A review on efficiency enhancement of Silicon solar cells using nanomaterials

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Abstract

Nanotechnology offers promising solutions to overcome current efficiency challenges of solar energy devices and significantly enhances both the generation and storage capabilities. Utilizing nanotechnology in solar cells has paved the way for the creation of advanced, high-performance products. In this article, we review advancements made in the application of some nanomaterials to enhance the performance of Si solar cells. Innovations in light trapping, surface passivation, and charge carrier dynamics are discussed, alongside breakthroughs in the fabrication of nanostructured Si solar cells.

Graphical Abstract
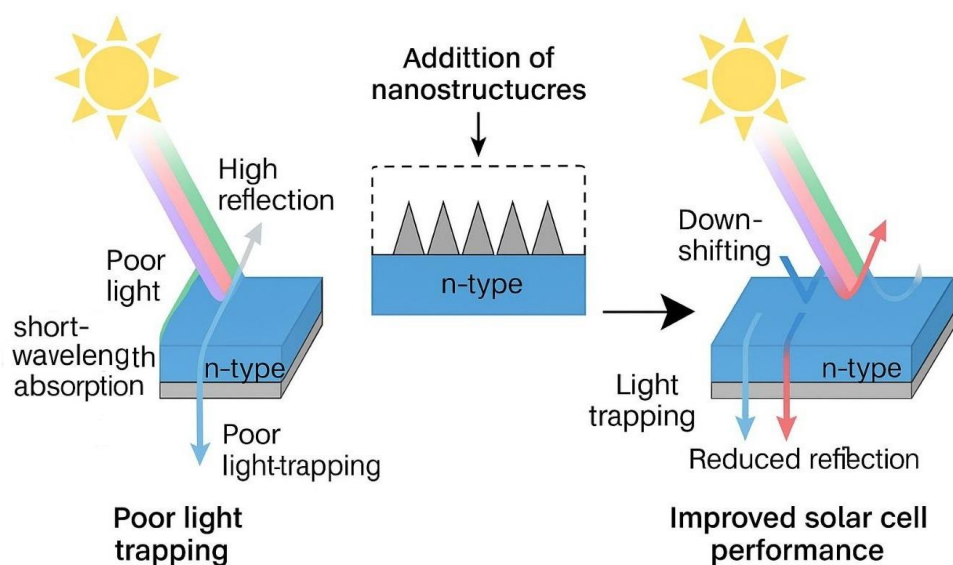
1. Introduction

Silicon-based solar cells currently dominate the photovoltaic market due to the abundance of raw materials, mature manufacturing techniques, and relatively high efficiency[1-3]. Further improvements in efficiency and cost reduction are required in order to meet the ever-growing energy demand. Nanotechnology offers transformative solutions to key challenges like reflection losses, recombination rates, and suboptimal light absorption[4, 5]. Innovations such as nanowires, quantum dots, and plasmonic nanoparticles enable precise tuning of optical and electrical properties, unlocking new potential for solar technology[6]. Nanomaterials—ranging from 1nm to 100nm in size-exhibit unique advantages due to their high surface-to-volume ratios and quantum properties[4, 7]. These materials enable the modification of optical and intrinsic characteristics, making them suitable for improving solar cell performance. For example, transparent nanomaterial coatings on solar cell components can enhance light absorption and energy conversion [8-17].

1.1 Benefits of Using Nanostructures

1. **Antireflective Coatings**: Biomimetic nanostructured coatings effectively minimize reflection across a broad spectrum (**Fig. 1**), significantly reducing energy losses in the visible range (reduce reflection losses)[18, 19].

2. **Nanowire Arrays**: Vertical silicon nanowires, with their high aspect ratios, enhance light trapping and broadband absorption (Increase in light absorption)[19].
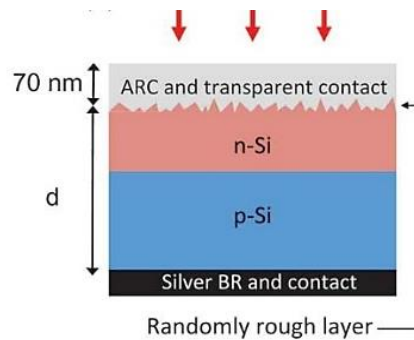

Fig. 1. Coating nanomaterials on Si solar cell as antireflective layer.

