regions, creating a wider depletion region. This design enhances their sensitivity and reduces capacitance, allowing for higher-speed operation. PIN photodiodes are commonly used in optical communication, laser rangefinders, and scientific instrumentation [26].

The advancement and separation of electron-hole pairs in a semiconductor material upon exposure to light is the basis for the operation of a PIN photodiode. In Figure 2.8 depicts the explanation for working principle of PIN photodiode [28]. Through optical absorption, the PIN photodiode produces electron-hole pairs by absorbing incident light. Diffusion and the electric field cause the majority of the charge carriers in the depletion region—between the P-type and N-type layers—to be eliminated. An electric field pushes holes toward the P-side and electrons toward the N-side when reverse bias voltage is supplied. This makes it easier for charges to separate, which produces photocurrent. The photocurrent is directly correlated with the absorption efficiency and intensity of the incident light. It is possible to measure and analyze the produced photocurrent to learn more about the incident light.

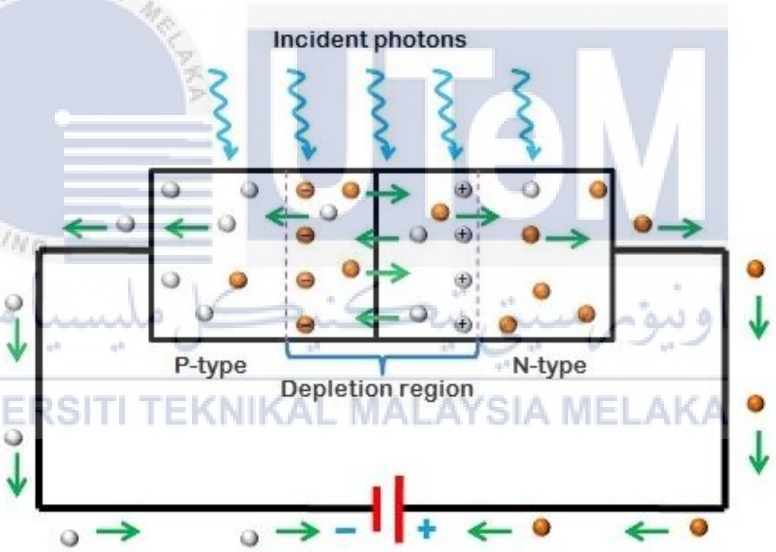


Figure 2.8 Working Principle of PIN Photodiode

Source: PIN Photodiode (https://quick-learn.in/pin-photodiode/)

b. Avalanche Photodiode (APDs)

Avalanche photodiode are highly sensitive photodiodes that exploit the avalanche effect to amplify the photocurrent. It also can detect very weak light signals and are often used in applications where extremely low light levels need to be measured, such as in lidar systems, fluorescence spectroscopy and low-light-level imaging [27]. The principles underlying Avalanche Photodiodes' operation combine electronics and optics in an efficient way. Primarily, the functioning of an APD may be divided into three primary phases: the process of light absorption, carrier multiplication, and gain regulation, in Figure 2.9 illustrates the APDs operating principle. In an APD, photon absorption produces electron-hole pairs that are prepared to conduct electricity. An "avalanche" process occurs when these couples are subjected to the internal electric field of the electronic device. Additional electron-hole pairs are produced via the avalanche process, where primary carriers are primary and secondary carriers are secondary. The APD's internal multiplication, which is regulated by the reverse-bias voltage applied, is represented by the gain factor. The output signal might become noisier [29] because of higher multiplication.

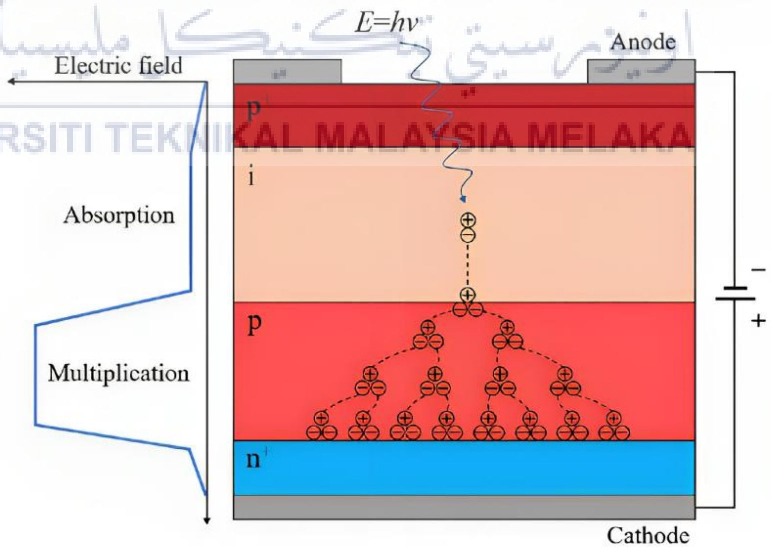


Figure 2.9 Working Principle for APDs Photodiode.

Source: Wang and Mu PhotoniX "High-speed Si-Ge avalanche photodiode"

2.9 Electromagnetic Radiation and Light

The electromagnetic spectrum is a fundamental concept in physics, encompassing various regions of electromagnetic waves with specific wavelengths, frequencies, and energies. Radio waves have the longest wavelengths and lowest frequencies, used in communication methods like AM and FM radio. Microwaves have shorter wavelengths and higher frequencies, used in microwave ovens, satellite communications, and radar technology. Infrared radiation, associated with heat, is used in thermal imaging cameras and wireless data transmission. Visible light, ultraviolet (UV) radiation, X-rays, and gamma rays are the highest-energy end of the spectrum [30]. Electromagnetic waves of all wavelengths travel exactly at the same speed in vacuum. The speed of light in a vacuum, or c, is the precursor to this fundamental constant of physics. The wavelength, λ, and frequency, *v*, are related $v = c\,\lambda^{-1}$. In contrast, waves can also be defined by inherent wave number, *σ*, which is the wavelength inverse, as $\sigma = \lambda^{-1}$. An electromagnetic wave's frequency remains unchanged when it passes through other mediums such as air, glass, or water, but its wavelength and speed are reduced by a quantity called n, which is the material's refractive index. The value of *n* is a function of frequency and ranges from 1.52 to 1.72 for often used optical glasses. The value of *n* for regular air is 1.00028 [31].

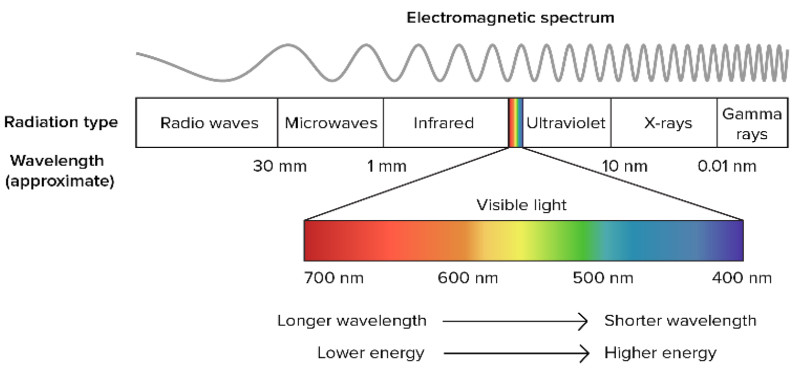


Figure 2.10 Electromagnetic Radiation

Source: Electromagnetic Spectrum Order. (n.d.). Mavink.com. [https://mavink.com/explore/Electromagnetic-Spectrum-Order]

CHAPTER 3

METHODOLOGY

This chapter covers the process of making decisions as well as the overall execution of the goal. This project's tasks were detailed, along with the precise equipment and materials that were used. This chapter describes in detail the experiment that determined the concentration of growth on tapered thin cover glass substrates coated with ZnO at three different time duration 3h, 6h, and 9h.

3.1 Flowchart of Methodology Research

The flowchart methodology of this research is shown in Figure 3.1. In this project, a sensor body setup was designed using Thinker CAD software. The design of the sensor body setup has a permanent holder for the glass substrate as the main sensing medium. An LED and photodiode were mounted at both edges of the sensor body, set up closer to the glass substrate, to serve as the light source and detector, respectively. The sensor body was manufactured through 3D printing via Ender 3 Pro. An amplifier with the LT1884 chip was used to amplify the output signal from the photodiode to a level that the Arduino could read. The amplifier circuit was then integrated with the 3D-printed sensing setup. Moreover, the ZnO nanorods were fabricated onto the surface of several thin cover glasses, with the variations in growth time being 3 h, 6 h, and 9 h. Besides, the proposed growth durations were implemented. The successfully coated thin cover glasses were characterized by humidity sensing. The coated thin cover glass was placed onto the surface of the glass substrate in the sensing setup to observe the sensing response at different humidity levels. The thin cover glass was replaced with another thin cover glass for different durations to analyze the effect of growth time on the sensing performance.

