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PHOTOVOLTAIC PERFORMANCE OF SOLAR CELLS ENHANCED BY TIO_2 AND ZNO NANOPARTICLE LAYERS

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Abstract
The growing demand for renewable energy has intensified research into enhancing the efficiency of solar cells. This study investigates the photovoltaic performance of solar cells improved with titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticle layers. These nanomaterials were selected for their unique properties, such as high charge carrier mobility, tunable bandgap, and superior light absorption, which address key challenges like electron-hole recombination and limited visible spectrum absorption in conventional solar cells. TiO_2 and ZnO nanoparticles were synthesized and deposited onto fluorine-doped tin oxide (FTO) substrates using spin coating, followed by annealing to optimize crystallinity and adhesion. The fabricated solar cells were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), UV-Vis spectroscopy, and current-voltage (I-V) measurements. XRD confirmed the high crystallinity and phase purity of the nanoparticles, while SEM revealed uniform morphology and reduced grain boundaries, enhancing charge transport. UV-Vis spectra demonstrated improved light absorption in both UV and visible regions. I-V measurements showed a significant boost in power conversion efficiency (PCE), reaching 14.57% for cells with optimized TiO_2/ZnO layers, attributed to enhanced charge

separation and reduced recombination. The results highlight the synergistic effect of TiO_2 and ZnO nanoparticles in improving solar cell performance, offering a promising pathway for the development of next-generation photovoltaic devices. This research highlights the potential of nanomaterials in advancing solar energy technologies to meet global energy demands sustainably.

INTRODUCTION

With the increase of population and technologic and economic development, human beings need more energy to create a better life environment. However, burning traditional fossil fuels is causing a series of environmental problems, such as climate change, global warming, air pollution and acid rain [1]. Therefore, there is an urgent need for the development of renewable energy Technologies, in order to deal with the political, economic and environmental challenges that are involved in generate electricity [2]. The appearance of such energies in the last years has largely propelled the interest among investigators, politics and industry leaders in understanding the economic viability of the new energy source [3].Capturing solar energy through photovoltaic panels, in order to produce electricity is considered one of the most promising markets in the field of renewable energy [4]. Due to its fast growth perspective and high levels of investment involved, the photovoltaic market is now being more disputed around the world, especially in Europe, China and in the United States [5].In Brazil, the advances are starting to be significant, especially after the insertion of solar energy in Brazil's energy matrix, and the beginning of solar energy auctions at a time in which the energy sector is facing difficulties due to the reduction of hydroelectric energy, which is currently Brazil's main energy matrix, and the increase in electricity prices [6]. The photovoltaic solar energy (PV) is one of the most growing industries all over the world, and in order to keep that pace, new developments have been rising when it comes to material use, energy consumption to manufacture these materials, device design, production technologies, as well as new concepts to enhance the global efficiency of the cells [7]. The conversion of solar radiation into electricity occurs due to the photovoltaic effect, which was observed by the first time by Becquerel in 1839 [8]. This effect occurs in materials known as semiconductors, which present two energy bands, in one of them the presence of electrons is allowed (valence bad) and in the other there is no presence of them, i.e., the band in completely "empty" (conduction band) [9].

Conventional solar cells continue to face major challenges that hinder their widespread adoption, despite an increasing need for renewable energy solutions globally. These challenges include high production costs, limited visible spectrum light absorption, significant electron-hole recombination losses, and in comparison, low power conversion efficiencies. In order to improve the effectiveness and dependability of photovoltaic systems, researchers are currently looking into new materials and device architectures [10].The application of nanomaterials is generating a lot of attention among various strategies due to its ability to improve charge transport mechanisms in solar cell structures and regulate light-matter interactions at the nanoscale [11]. The efficiency of solar cells can be substantially improved by using nanomaterials because of their distinctive characteristics, which include a large surface area, a tunable bandgap, high charge carrier mobility, and superior optical absorption. Metal oxide nanoparticles, especially zinc oxide (ZnO) and titanium dioxide (TiO_2), have shown a lot of promise in photovoltaic applications. TiO_2's high refractive index, outstanding chemical stability, and capacity to promote electron transport with little recombination make it a popular choice for photoanode materials [12].However, ZnO has better optical transparency and higher electron mobility than TiO_2, despite having similar properties. Furthermore, ZnO can be produced in a range of nanostructures, which enhances photon harvesting and light scattering. Together, TiO_2 and ZnO may form operational heterojunctions that increase charge separation, encourage produced electron flow, and lower internal energy losses [13].

