A Comprehensive Review of Antireflection Coating Materials for Solar Cell Efficiency

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Abstract: The efficiency of solar photovoltaic systems is significantly impacted by reflection losses at the top of the solar cells. In order to lower these losses and increase the efficiency of solar cells in converting light into electricity, anti-reflection coatings are crucial. An extensive examination of the most recent advancements in anti-reflective (AR) coating technology designed specifically for solar cells is given in this research article. The paper covers the mechanical, optical, and chemical characteristics of a number of materials, including silicon dioxide (SiO_2), zinc oxide (ZnO), magnesium fluoride (MgF_2), and titanium dioxide (TiO_2). Also covers several nanocoating techniques in addition to single-layer and multi-layer coatings. Improved anti-reflective (AR) coatings are a result of developments in materials science and nanotechnology. Solar PV systems that have these coatings applied can function better and endure longer. This field also focuses on future research and development paths that could lead to more durable and efficient solar cells.

1 INTRODUCTION

Solar photovoltaic (PV), which harnesses energy from the sun, is more crucial in the modern day due to energy problems in many regions and the rapid depletion of fossil fuels. Currently, solar energy is harnessed using either photovoltaic (PV) or solar thermal technologies. Both approaches utilize protective glass to shield the solar cell from the harsh external climate, physical impacts, and other potential hazards [1]. The majority of solar PV equipment, whether it is first generating or second generation, employs borosilicate glasses as front glass. These glasses reflect approximately 9% of light because the discrepancy in refractive indices between the glass and air. The glasses utilized by lenses, lasers, and other optoelectronics equipment require exceptionally high transmission, as observed in various studies [2]. The number of silicon solar cells has been rising continuously since Bell Laboratories created the first silicon p-n junction solar cell ever [3]. Novel technologies were introduced in the 1990s and 2000s, including surface texturing, screen printing, passivated emitter and rear contact, and firing technology. These technologies were instrumental in lowering production costs and increasing cell efficiency, which in turn aided in the industrialization of silicon photovoltaics (PV). With a 90% global market share in photovoltaics, crystalline silicon solar cells, encompassing monocrystalline and polycrystalline technologies, are currently the most significant photovoltaic technology [4]. Thus far, silicon solar cells can be categorized as Si heterojunction solar cells or diffusion-based homojunction solar cells based on their respective device techniques. For PV production, homojunction c-Si solar cells are the most widely used variety at the moment. Passivated emitter and rear cells (PERC) and aluminium back surface field (Al-BSF) cells make up the majority of these cells; in 2019, they accounted for 40% and 50% of the market, respectively [5]. A solar cell's power conversion efficiency (PCE) can be increased, reflection loss can be decreased, and absorption can be increased by adding an anti-reflection (AR) coating. In order to lower the reflection loss, several researchers have applied single- and double-layer antireflection coatings on solar cells. AR coatings have been widely utilized to increase transmittance and decrease reflectance at the appropriate thickness. A decrease in reflectance results from an incongruity between the various layers caused by the AR coating's differing refractive index. Researchers have developed AR coatings using a range of different materials, and there are both expensive and low-cost methods for applying AR coatings [6]. Classifying solar panels based on cell types is necessary for looking into anti-reflection coatings. The coatings' physical characteristics must not change, and they must be oxidation- and corrosion-resistant. The ability of anti-reflective coatings to hold their stability across extended fluctuations in temperatures and a range of seasonal weather conditions is another characteristic that they have in common. The surface adhesion is another anticipated with this seasonal shift. The coatings used on the glass surface prioritize protection against seasonal conditions [7]. Almost all of the technology of the present period is mostly dependent on nanotechnology. The digital world that seeks to become more efficient and compact has found its definitive solution in nanotechnology. Synthetic nanoparticles are materials that can be engineered. In comparison to their counterparts on a larger scale, they exhibit superior conductivity, strength, and chemical reactivity [8]. One of the most important elements in the advancement of solar cell efficiency and many optical devices functioning in particular electromagnetic spectrum ranges particularly in the visible and infrared spectra is anti-reflection coating. The fact that the materials used to make solar cells have nanomaterials as their particle size plays a significant role in increasing the efficiency of solar cells. When a material's dimension falls inside the nanoscale dimension, its optical and electronic properties alter, allowing it to utilize more spectrum than just the electromagnetic one [9]. The superior surface-to-area ratio and physicochemical properties of nanoparticles and their associated materials offer various advantages for their application. Because of these characteristics, they are perfect for usage in industrial settings and can be coated as nanostructured layers on thin-film solar cells. The optical pathway for light absorption is the primary justification for the use of nanoparticles in appliances. This is significantly greater than the common materials with subpar reflections. However, because of their numerous reflections, photovoltaic cells are far more accessible to a wider range of applications [10].