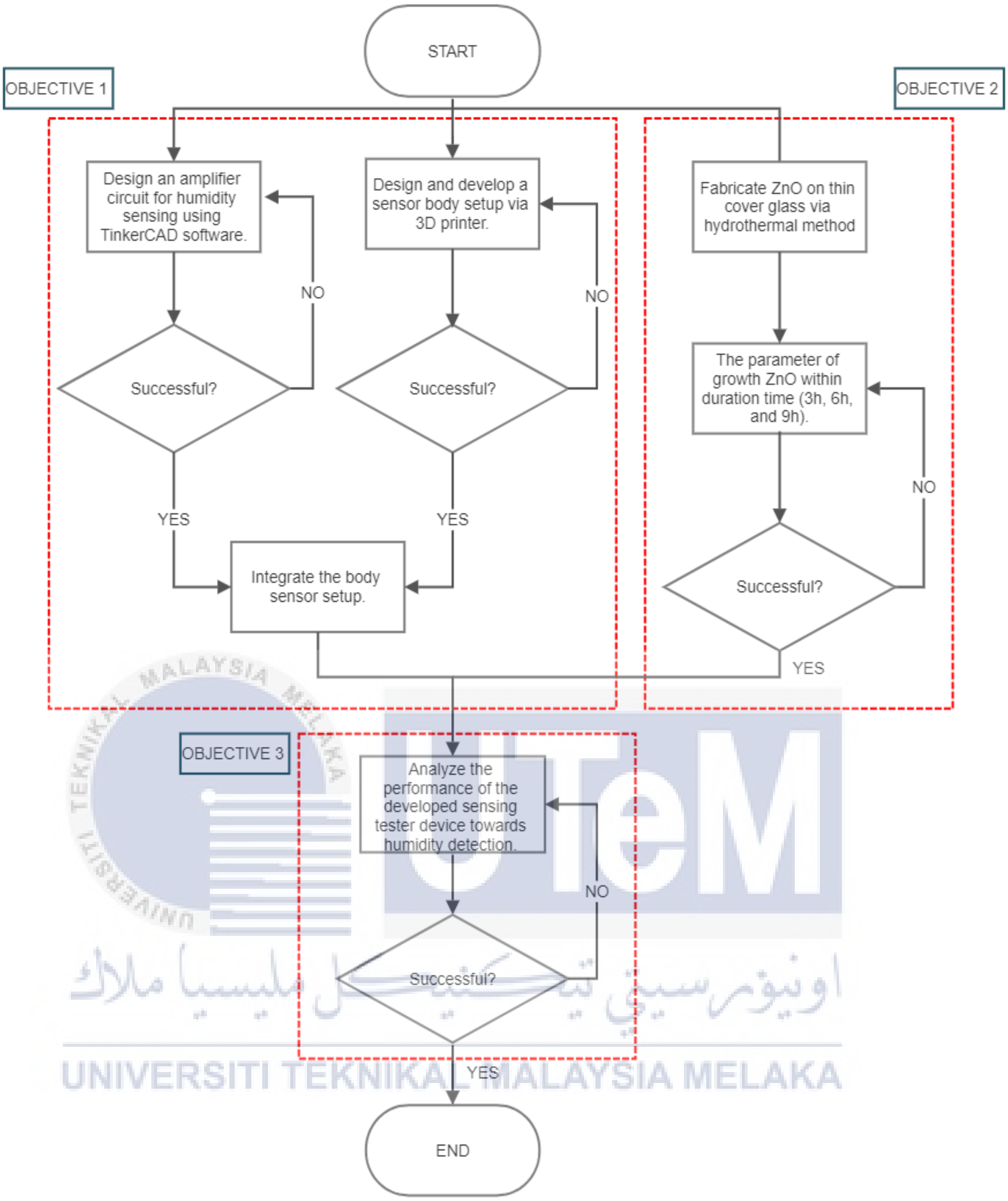


Figure 3.1 Flowchart of Methodology Research

3.2 Design of Body Sensor Setup

Realizing a low-cost sensor device, a commercial green LED emitting light with a central wavelength of 525nm was chosen as the light source while a photodiode SFH203 [7] has been used as the light detector. The physical structure of the sensor device was manufactured via a 3D printer Ender 3 Pro [32], and the design was developed using TinkerCAD Software as shown in Figure 3.2 for the overall diamension. Polylactic acid (PLA) filament served as the material for 3D printing. The fabrication process of the sensor device body was carefully optimized to ensure precise positioning of the various components. This included the placement of the sensing medium, which in this case was a thin cover glass. Additionally, the LED, photodiode, and glass substrate were positioned accurately to enable efficient light emission and detection, respectively. The sensor body was divided into two parts to facilitate its assembly and functionality that illustrate in Figure 3.3. These parts consisted of the LED holder, photodiode holder, and sensing medium holder (glass substrate) in one part, which could provide a stable position permanently to slide into the main body setup. While the body setup is to place the sample that is coated with ZnO nanorods (thin cover glass). By employing these design and fabrication techniques, the sensor device was able to achieve reliable performance while maintaining a low-cost profile.

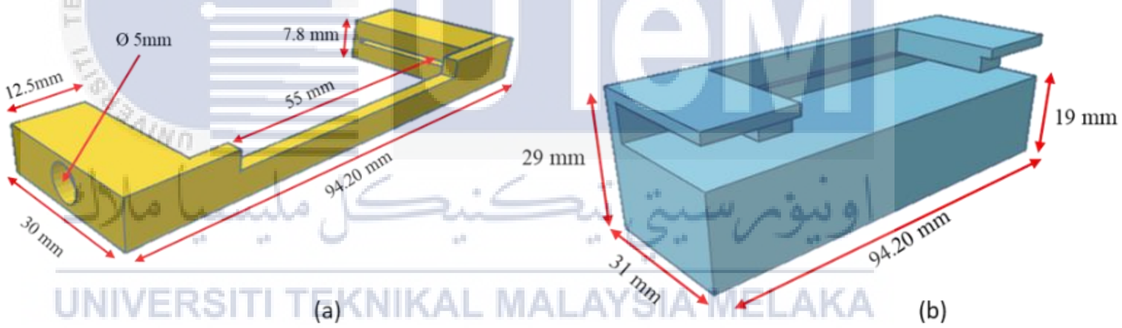


Figure 3.2 Dimension for (a) holder of LED and Photodiode and (b) sensor body setup

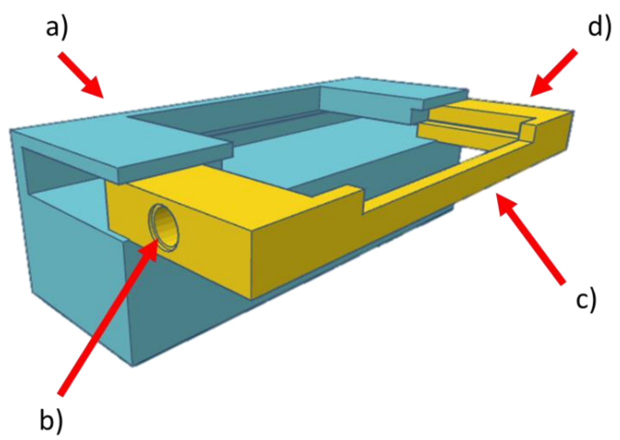


Figure 3.3 (a) Main sensor tester device and (b) LED holder, (c) Glass Substrate holder (slide permanently), and (d) a photodiode holder

3.3 Circuit Implementation of Receiver

In this part, the sensor device light passes through both the sample and the region coated with ZnO nanorods. At the output, the collected light is converted into a linearly proportional current by the photodiode. To prevent the interference of stray light, a small aperture has been designed at both sensor devices, resulting in a very low intensity of light reaching the photodiode. Hence, a straightforward transimpedance amplifier (TIA) [33] is utilized to convert the output current from the photodiode into an appropriate processing voltage for the sensing system based on Arduino. The schematic diagram in Figure 3.4 illustrates the receiver circuit, which incorporates the LT1884 op-amp chip [34]. This chip is a dual rail-to-rail output device with high input precision in the pico-amp range. The input offset voltage is adjusted to be below 50µV, ensuring high precision, and its low drift maintains this accuracy across the entire operating temperature range. Furthermore, the input bias currents are exceptionally low, with a maximum of only 400pA. The output voltage of the op-amp can be defined as:

$$\boldsymbol{V_{out} = R_f x\, I_d} \quad (1)$$

where $\boldsymbol{R_f}$ represents the feedback resistor and $\boldsymbol{I_d}$ is the photocurrent. A feedback capacitor (C_f) is included to ensure stability [34], but it does not affect the measurement significantly since, at low frequencies (where changes in humidity occur), almost the entire id flows through $\boldsymbol{R_f}$. The op-amp chip can produce an output voltage of at least 4.7 V as long as the load remains below 1mA. As measuring the small photocurrent with a regular multimeter is impractical, the value of $\boldsymbol{R_f}$ was adjusted in practice to achieve an appropriate output voltage level for the sensor system.

In this project, the list of components has been listed in Table 3.1 which consists of several pieces of resistor 1Mohm and 220ohm, LT1884 Op-Amp, SFH203 photodiode, 10uF of capacitor and bright LED (green color). By using EasyEDA, circuit design was constructed as shown in Figure 3.5 (a) and (b).