3. **The bridge effect:** Here, I, I_{ph}, I_S, V, V_T, and m denote the output current, light-generated current, saturation current, voltage across cell terminals, thermal voltage, and ideality factor, respectively.

$$I = I_{ph} - I_S.\left(e^{\frac{V+I.R_s}{m.V_T}} - 1\right) - \frac{V + I.R_s}{R_{sh}}.$$

(1)

Equation emphasizes that the output current is a function of R_s and R_{sh}[19-21]. As seen in **Fig. 2**, to obtain a large FF for an efficient power conversion, a very low series resistance (ideally zero) and a large shunt resistance (approaching infinity) are desirable. The bridging effect through NRs/nano-plates that gives rise to a sharp increase in conduction. The nanostructures generate excessive carriers and efficiently collect charge. As a consequence, the nanostructures negligibly influence the shunt resistance of the p–n junction, while simultaneously reducing the series resistance. Nano-structures and NRs decrease R_s due to the bridge effect [22].
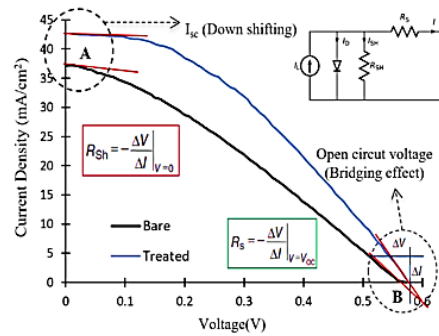
Fig. 2. Typical I-V characteristics of Si solar cell; R_s and R_{sh} for untreated and treated solar cell.

4. **Plasmonic Nanoparticles**: Metallic nanoparticles, such as gold and silver, leverage plasmonic effects to scatter incident light, increasing optical path length and absorption.

5. **Luminescent downshifting layer (LDSL):** which allows for conversion of high-energy photons, which are inefficiently utilized by the photovoltaic material, to photons with energy that can be efficiently converted to electricity [19, 23-25]. One possible strategy for further efficiency improvements is to optimize the response of the photoactive materials at shorter wavelengths (blue and UV), as illustrated in **Fig. 3**. In the most straightforward practice, an LDSL can be conveniently deposited on top of the existing photovoltaic material layer so that no adjustment in the overall architecture and the already optimized electrical properties is required.
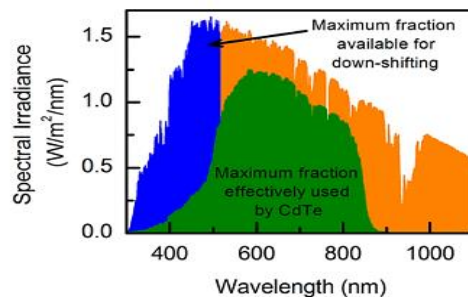

Fig. 3. Global solar spectrum at air mas 1.5, The spectral region that can be utilized through down-shifting process.

In recent years, several classes luminescent materials capable [23, 26-30] of converting a broad incident solar spectrum into photons of a narrower, longer wavelength band, such as organic dyes and lanthanide-based luminophores and colloidal semiconductor quantum dots (QDs), have been considered for LDSLs, alongside yet another related solar concentrator technology. As compared with organic dyes and lanthanide-doped phosphors, QDs have a number of attractive optical properties: (i) an absorption that gradually increases toward shorter wavelengths (below the first absorption band) and a narrow emission band; (ii) the spectral positions of both absorption and emission are easily tunable by particle size and shape due to the quantum confinement effect; (iii) the size-dependent molar absorption coefficients at the first absorption band of QDs generally exceed those of organic dyes by one to two orders of magnitude, which is combined with their superior photostability; (iv) photoluminescence quantum yields (PLQYs) of properly surface-passivated QDs can reach 80−90% in the visible and near-infrared spectral ranges[23, 26-33]. Now, we discuss the types of nanostructures effective in improving the performance of solar cells and the mechanism of their influence.