In this paper, the latest applications of anti-reflective optical films in different types of solar cells are reviewed, and the experimental data are summarized. Important developments in ARC technology are examined, with a focus on a range of materials, including magnesium fluoride (MgF_2), zinc oxide (ZnO), titanium dioxide (TiO_2), and silicon dioxide (SiO_2). The study looks at single-layer and multi-layer coatings, focusing how nanotechnology can enhance the mechanical, optical, and chemical characteristics of these coatings. By greatly reducing reflection losses, nano-coatings showed promising results in improving solar cell performance. The study discusses the importance of ideal coating thickness and material stability in various environmental conditions. It emphasizes the need for self-cleaning coatings and stable ARCs for solar technology. Future research directions aim to improve solar PV systems' efficiency and shift towards sustainable energy sources. In summary, anti-reflective coating (ARC) suppresses surface light loss, thereby improving the power conversion efficiency (PCE) of solar cells, which is its basic function

2 ANTIREFLECTION COATING FOR SOLAR CELLS

In the manufacture of silicon photovoltaic cells, the reduction of reflection losses must be considered. These losses are estimated to be more than 30% on the surface of the silicon [11]. Appreciable improvements in the performance of the photovoltaic cell can be achieved by reducing these losses. The quality of anti-reflective coatings (ARC) is therefore an essential parameter for achieving high-efficiency solar cells. The basic optical theory of anti-reflective coating design commonly uses anti-reflective materials, and their classic combinations are introduced [12]. Therefore, the focus of current research is mainly on anti-reflection coatings with multi-material composition or the gradient refractive index (GRIN) structure that performs, resulting in a significant increase in adhesion and osmosis efficiency [13]. Where the operation of anti-reflective layers is based on the adaptation of the refractive index of the layer in such a way as to produce destructive interference at a certain wavelength, taking into account the thickness of the layer. The material used as an anti-reflective layer must be non-absorbent in the solar spectrum range [14].

In this context we review in detail the structures of AR coatings and their techniques in addition to the most common transparent conductive nanoparticle materials used recently for anti-reflective coating of solar cells, such as zinc oxide

(ZnO), Magnesium fluoride (MgF_2), titanium dioxide (TiO_2), etc.

2.1 Single-Layer Coating (SLARC)

At an interface when the two mediums have different refractive indices (n), light is reflected; the greater the difference, the greater the reflection. According to this rule, putting a layer of intermediate refractive index between the two media can help reduce reflection by minimizing the difference between them. This is the basic principle of single-layer anti-reflection coatings, which initially noticed by Lord Rayleigh and which can be proven by the following equation:

$$ni = \sqrt{n1n2} \tag{1}$$

$$di = \frac{\lambda}{4 \times ni} \tag{2}$$

where ni is the refractive index of ARC (the ideal refractive index RI), $n1$ and $n2$ are the refractive indices of the existing layers [15], and di is the ARC thickness. It should be mentioned that these equations only work with nonadsorbing, homogeneous media; otherwise, the loss of each medium will complicate the computation. The primary obstacle for single-layer quarter-wavelength ARCs is their disappearance at glazing incidence angles due to a loss in reflectivity for partial wavelengths and incidence angles. The different incident light optical path-lengths of the glazing incidence are the reason of this. And since the glazing incidence depends on the norm, the phase difference between the incident and reflected waves cancels each other out. Additionally, since low RI single-layer ARCs often have fewer RI substrates, it is challenging to locate any material in their clear surface as shown in Figure 1 (a) [13]. Khalaf A. M. and Obaid A. S. (2018) [9], the study focused on the impact of a single layer of anti-reflective coating (Ge) on the quantitative efficiency of a silicon solar cell. MATLAB programs were used to analyze the cell's efficiency within the 400-700 nm visible wavelength region. The results showed that applying an anti-reflective coating with adjusted particle size significantly at the specified design wavelength of 550 nm for vertical fall the maximum quantitative efficiency of 96.9004% was attained of silicon solar cells and the quantitative efficiency for horizontal polarization (P) was 96.3131%. However, the study had limitations, such as the observed increase in reflectivity and decrease in efficiency as the design wave length increased.

2.2 Multi-Layer Coating (MAR)

Multilayer anti-reflection (MAR) coatings solve the restrictions of single - layer AR coatings. The apply of multiple layers with high and low refractive index creates a coating that reduce the reflection across a wide wavelength range [15]. throughout suitable selection to the thickness of the layer and the materials type, and this could control the light interference by decreasing the losses of reflection [16].

The theory of the multi-layered antireflection coatings is the same as for the single-layer antireflection coatings, but the mathematical model employed in this case includes a vector analysis of the reflected individual rays. As shown in Figure 1 (b), the light reflected from the junction of the two layers, i and j (suppose there are no losses), is provided in (3) as follows:

$$Rij = |Rij|e^{[-2(\delta i+\delta ij)]} \tag{3}$$

where:

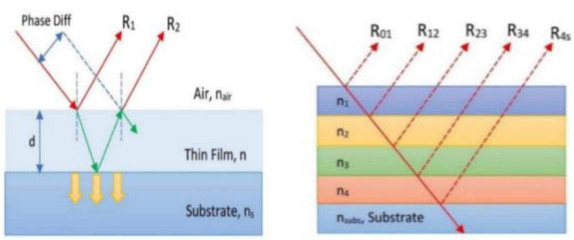
$$|Rmn| = \frac{(ni - nj)}{(ni + nj)}$$

and

$$\delta i = \frac{2\pi nidi\cos\theta i}{\lambda}$$

$di, \theta i$ and λ are the optical film thickness, the angle of refraction and wavelength of the light respectively. After that, reflectance at each layer's interface is integrated to determine the overall reflectivity ($Rsum$), which is written as:

$$Rsum = R01 + R12 + R23 + \cdots + Rns. \tag{4}$$



(a) (b)

Figure 1: Schematic illustration of diffusion of light in (a) single layer film (ns > n) and (b) multiple layer film [17].

