

**SYNTHESIS AND CHARACTERIZATION OF ZnO:Al:Ga CO-DOPED  
NANOPARTICLES FOR POSSIBLE SOLAR CELL APPLICATION**

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**A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of  
Master of Science in Physics of Murang'a University of Technology**

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## DECLARATION

I hereby declare that this Thesis is my original work and to the best of my knowledge has not been presented for a degree award in this or any other university. I understand what plagiarism is and I am aware of the University's policy in this regard. I understand that any false claim in respect of this work shall result in disciplinary action in accordance with the University Anti-Plagiarism Policy.

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The undersigned certify that they have read and hereby recommended for acceptance of Murang'a University of Technology a thesis entitled **“Synthesis and Characterization of ZnO:Al:Ga Co-Doped Nanoparticles for Possible Solar Cell Application”**.

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## **DEDICATION**

I dedicate the success of my research thesis to my mother Hellen Chepkirui Ruto.

## ACKNOWLEDGEMENT

All thanks be to Almighty God.

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## ABSTRACT

Pollution is a major reason traditional energy sources like crude oil and fossil fuels are not environmentally friendly, negatively impacting climate change. Creating of alternative clean energy sources such as solar energy is a solution. Solar cells have employed silicon-based technology extensively, although it is costly. Herein, creating alternative materials with cheap production costs for solar cell applications is key. This research focuses on the synthesis and characterization of ZnO:Al:Ga co-doped nanoparticles with the aim of possible solar cell applications, a substitution for silicon. Zinc oxide co-doped with aluminum and gallium, possesses good optical and electrical properties that can potentially enhance solar cell performance. The proposed study involved the synthesis of the Zinc oxide co-doped with aluminum and gallium nanoparticles using the sol-gel technique by controlling the pH, stirring speed in the precursor, and annealing with various temperatures (i.e 600 °C, 700 °C, 800 °C, 900°C) to obtain optimized nanopowders. The synthesized nanoparticles' structural properties, optical properties, elemental composition and morphological properties, and chemicals corresponding bonding structure were examined using characterization techniques; X-Ray Diffractometer (XRD), Ultraviolet- Visible Spectroscopy (UV-Vis), Scanning Electron Spectroscopy (SEM) and Fourier Transform Infrared spectroscopy (FTIR) respectively. XRD analysis showed hexagonal wurtzite of ZnO with the crystallite size estimated to be ranging from 12 to 21 nm for for the experimental factors; the pH, annealing temperature and stirring speed. The XRD pattern of ZnO:Al:Ga Nps matched well with the Wurtzite ZnO crystal structure with variation in peak intensities observed. SEM displayed aggregation of nanoparticles when the precursor pH increased from 7 to 13, therefore confirming that alkaline medium promotes crystallization. The morphological changes caused by the annealing temperatures were better understood by using SEM imaging, which showed differences in particle size, shape, and aggregation patterns with the desired spherical grain-like structure. As was confirmed in this study nanoparticles showed the most enhanced crystallinity at 1000 rpm further homogeneous doping was confirmed through SEM micrographs, increased surface area, and optimized optical properties. This affirms good properties enhance high efficiency in solar cells for the production of clean renewable energy. UV-Vis analysis showed absorption peaks varying from 380 – 376 nm for precursor pH values 7 – 13, with band gap energy ranging between of 3.26 – 3.29 eV. The decreased transmittance was observed with the higher pH values of 11–13 attributed to it's larger particles. Also, the optical properties of the nanoparticles annealed at different temperatures showed absorbance wavelength range of 371–383 nm, the analysis showed a noticeable redshift in the absorption edge and a decrease in the optical band-gap energy as the annealing temperature increased. This resulted in 3.24 - 3.34 eV, respectively, confirming modifications in the electronic structure. Similar results on stirring speed on the precursor solution were obtained that showed band-gap of wavelength 378 nm equivalent to 3.29 eV. FTIR peaks confirmed the presence of Zn-O, Al-O, and Ga-O stretching modes between 400 and 590  $\text{cm}^{-1}$  with OH stretching bands observed above the 3000  $\text{cm}^{-1}$  region indicating surface hydroxylation in all the experimental factors. In conclusion, the findings of this study confirmed a pH of 8, annealing temperature of 700 °C and stirring speed of 1000 rpm as the best conditions for development of sustainable and cost-effective solar cell for utilization of renewable energy sources and global solution of energy crisis.

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## ACRONYMS AND ABBREVIATIONS

|         |                                         |
|---------|-----------------------------------------|
| $E_v$   | Valence band                            |
| $E_c$   | Conduction band                         |
| $E_g$   | Band gap energy                         |
| Al      | Aluminum                                |
| DSSC    | Dye-Sensitized Solar cells              |
| EDX     | Energy Dispersive Spectroscopy          |
| FTIR    | Fourier Transform Infrared Spectroscopy |
| FWHM    | Full width at half maximum              |
| Ga      | Gallium                                 |
| NBE     | Near Band Edge                          |
| Nps     | Nanoparticles                           |
| SEM     | Scanning Electron Spectroscopy          |
| TCO's   | Transparent Conductive Oxides           |
| UV- Vis | Ultraviolet - Visible Spectroscopy      |
| XRD     | X-ray Diffraction                       |
| ZnO     | Zinc Oxide                              |

## DEFINITION OF OPERATIONAL TERMS

**Annealing Temperatures:** The precise temperatures at which organic residues are removed, structural and morphological properties are altered, or crystallinity is increased in the synthesis of ZnO:Al:Ga co-doped nanoparticles.

**Characterization:** The analysis and evaluation of the structural, morphological and optical properties of the synthesized ZnO:Al:Ga co-doped nanoparticles.

**Co-doping:** The concurrent addition of two distinct dopants; in this case, gallium (Ga) and aluminum (Al) to the zinc oxide (ZnO) lattice in order to modify the material's properties.

**Morphological properties:** The shape, size, surface texture, and distribution of the ZnO:Al:Ga co-doped nanoparticles as well as their physical aggregation form and structure as revealed by methods like transmission electron microscopy (TEM) and scanning electron microscopy (SEM).

**Nanoparticles:** Particles having a large surface-to-volume ratio and small size, ranging from 1 to 100 nanometers, which have unique properties.

**Optical properties:** The properties of ZnO:Al:Ga co-doped nanoparticles that describe their interaction with light, regarding absorption, emission, and transmission, which are important in evaluating their capability for use in solar cell fabrication.

**pH of Precursor:** The degree of acidity or alkalinity of the precursor solution used to ZnO:Al:Ga co-doped nanoparticles, that affect the hydrolysis and condensation reactions in the sol-gel process, finally influencing the size, shape, and quality of the nanoparticles.

**Solar Cell Application:** The potential use of the synthesized ZnO:Al:Ga co-doped nanoparticles as active materials in photovoltaic devices to enhance efficiency of converting sunlight into electrical energy.

**Sol-Gel Technique:** A chemical procedure for producing ZnO:Al:Ga co-doped nanoparticles by heating and drying a solution (sol) containing precursors (metal salts) via facile reactions that result in a gel.

**Stirring Speeds of the Precursor:** The velocity at which the precursor solution is mechanically agitated during the sol-gel process, since this affect the final ZnO:Al:Ga co-doped nanoparticles' homogeneity, size, and dispersion.

**Structural properties:** The internal arrangement and crystallographic properties of the ZnO:Al:Ga co-doped nanoparticles, regarding crystal phase, lattice parameters, and crystallinity, determined using X-ray diffraction (XRD) technique.

**Synthesis:** The controlled process used to prepare ZnO:Al:Ga co-doped nanoparticles by combining zinc oxide (ZnO) with aluminum (Al) and gallium (Ga) dopants under some conditions.

## CHAPTER ONE INTRODUCTION

This chapter discuss the background study, statement of problem, objectives both general and specific, research questions, justification of the study, significance of the study, scope and limitations of the study; synthesis and characterization of ZnO:Al:Ga nanoparticles for possible solar cells application.

### 1.1 Background to the Study

Solar cells are the devices that convert light energy into solar energy. There are many types of solar cells for instance, the Silicon- based and Dye-Sensitized Solar cells (DSSC). The available silicon- based solar cells are expensive since the silicon as material component is costly and not readily available. DSSC are current solar cells which have gain interest as potential substitute but suffers low efficiency power output. The DSSC uses Zinc oxide (ZnO) and TiO<sub>2</sub> as Transparent Conductive Oxide (TCO's) in the photo anode. ZnO is most preferred potential candidate because of its tunable unique properties.

ZnO nanoparticles have been studied mainly due to their unique properties that make them ideal for use in solar cell applications. However, its efficiency needs to be improved to enhance most reliable, sustainable and large power out-put production in the extreme weather conditions in the different parts of the globe. Also to meet global, regional and local demand due arising population growth. Conversely, mitigate the adverse effects of climate change caused by the pollution from the unreliable traditional sources of non-renewable energy. These modifications improvement includes co- doping ZnO with aluminum and gallium considering parameter of pH on the precursor materials, annealing temperature and the stirring speed on the precursor solution (Smith *et al.*, 2023).

In the recent studies, (Chen *et al.*, 2021) ZnO:Al:Ga nanoparticles have been synthesized using a sol-gel method, which involves hydrolysis of metal oxides in a solution. X-ray diffraction (XRD), Transmission Electron Microscopy (TEM), Scanning Electron Spectroscopy (SEM), Energy Dispersive Spectroscopy (EDX), and Ultraviolet-Visible Spectroscopy (UV-VIS) were among the methods used to

characterize the resultant nanoparticles. The characterization results showed that the synthesized nanoparticles were of high quality.

The potential applications of ZnO:Al:Ga nanoparticles in solar cells have been largely investigated. These nanoparticles can be incorporated into the active layer of a solar cell to enhance its efficiency by increasing absorption of light and charge carrier mobility. This is achieved through optimization of pH on the precursor of ZnO:Al:Ga materials, annealing temperatures of prepared ZnO:Al:Ga nanoparticles in the furnace and stirring speed on synthesis process in the precursor. The high electron mobility of these nanoparticles also makes them useful in the development of Transparent Conductive Oxides (TCO's) that are used as electrodes in solar cells (Wang *et al.*, 2023).

## **1.2 Statement of Problem**

Energy is one of the key essential in production of goods and services. The current global energy crisis is high energy demand due to rapidly increasing population. Also geo-political wars among people on scarce non- renewable sources of energy that are not friendly to the environment. Moreover, available silicon-based solar energy is a promising renewable energy source, but it is expensive and not readily available with low performance efficiency (Esakki *et al.*, 2022).

## **1.3 Objectives**

### **1.3.1 General objective**

To synthesize and characterize ZnO:Al:Ga co-doped nanoparticles for possible solar cell application.

### **1.3.2 Specific Objectives**

- i. To study the effects of pH on the material properties of ZnO:Al:Ga co-doped nanoparticles for solar cell applications.
- ii. To investigate the effects of annealing temperature on the material properties of ZnO:Al:Ga co-doped nanoparticles for solar cell applications.
- iii. To examine the effects of stirring speed of precursor solution on the material properties of ZnO:Al:Ga co-doped nanoparticles for solar cell applications.

#### **1.4 Research Hypothesis**

- i. The material properties of ZnO:Al:Ga co-doped nanoparticles synthesized under varying pH conditions will exhibit changes in particle size, morphology, and doping concentration due to variations in the nucleation and growth processes, resulting in changes in the electrical and optical properties.
- ii. Annealing ZnO:Al:Ga co-doped nanoparticles at different temperatures will result in changes in the crystal structure, particle size, and doping concentration, which will have an impact on the electrical and optical properties of the nanoparticles.
- iii. Stirring the precursor solution at different speeds during the synthesis of ZnO:Al:Ga co-doped nanoparticles will affect the nucleation and growth processes, leading to changes in particle size, morphology, and doping concentration, which will impact the electrical and optical properties of the nanoparticles.

#### **1.5 Significance of the Study**

The study is significant in several ways; the necessity for alternative energy technologies has arisen due to the growing need for sustainable energy sources, among which solar energy is one of the most promising clean energy. For solar energy to be widely used; efficiency, reasonably priced and durability is essential to consider. Consequently, it is necessary to incorporate ZnO:Al:Ga co-doped nanoparticles rather than expensive silicon-based solar cells. Also, study of ZnO:Al:Ga co-doped nanoparticles contributes to the overall advancement of nanotechnology, as it provides insights into the fabrication and characterization of nano-materials. The findings of this study may also be applicable to other fields beyond solar cell technology, such as sensors and optoelectronics development.

#### **1.6 Scope of the Study**

The purpose of the project was to synthesize and characterize ZnO nanoparticles doped with Ga and Al for possible usage in solar cell technology. The nanoparticles were synthesized using sol-gel technique and characterized using UV-Vis spectrophotometry, scanning electron microscopy (SEM), Fourier Transform Infrared spectroscopy (FTIR), and X-ray diffraction (XRD).

### **1.7 Limitations of the Study**

These were the study's limitations

- i. The study was limited to synthesis and characterization of the NPs only. Fabrication will be carried out in the future research.
- ii. The study was limited to examining the effects of three factors; pH, annealing temperatures and stirring speed on the material properties of ZnO:Al:Ga co-doped nanoparticles.
- iii. Method of synthesis: Sol-gel method of synthesis was the only synthesis technique utilized in the study.
- iv. Dopants: The study was limited to two dopants; Aluminum and gallium.

### **1.8 Contribution of the Thesis**

The study's contributions lies in the potential application of optimized ZnO:Al:Ga co-doped nanoparticles in solar cells, where their unique properties leads to improved efficiency and performance of the solar cell. This study contribute to the development of optimized nanoparticles that is used in the photo-anode of the Dye- Sensitized Solar Cells (DSSC) to provide green energy. This research addresses, climate change problems by reducing dependence on environmental unfriendly sources of non-renewable energy, the current global energy crisis and offers a sustainable solution to the growing demand for energy. The use of renewable energy sources such as solar energy is crucial for reducing the dependence on unfriendly energy sources to the environment and promoting a sustainable future. Moreover, the knowledge gained in this study contributes to advancement in other fields, such as optoelectronics, photocatalysis, and sensors, where optimized ZnO:Al:Ga co-doped nanoparticles finds its potential applications.

### **1.9 Organization of the Thesis**

The thesis commences in chapter one with a discussion of the fundamental aspects of renewable energy, emphasizing the significance of solar energy and articulating the problem statement, objectives, hypothesis, rationale of the study and its scope and limitations. The second chapter reviews previous studies of the properties of ZnO, Al, and Ga. It also give details on synthesis and characterization of ZnO:Al: Ga co-doped nanoparticles. This focuses on the impact of pH, annealing temperature, and stirring speed on their structural, optical, morphological, and luminescent properties for solar

cell applications. Chapter 3 describes the sol-gel synthesis method and characterization techniques EDX, SEM, XRD, FTIR, and UV-Vis spectroscopy that were used to analyze the ZnO:Al: Ga co-doped nanoparticles' properties. Chapter 4 presents the results and discusses how varying pH, annealing temperature, and stirring speed affect the characteristics of ZnO:Al: Ga co-doped nanoparticles. The chapter five summarizes the results, and offers recommendations and suggests directions for future work.

## **CHAPTER TWO LITERATURE REVIEW**

### **2.1 Introduction**

Chapter two discusses solar cells and related work done on the solar cells. This has been achieved through rigorous research showing that ZnO is potential candidate for improvement and maximum efficiency of production of clean energy. Therefore, the chapter also describe properties of ZnO under the structural, optical, morphological and luminescence in its solar cell application. Lastly, group 13 elements regards the properties for Al and Ga being best dopants of ZnO on solar cell applications.

### **2.2 The Effects of pH on the Material Properties of ZnO:Al:Ga Co-Doped Nanoparticles**

Over the years research has been done due to the unique properties of ZnO- matrix structure. The existing theory showed the ability of structure to incorporate the impurities so as to improve in its properties. In the synthesis of ZnO:Al:Ga nanoparticles, the pH of the precursor solution serves as a critical parameter influencing various aspects of nanoparticle properties. Previous studies by Darr *et al.* (2017) employing chemical precipitation, sol-gel, and hydrothermal synthesis methods reveal that pH adjustments significantly impact particle size, crystallinity and phase composition. Specifically, the chemical precipitation method demonstrates a direct correlation between pH variations and structural characteristics (Darr *et al.*, 2017), while the sol-gel process shows the influence of pH on gelation and final nanoparticle properties (Droepenu *et al.*, 2022). Additionally, the hydrothermal synthesis approach exhibits sensitivity to pH, leading to variations in the morphology and size distribution of the nanoparticles. These alterations in pH have been observed to induce changes in the crystal structure, lattice parameters, and band-gap energy, ultimately affecting the suitability of ZnO:Al:Ga nanoparticles for solar cell applications. Similarly, enhancing better ZnO nanoparticles possibly to be applied in assembling the TCO's and photo anode of DSSC components. Despite its pivotal role, maintaining pH stability during synthesis poses challenges, prompting ongoing research to address fluctuations and ensure reproducibility in pH-dependent synthesis methods (Nagorski, 2021). This comprehensive understanding underscores the significance of pH control in tailoring the synthesis process and optimizing ZnO:Al:G nanoparticles for enhanced performance in solar energy.

Solar energy is leading source of energy for addressing global climate changes due to its reliance on unfriendly energy sources and meeting the world's energy demands for rapidly increasing population growth. In recent years, the search for efficient and sustainable clean energy sources has been intensified as a solution to the negative problems like pollution and the greenhouse effect brought about by the impacts of high dependents on fossil fuels (Huang *et al.*, 2011). The silicon-based solar cells are associated with challenges such as high cost, unreliability, and narrow band gap when it comes to photovoltaic materials. Zinc oxide (ZnO) has attracted a lot of interest due its availability, affordability and unique properties including its ability to be engineered for high efficiency and sustainability of solar energy. The performance of ZnO can be improved by doping with group 13 elements like boron (B) and indium (I) (Bose *et al.*, 2020). However, B and I are not the best dopants because their ionic radii are not as close to Zinc's ionic radius. Aluminum (Al) and Gallium (Ga) are attractive dopants with tailorable properties for high efficiency of ZnO based solar cell applications such as close ionic radii to Zinc, durability, optical transparency, and band-gap tuning (Burunkaya *et al.*, 2010).

Previous studies show that synthesis of ZnO at different pH levels have a significant impact on the properties of nanoparticles. It is well known that strongly alkaline solutions improve the optical and structural properties of nanostructures. For example, Sagar *et al.* (2007) found that the acidic environment inhibits the formation of ZnO nanostructures. According to Sivakumar *et al.* (2012), there is an improvement in surface morphology as pH levels rise. This was demonstrated by scanning electron microscopy (SEM) images which showed that at lower pH levels, less uniform grain size distribution was observed but at higher pH levels a distinct and enlarged spherical morphology with self-aligned prismatic nanoparticles is obtained. According to Alias *et al.* (2010), ZnO prepared between pH 8 and pH 11 had good optical properties, with the band gap energy ( $E_g$ ) ranging from 3.14 to 3.25 eV. The synthesis of the nanomaterial under lower pH 7 - 9 conditions resulted in agglomerated particles. ZnO nanoparticles' suitability for solar cell applications can be greatly impacted by the addition of dopants, which can change the material's energy band gap, transmittance, crystallite size, and light absorption (Chand *et al.*, 2012). Furthermore, the parameters of synthesis, such as the pH of the precursor solution, growth temperatures, aging and calcination are critical in defining the final properties of the nanoparticles.

Comprehending the impact of pH on the material properties of ZnO:Al:Ga co-doped nanoparticles is crucial in achieving effective high performance solar cells.

The objective of this research is to examine how different pH levels affect the growth of ZnO:Al:Ga nanoparticles for possible solar cell application. The ZnO:Al:Ga co-doped nanoparticles' morphological, structural, and optical properties are all influenced by the synthesis process. The ZnO:Al:Ga co-doped nanoparticles produced by the sol-gel synthesis method were characterized using various techniques to explore the optimum pH of the precursor solution to grow nanoparticles to be incorporated in manufacturing of high performance solar cells.

### **2.3 The Effects of Annealing Temperature on the Material Properties of ZnO:Al:Ga Co-Doped Nanoparticles**

In the recent studies thermal treatment played important role in modifying the material properties of ZnO. The annealing temperature is a critical parameter influencing the synthesis and characterization of ZnO:Al:Ga nanoparticles, with direct implications for their application in solar cells. Research by Samavati *et al.* (2017) highlights the profound impact of annealing temperature on the structural aspects of the nanoparticles, revealing variations in crystal structure and lattice parameters. Concurrently, studies conducted by Lee *et al.* (2012) shed light on the morphological changes induced by different annealing temperatures, influencing particle size and shape. These structural and morphological variations play a pivotal role in shaping the surface characteristics of the nanoparticles, which are crucial for their performance in solar cell applications (Slimi *et al.*, 2018). Optimization efforts are underway to harness the full potential of annealing temperature, but challenges related to reproducibility and scalability necessitate further research (Droepenu *et al.*, 2022). Striking a balance between optimizing annealing conditions and practical considerations creates the imperative gap to unlock the full potential of ZnO:Al:Ga nanoparticles for the possible solar cells application, contributing to advancements in sustainable energy solutions that is free pollutant to the environment.

Solar cell technologies have become essential parts of the renewable energy landscape in the modern search for sustainable energy solutions, providing a plentiful and clean source of electricity generation (Sarkar *et al.*, 2020). Zinc oxide (ZnO) has attracted a lot of attention among the wide range of materials being researched for photovoltaic

applications because of its beneficial optical and electrical properties. One way to modify the properties of ZnO matrix and improve its performance in solar cells is to add dopants like gallium (Ga) and aluminum (Al) to it (Kamarulzaman *et al.*, 2019).

ZnO can be co-doped with Al and Ga to enhance its conductivity and optoelectronic properties, which will increase its effectiveness as a photoactive material in solar energy conversion devices. Still, there is a critical knowledge gap about how the annealing temperature affects the material properties of ZnO:Al:Ga nanoparticles, despite significant progress in their synthesis and characterization. Thermal treatment known as annealing has a significant impact on the structural, morphological, and optical characteristics of nanoparticles, as well as their functional properties and performance in solar cell devices (Hsu *et al.*, 2018). Nevertheless, it is still difficult to fully understand how the annealing temperature affects the properties of ZnO:Al:Ga nanoparticles. Closing this gap will help clarify the complex interactions between annealing parameters and material properties, which will make it easier to optimize synthesis procedures and increase the productivity and affordability of ZnO-based solar cells. With implications for the development of next-generation photovoltaic technologies, this research aims to provide detailed understanding into the underlying mechanisms governing the behavior of ZnO:Al:Ga nanoparticles by examining the effects of annealing temperature on their material properties.

An explanation of the structural, morphological, and optical alterations brought about by different annealing temperatures is one of the study's expected outcomes. As demonstrated by X-ray diffraction (XRD) analysis, it is specifically showed the wurtzite nanostructure of crystal diameter of approximately 20 nm. The imaging of scanning electron microscopy (SEM) disclosed morphological changes like surface restructuring and grain growth with porous texture. UV-Vis spectroscopy revealed changes in the optical band-gap that range between 3.6 – 5.4 eV which confirmed of electronic structure changes. Fourier-transform infrared spectroscopy (FTIR) shedded light on the nanoparticles' surface functionalization and chemical bonding. It showed the stretching modes vibrations between the wavenumber 400 – 800  $\text{cm}^{-1}$  this affirms the present of dopants incorporation within the ZnO nanostructure under varying annealing temperatures.

## **2.4 The Effects of Stirring Speed of Precursor Solution on the Material Properties of ZnO:Al:Ga Co-Doped Nanoparticles**

The stirring speed employed in the synthesis of ZnO:Al:Ga nanoparticles plays a pivotal role in shaping their structural, morphological and optical properties for potential use in solar cells. Studies conducted by Darr *et al.* (2017) underscore the pronounced impact of stirring speed on morphological evolution, with variations in particle size and shape directly influencing the nanoparticles' surface morphology. Additionally, optimal stirring speed is crucial for ensuring homogeneity in the precursor solution, as highlighted by Droepenu *et al.* (2022). This homogeneity significantly impacts subsequent synthesis processes, affecting nucleation, growth, crystallinity, and phase composition (Nagorski, 2021). The nuanced understanding of the effects of stirring speed on the precursor is vital for optimizing the synthesis and characterization of ZnO:Al:Ga nanoparticles, contributing to their potential success in solar cell technologies. Supporting the fact that stirring speed studies are open to be exploited so as to establish optimal stirring speed of the precursor that can produce desired nanoparticles for use in solar cells.

With its clean and renewable nature, solar energy has great promise to both reduce environmental pollution and meet the world's energy needs (Lewis & Nocera, 2006). Zinc oxide (ZnO) solar cells are one of the most popular photovoltaic technologies because of their abundance, sustainability, and unique optoelectronic properties (Liang *et al.*, 2015). Specifically, co-doped ZnO:Al:Ga nanoparticles with gallium (Ga) and aluminum (Al) show improved optical and electrical conductivity, which makes them attractive candidates for efficient solar cell applications (Afre *et al.*, 2018).

Sol-gel synthesis of ZnO:Al:Ga nanoparticles provides a flexible way to modify their material properties to suit solar cell technology needs (OTHMANE *et al.*, 2018). To maximize their performance in photovoltaic systems, control over the material properties such as particle size, crystallinity, and doping must be achieved (Zhou *et al.*, 2018). The stirring speed during the creation of the precursor solution stands out among the other synthesis factors as crucial in determining the final properties of the prepared nanoparticles (Gatou *et al.*, 2023).

With an emphasis on their applicability to solar cell applications, this study examines the impact of stirring speed on the material properties of ZnO:Al:Ga co-doped nanoparticles produced using the sol-gel method followed by characterization. The study aims to clarify the ideal stirring conditions that facilitate the synthesis of nanoparticles with improved surface area, homogeneous doping distribution, and optical properties, all of which can further their potential for effective solar energy conversion. In addition, the research helps in growing knowledge on nanoparticle engineering and facilitates the sensible design of ZnO-based materials for use in sustainable energy applications.