2. Nanostructures

2.1. ZnO

Nano-sized ZnO has been of the greatest interest in recent years because of its fascinating, unique properties and potential in practical aspects of solar cells. Significant characteristics include high abundance, nontoxic nature, excellent electrical conductivity, good chemical stability, large bandgap, and high refractive index[34-39]. ZnO nano-rods (NRs) have already been extensively investigated as photoelectrodes in organic, amorphous, and dye-sensitized solar cells[40-43]. ZnO is efficiently utilized as an antireflective coating to suppress spectral reflectance and light scattering events into the surroundings [40, 44-50].

Nowak R-E et al. [40] demonstrate that the nanorod arrays can act as efficient light trapping structures, additional to their antireflective behavior. They show that the transmission haze strongly depends on the array geometry and that for certain array shapes, scattering properties superior to those of standard commercial light trapping substrates can be achieved. SEM images, showing the morphologies of the nanorod arrays NR1–NR4, are displayed in **Fig. 4**[40].
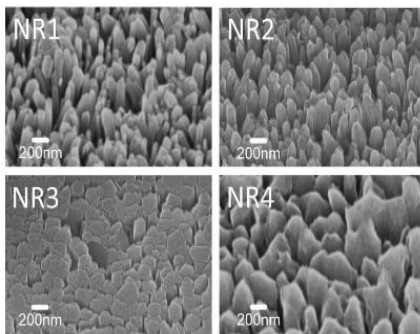

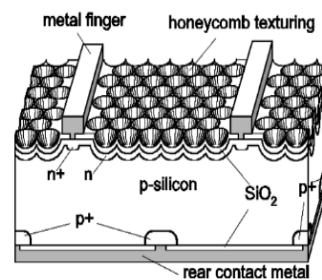**Fig. 4.** SEM images of nanorods arrays.

Fig. 5. Schematic of multicrystalline Si soalr cell with honeycomb surface texturing.

Zhao et al. [46] improved multi-crystalline cell performance results from enshrouding cell surfaces in thermally grown oxide to reduce their detrimental electronic activity and from isotropic etching to form an hexagonally symmetric ''honeycomb'' surface texture(**Fig. 5**). A new "honeycomb" surface texturing method was applied to multi-crystalline silicon, enhancing light absorption and minimizing reflection [46]. *Lee et al.*[44] investigates the use of ZnO nanostructures as antireflection coatings (ARCs) for silicon solar cells as illustrated in **Fig. 6**. Tapered ZnO NRAs showed a broadband suppression of reflectance, achieving a weighted global reflectance (Rw) of 6.6%, better than an optimized SiN ARC (Rw of 7.8%).
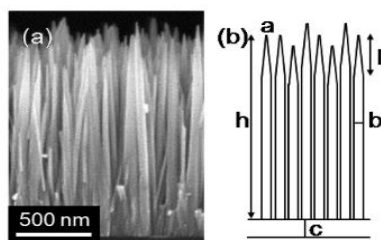

Fig. 6. Example of ZnO NR, Cross section SSEM image of a highly tapered ZnO NRA.
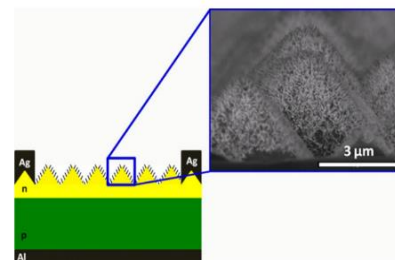

Fig. 7. Schematic of the fabricated Si solar cell with an Sem image of ZnO nanorod.

Aurang et al. [51] used ZnO nanorods as antireflection coatings (ARCs) for industrial-scale single-crystalline silicon solar cells to reduce reflection losses and improve photovoltaic efficiency by applying ZnO nanorods on industrial-scale silicon wafers (**Fig. 7**). ZnO nanorods reduced reflectivity significantly; reflectivity decreased from 35.2% to 9.6%. *Zezeng Feng et al*. [52] combined ZnO NRs with silicon (Si) nanostructures for solar cell application (**Fig. 8**). The improvement in the photovoltaic performance can benefit from the enlargement of the internal surface area for electrode contact and the higher efficiency in collecting photo-generated carriers.
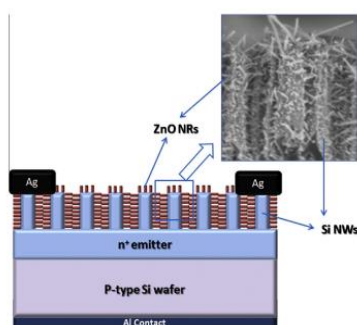

