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OPTIMIZATION OF ANTI REFLECTING COATING FOR EFFICIENCY IMPROVEMENT OF SOLAR PHOTOVOLTAIC SYSTEM USING TCAD

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ABSTRACT

Today, the importance of sustainable energy is growing, due to government policy for reduction in carbon content and climatic abnormal change. More research work is given to renewable energy such as solar and wind energy systems. In this paper, improvement on the efficiency of solar rays incident to electrical energy conversion is taken as a priority work. Modeling and simulation of anti-reflecting coating (ARC) for light extracting system and its efficiency improvement of solar photovoltaic system has been presented in this paper. Anti-Reflecting coating used to make a new geometrical shape for the evaluation of different modules to provide for light trapping in all directions and enables full space utilization when bringing together into device arrays. Simulation of single layer Anti-Reflective Coating (ARC) on silicon solar cells that are based on the refractive index limit of silicon dioxide (SiO_2), Silicon nitride (Si_3N_4), Aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), and Zinc oxide (ZnO) are used for performance analysis. Simulations of ARC combination material such as Si_3N_4+ ZnO, Si_3N_4+Tio_2, ZnO+Tio_2, SiO_2+ Si_3N_4, SiO_2+Al_2O_3, SiO_2+TiO_2, and SiO_2+ZnO were simulated to compare the performance of the silicon solar cell surface. The higher available photocurrent can be achieved by maintaining the high range of refractive index over a wide wavelength. In ARC analysis, the combination of Si_3N_4+ ZnO coating has performed more efficiently on a wide range of wavelengths compared to other chosen ARC materials.

Keywords: anti reflecting coating, simulation, solar cell.

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1. INTRODUCTION

The conversion of solar energy to electrical energy (photovoltaic power) has several advantages, including safety, simplicity, ease of installation, longer life, and environmental friendliness. Among numerous renewable energy resources, photovoltaic (PV) power production systems have the potential to play an important role as environmentally friendly electrical power generation resources. It is necessary to boost the efficiency and reliability of the photovoltaic power producing system. A PV system consists of solar cells linked in series and parallel to produce a PV module. In general, individual cells are connected in series to achieve the desired voltage of the module, which encloses the cells and protects them from dust, water, and other damage. The modules are joined to make a PV array. Individual cells are connected in series to generate higher voltage, and in parallel to obtain higher current. The entire performance of the array depends on the alignment of its cells, modules, and structure. Modeling and experimental data have demonstrated the importance of AR coating thickness on the performance CIGS solar cells. Using a TMT model, the significance of adjusting the deposited MgF_2 AR layer thickness for optimal device performance has been determined [1-2]. Silicon-based antireflection coatings are silica, Silicon nitride, and Porous silicon. Metal based antireflection coatings are Au, TiO_2, Zinc oxides (ZnO), Metal Fluorides (MgF_2) and Indium tin oxide (ITO). A detailed review of multifunctional coatings is provided in the referred study [3].

The maturation of effective light management strategies involving antireflection coatings and light-trapping structures has helped to enhance the performance of solar PV cells [4]. To store and distribute the electricity produced by a photovoltaic module or PV array, energy storage devices such as batteries and AC and DC converters are also essential components of the PV system. The crucial component that directly transforms solar energy into electricity is the solar cell. It is made up of a p-n junction that is created in a thin silicon wafer because silicon wafer technology has a wealth of data accessible from the semiconductor sector. The optical substance silicon is used in semiconductors and has a high refractive index. These days, it's the perfect material for solar cells. In addition to being non-toxic, silicon is the second most plentiful element in the crust of the Earth, after oxygen, thus if utilized extensively, there shouldn't be any problems with resource depletion or the environment. Pure silicon is a glossy substance. Up to 35% of the sun's light can be reflected off the silicon wafer when it strikes it. The silicon wafer is coated with an anti-reflective coating (ARC) to lessen the quantity of sunlight lost. Although there are other coatings utilized, titanium dioxide (TiO_2) and silicon oxide (SiO) are the most often used ones. In this instance, zinc oxide (ZnO) and zinc sulfide (ZnS) materials were investigated as ARCs and contrasted with silicon dioxide (SiO_2) coatings. The silicon wafer is coated with an anti-reflective coating (ARC) to lessen the quantity of sunlight lost. Because it minimizes reflection and guarantees a high photocurrent, a good ARC is