## **2.5 ZnO Properties**

### **2.5.1 Structural Properties**

A hexagon-shaped ZnO semiconductor material with a distinct wurtzite crystal structure is shown in Figure 2.1 (Debnath *et al.*, 2018). Zinc atoms are positioned between layers of hexagonally packed oxygen atoms that make up the crystal structure of zinc oxide. Each zinc atom is surrounded by four oxygen atoms to form a tetrahedral structure. The coordination numbers of the zinc and oxygen atoms are two and four, respectively. ZnO's hexagonal symmetry gives rise to two different kinds of lattice constants: c- and a-axis. The hexagonal basal plane is perpendicular to the c-axis, while the a-axis is 60° angled with respect to the c-axis (Wang *et al.*, 2022)

These properties confirm the dopant ability of ZnO structure, being incorporated without change in the hexagonal structure. The mechanical, electrical, optical, magnetic, and other physical and chemical properties of zinc oxide are significantly influenced by its crystal structure. For example, the hexagonal symmetry of ZnO makes it anisotropic, which causes a variation in electrical conductivity along the c- and a-axes stated by Mehrabian & Aslyousefzadeh. (2015). Furthermore, the production of different morphologies of ZnO, such as nanowires, Nano rods, and nanoparticles, is significantly influenced by the crystal structure of ZnO (Liu *et al.*, 2023).

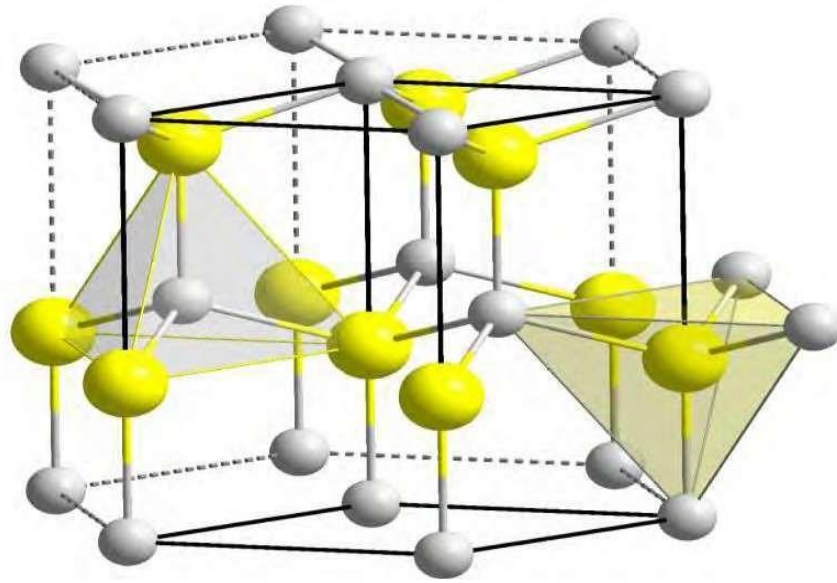


**Figure 2.1: Typical Hexagonal Wurtzite Structure of ZnO (Debnath,et al., 2018)**

### **2.5.2 Optical Properties**

Because of their special optical qualities, ZnO materials show promise in solar cell technology. ZnO nanoparticles are capable of effective light absorption and exciton dissociation because of its wide band-gap energy of 3.37 eV and high exciton binding energy of 60 meV, as reported by Wang *et al.* (2022). ZnO nanoparticles' absorption edge can be adjusted by varying their size; smaller particles have absorption edges that are blue-shifted. This is achieved by co- doping ZnO with Al and Ga under optimized synthesized parameters. Its near band-edge transitions, ZnO also shows significant ultraviolet (UV) emission, which makes it valuable and promising material for use in solar cell applications, and due to its unique optical features and the possibility of further improvement through doping.

### **2.5.3 Morphological Properties**

With a broad variety of morphologies, including nanoparticles, nanorods, nanowires, nanotubes, and nanospheres, as well as hierarchical structures like spheres, flowers, and rods, zinc oxide is a highly versatile material. Further, it is a potential material for a variety of applications, including photocatalysis, gas sensing, and energy storage, because of its shape that has a substantial impact on its physical and chemical properties (Liu *et al.*, 2021).

ZnO can be synthesized using a variety of techniques, including chemical vapor deposition, sol-gel, hydrothermal, and electro deposition, to produce it in diverse morphologies required in photo anode of DSSC. For example, ZnO nanowires and nanorods are commonly synthesized via the hydrothermal approach, whereas thin films and nanoparticles are synthesized with the sol-gel method (Kumar *et al.*, 2024).

ZnO's surface area, crystallinity, band gap, and reactivity, among other properties, can all be impacted by its morphology. For instance, ZnO nanowires and nanorods are appropriate for gas sensors and photocatalytic applications due to their large surface area and high aspect ratio of transmittance (El Filali *et al.*, 2023). However, because of their tiny size and high reactivity, zinc oxide nanoparticles are a good choice for drug delivery and water filtration. All these poses a need to explore more on the surface morphology that suites its applications. Furthermore, understanding on the method techniques with optimum parameters for suitable material properties.

#### **2.5.4 Luminescence Properties**

Zinc oxide (ZnO) exhibits interesting luminescence properties due to its wide band-gap and unique crystal structure which can be tailored by incorporating dopants to increase its luminescence characteristics. ZnO exhibits two types of luminescence, namely ultraviolet (UV) emission and visible emission, both of which have attracted significant research interest for various applications, such as lighting, display, and sensors (Hadi *et al.*, 2023). The near-band-edge (NBE) transition, which results from excited electrons recombining with valence band holes, is responsible for ZnO's UV emission. The peak intensity of ZnO's UV emission band depends on the crystal quality and shape of the material and usually appears at 380 nm. Defects including oxygen vacancies, interstitial zinc, and zinc vacancies are mostly responsible for the visible emission of ZnO, which is mostly detected in the blue-green part of the spectrum and has a broad peak at about 500 nm (Javed *et al.*, 2021).

ZnO's luminescence qualities can be adjusted by a variety of parameters, including surface modification, annealing, and doping. For example, doping ZnO with other elements, like rare-earth elements and transition metals, may change its luminescence properties by introducing trap states to the band-gap. Furthermore, Hussain *et al.* (2020) found that annealing ZnO at high temperatures can improve the NBE emission and lower the concentration of flaws.

## 2.6 Solar Cell Applications of ZnO

Since ZnO possesses special optical and electrical properties, it has been investigated and employed extensively in solar cell technology. Schematic representations of typical ZnO-based solar cells are shown in Figure 2.2 (Debnath *et al.*, 2018). In addition to acting as a window layer that lets light into the active layer, the ZnO layer is an electron transport layer (ETL) that helps move electrons from the active layer to the electrode.

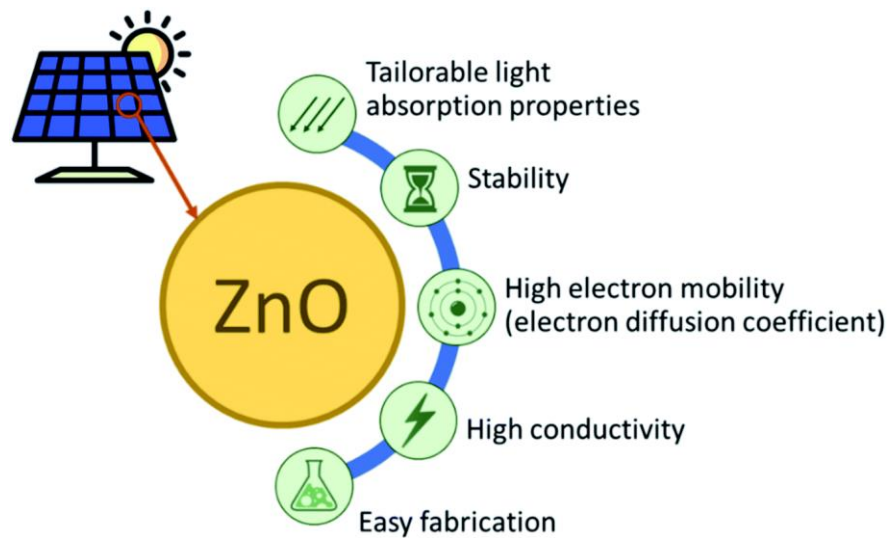


**Figure 2.2: Schematic Diagram of a ZnO-based Solar Cell (Debnath,et al., 2018)**

Compared to conventional silicon-based solar cells, ZnO-based solar cells have a number of benefits, such as increased flexibility, reduced cost, and improved efficiency as indicated in figure 2.2. The ZnO has a larger band gap than silicon, it can produce more photocurrent and absorb a greater portion of the solar spectrum. Additionally, (Chen *et al.*, 2021) ZnO is a promising material for large-scale solar cell manufacture since it is affordable and simple to synthesize utilizing solution-based processes.

ZnO-based solar cells can also be engineered to exhibit other desirable properties, such as increased stability, improved light trapping, and enhanced charge carrier mobility. For instance, the morphology and surface structure of the ZnO layer can be modified using various techniques, such as doping and annealing to improve its efficiency and

stability (Smith *et al.*, 2023). This is done through parameters' optimization via simple route sol-gel method of synthesis.

## 2.7 Properties of Aluminum

The primary mineral of bauxite, aluminum is a chemical element with the atomic number 13. It is a thin, silvery-white metal that is incredibly malleable and ductile. Table 2.1 lists a number of characteristics of aluminum, such as its high strength-to-weight ratio, resistance to corrosion, and electrical conductivity, that make it a valuable dopant to improve properties of ZnO.

**Table 2.1: Basic properties of Aluminum**

| Name of the Property | Value/Type            |
|----------------------|-----------------------|
| Molecular formula    | Al                    |
| Atomic weight        | 26.98                 |
| Odor                 | Odorless              |
| Melting point        | 933.47K               |
| Boiling point        | 2743K                 |
| Appearance           | Silvery-gray metallic |

Aluminum is also helpful in the fabrication of semiconductor materials like ZnO:Al:Ga nanoparticles because it has a high thermal conductivity and is an excellent electrical conductor (Mouzaia *et al.*,2020).

## 2.8 Properties of Gallium

The chemical element gallium has an atomic number of 31. It is an extremely malleable and ductile soft silvery-white metal. Table 2.2 lists several of the features of gallium that make it valuable to be used as dopant so as to promotes properties that enhance high efficiency performance. Gallium has a low melting point, which is just above room temperature. This is one of its special qualities in the synthesis process of ZnO:Al:Ga nanoparticles. Gallium's ease of melting and alloying with other metals,

including zinc and aluminum, to produce new materials with certain qualities is made possible by this feature (Wang *et al.*, 2022). Additionally, gallium is appropriate for usage in high-temperature since solar cells are subjected to high solar intensity therefore it will make solar panels withstand adverse effect of sunrays. This is supported by the recent research that indicates Ga has high boiling point (Jayathilake *et al.*, 2017)

**Table 2.2: Basic Properties of Gallium**

| Name of the Property | Value/Type            |
|----------------------|-----------------------|
| Molecular formula    | Ga                    |
| Atomic weight        | 69.723                |
| Odor                 | Odorless in pure form |
| Melting point        | 29.76°C               |
| Boiling point        | 2,204°C               |

In summary, the use of Al and Ga in the synthesis of ZnO nanoparticles for possible solar cell applications is preferred over B and In due to their closer ionic radii, higher thermal stability, and cost-effectiveness.

## 2.9 Summary

Chapter two comprehensively reviewed the literature pertaining to the synthesis and characterization of ZnO:Al:Ga co-doped nanoparticles, focusing on the effects of pH, annealing temperature, and stirring speed on their material properties. It also examined the intrinsic properties of ZnO, including its structural, optical, morphological, and luminescence characteristics, as well as its applications in solar cell technology. Furthermore, the literature review discussed the properties of aluminum and gallium as dopants, highlighting their significance in modifying the properties of ZnO nanoparticles. By synthesizing existing research findings, this chapter provided a

comprehensive understanding of the factors influencing the synthesis and performance of ZnO:Al:Ga co-doped nanoparticles, laying the groundwork for the experimental investigations conducted in subsequent chapters.

## CHAPTER THREE MATERIALS AND METHODS

### 3.1 Introduction

Chapter three, discusses materials and designed methodology used to synthesize and characterize ZnO:Al:Ga co-doped nanoparticles for possible solar cell applications.

### 3.2 Experimental Materials

The following materials were used as purchased in analytical grade without any alterations as presented in Table 3.1

**Table 3.1: Experimental materials**

| Chemical Substance           | Symbol                                                |
|------------------------------|-------------------------------------------------------|
| Zinc nitrate hexahydrate     | $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$  |
| Aluminum nitrate nonahydrate | $\text{Al}(\text{NO}_3)_3 \cdot 9 \text{H}_2\text{O}$ |
| Gallium nitrate hydrate      | $\text{Ga}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$  |
| Sodium hydroxide             | NaOH                                                  |
| Ethanol                      | $\text{C}_2\text{H}_5\text{OH}$                       |
| Deionized water              | $\text{H}_2\text{O}$                                  |
| Hydrochloric acid            | HCl                                                   |

Furthermore, the following supplies and tools were used: Beakers, pH meter, hot plate, magnetic stirrer and X-ray diffractometer (XRD), Fourier Transform Infrared Spectroscopy (FTIR), UV-Vis spectrophotometer and Scanning Electron Microscopy (SEM).

The supplies were deionized water, sodium hydroxide, zinc acetate hexahydrate, aluminum nitrate nonahydrate, gallium nitrate hydrate and ethanol. Zinc acetate hexahydrate was utilized as the precursor for zinc, while sources of aluminum and

gallium dopants were gallium nitrate hydrate and aluminum nitrate nonahydrate, respectively. The pH of the solution was adjusted using sodium hydroxide as a base and hydrochloric acid as acid. The synthesis process was aided under controlled conditions by the use of ethanol, and deionized water as a solvent. A variety of methods, such as energy dispersive X-ray spectroscopy, UV-vis spectroscopy, scanning electron microscopy, and X-ray diffraction were utilized to analyze properties and composition of the prepared ZnO:Al:Ga nanoparticles.

### 3.3 ZnO:Al:Ga Co-Doped Nanoparticles Synthesis

For the synthesis and characterization of ZnO:Al:Ga nanoparticles for potential solar cell applications, the ZnO:Al:Ga synthesis was essential. The process involved multiple phases, as shown in Figure 3.1, such as creating a precursor solution, hydrolyzing and condensing, and drying and calcining.

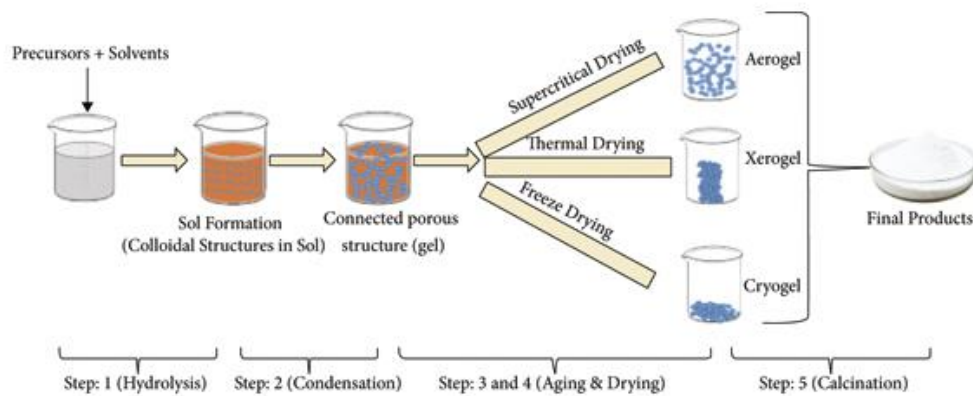


**Figure 3.1: Schematic Diagram of the ZnO:Al:Ga Synthesis Process (Parashar et al., 2020)**

To synthesize ZnO:Al:Ga co-doped nanoparticles, a precursor solution was prepared by dissolving 2.195 g of Zinc nitrate hexahydrate, 0.188 g aluminum nitrate and 0.128 g gallium nitrate in a solvent ethanol. Hydrolysis of the precursor solution was then initiated by adding 25 ML deionized water, which lead to the formation of metal hydroxides. In the final step leftover solvent was removed from the gel and calcined it at a high temperature to produce ZnO:Al:Ga nanoparticles. The structural, optical, morphological, and elemental content of the produced nanoparticles were subsequently ascertained by characterizing them using a variety of methods, including

energy-dispersive X-ray spectroscopy, UV-Vis spectroscopy, scanning electron microscopy, and X-ray diffraction.

### **3.3.1 Determination of Effects of pH on the Material Properties of ZnO:Al:Ga Co-Doped Nanoparticles**

To study the effects of pH of the precursor solution, ZnO:Al:Ga co-doped nanoparticles were prepared from Zinc acetate dehydrate, Aluminum nitrate, gallium nitrate, sodium hydroxide, ethanol and deionized water. In a 250 ML beaker, 2.195 g of zinc acetate was dissolved in 50 mL of ethanol until clear solution was formed, followed by drop wise addition of 25 mL of 1M sodium hydroxide from the burette. The precursor solution was kept under constant stirring speed of 2500 rpm at growth temperature of 75 °C on the hot plate. The pH of the precursor solution was varied for the values: 7, 8, 9, 10, 11, 12 and 13 using 5M Hydrochloric acid and 1M Sodium hydroxide. Thereafter, a 25 ml solution containing 0.188 g of aluminum nitrate, 0.128 g of gallium nitrate was added to the precursor solution. After one hour the suspension of ZnO:Al:Ga was removed from hot plate and allowed to age. The ZnO:Al:Ga nanoparticles in the beaker were then washed with deionized water through decantation. The washed samples were dried at 120 °C in the oven and annealed at 600 °C. The as-prepared ZnO:Al:Ga co-doped nanoparticles samples were taken for characterization using various techniques.

### **3.3.2 Determination of Effects of Annealing Temperature on the Material Properties Of ZnO:Al:Ga Co-Doped Nanoparticles**

To study the effects of annealing temperature, ZnO:Al:Ga co-doped nanoparticles were prepared from Zinc acetate dehydrate, Aluminum nitrate, gallium nitrate, sodium hydroxide, ethanol and deionized water. In a 250 ML beaker, 2.195 g of zinc acetate was dissolved in 50 mL of ethanol until clear solution, followed by drop wise 25 mL of 1M sodium hydroxide from a burette. The precursor solution was kept on hot plate under constant stirring speed of 2500rpm at growth temperature of 75 °C and a pH of 9. Thereafter, a 25 ml solution containing 0.188 g of aluminum nitrate, 0.128 g of gallium nitrate added to the precursor solution under duration of one hour. The suspension formed of ZnO:Al:Ga was allowed to stand for one hour until the gel formation. The ZnO:Al:Ga co-doped nanoparticles washed with deionized water through decantation. The washed sample was dried in microwave oven at 120 °C 1

hour and annealed at different annealing temperatures 400 °C, 500 °C, 600 °C, 700 °C, 800 °C and 900 °C in a duration for 60 minutes. Finally, the prepared ZnO:Al:Ga co-doped nanoparticles samples were characterized using various techniques.

### **3.3.3 Determination of Effects of Stirring Speed of Precursor Solution on the Material Properties of ZnO:Al:Ga Co-Doped Nanoparticles**

To examine the effects of stirring speed of precursor, ZnO:Al:Ga co-doped nanoparticles was prepared from Zinc acetate dehydrate, Aluminum nitrate, gallium nitrate, sodium hydroxide, ethanol and deionized water. In a 250 ML beaker 2.195 g of zinc acetate was dissolved with 50 mL of ethanol until clear solution was formed, add drop wise 25 mL of 1M sodium hydroxide from the burette, once mixture of zinc acetate, ethanol and sodium hydroxide is formed under constant growth temperature of 75 °C, pH value 9 and varying stirring speed of values: 1, 1.5, 2, 2.5, 3, 3.5 and  $4 \times 10^3$  r.p.m. Thereafter, a 25 ml solution containing 0.188 g of aluminum nitrate, 0.128 g of gallium nitrate added to the precursor solution and left until duration of one hour was over. The suspension formed of ZnO:Al:Ga was removed from hot plate and allowed to age. The ZnO:Al:Ga nanoparticles were washed with deionized water through decantation. The washed sample was dried for 60 minutes at 120 °C in the oven, finally annealed at 600 °C for 1 hour in the muffle furnace. The ZnO:Al:Ga co-doped nanoparticles samples were taken for characterization.

## **3.4 Structural and Elemental Characterization**

### **3.4.1 X-Ray Diffraction**

The XRD, a non-destructive analytical method for figuring out a material's crystalline structure. It is made up of an X-ray tube that emits an X-ray beam, a sample chamber that holds the sample, and a detector that records the pattern of X-rays that the sample diffracts. The sample's crystal structure determines the precise angles at which the atoms scatter the X-rays when the X-ray beam interacts with them. Figure 3.2 is ARL Equinox 100 X-Ray diffractometer (XRD) with a resolution power of incidence angle of 10 ° for 2 $\theta$  and a Cu-K $\alpha$  x-ray tube ( $\lambda = 0.154056$  nm) used. All the synthesized samples of ZnO:Al:Ga co-doped nanoparticles were analyzed with the equipment. The data were utilized to evaluate crystallite size, lattice parameters, strain and dislocation density of the ZnO:Al:Ga co-doped nanoparticles.



**Figure 3.1: ARL Equinox 100 X-Ray Diffractometer (XRD) at Murang'a University of Technology**

### **3.4.2 Scanning Electron Microscopy (SEM)**

The integrated equipment in figure 3.3 that included an energy-dispersive X-ray spectroscopy (EDX) and a scanning electron microscope (SEM) was crucial in analyzing ZnO:Al:Ga co-doped nanoparticles. SEM micrographs of the particle size distribution and surface morphology was made possible by SEM Phenom XLG2 under the resolution of 2000 KV, which was helpful in revealing important structural details about the nanoparticles. Furthermore, elemental composition of ZnO:Al:Ga was analyzed using at 5 - 15 KV EDX, which detected distinctive X-rays that were released by the sample when it came into contact with the electron beam. This integrated machine made it possible to identify and quantify constituent elements, also to visualizing the morphology of nanoparticles.



**Figure 3.2: Phenom XLG2 Scanning Electron Spectroscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) at Vision Scientific Laboratory**

### **3.4.3 Fourier-Transform Infrared (FTIR)**

IR spirit Shimadzu Fourier Transform Infrared (FTIR) spectrophotometer equipment that was used to characterize ZnO:Al:Ga co-doped nanoparticles is shown in Figure 3.4. The critical task of examining the infrared absorption patterns the nanoparticles displayed was performed by the FTIR spectrometer. The FTIR machine made it easier to measure the sample's infrared spectrum by producing infrared radiation and using an interferometer to split it into two beams, one of which passed through the sample and the other through a reference mirror. This spectrum gave important details on the chemical bonds present in ZnO:Al:Ga co-doped nanoparticles. The powder form of ZnO:Al:Ga co-doped nanoparticles were analyzed after back ground check of the machine under range scan  $200 - 1200 \text{ cm}^{-1}$  wavenumber.

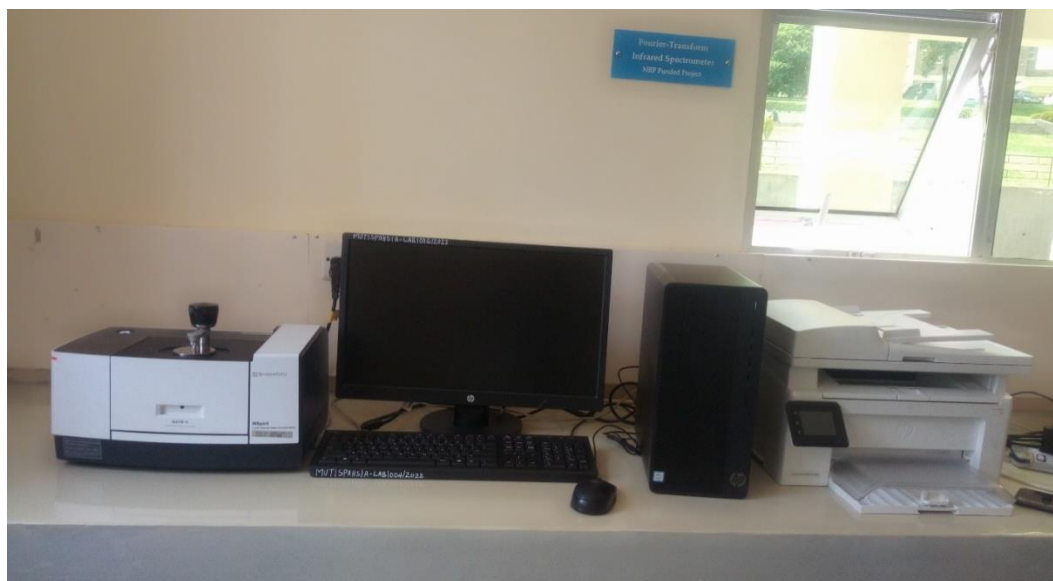


**Figure 3.3: IR spirit Shimadzu Fourier Transform Infrared (FTIR) Spectrophotometer at Murang'a University of Technology**

### **3.5 Optical Analysis Technique**

The spectroscopic equipment, Ultraviolet-Visible Spectroscopy (UV- Vis) analysis was used measure how much light a sample absorbed or transmitted in the ultraviolet and visible range 200 – 1100 nm. It constituted light source, a monochromatic light selector used to determine the wavelength of light, a sample chamber that held the sample, and a detector that calculated how much light the sample absorbs or transmits. The sample was in the solution form. It was obtained by dissolving 0.1 g in 10 ml of deionized water using 10 ml density bottle. Figure 3.5 shows a UV-1800 Shimadzu UV spectrophotometer (UV-Vis) that was used to analyze optical properties of ZnO:Al:Ga co-doped nanoparticles.