In order to provide an antireflection effect, the index of refraction and optical film thickness can be suitably optimized to lower the $Rsum$ [18]. In 2023, Koysuren O. et al. [19], the study discussed the development of solar cell coatings that can self-clean themselves, reducing efficiency losses caused by contaminants. The SiO_2/WO_3 and $SiO_2/WO_3/ZnO$ composite coating was used to coat glass substrates, showing over 90% photocatalytic dye removal efficiency after 240 minutes of UVA light irradiation. The composite coating maintained the cell's efficiency nearly identical to untreated cells, with minimal effect on efficiency.

2.3 Gradient Refractive Index (GRIN) Coating

The GRIN coating is a unique non-uniform ARC that has a refractive index that gradually changes from the incident medium to the substrate in a vertical direction. It could be considered as a structure consist of a series of very thin films, which lead to broadening the antireflection bandwidth and angle. If each film thickness is much smaller than the reference wavelength, then the GRIN film could be considered as a continuously system without interfaces. For this cause, the light reflection that entering to the substrate from the incident medium is very small [20]. Lord Rayleigh has really theoretically verified the gradual transition problem, which states that the beam bends and the reflection reduces as the density in a variable medium change [18]. Various profiles of gradient refractive index layers have been proposed for omnidirectional and broadband anti-reflection coatings, which consist of linear, gaussian, parabolic, exponential, exponential-sine, quintic, cubic, and Klopfenstein [17].

The following lists typical expressions for the continuously changing RI with linear, cubic, and quintic profiles.

- Linear index profile:

$$n = ni + (ns - ni)t, \ 0 \le t \le 1; \quad (5)$$

- Cubic index profile:

$$n = ni + (ns - ni)(3t2 - 2t3); \quad (6)$$

- Quintic index profile:

$$n = ni + (ns - ni)t(10t3 - 15t4 - 6t5). \quad (7)$$

Where ni and ns are the refractive indices of the incident and substrate media, t is the thickness of gradient interface region, respectively. [18]. Adwan Y. M. et al (2023) [21], the study focused on the optical characteristics of a three-layer anti-reflective coating (TLAR) structure using graded refractive index material (GIM). The structure, which consists of materials with varying indices, can increase transmittance while decreasing reflectance, improving solar cell performance. The study found that the highest reflectance occurs when the ARC thickness is $x = 0$, and it gradually declines before increasing again. The study also found that TE-polarized light is reflected more when the contact angle rises, lowering transmittance.

3 EFFECTS OF MAJOR COATING MATERIALS ON PV EFFICIENCY

3.1 SiO_2 as Antireflection Coating

SiO_2, also known as silicon dioxide, is the second most prevalent element on Earth, after oxygen, and makes up around 25.7% of the Earth's crust [22]. It is cost-effective and has excellent optical, mechanical, and electrical features, although it is seldom encountered in its pure crystal form in nature. Each of the elements undergo a chemical reaction in order to create Si-O-Si connections, and it is the arrangement of the atoms in the system which determines the precise shape of the SiO2 particles as shown in Figure 2 [23]. There are several works that has been achieved to synthesis a nanometer SiO_2 antireflection coating for solar modules. Wei W. et al (2015) [24], the paper focused on the development of a nanometer SiO_2 antireflection coating for solar modules, aiming to reduce reflection losses and improve efficiency. The coating, created using the sol-gel process, achieved a 5.6% increase in transmittance and reduced reflection losses to 3.44%. It also demonstrated uniform antireflection and high scratch resistance, demonstrating its potential for PV system efficiency.

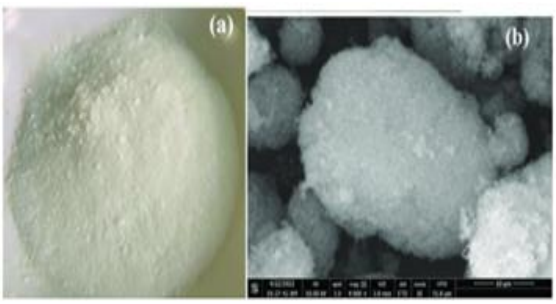


Figure 2: SiO_2 material (a) raw material (b) SEM image [25].

Sharma R. et al. (2017) [26], researchers studied the impact of anti-reflection coatings on silicon solar cells using PV Education and the PC1D simulator. They found that DLARC, specifically SiO_2/TiO_2 DLARC, improved photovoltaic performance and short current, resulting in a 14.34 solar efficiency. This was achieved by lowering the weighted reflectance of the solar cells, resulting in better efficiency and shorter current. Liao K. et al (2020) [27], the study was focused on the open-circuit voltage, conversion efficiency, and fill factor of solar panels made with different antireflection coating (ARC) stacks and compared them. Where the coating had a thickness of approximately 70 nm with a refractive index of about 2.01. And thus Mc-Si solar cells covered with TiO_2-SiO_2/SiO_2/SiNx ARC stacks under encapsulation circumstances had an average conversion efficiency of 16.27%. Comparing this value to commercial Mc-Si solar cells (16.09%) made with SiNx ARCs, the difference was 0.18% as shown in Figure 3.