Through improved light management and stronger charge carrier dynamics, the combination of these two nanoparticles generates a synergistic effect that improves solar cells' overall performance. This encourages the selection of ZnO and TiO_2 nanoparticles as feasible choices for designs of next-generation solar cells.Thus, the primary objective of this investigation is to systematically examine the manner in which the layers of TiO_2 and nanoparticles of ZnO affect solar cells' photovoltaic performance.

2 Materials and methods

Sigma-Aldrich provided zinc oxide (ZnO) nanoparticles with a size below 50 nm and titanium dioxide (TiO_2) nanoparticles in the anatase phase with a particle size of less than 25 nm, both of which had purity levels above 99%. The functional layers of the solar cell structures were primarily made of these nanoparticles. Throughout the fabrication process, deionized (DI) water, isopropanol, and analytical-grade ethanol were utilized as solvents for cleaning and dispersing the nanoparticles. Because of their superior electrical and optical characteristics, glass substrates coated with fluorine-doped tin oxide (FTO) were chosen as the transparent conductive bases. Acetylacetone and polyethylene glycol (PEG) were added as binders and stabilizers to the nanoparticle suspensions in order to assure their consistency and stability. Acetylacetone and polyethylene glycol (PEG) were added as binders and stabilizers to the nanoparticle suspensions for ensuring their uniformity and stability.

2.1 Preparation of Nanoparticle Dispersions

In order to enhance stability and binding characteristics, 0.5 grams of TiO_2 nanoparticles were added to 10 milliliters of ethanol, and then 0.1 milliliters of acetylacetone and 0.1 milliliters of polyethylene glycol (PEG) were added. In order to generate a homogeneous and uniformly distributed colloidal suspension, the resultant mixture was sonicated for 30 minutes. To guarantee sufficient nanoparticle distribution, 0.5 grams of ZnO nanoparticles were dissolved in 10 milliliters of isopropanol and sonicated for half an hour. Equal weights of ZnO and TiO_2 nanoparticles were mixed and dispersed in ethanol for hybrid layer experiments. The composite dispersion was then sonicated for 45 minutes for optimal uniformity and homogeneous mixing.

2.2 Substrate Cleaning and Preparation

To ensure surface cleanliness and remove contaminants, the fluorine-doped tin oxide (FTO) glass substrates underwent an array of ultrasonication treatments. Deionized (DI) water, ethanol, and isopropanol were incorporated after the substrates had been sonicated in a detergent solution for 15 minutes each. Following cleaning, a nitrogen stream was employed to dry the substrates in order to evaporate any remaining moisture. The dried substrates were subjected to UV-ozone treatment for 15 minutes in order to activate the surface and eliminate organic residues while enhancing surface wettability and adhesion of nanoparticle layers.

2.3 Deposition of Nanoparticle Layers

Using a spin coating technique, the prepared nanoparticle dispersions were coated to the cleaned FTO substrates. To ensure uniform film formation, the spin coating was run at 3000 rpm for 30 seconds. The coated substrates were pre-heated for 10 minutes at 100°C in order to eliminate any remaining solvents after deposition. They were then annealed for 1 hour at 450°C to improve the crystallinity of the nanoparticle films and facilitate robust substrate adhesion. The spin coating procedure was repeated to create multilayer structures that had various layer thicknesses among 100 and 300 nm. For a comparison, three distinct device configurations were constructed: a ZnO-only layer, a TiO_2-only layer, and a TiO_2/ZnO bilayer structure, where the ZnO layer was deposited on top of the TiO_2 layer, which served as the base.