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essential to the performance of solar cells. Solar cells require a broadband ARC because, in contrast to many other optoelectronic devices, they function in a range of wavelengths, from 300 to 1200 nm. An ARC is constructed on the surface of solar cells to increase their short circuit current density (J_{sc}). Because Si and Si-related materials may be utilized as the top cell in an all-silicon tandem solar cell or as a surface passivating ARC, they are interesting for solar cell research. Because zinc oxide can be made with outstanding optical transparency and electrical conductivity, it has garnered increasing attention recently. The development of advanced anti-reflective coatings (ARCs) has become a critical area of research in the field of photovoltaics, as these coatings significantly influence the efficiency of solar cells by minimizing reflection losses and enhancing light absorption. The choice of materials, thickness, and deposition techniques for ARCs are pivotal in determining the overall performance of solar cells.

2. MATERIALS AND METHODS

Specified properties of ARC are represented in the table 1, including the input parameters, geometry of nanoparticles ranging from 5-50µm.

Combination of silicon dioxide SiO_2, Silicon nitride Si_3N_4, Aluminium oxide Al_2O_3, titanium dioxide TiO_2, and Zinc oxide ZnO employed as composite material antireflection coating. In the context of a reflecting coating, the term mesh size might refer to the size of particles or features within the coating. Including mesh size as a property allows manufacturers to control the structure and effectiveness of the coating in reducing reflections. Finer mesh sizes can help create smoother coatings with optical properties, while larger mesh size might be more cost effective but offer slightly reduced performance.

Terminating with the domain wavelength of unit λ (µm) and range of 0.380-0.720 µm over resolution 10 µm.

Table-1. Properties of ARC.

Input Parameters	Details
Geometry	Nanoparticle size range: 5-50 µm
Nanoparticles Materials-Composite material antireflection coatings	SiO_2, Si_3N_4, Al_2O_3, TiO_2, and ZnO are used as Composite material antireflection coatings.
Model Physics	Top and bottom surfaces: Periodic
Mesh size	Physics-controlled mesh with element size (Fine)
Study	Type: Wavelength domain • Unit: λ (µm) • Range: 0.380-0.720 µm, with resolution: 10 µm

Dimension are used for ARC to control the thickness of the coating layer applied to optical surfaces. The thickness of the coating is crucial for achieving the desired optical properties by minimizing reflection and maximizing light transmission. By specifying dimensions manufacturers can ensure uniformity and accuracy in applying the coating, resulting in better performance across the optical surface. Controlling the dimensions helps optimize the coating for specific wavelengths of light, further enhancing its anti-reflective properties. Thermal stability of the ARC is also a crucial parameter, as solar cells are exposed to varying environmental conditions. Materials such as Si_3N_4 and Al_2O_3 offer excellent thermal and mechanical stability, preventing degradation or delamination of the coating over prolonged exposure. The incorporation of Al_2O_3 further aids in surface passivation, reducing surface recombination velocities and thus enhancing carrier collection efficiency.

Table-2 signifies the dimension for Si_3N_4+ZnO for various regions with different composition of material. Silicon N-type material holds the dimension of 0.01 µm, conversely, region 6 with silicon material holds the dimension of 2.2 µm. Ternary composition of Indium, tin, and oxygen holds a dimension of 0.01 µm. The optimization of ARC dimensions also considers the angle of incidence of sunlight, ensuring that reflection is minimized not only at normal incidence but across a range of angles. This aspect is particularly important for fixed-tilt solar installations, where the incident angle varies throughout the day. The optimization of ARC dimensions is also influenced by the refractive index of the materials used. For instance, materials like Si_3N_4 and ZnO have refractive indices that can be finely tuned to match the optical properties of silicon, reducing reflections and enhancing light coupling into the solar cell.

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Table-2. Dimension for Si_3N_4+ ZnO.

Region	Material	Dimension
Region 1	Si_3N_4 -Silicon nitride	0.5 µm
Electrode - anode	Zno- Zinc oxide	0.5 µm
Region 2	Silicon P type	0.01 µm
Region 3	silicon	0.2 µm
Region 4	Silicon N type	0.015 µm
Electrode - com	ITO- Indium tin oxide	0.01 µm
Region 5	Silicon P type	0.01µm
Region 6	silicon	2.2 µm
Region 7	Silicon N type	0.015 µm
Region 8	Zno	0.1 µm
Region 9	Silver conductor	0.1 µm
Electrode - cathode	Aluminum	0.2 µm