**Figure 3.4: UV-1800 Shimadzu UV Spectrophotometer (UV-Vis) at Chuka University**

### **3.6 Summary**

Chapter three detailed the materials and methods employed in the synthesis and characterization of ZnO:Al:Ga co-doped nanoparticles using the sol-gel method. It provided a systematic overview of the experimental procedures designed to investigate the effects of pH, annealing temperature, and stirring speed on the material properties of the nanoparticles. Additionally, the chapter outlined the methodologies utilized for structural and elemental characterization through techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX). It also described the procedures for chemical bonding analysis using Fourier-transform infrared spectroscopy (FTIR), elucidating the chemical interactions within the nanoparticles. Moreover, the chapter discussed the methodologies employed for investigating the optical properties of the nanoparticles using UV-Vis spectroscopy. By detailing the materials and methodologies employed, this chapter provided a robust framework for the subsequent experimental investigations, ensuring the reliability and reproducibility of the research findings

## CHAPTER FOUR RESULTS AND DISCUSSION

### 4.1 Introduction

This chapter delves deeply results and discussions under the structural, morphological, elemental composition, chemical- functional bonding and optical properties of ZnO:Al:Ga co-doped nanoparticles.

### 4.2 Structural and Optical Properties of ZnO:Al:Ga Co-Doped Nanoparticles: Investigation on the Effects of pH of the Precursor Solution Via a Simple Sol-Gel Route

#### 4.2.1 XRD Analysis

The XRD analysis of the synthesized ZnO:Al:Ga co-doped nanoparticles are presented in Figure 4.1. As observed, the diffraction pattern exhibits distinct peaks corresponding to the crystalline phase of hexagonal wurtzite present in the sample across all pH values (8, 9, 10, 11, 12, and 13). Wahab *et al.* (2009) provided similar results, indicating that the diffraction peaks were indexed to the hexagonal wurtzite structure of ZnO that matched with the available Joint Committee on Powder Diffraction Standards for bulk ZnO (JCPDS 36- 1451).

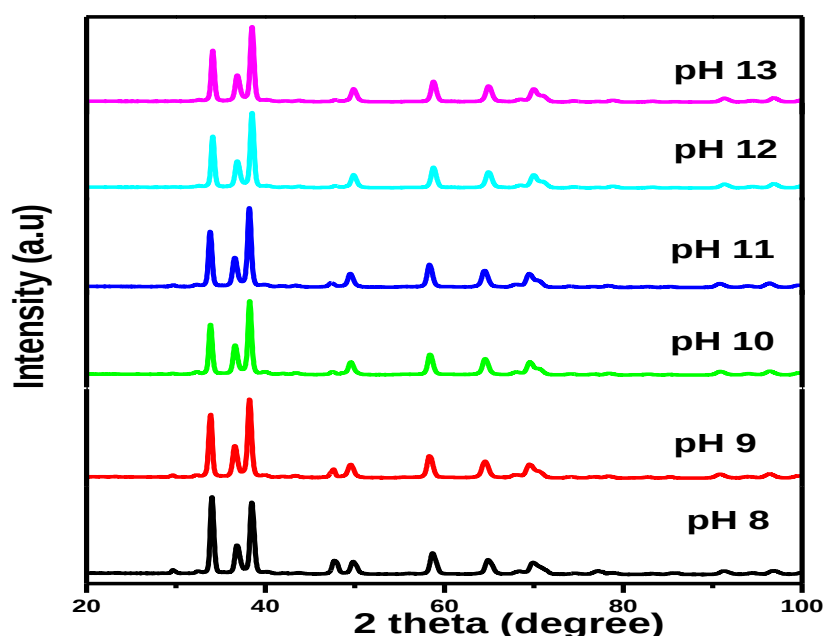


**Figure 4.1: XRD Pattern for ZnO:Al:Ga Co-Doped Nanoparticles Synthesized at Different pH levels.**

It shows that as pH was varied, no change in crystal phase was observed. No impurity peaks were observed indicating that the synthesized material was of good crystallinity. This was also confirmed by the reduced full width at half maximum (FWHM) and higher XRD peak intensities of ZnO:Al:Ga Nps as shown by analysis of 101 plane in figure 4.2.

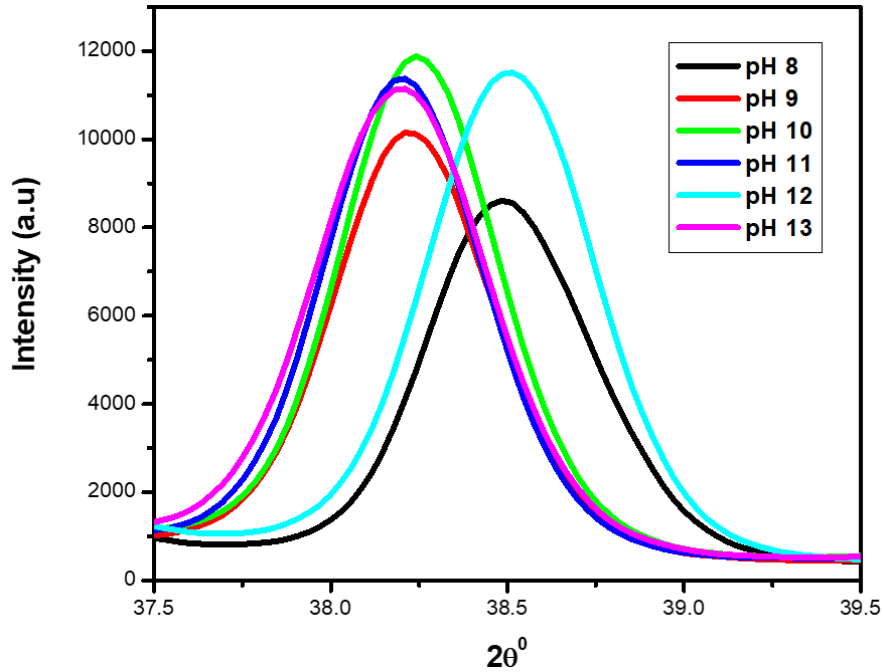


**Figure 4.2: XRD Pattern Showing Magnified (101) Peak for the Synthesized ZnO:Al:Ga Co-Doped Nanoparticles under Varying pH**

It was noted that variation in the FWHM and peak intensities when pH values of the precursor solution was varied. Further analysis was conducted and the results represented in figure 4.3. The graph in Figure 4.3 depicts variations in  $2\theta$  and XRD peak intensity of (101) plane of the corresponding hexagonal wurtzite ZnO:Al:Ga co-doped nanoparticles. Generally, the diffraction angle  $2\theta$  (degrees) was observed to decrease with increase in pH while the peak intensities increased with increase in pH. The decrease in the diffraction angle with an increase in pH confirmed changes in the nanoparticle standard lattice parameters of ZnO were brought by imperfections and defects within the material (Seid *et al.*, 2019). The shift to lower diffraction angle were attributed to increase in the crystallite sizes caused by increase in the lattice parameters as seen in Table 4.1.

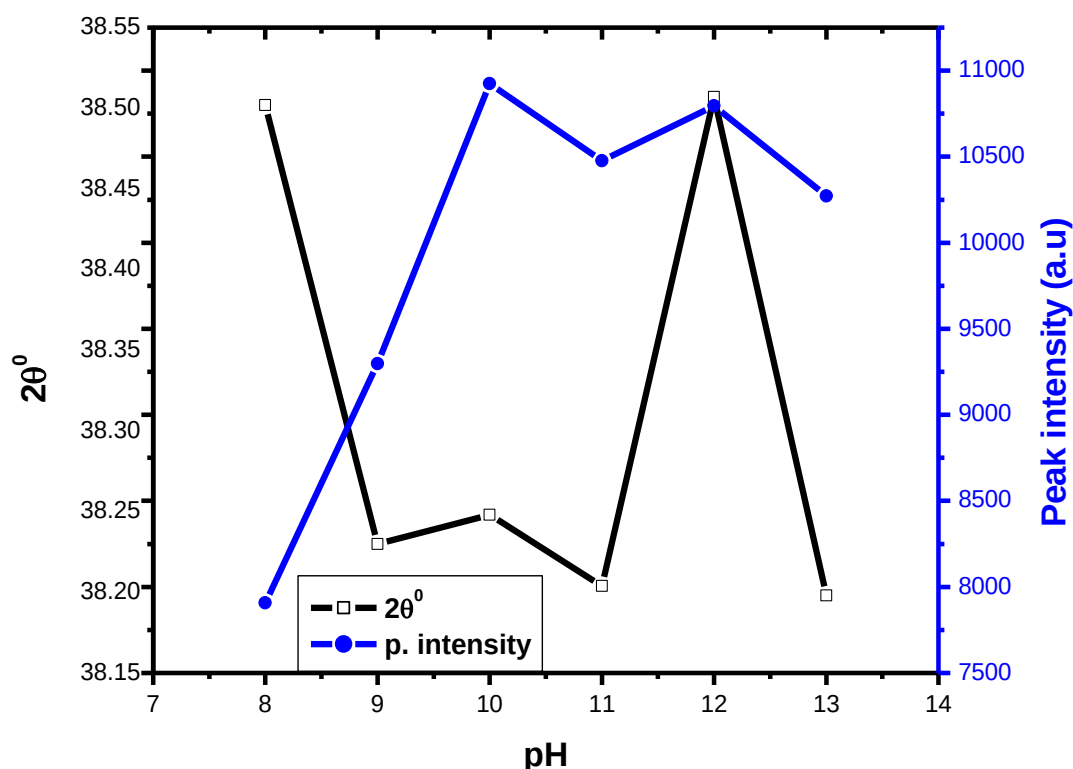


**Figure 4.3: The Graph of 2 Theta and Peak Intensity Verses pH Values of ZnO:Al:Ga Co-Doped Nanoparticles Synthesized under Varying pH**

The crystallite size was calculated using the Scherrer equation (1)

$$D = \frac{K\lambda}{\beta \cos \theta} \text{ (Gherbi et al., 2022)} \dots\dots\dots (1)$$

Where D is crystalline size, K is constant (0.89),  $\lambda$  is 0.154056 nm, mean wavelength of CuK $\alpha$ 1 radiation,  $\beta$  is full width half maxima (FWHM) and  $\theta$  is Bragg's angle in radians. Table 1 shows nano-sized particles with average diameters; 18.69, 19.05, 20.21, 19.52, 19.99 and 19.03 nm for pH values of 8, 9, 10, 11, 12, and 13, respectively. Similar findings were reported by Alias *et al.* (2010). The sample pH of 8 registered a smallest crystallite size of 18.69 nm while the pH 10 showed the largest crystallite size of 20.21 nm. This is mainly because at pH of 8 the precursor solution is less basic medium whereas at pH of 10, the medium is more alkaline which promotes crystallization as a result of supersaturating (Chen *et al.*, 2021).

The size of the ZnO:Al:Ga co-doped crystallites is affected by the size of the FWHM of the XRD peaks. Figure 4.4 shows the relationship between the crystallite size and

the full width at half maximum as pH values of the synthesized ZnO:Al:Ga co-doped nanoparticles are varied. The results affirmed that crystallite size of nanoparticles are directly proportional to the increase in the pH values on the material properties of the precursor solution while the FWHM decrease with increase in the pH values from 7 – 13. It demonstrates that raising the pH level facilitates the nucleation and development of nanoparticles, the alkaline medium speed up the hydrolysis whereas the acidic medium limits. Alkaline atmosphere promotes hydrolysis when the pH is higher than 7, which increases particle development Sivakumar *et al.* (2012) and Jay Chithra *et al.* (2015).

**Table 4.1: Summary Table Showing Structural Parameters of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles under Varying pH**

|                                                          |              | pH 8    | pH 9    | pH 10   | pH 11   | pH 12   | pH 13       |
|----------------------------------------------------------|--------------|---------|---------|---------|---------|---------|-------------|
| <b>2<math>\theta</math></b>                              | (100)        | 34.025  | 33.855  | 33.860  | 33.823  | 34.108  | 33.823      |
|                                                          | D            | 21.29   | 20.83   | 21.68   | 21.07   | 22.59   | 20.26       |
|                                                          | (002)        | 36.869  | 36.611  | 36.638  | 36.600  | 36.885  | 36.610      |
|                                                          | D            | 15.95   | 16.83   | 18.00   | 17.03   | 16.83   | 16.79       |
|                                                          | (101)        | 38.502  | 38.230  | 38.248  | 38.204  | 38.507  | 38.198      |
|                                                          | D            | 18.83   | 19.48   | 20.94   | 20.47   | 20.56   | 20.03       |
|                                                          | D<br>Average | 18.69   | 19.05   | 20.21   | 19.52   | 19.99   | 19.03       |
| <b><math>\beta</math></b>                                | (100)        | 0.39018 | 0.39844 | 0.38299 | 0.39402 | 0.36772 | 0.4096<br>2 |
|                                                          | (002)        | 0.52492 | 0.49710 | 0.46463 | 0.49129 | 0.49749 | 0.4983<br>7 |
|                                                          | (101)        | 0.46660 | 0.45116 | 0.44502 | 0.45090 | 0.47516 | 0.4872<br>4 |
| <b>Peak<br/>intensity</b>                                | (100)        | 9058.7  | 8062.7  | 8329.6  | 8189.9  | 8432.5  | 7632.3      |
|                                                          | (002)        | 3178.1  | 3787.1  | 4517.3  | 4002.8  | 4061.0  | 4314.2      |
|                                                          | (101)        | 7908.1  | 9296.7  | 10924   | 10476   | 10795   | 10271       |
| <b><math>\delta</math></b>                               |              | 0.0029  | 0.0026  | 0.0024  | 0.0026  | 0.0025  | 0.0027      |
| <b><math>\epsilon</math></b>                             |              | 0.3324  | 0.3235  | 0.3008  | 0.3080  | 0.3044  | 0.3148      |
| <b>Lattice</b>                                           | D            | 0.2103  | 0.2117  | 0.2116  | 0.2118  | 0.2102  | 0.2119      |
|                                                          | a=b          | 0.2698  | 0.2716  | 0.2715  | 0.2718  | 0.2697  | 0.2718      |
|                                                          | C            | 0.4908  | 0.4866  | 0.4853  | 0.4856  | 0.4889  | 0.4861      |
| <b>Unit<br/>volume<br/>(V)</b>                           |              | 0.0315  | 0.0311  | 0.0310  | 0.0311  | 0.0308  | 0.0311      |
| <b><math>E_g^{Nps}=E_g^{Bulk}+\frac{1.6}{r^2}</math></b> |              | 3.39    | 3.39    | 3.38    | 3.38    | 3.38    | 3.39        |

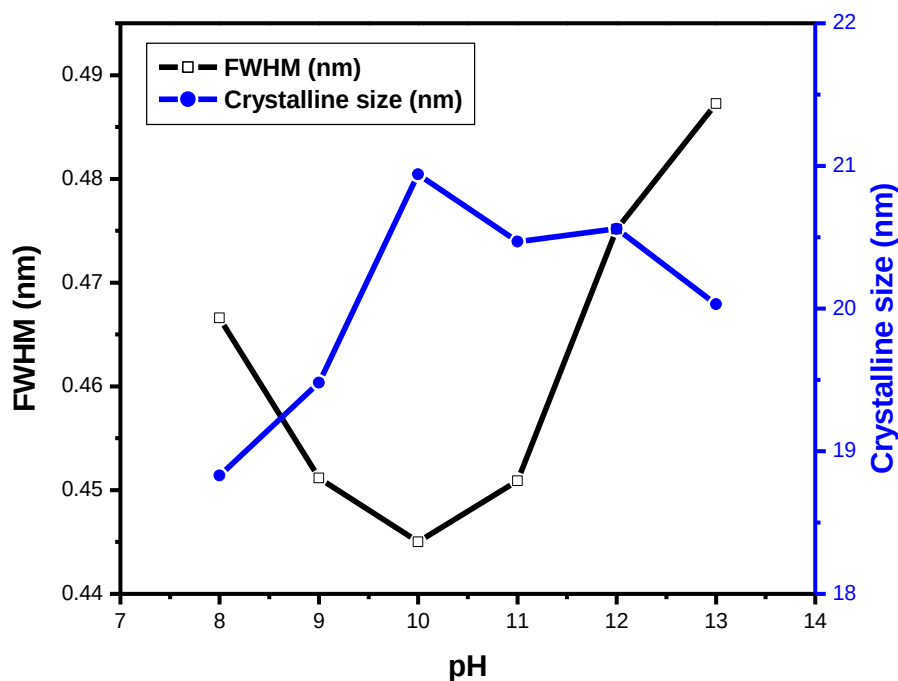


**Figure 4.4: The Variation of FWHM and Crystallite Size (nm) of Prepared ZnO:Al:Ga Co-Doped Nanoparticles at Different pH**

According to Jay Chithra *et al.* (2015), the XRD peak intensities increased as pH rose, aiding in grain formation and indicating a preference for orientation along the c-axis. The inter-planer, d-spacing was calculated using the Bragg's equation (2)

$$\lambda = 2d \sin \theta \quad (\text{Verma } et al., 2017) \dots \dots \dots (2)$$

Where d is the lattice spacing,  $\theta$  is the angle of incidence,  $\lambda$  is the wavelength, and n is the diffraction order. The lattice parameters in Table 4.1 were obtained from the equation (3)

$$\frac{1}{d^2} = \frac{4}{3} \left( \frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2} \quad (\text{Jay Chithra et al., 2015 \& Verma et al., 2017}) \dots \dots \dots (3)$$

Where 'a' and 'c' are the lattice parameters, h, k, and l are the Miller indices and d is the inter-planer spacing. The prepared ZnO:Al:Ga Nps showed 'a' range from 0.2697 – 0.2718 nm and 'c' to be between 0.4853 – 0.4908 nm. The obtained values confirm the presence of imperfections, defects and strain within the nanoparticles since the values deviated slightly from the values of the ZnO bulk structure.

To find out the dislocation density of the as-prepared Nps, the equation (4)

$$\delta = \frac{1}{D^2} \text{ (Kiprotich *et al.*, 2022 & Ungula *et al.*, 2024)..... (4)}$$

Where  $\delta$  is the length of dislocation density and D is the crystalline size was utilized. Also, for the micro-strain ( $\epsilon$ ) values, the equation (5)

$$\epsilon = \frac{\beta}{4 \tan \theta} \text{ (Kiprotich *et al.*, 2022)..... (5)}$$

Where  $\theta$  is the diffraction angle and  $\beta$  is the full width at half maximum (FWHM) were used to find out the cause of the material's imperfections and defects within the structure. The dislocation density and micro-strain values calculated were recorded in Table 4.1. In figure 4.5, dislocation density and micro-strain are plotted verses pH values. The graph shows that both the micro-strain and dislocation density of the prepared nanoparticles decrease with increase in pH values up to pH = 10 where it starts to rise. This shows that higher pH of the precursor solution would promote formation of defects in the material.

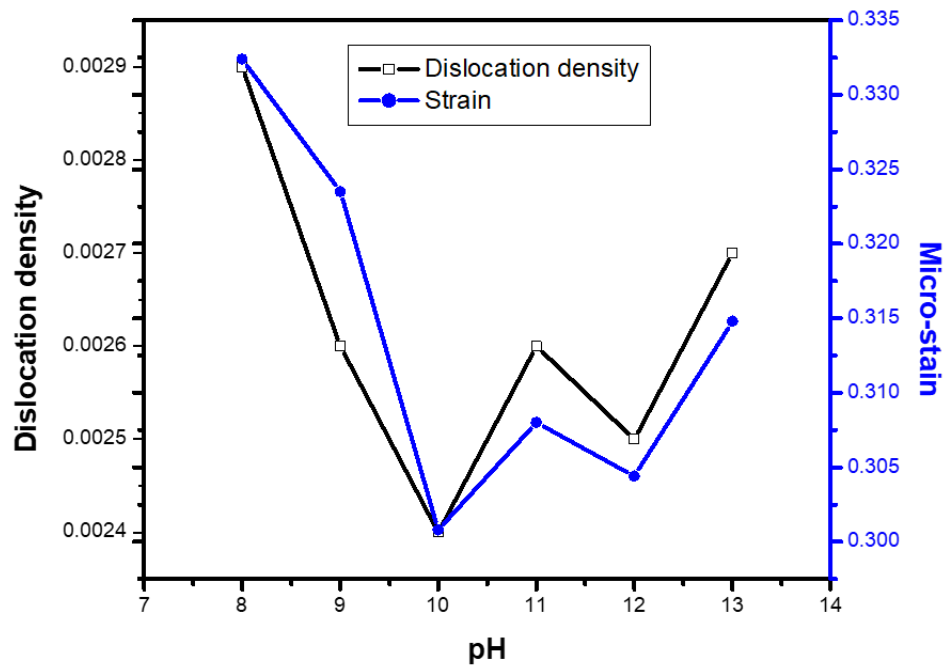


**Figure 4.5: The Graph of Dislocation Density and Micro-Strain Verses pH Values of ZnO:Al:Ga Co-Doped Nanoparticles Synthesized under Varying pH**

Additionally, the volume (V) of the unit cell for hexagonal wurtzite structure was calculated by using the equation (6)

$$V = 0.866 \times a^2 \times c \text{ (Chand et al., 2012).} \dots\dots\dots (6)$$

Perhaps, the results were tabulated in Table 4.1. The energy band gap can also be calculated using the effective mass model expression from XRD results. The equation (7)

$$E_g^{Nps} = E_g^{Bulk} + \frac{1.6}{r^2} \dots\dots\dots (7)$$

Where  $E_g^{Nps}$  is energy band gap of prepared ZnO:Al:Ga co-doped nanoparticles,  $E_g^{Bulk}$  is the energy gap of bulk ZnO (3.37 eV) and r is radius of crystal calculated from XRD data results (Jay Chithra *et al.* (2015)). From the expression (7) the band-gaps values were obtained and recorded in table 1 as follows 3.39, 3.39, 3.38, 3.38, 3.38 and 3.39 eV for the pH values 8 – 13 respectively. From the estimated band gap values, it can be deduced that the energy gaps of the as prepared nanoparticles was inversely proportional to its crystallite radius. This due to the spatial confinement of electrons within the volumes of nanoparticles increases with decreasing crystallite size, leading to discrete energy levels because of quantum confinement (Ramalingam *et al.*, 2020). The nanoparticles' electrical properties are changed by this confinement, specifically their band gap, which is the energy difference between the lowest unoccupied energy level (conduction band) and the highest occupied energy level (valence band). The energy gap between these levels widens as the crystallite size of the nanoparticle decreases due to quantum confinement.

#### 4.2 .2 Optical Analysis

Optical properties of the ZnO:Al:Ga co-doped nanoparticles synthesized under varying pH were obtained from the UV-Vis spectroscopy analysis. Figure 4.6 displays transmittance spectra with comparable patterns at different pH values. The nanoparticles showed higher transmittance a measure of their degree of transparency to incident light at pH 7. This is attributed by reduced agglomeration at pH 7 which is less alkaline, and that promotes optimal crystallinity which is uniformly minimizing the presence of defects within the material. The enhanced crystallinity reduces light scattering and absorption, allowing more incident light to pass through the

nanoparticles without being hindered hence higher transmittance measure. On the other hand, transmittance progressively dropped as pH rose, indicating a decrease in light transmission through the nanoparticles. This pattern demonstrated how the optical properties of the nanoparticles are pH-dependent, with pH being a key factor in determining how transparent the particles are to light (Chand *et al.*, 2012).

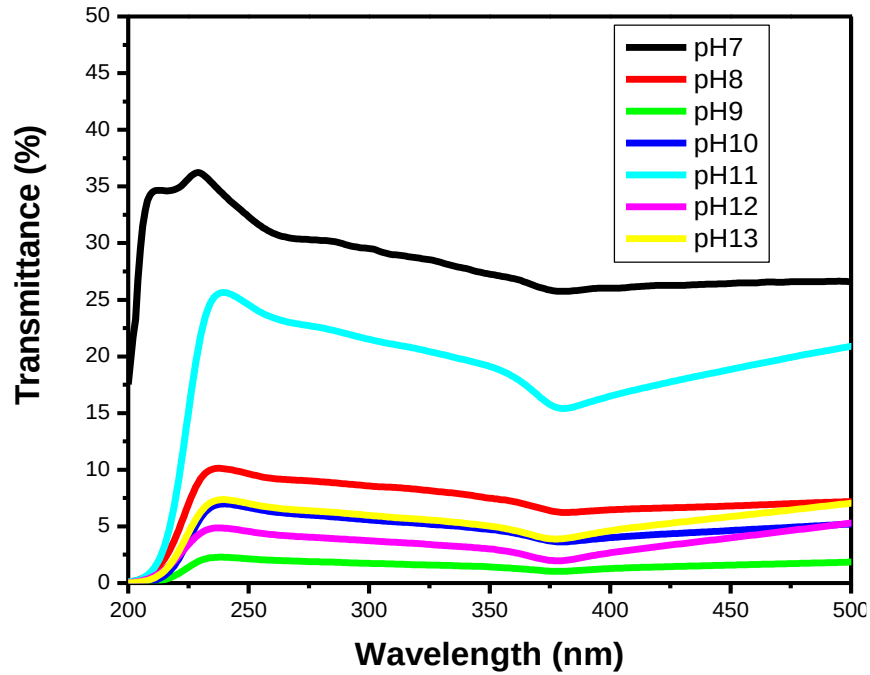


**Figure 4.6: UV-Vis Spectrum Showing Transmittance (%) against Wavelength (nm) of As Prepared ZnO:Al:Ga Co-Doped Nanoparticles for Varying pH Values**

According to figure 4.7 and the tabulated data in Table 4.2, the absorbance peaks in the spectra indicated the wavelengths at which the nanoparticles absorbed light approximately to be 376 - 380 nm. This indicates efficient light absorption and corresponds to a band-gap energy of approximately 3.26 – 3.29 eV. A decrease in the band gap energy and electrical structure of the nanoparticles were confirmed by the absorbance peaks shifting towards longer wavelengths with high peak intensity as pH increased. This is because increasing particle sizes exhibit declining quantum confinement effects that lower the band gap energy (Smith & Nie, 2010). The band gap decreases as the energy levels within the nanoparticles go closer together, since the de Broglie wavelength of electrons is no longer limited by the size of the particle.