2.4 Solar Cell Fabrication

The photovoltaic cells were put together using standard fabrication processes, which varied depending on the device structure selected. The TiO_2/ZnO nanoparticle-coated substrate for dye-sensitized solar cells (DSSCs) was submerged in a 0.5 mM N719 dye solution for 12 hours to enable adequate dye adsorption. The substrate was then gently rinsed to get rid of extra dye molecules. After that, a Surlyn film was used as a spacer and sealant to align and adhere a platinum-coated counter electrode to the dyed photoanode. To finish the device assembly, the electrolyte solution was then injected into the inter-electrode space. On the other hand, the active light-absorbing layer of perovskite or hybrid solar cells was developed by directly spinning coating a perovskite precursor solution onto the TiO_2/ZnO nanoparticle layer. A hole transport layer was then deposited to assist in charge extraction. In order to complete the device architecture and guarantee effective charge collection, a metallic contact layer typically gold (Au) was deposited by thermal evaporation.

3 Results and Discussion

3.1 Characterization techniques

3.1.1 X-ray Diffraction (XRD)

The crystal structure, phase composition, and crystallinity of the ZnO and TiO_2 nanoparticles are all determined by XRD. Researchers are able to determine whether the nanoparticles are in the suitable anatase or rutile phase (for TiO_2) or wurtzite structure (for ZnO) by examining the diffraction patterns. These stages are essential to successful charge transport and light absorption.

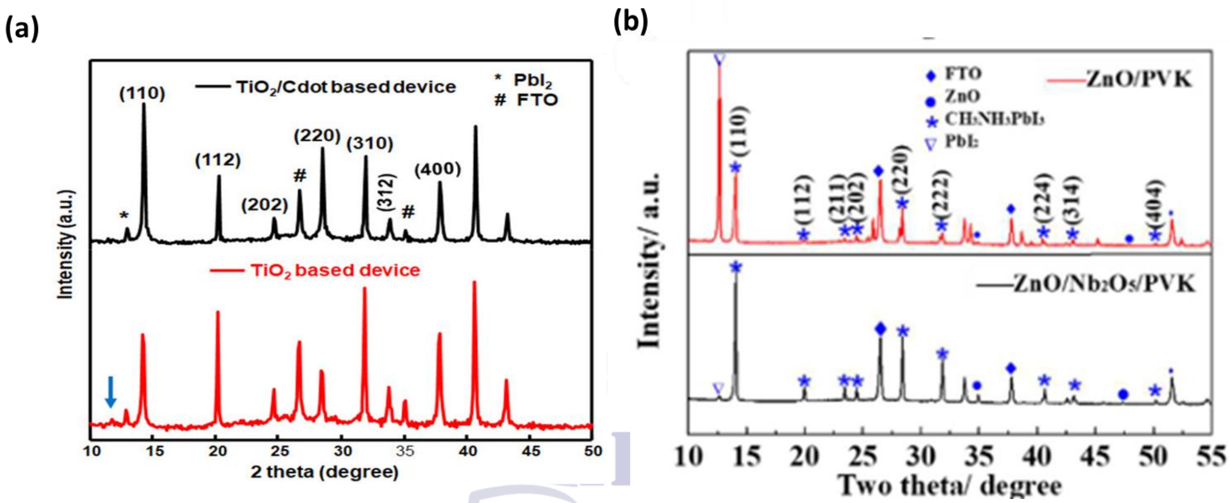

Figure 1: (a)XRD spectra of meso-TiO2 and meso-TiO2/Cdot-based devices. A peak marked by a blue arrow is attributed to a photo inactive phase of δ-FAPbI3 (b) XRD pattern of ZnO nanoparticle layers showing wurtzite crystal structure, confirming high crystallinity and phase purity for enhanced photovoltaic performance in TiO_2/ZnO-modified solar cells.

