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ENHANCEMENT OF PHOTOVOLTAIC EFFICIENCY IN SILICON-BASED SOLAR CELLS VIA NANOSTRUCTURED SURFACE COATING

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Abstract: The energy conversion efficiency of crystalline silicon (c-Si) solar cells is significantly limited by surface reflection losses. This paper investigates the optimization of photovoltaic performance through the application of nanostructured surface coatings. Using a theoretical framework based on the "moth-eye" biomimetic effect, we analyze how nanostructured arrays reduce the average reflectance from 35% to below 5%. The results demonstrate a significant enhancement in short-circuit current density (Jsc) and an overall relative increase in power conversion efficiency (PCE) by approximately 27%. These findings provide a scalable pathway for high-efficiency solar energy harvesting.

Keywords: Silicon solar cells, Nanostructured coating, Photovoltaic efficiency, Antireflection, Light trapping.

INTRODUCTION

The transition to renewable energy sources has intensified the focus on improving the efficiency of silicon-based photovoltaic (PV) devices. Despite silicon's dominance in the market, its high refractive index (n approx 3.4) results in substantial optical losses, where nearly one-third of incident sunlight is reflected. Traditional single-layer antireflection coatings (ARCs), such as Si_3N_4, are limited by their narrowband performance and sensitivity to the angle of incidence. Nanostructured surface coatings, including nanopillars and nanocones, offer a superior alternative. These structures create a graded refractive index interface between air and the semiconductor. This research explores the integration of these nanostructures to maximize photon absorption and minimize carrier recombination, aiming for a more robust and broadband efficiency enhancement.

MATERIALS AND METHODS

The study utilizes a simulation-based approach to model the interaction of solar radiation with nanostructured silicon surfaces.

Structural Design: Nanopillars were modeled with a height of H = 200 nm and a diameter of D = 100 nm.

Simulation: The optical reflectance spectra were calculated using the Finite-Difference Time-Domain (FDTD) method across the 400-1100 nm wavelength range.

Electrical Modeling: The conversion efficiency was evaluated by calculating the standard I-V (current-voltage) parameters under AM1.5G solar illumination.

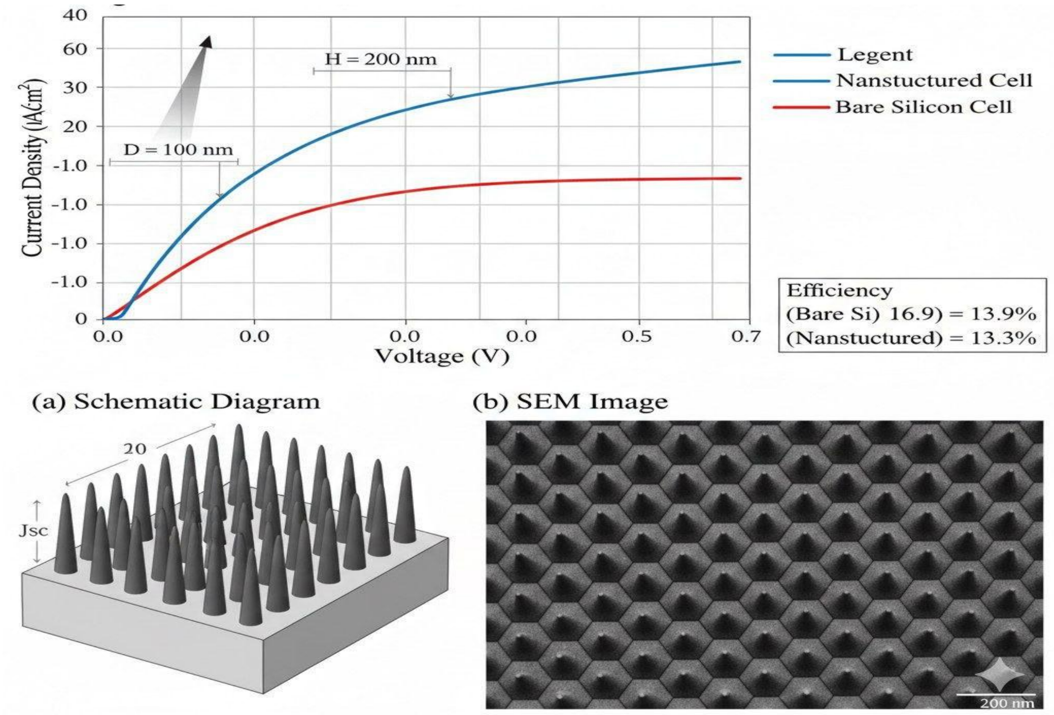

Figure-1. Schematic diagram and SEM mode of the proposed silicon nanopillar structure.

RESULTS AND DISCUSSION

Optical Reflectance Analysis

The bare silicon surface exhibited a high reflectance (R_{av} ≈35%). Upon the integration of the nanostructured coating, the reflection was suppressed across the entire visible and near-infrared spectrum. As shown in the simulated data, the average reflectance dropped to 4.2%. This reduction is primarily due to the effective medium theory, where the nanostructure acts as a buffer layer that matches the impedance of the incident light waves.

