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Absorption improvement of an ultra-thin silicon solar cell using cubic and disk-shape nanoclusters

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Abstract

The increasing demand for highly efficient and cost-effective solar cells has driven advancements in ultra-thin solar technologies, addressing critical challenges in renewable energy. This study focuses on harnessing surface plasmon-induced electric fields to design an ultra-thin silicon-based solar cell with enhanced performance. A key innovation lies in integrating clustered nanoparticles with cubic and disk geometries across a range of sizes to improve light absorption and photocurrent generation. Initially, a baseline solar cell without nanoparticles was modeled, achieving a photocurrent of 4.779 mA/cm². By systematically optimizing nanoparticle size and cell thickness, the photocurrent significantly increased to 21.885 mA/cm² with cubic nanoparticles and 20.777 mA/cm² with disk-shaped clusters. These results highlight the transformative potential of nanoparticle incorporation in boosting photocurrent in ultra-thin silicon solar cells. The methodology and findings offer a scalable framework for enhancing various solar cell designs and geometries, paving the way for more efficient and adaptable photovoltaic technologies in sustainable energy applications.

Keywords: Nanoclusters; plasmonic solar cells; silicon solar cell; Surface plasmon resonances; ultra-thin

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1. INTRODUCTION

Renewable energy sources, which are abundantly accessible worldwide, provide a range of benefits such as cost reduction, minimized chemical pollution, and enhanced environmental sustainability. Solar energy, as one of the most critical forms of renewable resources, plays a pivotal role in addressing the global energy demand. Extensive research has been conducted on solar energy thus far. Solar cells stand as the only devices capable of directly transforming light into electrical energy (Heidarzadeh et al., 2016a). The generation of electron-hole pairs and the production of photocurrent in semiconductors are directly influenced by the amount of radiant light absorbed (Eicker et al., 2015). As a result, light absorption is considered a key factor in the conversion of light into electricity (Müller et al., 2004).

A wide range of materials, each with varying levels of efficiency and cost, have been employed in the design and fabrication of solar cells. Nevertheless, the low efficiency of thin-film solar cells and the high production costs associated with crystalline silicon cells have posed significant challenges to the widespread commercialization of these technologies, particularly in developing nations (Green, 2000). Due to crystalline silicon's indirect band gap, its light absorption efficiency is relatively low, and the manufacturing process of crystalline silicon-based solar cells is both time-intensive and expensive. To address these issues, thin-film solar cells have been developed at reduced costs; however, their conversion efficiency remains lower compared to crystalline silicon cells (Wang et al., 2014).

Given silicon's widespread availability and low cost, it remains the most suitable material for solar cell production. With a bandgap of 1.12 electron volts, Silicon can convert a substantial portion of the solar spectrum into electrical energy. However, the considerable thickness of crystalline silicon solar cells, typically exceeding 100 micrometers', continues to be one of the major challenges associated with this technology (Yoshikawa et al., 2017). As a result, nearly 40% of the total production cost of crystalline silicon-based solar modules is attributed to the expense of raw materials (Nemet, 2006).

Reducing the thickness of solar cells is a viable solution for lowering production costs. To increase the efficiency of thin-film solar cells, several approaches have been proposed, including grating structures for light trapping, light trapping using the plasmonic effects of precious metal nanoparticles, and employing intermediate band solar cells (Zand et al., 2023; Heidarzadeh & Shahabi 2024; Heidarzadeh et al., 2016b; Mokari & Heidarzadeh 2019; Heidarzadeh & Mehrfar 2018; Heidarzadeh, 2019). The use of metallic nanoparticles is one method that can enhance light absorption in solar cells (Ivriq et al., 2025; Mokari & Heidarzadeh 2019; Heidarzadeh & Mehrfar 2018; Heidarzadeh, 2019; Bajpai et al., 2018). Plasmonic phenomena refer to the interaction between light and the free electrons present in metals (Heidarzadeh et al., 2016b; Ping, 2024). In thin solar cells, plasmonic effects result in increased light absorption through light scattering by metallic nanoparticles and their plasmonic resonance frequency (Mulat et al., 2024). At resonance frequency, the incident light induces oscillations in the electrons on the nanoparticle surface (Heidarzadeh et al., 2016b).