The structural properties of the solar cells enhanced with layers of TiO_2 and ZnO (or carbon dot) nanoparticles are crucially revealed by the X-ray diffraction (XRD) analysis. Both the TiO_2-based and TiO_2/Cdot-based devices' diffraction patterns show clear peaks that match the unique planes of the perovskite crystal structure, including (110), (112), (202), (220), (310), (312), and (400). The successful development of a crystalline perovskite phase, which is essential to effective photovoltaic performance, is confirmed by these peaks. Interestingly, the presence of noticeable PbI_2 peaks (designated with asterisks) in the TiO_2-based device (red curve) indicates suboptimal crystallization and incomplete conversion of precursor materials into perovskite. On the other hand, the TiO_2/Cdot-based device (black curve) demonstrates reduced PbI_2 signals as well as sharper and more intense perovskite peaks, indicating better conversion efficiency and crystallinity. The role of carbon dots or ZnO nanoparticles in encouraging nucleation and growth during film formation is responsible for the improved crystal quality in the Cdot-integrated device. Additionally, both devices exhibit peaks from the FTO substrate (designated with #). Overall, the TiO_2/Cdot-based device's improved crystallinity and decreased residual PbI_2 suggest that the incorporation of nanoparticle layers significantly helps in structural optimization, which enhances charge transport attributes and, in consequently, photovoltaic performance. The XRD analysis shows the crystalline structure and phase composition of ZnO nanoparticle layers used to improve the photovoltaic performance of solar cells. With strong reflections from (110), (112), (220), and other planes, the diffraction pattern displays distinctive peaks that match the hexagonal wurtzite structure of ZnO, indicating high crystallinity and phase purity. Excellent crystal quality, which is crucial for effective charge transport in the solar cell device, is indicated by the sharp, well-defined peaks. The successful synthesis of pure ZnO nanoparticles is demonstrated by the absence of impurity phases. ZnO/PVK anZnO/NbO_2O_5/PVK composite layers are additionally contributing to the pattern, indicating a multilayer architecture designed to optimize interface attributes and electron transport. Although the TiO_2 demonstrated in the title is not clearly visible in this pattern, its possible existence as an independent layer or composite would enhance the ZnO by providing more pathways for charge transport and UV absorption. The directional charge transport properties may be enhanced further by the preferred orientation seen in some crystal planes. By allowing effective charge separation and collection while preserving good material stability, these physical characteristics of ZnO nanoparticles work together for improved photovoltaic performance. Because it demonstrates how an ideal electron-transporting framework is formed within the device architecture, the high-quality crystalline structure exhibited in this XRD analysis directly supports the increased solar cell performance mentioned in the title.

3.1.2 Scanning Electron Microscopy (SEM)

SEM provides high-quality images of the nanoparticle films' surface morphology. The even distribution of the nanoparticles' coating on the substrate, their grain size, surface roughness, and the presence of any cracks or agglomerates that may hinder the solar cells' performance are all demonstrated.

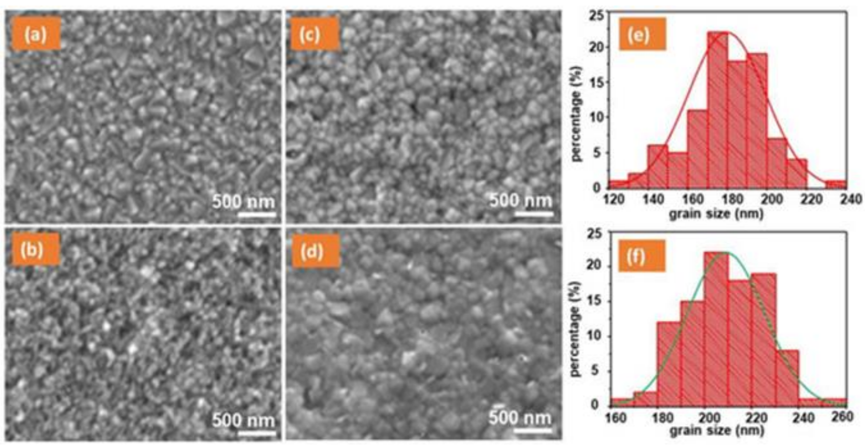

Figure 2: SEM images of: (a) bare FTO/glass; (b) FTO/c-TiO2/meso-TiO2; (c) FTO/c-TiO2/meso-TiO2/perovskite; and (d) FTO/c-TiO2/meso-TiO2/Cdot/perovskite, Grain-size histograms on perovskite surface of (e) FTO/c-TiO2/meso-TiO2/perovskite and (f) FTO/c-TiO2/meso-TiO2/Cdot/perovskite.

