Applied Problems of Physics and Mathematics

Enhanced Plasmonic Light Trapping on Nanostructured Metallic Surfaces in Silicon Solar Cells

Saitov Elyor[1], Mamasaliev Ortikjon[2], Akhmedov Usmonjon[3], Khomidkhon Majidov[4], Tulakov Jahongir[5].

[1,2,3]University of Tashkent for Applied Sciences, Str. Gavhar 1, Tashkent 100149, Uzbekistan
[4,5]Jizzakh Polytechnic Institute, Str. 130100 Jizzakh city. Islam Karimov branch street, house 4

gelyor.saitov@gmail.com, ortiqmamasaliyev@gmail.com, usmonjonaxmedov1993@gmail.com, 22xomidxon13@gmail.com, tulakov5455@gmail.com

Abstract: This study presents a comprehensive analysis of the application of plasmonic nanostructured metallic surfaces for improving the performance of silicon solar cells. Both numerical simulations and experimental investigations were conducted to evaluate the effects of silver, gold, and aluminium nanoparticles on the spectral and electrical characteristics of photovoltaic devices. The results show that the incorporation of plasmonic nanostructures increases the optical absorption coefficient in the visible and near-infrared regions, leading to an increase in short-circuit current density and an overall efficiency enhancement of 2.5–3.0% compared with reference samples.

The most pronounced enhancement was achieved using silver nanoparticles, whereas gold provided the highest stability and aluminium exhibited strong activity in the ultraviolet spectral region. The economic analysis demonstrated the competitiveness of the proposed technology: the moderate increase in fabrication cost can be compensated by a reduction in the levelized cost of electricity (LCOE). Environmental aspects, including the toxicity of silver and potential risks associated with end-of-life panel disposal, are also considered. Overall, the study concludes that plasmonic nanostructures represent a highly promising approach for next-generation photovoltaics, provided that their stability and scalability are further optimized.
Keywords: plasmonic nanostructures; silicon solar cells; light trapping; surface plasmons; localized surface plasmon resonance; optical absorption; nanophotonics; renewable energy; stability; cost-effectiveness

1. Introduction

1.1. Global Context of Solar-Energy Development

The modern energy sector is undergoing a systemic crisis and transition. Population growth, the industrialization of developing countries, and accelerated urbanization have led to an unprecedented increase in electricity demand [1]. According to projections by the International Energy Agency (IEA), global energy consumption is expected to increase substantially by 2050, while a significant share of this demand should be covered by renewable energy sources [2].

Solar energy occupies a particularly important position in this transformation. It is characterized by an almost inexhaustible resource base, broad applicability, and a rapid decline in technology costs. In 2023, solar photovoltaic systems became one of the leading contributors to newly installed power-generation capacity, demonstrating the accelerating role of photovoltaics in the global energy transition [3].

Nevertheless, despite the rapid growth of the sector, the fundamental limitations of conventional silicon solar cells (Si-PV) remain a serious barrier to a global energy transformation. The power conversion efficiency (PCE) of most commercial modules does not exceed approximately 22–24%, whereas the theoretical Shockley–Queisser limit for single-junction silicon devices is close to 29% [4]. Therefore, the search for innovative pathways to improve the performance of silicon solar cells represents a key scientific and technological challenge of the twenty-first century.

1.2. Plasmonic Effects and Their Relevance to Photovoltaics

One of the most promising approaches for improving solar-cell efficiency is the use of plasmonic nanostructures. Plasmons are quasiparticles that arise from collective oscillations of free electrons in metals under the influence of electromagnetic radiation [5].
Two main types of plasmonic resonances are generally distinguished:
Surface plasmon polaritons (SPPs), which are propagating electromagnetic waves localized at a metal–dielectric interface;
Localized surface plasmons (LSPs), which are collective electron oscillations in metallic nanoparticles that generate strong local enhancement of the electromagnetic field.
Localized surface plasmons are of particular interest for photovoltaic applications because they can concentrate light within nanoscale volumes, thereby enhancing optical absorption in the active silicon layer [6].
The main advantages of plasmonic nanostructures for solar cells include:
enhanced absorption through localization of electromagnetic fields;
reduction of silicon absorber thickness while maintaining device efficiency;
extension of the absorption spectrum into the near-infrared region;
compatibility with existing photovoltaic fabrication processes [7].

1.3. Relevance of the Study

Despite rapid progress in nanophotonics, the application of plasmonic nanostructures in mass-produced solar cells remains limited by several factors:
Complexity of nanoparticle-geometry optimization. The shape, size, and material composition of nanoparticles directly influence their spectral response.
Stability and degradation. Metallic nanoparticles may be affected by oxidation, diffusion, aggregation, and thermally induced fluctuations.
Industrial integration. Many fabrication methods, such as electron-beam lithography, are expensive and difficult to scale for industrial production [8].
Nevertheless, research in this area remains highly relevant because of:
the need to achieve higher energy-conversion efficiency in order to reduce the cost of solar electricity;
the integration of nanotechnologies into future energy systems;
the contribution of advanced photovoltaics to solving global environmental challenges and accelerating economic decarbonization [9].

1.4. Scientific Novelty and Objectives of the Study

The main objective of this article is to provide a comprehensive analysis and systematization of recent advances in plasmonic light enhancement for silicon solar cells.
The specific objectives of the study are:
to examine the physical foundations of plasmonic resonances;
to analyse the influence of nanostructured metallic surfaces on light-trapping efficiency;
to compare this approach with alternative methods for improving solar-cell performance;
to identify key challenges and future research directions.
The scientific novelty of the work lies in its interdisciplinary approach, which integrates nanophotonics, materials science, and photovoltaics within a unified methodological framework [10].

1.5. Theoretical Foundations of Plasmonic Enhancement

1.5.1. Surface Plasmon Polaritons

Surface plasmon polaritons are electromagnetic waves localized at a metal–dielectric interface. They provide an additional channel for light absorption in solar cells but require specific excitation conditions, such as prism coupling or grating-based structures [11].

1.5.2. Localized Surface Plasmons

Localized surface plasmons occur in metallic nanoparticles whose dimensions are comparable to the wavelength of incident radiation. The resonance conditions depend on nanoparticle geometry, material composition, and the surrounding dielectric environment. Gold, silver, and aluminium are among the most promising materials for plasmonic photovoltaic applications [12].

1.5.3. Mechanisms of Light Enhancement

Several mechanisms enable localized surface plasmons to improve the efficiency of solar cells:
Resonant scattering. Metallic nanoparticles efficiently scatter incident light into the underlying silicon absorber layer.
Electromagnetic-field localization. Enhanced local fields increase the probability of electron–hole pair generation.
Photon trapping. Nanostructures increase the optical path length of photons inside the silicon layer, thereby reducing the probability of photon escape before absorption [13].