Fig. 8. schematic of the proposed Si nano-textured solar cell. The inset is the SEM image of ZnO NRs.
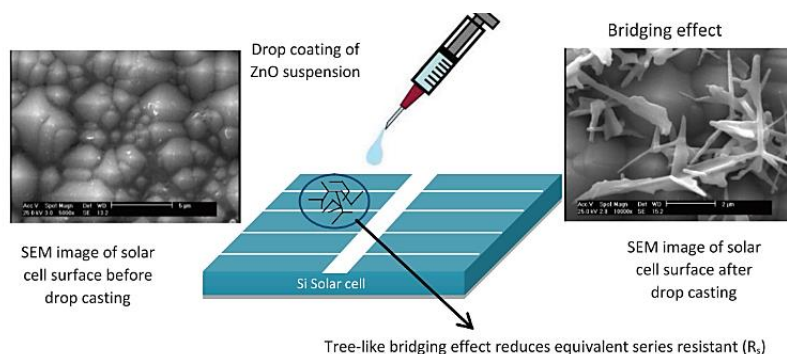

Fig. 9. Process of drop-casting, the left and right images display the SEM before and after drop-casting of the Si solar cell, respectively. The middle image illustrates a schematic drop-casting of ZnO suspension. Tree-like bridging of the nanostructures reduces Rs.

Our team investigates the enhancement of commercial multi-crystal silicon solar by ZnO as demonstrated in **Fig. 9** [19, 24]. The quality of ZnO nanostructures Photovoltaic characteristics based on the drop-casting on Si solar cells reveals three dominant factors, namely, the equivalent series resistance, decreasing reflectance, and downshifting, in order to scale up the absolute efficiency by 3% As a consequence, the oxygen vacancies in ZnO nanostructures give rise to the down-shifting and increase of free-carriers, leading to a reduction in the equivalent series resistance and an enlargement of fill factor. To obtain a larger I_{sc}, reduction of spectral reflectance is essential; however, the down-shifting process is shown to be dominant by lessening the surface electron-hole recombination rate over the UV–blue spectral range.[19]. Also, there are some works that use simulation methods to demonstrate the effectiveness of ZnO on silicon solar cells[53, 54].

2.2. CdSe

Among the colloidal II–VI semiconductors, CdSe QDs are the most extensively studied because of their controllable optical properties. The band gap of CdSe nanocrystals increases as their size decreases, due to the quantum confinement effect, and thus their emission shifts continuously from red (centered at 650 *nm*) to blue (centered at 450 *nm*). The optical gap of CdSe QDs can be tuned from deep red (~ 1.7 *eV*) to green (~ 2.4 *eV*) by reducing the dot diameter from 20 to 2 nm. Thus, tuning their size allows the tailoring of their optical properties, thereby making QDs a hopeful resource for developing various devices.[29, 55, 56]

As we investigated ZnO downshifting, CdSe QDs [25] were deposited on Si solar cells by the drop casting method to enhance photovoltaic efficiency. In general, the frequency conversion to the longer wavelengths certainly improves the performance of solar cells. It is noteworthy that maximum photon absorption of Si solar cell takes place at the green region wavelength, and so this down-shifting can promote the amount of incident "useful" photons, which could enhance the solar cell's performance. CdSe has the most impact on the efficiency of solar cells, which could increase the output of solar cells by about 2.48%. The mechanism responsible is based on the down-shifting phenomenon. *Kalytchuk et al*. [56] also used the

downshifting of Cds to improve Crystalline silicon and CdTe photovoltaics are leading solar technologies with high efficiencies. CdTe/CdS solar cells lose energy from UV photons absorbed in the CdS layer. LDSL can be easily added to existing solar cell structures without major changes. *Nguyen et al.* [30] demonstrate that the assistive plasmonic of metal nanoparticles (MNPs) integrating with the downshifting on luminescent materials attracts much attention. CdSe/ZnS quantum dots (QDs) with different gold nanoparticles (Au NPs) sizes were incorporated into a Si light-absorbing layer. This integration results in elevated EQE for the entire solar spectrum, on average of 10%. The increase in the solar cell parameters, including the J_{SC}, FF, and the efficiency enhancement (η), are achieved of 20%, 8%, and 28%, respectively.