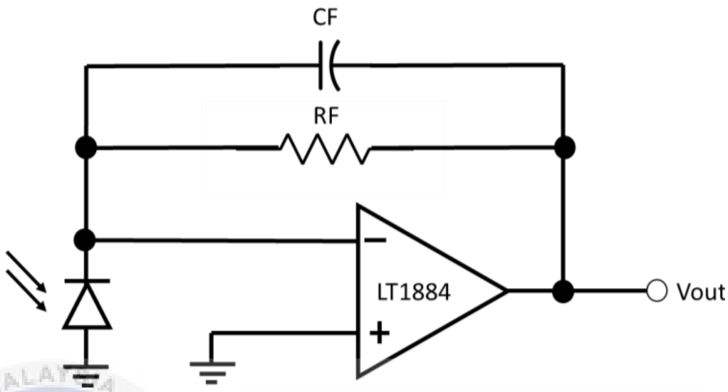
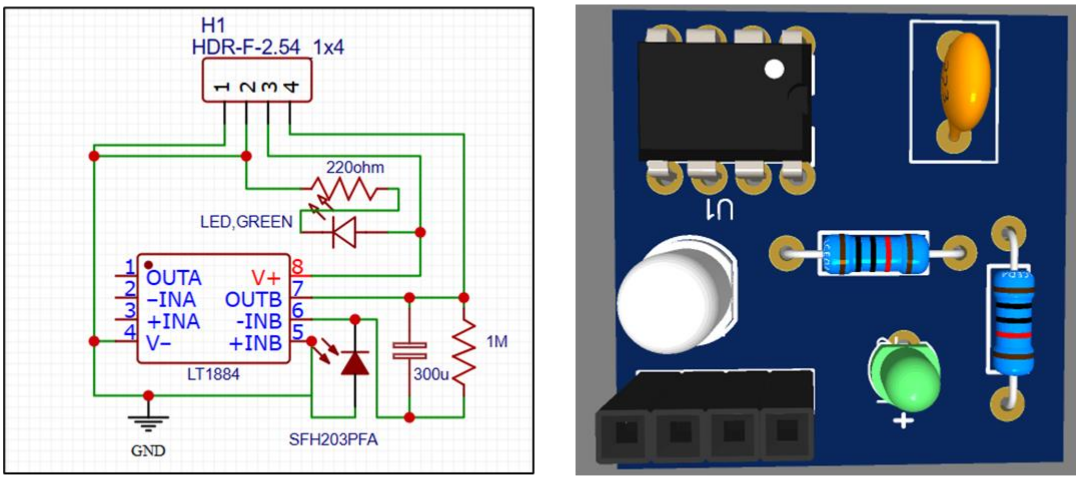


Figure 3.4 A photodiode connected with Transimpedance Amplifier (TIA).

Table 3.1 List of Component.

QUANTITY	COMPONENT
3	1Mohm resistor
1	LT1884 Op-Amp
1	SFH203 Photodiode
1	10uF Capacitor
1	Bright LED (Green color)
1	220Ohm



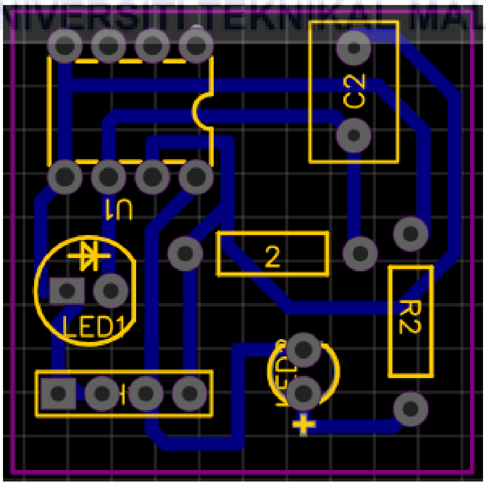
(a) (b)

Figure 3.5 The image of circuit design in (a) schematic view , and (b) 3D view in EasyEDA

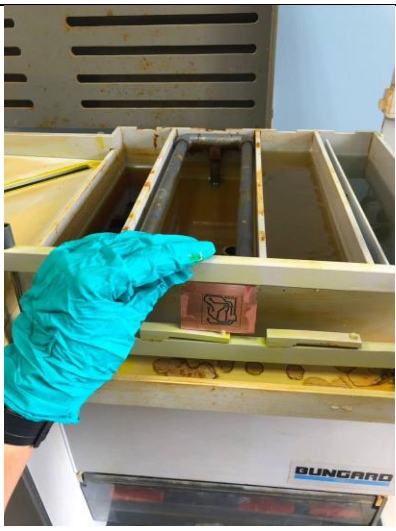
3.3.1 Fabricate the circuit with etching process

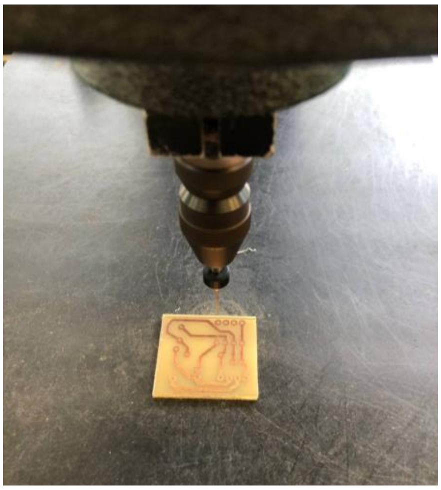
Table 3.2 below shows the step by step of etching process.

Table 3.2 Etching process.

NO	PROCESS OF ETCHING	DESCRIPTION
1.	Prepare the Circuit Layout 	Design the circuit layout using EasyEDA online software. Then print the layout onto a transparent film.
2.	Prepare the Copper-Clad Board.	Clean the copper-clad board using a fine abrasive to remove any

		oxidation or contaminants and to ensure the board is dry and free from dust or debris.
3.	UV LED Exposure Unit / Vacuum Exposure Unit (Bungard)  	The equipment used in the fabrication of printed circuit boards (PCBs), especially in the photolithography step. It is employed during the production of PCBs through processes like photoresist exposure.
4.	Develop the Board. 	Immerse the board in a developer solution to remove the unexposed resist, revealing the copper circuit pattern.
5.	Etch the board.	Place the PCB into the etching solution and agitate for 2 minutes until all the copper has dissolved around the design.

	 	
6.	Remove resist material 	Once all the copper is remove, rinse it in the water bath, let it dry and use rubbing alcohol to whip off the ink transferred onto the PCB.

7.	Drilling hole for component. 	This part is used to make a hole for soldering process that enable the component can be soldered.

After the etching process, the solder is used to connect the component in one circuit and several wires male-female and female-female are used for a longer connection. Below is the final product in the circuit for the implementation circuitry and the connection to the Arduino. Figure 3.6 and 3.7 shows the Top and Bottom view of the circuitry.

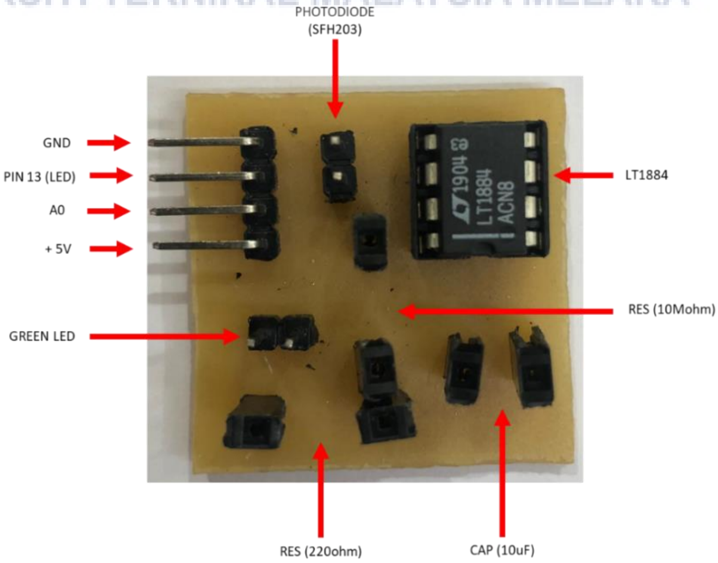


Figure 3.6 Top view of fabrication circuit

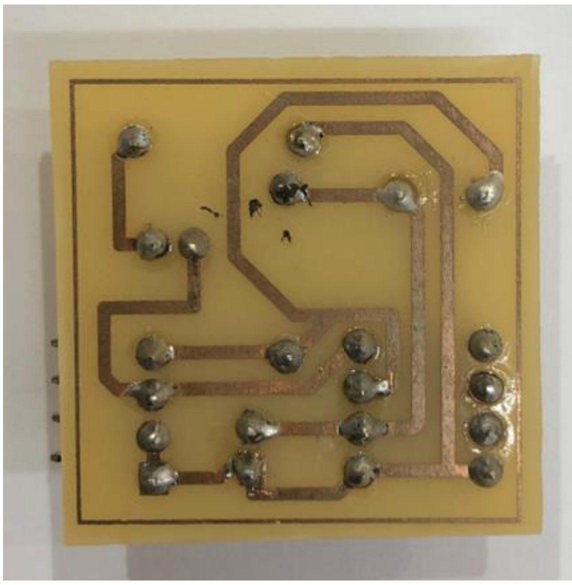
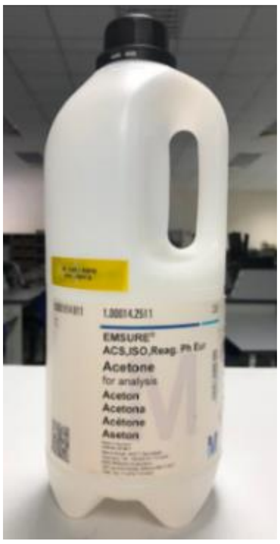


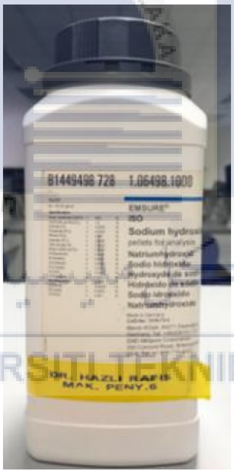
Figure 3.7 Bottom view of fabrication circuit.

3.4 Materials and Equipment

Table 3.3 is the used of materials and solution during the project and Table 3.4 shows the equipment used during the project.

Table 3.3 Material used.