Although significant research has been conducted in this area, further studies are needed to fully realize the potential of this technology and to commercialize plasmonic-based solar cells. Key aspects, such as the size, shape, and placement of nanoparticles within the solar cell structure, remain areas of active debate. Current efficiency levels for thin-film silicon solar cells range between 10 to 13%, significantly lower than the 25% efficiency of thick crystalline silicon solar cells. As mentioned, the oscillations of free electrons on the nanoparticle surface induced by incident light can enhance the performance of solar cells (Green, 2000).

Several plasmonic mechanisms have been employed to improve photovoltaic efficiency. The initial mechanism involves plasmonic nanoparticles serving as scattering dipoles, generated by the elevated density of free electrons within the materials (Dlamini & Mola 2019). These dipoles interact with incident light at the resonance frequency and can help manage the light absorption spectrum. The second mechanism pertains to the near-field enhancement induced by nanoparticles, which is governed by the non-radiative components of the electric field in proximity to the dipole. (Sarkar et al., 2019). When nanoparticles are incorporated into the active layer of the solar cell, there is an increase in light absorption resulting from the elevated photon density of states surrounding the nanoparticles. The dimensions, morphology, and concentration of these nanoparticles are essential factors in optimizing solar cell design.

In many previous studies, metallic nanoparticles were strategically placed on the upper surface of the solar cell (Temple et al., 2009). When incident light interacts with these metallic nanoparticles at their surface Plasmon resonance frequency, it is scattered in different directions (Atwater & Polman 2010). This scattering phenomenon enables light to travel within the cell, reflecting between the nanoparticles and the substrate, thereby promoting greater light absorption by the solar cell (Micha et al., 2019). For embedded nanoparticles, the heightened near-field intensity generated by localized surface Plasmon resonance further amplifies light absorption in semiconductors. Studies have shown that embedded nanoparticles yield higher efficiency compared to surface nanoparticles.

1.1. Purpose of study

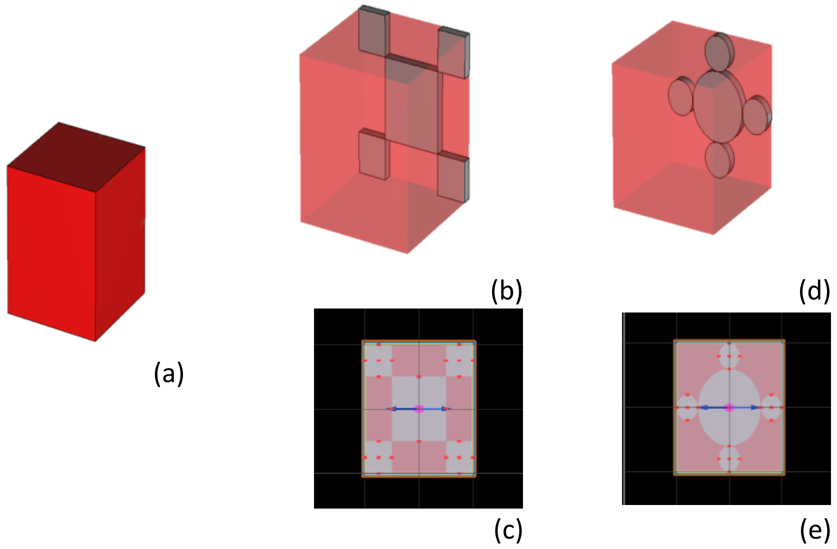
In this research, we focus on two types of nanoparticle clusters cubic and disk-shaped embedded within an ultra-thin silicon absorber. These nanoparticles are expected to exhibit desirable plasmonic properties in the photovoltaic domain. The study investigates the effects of silver and aluminum plasmonic nanoparticles with cubic and disk-shaped structures of varying sizes and thicknesses, comparing the results with structures without nanoparticles and reporting the resulting improvements.

