CHAPTER I INTRODUCTION

1.1 Background

Renewable energy has been an intensive topic of discussion and research in the past two decades due to the limited reserve and volatility of petroleum prices and its environmental impacts, such as pollution and global warming. Sunlight is a promising energy source because it is readily available and environmentally friendly (Cousse, 2021). There are several methods to convert solar energy into electrical energy; the most promising is the use of solar cells (Chopra et al., 2004; Zhu et al., 2019). Solar cells are used to convert photon energy directly into electricity (Amalathas and Alkaisi, 2019). Among various types of solar cells, thin-film solar cells like Copper Indium Gallium Diselenide ($Cu(In,Ga)Se_2$; CIGS) have great potential. CIGS solar cells have a higher efficiency than any other non-single crystalline silicon solar cells (Kovacic et al., 2019; Royanian et al., 2020), have a higher optical absorption (Kaelin et al., 2004), and more easily adjustable band gap of the active layer (Boukortt et al., 2023; Ali and Abdullah, 2011).

CIGS solar cells use expensive metals such as indium and gallium as light absorber layers, leading to a higher production cost (Licht et al., 2015; Ouédraogo et al., 2013). The production cost can be suppressed by reducing the thickness of the absorber layer (Sobhani et al., 2020; Yousefi et al., 2020; Zarerasouli et al., 2022), but this leads to a significant decrease in solar cell efficiency due to a much lower number of absorbed photons. Several studies have been conducted to address this issue, such as bandgap grading (Royanian et al., 2020), the use of perovskite (Jošt et al., 2022), the addition of a Back Surface Field (BSF) layer (Barman and

Kalita, 2021), and the addition of nanowire (Sim et al., 2018) or quantum dot in the luminescent downshifting layer (Sui et al., 2020). One of the most effective approaches to increase solar cells' efficiency is using metal nanoparticles (NPs). Many studies have been conducted on the addition of metal NPs to various solar cells (Mirzaei et al., 2020; Royanian et al., 2020; Sobhani et al., 2020; Yassin et al., 2022; Gezgin and Kılıç, 2020; Yousefi et al., 2020; Zarerasouli et al., 2022) that have shown significant improvement in solar cell efficiency.

When light strikes metal NPs, Surface Plasmon Resonance (SPR) occurs around the metal NPs(Yousefi et al., 2020). The occurrence of SPR around metal NPs is referred to as Localized Surface Plasmon Resonance (LSPR) (Gezgin and Kılıç, 2020; Zhang et al., 2021). LSPR will generate a near field extending light's optical path length within the solar cell. The extension of the light path will enhance light absorption in the solar cell without an increase in the physical thickness of the solar cell (Heidarzadeh & Tavousi, 2021). Light absorption highly depends on metal NPs' shape, size, type, and position. Metal such as silver (Ag), gold (Au), and aluminum (Al) are widely utilized in solar cells due to their plasmon resonance frequencies falling within the visible light range and their much lower resonance damping (Garcia, 2011; Muldarisnur et al., 2023; Yu et al., 2017).

For CIGS solar cells, more research still needs to be done regarding the impact of adding metal NPs on efficiency enhancement (Yousefi et al., 2020). Zarerasouli et al. (2022) studied using metal NPs to enhance the efficiency of thin-film CIGS-based solar cells with optimized bandgap. The study analyzed the influence of changing nanoparticle parameters, such as shape, material, size, and period, combined with an optimized bandgap by adjusting the active layer's molar concentration on solar cells efficiency using the FDTD method. In that study, metal NPs were placed on the back surface. Cubic Ag NPs with a size of 55 nm and a period of 220 nm exhibited a significant increase in short-circuit current density (J_{sc}), reaching 19.96 mA/cm^2 compared to solar cells without NPs, which only achieved 16.63 mA/cm^2. Another approach also conducted by Zarerasouli et al. (2023) by using cluster of four NPs and achieve maximum J_{sc} of 27.2 mA/cm2 by using cylindrical Ag NPs with diameter-x equal to 70 nm, diameter-y equal to 60 nm, and height equal to 60 nm.