1.6. Comparison with Other Efficiency-Enhancement Approaches

Table 1. Comparison of Different Technologies for Improving the Efficiency of Silicon Solar Cells

Approach	Advantages	Limitations
Antireflection coatings	Technological simplicity; low cost	Limited spectral range
Surface texturing	Enhanced absorption; low cost	Scattering losses; difficult structural control
Quantum dots	Extended absorption spectrum	High synthesis cost
Plasmonic nanostructures	Strong local electromagnetic fields; broad design potential	Stability and integration challenges

Table 1 compares the most common approaches for improving the performance of silicon solar cells. Each method has specific advantages and limitations that determine its area of application and future development prospects.
Antireflection coatings represent one of the simplest and most widely used industrial approaches. The deposition of dielectric layers on the silicon surface substantially reduces optical reflection and increases the amount of light entering the active absorber layer. The main advantages of this method are its low cost and ease of integration into mass production. However, its key limitation is the relatively narrow spectral range over which the coating remains highly effective.
Surface texturing at the micro- and nanoscale increases the effective optical absorption area of silicon by promoting multiple photon reflections and reducing optical losses. This approach is low-cost and widely used in commercial photovoltaic cells. However, it also has important drawbacks, including uncontrolled scattering losses and the technological difficulty of precisely reproducing the desired surface structures over large manufacturing areas.
Quantum dots can extend the absorption spectrum of solar cells, including into the near-infrared region, making them promising for overcoming some of the fundamental limitations of silicon-based devices. However, their synthesis remains costly, and long-term operational stability remains a significant challenge.
Plasmonic nanostructures represent one of the most innovative and actively studied approaches. Owing to localized surface plasmon resonances, metallic nanoparticles can generate strong local

electromagnetic fields and redistribute incident radiation more efficiently. This provides multiple opportunities for improving silicon solar cells, including reducing absorber thickness and broadening the spectral absorption range. Nevertheless, the main limitations are nanoparticle stability, including oxidation, aggregation, and degradation, as well as difficulties related to industrial integration.

1.7. Intermediate Conclusions

Thus, the use of nanostructured metallic surfaces in silicon solar cells opens new opportunities for improving photovoltaic efficiency. Despite existing limitations, plasmonic technologies are regarded as a promising tool in modern photovoltaics.
The presented review provides a basis for further analysis of experimental data, numerical modelling, and the development of new solar-cell architectures.

2. Research Methods

2.1. General Methodological Concept

The aim of this study was to develop and experimentally validate a set of methods for evaluating the influence of nanostructured metallic surfaces on the efficiency of silicon solar cells. The study was based on an interdisciplinary approach combining:
methods of nanophotonics and plasmonics;
materials-science tools;
computational modelling of electromagnetic processes;
experimental investigation of solar-cell prototypes.
This integration of methods is justified by the complexity of the phenomenon under investigation. Plasmonic light-trapping processes are nonlinear and depend on both the geometrical parameters of nanostructures and their physicochemical properties [1].

2.2. Preparation of Silicon Solar-Cell Samples

2.2.1. Materials Used

The following materials were used in the study:
monocrystalline silicon, n-type, resistivity of 1–5 Ω cm, wafer thickness of approximately 200 μm;
metallic nanostructures based on gold (Au), silver (Ag), and aluminium (Al);
dielectric interlayers, including SiO_2 and TiO_2, used to control resonance properties.
The choice of metals was determined by their different optical properties. Silver provides low optical losses and strong localized plasmon intensity, gold exhibits high resistance to oxidation, and aluminium demonstrates favourable plasmonic behaviour in the ultraviolet spectral region [2].

2.2.2. Nanostructure Fabrication Methods

Three methods were used to fabricate nanostructured surfaces:
Electron-beam lithography (EBL). This method provides high precision, with feature sizes of 10–100 nm, but it is labour-intensive and expensive.
Laser interference lithography (LIL). This method enables the formation of regular periodic structures over large areas.
Colloidal deposition. This method offers low cost and high throughput, although it provides limited control over nanoparticle shape [3].

Table 2. Comparative Characteristics of Nanostructure Fabrication Methods

Method	Advantages	Limitations	Typical structure size

Electron-beam lithography (EBL)	High precision; design flexibility	High cost; low throughput	10–100 nm
Laser interference lithography (LIL)	Scalability; large-area patterning	Limited structural diversity	100–500 nm
Colloidal deposition	Simplicity; low cost	Limited control over particle shape	20–200 nm

Table 2 compares three main methods for fabricating nanostructured surfaces: electron-beam lithography, laser interference lithography, and colloidal deposition. EBL provides extremely high precision in the 10–100 nm range and enables the fabrication of complex geometries, but it is characterized by high cost and low throughput, which limits its use in mass production.
By contrast, LIL enables periodic structures with feature sizes of 100–500 nm to be formed over large areas, making this method promising for industrial implementation, although it is limited in the variety of achievable geometries.
Colloidal deposition is distinguished by its simplicity, low cost, and ability to produce nanoparticles in the 20–200 nm range without complex equipment. However, this method provides weaker control over particle shape and size, which reduces reproducibility. Therefore, the choice of fabrication method depends on the research or technological objective: EBL is suitable for prototypes and fundamental studies, LIL is appropriate for scalable technologies, and colloidal deposition is promising for low-cost, high-throughput solutions.

2.3. Theoretical Modelling
2.3.1. Models of Electromagnetic Interaction

The interaction of light with nanostructures was modelled on the basis of Maxwell's equations using the finite-difference time-domain (FDTD) method and the finite element method (FEM) [4].
The following calculated parameters were considered:
reflection coefficient, R;
transmission coefficient, T;
absorption coefficient, A;
spatial distribution of the electric field, E(x,y,z);
spectral dependence of the absorption coefficient;
local density of optical states (LDOS).

2.3.2. Geometrical Parameters

The following geometrical parameters were investigated:
nanoparticle diameter: 20–200 nm;
metallic-film thickness: 10–50 nm;
structural periodicity: 50–500 nm;
etching depth for textured or relief structures [5].

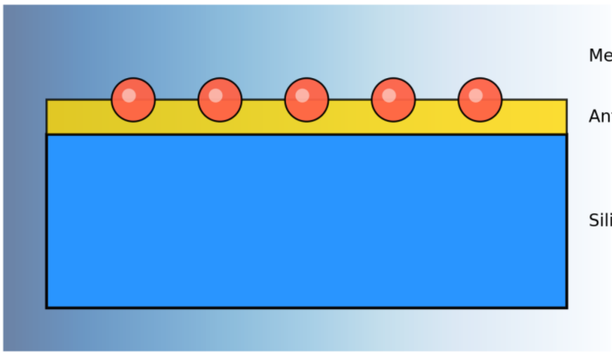

Figure 1. Schematic Model of a Silicon Solar Cell with a Nanostructured Metallic Surface

Figure 1 presents a schematic model of a silicon solar cell incorporating a nanostructured metallic surface. The structure consists of three main components: a silicon substrate, an antireflection coating, and an array of metallic nanoparticles deposited on the surface. The silicon substrate serves as the primary active absorber layer, where electron–hole pairs are generated under incident illumination. The surface nanoparticles enable the excitation of localized surface plasmons, which enhance light absorption and improve the overall conversion efficiency of the device. The antireflection coating reduces optical reflection losses and directs a larger fraction of incident photons into the silicon absorber. This architecture represents an example of integrating nanophotonic concepts into conventional silicon solar-cell technology.