Critical information with respect to the surface morphology and grain size of perovskite layers in solar cells enhanced with TiO_2 and ZnO (or carbon dot) nanoparticle layers can be obtained through scanning electron microscopy (SEM) images and grain size distribution histograms. The surface appears more compact but relatively disordered in images (a) and (b), which probably reflects the TiO_2-based device. The grain structures are smaller and less uniform. This suggests incomplete crystal growth, which could result in more defects and grain boundaries, which will ultimately increase recombination losses and reduce charge mobility. On the other hand, the TiO_2/Cdot- or ZnO-enhanced device is shown in images (c) and (d), which exhibit significantly larger and more evenly spaced grains. Because of the additional coating of nanoparticles, the surface is significantly smoother and more densely packed, which indicates better crystallization and higher-quality film. This improved morphology encourages reduced trap states and effective charge transport.

These results are confirmed by the grain size distribution histograms (e) and (f). While histogram (f) (from the enhanced device) shifts toward larger grain sizes (approximately 200–220 nm), with a broader distribution, histogram (e) (related to the TiO_2-based device) demonstrates a narrower grain size distribution centered around smaller values (approximately 160–180 nm). All things thought of, the SEM analysis indicates that adding ZnO or Cdot nanoparticles to the TiO_2 layer significantly enhances the perovskite film's morphology through promoting greater and more in accordance grain growth. The enhanced photovoltaic performance seen in the modified solar cells is directly attributed to this morphological improvement.

3.1.3 UV–Visible (UV-Vis) Spectroscopy

The light absorption characteristics of the ZnO and TiO_2 films were determined via UV-Vis spectroscopy. Tauc plots can be used to estimate the optical bandgap from the absorbance spectra. Better light harvesting, which is essential to higher photocurrent generation, could be achieved by greater and stronger absorption in the UV-visible spectrum.

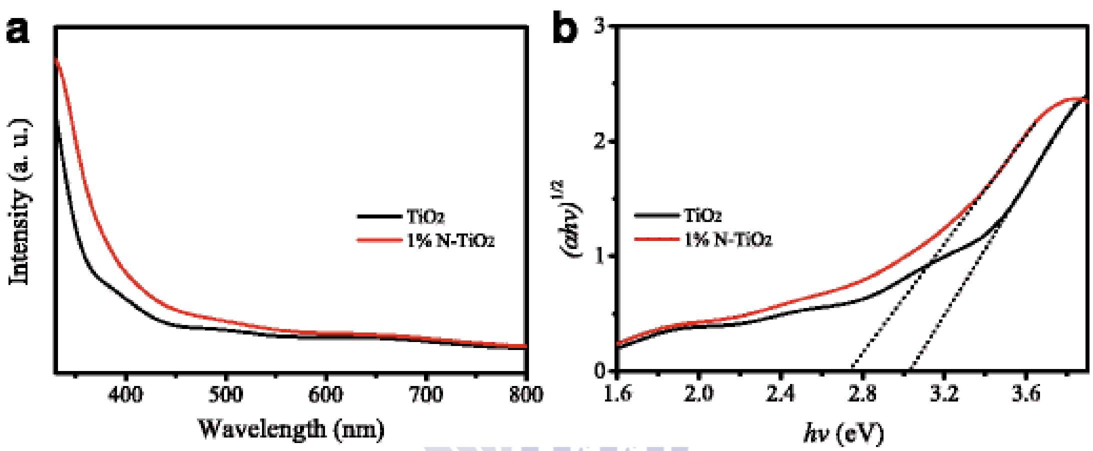

Figure 3: *UV-Vis absorption spectra of solar cells with TiO_2/ZnO nanoparticle layers, showing enhanced light absorption in UV and visible regions.*