NO	MATERIAL	DESCRIPTION
1.	Acetone  	Chemical formula: $(CH_3)_2CO$. Molar Mass: 58.080 g/mol^{-1} Appearance: Colorless, highly volatile, and flammable liquid with a characteristic pungent odor.

2.	Ethanol  	Chemical formula: CH_3CH_2OH. Molar Mass: 46.069 g/mol^{-1} Appearance: White Solid
3.	Sodium Hydroxide  	Chemical Formula: NaOH Molar Mass: 40 g/mol^{-1} Appearance: White, hard, opaque crystals.
4.	Zinc Acetate Dihydrate  	Chemical Formula: $Zn(CH_3COO)_2(H_2O)_2$ Molar Mass: 219.5 g/mol^{-1} Appearance: White Solid

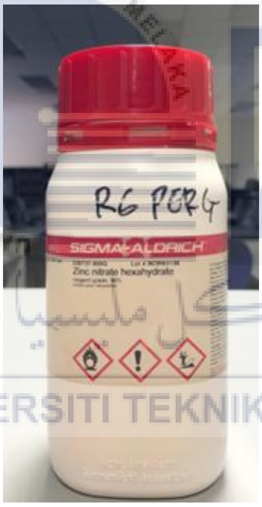
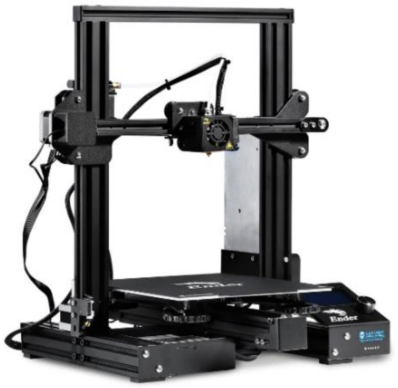
5.	Hexamethylenetetramine (HMT) 	Chemical Formula: $C_6H_{12}N_2$ Molar Mass: 140.19 g/mol^{-1} Appearance: White crystalline solid
6.	Zinc Nitrate Hexahydrate 	Chemical Formula: $Zn(NO_3)_2 . 6H_2O$ Molar Mass: 297.49 g/mol^{-1} Appearance: White crystal
7.	Deionized water (DI Water) 	DI water is water that removes all ions such as cations like sodium, calcium, iron, and copper, and anions such chloride and sulfate.

Table 3.4 Equipment and Device used.

NO	EQUIPMENT	DESCRIPTION
1.	Ultrasonic cleaner 	The equipment comes in ultrasonicator and heating of water bath. Sonicator breaks down the molecule in the solution by producing high frequency and water bath to provide uniform of heating. In this project it is use for water bath process and cleaning.
2.	Magnetic Stirrer and Hot Plate 	It is used to mix and heat aqueous solutions for a great variety of chemical reactions such as synthesis.
3.	Eco-Cell Laboratory Oven 	The electrically heated oven/incubator are designed for laboratories, especially for tempering of various materials by hot air at adjustable temperature and optional time mode. Maximum Temperature: 250˚C

4.	Latex Glove 	Lab safety gloves prevent the chance of contamination, offer a safe working environment, and protect the hands and skin from harmful substances. The type of task being performed, and the materials being handled are the main factors that determine how laboratory gloves are specifically used.
5.	Pipette Joan Lab 	A type of laboratory tool commonly used in chemistry and biology to transport a measured volume of liquid. In this project is used to drop the solution onto the glass substrate during process annealing.
6.	PTFE Tape 	A simplistic yet versatile lubricating material and thread sealant. In this project PTFE tape is for masking the thin cover glass substrate to leave an exposed rectangular area of 3cm x 1cm for ZnO nanorod growth.

7.	Thin Cover Glass 	It is used as a platform for sensing element for the humidity sensor device. Thickness: 85 – 115 µm Sizes: Rectangular (24mm x 50mm)
8.	Microscope Glass Slide 	It is used as a sensing medium that is fixed into sensor body setup. Thickness: 1mm Size: 75mm x 26mm
9.	Filament PLA 	Polylactic acid, or PLA, is a thermoplastic substance that is usually utilized in additive manufacturing processes. It is one of the most widely used materials in 3D printing and may be used to create a variety of parts, packaging, and prototypes for a wide range of industries, including the textile, culinary, medical, and cosmetics sectors.

10.	Ender 3D Pro Printer 	This product are consumer-grade 3D printers and industrial-grade 3D printers.

3.5 Preparation of Thin Cover Glass Substrate

The procedures for setting up the thin cover glass substrate in advance of the synthesis process are depicted in Figure 3.8. The cleaning, drying, and masking processes are part of the preparation steps. Several thin cover glass substrates were constructed for this work in order to investigate various ZnO nanorod conditions, such as duration time.

Figure 3.8 Thin cover glass substrate preparation process.

Following the steps outlined in Figure 3.8, the thin cover glass substrate was cleaned. The thin cover glass substrates were cleaned in an ultrasonic bath for 5 minutes each using soap water, acetone, ethanol, and deionized (DI) water in that order. The thin cover glass substrates must be cleaned in order to ensure that there are no stains, dirt, or other particles on their surfaces. Following cleaning, the substrates were dried for 30 minutes at 70˚C in an atmospheric oven.

After drying procedure, the thin cover glass substrates were allowed to reach ambient temperature before being covered with polytetrafluoroethylene (PTFE) tape, leaving a rectangular portion of the surface unveiled for the application of ZnO nanorods, as depicted in Figure 3.9. Since PTFE tape adheres to thin cover glass substrates easily and doesn't require glue, it was used in the masking process. Due to chemical reactions that occur during the growth process, the presence of adhesive may have an impact on the formation of ZnO nanorods.

This work proposed a rectangular shape of ZnO nanorod coating on a thin cover glass substrate to analyse the effect of ZnO nanorod coating on the different time duration towards intensity. As a result, the surface of each thin cover glass substrate exposed a rectangular section that measured 30mm (L) x 10mm (W), as illustrated in Figure 3.9. It displays the finalised thin cover glass substrate to prepared for the ZnO seeding process, with a rectangular area covered with PTFE tape and exposed.

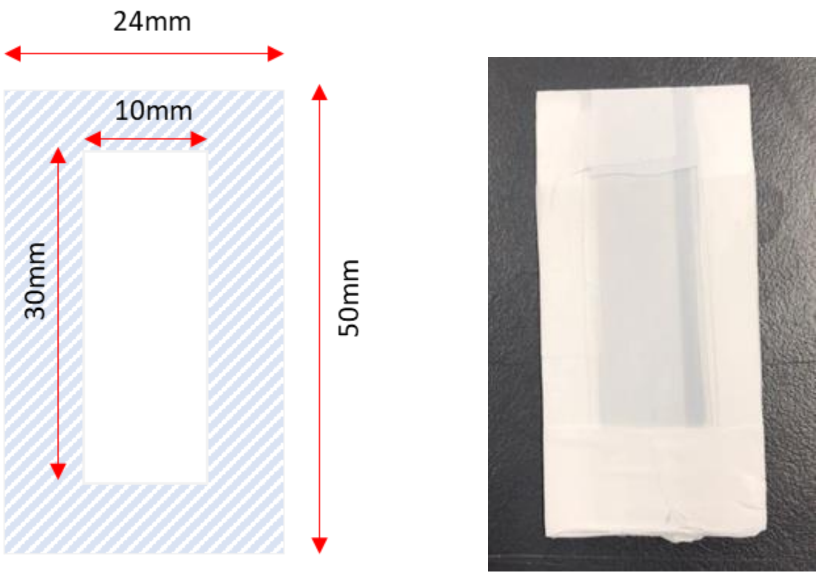


Figure 3.9 Measurement of thin cover glass.

3.6 Preparation of Hydrothermal Process

In this work, the growth of ZnO nanorods on thin cover glass substrates was done via hydrothermal synthesis method. This method requires three major steps which are seeding process, annealing process and growth process that shown in Figure 3.10.

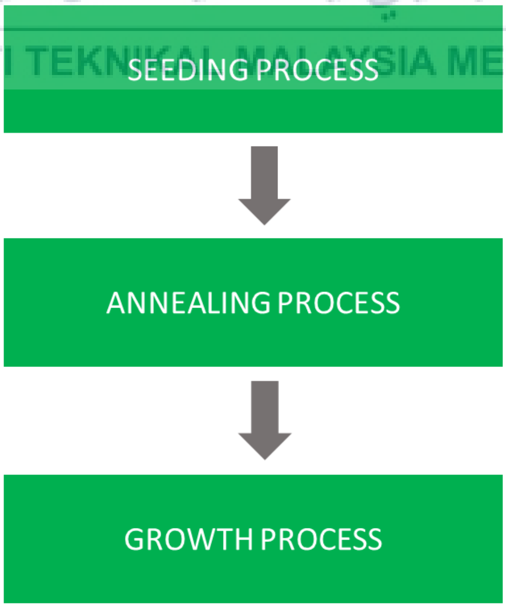


Figure 3.10 Flow of the Hydrothermal Process.

3.6.1 Seeding Process

After the thin cover glass substrate is prepared to the proper exposed length and diameter by masking at the surface area that indicated in Figure 3.9, it must first go through a seeding process in order to grow ZnO nanorods. The length, uniformity, density, and diameter of ZnO can grow differently depending on how much time is spent on it. Three significant steps in the seeding process alone have been identified: preparing the seeding solution, forming the nucleation site on thin cover glass, and annealing. The seeding process block diagram is displayed in Figure 3.11.

Figure 3.11 Flow of the Seeding Process.