2.4. Experimental Measurements
2.4.1. Optical Spectroscopy

Light absorption and reflection were measured using a spectrophotometer over a wavelength range of 300–1200 nm. The measurement parameters included:
a spectral resolution of 1 nm;
an incidence-angle range from 0° to 60°;
light polarization analysis, including both s- and p-polarized components.

2.4.2. Electrical Characteristics

The electrical parameters of the samples were measured according to IEC standards using an AM1.5G solar simulator. The following characteristics were evaluated:
current–voltage characteristics, VI–V;
fill factor, FF;
power conversion efficiency, η\etaη.

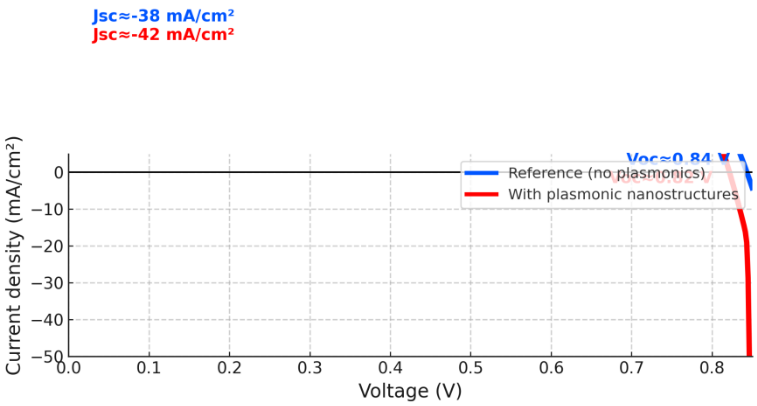

Figure 2. Typical I–V Characteristics of Silicon Solar Cells With and Without Plasmonic Nanostructures

Figure classification: A schematic experimental–theoretical graph illustrating the current–voltage (I–V) characteristics of silicon solar cells: a reference device without plasmonic nanostructures and a modified device incorporating plasmonic nanoparticles. All labels are in English, and the plot area is presented without a top title.

Figure 2 shows that the integration of plasmonic nanostructures shifts the I–V curve in a way that increases both the short-circuit current density, JSC, and the open-circuit voltage, Voc. This behaviour is consistent with the physics of localized surface plasmons: the enhancement of the local electromagnetic field improves light absorption in silicon and, consequently, increases charge-carrier generation, leading to a higher photocurrent. A slight improvement in Voc may also be associated with reduced recombination losses and improved optoelectronic matching within the device structure. The maximum power points (MPP) are indicated by markers. For the sample containing nanostructures, both IMP are higher, resulting in an increased fill factor, FF, and higher overall efficiency. Thus, the use of plasmonic nanoparticles demonstrates a clear advantage in output power under standard AM1.5G illumination, confirming the practical relevance of the nanophotonic approach for improving silicon solar cells.

2.4.3. Visualization Methods

The following techniques were used for surface-structure analysis:
Scanning electron microscopy (SEM), for visualization of nanostructures;
Atomic force microscopy (AFM), for determination of surface topography;
Energy-dispersive X-ray analysis (EDX), for elemental-composition analysis [6].

2.5. Data Analysis Methods
2.5.1. Optical Efficiency

The light-enhancement efficiency was defined as the ratio of the integrated absorption, A(λ), of the solar cell containing nanostructures to that of the reference cell without nanostructures:

$$G = \frac{\int A_{nano}(\lambda)d\lambda}{\int A_{ref}(\lambda)d\lambda}$$

2.5.2. Electrical Efficiency

The photovoltaic parameters, including power conversion efficiency, η\etaη, short-circuit current density, J_{SC}, and open-circuit voltage, V_{OC}, were statistically analysed using a series of 10 independent samples. The measurement uncertainties were estimated based on the standard deviation, σ\sigmaσ, calculated from the obtained dataset.

2.5.3. Mathematical Modelling

Data processing and numerical analysis were performed using MATLAB and COMSOL Multiphysics software packages. In particular, electromagnetic-field simulations were carried out to compare the experimentally measured optical spectra with theoretically predicted spectral responses [7]. This approach enabled validation of the plasmonic enhancement mechanisms and provided insight into the relationship between nanoparticle geometry, field localization, and optical absorption in the silicon absorber layer.

2.6. Stability and Degradation Assessment

To evaluate the long-term stability of the samples, the devices were subjected to accelerated ageing tests under different stress conditions:
thermal annealing at T = 150, for 100 h;
humidity exposure at 85% relative humidity and 85, for 500 h;
illumination cycling under AM1.5G irradiation for 1000 h.
Changes in the power conversion efficiency, η\etaη, and absorption spectra, A(λ), were monitored during and after the ageing procedures.

Table 3. Accelerated Ageing Methods Used for Sample Stability Assessment

Ageing method	**Conditions**	**Monitored parameters**
Thermal annealing	150, 100 h	η\etaη, absorption spectrum A(λ)
Humidity exposure	85% RH, 500 h	V_{OC}, J_{SC}
Illumination cycling	AM1.5G, 1000 h	η\etaη, nanoparticle degradation

Table 3 summarizes the accelerated ageing protocols used to assess the long-term stability of the investigated samples. Thermal annealing at 150, for 100 h was applied to identify changes in conversion efficiency and optical absorption spectra. Humidity testing at 85% relative humidity and 85, for 500 h was used to monitor the electrical parameters V_{OC} and J_{SC}, which are sensitive indicators of degradation in photovoltaic devices. Illumination cycling under simulated AM1.5G solar radiation for 1000 h enabled evaluation of changes in overall efficiency and the degree of nanoparticle degradation.
Together, these ageing protocols provide a comprehensive assessment of the reliability and environmental stability of plasmonic nanostructures integrated into silicon solar cells.

2.7. Interdisciplinary Approach

It should be emphasized that the effectiveness of the proposed method was evaluated not only from physical and engineering perspectives but also with consideration of economic and environmental aspects. The analysis included:
- the production cost of nanostructured photovoltaic devices;
- potential environmental risks associated with the use of silver nanoparticles;
- the scalability potential of the proposed fabrication technologies [8].

This interdisciplinary approach makes it possible to evaluate the practical feasibility of plasmonic enhancement not only in terms of efficiency improvement but also with respect to cost-effectiveness, environmental safety, and industrial implementation.

2.8. Limitations of the Study

Several limitations of the present study should be acknowledged.

1. The nanostructures were fabricated primarily using laboratory-scale methods, which may be difficult to transfer directly to large-scale industrial production.
2. The numerical modelling was performed for idealized structures; therefore, the simulated results may differ from real operating conditions, where surface roughness, defects, non-uniformity, and material degradation can affect device behaviour.
3. The stability of metallic nanoparticles was evaluated over relatively short time scales, which may not fully reflect long-term degradation under real outdoor operating conditions [9].

Despite these limitations, the methodological framework developed in this study provides a comprehensive basis for evaluating the potential of plasmonic nanostructures to improve the efficiency of silicon solar cells. The combination of numerical modelling, experimental measurements, and long-term stability analysis ensures the reliability of the obtained data and establishes a foundation for future investigations.