The density and distribution of surface states and defects are also influenced by changes in surface chemistry and morphology, which are brought about by pH variations. The electrical structure of the nanoparticles is directly affected by these surface characteristics changes, which in turn affects the absorption properties of the particles. As a result, as pH rises, the absorbance peaks move towards longer wavelengths at higher intensities. Additionally, the dynamics of charge carriers, such as the processes of creation, recombination, and transport, are impacted by pH-dependent changes in the chemical environment around the nanoparticles. These modifications in charge carrier behavior also affect peak intensity and position in the absorption spectrum. The shifting of absorbance peaks and edges demonstrated how pH influences optical properties of the nanoparticles.

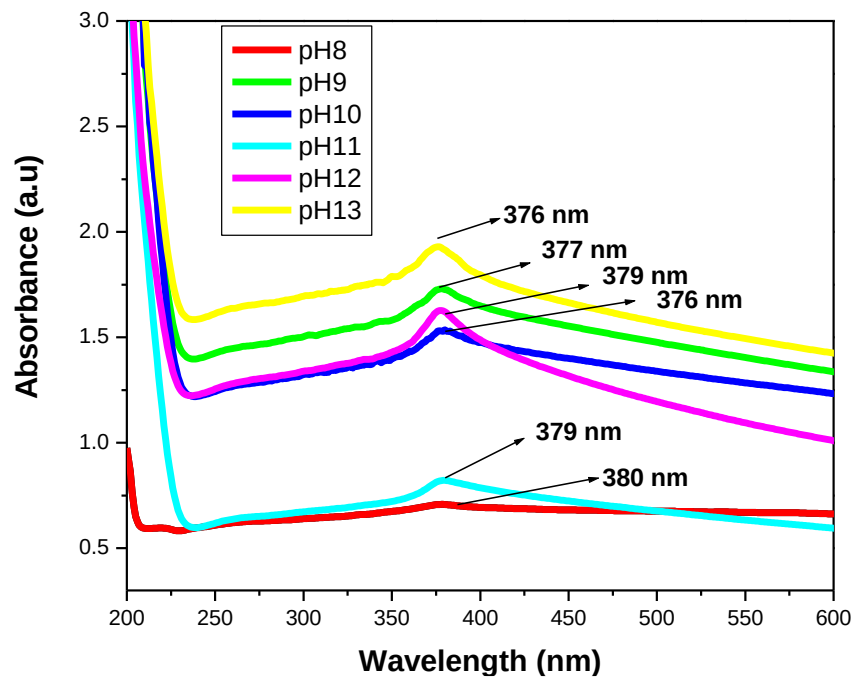


**Figure 4.7: UV-Vis Spectrum Absorbance (a.u) against Wavelength (nm) of ZnO:Al:Ga Co-Doped Nanoparticles with pH Values with Respective Peaks**

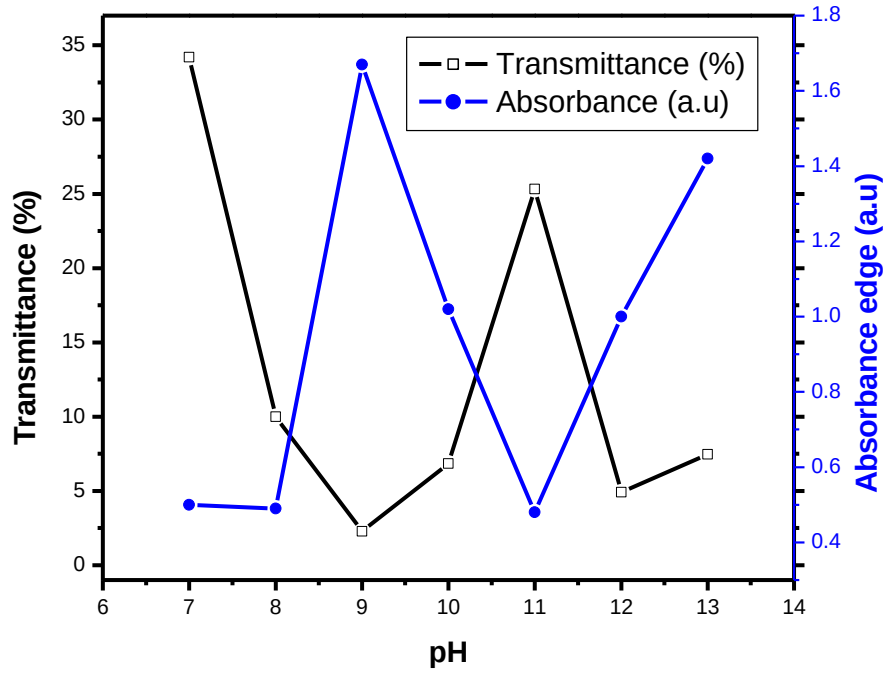


**Figure 4.8: (%) Transmittance and Absorption Edge Verses pH Values of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles with Varying pH Values**

The pH-dependent optical behavior of the ZnO:Al:Ga co-doped nanoparticles is briefly summarized in Table 4.2 & Figure 4.8, which shows the trends of transmittance (%) and absorbance (in arbitrary units, a.u.) against pH values. The decrease in the transmittance and absorbance at enhanced pH values could be due to defects in the material as confirmed from the XRD results and also by Kara *et al.*, 2020. The sensitivity of ZnO:Al:Ga co-doped nanoparticles' optical properties to pH changes was confirmed by this graphical representation, which also emphasizes how crucial pH affect optical properties.

By applying Tauc's equation (8)

$$(\alpha h\nu)^2 = A(h\nu - E_g) \text{ (Ungula et al., 2016)..... (8)}$$

The energy band gap was obtained through extrapolation of the graph of  $(\alpha h\nu)^2$  against  $h\nu$  (eV), where A is constant,  $\alpha$  is the absorption coefficient ( $\alpha = 4\pi k/\lambda$ ; k is the absorption index),  $h\nu$  is the photon's energy,  $E_g$  is the nanoparticles' energy gap.

On the other hand this was estimated theoretically using relationship  $E_{bg} = \frac{1240}{\lambda_{abs}}$  which was obtained by;

$$E = h\nu = \frac{hc}{\lambda} \dots\dots\dots (9)$$

$$\frac{6.625 \times 10^{-34} Js \times 2.998 \times 10^8 m/s}{\lambda(m)}$$

$$\text{But } 1\text{eV} = 1.602 \times 10^{-19} Js$$

$$E = \frac{6.625 \times 10^{-25} Js \text{ (eV)}}{\lambda(m) \times 1.602 \times 10^{-19} Js}$$

$$\text{But } 1\text{nm} = 10^{-9} m$$

$$E = \frac{1240 \text{ (eV)nm}}{\lambda(nm)} \dots\dots\dots (10)$$

From the mathematical equation of a straight line  $y = mx + c$

$$(\alpha h\nu)^2 = A(h\nu - Eg) \dots\dots\dots (8)$$

$$\text{Taking } y=0, \text{ also will be } (\alpha h\nu)^2 = 0$$

$$0 = A(h\nu - Eg)$$

$$\text{But } A=1$$

$$\text{Now } h\nu = Eg = E$$

$$\therefore E_{bg} = \frac{1240 \text{ (eV)}}{\lambda(nm)} \dots\dots\dots (11)$$

Therefore, the relation in equation (11) was used to estimate the energy band-gap of the nanoparticles, and the results showed was 3.27, 3.26, 3.28, 3.28, 3.29, 3.27, 3.29, and 3.29 eV for the samples with pH values of 7, 8, 9, 10, 11, 12, and 13, respectively, as summarized in Table 4.2. These estimated results for energy band-gap matches with the values obtained by Jay Chithra *et al.* (2015), Verma *et al.* (2017) & Alias *et al.* (2010). Perhaps, extrapolation of the Tauc's plot in figure 4.9 shows different energy band-gaps values that range between 4.6 - 5.8 eV. This is supported by a similar report by Chand *et al.* (2012) with the result of energy band gap of range 5.57- 5.579 eV.

This finding confirmed the effect pH in adjusting the optical characteristics of the nanoparticles for particular uses, including solar cell devices, where ideal band gap engineering is necessary for effective light absorption and energy conversion. Since pH regulation is essential for tailoring required optical properties of nanoparticles that are suitable for use in solar cells. By precisely controlling the precursors' pH synthesis it tune the band gap that enhance light absorption, stability and durability of the material that improved performance and efficiency of solar cells (Ali *et al.*, 2018)

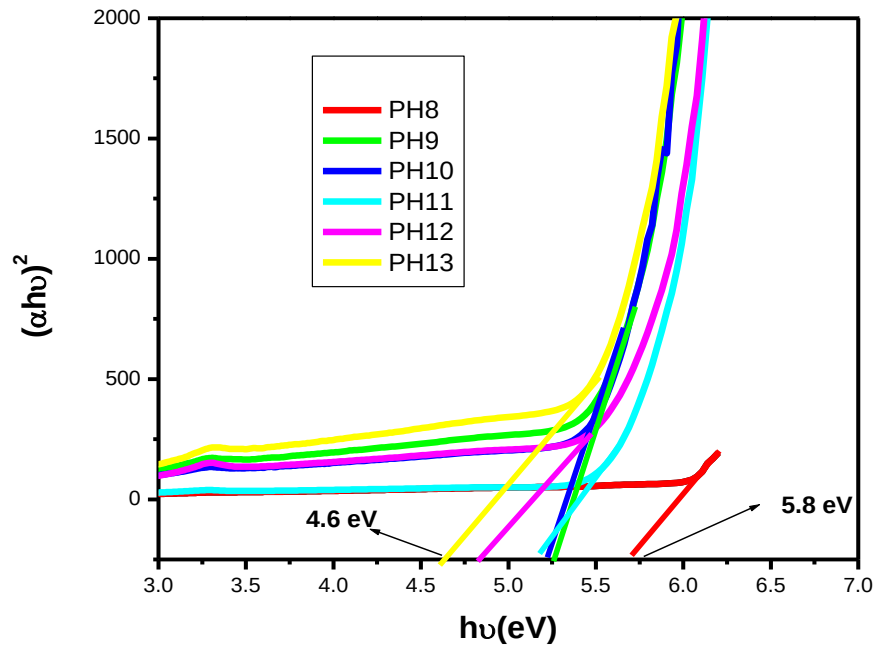


**Figure 4.9: The Tauc's Plot for Determination of Energy Band-Gaps of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles with Varying pH Values**

Furthermore, Table 4.2 summarizes the data obtained from UV-Vis absorbance spectrum and Tauc's relationship for the prepared ZnO:Al:Ga co-doped nanoparticles under varying pH values. In figure 4.10, the graph of estimated band-gaps against pH values for synthesized nanoparticles. The findings showed that Tauc's energy band gap of synthesized nanoparticles is inversely proportional to the increase in pH contrary to theoretically energy band gaps and the report done by Chand *et al.* (2012). The inverse relation of the band gap with pH could be due to increase in the crystallite sizes as depicted in the XRD results.

**Table 4.2: Optical Data for the As-Prepared ZnO:Al:Ga Co-Doped Nps as the pH is Varied**

| Sample | Trans (%) | Absorbance<br>edge-gap | $\lambda_{\text{abs}}(\text{nm})$ | $E_{\text{bg}} = \frac{1240 \text{ (eV)}}{\lambda(\text{nm})}$ | Tauc's<br>$E_{\text{bg}} \text{ (eV)}$ |
|--------|-----------|------------------------|-----------------------------------|----------------------------------------------------------------|----------------------------------------|
| pH 7   | 34.2      | 0.50                   | 379                               | 3.27                                                           | 5.90                                   |
| pH 8   | 10.0      | 0.49                   | 380                               | 3.26                                                           | 5.80                                   |
| pH 9   | 2.28      | 1.67                   | 377                               | 3.28                                                           | 5.30                                   |
| pH 10  | 6.85      | 1.02                   | 376                               | 3.29                                                           | 5.25                                   |
| pH 11  | 25.32     | 0.48                   | 379                               | 3.27                                                           | 5.20                                   |
| pH 12  | 4.92      | 1.00                   | 379                               | 3.27                                                           | 4.80                                   |
| pH 13  | 7.46      | 1.42                   | 376                               | 3.29                                                           | 4.60                                   |

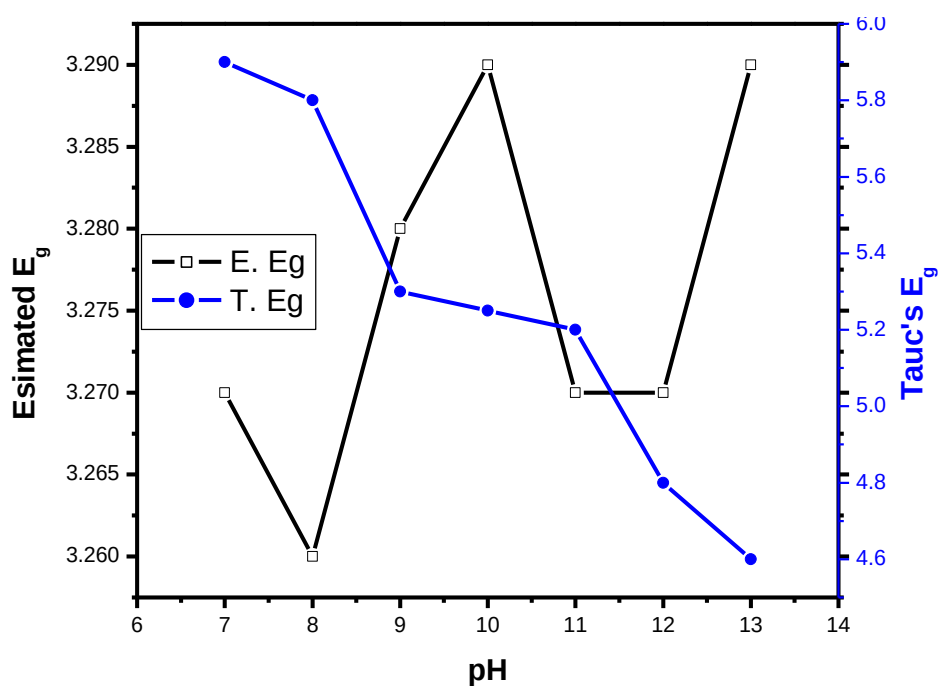


**Figure 4.10: The Graph of Estimated Energy Band Gaps of Prepared ZnO:Al:Ga Co-Doped Nanoparticles**

### 4.2.3 FTIR Analysis

Significant findings about the ZnO:Al:Ga co-doped nanoparticles' chemical bonding and functional groups were clarified through Fourier-transform infrared spectroscopy (FTIR) analysis. The nanoparticles' vibrational modes and molecular interactions were also revealed by the FTIR spectra, which provided important information about their structural composition. Figure 4.11 shows that the ZnO:Al:Ga co-doped nanoparticles have different absorption peaks in their FTIR spectra, which correspond to different functional groups. The Peaks in 400–1500  $\text{cm}^{-1}$  fingerprint range were indicative of metal–oxygen (M–O) stretching vibrations, which are typical of Zn–O bonds in the crystalline lattice structure of the nanoparticles. As confirmed by research done by Swaroop *et al.* (2015). Furthermore, peaks above 3000  $\text{cm}^{-1}$  indicated the presence of hydroxyl (OH) groups, which come from adsorbed water molecules or surface hydroxylation (Dastider *et al.*, 2023). Changes in the FTIR spectra were noted when pH rose from 7 to 13, indicating modifications in the chemical composition and surface characteristics of the nanoparticles. Peaks corresponding to functional groups, like carboxylates and hydroxyls, expand during synthesis, suggesting alterations in their environment or abundance brought on by pH shifts. Perhaps, as shown in figure 4.11, the stretching mode peaks at 400  $\text{cm}^{-1}$  are a sign of a successfully synthesized ZnO:Al:Ga nanoparticle. Additionally, shifts in the absorption peaks of systematic pH values of 8, 10, and 12 from 415, 410, and 412  $\text{cm}^{-1}$ , respectively. This indicated that dopant-oxygen interactions or metal-oxygen bonds occurred, reflecting modifications in the coordination geometry and bonding environment of dopant atoms within the ZnO lattice. These findings offer a true picture of the doping effects of Al and Ga on the chemical structure of the nanoparticles.

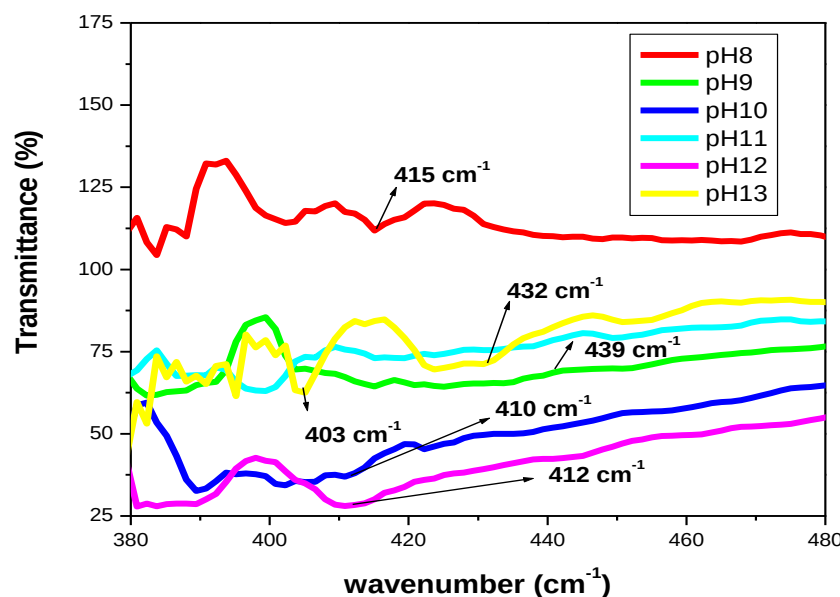


**Figure 4.11: FTIR Spectrum % Transmittance against Wavenumber (cm<sup>-1</sup>) of ZnO:Al:Ga Co-Doped Nanoparticles with pH Values**

#### 4.2 .4 SEM Analysis

Using a SEM, the surface morphologies of various samples were determined. With regard to the samples, image in figure 4.12 demonstrated the development of a distinct surface morphology. The lamina like-spherical is seen in sample (a) pH 8 in SEM micrographs of figure 4.12. Also from figure 4.12, porous grain-like formations can be observed. ZnO:Al:Ga co-doped nanoparticles synthesized at lower pH levels for example 8, showed a more uniform size distribution on surface. A substantial rise in nanoparticle size and aggregation tendency was seen as the pH level rose from 8 to 12 which are in line with the observations made from the XRD results. According to Jay Chithra *et al.* (2015), the aggregation phenomena can be explained by the impact of pH on nucleation and growth kinetics during nanoparticle synthesis. The findings of Gherbi *et al.* (2022), proposed that alkaline medium promote quicker nucleation and growth rates, resulting to larger nanoparticles and these findings are supports the observed rise in nanoparticle size with higher pH values.

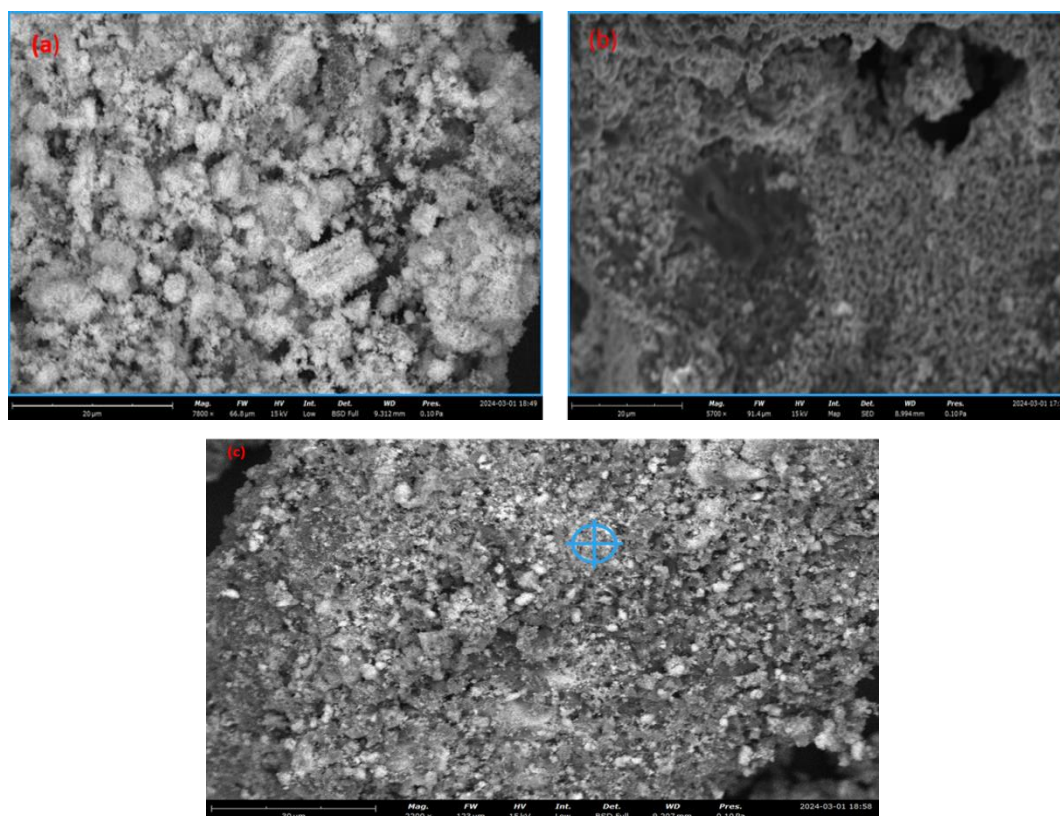


**Figure 4.12: SEM Micrographs of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles at (a) pH 8 (b) pH 12 (c) pH 10**

Additionally, figure 4.13 shows energy-dispersive X-ray spectroscopy (EDS) investigation on the elemental composition of pH 12. As shown in Table 4.3, contaminants such as sodium, carbon, and chlorine were found in the nanoparticles in addition to the actual zinc, aluminum and gallium. It is important to carefully manage the synthesis conditions to reduce impurity inclusion, as these impurities may come from precursor compounds or reaction intermediates employed during nanoparticle formation. On the other hand, the Zn and O elements present in the pH 8 nanoparticle EDS micrograph, figure 4.14 supported the establishment of a pure ZnO composition (Zn- 72.3 % and O<sub>2</sub>- 27.7 %). These findings were close to the research done by Hasnidawani. (2016) where the EDX characterization gave Zinc content - 55.38%; Oxygen content - 44.62% with very little impurities observed. Theoretically, the expected stoichiometric mass per-cent of Zn and O are 80.3% and 19.7% as reported by Bari *et al.*, 2009. Table 4.4 lists the atomic weights and concentrations of the elements Zn and O of the prepared ZnO:Al:Ga co-doped nanoparticles. The observed

pH-dependent changes in the morphology and content of nanoparticles point to the possibility of adjusting ZnO:Al:Ga nanoparticles' optical, morphological and structural characteristics for improved solar cell performance.

**Table 4.3: Table Showing Elements of ZnO:Al:Ga Sample Prepared at pH 12**

|  | Element Number | Element Symbol | Element Name | Atomic Conc. | Weight Conc. |
|--|----------------|----------------|--------------|--------------|--------------|
|  | 6              | C              | Carbon       | 21.394       | 11.211       |
|  | 8              | O              | Oxygen       | 44.163       | 30.831       |
|  | 11             | Na             | Sodium       | 20.448       | 20.521       |
|  | 13             | Al             | Aluminum     | 0.425        | 0.501        |
|  | 17             | Cl             | Chlorine     | 1.359        | 2.102        |
|  | 30             | Zn             | Zinc         | 12.211       | 34.835       |

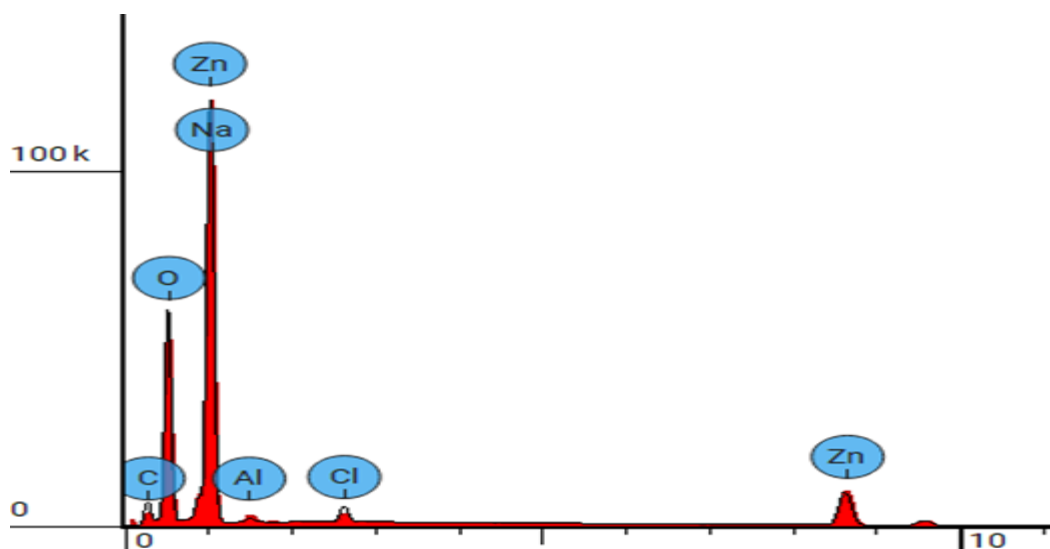


**Figure 4.13: EDS Spectrum for ZnO:Al:Ga Nps Prepared at pH 12**

**Table 4.4: Showing Elemental Composition of ZnO:Al:Ga Nps Sample Prepared at pH 8**

|  | Element Number | Element Symbol | Element Name | Atomic Conc. | Weight Conc. |
|--|----------------|----------------|--------------|--------------|--------------|
|  | 8              | O              | Oxygen       | 61.022       | 27.700       |
|  | 30             | Zn             | Zinc         | 38.978       | 72.300       |

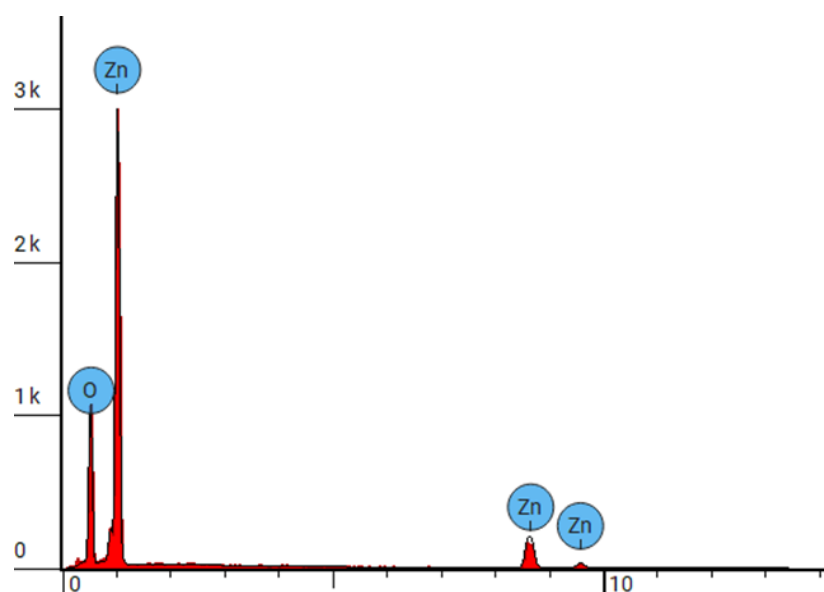


**Figure 4.14: EDS Spectrum for ZnO:Al:Ga NPs Sample Prepared at pH 8**

### 4.3 Effects of Annealing Temperature on the Material Properties of ZnO:Al:Ga Co-Doped Nanoparticles for Solar Cell Applications

#### 4.3.1 Structural Properties

To clarify the crystalline nature of the synthesized ZnO:Al:Ga nanoparticles, their structural properties were characterized. The X-ray diffraction (XRD) pattern in Figure 4.15 displays intensity peaks that correspond to ZnO:Al:Ga co-doped nanoparticles that were synthesized and annealed at different temperatures ranging from 400°C to 900°C. The graph is found to be almost in agreement with the hexagonal wurtzite of ZnO nanoparticles, which is in line with earlier research (Sangeetha *et al.*, 2019) that matches JCPDS No. 36 - 1451.