The process begins with the preparation of the seeding solution, which is made up of two solutions: sodium hydroxide (NaOH) and zinc acetate. In the first solution, a 5 mM solution was produce by dissolving 0.88g of zinc acetate dihydrate in 80 ml of ethanol for 30 minutes at 50˚C using stirrer. To cool the mixture down, add 80 ml of ethanol. Subsequently, the second solution is made by dissolving 0.016g of NaOH in 80ml for 30 minutes at 50˚C using stirrer.

Finally, to prepare the seeding solutions, use a 1 ml pipette every minute to gradually mix NaOH solutions into the Zinc Acetate solutions. After all of the NaOH solutions have been mixed, the process is repeated the solution is finished. As a result of this process, the zinc acetate solutions contain more hydroxyl ions. Next, the combined solution was left in the water bath at 60˚C within 3 h. A clear solution turns into a cloudy solution as the solution's final result. In Figure 3.12, the procedure solution is depicted.

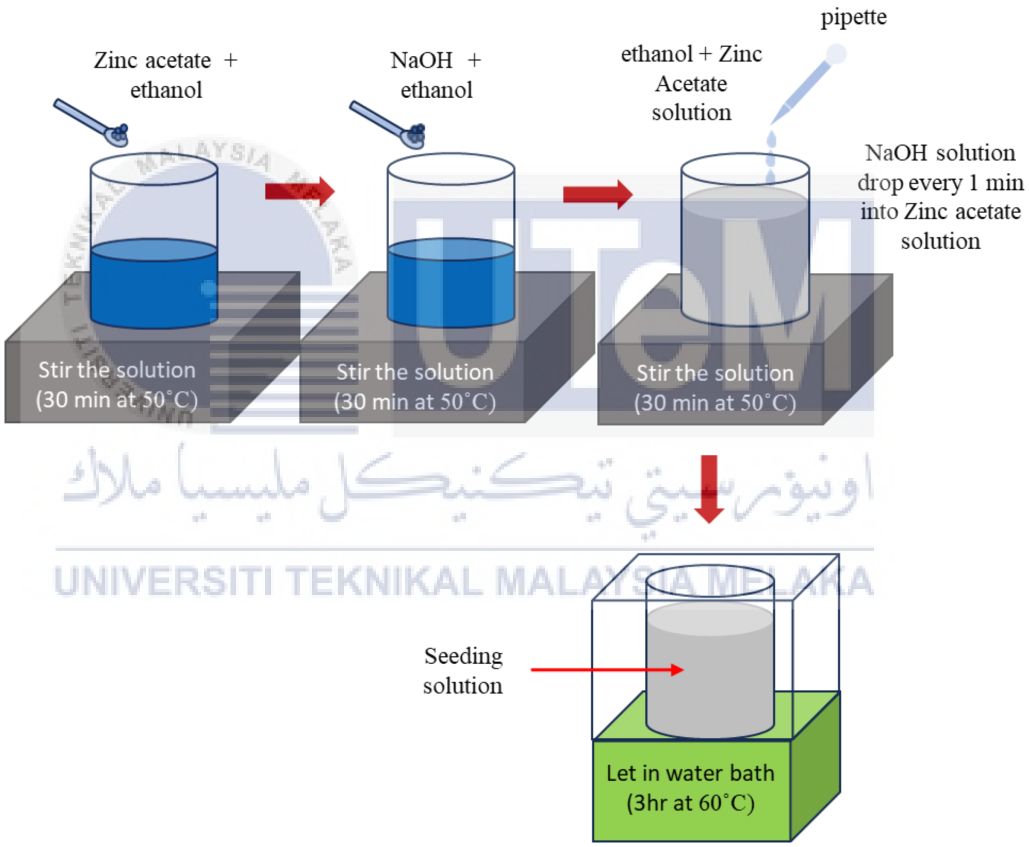


Figure 3.12 Procedure for Seeding Solution.

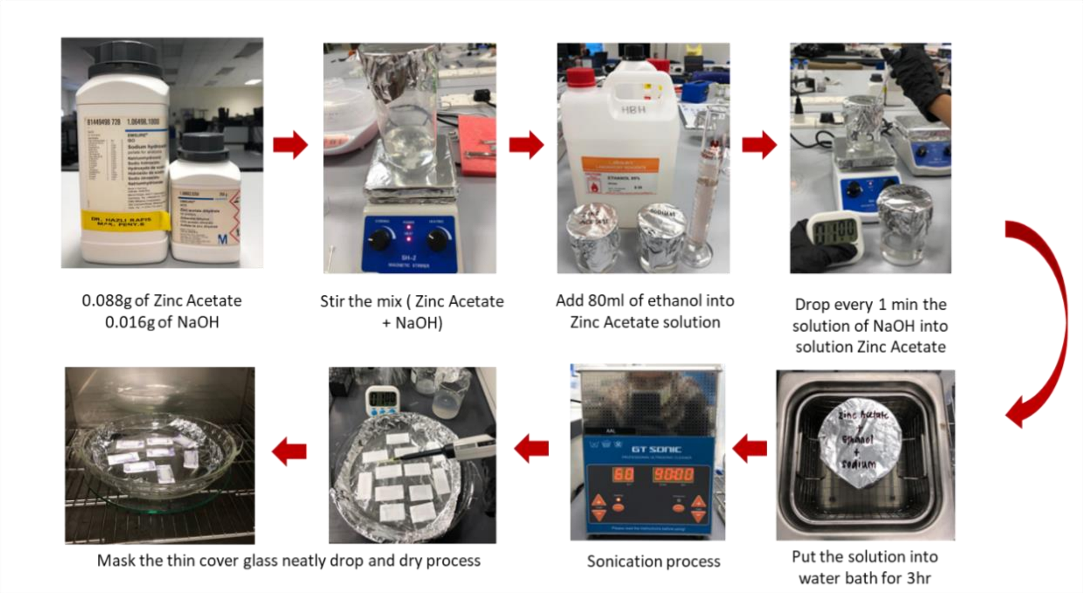


Figure 3.13 Process of Seeding

After the seeding process, Figure 3.13 demonstrates the task of forming a nucleation site on the thin cover glass substrate's surface. The drop and dry approach are being used in the work to carry out the seeding process, which resulted in improved uniformity [4]. The samples with masks were put inside a tray. An amount of 50µl of Zinc Acetate solution was drop cast onto the exposed surface of each glass substrate using a pipette from Joan Lab, and the process was then dried in an oven. The entire process was done ten times over. Figure 3.13 shows the process of dropping seeding solution onto the exposed surface of the thin cover glass substrates.

Figure 3.14 illustrates the process of annealing the seeded samples in an atmospheric furnace. The furnace was gradually heated up to its maximum annealing temperature of 250˚C during the annealing process.

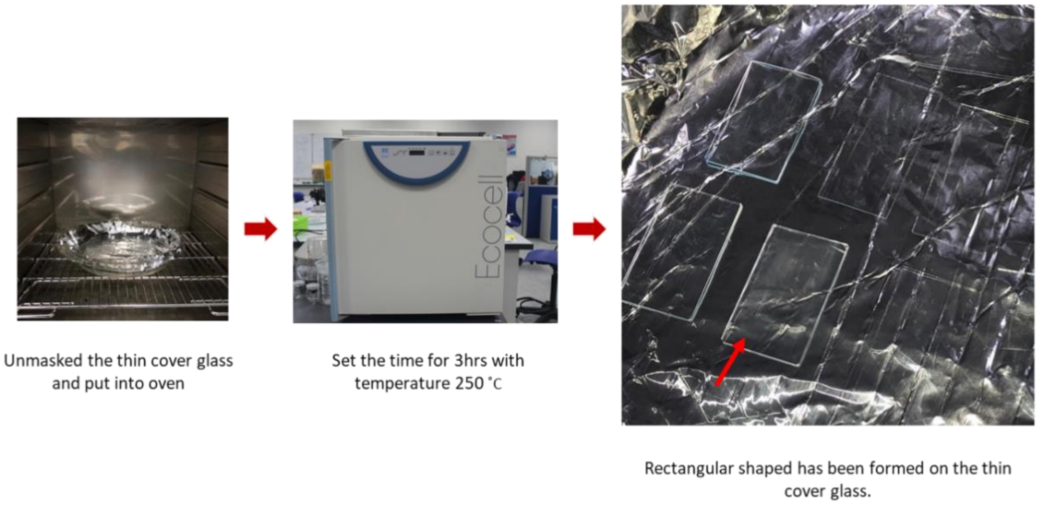


Figure 3.14 Process of Annealing

3.6.2 Growth Process

The growth process as shown in Figure 3.15 was the final step in the hydrothermal method's coating process. In order to produce a 10mM solution, 2.97g of zinc nitrate hexahydrate and 1.40g of hexamethylenetetramine were first dissolved in 1000 ml of deionized water. A platform setup was built for the samples before the growth process to maintain a consistent and even dispersion of the growth solution onto the surface of the thin-cover glass substrates. All of the seeded thin-cover glass substrates are heated with different time durations for 3 h, 6 h, and 9 h at a temperature of 90˚C in an oven while submerged facing down vertically in the synthesis solution.