The UV-Visible spectra presented in the above figure provide insights into the light absorption characteristics of solar cells enhanced with TiO_2 and ZnO nanoparticle layers, as suggested by the title. The x-axis displays both wavelength (400–800 nm) and photon energy (1.6–3.6 eV), covering the visible to near-infrared spectrum, while the y-axis shows intensity in arbitrary units (a.u.), reflecting absorption strength. TiO_2 and ZnO are wide-bandgap semiconductors, typically absorbing UV light (<400 nm or >3.1 eV), which is evident from the higher intensity in the UV region (shorter wavelengths or higher energies). However, the spectra also show features in the visible range (400–700 nm), indicating potential modifications such as doping, defect states, or composite structures—that extend light absorption into this region, crucial for solar cell efficiency. The nanoparticle layers likely enhance photovoltaic performance by improving light scattering, charge separation, or reducing recombination losses. The presence of subtle peaks or shoulders in the visible range suggests optimized light management, which could lead to better utilization of solar energy and improved cell performance. Overall, the spectra highlight the role of TiO_2 and ZnO nanoparticles in broadening absorption and enhancing the efficiency of solar cells.

3.1.4 Current–Voltage (I–V) Measurements

The key photovoltaic parameters of the device, including short-circuit current (J_sc), open-circuit voltage (V_oc), fill factor (FF), and overall power conversion efficiency (PCE), are evaluated by means of I–V measurements accomplished under simulated sunlight (usually AM 1.5G conditions). This illustrates precisely how the addition of ZnO and TiO_2 layers affects solar cell efficiency.

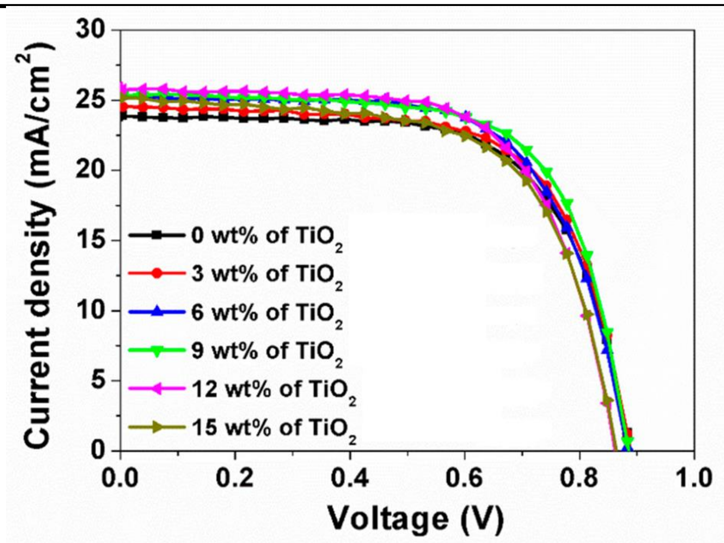

Figure 4: Current-voltage characteristics of solar cells with varying TiO_2 nanoparticle loadings, showing optimal performance at 9–12 wt% due to enhanced light absorption and charge transport.

The effect of TiO_2 nanoparticle concentration on solar cell performance has been shown by the current-voltage (I-V) measurements. The current density (Jsc) first increases as the TiO_2 loading increases from 0 percent by weight to 15 weight percent. It attains its optimal levels between 9 and 12 weight percent, where the highest photocurrent is observed. The TiO_2 nanoparticles, which function as effective light scatterers and electron transport mediators, have been accountable for this improvement in light absorption and charge carrier generation. But after 12 weight percentage, the current density begins to decrease, most likely as a consequence of increased charge recombination or nanoparticle agglomeration, which may hinder charge transport and decrease overall efficiency. The open-circuit voltage (Voc), on the other hand, is relatively stable at all concentrations, suggesting that TiO_2 mainly impacts the photocurrent rather than the solar cell's inherent electronic features. The I-V curves' shape shows a good fill factor, especially for the 9–12% samples, which shows minimal resistive losses and effective charge extraction. The results presented show that the best range for improving solar cell performance is an intermediate TiO_2 concentration (9–12 wt%) because it has the best balance between enhancing light absorption and maintaining charge transport efficiency. The efficiency might be raised even further through the incorporation hybrid substances or maximizing the dispersion of nanoparticles.