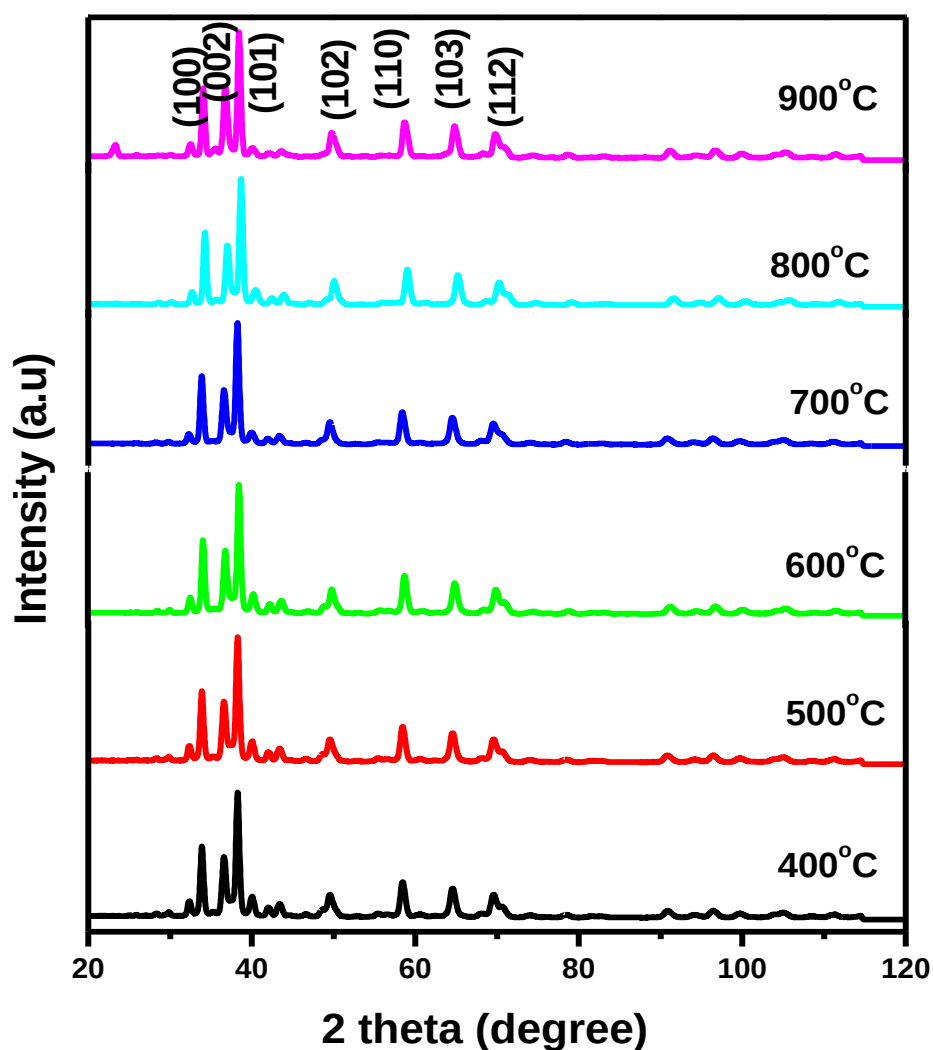


**Figure 4.15: XRD Pattern for Prepared ZnO:Al:Ga Co-Doped Nanoparticles with Varying Annealing Temperatures**

Figure 4.16 shows an analysis of the ZnO:Al:Ga co-doped nanoparticles' diffraction peak intensity and position variation with annealing temperatures in the  $2\theta$  region, ranging from  $37.5^\circ$  to  $39.5^\circ$ . As the annealing temperature increases, the diffraction peak gets narrower (reduce full width at half maximum) and more intense, confirming that the nanoparticles' crystallinity has improved (Zhi *et al.*, 2003). An annealing temperature of  $700^\circ\text{C}$  yielded the highest intensity of ZnO:Al:Ga co-doped nanoparticles, indicating enhanced crystallinity and grain growth. This is because dopants have already partially integrated into the ZnO matrix at this annealing

temperature. However, in figure 4.17 it showed decline in full width at half maximum (FWHM) and peak intensity at thermal treatment 800° C and 900° C. This is due to an increase in temperature causes dopants to be displaced from sub-stitutional positions to interstitial or grain boundaries, resulting in poor crystallinity, therefore the FWHM and peak intensity decrease.

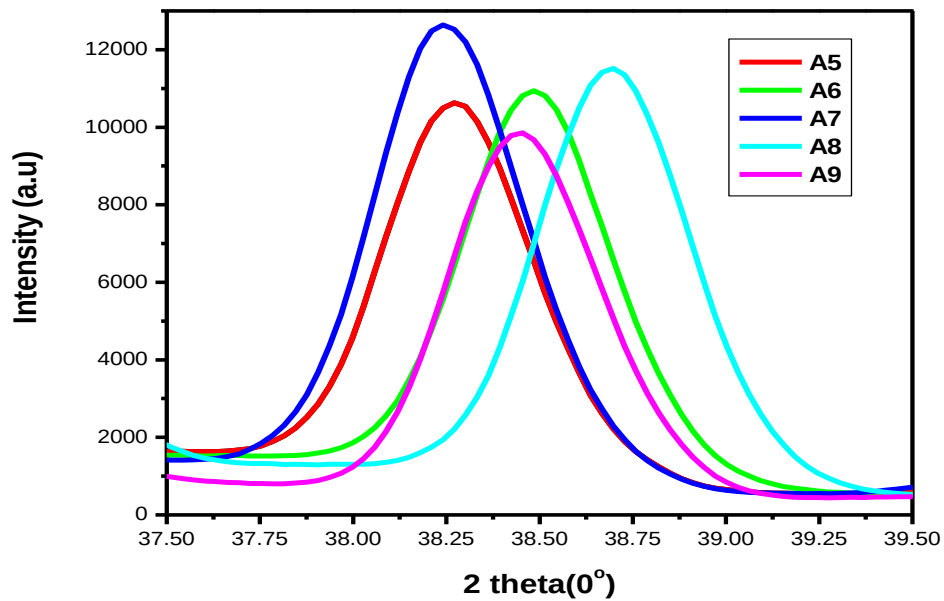


**Figure 4.16: XRD Graph of Intensities in arbitrary units against 2 Theta in Degrees Range 37.5 ° - 39.5 ° for Prepared ZnO:Al:Ga Co-Doped Nanoparticles with Varying Annealing Temperatures; A5 – 500° C, A6 – 600° C, A7 – 700° C, A8 - 800° C, A9 – 900° C**

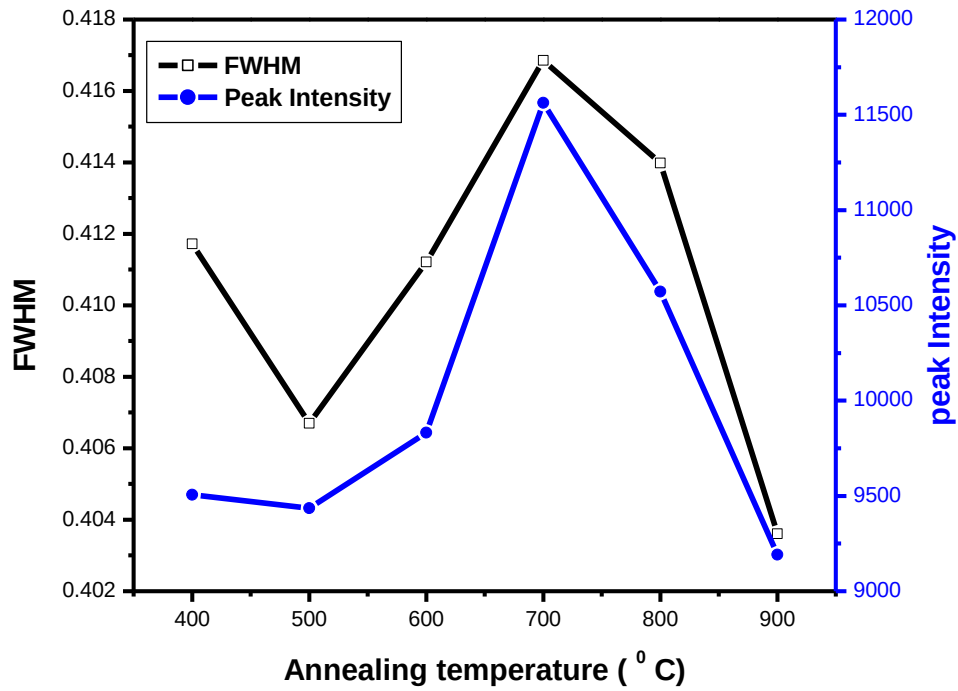


**Figure 4.17: Showing FWHM and Peak Intensities for Synthesized ZnO:Al:Ga Co-Doped Nanoparticles**

The crystallite size was calculated using the Scherrer equation (12)

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (\text{Gherbi } et al., 2022) \dots\dots\dots (12)$$

where D is crystalline size, K is constant (0.89),  $\lambda$  is 0.154056 nm, mean wavelength of CuK $\alpha$ 1 radiation,  $\beta$  is full width half maxima and  $\theta$  is Bragg's angle in radians, the crystallite size analysis presented in Table 4.5, revealed dimensions of prepared ZnO:Al:Ga nanoparticles between 20.2 and 20.8 nm throughout the annealing temperatures range. These nano-scale measurements are consistent with findings from related studies (Droepenu *et al.*, 2022). In those studies, nano-crystalline ZnO:Al:Ga co-doped nanoparticles of similar sizes demonstrated improved charge transport properties appropriate for photovoltaic applications. Additionally, from the crystallite size XRD results. The energy band gap can also be calculated using the effective mass model expression by expression (13)

$$E_g^{Nps} = E_g^{Bulk} + \frac{1.6}{r^2} \dots\dots\dots (13)$$

Where  $E_g^{Nps}$  is energy band gap of prepared ZnO:Al:Ga-co-doped nanoparticles,  $E_g^{Bulk}$  is the energy gap of bulk ZnO (3.37 eV) and  $r$  is radius of crystallite nanoparticles (Jay Chithra *et al.* (2015). The calculated energy band-gap values were recorded in table 1 ranging approximately 3.5 eV.

**Table 4.5: Table Showing Variation Crystallite Size Prepared ZnO:Al:Ga Co-Doped Nanoparticles under Various Annealed Temperatures**

| Temp<br>(°C) | 2 $\theta$ | $\beta$ | D(nm) | Peak<br>intensity | Energy<br>band-gap<br>(eV) |
|--------------|------------|---------|-------|-------------------|----------------------------|
| 400          | 38.275     | 0.41172 | 20.4  | 9506.2            | 3.5368                     |
| 500          | 38.275     | 0.40670 | 20.6  | 9435.9            | 3.5253                     |
| 600          | 38.486     | 0.41121 | 20.5  | 9831.6            | 3.5260                     |
| 700          | 38.253     | 0.41686 | 20.2  | 11562             | 3.5284                     |
| 800          | 38.696     | 0.41398 | 20.3  | 10572             | 3.5276                     |
| 900          | 38.457     | 0.40361 | 20.8  | 9191.0            | 3.5238                     |

Furthermore, figure 4.18 shows the relationship between the crystallite size and energy band-gap. The crystallite size showed decrease in nanoparticle size until annealing temperatures of 700° C then started to rise up to 900° C while energy band- gap increase gradually up to 800° C thereafter declines slightly. The decrease in crystallinity confirms the increase in energy band-gap.

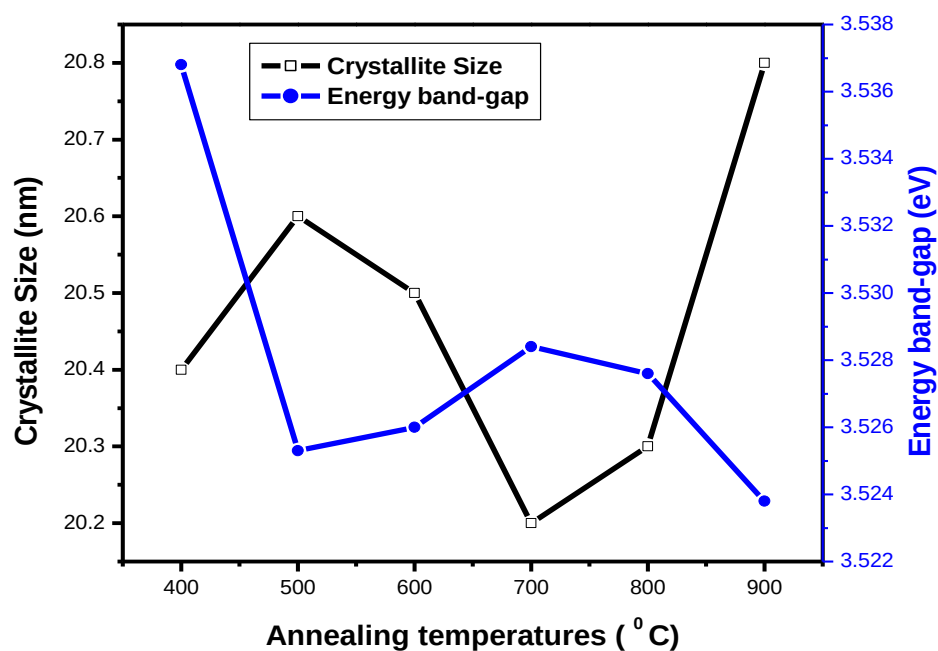


**Figure 4.18: The Graph of Crystalline size (nm) and Energy Band-Gap against Annealing temperatures (° C) of ZnO:Al:Ga Co-Doped Nanoparticles**

The lattice parameters of ZnO:Al:Ga co-doped nanoparticles were calculated using the Bragg's equation (14)

$$\lambda = 2d \sin \theta \quad (\text{Verma } et al., 2017) \dots \dots \dots (14)$$

Where  $d$  is the inter-planar spacing,  $\theta$  is the angle of incidence,  $\lambda$  is the wavelength, and  $n$  is the diffraction order. Also, the equation (15)

$$\frac{1}{d^2} = \frac{4}{3} \left( \frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2} \quad (\text{Jay Chithra } et al., 2015 \text{ \& Verma } et al., 2017) \dots \dots \dots (15)$$

Where 'a' and 'c' are the lattice parameters, h, k, and l are the Miller indices and  $d$  is the inter-planer spacing. The prepared ZnO:Al:Ga nanoparticles showed 'a' range between 0.2685 – 0.2715 nm and 'c' to be 0.4384 – 0.4433 nm. The obtained lattice parameters were recorded in table 4.6. The slight changes in the bulk's ZnO standard lattice parameters affirms nanoparticles have underwent mechanical stress or existence of imperfections, defects in the ZnO:Al:Ga nanoparticles formation.

**Table 4.6: Table Showing Variation Crystallite Size Prepared ZnO:Al:Ga Co-Doped Nanoparticles under Various Annealed Temperatures**

| Temp (° C) | 2 $\Theta$ | 'd'    | 'a'    | 'c'    |
|------------|------------|--------|--------|--------|
| 400        | 38.275     | 0.2115 | 0.2713 | 0.4430 |
| 500        | 38.275     | 0.2115 | 0.2713 | 0.4430 |
| 600        | 38.486     | 0.2103 | 0.2699 | 0.4407 |
| 700        | 38.253     | 0.2116 | 0.2715 | 0.4433 |
| 800        | 38.696     | 0.2092 | 0.2685 | 0.4384 |
| 900        | 38.457     | 0.2105 | 0.2700 | 0.4409 |

The equation (16)

$$\delta = \frac{1}{D^2} \text{ (Kiprotich *et al.*, 2022 & Ungula *et al.*, 2024)..... (16)}$$

Where  $\delta$  is the length of dislocation density and D is the crystalline size; was applied calculate the dislocation density of the prepared samples. The dislocation density of prepared ZnO:Al:Ga co-doped nanoparticles under varying annealing temperatures were recorded in Table 4.7. In addition lattice strain ( $\epsilon$ ) was computed with the equation (17)

$$\epsilon = \frac{\beta}{4 \tan \Theta} \text{ (Kiprotich *et al.*, 2022)..... (17)}$$

Where  $\Theta$  is the angle of diffraction and  $\beta$  is the full width at half maximum (FWHM). Also lattice strain values were recorded in Table 4.7.

**Table 4.7: Table Showing Variation in Dislocation Density and Lattice Strain for the Synthesized ZnO:Al:Ga Co-Doped Nanoparticles Under Various Annealed Temperatures**

| Temp (° C) | D(nm) | $\delta$ | $\beta$ | 2 $\Theta$ | $\epsilon$ |
|------------|-------|----------|---------|------------|------------|
| 400        | 20.4  | 0.0490   | 0.41172 | 38.275     | 0.2966     |
| 500        | 20.6  | 0.0485   | 0.40670 | 38.275     | 0.2930     |
| 600        | 20.5  | 0.0488   | 0.41121 | 38.486     | 0.2945     |
| 700        | 20.2  | 0.0495   | 0.41686 | 38.253     | 0.2984     |
| 800        | 20.3  | 0.0493   | 0.41398 | 38.696     | 0.2947     |
| 900        | 20.8  | 0.0480   | 0.40361 | 38.457     | 0.2893     |

Previous studies have shown that higher FWHM values are associated with smaller crystallite sizes and increased lattice strain (Bindu & Thomas 2014). Which is consistent with this findings from the figure 4.19 that revealed information about the degree of lattice strain and dislocation density which reduce crystallinity within the nanoparticles. The trend showed that at 400 – 500 °C and 700 – 900 °C both the strain and dislocation densities are reducing while at 500 – 700 °C increases. This correlation emphasizes how important lattice perfection is for maximizing the material's optical and electrical performance.

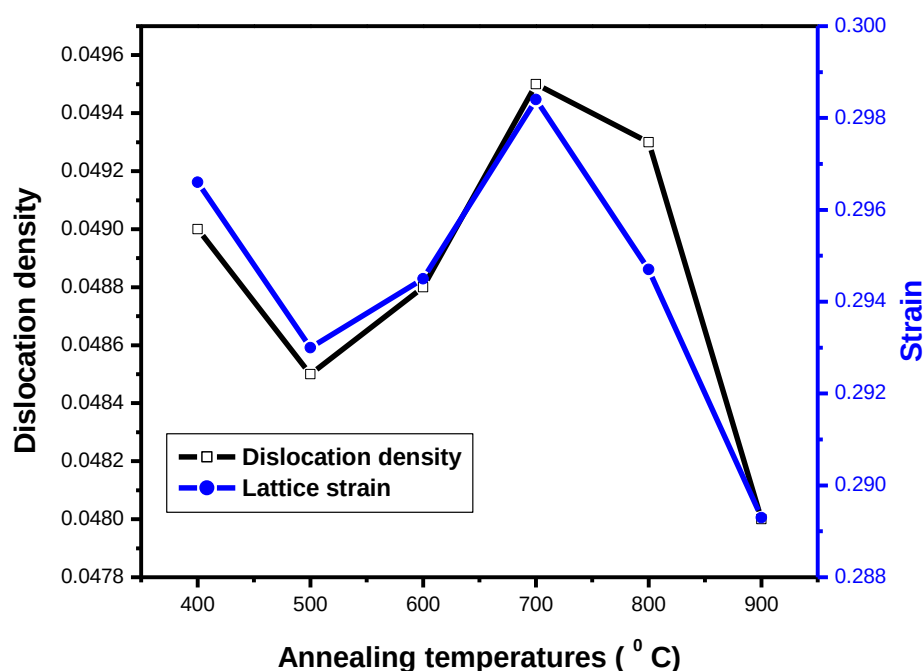


**Figure 4.19: The Graph of Dislocation Density And Lattice Strain for Prepared ZnO:Al:Ga Co-Doped Nanoparticles under Various Annealing Temperatures**

#### 4.3.2 Optical Properties

The UV-Vis spectra presented in Figures 4.20 and 4.21 offer important information about the optical properties of the ZnO:Al:Ga co-doped nanoparticles that were synthesized at different annealing temperatures. The transmittance spectrum in Figure 4.20 reveals specific absorption properties in the ultraviolet region. The transmittance of the nanoparticles gradually increases as the annealing temperature rises from 400° C to 900° C, suggesting that the material's optical transparency has improved (Sabeeh & Jassam 2018). According to Zak *et al.* (2011), the decrease in structural defects and the improvement of grain boundaries during annealing are responsible for the increase in transmittance, which in turn results in less light scattering and better photon transmission through the material.

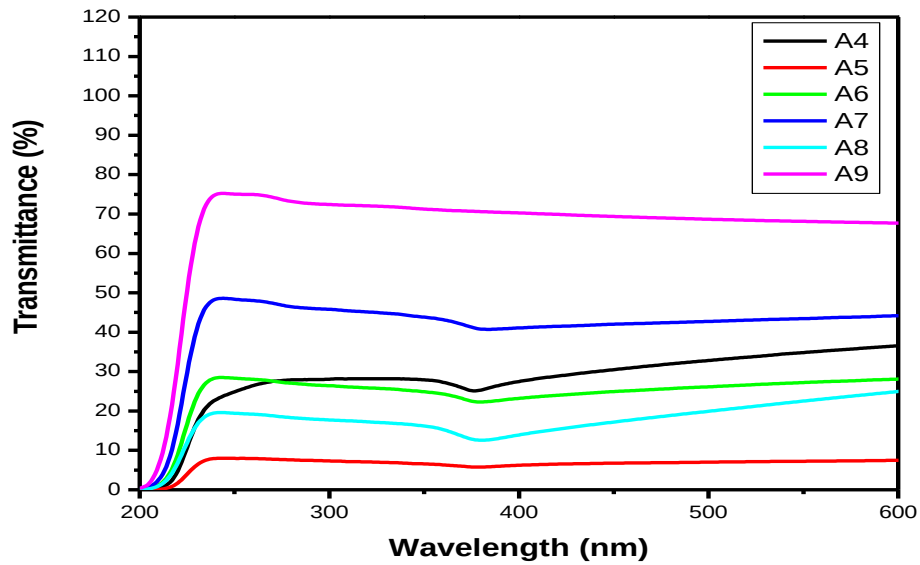


**Figure 4.20: UV-Vis Spectrum Showing Transmittance (%) against Wavelength (nm) of Prepared ZnO:Al:Ga Co-Doped Nanoparticles for varying Annealed Temperatures; A4 – 400° C, A5 – 500° C, A6 – 600° C, A7 – 700° C, A8 - 800° C, A9 – 900° C**

In figure 4.21, which complements the transmittance spectra, shows the absorbance (a.u.) of the nanoparticles as a function of wavelength and sheds light on the material's absorption properties. Different absorption peaks at different wavelengths are seen in each spectrum, which confirms that the ZnO:Al:Ga nanoparticles are undergoing electronic transitions. The bandgap energy and electronic structure of the material change as the annealing temperature rises, as seen by shifts in the absorbance spectra's peak position and intensity (Vadivel *et al.*, 2014). These changes are ascribed to annealing-induced modifications in the crystalline structure, grain size, and defect density, which affect the nanoparticles' optical characteristics (Ungula *et al.*, 2022).