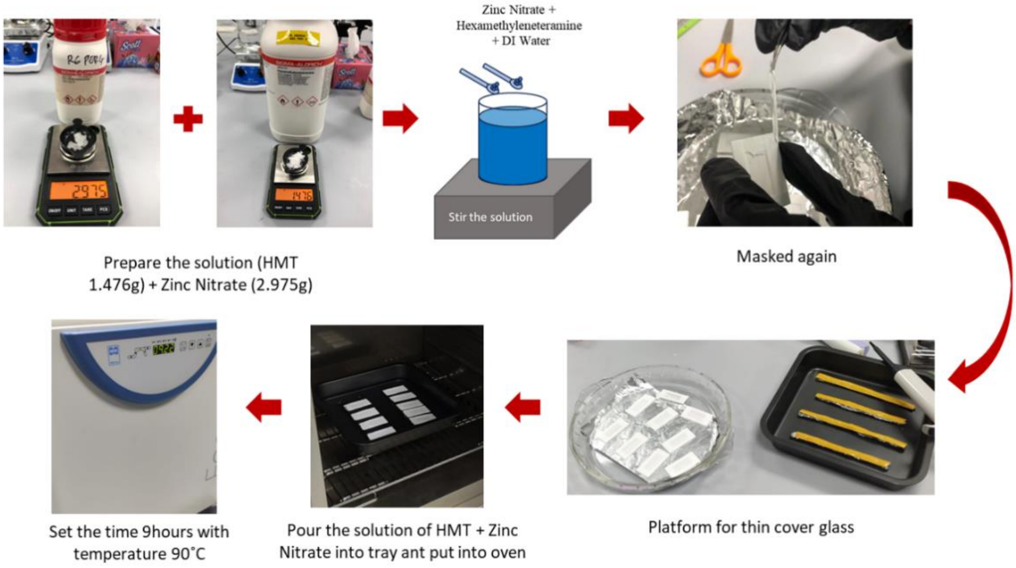


Figure 3.15 Process of Growth

3.7 Humidity Sensing Experiment

Figure 3.16 illustrates the experimental configuration employed for humidity measurements, utilizing a humidity chamber with dimensions of 32.5 cm (length) x 21 cm (width) x 11 cm (height). This chamber was consistently employed across all experiments. The sensor device, thoroughly devised for this study, was positioned within the confines of the chamber, and interfaced with the Arduino platform for systematic data collection. Concurrently, a hygrometer was employed as a reference to ascertain the actual relative humidity (RH) levels.

In this particular experimental setup, silica gel was employed to attenuate humidity levels, whereas moistened tissues were utilized to induce an increase in humidity. Humidity readings were recorded at 5% intervals to capture the stability of both humidity reduction and elevation. Voltage readings were concurrently recorded to correlate with fluctuations in humidity levels during testing.

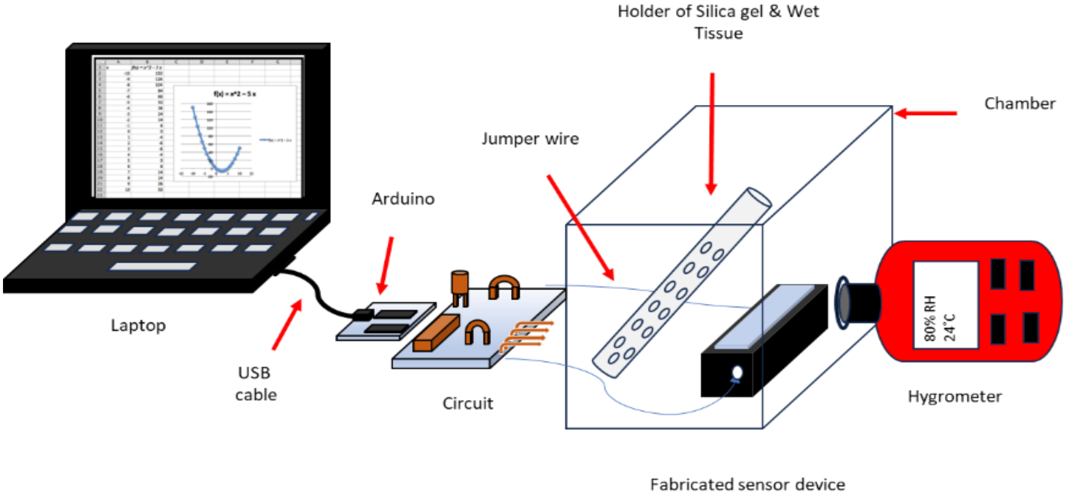


Figure 3.16 Schematic representation of the experimental setup for humidity sensor.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the outcomes of the proposed project are based on the three objectives, as well as the associated costs are presented.

4.1 Fabricated sensor body setup via 3D printing

Figure 4.1 depicts the fabrication of the sensor body setup using Ender 3D printing. The sensor body was specifically printed using black-colored PLA filament to mitigate the issue of stray light reflection within the sensing system. The use of 3D printing allowed for the precise fabrication of the sensor body, ensuring compatibility with the overall system design. By utilizing a black PLA filament, any stray light that exposed to the sensing body is efficiently absorbed, minimizing the risk of interference with the sensor's functionality. The choice of black color PLA filament was based on its ability to effectively minimize the reflection of light. This is particularly crucial in sensitive sensing applications where accurate detection and measurement are essential. By eliminating stray light reflection, the sensor is able to operate with improved precision and reliability. The 3D printing process facilitated the creation of a customized sensor body design that perfectly aligns with the requirements of the sensing system. As shown in Figure 4.1, the overall measurements of this body sensor setup are 94.20 mm (L) x 31 mm (W) x 29 mm (H), with an LED and Photodiode holder diameter of 5 mm.

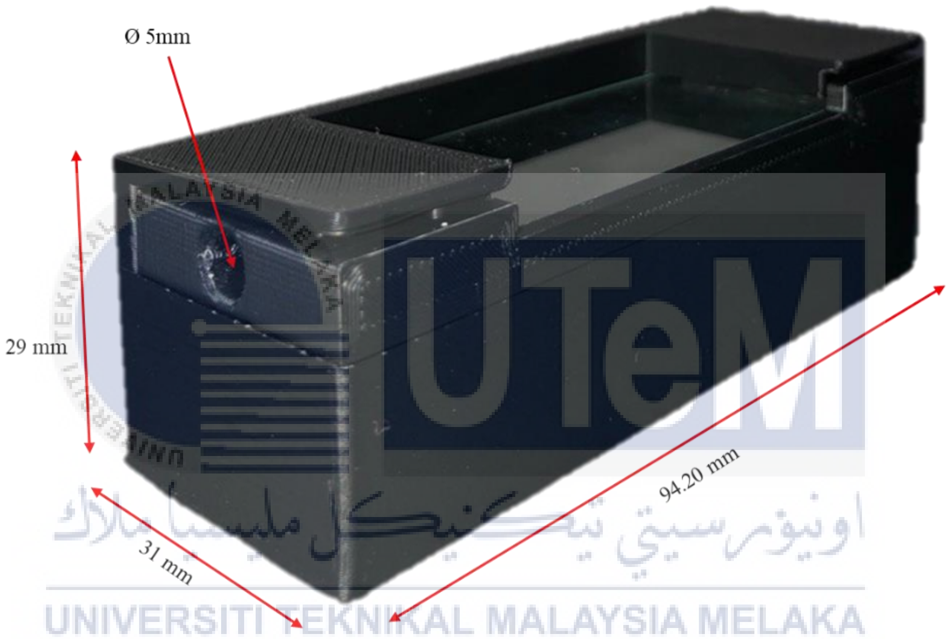


Figure 4.1 The 3D body sensor setup

4.2 ZnO Nanorods on Thin Cover Glass Substrates

Figure 4.2 depicts the image of samples displaying the successful growth of ZnO nanorods in rectangular shape on thin cover glass substrates. Comparison with the images presented in Figure 3.16, ZnO nanorod coatings were formed on the thin cover glass substrates for growth duration times of 3 h, 6 h, and 9 h. It was reported that, after growth duration of 9h, the density of ZnO nanorods at the coating layer was the highest; this density exceeded that of 3h and 6h. The brightest white coating layer is produced on the thin cover glass substrates after a growth period of 9h. The sample that was exposed to the coating for 3 h had a slightly clearer layer than the other two.

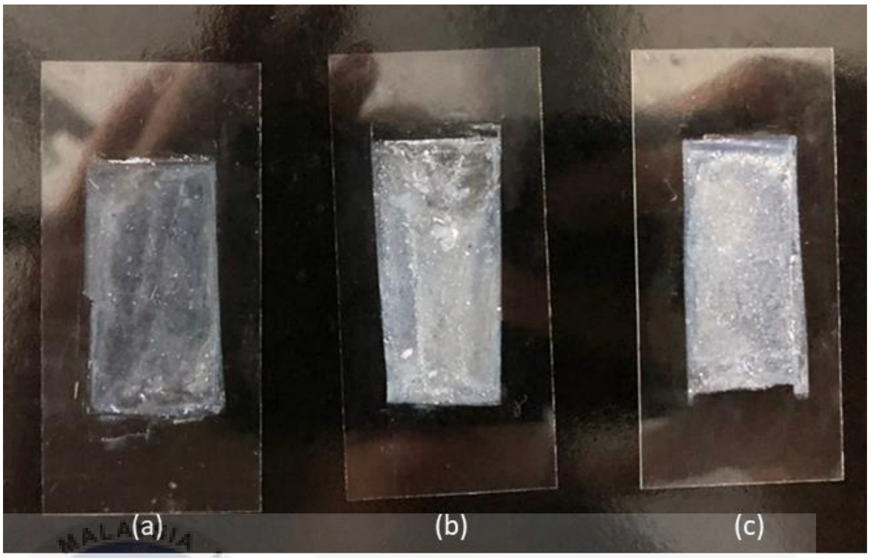


Figure 4.2 ZnO nanorods coating in rectangular shapes on thin cover glass substrates for growth duration (a) 3h (b) 6h and (c) 9h.