Another effort to enhance the efficiency of CIGS solar cells has been made by Hasheminassab et al. (2021), who placed Ag NPs on the front layer of CIGS solar cells. In this study, various parameters were also analyzed computationally, including the shape (sphere and cylinder), size, and periodicity of the NPs. This study found that NPs with a cylindrical shape and a diameter of 50 nm exhibited the highest efficiency. Both studies mentioned above show that a size of around 50 nm exhibits superior scattering and lower metal absorption characteristics, leading to higher efficiency.

In addition to the front surface and back surface, metal NPs can be placed in the active layer (Yousefi et al., 2020). Yousefi et al. conducted a computational study by adding spherical Al NPs to the active layer with varied positions (top, middle, and bottom). From this research, the highest J_{sc} was obtained when the NPs were placed in the middle of the active layer, reaching 32.03 mA/cm^2.

Jangjoy et al. (2019) investigated the computational study of influence of adding pairs of metal NPs to silicon solar cells. In this study, solar cells' photocurrent density was analyzed by adding a single nanoparticle, two NPs with the same radius, and two NPs with different radii. A drastic increase in photocurrent density is obtained when adding two metal NPs. Interestingly, the highest photocurrent density is achieved when the NPs differ in their radii, specifically with r_1= 78 nm and r_2= 89 nm, reaching 21.84 mA/cm^2. In contrast, solar cells without adding NPs have a photocurrent density of only 8.41 mA/cm^2.

So far, research directly analyzing how the positioning of NPs in various layers of CIGS solar cells influences their performance has rarely been conducted. Therefore, the optimal position for placing NPs on CIGS solar cells remains to be determined. This study computationally analyzed the influence of the material, geometry, and size of NPs in various layers of CIGS solar cells. There are several methods to analyse the optical properties of solar cells, such as the Finite Difference Time Domain (FDTD) and the Finite Element Method (FEM). The research utilized the FDTD method to simulate the electric field that arises when light passes through solar cells and interacts with metal NPs. FDTD was chosen because this method is highly efficient and accurate for studying the propagation of electromagnetic waves within solar cells. The efficiency of adding cluster NPs was also compared with that of solar cells without the addition of metal NPs.

1.2 Research Objectives and Benefits

This research aims to analyze the influence of material, shape, size, spacing between NPs, and the position of a cluster of two NPs within various layers of ultra-thin CIGS solar cells. The study is conducted to enhance the efficiency of ultra-thin CIGS solar cells.

1.3 Scope and Limitations of the Research

This research is conducted using the Finite Difference Time Domain (FDTD). The scope of this research is limited to the following aspects:

1. The used solar spectrum is the AM 1.5 in the range of 300 - 984 nm.
2. The utilized NPs are silver (Ag), gold (Au), and aluminum (Al) because their surface plasmon resonance frequencies are located in the UV and visible light ranges.
3. The proposed shapes of NPs are sphere, cylinder, cube, and triangle, characterized by two parameters, width (*d*) and height (*h*), with sizes ranging from 40-60 nm. This variation range is intended to prevent absorption by metal NPs (NPs losses).
4. The position of NPs was varied in the back-surface layer, active layer, and front surface.
5. The distance between two NPs in one cluster was varied from 10-40 nm.
6. The thickness of the modeled CIGS solar cell structure ordered from the topmost layer is Molybdenum (Mo) = 20 nm, Copper Indium Gallium Selenide (CIGS) = 120 nm, Cadmium sulfide (CdS) = 20 nm, Zinc Oxide (ZnO) = 30 nm, Aluminum−doped Zinc Oxide (AZO) = 20 nm. The thickness value is obtained based on Zarerasouli’s research (2023).
7. The addition of NPs is not mean for doping and thus does not change the initial properties of the solar cells.

8. The unit cell size is kept constant at 220 nm x 150 nm to avoid NP losses. This unit cell size is obtained based on Zarerasouli's research (2022).