2. METHOD AND MATERIALS

As described in this paper, two configurations of clustered nanoparticles, disk-shaped and cubic, have been utilized to enhance the efficiency of an ultra-thin silicon solar cell. The schematic illustrations of these structures are presented in Figures 1(a) to 1(e). For the development of an optimal ultra-thin silicon solar cell, it is vital to improve the light absorption spectra over an extensive range of the solar spectrum. To accomplish this objective, a variety of silver and aluminum nanoparticles have been utilized in this study. As shown in Figure 1, our main strategy involves using cluster nanoparticles embedded within the active layer and at the bottom of the structure. In this model, it is posited that the solar cell consists of a p–n junction, with the nanoparticles positioned within the depletion region.

Figure 1

Schematic of simulated proposed plasmonic silicon solar cell



Note: (a): without cluster nanoparticles (b), (c): with cubic Nanoparticles (d), (e): with disk-shaped Nanoparticles.

The depletion region is characterized by a concentrated electric field, which is essential for the effective separation of charge carriers. When a photon strikes this region, the generated electric field directs electrons toward the n-region and holes toward the p-region, which increases the efficiency of charge carrier collection. Therefore, positioning the nanoparticles in this area is significantly more important than in other regions and can have a substantial impact on enhancing the performance of solar cells. In this study, an initial solar cell with dimensions of 200 nm × 200 nm × 200 nm is designed. To simulate the plasmonic solar cell, the finite-difference time-domain (FDTD) method is employed using the Lumerical software package (Taflove et al., 2005; Duche et al., 2009; Palanchoke et al., 2012). Perfectly matched layer (PML) boundary conditions are implemented on the top and bottom surfaces of the cell, while periodic boundary conditions are applied to the other sides. A plane wave source is employed across the wavelength range of 0.3 micrometers to 1.1 micrometers. Initially, the thickness of the nanoparticles is varied within a range from 5 to 20 nanometers to identify the optimal thickness and calculate the maximum photocurrent. The cluster nanoparticles are embedded within the cell. Finally, both the non-embedded and coupled nanoparticles are analyzed. To assess the proposed structures, Maxwell's equations are solved to obtain the electric field intensity |E (r, ω) |. This information, combined with the imaginary component of the permittivity, is then used to compute the absorption spectra per unit volume, following the method described in Equation (1).

$$A(r,\lambda)=\frac{\omega\varepsilon_0}{2}\frac{\mathrm{Im}(\varepsilon(r,\omega))\left|E(r,\omega)\right|^2}{P_{in}} \tag{1}$$

Here, E refers to the electric field, Pin represents the incident light power, ω is the angular frequency, and ϵ0 denotes the dielectric constant. The total absorbed power as a function of wavelength is calculated using the following formula:

$$A(\lambda)=\int A(r,\lambda)dV \tag{2}$$

The electrical generation rate as a function of x, y, z, and λ is computed using Equation (3). This process allows us to investigate the impact of various parameters on electricity generation.

$$g(x,y,z,\lambda)=\frac{P_{abs}}{h\omega}=\frac{\varepsilon_0}{2h}\frac{\mathrm{Im}(\varepsilon(r,\omega))\left|E(r,\omega)\right|^2}{P_{in}} \tag{3}$$

The total generation rate at each point is calculated as follows:

$$G(x,y,z)=\int g(x,y,z,\lambda)d\lambda \tag{4}$$

Finally, the photocurrent is obtained from the generation rate G. This relationship enables us to analyze the photocurrent generated from the electricity production process at various points within the solar cell.

3. RESULTS

The use of plasmonic effects in ultra-thin silicon solar cells is proposed as an innovative solution to address the energy crisis and reduce costs. As mentioned, the main issue in these types of cells is the short optical path length, which prevents complete absorption of sunlight energy, leading to decreased photovoltaic conversion efficiency. The key to solving this problem lies in enhancing solar energy absorption. In this paper, the structures depicted in Figure 1 have been simulated. Figure 2 shows a comparative absorption spectrum between configurations with and without cluster nanoparticles, including cubic and disk-shaped silver nanoparticles. The simulations were conducted to demonstrate the impact of cluster nanoparticles on light absorption in solar cells. These results can contribute to the improvement of solar cell design and efficiency.