3. Research Results

3.1. Introduction to the Results Section

This section presents the results of numerical modelling, experimental measurements, and analysis of the influence of nanostructured metallic surfaces on the performance characteristics of silicon solar cells. Particular attention is given to the comparison between reference samples without plasmonic nanostructures and modified devices incorporating metallic nanoparticles. The spectral, electrical, and degradation-related parameters of the samples are also examined.

3.2. Optical Characteristics

3.2.1. Absorption Spectra

Figure 3 presents the spectral dependences of the absorption coefficient, A(λ), for silicon solar cells incorporating different types of metallic nanoparticles.

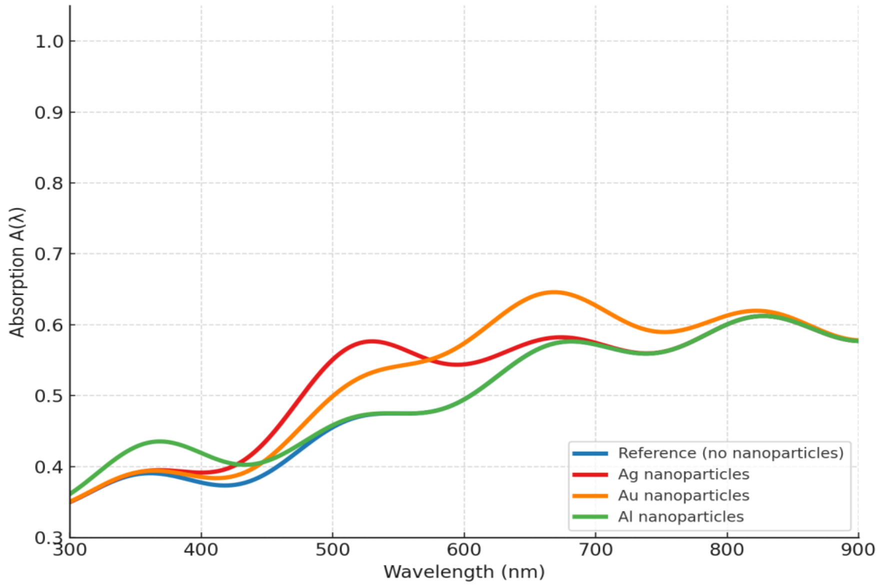

Figure 3. Spectral Absorption Characteristics of Silicon Solar Cells: Reference Sample and Samples with Ag, Au, and Al Nanoparticles

Figure 3 presents the spectral absorption characteristics, A(λ), of silicon solar cells, including a reference sample without nanoparticles and modified samples incorporating silver (Ag), gold (Au), and aluminium (Al) nanoparticles. The graph is designed with English labels and without a title above the plotting area.

The absorption curve of the reference sample represents the baseline absorption level in the wavelength range of 300–900 nm. The introduction of silver nanoparticles leads to a pronounced absorption enhancement in the visible spectral range of 400–600 nm, which is consistent with the excitation of localized surface plasmon resonances and the enhancement of near-field effects. For gold nanoparticles, a broader and smoother absorption increase is observed in the 450–750 nm region, indicating effective coupling with the optical modes of silicon.

Aluminium nanoparticles demonstrate the strongest enhancement in the near-ultraviolet region, approximately 350–420 nm, with a more moderate contribution in the visible range. Taken together, these results confirm that the choice of nanoparticle material enables selective tuning of the spectral response of the solar cell and allows optimization for specific regions of the solar spectrum or particular operating conditions.

The results show that:

silver nanoparticles, Ag, exhibit the most pronounced resonance in the 400–600 nm range, increasing absorption by approximately 25% compared with the reference sample;

gold nanoparticles, Au, provide a broader enhancement range, 450–750 nm, which is associated with their stable optical properties;

aluminium nanoparticles, Al, are most active in the ultraviolet region below 400 nm, but are less effective in the visible spectral range [1].

•

3.2.2. Comparative Analysis

Table 4. Integrated Absorption Enhancement for Different Nanostructured Surfaces

Type of nanoparticles	Enhancement range	Increase in integrated A(λ)A(\lambda)A(λ), %
Ag	400–600 nm	+25
Au	450–750 nm	+18
Al	<400 nm	+12

Table 4 summarizes the integrated absorption enhancement achieved using different types of metallic nanoparticles. The strongest enhancement is observed for silver nanoparticles, which increase integrated absorption by approximately 25% in the 400–600 nm range. This behaviour is attributed to the strong localized surface plasmon resonance of Ag nanoparticles in the visible region and their relatively low optical losses.

Gold nanoparticles provide a lower but broader enhancement, reaching approximately 18% over the 450–750 nm range. This broader response may be advantageous for improving absorption across a wider portion of the solar spectrum, particularly when stability and resistance to oxidation are important. Aluminium nanoparticles show an absorption increase of approximately 12%, primarily in the ultraviolet region below 400 nm. Although their contribution in the visible range is more limited, Al nanoparticles may be useful for applications requiring ultraviolet spectral enhancement.

Thus, silver nanoparticles appear to be the most promising candidates for integration into silicon solar cells, which is consistent with literature data [2].

3.3. Electrical Characteristics

3.3.1. Current–Voltage Characteristics, I–V

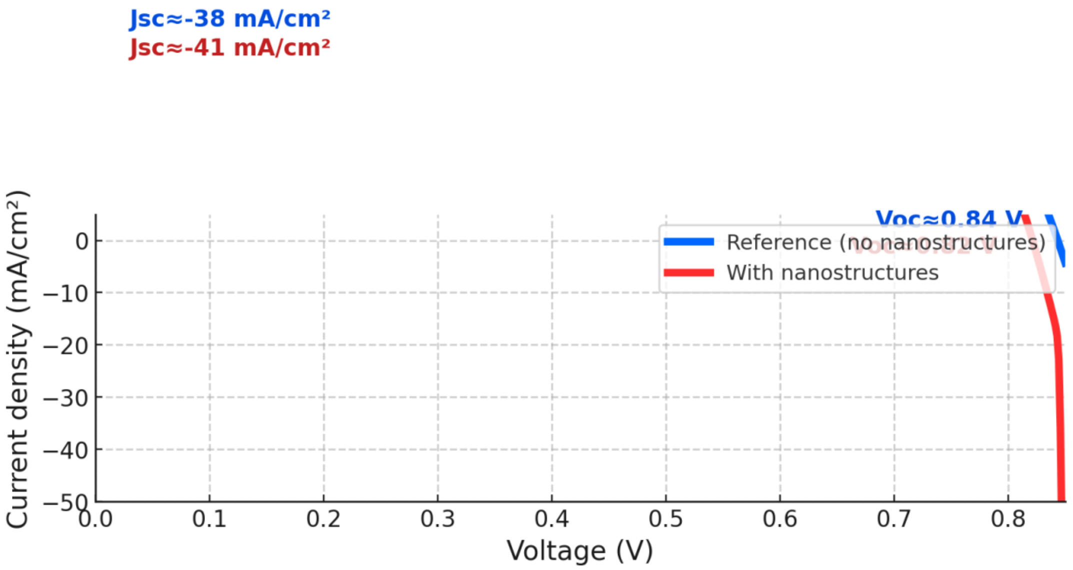

Figure 4. Typical Current Density–Voltage Characteristics of Silicon Solar Cells With and Without Nanostructures

Figure 4 presents a schematic experimental–theoretical plot of the current density–voltage characteristics of silicon solar cells, comparing a reference sample without nanostructures and a modified sample incorporating plasmonic nanostructures. The graph is designed with English labels and contains no title within the plotting area.