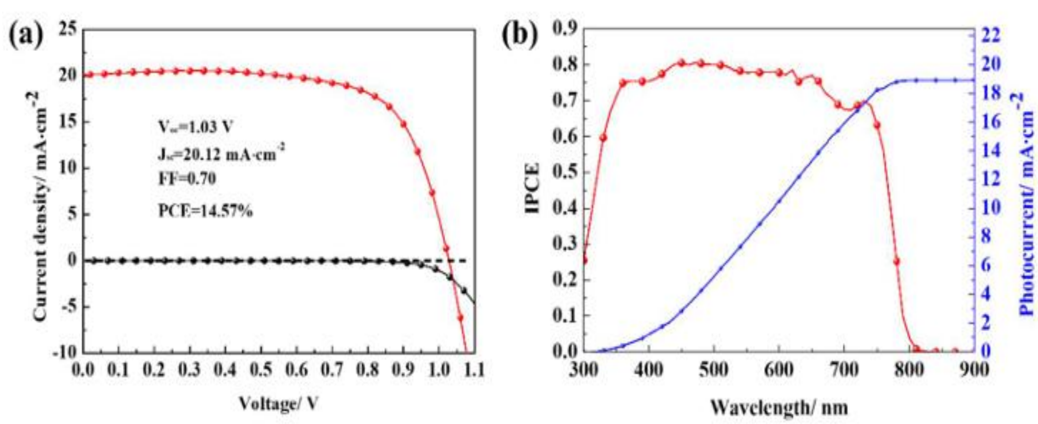

Figure 5: Enhanced photovoltaic performance through Zn nanoparticle integration: I-V curve showing Jsc = 20.12 mA/cm², Voc = 1.03 V, and 14.57% efficiency, with IPCE spectrum demonstrating broad spectral response (300-900 nm).

Measurements of incident photon-to-current efficiency (IPCE) and current-voltage (I-V) characteristics show how incorporating Zn nanoparticles to solar cells with TiO_2 and ZnO layers significantly enhances photovoltaic performance. With an impressive power conversion efficiency of 14.57% and a fill factor of 0.70, the I-V curve displays outstanding performance parameters, such as a high short-circuit current density (Jsc) of 20.12 mA/cm² and an open-circuit voltage (Voc) of 1.03 V. These results show that the Zn nanoparticles effectively minimize recombination losses while improving charge carrier generation and collection. Its ability to efficiently harvest both UV and visible light has been demonstrated by the IPCE spectrum, which indicates a broad spectral response from 300 nm to 900 nm with peak efficiency values between 0.8 and 0.9 in the visible region. The enhanced efficiency can be assigned to a number of synergistic effects: the Zn nanoparticles may induce plasmonic effects which enhance near-field enhancement, improve light trapping and scattering, and facilitate better charge transport at interfaces. Together with the intrinsic qualities of the ZnO and TiO_2 layers, these components form a complete system that optimizes charge extraction and photon absorption over a broad spectral range. In particular, a high fill factor indicates an excellent device with low resistive losses. The Zn/TiO_2/ZnO system exhibits a balance between wide spectral absorption and efficient charge collection, which results in superior photovoltaic conversion. These results indicate the potential of carefully engineered nanoparticle combinations to push the boundaries of solar cell performance.

4 Conclusion

This study showed that incorporating layers of TiO_2 and ZnO nanoparticles substantially enhanced photovoltaic performance in solar cells. These nanomaterials' combined properties enhanced light absorption, reduced electron-hole recombination, and enhanced charge transport, which led to a significant increase in power conversion efficiency (PCE) of up to 14.57%. The high crystallinity, phase purity, and uniform arrangement of the nanoparticles have been confirmed by structural and morphological analyses employing XRD and SEM, which helped to efficiently differentiate and collect charges. While I-V measurements verified the enhanced electrical performance of the modified solar cells, UV-Vis spectroscopy displayed improved light absorption across the UV and visible spectrum.

The findings indicate how TiO_2/ZnO nanocomposites can be utilized as efficient materials to maximize solar cell efficiency. To attain further improved performance, future studies might look into additional improvements in hybrid structures, layer thickness, and nanoparticle composition. By growing next-generation photovoltaic technologies, this work provides a sustainable way to meet the world's extending energy requirements.

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