Figure 2

Comparison of the absorption spectrum for configurations with and without cluster nanoparticles.

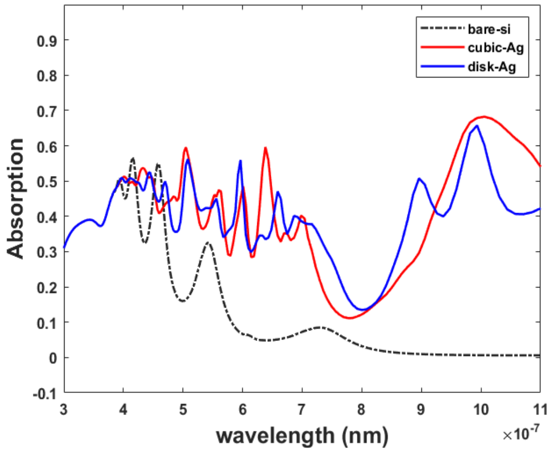
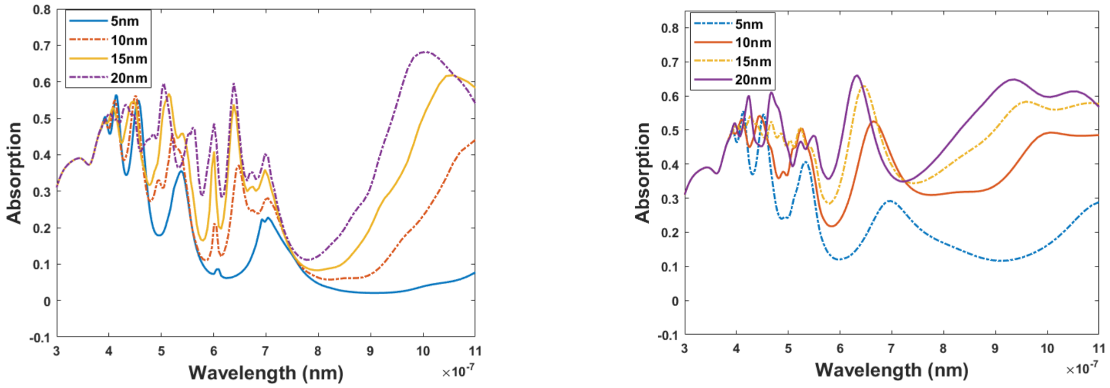


Figure 3 compares the absorption spectra of a solar cell with cubic cluster nanoparticles at different nanoparticle thicknesses. As observed, a significant improvement in light absorption occurs with increasing nanoparticle thickness. This enhancement in absorption is due to the plasmonic effects of metallic nanoparticles, which strengthen the interaction between light and the material. In this case, the incident light is concentrated at specific wavelengths, leading to an increase in the absorption spectra. This method effectively boosts solar energy absorption in a thin active layer, contributing to improved solar cell performance.

Figure 3

Comparison of absorption spectra for a solar cell incorporating cubic cluster nanoparticles at various thicknesses. (a) Silver nanoparticles (b) Aluminum nanoparticles