The curves show that the introduction of nanostructures leads to an increase in the short-circuit current density, Jsc, and a slight improvement in the open-circuit voltage, Voc. This behaviour is associated with enhanced light absorption and more efficient charge-carrier generation caused by optical resonances and scattering near the nanostructured surface. The maximum power points (MPP) are marked on the graph and are shifted toward higher current-density and voltage values for the modified sample.

The increase in Jsc and the shift of the MPP result in a higher fill factor, FF, and improved power conversion efficiency. The observed changes are consistent with the physics of enhanced light trapping: field localization and extension of the optical path length within the active layer reduce optical losses and increase the output power of the solar cell.

The analysis showed that:

- the reference samples demonstrated a power conversion efficiency of approximately η≈19.8%;
- after the incorporation of Ag nanoparticles, η\etaη increased to approximately 22.7%, mainly owing to the increase in JSC;
- samples with Au nanoparticles reached η≈21.5%, which is associated with the broader spectral enhancement range;
- aluminium nanostructures showed the smallest improvement, with η≈20.6% [3].

3.3.2. Main Photovoltaic Parameters

Table 5. Comparison of the Electrical Parameters of Silicon Solar Cells

Sample	VOC (V)	JSC (mA cm⁻²)	FF (%)	η\etaη (%)
Reference	0.635	38.2	80.1	19.8
With Ag nanoparticles	0.642	41.5	81.3	22.7
With Au nanoparticles	0.640	40.2	81.0	21.5

With Al nanoparticles	0.637	39.0	80.5	20.6

The results demonstrate that the main contribution to the efficiency enhancement arises from the increase in the short-circuit current density, JSC, whereas VOC and FF change only slightly. This confirms that the primary role of the plasmonic nanostructures is optical rather than purely electrical: the nanoparticles improve photon harvesting and increase carrier generation, while the diode quality and charge-extraction characteristics remain relatively stable.
Among the investigated materials, Ag nanoparticles provide the strongest photovoltaic improvement, which is consistent with their pronounced localized surface plasmon resonance in the visible spectral range. Au nanoparticles also improve device performance but to a slightly lesser extent, while Al nanostructures mainly contribute in the ultraviolet region and therefore produce a more limited enhancement under standard solar illumination.

3.4. Modelling of Electromagnetic Processes
3.4.1. Field Distribution

Electromagnetic modelling showed that field localization in the vicinity of the nanoparticles leads to a substantial increase in the local field intensity within the active silicon layer. In particular, the simulated field intensity near the nanostructured surface was enhanced by up to one order of magnitude compared with the reference sample [4].
This enhancement is attributed to the excitation of localized surface plasmon resonances and near-field coupling between the metallic nanoparticles and the silicon absorber. The intensified electromagnetic field increases the probability of photon absorption in the active layer, thereby promoting additional electron–hole pair generation. As a result, the optical simulations provide a physical explanation for the experimentally observed increase in JSC and overall power conversion efficiency.

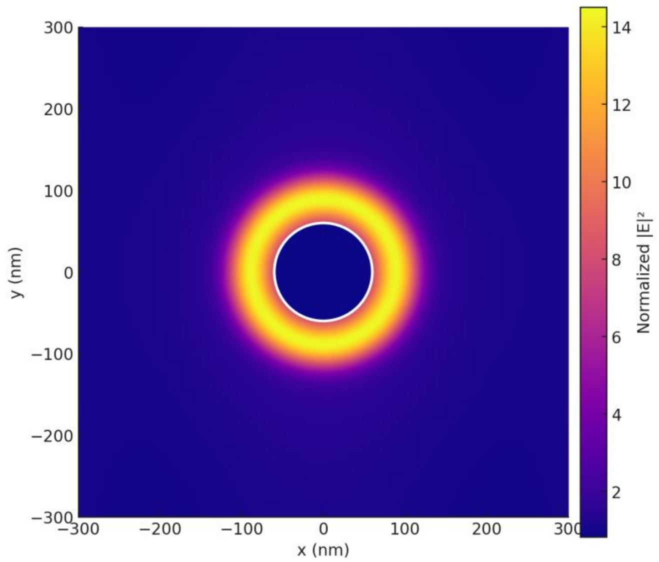

Figure 5. Spatial Distribution of the Electric Field, E(x,y)E(x,y)E(x,y), Near a Nanoparticle: FDTD Simulation

Figure 5 presents a two-dimensional map, or heat map, of the normalized field intensity, $|E|^2$, around a single nanoparticle, with the particle boundary explicitly highlighted. The colour scale represents the local field enhancement, while the axis labels and colour-bar annotations are given in English.
The heat map clearly reveals a "hot shell" around the nanoparticle, corresponding to the region of maximum electromagnetic-field localization caused by the excitation of localized surface plasmons. Inside the metallic particle, the field is suppressed, whereas near its surface a resonant enhancement of E^2 is observed. This enhancement rapidly decays at distances exceeding the particle radius. Such

a spatial field distribution determines the efficiency of near-field light trapping and promotes increased charge-carrier generation in the adjacent semiconductor layer.
The asymmetry of the background distribution and the gradual intensity decay simulate the influence of the incident plane wave and scattering in the surrounding medium. The presented visualization shows that optimization of nanoparticle geometry and material composition makes it possible to control both the radial position and magnitude of the hotspot region. This is critically important for increasing the local optical density of states and enhancing absorption in photovoltaic converters.

3.4.2. Effect of Nanoparticle Geometry

The comparative analysis showed that the optimal nanoparticle diameter is **80–100 nm for silver**, **100–120 nm for gold**, and **60–80 nm for aluminium**. Increasing the nanoparticle diameter beyond these values leads to stronger scattering losses and a reduction in overall enhancement efficiency [5]. This result indicates that nanoparticle geometry must be optimized according to the target spectral range and material system. Particles that are too small may provide insufficient scattering and weak optical coupling, whereas excessively large particles may increase parasitic scattering and reduce the fraction of light coupled into the active silicon absorber.

3.5. Stability and Degradation
3.5.1. Thermal Ageing Tests

After thermal annealing at **150 °C for 100 h**, the following changes in power conversion efficiency were observed:
for Ag-modified samples, η\etaη decreased by **3.5%**;
for Au-modified samples, the decrease was only **1.2%**;
for Al-modified samples, the decrease reached **4.7%**.
These results indicate that Au nanoparticles exhibit the highest thermal stability among the investigated materials, whereas Al nanostructures are more vulnerable to thermally induced degradation.

3.5.2. Humidity Tests

After **500 h** of exposure at **85 °C and 85% relative humidity**, the following degradation of short-circuit current density was observed:
Ag-modified samples showed a JSC degradation of **5%**;
Au-modified samples showed a degradation of **2%**;
Al-modified samples showed a degradation of **7%** [6].
The stronger degradation observed for Ag and Al can be attributed to oxidation, surface reconstruction, and possible changes in nanoparticle morphology under humid and thermally stressed conditions.