4.3 Humidity Sensing Setup Integrate with receiver circuit to Arduino board

Figure 4.8 illustrates the experimental configuration for measuring humidity using the setup sensor device with orthogonal overview. The setup comprises three main components: the connection of the receiver circuit to the Arduino controller board, a chamber housing the sensor body arrangement along with holders for wet tissue and silica gel, and a hygrometer device for reading the humidity in the surrounding environment. The sensor device, crafted for this experiment, was positioned within the chamber, and linked to the Arduino platform, which, in turn, was connected to a computer or an alternate power source for data collection. A hygrometer, serving as a reference for the actual relative humidity (RH) level within the chamber, was mounted outside the chamber wall throughout the experimental process. The electronic components integrated into the PCB board of the receiver circuit were powered by the Arduino platform. The LED, powered through the digital pin D13 and GND, was accompanied by a connected 220-ohm resistor. The digital pin was configured in a HIGH state, generating +5V when activated and reverting to 0V when in an OFF condition. On the receiver circuit, the amplifier derived its power from the +5V supply and GND of the Arduino platform, connected to the V+ and V- of the amplifier chip, respectively. The output signal from the amplifier was then directed to the analog pin A0, responsible for reading the analog voltage. This voltage was subsequently processed and converted into digital form using the built-in analog-to-digital converter (ADC) of the Arduino, facilitating computer-readable data.

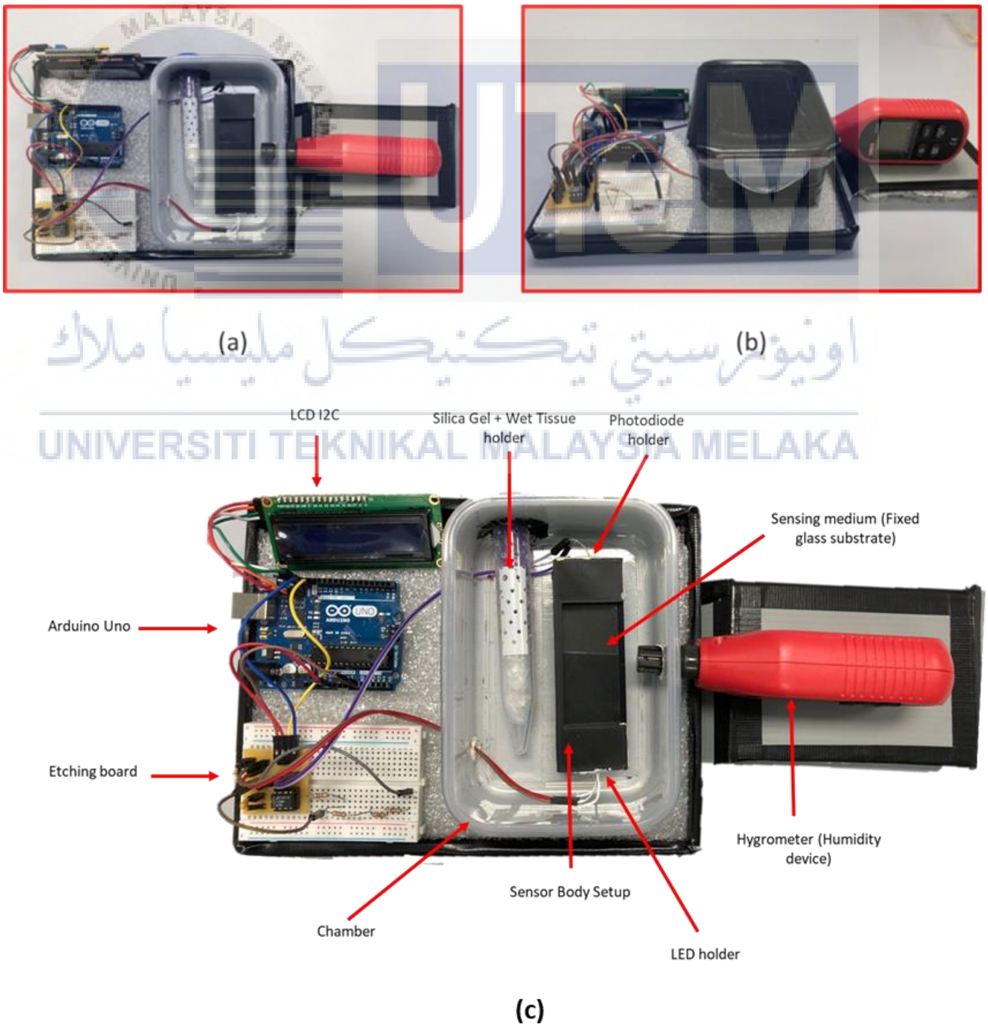


Figure 4.3 Orthogonal overview for the (a) top view , (b) front view, and (c) full sensor body setup for actual of humidity experiment conducted with integrated sensor device.

4.4 Linearity of intensity

According to the Beer-Lambert principles, the variation in light intensity at the receiver can be expressed as [35].

$$\boldsymbol{I = I_O e^{-ax}} \tag{2}$$

where a is the scattering coefficient, x is the medium's length, I_o is the intensity of light entering the medium, and I is the intensity of light leaving the medium. The purpose of ZnO nanorod scattering in this mechanism is a. Before reaching the end of the medium, the light beam travelling within the glass substrate towards the area which the thin glass coated with ZnO nanorods was placed onto the glass substrate along the x direction and interacts at multiple spots on the thin cover glass-ZnO interface. At ambient circumstances, light leakage via ZnO nanorods was detected due to their higher refractive index $(n_{zno} \approx 2)$ [36] in comparison to air$(n_{air} \approx 1)$. When subjected to elevated humidity concentrations, the parameters a undergoes variations, thereby influencing the effective optical characteristics of ZnO nanorods and subsequently altering the light intensity reaching the detector. This phenomenon was characterized by changes in the effective index (RI) of ZnO nanorods. The interaction of water molecules with the surface of ZnO nanorods led to modifications in their optical properties, resulting in increased scattering losses through the nanorods. Consequently, in this envisioned sensor system, exposure to higher relative humidity (RH) levels led to a heightened leakage of light scattered by ZnO nanorods, causing a reduction in the intensity of light detected by the photodiode. The output voltage exhibited a decrease with rising RH levels within the test chamber.

4.5 Characterization of ZnO towards Humidity Sensor

4.5.1 ZnO Characterization for Different Growth Time

Based on the recorded results in Figure 4.4, the graph indicates a higher sensitivity on the 9h sample compared to the 6h and 3h durations. This phenomenon is attributed to one of the factors in the hydrothermal synthesis process that cannot be fully controlled during the processing. Even minor changes, such as in the preparation of materials, can impact the fabrication of ZnO. Most likely, this is attributed to the ZnO structure becoming denser. Consequently, when the fabrication is extended for a longer duration (9 h), ZnO becomes denser, leading to a reduction in the dominance of forward scattering of light. The results in Table 4.1 demonstrate a more pronounced occurrence of backward scattering of light. In previous study [37] has been mentioned the less light exits through the nanorods by forward scattering, and more light is reflected back into the glass substrate towards the photodiode. This causes an increased amount of light to be received by the photodiode in the 9h sample. Furthermore, the result can relate to [37] which the presented works reveal in Figure 4.5 the inconsistencies regarding the optimal growth times aimed at achieving the highest light coupling efficiency. This suggests that comparable device performance may not necessarily result from processes impacting the physical structure or dimensions of ZnO nanorods, thereby inducing variations in the characteristics of the fabricated devices. Such variations indirectly impact the performance when these fabricated devices are employed for sensing applications, such as humidity or chemical vapor concentrations. Consequently, a novel approach to establishing a standard reference for the operating conditions of sensing devices is deemed necessary and is proposed within this study. As a period of time grows, theoretically, the backward scattering would become more dominant. It was discovered that for all three samples, the backward scattering increased as the growth duration increased from 3h, 6h and 9h. This demonstrates that the ZnO nanorods ability to reflect light increases with longer growth time.

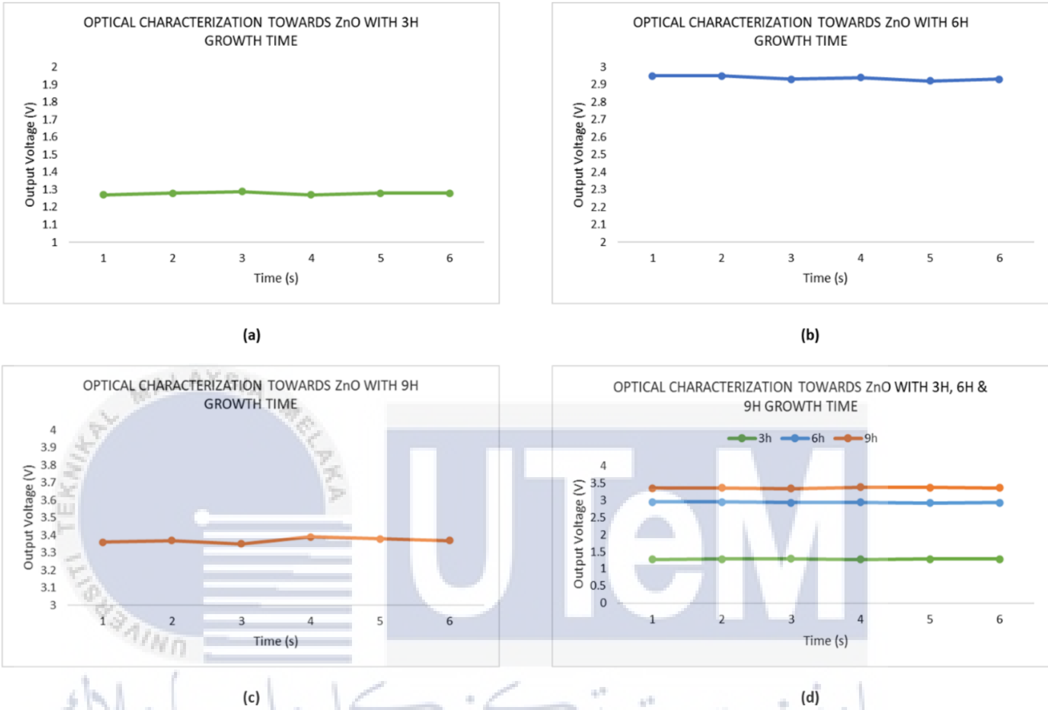


Figure 4.4 The Optical Characterization Towards ZnO with different Growth Time (a) 3h, (b) 6h, (c) 9h