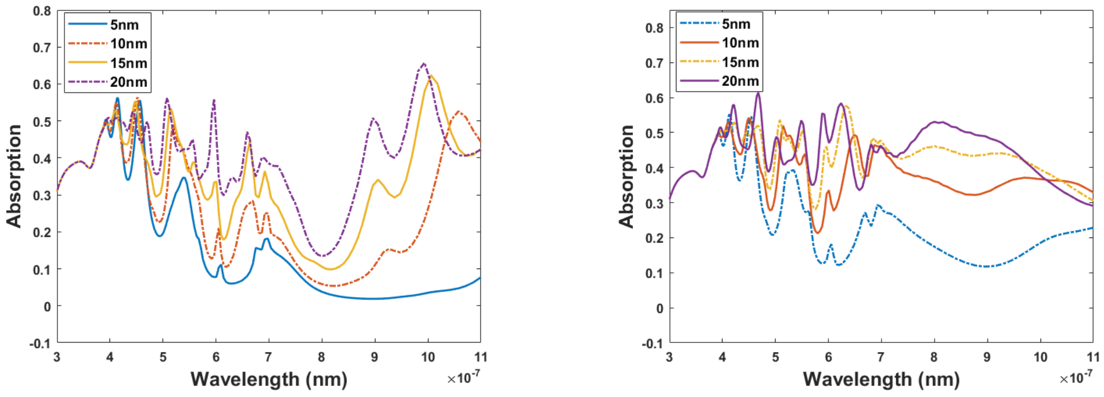


(a) (b)

In Figure 4, the absorption spectra of the solar cell with disk-shaped cluster nanoparticles at varying nanoparticle thicknesses are presented. As seen, the embedded nanoparticles significantly enhance the absorption spectra, and this enhancement becomes more pronounced as the nanoparticle thickness increases. Embedded nanoparticles have a greater impact on improving the absorption spectra compared to non-embedded ones. This is due to the concentration of the electromagnetic field, associated with enhanced near-field scattering around the nanoparticles, which increases light absorption in the active layer of the solar cell.

Figure 4

Comparison of absorption spectra for a solar cell incorporating disk-shaped cluster nanoparticles at various thicknesses. (a) Silver nanoparticles (b) Aluminum nanoparticles.



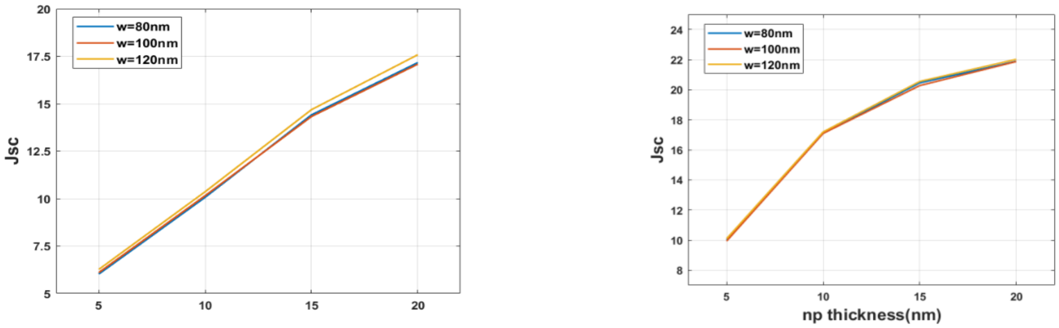
(a) (b)

To investigate the effect of nanoparticle dimensions on solar cell absorption, Figure 5 shows variations in the parameter w and the thickness of the nanoparticles, with the resulting photocurrents presented. In Figures 5(a) and 5(b), cubic-shaped cluster nanoparticles made of silver and aluminum are used, while Figures 5(c) and 5(d) depict disk-shaped cluster nanoparticles made of the same materials. Embedded nanoparticles enhance the generation rate due to the plasmonic effects of the metal nanoparticles.