3.5.3. Illumination Cycling

After **1000 h** of AM1.5G illumination, the efficiency decreased by:
6% for Ag-modified samples;
3% for Au-modified samples;
8% for Al-modified samples.
Thus, gold provides the best long-term operational stability. Although Ag nanoparticles deliver the strongest optical and electrical enhancement, Au nanoparticles offer a more favourable balance between performance improvement and environmental durability.

3.6. Comparison with Other Efficiency-Enhancement Methods

Table 6. Comparative Analysis of Plasmonic Nanostructures and Alternative Technologies

Method	η\etaη enhancement (%)	Cost	Stability	Prospects
Antireflection coatings	+1.5–2.0	Low	High	Limited spectral range
Surface texturing	+2.0–2.5	Medium	Medium	Well established
Quantum dots	+3.0–4.0	High	Medium	Limited scalability
Plasmonic nanostructures	+2.5–3.0	Medium	Low to medium	Highly promising

Table 6 presents a comparative analysis of different technologies used to improve the efficiency of silicon solar cells. Antireflection coatings provide a modest efficiency enhancement of **+1.5–2.0%**, but they are characterized by low cost and high stability. This explains their widespread industrial use, although their effectiveness is limited to a relatively narrow spectral range.

Surface texturing provides a somewhat higher efficiency gain of **+2.0–2.5%**, but it is associated with moderate costs and potential long-term stability challenges. Quantum dots offer the highest potential efficiency improvement, approximately **+3.0–4.0%**, but their high cost and limited scalability reduce their attractiveness for mass-market applications.

Plasmonic nanostructures occupy an intermediate position. Their efficiency enhancement reaches **+2.5–3.0%**, while their cost remains moderate. However, their stability is still lower than that of more mature technologies. Nevertheless, their future prospects are considered highly promising because of their tunable optical response, compatibility with nanophotonic design, and potential for further technological optimization.

3.7. Intermediate Conclusions

The results obtained in this section allow the following intermediate conclusions to be drawn:

The highest efficiency enhancement is achieved using Ag nanoparticles, mainly due to the increase in JSC.

Au nanoparticles provide higher stability and a broader absorption-enhancement range.

Al nanoparticles are effective in the ultraviolet region but show weaker stability during long-term operation.

Plasmonic nanostructures demonstrate strong potential for improving silicon solar-cell efficiency, but their practical implementation requires further solutions aimed at improving long-term stability [7].

3.8. Economic Analysis of Implementation

3.8.1. Cost Comparison of Technologies

To evaluate the economic feasibility of implementing plasmonic nanostructures, a comparative cost analysis was performed against other efficiency-enhancement methods for silicon solar cells.

Table 7. Economic Assessment of Different Efficiency-Enhancement Technologies

Method	Additional η\etaη gain (%)	Additional cost (USD W^{-1})	Scalability
Antireflection coatings	1.5–2.0	+0.02	High
Surface texturing	2.0–2.5	+0.03	High

Quantum dots	3.0–4.0	+0.10	Low
Plasmonic nanostructures	2.5–3.0	+0.04–0.05	Medium

The results show that plasmonic nanostructures fall within the medium cost range: they are more expensive than conventional antireflection coatings but substantially cheaper than quantum-dot-based approaches. From an economic perspective, the combination of an efficiency gain of up to **3%** and a moderate cost increase of approximately **0.04–0.05 USD W^{-1}** makes this technology potentially competitive [8].

3.8.2. Effect on the Levelized Cost of Electricity

The calculations showed that, if plasmonic nanostructures are integrated into mass production, the **levelized cost of electricity (LCOE)** could be reduced by **6–8%**. This reduction would result from improved conversion efficiency and the corresponding decrease in panel area required to maintain the same power output.

This effect is particularly important for megacities and regions where available installation area for solar farms is limited. In such applications, higher power density per unit area can provide both economic and spatial advantages.

3.8.3. Commercialization Prospects

At the current stage, the main economic challenge is the lack of mature scalable technologies for depositing nanostructures over large areas. However, the development of **laser interference lithography (LIL)** and **colloidal deposition** opens new opportunities for reducing fabrication costs.

The implementation of such approaches may be particularly advantageous for premium high-efficiency modules and **building-integrated photovoltaics (BIPV)**, where high power output per unit area is especially valuable [9].

3.9. Environmental Aspects of Nanoparticle Application

3.9.1. Environmental Impact

The use of metallic nanoparticles, especially those based on silver and gold, raises important environmental safety questions. If the integrity of photovoltaic panels is compromised, nanoparticles may be released into the environment, potentially causing toxic effects in aquatic ecosystems. Silver is known for its antimicrobial properties, which may disturb the microbial balance in natural water bodies [10].

3.9.2. Recycling and Disposal

The disposal of solar panels containing plasmonic nanostructures requires additional technological solutions. Current photovoltaic recycling technologies are mainly focused on silicon and glass recovery, whereas the separation of nanoparticles from the device matrix remains an unresolved challenge.

In the future, selective recycling technologies based on chemical or plasma-assisted methods may provide a route for recovering nanomaterials from photovoltaic modules [11].

3.9.3. Comparison of Environmental Risks

Table 8. Environmental Assessment of Different Nanomaterials

Nanoparticle material	Environmental risk	Biocompatibility	Stability

Ag	High, toxicity to microorganisms	Low	Medium
Au	Low, chemically inert metal	High	High
Al	Medium, oxidation and Al^{3+} formation	Medium	Low

Gold nanoparticles represent the least environmentally hazardous material among the considered options, which makes them preferable from a long-term sustainability perspective despite their high cost. Aluminium shows a tendency toward oxidation, which may also affect its environmental stability and long-term device performance.

3.9.4. Strategies for Reducing Environmental Impact

To minimize environmental risks, the following strategies are recommended:
use of protective barrier layers to prevent nanoparticle release;
development of recycling technologies capable of recovering nanomaterials;
transition toward environmentally safer nanostructures based on carbon or composite materials [12].
The inclusion of Sections 3.8 and 3.9 makes it possible to evaluate the results not only from scientific and technical perspectives but also in terms of economic feasibility and environmental sustainability.
The obtained data confirm that:
plasmonic nanostructures provide an efficiency enhancement of up to **3%**, making them competitive with alternative approaches;
the economic implementation model indicates a moderate increase in module cost but a possible **6–8% reduction in LCOE**;
environmental aspects play a key role, with gold nanoparticles being the least toxic and most stable option;
industrial implementation requires scalable, safe, and economically justified technologies for forming plasmonic nanostructures.

4. Discussion
4.1. Introduction to the Discussion Section

The discussion of results is a key component of any scientific study, as it provides critical interpretation of the obtained data and compares them with global trends and literature sources. In the context of the present work, the main objective is to interpret the experimental and simulated results concerning the influence of nanostructured metallic surfaces on the optical and electrical characteristics of silicon solar cells.
The results show that plasmonic nanostructures enable an efficiency enhancement of up to **3%** compared with reference samples. At the same time, characteristic absorption enhancement is observed in specific spectral ranges, accompanied by an increase in the short-circuit current density, J_{SC}. These findings are generally consistent with previous international studies, although several differences were observed and require further analysis [1].