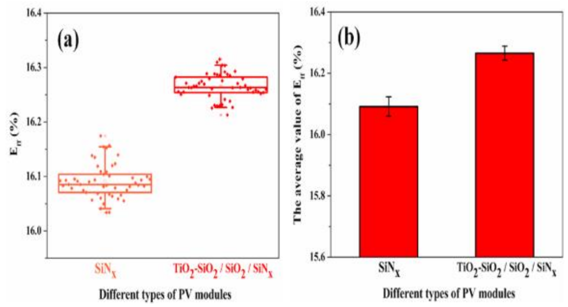


Figure 3: (a) Displays the distribution of conversion efficiency in comparison, and (b) displays the average conversion efficiency of solar modules assembled using various ARC stacks.

Table 1 shows the thickness and limitations with the efficiency of the solar cell using the material SiO_2.

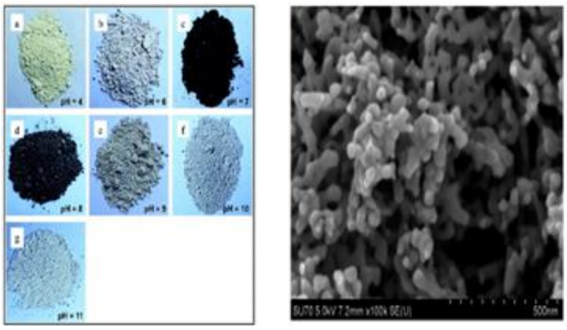
3.2 ZnO as Antireflection Coating Material

Zinc oxide (ZnO) is an atypical semiconductor with a direct band gap of 3.4 electron volts (eV) and an incredibly high exciton binding energy of 60 millielectron volts (meV). It is considered to be the most promising semiconductor for a wide range of applications. These features are really intriguing for enhancing several optoelectronic devices. The unique properties of ZnO can be attributed to the fact that among all the elements in the sixth group of the periodic table, oxygen offers the greatest potential for ionization. As a result, the Zn (3d) and O (2p) orbitals interact significantly with one another [28]. Antibacterial treatments, sunscreen lotions, photocatalysis, catalysts, UV absorption, and biological applications are just a few of the many uses for zinc oxide (ZnO) [29]. This is because it is inexpensive, has little toxicity, and is very biocompatible. A wide variety of industrial products, such as paint, rubber, cosmetics, and coating, incorporate zinc oxide (ZnO) as an additive.

Useful in mechanical actuators with enhanced piezoelectric and pyroelectric capabilities, as well as piezoelectric sensors, ZnO's wurtzite structure, which lacks a center of symmetry, produces strong electromechanical coupling effects [30]. Figure 4 shows the raw material and SEM image.

Table 1: Previous research results of SiO_2.

Ref	Material used	Thickness	Limitation	Results
Wei W. et al (2015) [24]	SiO_2	----------	Over the 400–800 nm wavelength range, the transmittance grows at short wavelengths and drops at long wavelengths as lifting speed increases.	A 5.6% improve-ment in transmit-tance and a reduction in reflection losses to just 3.44 percent
Sharma R. et al (2017) [26]	SiO_2 /TiO_2 SLARC and DLARC	110, 105, 85, 75, 65, and 60 nm	The front surface of the solar cell with SLARC enhances its performance to a certain extent.	Efficiency 14.34 %
Liao K. et al (2020) [27]	TiO_2–SiO_2/ SiO_2/ SiNx	70 nm for SiNx 25 nm for SiO_2 55 nm for TiO_2–SiO_2	It appears that there is need for improvement in the sintering and welding processes, as the average fill factor of PV modules covered with TiO_2-SiO2/SiO_2/SiNx ARC layers did not show consider-able improve-ment.	Efefficiency 16.27%



(a) (b)

Figure 4: The ZnO material. (a) photographs of ZnO nanoparticle powders with different pH values [31] (b) SEM microscopy of zinc oxide ZnO nanoparticles at x 100 magnifications [32].

Several studies have been achieved for using ZnO nanoparticles as anti-reflective coting layer. Jalali A. et al (2019) [33] study in deep the effects of sol-gel solution quantity on the performance of silicon solar cells that use ZnO thin films as anti-reflective layers. The sol-gel method was used to make thin films of ZnO, which were then spin-coated onto a P-N silicon base. Where Nano-structured ZnO films with hexagonal crystallites and particle sizes ranging from 30 to 50 nm were successfully made on the silicon base. As anti-reflection sheets, coated ZnO films made silicon solar cells work better. It was found that the quantity of the sol-gel solution was significantly related to the efficiency of the silicon solar cell.