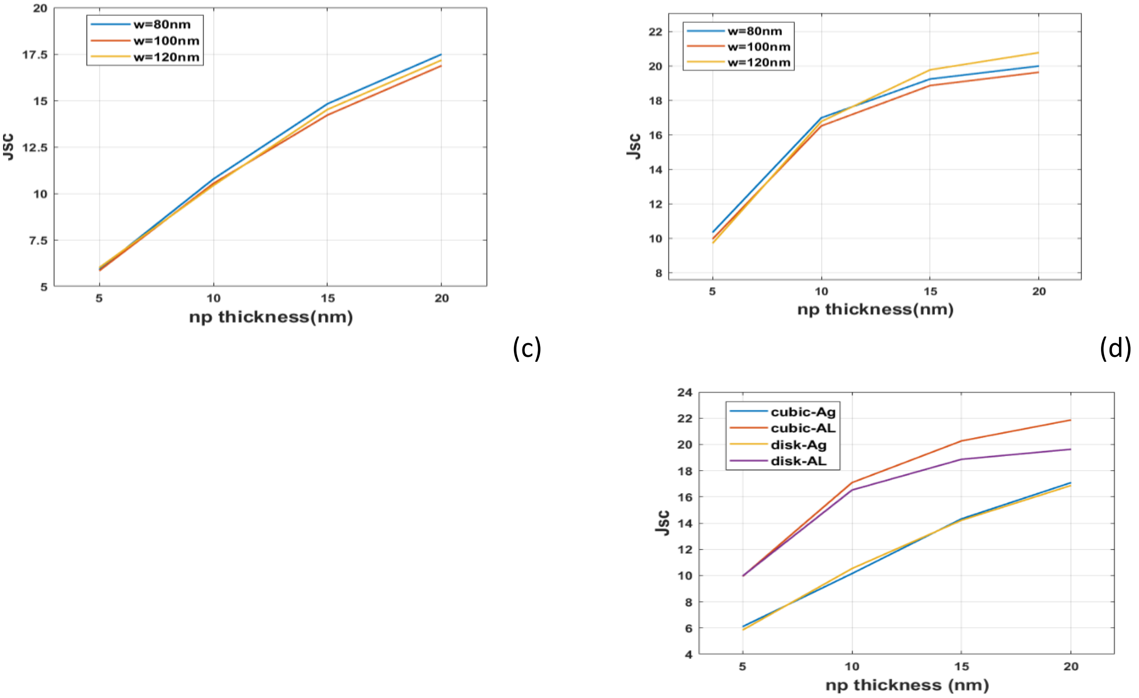
The results indicate that the photocurrent increases across all curves as the thickness of the embedded nanoparticles grows. Additionally, changes in the nanoparticle dimensions have a negligible effect on the photocurrent, suggesting that the plasmonic effect continues to enhance absorption regardless of dimensional variations in the nanoparticles.

Figure 5

The effect of nanoparticle dimensions on solar cell absorption



(a) (b)



(c)

(d)

(e)

In Figure 5, The effect of nanoparticle dimensions on solar cell absorption, showcasing variations in the parameter w and nanoparticle thickness, along with the corresponding photocurrent results (a) and (b) illustrate cubic-shaped cluster nanoparticles made of silver and aluminum, respectively, while (c) and (d) display disk-shaped cluster nanoparticles of the same materials (e) present an analysis of the influence of embedded nanoparticles with varying structures on the photocurrent in solar cells.

The subsequent analysis, presented in Figure 5(e), illustrates the impact of embedded nanoparticles with different structures on the photocurrent. A key factor to note is that the surface plasmon resonance in metal nanoparticles is influenced by various factors, including size, shape, and the refractive index of the surrounding medium. By comparing the obtained results, it can be concluded that cubic aluminum nanoparticles exhibit the best performance, making them highly suitable for the development of ultra-thin solar cells with high photocurrents. The primary reason for this significant improvement is the presence of plasmonic resonance modes in the aluminum nanoparticles, which optimize the interaction between light and matter, thereby enhancing solar energy absorption.

4. CONCLUSION

In this study, the photocurrent of an ultra-thin silicon solar cell significantly increased by embedding cluster-shaped nanoparticles. By adjusting the thickness of the nanoparticles, a notable rise in photocurrent was observed within the structure. For example, the photocurrent increased from 4.779 mA/cm² for a silicon cell with dimensions of 200×200×200 nanometers without nanoparticles to a maximum value of 21.885 for the silicon cell embedded with cubic aluminum nanoparticles, and to a maximum value of 20.777 for the silicon cell embedded with disk-shaped aluminum nanoparticles.

Additionally, the effect of changing the size and thickness of the embedded nanoparticles on the photocurrent was evaluated, with results showing that an increase in thickness led to improved photocurrent.

Conflict of interest: No potential conflict of interest was reported by the authors.

Ethical Approval: The study adheres to the ethical guidelines for conducting research.

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