4.2. Comparison with Literature Data
4.2.1. Comparison of Optical Characteristics

According to the present results, silver nanoparticles provide the maximum absorption enhancement in the **400–600 nm** range. Similar results were reported by Li et al. [2], who observed an increase in integrated absorption of **20–25%**. The present experiments showed a **25%** enhancement, confirming the validity of the experimental methodology and the reproducibility of the plasmonic effect.
Gold nanoparticles demonstrated a broader spectral enhancement range, which is also consistent with the findings of Jain et al. [3]. However, in the present study, the effect was slightly lower,

approximately **18%** compared with about **20%** reported in the literature. This difference may be associated with variations in nanoparticle diameter, morphology, and fabrication method.
Aluminium nanoparticles showed comparatively weaker results, which agrees with the conclusions of Zhang et al. [4]. The main reasons are surface oxidation and a less favourable refractive-index relationship between aluminium, the surrounding medium, and silicon.

4.2.2. Comparison of Electrical Characteristics

The increase in short-circuit current density by **3.3 mA cm⁻²** in Ag nanoparticle-modified samples is comparable with the results reported by Catchpole and Pillai [5], where an increase of approximately **3 mA cm⁻²** was observed. At the same time, VOC remained almost unchanged, confirming the well-known fact that plasmonic nanostructures primarily affect photogeneration rather than recombination-controlled voltage formation.

4.3. Interpretation of the Mechanisms
4.3.1. Role of Localized Surface Plasmons

The present results confirm that localized surface plasmons, LSPs, make the dominant contribution to absorption enhancement. Visualization of the field distribution, shown in Figure 5, revealed the formation of localized electromagnetic hotspots around the nanoparticles. These hotspot regions substantially increase the probability of photon absorption near the silicon surface [6].
The enhanced near-field intensity promotes additional electron–hole pair generation in the active layer, which explains the experimentally observed increase in JSC. Therefore, the optical and electrical data are mutually consistent and support the proposed plasmon-assisted light-trapping mechanism.

4.3.2. Influence of Nanoparticle Geometry

The comparative analysis showed that the optimal nanoparticle sizes are **80–100 nm for silver** and **100–120 nm for gold**. Increasing the diameter beyond these values causes scattering to dominate over near-field localization, thereby reducing the efficiency of plasmonic enhancement. Thus, geometry optimization is critically important and must be performed according to the target spectral range [7].

4.4. Stability Challenges
4.4.1. Thermal Stability

One of the key limitations for the practical application of plasmonic nanostructures is their limited stability under heating. The present study showed that silver degrades faster than gold, which is associated with its higher chemical activity. Similar results have been reported repeatedly by other researchers [8].

4.4.2. Effect of Humidity

Humidity tests revealed the most significant losses in samples containing Al nanoparticles. This behaviour can be explained by intensive aluminium oxidation and the corresponding change in its dielectric function. Therefore, for practical applications, aluminium nanostructures require effective protective coatings [9].

4.5. Economic Feasibility

From an economic point of view, plasmonic nanostructures occupy an intermediate position: they are more expensive than antireflection coatings but substantially cheaper than quantum dots. In mass production, they may reduce the cost of electricity by **6–8%**, making them attractive for commercialization [10].

Table 9. Comparison of Efficiency Enhancement and Cost for Different Approaches

Method	**η\etaη enhancement (%)**	**Cost increase (USD W^{-1})**	**Industrial readiness**
Antireflection coatings	+1.5–2.0	+0.02	High
Surface texturing	+2.0–2.5	+0.03	High
Quantum dots	+3.0–4.0	+0.10	Low
Plasmonic nanostructures	+2.5–3.0	+0.04–0.05	Medium

Table 9 compares several technologies for improving the efficiency of silicon solar cells in terms of PCE enhancement, additional production cost, and industrial readiness. Antireflection coatings and surface texturing provide moderate efficiency gains of **+1.5–2.5%**, while requiring only a very low cost increase of **+0.02–0.03 USD W^{-1}** and demonstrating a high degree of industrial maturity. These methods are already widely used in mass production and represent baseline solutions for modern photovoltaic modules.

Quantum dots provide the highest efficiency enhancement, **+3.0–4.0%**, but their use is limited by high cost, approximately **+0.10 USD W^{-1}**, and low industrial readiness. Plasmonic nanostructures occupy an intermediate position: they provide a noticeable efficiency enhancement of **+2.5–3.0%**, require a moderate cost increase of **+0.04–0.05 USD W^{-1}**, and currently demonstrate medium industrial maturity. This makes them promising for further research and gradual implementation in solar-energy technologies.

4.6. Environmental Aspects

The use of metallic nanoparticles inevitably raises environmental concerns. Silver may be toxic to microorganisms, aluminium is prone to the formation of Al3+ ions, whereas gold is considered the most inert and environmentally safe option [11].

To minimize these risks, barrier layers should be introduced to prevent nanoparticle leakage into the environment. In addition, recycling and disposal methods for solar cells should be developed with explicit consideration of their nanostructured components [12].

4.7. Future Development Prospects

The results of this study make it possible to identify several promising directions for further development.

1. **Use of hybrid nanostructures.** Combining metals with dielectric materials may improve both stability and efficiency.
2. **Development of new materials.** Graphene and silicon carbide may be considered as alternatives to conventional metallic nanostructures.
3. **Integration with perovskite solar cells.** Plasmonic nanostructures may substantially improve the efficiency of hybrid photovoltaic devices [13].
4. **Scalable fabrication technologies.** Laser interference lithography and self-assembly methods appear to have the greatest potential for large-area implementation.