2.3. CsGeBr$_3$

Among the various types of perovskites, cubic lattice structures (ABX$_3$) have excellent photoelectric properties, lower exciton binding energy, high optical absorption coefficients, and large dielectric constant[57]. *Soltani et al.* [58] investigate the effect of the CsGeBr$_3$ perovskite on the performance of Si solar cells as illustrated in **Fig. 10**, where the CsGeBr$_3$ is coated on the surface of the Si solar cells. While the efficiency of the bare solar cell before drop coating is 17.3%, the first step of drop-casting shows the highest enhancement in efficiency with respect to the bare cell, and it increases to 19.1%. Indeed, LSC effect of CsGeBr$_3$ perovskite nanostructure coated on the surface of cell improves QE related to shorter wavelengths in comparison with bare solar cell.
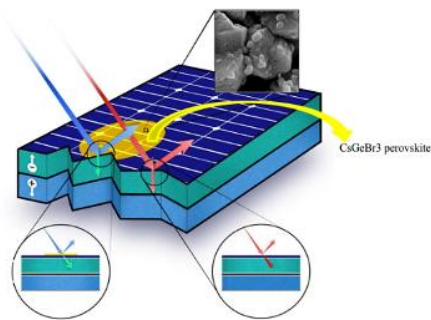

Fig. 10. Drop-casting schematic of the CsGeBr$_3$ suspension on the Silicon solar cell and SEM image of the CsGeBr$_3$ perovskite powder.
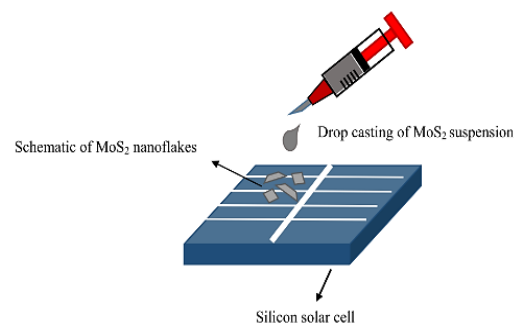

Fig. 11. Drop-casting schematic of MoS$_2$ suspension.

2.4. MoS$_2$

Molybdenum disulfide (MoS$_2$) and tungsten disulfide (WS$_2$) have semiconducting properties, as their band structure has drastically changed by reducing the number of layers. Bulk MoS$_2$ has an indirect band gap of about 1.2 *eV,* and the monolayer MoS$_2$ is a direct band gap semiconductor with the amount of 1.8 *eV*[59]. We investigate MoS$_2$ in the same way[60]. The schematic drop-casting of MoS$_2$ nanoflakes on the Si solar cell is shown in **Fig. 11.** The data taken shows a discrepancy of EQE at shorter wavelengths before and after drop-casting of the obtained nanoflakes. It is attributed to down-shifting phenomena and the decrease of the Si solar cell reflection in the presence of the MoS$_2$ nanoflakes[60].

2.5. TiO$_2$

Voarino et al. [61] studied UV filtering solutions in order to improve the thermos-optics properties of rigid but also of flexible solar panels. They focused on particles and more particularly on down-converters particles which can be incorporated into a silicone matrix. Two strategies are assessed: the first one uses UV absorbers (TiO$_2$) without light reemission, and the second one uses down-conversion phosphors. The transmission measurements associated with the estimation of the solar absorbance show that TiO$_2$ is a good candidate for absorbing associated with down-conversion phosphors.