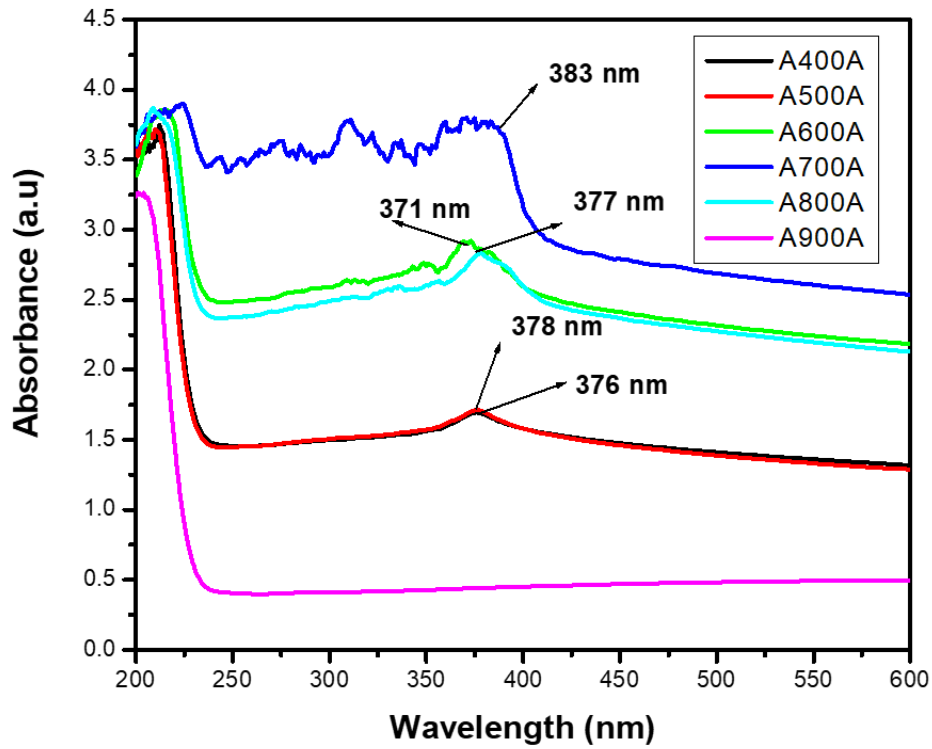


**Figure 4.21: UV-Vis Spectrum Absorbance (a.u) against Wavelength (nm) of ZnO:Al:Ga Co-Doped Nanoparticles with Varying Annealed Temperatures; A400A – 400 °C, A500A - 500 °C, A600A - 600 ° C, A700A - 700 ° C, A800A - 800 ° C, A900A - 900 ° C**

$$E_g = \frac{hc}{\lambda} \dots\dots\dots (18)$$

Moreover, the equation (18) by Venu & Kamila (2017) was applied to work out the energy band-gap, where  $h$  is the Plank's constant  $c$  is the velocity of light and  $\lambda$  is the absorbance peak . All of the synthesized ZnO:Al:Ga nanoparticles have  $E_g$  values between 3.24 and 3.34 eV shown in Table 4.8. According to published research by Harun *et al.*, 2016, ZnO's  $E_g$  was found to be 3.37 eV. The energy band gaps that were found, which range from 3.24 to 3.34 eV, agree with the results of earlier studies (Zak *et al.*, 2011; Vadivel *et al.*, 2014; Ungula *et al.*, 2017). These values are in line with ZnO-based materials' typical bandgap of 3.37 eV, which facilitates effective light absorption and charge generation in photovoltaic devices. Consequently, the

examination of energy band gaps and UV-Vis spectra emphasizes the importance of annealing temperature in modifying ZnO:Al:Ga nanoparticle optical characteristics for improved solar energy harvesting applications.

**Table 4.8: Summarize Table of Wavelength and Energy Band-Gap**

| Sample ( ° C) | Wavelength (nm) | E <sub>bg</sub> (eV) |
|---------------|-----------------|----------------------|
| 400           | 376             | 3.30                 |
| 500           | 378             | 3.29                 |
| 600           | 371             | 3.34                 |
| 700           | 383             | 3.23                 |
| 800           | 377             | 3.29                 |
| 900           | -               | -                    |

$$(\alpha h\nu)^2 = A(h\nu - E_g) \text{ (Ungula et al., 2016)..... (19)}$$

The Tauc's equation (19) was used to estimate the energy band gap through extrapolation of the x-axis in the figure 4.22. The graph of  $(\alpha h\nu)^2$  against  $h\nu$  (eV), where A is constant,  $\alpha$  is the absorption coefficient ( $\alpha = 4\pi k/\lambda$ ; k is the absorption index),  $h\nu$  is the photon's energy,  $E_g$  is the nanoparticles' energy gap. The values were obtained in the range of 2.6 - 5.5 eV which supported similar energy band-gaps computed by effective mass model formula but slightly different from the results calculated theoretically using the formula equation (20)

$$E_g = \frac{hc}{\lambda} \text{ ..... (20)}$$

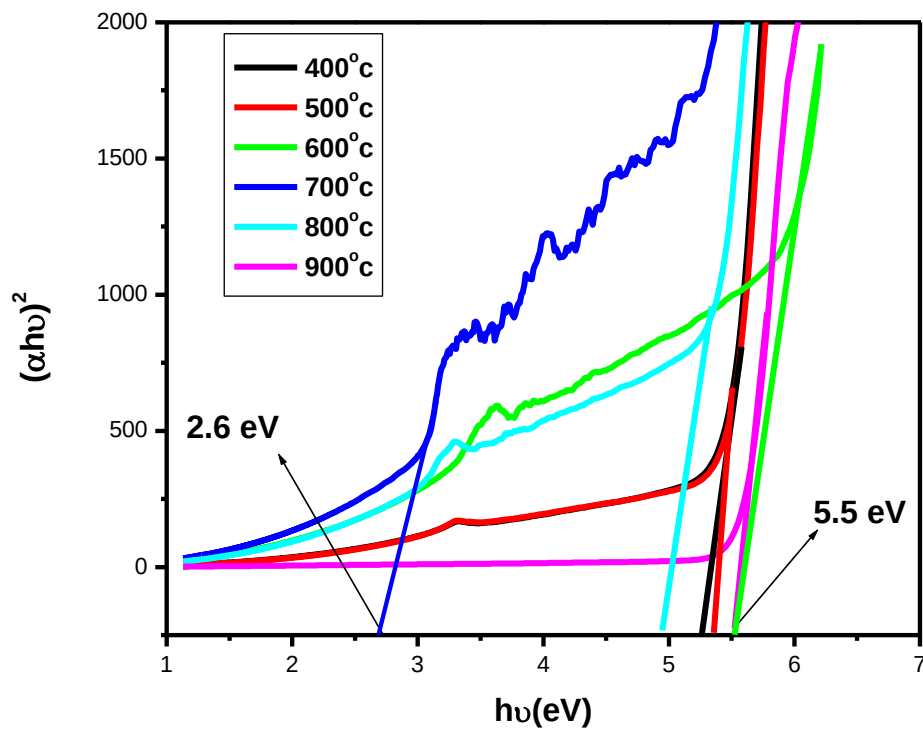


**Figure 4.22: The Tauc's Plot for Determination of Energy Band-Gaps of ZnO:Al:Ga Co-Doped Nanoparticles with Varying Annealing Temperatures**

### 4.3.3 Morphological Properties

The surface morphological properties of the ZnO:Al:Ga co-doped nanoparticles were synthesized at different annealing temperatures are shown in Figure 4.23(a). SEM micrographs showed nanoparticles annealed at 600° C had a porous texture and grain-like lamina structures, whereas the nanoparticles that were annealed at 900°C had a smoother surface texture as in Figure 4.23(b). The study by Venu & Kamila (2017), which showed similar porous structures in sol-gel derived ZnO nanoparticles annealed at comparable temperatures, is consistent with the porous texture observed in nanoparticles annealed at 600°C. Similarly, Mallika *et al.* (2015) explained that the organic precursors' breakdown during thermal treatment was responsible for the porous texture of ZnO nanoparticles.

On the other hand, the smoother surface texture found in nanoparticles annealed at 900°C is consistent with what Li & Meng (2014) found. It stated that by increasing

particle sintering and calcination ZnO nanoparticles at high temperatures produced smoother surface textures. ZnO-based nanoparticles annealed at higher temperatures also showed a decrease in surface roughness and porosity, which was attributed to improved particle mobility and coalescence.

The synthesized nanoparticles' morphological alterations support earlier findings in the literature that annealing temperature affects nanoparticle morphology. These findings highlight the significance of annealing conditions in modifying ZnO:Al:Ga co-doped nanoparticle morphological properties for particular uses, like solar cell devices. Researchers can control the morphology of nanoparticles and improve the efficiency and performance of solar energy conversion technologies by optimizing the annealing parameters.

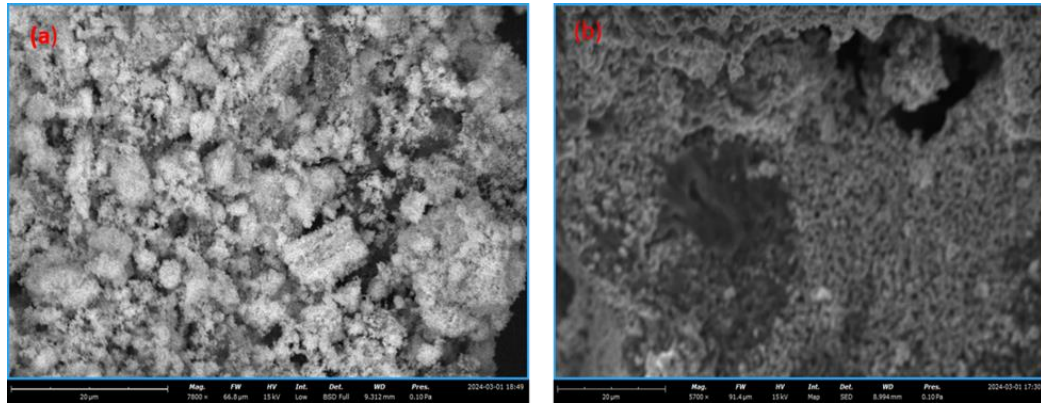


**Figure 4.23: SEM Micrographs of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles at Annealing Temperatures at (a) 600° C (b) 900° C for 1 Hour**

#### 4.3.4 Elemental Composition

In figure 4.24 and Table 4.9 illustrates pure composition of nanoparticles that were annealed for one hour at 600°C. This is consistent with earlier research findings. As an example, Raoufi *et al.* (2013) showed that annealing ZnO nanoparticles at room temperature reduces the amount of impurities that are introduced while maintaining their purity. In a similar, Pandey *et al.* (2017) reported that high elemental purity, mainly consisting of oxygen and zinc, was demonstrated by nanoparticles synthesized using sol-gel methods and annealed under similar conditions. These results supports

the idea that impurity incorporation into ZnO-based nanoparticles can be minimized by using lower annealing temperatures.

On the other hand, as in figure 4.25 and Table 4.10 shows, impurities such as sodium, aluminum, carbon, and chlorine were present in nanoparticles that were annealed at 900° C for one hour. This finding is in line with research by Li & Meng (2014), which showed that precursor materials or environmental impurities may be introduced into ZnO nanoparticles during higher temperature annealing. The diffusion of contaminants from the substrate or annealing environment to the presence of impurities in high-temperature annealed nanoparticles. Elevated annealing temperatures facilitated the incorporation of impurities into ZnO nanoparticles by increasing diffusion kinetics, as reported by Raoufi (2013). These results highlight how crucial it is to regulate annealing conditions in order to minimize impurity incorporation in ZnO-based nanoparticles for the best possible performance.

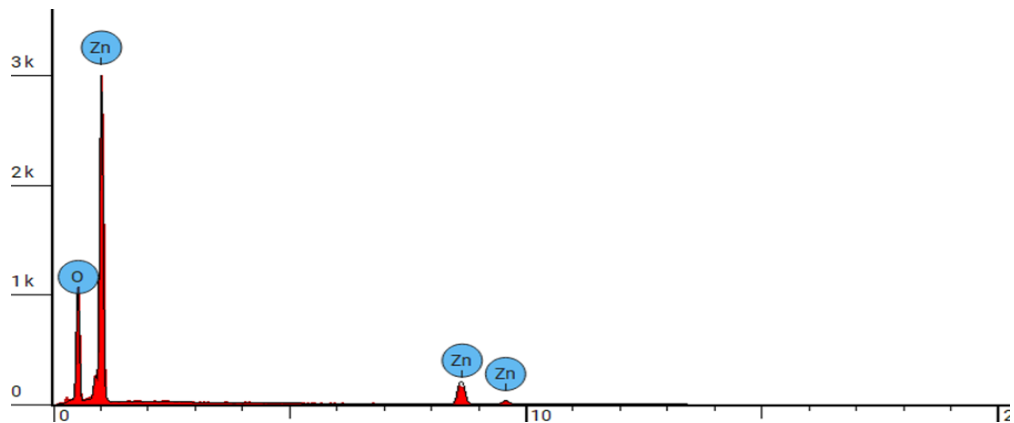


**Figure 4.24: Showing EDS Elemental Spectrum Pattern of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles at Annealed at 600 °C for 1 Hour**

**Table 4.9: Table Showing Elements of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles at Annealed at 600 °C for 1 Hour**

|  | Element Number | Element Symbol | Element Name | Atomic Conc. | Weight Conc. |
|--|----------------|----------------|--------------|--------------|--------------|
|  | 8              | O              | Oxygen       | 61.022       | 27.700       |
|  | 30             | Zn             | Zinc         | 38.978       | 72.300       |

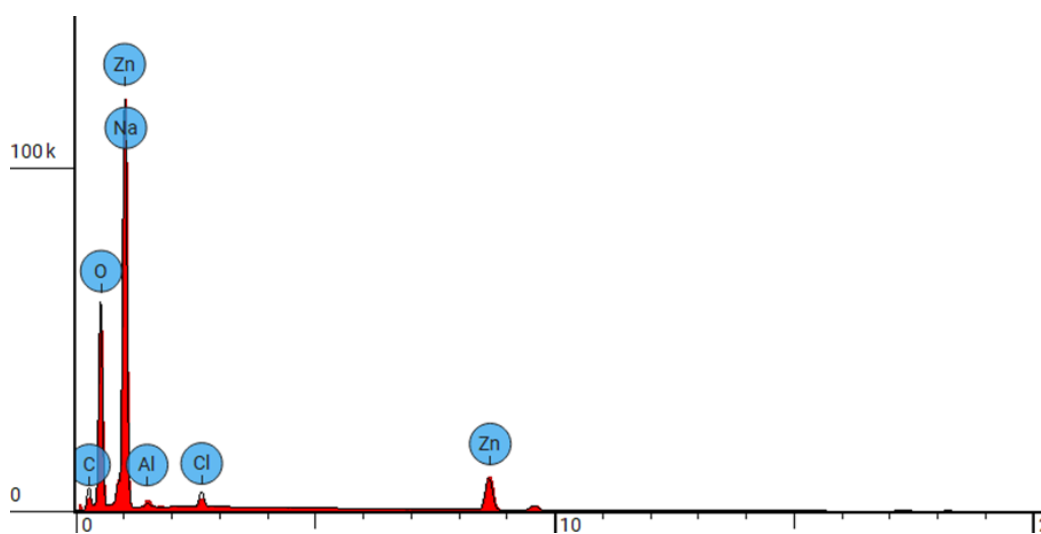


**Figure 4.25: Showing EDS Elemental Spectrum Pattern of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles at Annealed at 900° C for 1 Hour**

**Table 4.10: Table Showing Elements of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles at Annealed at 900° C for 1 Hour**

|  | Element Number | Element Symbol | Element Name | Atomic Conc. | Weight Conc. |
|--|----------------|----------------|--------------|--------------|--------------|
|  | 6              | C              | Carbon       | 21.394       | 11.211       |
|  | 8              | O              | Oxygen       | 44.163       | 30.831       |
|  | 11             | Na             | Sodium       | 20.448       | 20.521       |
|  | 13             | Al             | Aluminum     | 0.425        | 0.501        |
|  | 17             | Cl             | Chlorine     | 1.359        | 2.102        |
|  | 30             | Zn             | Zinc         | 12.211       | 34.835       |

#### 4.3.5 Chemical Composition and Bonding Structure

Fourier Transform Infrared Spectroscopy (FTIR) was used to examine the chemical composition and bonding structure of the synthesized ZnO:Al:Ga nanoparticles, yielding important information about their atomic arrangement and surface chemistry. The nanoparticles' distinct absorption bands, identified by FTIR analysis, corresponded to different chemical bonds and molecular vibrations.

The FTIR spectrums' observed absorption bands show that particular functional groups and bonding arrangements are present. As an illustration, the wide absorption band centered at 3400 cm<sup>-1</sup> is representative of O-H stretching vibrations, which are generally connected to adsorbed moisture and surface hydroxyl groups (Piras *et al.*, 2022). These hydroxyl groups imply interactions between the surface of the nanoparticle and surrounding moisture, which affect the stability and reactivity of the surface.

Furthermore, the stretching and bending vibrations of metal-oxygen (M-O) bonds in the ZnO lattice structure are represented by absorption bands in the 400–1000 cm<sup>-1</sup> range of the FTIR spectrum (Menazea *et al.*, 2021). The predominant presence of zinc oxide (ZnO) in the synthesized nanoparticles is confirmed by these absorption bands,

which are typical of zinc oxide materials. The crystalline phase and purity of the ZnO matrix was confirmed from the intensity and location of these bands wavenumbers shown in figure 4.26.

Moreover, additional absorption bands that correspond to dopants Al-O and Ga-O bonds are present in the wavenumber between the range  $400 - 800 \text{ cm}^{-1}$ . These absorption bands show that dopant atoms were successfully incorporated into the ZnO lattice, affecting its optical and electronic properties (Kabir *et al.*, 2021). Seeing the shift changes in M-O bonding structure after annealing at different temperatures provides some interesting observations, as in Figure 6 the identified trough between  $403 - 409 \text{ cm}^{-1}$ . These shift Changes in transmittance, clarifying the dynamic interaction between oxygen and metal atoms in thermal treatment. This phenomenon highlights how annealing temperature control is crucial for modifying M-O bonding configurations, which could open the door to new material properties and functionalities for solar cell applications.

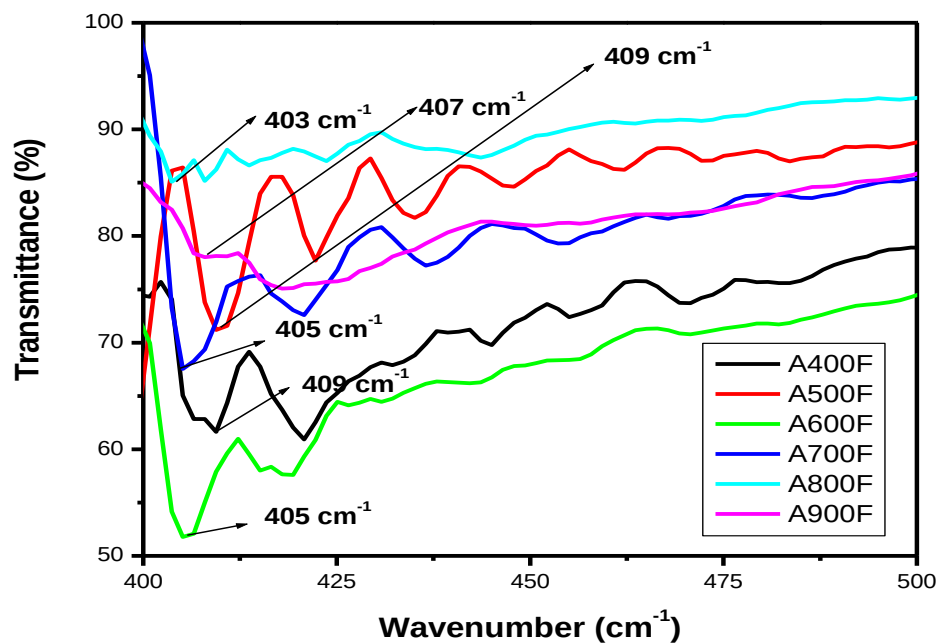


**Figure 4.26: FTIR Spectrum % Transmittance Against Wavenumber ( $\text{cm}^{-1}$ ) of ZnO:Al:Ga Co-Doped Nanoparticles with Annealing Temperatures; A400F –  $400^\circ \text{C}$ , A500F –  $500^\circ \text{C}$ , A600F –  $600^\circ \text{C}$ , A700F –  $700^\circ \text{C}$ , A800F –  $800^\circ \text{C}$ , A900F –  $900^\circ \text{C}$**

## **4.4 Effects of Stirring Speed of Precursor Solution on the Material Properties of ZnO:Al:Ga Co-Doped Nanoparticles for Solar Cell Applications**

### **4.4.1 XRD Analysis**

ZnO:Al:Ga co-doped nanoparticles have favorable electrical and optical properties that make them promising for use in solar cell applications (Chakraborti ., 2008). To maximize their performance, it is imperative to understand how synthesis factors like stirring speed affect their material properties. Figure 4.27 shows all synthesized samples, XRD examination showed distinctive peaks compatible with the hexagonal wurtzite structure of ZnO nanoparticles which correspond to the earlier research (Ungula *et al.*, 2017) that matches well with JCPDS No. 79–0208. This consistency attests to the synthesis's success at various stirring rates using sol-gel method. The XRD graph of samples 500 rpm, 1000 rpm, 1500 rpm, 2000 rpm, 2500 rpm, and 3000 rpm shows clear, identical peak patterns in Figure 4.27, demonstrating the synthesis process' effective in producing nanoparticles. Research indicates that stirring speed has a major impact on crystalline structure, and that stirring circumstances have a considerable impact on the synthesis of nanoparticles (Shaba *et al.*, 2021). The results support these observations by pointing out variations in crystallite size.

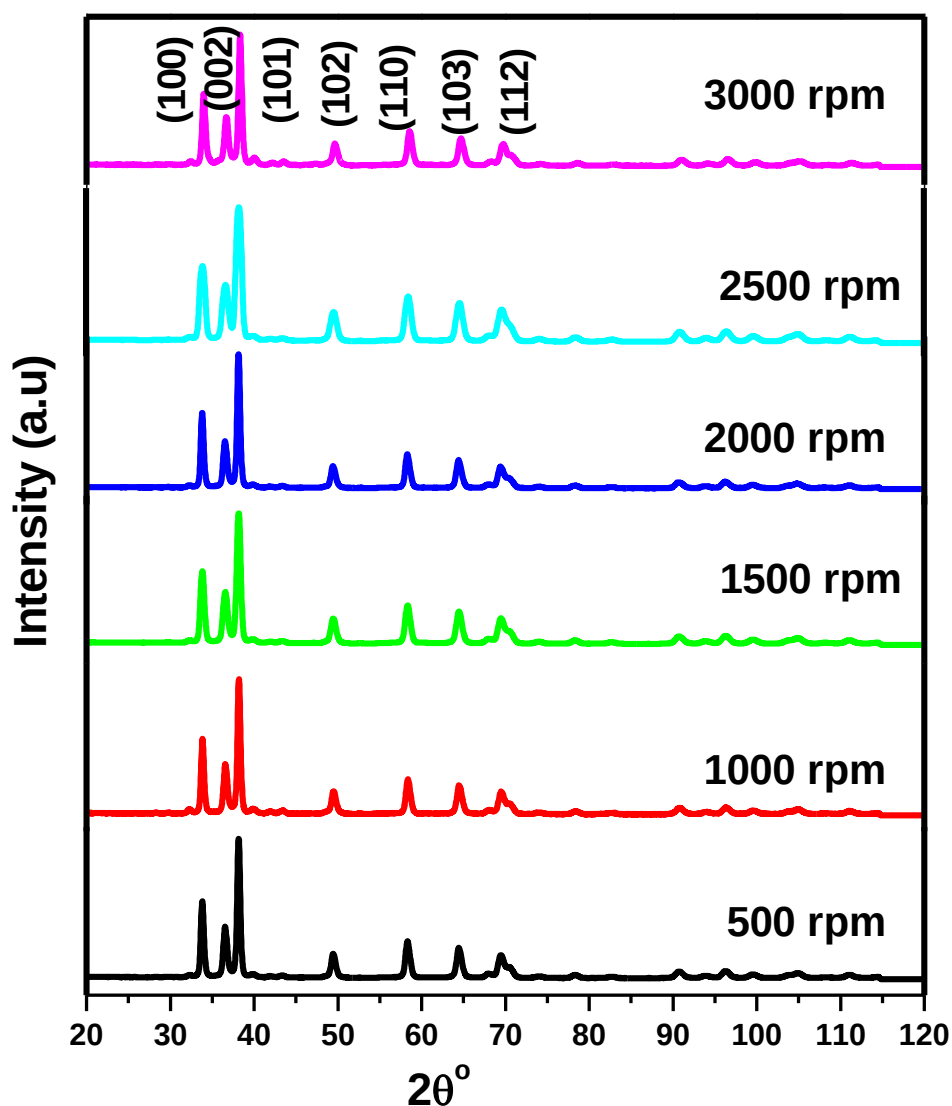


**Figure 4.27: XRD Pattern between  $20^\circ$  -  $120^\circ$  for all Synthesized Samples of ZnO:Al:Ga Co-Doped Nanoparticles under Varying Stirring Speed**

The examined peak  $2\theta$  range from  $37.5^\circ$  to  $39.0^\circ$  found significant variations in peak intensity figure 4.28. The peak intensity consistently decreases as the stirring speed increases from 500 to 3000 rpm. However, 3000 rpm peak intensity varied from the predicted trend pattern and this indicate the presence of other factors influencing crystallization. These changes were explained by Nagorski (2021) as peak intensity influence the crystallinity and particle size, which is consistent with study's findings of how stirring speed affects peak intensity of nanoparticles.