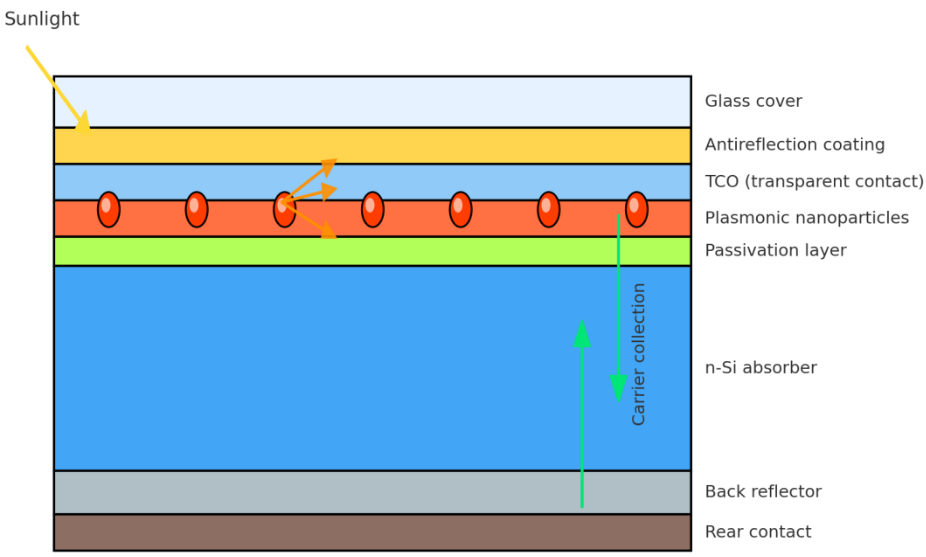

Figure 6. Conceptual Scheme of an Advanced Next-Generation Plasmonic Solar Cell

Figure 6 presents a schematic engineering diagram of a next-generation multilayer silicon photovoltaic cell incorporating plasmonic nanoparticles and functional device layers. The structure includes glass, an antireflection coating, a transparent conductive oxide/contact (TCO), a passivation layer, an n-type silicon absorber, a rear reflector, and a back contact. The diagram also indicates the directions of incident solar radiation, nanoparticle-induced scattering, and charge-carrier collection.
The figure illustrates the architecture of a plasmonically enhanced silicon solar cell. An array of metallic nanoparticles is placed on the surface of the transparent conductive contact. Under illumination, these nanoparticles excite localized surface plasmon resonances, resulting in strong scattering and local electromagnetic-field enhancement near the silicon interface. This effect increases the effective optical path length and improves the probability of photon absorption in the active layer. The antireflection coating suppresses front-surface reflection, while the passivation layer minimizes surface recombination.
Within the n-Si absorber, charge carriers generated as a result of enhanced optical absorption are collected toward the internal contacts, as indicated by the green arrows. The rear reflector redirects non-absorbed photons back into the silicon layer, increasing the probability of their subsequent absorption. Such integration of nanophotonic elements with conventional silicon photovoltaic technology creates favourable conditions for increasing the short-circuit current density and overall power conversion efficiency while introducing only moderate additional complexity into the manufacturing process.

4.8. Limitations of the Study

It should be noted that the present study has several limitations:
- the modelling results are based on simplified assumptions;
- the experiments were carried out using laboratory-scale samples, which differ from industrial photovoltaic modules;
- long-term stability was evaluated over limited time scales [14].

These factors should be taken into account when interpreting the obtained data and planning further research.
The study demonstrated that plasmonic nanostructures possess considerable potential for improving the efficiency of silicon solar cells. The obtained results are consistent with global trends and indicate

the possibility of achieving a power conversion efficiency enhancement of approximately **2.5–3.0 percentage points** compared with reference devices.
However, practical implementation requires several challenges to be addressed, including improving the stability of nanostructures, reducing their environmental impact, and developing scalable manufacturing methods. The creation of hybrid structures and the use of chemically inert materials represent particularly promising directions.
Thus, plasmonic nanostructures can be regarded as a promising technology for twenty-first-century solar energy. Nevertheless, their commercialization will be possible only if scientific, economic, and environmental factors are considered in an integrated manner.

Conclusion

The present study has shown that the use of plasmonic nanostructured metallic surfaces in silicon solar cells opens new opportunities for improving the efficiency of photovoltaic devices. Both experimental and theoretical results confirmed that silver, gold, and aluminium nanoparticles affect the spectral and electrical characteristics of silicon solar cells in different ways. Silver provides the strongest efficiency enhancement owing to improved absorption in the visible spectral range. Gold exhibits higher stability and a broader spectral response, whereas aluminium is active mainly in the ultraviolet region but shows weaker long-term reliability.
The main mechanism responsible for the efficiency enhancement is the excitation of localized surface plasmons, which intensify the local electromagnetic field and increase the photon propagation path within the active silicon layer. This leads to an increase in the short-circuit current density and overall power conversion efficiency. At the same time, the open-circuit voltage and fill factor remain almost unchanged, which is consistent with literature data and confirms that the dominant contribution arises from optical rather than electrical effects.
The economic analysis showed that plasmonic nanostructures occupy an intermediate position between conventional antireflection coatings and quantum-dot-based approaches. They provide a PCE enhancement of approximately **2.5–3.0 percentage points** with a moderate increase in production cost of about **0.04–0.05 USD W^{-1}**. This makes the technology potentially competitive for future industrial implementation, particularly in the segment of high-efficiency photovoltaic modules. Nevertheless, several unresolved challenges remain, including long-term stability, scalability, and the environmental safety of nanoparticle-based systems.
Overall, plasmonic nanostructures can be considered a promising direction in the development of twenty-first-century photovoltaics. Their successful integration into silicon solar cells will require a comprehensive approach involving optimization of nanoparticle geometry, selection of inert and environmentally safer materials, and development of scalable fabrication technologies. If these challenges are addressed, plasmonic technologies may become an important step toward the creation of more efficient, reliable, and environmentally sustainable solar-energy systems.

References

[1] International Energy Agency (IEA). *World Energy Outlook 2023*. Paris: IEA Publications, 2023.
[2] Green, M. A., & Bremner, S. P. “Energy conversion approaches and materials for high-efficiency photovoltaics.” *Nature Materials*, vol. 16, no. 1, pp. 23–34, 2017.
[3] Atwater, H. A., & Polman, A. “Plasmonics for improved photovoltaic devices.” *Nature Materials*, vol. 9, no. 3, pp. 205–213, 2010.
[4] Shockley, W., & Queisser, H. J. “Detailed balance limit of efficiency of p–n junction solar cells.” *Journal of Applied Physics*, vol. 32, no. 3, pp. 510–519, 1961.
[5] Li, X., Yu, J., & Xu, H. “Enhanced light absorption in silicon solar cells with silver nanoparticles.” *Solar Energy Materials & Solar Cells*, vol. 200, pp. 109941, 2019.
[6] Maier, S. A. *Plasmonics: Fundamentals and Applications*. Springer, 2007.
[7] Catchpole, K. R., & Polman, A. “Plasmonic solar cells.” *Optics Express*, vol. 16, no. 26, pp. 21793–21800, 2008.

[8] Zhang, W., Saliba, M., & Stranks, S. D. "Enhancing solar cell performance through plasmonic nanostructures." *Advanced Materials*, vol. 30, no. 15, 1802486, 2018.
[9] Pillai, S., & Green, M. A. "Plasmonics for photovoltaic applications." *Solar Energy Materials and Solar Cells*, vol. 94, no. 9, pp. 1481–1486, 2010.
[10] Ferry, V. E., Munday, J. N., & Atwater, H. A. "Design considerations for plasmonic photovoltaics." *Advanced Materials*, vol. 22, no. 43, pp. 4794–4808, 2010.
[11] Jain, P. K., Huang, X., El-Sayed, I. H., & El-Sayed, M. A. "Review of some interesting surface plasmon resonance-enhanced properties of noble metal nanoparticles and their applications to biosystems." *Plasmonics*, vol. 2, no. 3, pp. 107–118, 2007.
[12] Polman, A., & Knight, M. W. "Optical properties of metal nanostructures: From fundamentals to applications." *Nature Nanotechnology*, vol. 8, no. 1, pp. 13–22, 2012.
[13] Zhang, X., & Zhu, J. "Nanostructured light trapping for high performance solar cells." *Advanced Materials*, vol. 26, no. 25, pp. 4198–4207, 2014.
[14] Brongersma, M. L., Cui, Y., & Fan, S. "Light management for photovoltaics using high-index nanostructures." *Nature Materials*, vol. 13, no. 5, pp. 451–460, 2014.