Table 4.1 The output average voltage (ΔV) for different growth time 3h, 6h, and 9h

GROWTH TIME (hours)	AVERAGE VOLTAGE (ΔV)
3	1.27
6	2.9
9	3.37

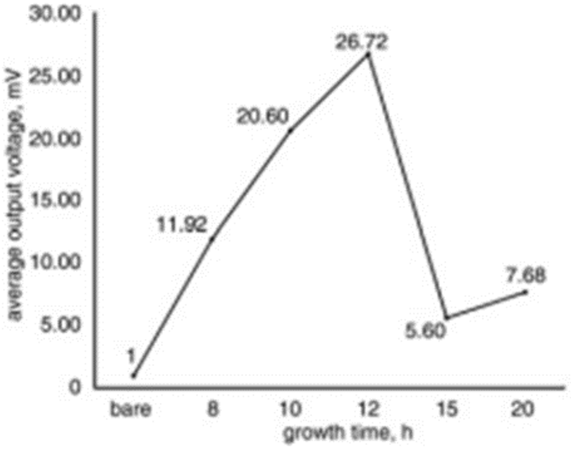


Figure 4.5 Average output voltage for all growth times

Source: Hazli Rafis et al [Research paper]

4.5.2 Humidity Response

The sensor's response to humidity, measured at three different growth times, is displayed in Figure 4.6. The humidity was measured from 40% to 90% RH levels, the output voltage (V) of the sensor system read by the Arduino platform at every 5% value indicates the amount light the sensor device transmitted. Findings indicate that throughout the test, the humidity response significantly reduced which observed that the 9h sample produced higher sensing response towards humidity detection with the sensitivity of -6.77mV% as shown in Table 4.2. The results indicate that when ZnO nanorods are utilized as sensing sensitive material, the presence of a humid environment causes a loss of light. In that case, the ZnO nanorods have two methods for their humidity detection mechanism. The main contribution to this sensing mechanism is established by the adsorption and desorption process of water molecule on the surface of ZnO nanorods [38]. The adsorption and desorption processes of water molecules on the surface of ZnO nanorods are pivotal in shaping the material's properties and performance. Initially, water molecules are drawn to the nanorods from the surrounding environment, forming interactions through hydrogen bonding and

Van der Waals forces. This adsorption induces modifications in the physical and chemical characteristics [39] of ZnO, potentially altering surface energy and introducing defects. Subsequently, environmental changes, such as variations in humidity or temperature, initiate the desorption process. External stimuli weaken the bonds between water molecules and the ZnO surface, facilitating the release of water molecules and returning the nanorods to a state with reduced water content. This desorption process may restore the original properties of ZnO nanorods, enabling effective functionality. Particularly crucial in applications like humidity or gas sensors, the dynamics of the adsorbed water layer impact the electrical, optical, and structural properties of ZnO, contributing to measurable variations in its response to external stimuli. A comprehensive understanding and control of these processes are imperative for optimizing the performance of ZnO nanorods in diverse applications.

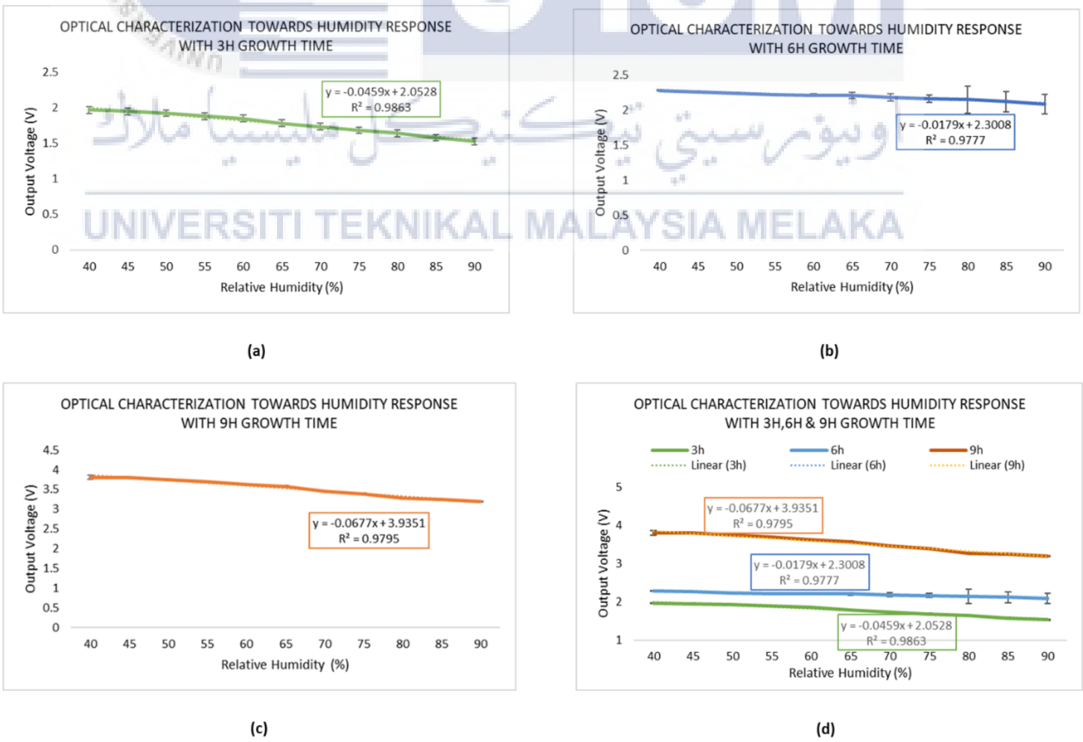


Figure 4.6 The Optical Characterization Towards Humidity Response with different Growth Time (a) 3h, (b) 6h, (c) 9h

Table 4.2 The output power voltage (mV) for different growth time 3h, 6h, and 9h

GROWTH TIME (hours)	POWER VOLTAGE (mV)
3	-4.59
6	-1.79
9	-6.77

4.6 Environment and sustainability

In this project, the relevant for Sustainable Development Goal (SDG) that aims to ensure sustainable consumption and production patterns which is SDG 12. It is suitable for this project because it presents a low-cost integrated humidity sensor device that uses zinc oxide nanorods as the sensing material, which are fabricated using a simple and green hydrothermal method [40]. It also demonstrates the advantages of the sensor device for humidity monitoring, such as fast sensing response, high sensitivity, and good repeatability, which can help to prevent corrosion of electronic components, spread of viruses and bacteria, and degradation of metallic structures.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

In conclusion, the use of a replaceable sensing material in the form of ZnO-coated thin cover glass on a glass substrate with a commercial LED as the light source and a photodiode as the photodetector placed at both ends of the glass is an effective way to ensure the consistency of the sensing setup. This research effectively demonstrated the hydrothermal synthesis method for ZnO nanomaterials growth on thin glass substrates. The investigation into the impact of ZnO coating time involved the creation of a rectangular layer of ZnO nanomaterials, revealing that longer growth durations resulted in decreased light leakage due to ZnO scattering, consequently leading to higher light intensity at the output. The fabrication process encompassed three different time intervals (3 h, 6 h, and 9 h), manifesting in the production of longer nanorods with larger diameters as the growth time increased. The scattering effects by ZnO nanorods showed that the growth process at 9h produces higher ZnO scattering coefficient which leads to higher leakage of light. The sensor device demonstrated good stability during replacement of samples ZnO onto sensor body setup. Furthermore, this study emphasizes the development of a cost-effective sensor body setup and the minimization of material waste throughout the optimization process. These findings significantly contribute to the comprehension and potential applications of ZnO nanomaterials across diverse fields. Further elaboration could involve discussing the specific implications of the observed ZnO nanorod characteristics on the sensor's performance, addressing the economic and environmental advantages of the proposed low-cost setup, and exploring potential avenues for the utilization of ZnO nanomaterials in specific applications such as sensing or optoelectronics.

5.2 Future work

Future research efforts could center on refining the sensor body setup, particularly by exploring variations in the dimensions of the glass substrate length. Such variations have the potential to influence the transmission of light through the photodiode, thereby impacting the overall sensor performance. Additionally, there is an opportunity to delve deeper into addressing the air band gap between sensing elements and devices. Elaborating further on this topic involves investigating the impact of different air band gap configurations on the sensor's response to humidity levels. It may entail optimizing the design to minimize air-induced interference and improve the reliability of sensing data. Furthermore, exploring novel materials or coatings that mitigate the effects of humidity on the band gap could be a valuable avenue for future exploration. Overall, a comprehensive examination of these aspects can contribute to advancing the understanding and development of humidity sensors with enhanced stability and reliability.

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