Sagar R. and Rao A. (2020) [34], focused on using transition metal oxide thin films (zinc oxide, magnesium oxide, and aluminum oxide) as anti-reflection coatings on silicon-based solar cells to improve energy conversion efficiency. Quantum efficiency measurement showed increased external quantum efficiency (EEQ) in the 450-680 nm wavelength range, with aluminum oxide exhibiting the highest EEQ. And the transition metal oxide films showed compact structures and good substrate adhesion. However, spectral response declined near the silicon gap, emphasizing the need for optimized anti-reflection layer design. Jamaluddin N. I. M. et al. (2024) [35], the study investigated the effectiveness of the performance of six different ARC materials on silicon solar cells using PC1D simulation software. The optimal wavelength for ARC development was found to be between 500 and 800 nm. AND found silicon nitride (Si_3N_4) and zinc oxide (ZnO) were found to be the most effective ARC materials for single-layer design in terms of reflectance reduction and efficiency (Eff) of 21.69% and 21.67%, respectively. Table 2 shows the comparison between several studies that utilized ZnO nanoparticles as anti-reflective coting layer.

3.3 MgF_2 as Antireflection Coating Material

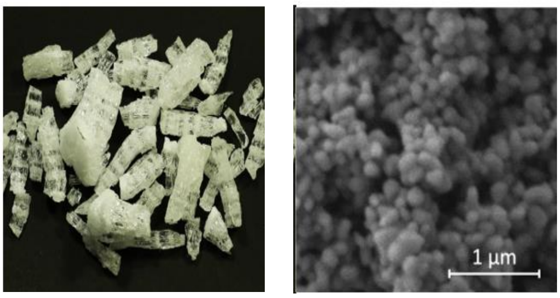
Magnesium fluoride is a colorless crystal (MgF_2) has a tetragonal crystal system and a rutile structure. It is frequently used as a coating material due to its superior optical properties.

Table 2: Previous research results of ZnO.

Ref.	Material used	Thickness	Limitations	Results
Jalali A. et al (2019) [33]	ZnO thin film	230 nm	Although ZnO thin films have many desirable properties, there is a restriction on their use.	Efficiency 9.19%
Sagar R. and Rao A. (2020) [34]	ZnO, MgO, and Al_2O_3 thin film	77 nm, 90 nm and 79 nm	The non-optimal thickness of the light absorber layer placed in the manufactured devices could be the cause of the quantum efficiency reduction at longer wavelengths.	Efficiency 9.633%, 9.864%,and 9.125%
Jamaluddin N. I. M. et al (2024) [35]	SiC, SiO_2, Si_3N_4, TiO_2, ZnO, and ZnS.	36.159nm, 101.351nm, 74.257nm, 62.396nm, 78.411nm, 63.479nm	SiC has the highest reflectance hence, causing the coating has to display the lowest efficiency	Efficiency 17.1%, 20.23%, 21.69%, 21.05%, 21.67%, and 21.16%

Also, Magnesium fluoride (MgF_2) coatings have several outstanding characteristics, such as a low refractive index (n = 1.38), a broad transparent range spanning from 120 nm to 8000 nm, and a significant energy gap of 11 eV. MgF_2 is a compound composed of several ions with varying charges that are attracted to each other through electrostatic forces [36].

Consequently, compressing it at normal temperature and pressure conditions is exceedingly challenging. Furthermore, MgF_2 possesses the benefits of exceptional mechanical resilience, outstanding thermal endurance, and a remarkable resistance to laser damage. It mitigates external material wear and extends the lifespan and efficiency. Hence, MgF_2 coatings has a multitude of uses in the production of optical coatings as shown in Figure 5 [36].



(a) (b)

Figure 5: MgF_2 material. (a) raw material [37] (b) SEM image [38].

Several studies have been achieved for using MgF_2 nanoparticles as anti-reflective coting layer. Nayak J. et al (2024) [39], with the transfer matrix method, the magnetic and electric fields of the light hitting the coats' surface were changed to make the AR coatings. A MATLAB program based on the transfer matrix model was used to figure out the reflectance. Materials with a high refractive index, like ZnS, Si_3N_4, and MgF_2, were used to model single, double, and three-layer ARCs. It was found that the reflected loss for single-layer ARCs was less than 34.66%, for double-layer ARCs it was 8.47%, and for three-layer ARCs it was 5.71%. Single-layer ARCs had an external quantum efficiency (EQE) of 65.34% on a silicon base, while double-layer ARCs had an EQE of 81.81%. Khadir Al. et al (2020) [40], the study used computer models to look into how an anti-reflective coating (ARC) affects the performance of CuInGaSe2 (CIGS) solar cells. It employed the Atlas module from SILVACO T-CAD for the numerical models. And it taken into consideration how different ARC and CIGS layer thicknesses affected a single magnesium fluoride (MgF_2) ARC layer in order to get the best electrical qualities from the solar cell. When a single 0.11µm MgF_2 ARC monolayer was used, the modelling showed that the CIGS solar cell's conversion rate went up by 8.10%. Future solar cell designs and implementations can benefit greatly from the findings as shown in Figure 6. Table 3 shows the thickness and limitations with the efficiency of the solar cell using the material MgF_2.