2.6. SiO₂-ZrO₂

Trabelsi et al. [62] employed SiO₂ (Silicon dioxide), ZrO₂ (Zirconium dioxide), and SiO₂–ZrO₂ blends to apply a protective layer onto polycrystalline silicon solar cells using the sputter coating process. By mechanically blending SiO₂ and ZrO₂, a composite powder was generated. Powdered nanoparticles of SiO₂, ZrO₂, and SiO₂–ZrO₂ blends, known for their minimal resistivity and high transparency, were applied as coatings on silicon solar cell substrates to reduce surface light scattering. When compared to alternative solar cells, the solar cell coated with a combination of SiO₂ and ZrO₂ demonstrated uniform deposition and a low light reflectance of only 6 %. SiO₂ – ZrO₂ gains the highest power conversion efficiency (PCE) of 17.6 % under a controlled light source. Consequently, SiO₂–ZrO₂ blends emerged as superior anti-reflective materials for achieving peak performance[62].

2.7. NaY(WO₄)2: Er³⁺/Yb³⁺

Zhang et al. [11] used NaY(WO₄)2: Er³⁺/Yb³⁺ for enhancing silicon solar cells, A type of multifunctional erbium (Er³⁺) and ytterbium (Yb³⁺) codoped NaY(WO₄)2 phosphors, with simultaneous photon up-conversion, photon quantum cutting, and luminescence ratio metric temperature sensing abilities, have been developed. By converting multiple low-energy infrared photons into higher-energy photons, the energy absorbed by the solar cell increases the generation of electron-hole pairs (**Fig. 12**). This process improves the utilization of ultraviolet light and boosts overall power conversion efficiency. Predictions suggest efficiencies beyond the Shockley-Queisser limit. They exhibit high quantum cutting efficiency (173%) and effective up-conversion, making them ideal for enhancing Si solar cells without modifying their existing structures.
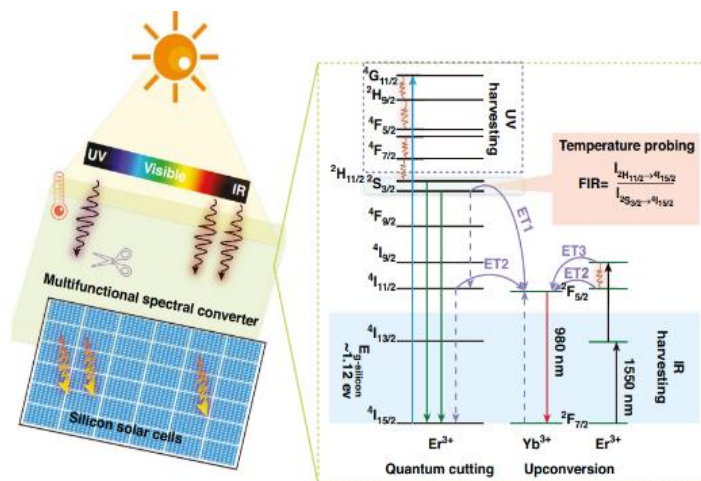

Fig. 12. A schematic illustration of multifunctional NaY(WO₄)2: Er³⁺/Yb³⁺ phosphors mounted on the front of silicon solar cells to enhance their performance.

2.8. TiO₂–Al₂O₃

Alkallas et al. [63] studied the improvement of performance in m-Si solar cells with the application of multiple-layer ARCs of TiO₂ and Al₂O₃. ARC materials such as Titanium dioxide (TiO₂), Aluminium oxide (Al₂O₃), and blended TiO₂– Al₂O₃ were utilized over the Si solar cells. The ARCs for the Si solar cell were coated using the RF sputtering method. The TiO₂– Al₂O₃ blend shows better performance than the other coatings. Solar cell demonstrated high power conversion efficiency (PCE) of 19.42 % and 20.16 %. The findings indicate that TiO₂–Al₂O₃ blends are a suitable material for ARC applications, since they effectively reduce the incident photons scattering [63].

3. Conclusion

The application of nanomaterials in silicon-based solar cells has demonstrated significant potential for improving efficiency through innovative mechanisms such as light trapping, surface passivation, and charge carrier management. Materials like ZnO, CdSe, MoS₂, TiO₂, SiO₂, ZrO₂, and others offer tailored enhancements, including antireflective properties, photon downshifting, and plasmonic effects. These advancements not only address the current limitations of silicon solar cells but also pave the way for next-generation photovoltaic technologies. Future research should focus on scalable fabrication methods and integrating these nanostructures into commercial solar cells to achieve widespread adoption and enhanced performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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