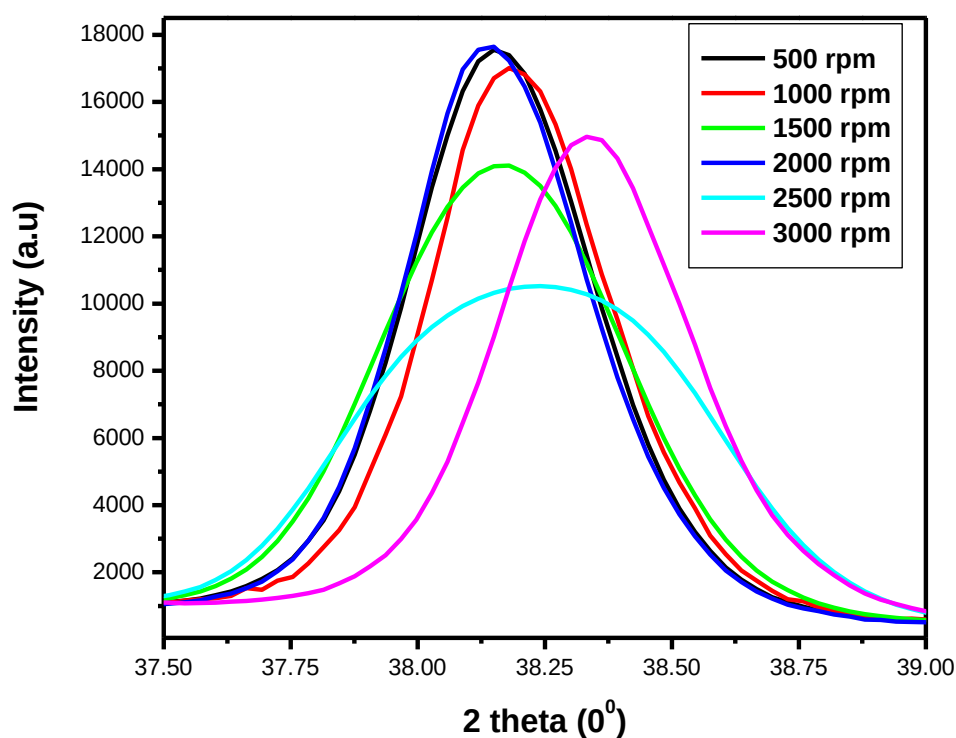


**Figure 4.28: Magnified XRD Pattern between 37.5 ° - 39.0 ° for the Synthesized ZnO:Al:Ga Co-Doped Nanoparticles under Varying Stirring Speed**

Figure 4.29 shows the relationship between the  $2\theta$  and peak intensity for the most intense peak that lies between 37.5 ° – 39.0 ° for the synthesized ZnO:Al:Ga co-doped nanoparticles under varying stirring speed. The angle  $2\theta$  for the prepared nanoparticles increase with the stirring speed of materials resulting to decrease in the peak intensity of ZnO:Al:Ga nanoparticles. However, the peak intensity showed the decrease with increase in stirring speed up to 2500 rpm then rise.

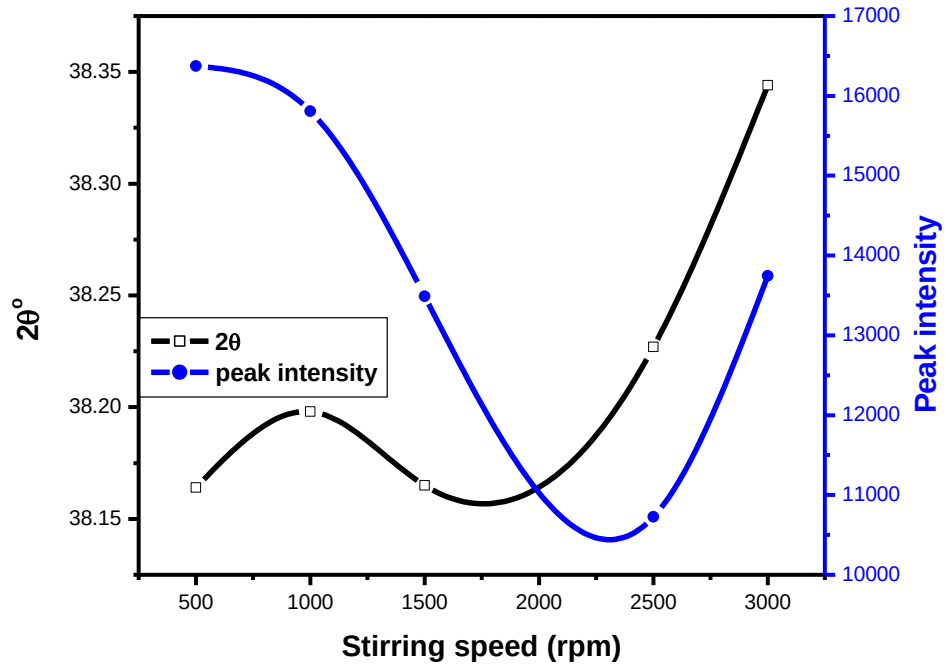


**Figure 4.29: A Graph of Most Intense Peak for the Synthesized ZnO:Al:Ga Co-Doped Nanoparticles under Varying Stirring Speed**

The lattice parameters were calculated using the equations (21) and (22)

$$a = \frac{\lambda}{\sqrt{3} \sin \theta} \dots \dots \dots (21)$$

$$c = a \sqrt{\frac{8}{3}} \dots \dots \dots (22)$$

Where ‘a’ and ‘c’ are the lattice parameters. The prepared ZnO:Al:Ga nanoparticles showed ‘a’ range between 0.2708 – 0.2721 nm and ‘c’ to be 0.4443 – 0.4422 nm as shown in Table 4.11.

**Table 4.11: Table Showing Lattice Parameters of Prepared ZnO:Al:Ga Co-Doped Nanoparticles**

| <b>Stirring speed<br/>(rpm)</b> | <b>2<math>\Theta</math></b> | <b>‘a’</b> | <b>‘c’</b> |
|---------------------------------|-----------------------------|------------|------------|
| 500                             | 38.164                      | 0.2721     | 0.4443     |
| 1000                            | 38.198                      | 0.2718     | 0.4438     |
| 1500                            | 38.165                      | 0.2721     | 0.4443     |
| 2000                            | 38.155                      | 0.2716     | 0.4435     |
| 2500                            | 38.227                      | 0.2716     | 0.4435     |
| 3000                            | 38.344                      | 0.2708     | 0.4422     |

The crystallite size was estimated using the Scherrer equation (23)

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (\text{Gherbi } et al., 2022) \dots\dots\dots (23)$$

where D is crystalline size, K is constant (0.89),  $\lambda$  is 0.154056 nm, mean wavelength of CuK $\alpha$ 1 radiation,  $\beta$  is full width half maxima and  $\theta$  is Bragg’s angle in radians, the average crystallite size analysis, as presented in Table 4.12 were as follows 21.46, 22.01, 17.19, 21.73, 12.52 and 20.61nm for 500 rpm, 1000 rpm, 1500 rpm, 2000 rpm, 2500 rpm and 3000 rpm respectively. The obtained lattice parameters and crystallite size of synthesized ZnO:Al:Ga nanoparticles showed minimal changes in the bulk’s ZnO standard lattice parameters.

**Table 4.12: Table Showing Crystallite Size Of Prepared ZnO:Al:Ga Co-Doped Nanoparticles**

|                             | <b>Stirring speed (rpm)</b> | <b>500</b> | <b>1000</b> | <b>1500</b> | <b>2000</b> | <b>2500</b> | <b>3000</b> |
|-----------------------------|-----------------------------|------------|-------------|-------------|-------------|-------------|-------------|
| <b>2<math>\theta</math></b> | (001)                       | 33.826     | 33.852      | 33.829      | 33.813      | 33.887      | 33.999      |
|                             | (002)                       | 36.565     | 36.594      | 36.573      | 36.552      | 36.642      | 36.703      |
|                             | (101)                       | 38.164     | 38.198      | 38.165      | 38.155      | 38.227      | 38.344      |
| <b><math>\beta</math></b>   | (100)                       | 0.36831    | 0.35666     | 0.46417     | 0.36107     | 0.63155     | 0.39622     |
|                             | (002)                       | 0.44483    | 0.43736     | 0.53003     | 0.44477     | 0.71578     | 0.44442     |
|                             | (101)                       | 0.36483    | 0.35608     | 0.46973     | 0.35934     | 0.66085     | 0.38177     |
| <b>Peak intensity</b>       | (100)                       | 9042.6     | 8776.6      | 7460.0      | 9280.2      | 5902.9      | 7430.5      |
|                             | (002)                       | 5704.0     | 5538.1      | 4975.3      | 5469.1      | 4122.0      | 4721.9      |
|                             | (101)                       | 16373      | 15808       | 13490       | 16426       | 10725       | 13743       |
| <b>Crystallite size (D)</b> | (100)                       | 22.54      | 23.28       | 17.89       | 22.99       | 13.15       | 20.96       |
|                             | (002)                       | 18.81      | 19.13       | 15.78       | 18.81       | 11.69       | 18.83       |
|                             | (101)                       | 23.04      | 23.61       | 17.89       | 23.39       | 12.72       | 22.03       |
| <b>D<sub>average</sub></b>  |                             | 21.46      | 22.01       | 17.19       | 21.73       | 12.52       | 20.61       |

The figure 4.30 depicted trigonometric curve of FWHM and crystallite size of synthesized ZnO:Al:Ga co-doped nanoparticles for various stirring speeds. The FWHM of the prepared nanoparticles showed increase with the increase of stirring speed in the precursor. Whereas there was decrease in the crystallite size as stirring speed on the material properties increase with exception of 3000 rpm. This confirmed

nanoparticles have undergoes strain or existence of imperfections defects in the synthesis of ZnO:Al:Ga nanoparticles.

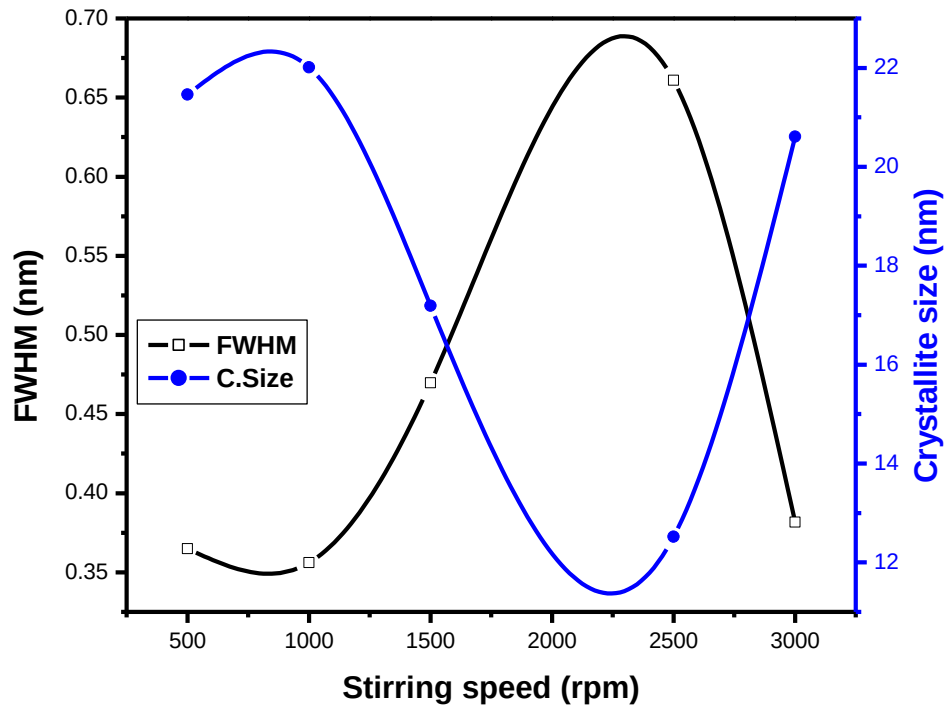


**Figure 4.30: The Graph of FWHM and Crystallite Size of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles for Various Stirring Speeds**

Therefore, the formula (24)

$$\delta = \frac{1}{D^2} \text{ (Ungula *et al.*, 2024).} \dots\dots\dots (24)$$

Where  $\delta$  is the length of dislocation density and D is the crystalline size; was applied in order to calculate the dislocation density, as table 4.13 illustrates the results. Also, Table 4.13 shows the micro-strain ( $\epsilon$ ) values, which were computed using the equation (25)

$$\epsilon = \frac{\beta}{4 \tan \theta} \text{ (Kiprotich *et al.*, 2022) ..... (25)}$$

Where  $\theta$  is the diffraction angle and  $\beta$  is the full width at half maximum.

**Table 4.13: Table Showing Dislocation Density and Strain of Prepared ZnO:Al:Ga Co-Doped Nanoparticles**

| <b>Stirring speed (rpm)</b> | <b>500</b> | <b>1000</b> | <b>1500</b> | <b>2000</b> | <b>2500</b> | <b>3000</b> |
|-----------------------------|------------|-------------|-------------|-------------|-------------|-------------|
| $\delta$                    | 0.0466     | 0.0454      | 0.0582      | 0.0460      | 0.0798      | 0.0485      |
| $\epsilon$                  | 0.2637     | 0.2571      | 0.3395      | 0.2598      | 0.4767      | 0.2745      |

The dislocation density is the concentration or density of dislocations within nanoparticles. Figure 4.31 shows dislocation density and strain impact on the nano-crystal structure of ZnO:Al:Ga nanoparticles where the regular arrangement of atoms is disrupted. The changes in lattice parameters and crystallite size of nanoparticles was due to thermal strain and presence of impurities. The figure 4.31 showed increase in the strain and dislocation densities as stirring speeds increase. This affirms the higher dislocation densities and strain the stronger nanoparticles but less ductile nanomaterials, while lower dislocation densities and strain the weaker nanoparticle but more ductile materials. In addition, it also quantifies the change in shape or size of a material relative to its original dimensions as shown in the difference in lattice parameters with standard of ZnO's bulk values.

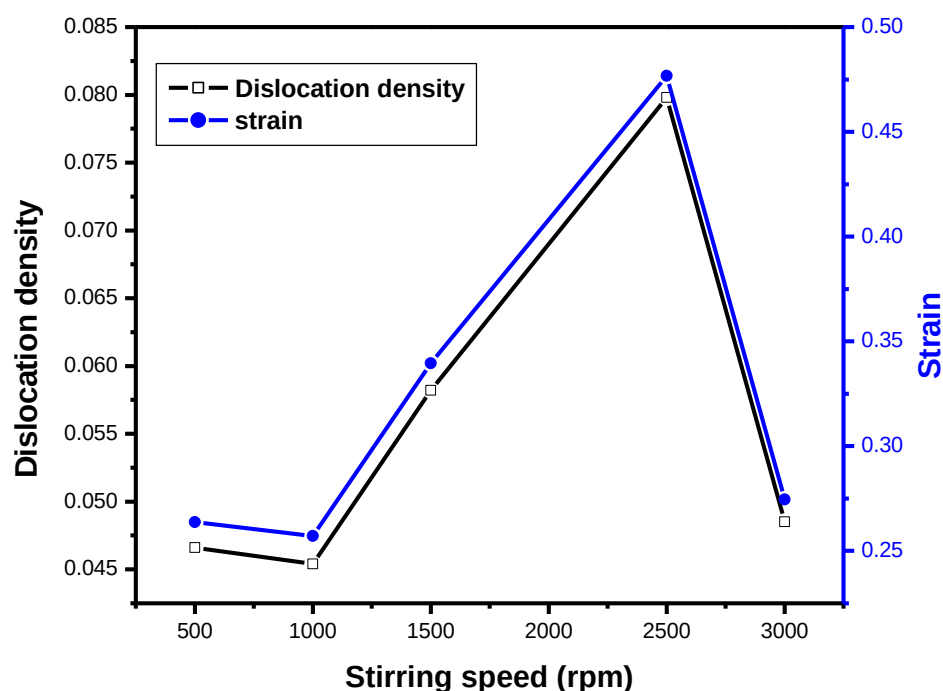


**Figure 4.31: The Graph of Dislocation Density and Strain of Prepared ZnO:Al:Ga Co-Doped Nanoparticles for Various Stirring Speeds**

#### 4.4. 2 UV- Vis Analysis

ZnO:Al:Ga co-doped nanoparticle characterization demonstrates the value of UV-Vis spectroscopy as a vital tool for understanding the optical properties of materials. The study's prepared nanoparticles' transmittance spectra, shown in Figure 4.32, show clear variations in transmittance peaks that correlate to different stirring rates throughout the synthesis in the precursor solution. The transmittance spectrum shows the largest peak at 5000 rpm, with subsequent peaks at 1500 rpm, 2500 rpm, and 3000 rpm, in that order. This pattern is consistent with earlier research by Khan *et al.* (2016) and Mukwakwa (2017), who also observed similar changes in transmittance spectra in response to varying synthesis stirring velocities.

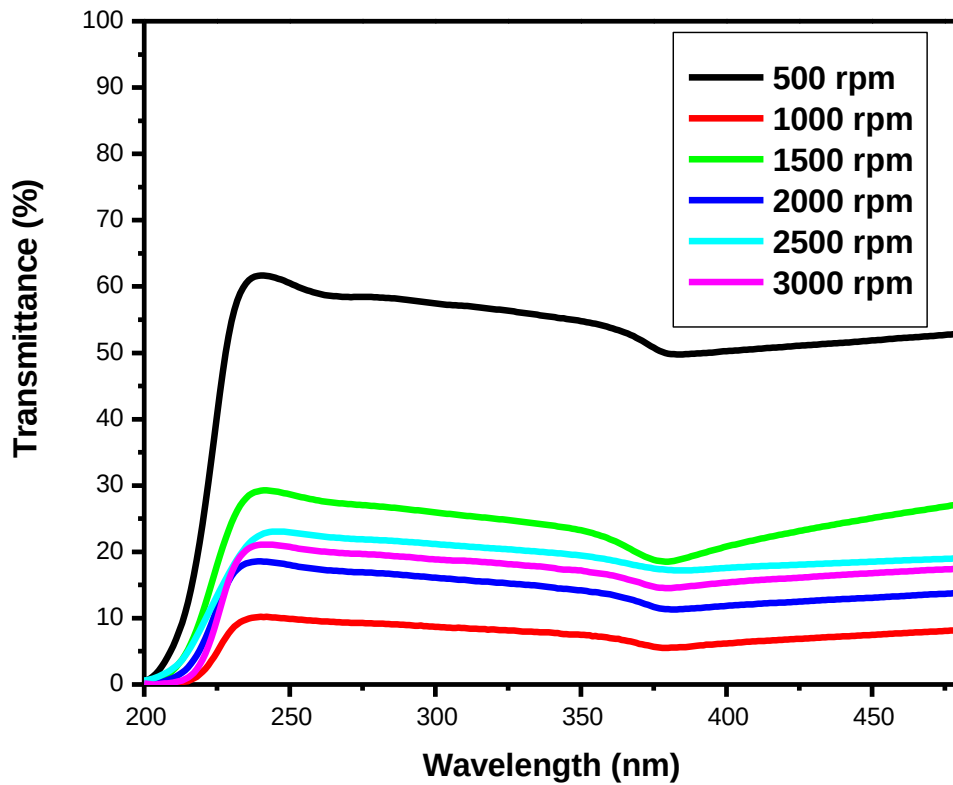


**Figure 4.32: UV-Vis Spectrum Showing Transmittance (%) against Wavelength (nm) of As Prepared ZnO:Al:Ga Co-Doped Nanoparticles for Varying Stirring Speed**

Further supporting the sensitivity of optical properties to synthesis stirring speed is the fact that, as shown in Figure 4.33, the absorbance spectra of ZnO:Al:Ga co-doped nanoparticles at wavelength range (377 - 379 nm) reflect the absorbance spectra seen by Rahman *et al.* (2018). Complementing spectral analysis, by the equation (26)

$$E_g = \frac{hc}{\lambda} \dots\dots\dots (26)$$

Where h is the Plank's constant c is the velocity of light and  $\lambda$  is the absorbance peak. The ZnO:Al:Ga co-doped nanoparticles' resultant energy band gaps are listed in Table 4.14 for each stirring speed. The energy band-gaps findings, which are around 3.27 and 3.29 eV, support patterns seen in earlier studies by Droepenu *et al.* (2022), who also found that stirring speed had a significant impact on band gap energies in zinc

oxide nanoparticles. The control of stirring speeds at optimum enhance good nanoparticles with light absorption and electron transport for manufacture of improved solar cell devices.

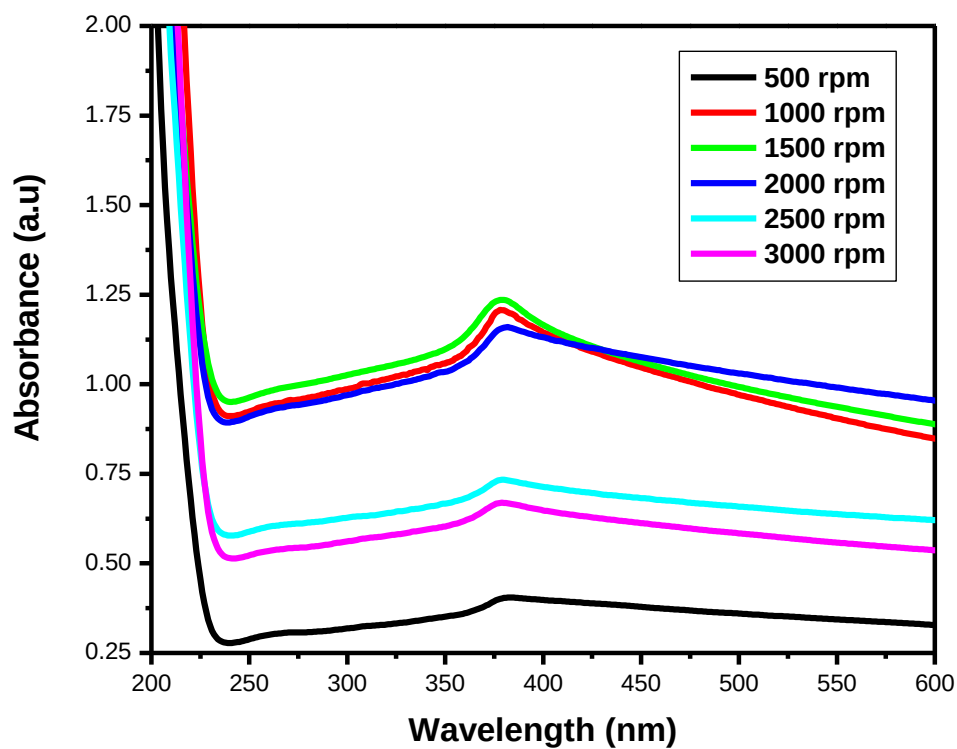


**Figure 4.33: UV-Vis Spectrum Absorbance (a.u) against Wavelength (nm) of ZnO:Al:Ga Co-Doped Nanoparticles with Varying Stirring Speed**

**Table 4.14: Summarize Table of Wavelength and Energy Band-Gap**

| sample   | Wavelength (nm) | $E_{bg}$ (eV) |
|----------|-----------------|---------------|
| 500 rpm  | 379             | 3.27          |
| 1000 rpm | 378             | 3.28          |
| 1500 rpm | 377             | 3.29          |
| 2000 rpm | 379             | 3.27          |
| 2500 rpm | 379             | 3.27          |
| 3000 rpm | 378             | 3.28          |

The optical properties of ZnO:Al:Ga co-doped nanoparticles under different stirring speeds was by analyzed Tauc's plot extrapolation in figure 4.34. This is an established technique for estimating semiconductor's band-gap energy from its absorbance spectrum. The estimated of the band-gaps energy were obtained by a graph of  $(\alpha h\nu)^2$  against the photon energy ( $h\nu$ ) and using linear extrapolation to the x-axis. Band-gap energy values between 5.0 and 5.6 eV were found in this investigation at stirring rates between 500 and 3000 rpm. The band-gap energy change with stirring speed. Regarding the variance in the standard band-gap energy of 3.37 eV ZnO, the existence of defects or impurities in the nanoparticles as well as doping with Al and Ga could cause differences. According to Singh *et al.* (2019), doping can bring energy levels into the band-gap, changing the material's overall electronic structure. Furthermore, alterations in the synthesis circumstances and techniques can result in changes to the size, shape, and crystallinity of nanoparticles, all of which can affect the band-gap energy (Droepenu *et al.*, 2022).

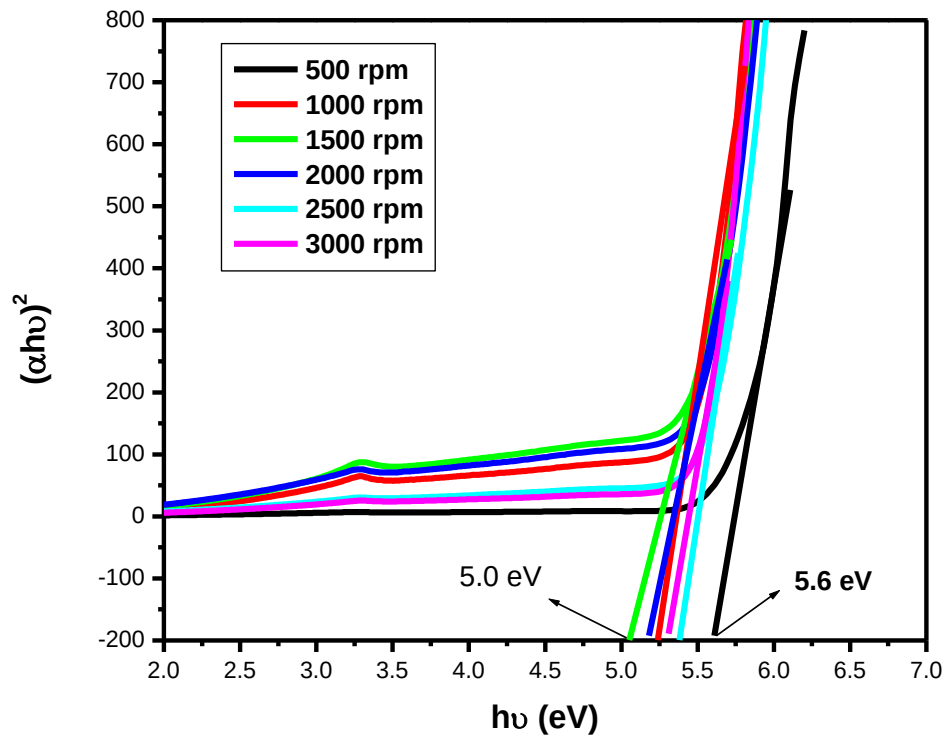


**Figure 4.34: Tauc's Plot of ZnO:Al:Ga Co-Doped Nanoparticles with Varying Stirring Speed**

#### 4.4. 3 SEM Analysis

SEM micrographs showing observable differences in particle size and shape throughout a range of stirring speeds are displayed in Figure 4.35. Similar findings were reported by Niroula (2022) for the ZnO:Al:Ga co-doped nanoparticles synthesized at 500 rpm, which show greater grain sizes, while those produced at 2500 rpm and 3000 rpm show smaller sizes with a porous texture. Higher stirring speeds facilitated more effective mixing and nucleation, resulting in to finer nanoparticles with more surface area and porosity. These are favorable characteristics for improving charge transport and light absorption in solar cells, according to this phenomena.