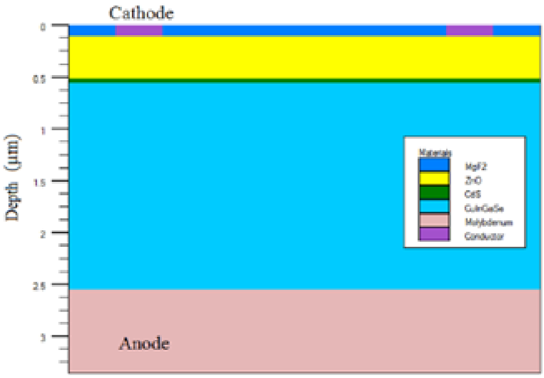


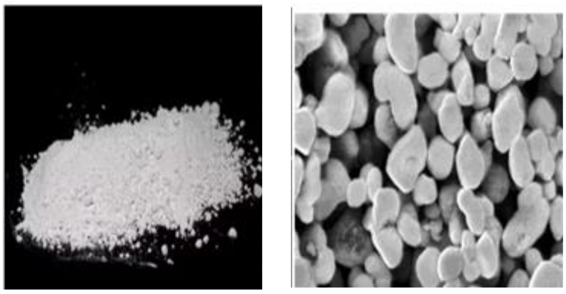
Figure 6: The simulated CIGS solar cell's schematic structure.

3.4 TiO_2 as Antireflection Material

TiO_2, a photo semiconductor, has gained significant attention as the most extensively studied material among metal oxides. This is due to its versatile uses in areas such as photocatalysis and photovoltaics, making it valuable for both fundamental study and practical use [41]. Owing to its lack of toxicity, excellent efficiency, photochemical stability, and afford ability. The material has been classified as a broad band gap semiconductor with an energy gap of 3.00 eV in the rutile phase and 3.20 eV in the anatase phase [42]. The rutile phase is the predominant natural form of TiO_2 among its various polymorphs, including anatase and brookite. Thermodynamically, rutile is the most stable phase of TiO_2 at all temperatures as shown in Figure 7 [43].

Table 3: Previous research results of MgF_2.

Ref.	Material was used	Thickness	Limitation	Results
Nayak J. et al (2024) [39]	ZnS, Si_3N_4, and MgF_2 double layer.	200 nm, 400 nm	Possible explanation for low EQE at higher wavelengths (>700 nm): ARCs and silicon surface have different impedances miss -matching.	The ARCs with a single layer on a silicon substrate achieved an external quantum efficiency (EQE) of 65.34%, whereas the ARCs with two layers achieved 81.8%.
Khadir Al. et al (2020) [40]	MgF_2	0.11μm	when ZnO and CdS layer thickness increases, conversion efficiency falls.	Growth in conversion efficiency from 18.99 to 20.52%



(a) (b)

Figure 7: TiO_2 material. (a) raw material [44] (b) SEM Image [45].

Several studies have been achieved for using TiO2 nanoparticles as anti-reflective coting layer. Rad A. S. et al (2020) [46], the research investigates the effect of porosity and roughness on the performance of anti-reflection and self-cleaning meso-porous TiO_2 coatings on glass substrates for solar systems protection. Using the sol-gel method and varying quantities of Pluronic F127, mesoporous TiO_2 coatings were produced. Etching the TiO_2 coatings with 5% HF enhanced their anti-reflective capabilities. Also, coating surface roughness was enhanced, and holes smaller than 30 nm formed as a result of F127 usage. Glass coated with TiO_2 and treated with F127 has a greater transmittance of the visible spectrum waves than uncoated glass. Therefore, coatings of higher porosity and roughness on mesoporous TiO_2 demonstrated better anti-reflective and self-cleaning capabilities.

Sagar R. and Rao A. (2021) [47], focused on improving the photon-to-electron conversion efficiency (PEC) of commercial monocrystalline silicon solar cells by using nanoscale TiO_2 and Ta_2O_5 as antireflection coatings (ARCs). Nanoscale TiO_2 and Ta_2O_5 ARCs were deposited on commercial silicon solar cells, with thickness determined using sputtering techniques. Where the efficiency (Eff) improved from 17.18% to 17.87% with TiO_2 ARCs and 18.8% with Ta_2O_5 ARCs. This improvement was attributed to increased fill factor and reduced reflectance. Table 4 shows the thickness and limitations with the efficiency of the solar cell using the material TiO_2.

3.5 Different Other Materials as Antireflection Coatings

Huanga Z. et al (2018) [48], researchers had developed a method to create antireflective and self-cleaning coatings on silicon-based solar cells, aiming to improve light harvesting efficiency and protect cells from dust and environmental damage. The transparent photopolymer with leaf surface morphologies was cured onto Si slabs, resulting in a 10.9% increase in photovoltaic cell power. The coatings were resistant to ambient liquid pH levels and hydrophobic, and can be printed onto glass for large-scale production.

Li W. et al. (2019) [49], the study aimed to create high-performance, broadband antireflective (AR) and superhydrophobic coatings on glass surfaces for solar cells. The coating was created using spin coating and hexadecyltrimethoxysilane (HDTMS), resulting in a hydrophobic surface and porous structure. The coating increased the short-circuit current density and conversion efficiency of dye-sensitized solar cells by 10.12%. However, the research had drawbacks, such as increased transparency and root means square roughness over time, and the formation of scratches that could damage the AR layer.

Jalaly S. et al. (2019) [50], the study discussed the use of a polymer-based anti-reflection coating (ARC) for solar panels, specifically designed for building-integrated and building-applied photovoltaic systems.

Table 4: Previous research results of TiO_2.