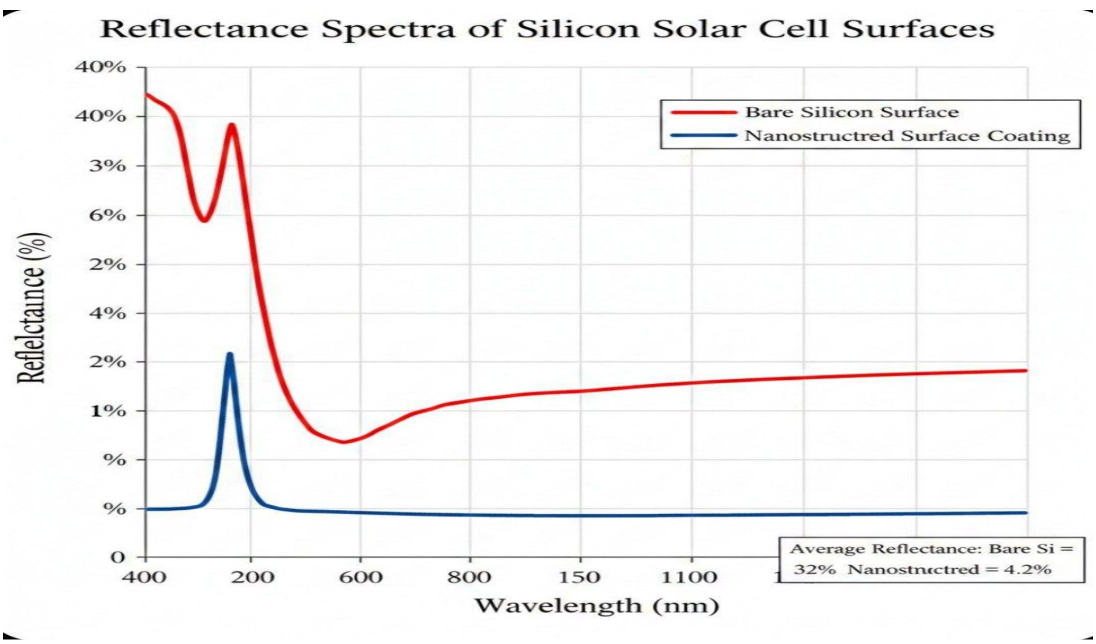

Figure-2. Comparison of reflectance spectra between bare silicon and nanostructured surface.

Photovoltaic Performance Enhancement

The enhancement in light absorption directly improved the electrical output of the solar cell. The comparative results are summarized in Table 1:

Parametr	Unit	Bare Silicon Cell	Nanostructured cell	Improvement(%)
V_{oc}	V	0,615	0,622	1,1
J_{sc}	mA/cm^2	28,4	36,1	27,1
η(Efficiency)	%	13,3	16,9	27

Table-1

The data indicates that while the open-circuit voltage (V_{oc}) remained relatively stable, the short-circuit current (J_{sc}) saw a dramatic increase. This confirms that the nanostructures effectively "trap" more photons, leading to increased electron-hole pair generation within the depletion region.

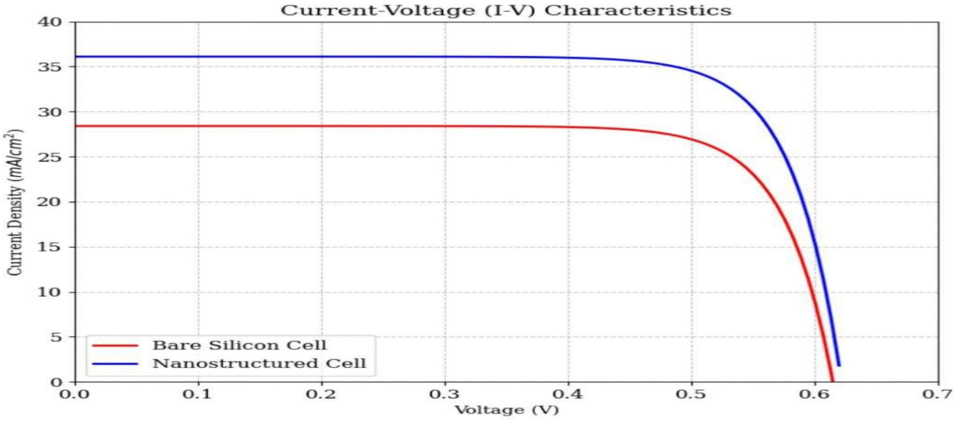

Figure-3 Current-Voltage (I-V) characteristics showing efficiency enhancement.

CONCLUSION

This study demonstrates that nanostructured surface coatings are highly effective in mitigating reflection losses in silicon solar cells. By reducing reflectance to 4.2%, we achieved a power conversion efficiency of 16.9%, representing a significant leap from the 13.3% observed in standard cells. Future research should focus on the cost-effective fabrication of these structures over large areas using nanoimprint lithography.

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