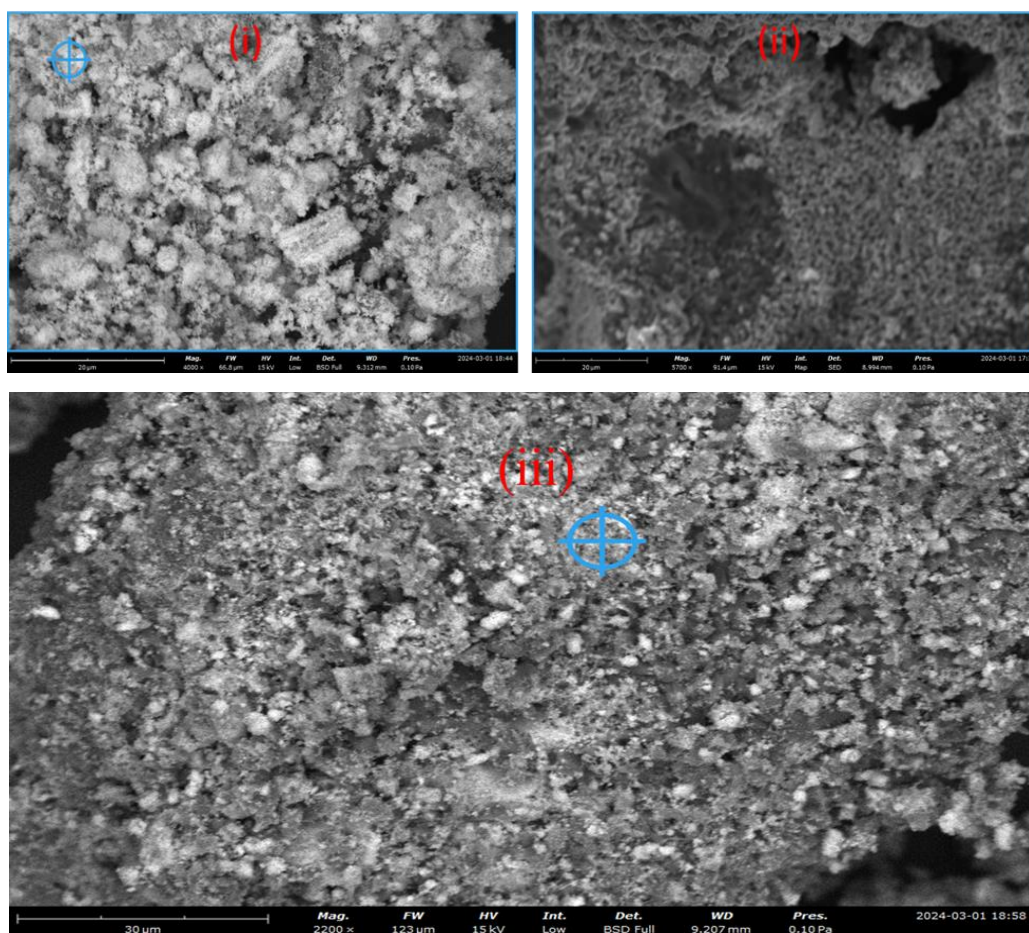


**Figure 4.34: SEM Micrographs of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles under Varying Stirring Speed (i) 500 rpm, (ii) 2500 rpm (iii) 3000 rpm**

Furthermore, Figure 4.36 – 4.38 shows EDS elemental spectrum analysis, which confirms hexagonal wurtzite structure, clarifies the crystalline nature of the prepared nanoparticles. The crystalline nanostructure does not change even with changes in stirring speed, indicating that particle size and shape are more affected by stirring condition changes than the crystalline phase (Sbeta, 2018). This result highlights the synthesis process's resilience and offers good information regarding the stirring speed and nanoparticle properties.

Moreover, all produced nanoparticles contain the necessary elements zinc and oxygen, according to elemental composition analysis in Tables 4.15, 4.16, and 4.17. At higher stirring speeds, contaminants such as carbon, salt, aluminum, and chlorine are found.

Impurity presence, especially at high stirring speeds, indicates possible contamination or unfinished synthesis processes, underscoring the significance of stirring condition optimization to reduce impurity incorporation and guarantee nanoparticle purity for intended applications.

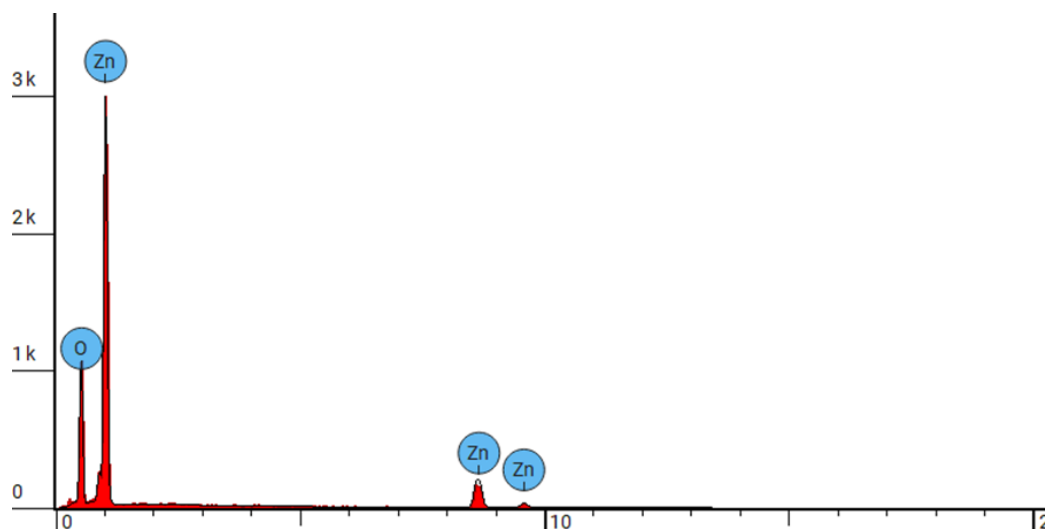


**Figure 4.35: Showing EDS Elemental Spectrum Pattern of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles with Stirring Speed 500 rpm**

**Table 4.15: Table Showing Elements of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles with Stirring Speed 500 rpm**

|  | Element Number | Element Symbol | Element Name | Atomic Conc. | Weight Conc. |
|--|----------------|----------------|--------------|--------------|--------------|
|  | 8              | O              | Oxygen       | 61.022       | 27.700       |
|  | 30             | Zn             | Zinc         | 38.978       | 72.300       |

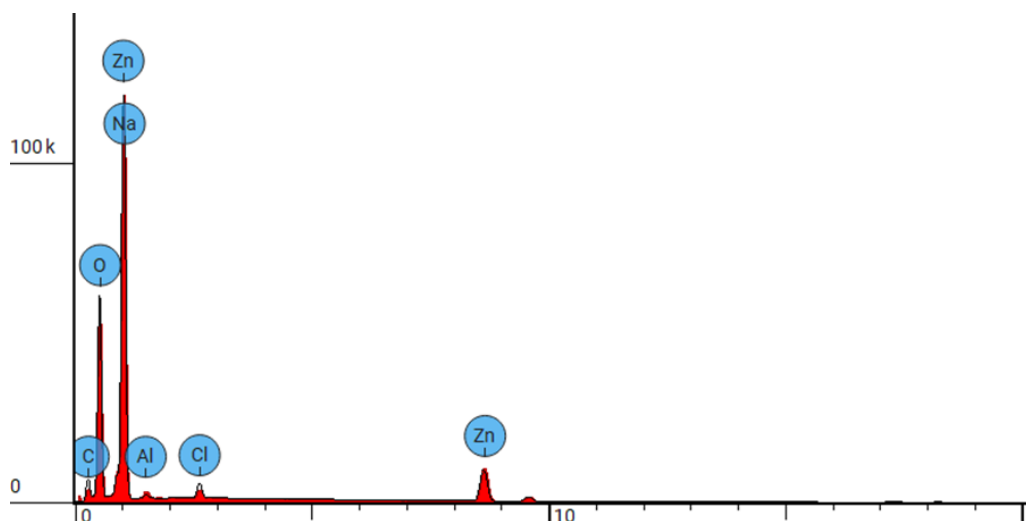


**Figure 4.36: Showing EDS Elemental Spectrum Pattern of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles with Stirring Speed 2500 rpm**

**Table 4.16: Table Showing Elements of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles with Stirring Speed 2500 rpm**

|  | Element<br>Number | Element<br>Symbol | Element<br>Name | Atomic<br>Conc. | Weight<br>Conc. |
|--|-------------------|-------------------|-----------------|-----------------|-----------------|
|  | 6                 | C                 | Carbon          | 21.394          | 11.211          |
|  | 8                 | O                 | Oxygen          | 44.163          | 30.831          |
|  | 11                | Na                | Sodium          | 20.448          | 20.521          |
|  | 13                | Al                | Aluminum        | 0.425           | 0.501           |
|  | 17                | Cl                | Chlorine        | 1.359           | 2.102           |
|  | 30                | Zn                | Zinc            | 12.211          | 34.835          |

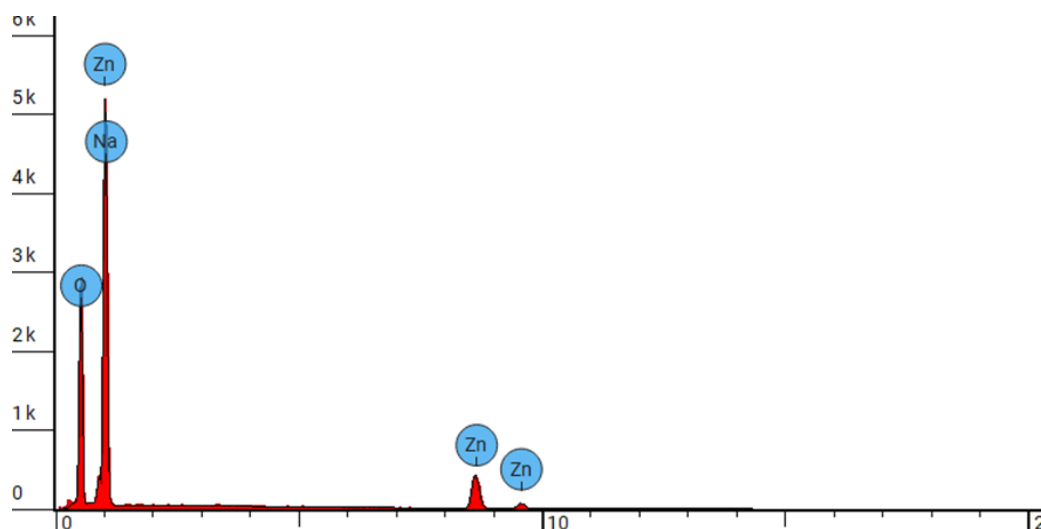


**Figure 4.37: Showing EDS Elemental Spectrum Pattern of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles With Stirring Speed 3000 rpm**

**Table 4.17: Table Showing Elements of Synthesized ZnO:Al:Ga Co-Doped Nanoparticles with Stirring Speed 3000 rpm**

|  | Element<br>Number | Element<br>Symbol | Element<br>Name | Atomic<br>Conc. | Weight<br>Conc. |
|--|-------------------|-------------------|-----------------|-----------------|-----------------|
|  | 8                 | O                 | Oxygen          | 54.676          | 31.832          |
|  | 11                | Na                | Sodium          | 25.716          | 21.522          |
|  | 30                | Zn                | Zinc            | 19.608          | 46.647          |

#### 4.4.4 FTIR Analysis

FTIR analysis makes it possible to identify and characterize important chemical bonds, such as the bonding wavenumbers of Al-O, Zn-O, and Ga-O that are present in the nanoparticles. Figure 4.39 shows the FTIR spectra of synthesized nanoparticle. The transmittance against wavenumber between 400 - 500  $\text{cm}^{-1}$  are the stretching vibration modes of zinc-oxygen (Zn-O) bonding. This is in a line with the research done by Aleksandrova *et al.* (2022), which reported aluminum-oxygen (Al-O) bonding

is observed in the 600 – 800  $\text{cm}^{-1}$  region, gallium-oxygen (Ga-O) bonding seen in 500 – 800  $\text{cm}^{-1}$  region and similarly zinc-oxygen (Zn-O) bonding takes place in the region 400–500  $\text{cm}^{-1}$  range. These bonding wavenumbers provide important details regarding the nanoparticles' functional and chemical groups. Different stirring speeds during synthesis affect the chemical composition of the nanoparticles, as indicated by variations in the intensity or position of these peaks. Additionally, knowing the properties of Al-O, Zn-O, and Ga-O bonds' bonding can help optimize synthesis conditions of nanoparticles' properties for particular uses.

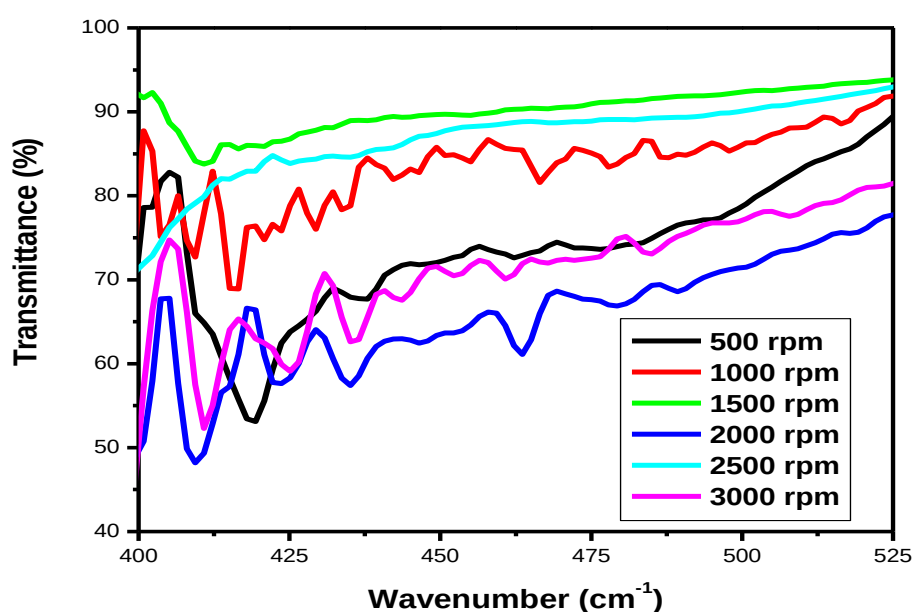


**Figure 4.38: FTIR Spectrum % Transmittance against Wavenumber ( $\text{cm}^{-1}$ ) of ZnO:Al:Ga Co-Doped Nanoparticles under Varying Stirring Speed**

#### 4.5 Summary

Chapter four synthesized the results and discussions pertaining to the effects of pH, annealing temperature, and stirring speed on the properties of ZnO:Al:Ga co-doped nanoparticles. It presented experimental findings obtained from varying these parameters, encompassing changes observed in structural, morphological, elemental, chemical bonding and optical characteristics as analyzed through techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR) and UV-Vis spectroscopy. The chapter conducted a

detailed analysis, discussing the observed effects of pH, annealing temperature, and stirring speed on the crystalline structure, particle size, and optical band-gap of the nanoparticles. Additionally, it explored the underlying mechanisms driving these effects, considering factors such as nucleation and growth kinetics, dopant incorporation, and phase transformation processes. By synthesizing the experimental results with theoretical insights, this chapter provided a comprehensive understanding of how variations in these parameters influence the material properties of ZnO:Al:Ga co-doped nanoparticles, thus laying the groundwork for optimizing their synthesis for specific applications in solar cell technology.

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

#### 5.1 Conclusion

XRD analysis showed hexagonal wurtzite of ZnO with the crystallite size estimated to be ranging from 12 to 21 nm for the experimental factors; the pH, annealing temperature and stirring speed. The XRD pattern of ZnO:Al:Ga Nps matched well with the standard hexagonal Wurtzite ZnO crystal structure with variation in peak intensities observed to be corresponding to miller plane indices of (100), (002), (101), (102), (110), (103) and (112) reference card number JCPDS No. 36 - 1451.

SEM displayed aggregation of nanoparticles when the precursor pH increased from 7 to 13 which confirms alkaline medium promotes crystallization (structural order) and particle formation or nucleation. The morphological changes caused by the annealing temperatures were confirmed by SEM micrographs imaging, which showed differences in particle size, shape, and aggregation (morphological random order) patterns with the desired spherical grain-like structure. In addition, the nanoparticles were uniformly distributed within its surface with porous texture. The study revealed that synthesized nanoparticles have enhanced best crystallinity at 1000 rpm, homogeneous doping as shown by SEM micrographs, increased surface area, and optimized optical properties that are good for solar cell efficiency for the production of clean renewable energy. EDX showed ZnO's pattern which supported hexagonal wurtzite structure obtained by XRD results.

UV-Vis analysis showed absorption peaks varying from 380 – 376 nm for precursor pH values 7 – 13, with band gap energy range of 3.26 – 3.29 eV. Decreased transmittance was observed with the higher pH values of 11–13 due to its larger particles. Also, the optical properties of the nanoparticles annealed at different temperatures showed absorbance wavelength range of 371–383 nm, the analysis showed a noticeable redshift in the absorption edge and a decrease in the optical band-gap energy as the annealing temperature increased. This resulted in 3.34–3.24 eV, respectively, confirming modifications in the electronic structure such as light absorption and transmittance. Similar results on stirring speed on the precursor solution were obtained that showed band-gap of wavelength 378 nm equivalent to 3.29 eV.

FTIR showed chemical bonds Zn-O, Al-O, and Ga-O stretching modes between 400 and 590  $\text{cm}^{-1}$  this affirms formation of ZnO:Al:Ga co-doped nanoparticles. Also, the presence of OH stretching bands above the 3000  $\text{cm}^{-1}$  region indicating surface hydroxylation in all the experimental factors; the pH, annealing temperature and stirring speed on the material properties.

The research findings showed optimize results at pH of 8, annealing temperature of 700 °C and stirring speed of 1000 rpm that possibly contribute to the development of sustainable and cost-effective solar cell for utilization of renewable energy sources and global solution of energy crisis.

## 5.2 Recommendations

The study recommends the following for the optimized ZnO:Al:Ga co- doped nanoparticles for possible solar cell application in order to improve its efficiency and enhance sustainable energy which is friendly to the environment;

- i. **Sol-gel technique:** The findings of the study from XRD analysis showed a hexagonal wurtzite of ZnO's matrix thus proves sol-gel is effective and cheap method of synthesis.
- ii. **The pH value of 8:** The results showed uniform growth formation or nucleation of nanoparticles with uniform distribution with the surface as evidenced by SEM analysis.
- iii. **The annealing temperatures of 700 °C:** The study showed improved nanoparticles at annealing temperatures of 700 °C as evidenced by the crystallite size of 20.2 nm. Also, UV-vis with energy band-gap of 3.23 eV which is close to standard bulk's ZnO 3.37eV.
- iv. **The stirring speed on the precursor materials:** The ZnO:Al:Ga co- doped nanoparticles synthesized under 1000 rpm showed good results of nanoparticles to be used in solar cells. The UV-Vis showed band-gap of wavelength 378 nm equivalent to 3.29 eV close to standard band-gap energy of ZnO. In addition, FTIR showed intense more stretching vibrations modes between 400 -500  $\text{cm}^{-1}$  confirming the chemical bonding of ZnO's as evidenced by EDX analysis.

### 5.3 Future Work

Future work in the field of ZnO:Al:Ga co-doped nanoparticles for solar cell applications could focus on several key areas to advance the understanding and utilization of these materials:

- i. **Fine-Tuning Synthesis Parameters:** Further improvement of nanoparticle properties may result from ongoing research into synthesis parameters such as dopant concentrations, precursor ratios, and synthesis methods. Examining the impact of extra variables, like reaction duration, temperature ramp rates, and pH stability of the precursor solution, could offer more profound understanding of the synthesis procedure and facilitate the creation of nanoparticles with improved performance attributes.
- ii. **Enhanced Characterization Techniques:** Better characterization methods to examine the optoelectronic, morphological, and structural characteristics of ZnO:Al:Ga co-doped nanoparticles with increased sensitivity and resolution may lead to a more thorough comprehension of their behavior. Advanced surface analysis techniques, like as time-resolved spectroscopy, AFM, TEM, and XPS, can be used to design materials specifically for a certain application and get extensive insights into the structure-property connections of nanoparticles.
- iii. **Integration into Functional Devices:** Beyond the synthesis of nanoparticles, future studies could concentrate on incorporating ZnO:Al:Ga co-doped nanoparticles into working solar cell systems and assessing how well they function under practical operating circumstances.
- iv. **Exploration of Novel Applications:** Investigating the potential of ZnO:Al:Ga co-doped nanoparticles in other optoelectronic and energy-related devices could open up new avenues for technological innovation, even outside of solar cell applications. Examining these materials' applications in photocatalysis, photodetectors, sensors, LEDs, and energy storage systems may lead to the discovery of new features and uses for them, hence increasing their usefulness in a variety of domains.
- v. **Theoretical Modeling and Simulation:** The electrical and optical characteristics of ZnO:Al:Ga co-doped nanoparticles can be predicted and understood by theoretical modeling and computational simulations, which

could support practical research and direct the creation of materials with specific functions. The logical design of next-generation materials can benefit from computational techniques including density functional theory (DFT) computations, Monte Carlo simulations, and device modeling, which can offer insightful information about the physics behind nanoparticle behavior.

- vi. **Scale-Up and Commercialization:** The first steps towards commercialization of ZnO:Al:Ga co-doped nanoparticles at industrial scale include addressing scaling ratios and investigating scalable synthesis pathways. The transition from laboratory-scale synthesis to large-scale production can be facilitated by working with industry partners and utilizing scalable manufacturing techniques, such as spray pyrolysis, continuous flow synthesis, or aerosol-assisted methods. This will open the door for the widespread use of these materials in real-world applications.

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## **APPENDICES**

## Appendix 1: Approval letter

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### MURANG'A UNIVERSITY OF TECHNOLOGY

*Office of the Director, Postgraduate Studies*

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Ref: MUT/ARP/PGS/19/2020 /VOL.1

Date: 3<sup>rd</sup> April, 2024

Mr. Kiprotich Bett Cornelius (AS402/5750/2021)  
School of Pure, Applied and Health Sciences  
Murang'a University of Technology,  
P.O. Box 75-10,200  
Murang'a.

Dear Mr. Kiprotich,

**RE: APPROVAL OF RESEARCH PROPOSAL AND SUPERVISORS.**

I am pleased to inform you that the Directorate of Postgraduate Studies on 25<sup>th</sup> March, 2024 considered and approved your Masters research proposal entitled *"Synthesis Characterization of ZnO:Al:Ga Co-Doped Nanoparticles for Possible Solar Cell Application"* and appointed the following as supervisors:

1. Dr. Sharon Kiprotich – Murang'a University of Technology
2. Dr. Warren A. Andayi - Murang'a University of Technology

You may now proceed with your data collection subject to obtaining research permit from NACOSTI, if required. You should also begin consulting your supervisors and submit through them quarterly progress reports to the Director Postgraduate Studies through your CoD and School Dean. Progress Reports forms can be accessed in the Student Portal.

It is the policy and regulations of the University that you observe deadlines. The guidelines on Postgraduate supervision can be accessed in the post graduate Handbook.

Your responsibilities as a student will include, among others;

- i. Maintain regular consultation with your supervisor(s), at least once a month
- ii. Submit quarterly reports on time, through your supervisors, CoD, Dean and to the Director of Postgraduate Studies;
- iii. Ensure quality work all through;



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- iv. Present your research findings at 2-3 seminars/conferences prior to thesis examination.
- v. Publish one article from your research findings in a refereed journal prior to thesis examination.

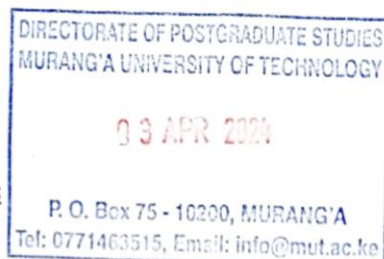
For any further clarification please contact the undersigned.

Yours Sincerely,



**Prof. Geoffrey Muchiri, PhD**  
**Director, Postgraduate Studies**

GM/PIM



Copy to:

- 1. Registrar, Academics, Research and Students Affairs
- 2. Dean, School of Pure, Applied and Health Sciences



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## **Appendix 2: Publications**

The following research papers have been submitted for publication by the authors;

Kiprotich Bett, Warren Andayi, Kiprotich Sharon, Ungula Jatani

1. Structural and Optical properties of ZnO:Al:Ga co-doped nanoparticles: Investigation on the Effects of pH of the precursor solution via a simple sol-gel route (Published by American Journal of Material Science).
2. Effects of annealing temperature on the material properties of ZnO:Al:Ga co-doped nanoparticles for solar cell applications (Submitted to Journal of Nanostructures).
3. Effects of stirring speed of precursor solution on the material properties of ZnO:Al:Ga co-doped nanoparticles for solar cell applications (Published by American Journal of Condensed Matter Physics).