Ref.	Material was used	Thickness	Limitations	Results
Rad A. S. et al (2020) [46]	TiO_2	80–90 nm	T0, T1, T2, and T3 samples showed had less porosity that's lead to less light transmittance than uncoated glass	T4 and T5 samples, which had TiO_2 coatings with 1.6 X 10-3 M and 2 X 10- 3 M of f127 in the coating solution, respectively, demonstrated higher visible light transmit-ttance compared to the non-coated glass.
Sagara R. and Rao A. 2021 [47]	TiO_2 and Ta_2O_5	55.2 nm and 70.8 nm	Both layers exhibit a sharp rise in reflec-tance between 370 and 440 nm.	Efficiency 17.87% and 18.8%

The ARC can be adjusted to fit specific light angles, and tests show a 5.6% increase in outdoor conversion efficiency compared to plain polymer-based sheet ARCs.

Kaliyannan G. V. et al. (2019) [51], a study on nanostructured gahnite spinel material for anti-reflection coating (ARC) on polycrystalline silicon solar cells was conducted. Transparent gahnite nano-microfilms were formed using radio frequency magnetron sputtering, resulting in a high optical transmittance of 97% and a maximum power conversion efficiency of 21.27% in open air and 23.83% in controlled air. The material's physical properties decreased with deposition time.

Huang X. et al. (2021) [52], carbon nanotube/silicon (CNT/Si) solar cells have been enhanced by solution-processable MoOx, which acted as a chemical dopant and anti-reflection coating. This coating reduced series resistance and increased short-circuit current density, resulting in a 39% increase in power conversion efficiencies (PCE) and 80% stability for two months without a protective layer. MoOx also improved CNT film properties, reduced reflection, and increased the built-in potential at the CNT/Si junction, resulting in a 10.0% increase in PCE.

El-Khozondar H. J. et al. (2021) [6], the research focused on the design and efficiency of solar cells with antireflection coatings, aiming to improve performance with low cost and high efficiency. Four suggested designs that utilize Borofloat glass, SiNx, and sol-gel-based materials were present. The transfer matrix method determined total transmission and reflection, considering film thicknesses and incidence angles. The sol-gel layer was promising for high-performance cells, while the second and third structures were suitable for low-efficiency cells.

Abed R. N. et al. (2021) [53], a unique nanocoating was created using CuO:NiO and carbon (fly ash) on copper and glass surfaces. The coating's optical characteristics were examined using UV-vis and reflectance spectroscopy. The study found that the high electron absorption energy varied according to the composition's absorption wavelength, potentially enhancing solar energy absorption. As CuO:NiO concentration increased, the nano thin films darkened and became less transparent.

Shah D. K. et al. (2022) [54], the study aimed to determine the optimal thickness of a niobium pentoxide (Nb_2O_5) anti-reflective coating (ARC) layer for c-Si solar cells. A low-cost sol-gel spin coating technique was used to achieve the maximum thickness. Simulation studies revealed the 75-nm thick ARC layer had the lowest average reflectance and achieved an external quantum efficiency of over 95% and a maximum power conversion efficiency of 17.92%.

4 ANALYSES OF ANTIREFLECTION COATINGS AND TECHNIQUES

According to these studies, by decreasing reflection and increasing absorption, all antireflective materials have been shown to increase solar cell efficiency. For instance, because of its special qualities and great effectiveness in optical and electrical applications, zinc oxide (ZnO) is considered to be one of the most promising materials. However, available industrial methods make it impossible to ensure its quality and stability, requiring additives to increase stability. Differently composed materials, including transition metal oxides (like magnesium and aluminum oxide), have been shown to increase power conversion efficiency when used as thin films on silicon solar cells. Their ability is found in their specific optical characteristics, which can be modified for certain uses.

A thin film of niobium pentoxide (Nb_2O_5) has also been employed because of its promise as an antireflective coating. Using sol-gel techniques, it may be additionally enhanced to reduce light reflection and increase power-generating capacity, exhibiting its practical use. The efficiency of solar cells could be greatly increased by hybrid coatings like CuO: NiO and composite coatings like $SiO_2/WO_3/ZnO$. However, because they depend on more special components, these materials may be less accessible than ordinary materials. Additionally, one of the best materials to lower the performance of solar cells is nano-coatings, which contain materials that enhance the advantages of nanotechnology and have the potential to improve anti-reflective and self-cleaning properties, so preserving efficiency in outdoor conditions. But its cost is relatively high due to advanced manufacturing processes.

Finally, several technologies are in use that are important to enhancing the performance of solar cells, such as SLARC, MAR, and GRIN. Based on research reviews, the gradient refractive index (GRIN) technology is considered an interesting selection for high-performance solar cells since it may improve transmittance over a broad wavelength range while decreasing reflectance. Its layered structure allows for more improvements in enhancing solar energy efficiency.

5 DISCUSSIONS

The review highlights the crucial role of anti-reflective coatings (ARCs) in improving the efficiency of solar cells. These coatings work by minimizing the reflection losses on the surface of the solar cells, thereby increasing the amount of light absorbed and converted into electrical energy. This is a key factor in enhancing the overall performance of photovoltaic cells, which is critical as the world seeks more efficient and sustainable energy solutions. Nanotechnology is revolutionizing the manufacturing and functionality of ARC materials, enhancing solar cell efficiency and resistance to external influences. Nanocoating's, with their unique surface characteristics, are being developed for various applications. Thus, this review focus in analysis the efficiency of solar photovoltaic systems with anti-reflection coatings based on recent related works, focusing on titanium dioxide, silicon dioxide, zinc oxide, magnesium fluoride and other different materials. Results show the material performs better, especially when nanostructured or in multilayer forms, increasing power conversion efficiency. This article discusses challenges in applying AR coatings in the real world, including accuracy, consistency, and thickness. It calls for further research on self-cleaning AR coatings, long-term performance, and solar cell efficiency. In the following we can summarize the aspects of:

5.1 Material Properties and Their Impact

In follows the main advantage and challenges which has been concluded by analysis of this review for each type of anti-reflective coatings materials.

A) SiO2 (Silicon Dioxide):
  1) SiO2 is favored for its excellent optical, mechanical, and electrical properties.
  2) The Sol-gel process to create nanometer SiO2 coatings shows promising results, with significant improvements in transmittance and reduction in reflection losses.

However, maintaining uniformity and mechanical durability of these coatings can be challenging, and stress build-up can lead to rapid failure.

B) ZnO (Zinc Oxide):
  1) ZnO's high exciton binding energy and direct band gap make it ideal for optoelectronic applications.
  2) Studies have demonstrated that ZnO thin films, particularly when optimized for sol-gel solution concentrations, can greatly enhance solar cell performance.

Challenges include managing the formation and stability of ZnO nanoparticles and ensuring consistent coating quality.

C) MgF2 (Magnesium Fluoride):
  1) MgF2's low refractive index and broad transparent range make it a valuable ARC material.
  2) Research indicates that single-layer MgF2 coatings can significantly improve the conversion efficiency of CIGS solar cells.

However, the difficulty in compressing MgF_2 and ensuring uniform application can pose manufacturing challenges.

D) TiO2 (Titanium Dioxide):
   1) TiO2 is a highly versatile material with applications in both photocatalysis and photovoltaics.
   2) Its various polymorphs, particularly rutile and anatase, offer different advantages for ARCs.

The challenge lies in optimizing the porosity and roughness of TiO_2 coatings to maximize their anti-reflective and self-cleaning properties.

5.2 Innovations and Future Directions

A) Multilayer Coatings:
   1) As single-layer and double-layer ARCs may not suffice, researchers are focusing on multilayer ARCs to achieve better refractive index matching and broader bandwidths;
   2) The gradient refractive index (GRIN) structure is a promising innovation, virtually eliminating interfaces and enhancing adhesion and osmosis efficiency.

B) Self-Cleaning Coatings:
   1) The incorporation of photocatalytic materials like WO3 into ARCs can improve self-cleaning capabilities, reducing efficiency losses due to contamination;
   2) Composite coatings like SiO2/WO3/ZnO show significant potential in maintaining high efficiency while offering self-cleaning properties.

C) Bionic and Nano-Structured Coatings:
   1) Replicating natural structures, such as leaf surfaces, onto solar cells can enhance light harvesting and provide self-cleaning benefits;
   2) Nanostructured materials like gahnite spinel and carbon nanotube-based coatings offer innovative ways to improve solar cell performance.

In summary, the comprehensive review underscores the importance of selecting the right materials and design strategies for ARCs to achieve high-efficiency solar cells. Each material brings unique properties and challenges, and ongoing research is crucial in overcoming these obstacles and exploring new possibilities. The future of solar technology lies in the continuous innovation and optimization of these anti-reflective coatings, paving the way for more sustainable and efficient energy solutions.

6 CONCLUSIONS

In summary, research on anti-reflective coatings (ARCs) for solar cells demonstrates their critical role in the development of photovoltaic technology, particularly in terms of extending their lifespan and improving their energy conversion efficiency. Because anti-reflective coatings drastically reduce reflection losses—which are serious issues when attempting to extract the maximum amount of energy from light—they are not just an add-on; they are critical to getting the most out of solar cells. It has been discovered that materials like MgF_2, TiO_2, ZnO, SiO_2 and hybrid composites can have their optical, mechanical, and chemical properties precisely adjusted to significantly alter their performance. The application of nanotechnology to anti-reflective coatings is a significant advancement since it improves light absorption and coating durability, two factors critical to the long-term viability of industrial solar cells. It's crucial to remember that AR coatings do have certain drawbacks. A number of questions have been raised regarding their potential longevity in various conditions, the potential impact of surface pollution on performance, and the necessity of using cautious application techniques.

The main conclusions of this study are that additional research on AR coatings is necessary in order to enhance coating techniques, discover novel material combinations, and develop long-lasting self-cleaning technologies such as Smart ARCs can adapt to environmental changes, enhance light absorption, and improve solar cell energy capture. and Sustainable materials, such as low-impact or biodegradable materials, can solve environmental issues without losing functionality. Also, Research into natural polymers and hybrid coatings can result in exceptional performance.

Future studies and projects can improve the stability and efficiency of solar cells by employing these innovative suggestions, which will help to create a more sustainable energy environment. The advancement of the solar field will depend on ongoing research into new materials, methods, and cooperative initiatives.

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