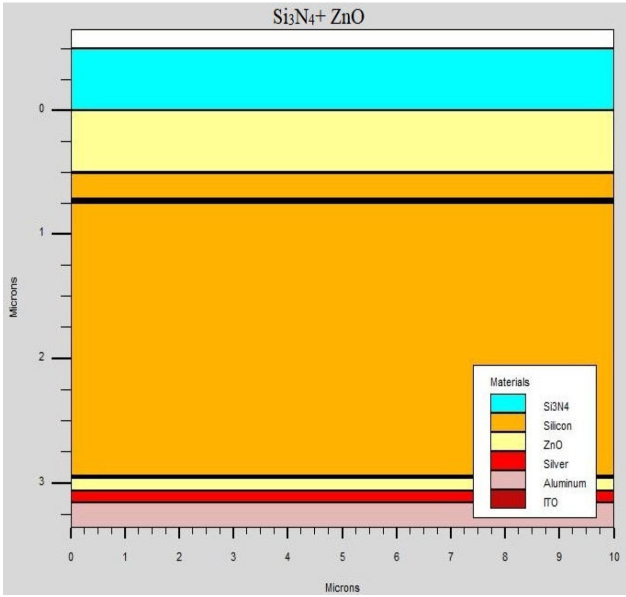

Figure-1. Fabrication of Si_3N_4+ ZnO.

Fabrication of Si_3N_4+ZnO ARC involves depositing thin films of Si_3N_4+ ZnO on a standard substrate using techniques like Chemical Vapour Deposition (CVD) or Physical Vapour Deposition (PVD). The Figure-1 depicts that aluminium acts as a base layer providing excellent electrical conductivity and serving as a reflective back contact to further improve light management within the solar cell.

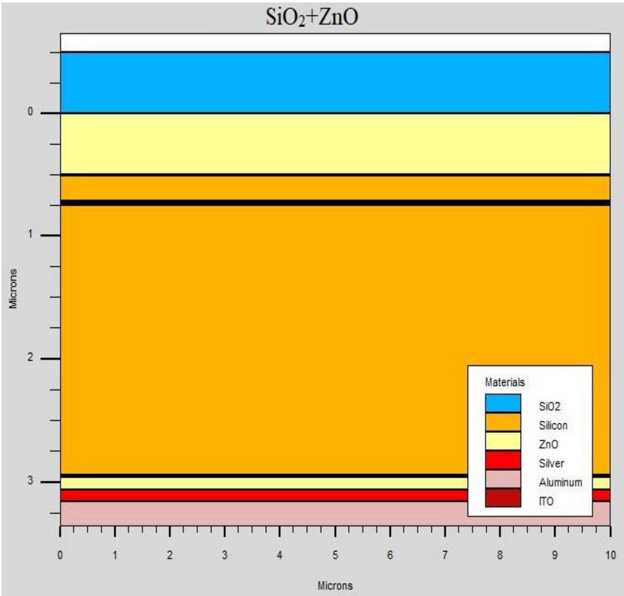

Figure-2. Fabrication of SiO_2+ZnO.

Construction of SiO_2 +ZnO must have the base region deposited with a ternary combination of indium tin oxide due to its excellent electrical conductivity and optical transparency. The use of indium oxide also provides a low resistive path for charge carriers. The topmost layer is occupied by SiO_2 followed by a zinc oxide layer. This is shown in Figure-2.

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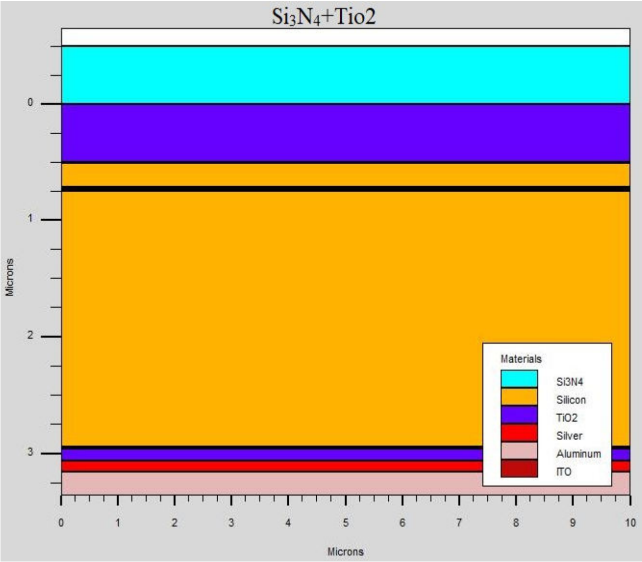

Figure-3. Fabrication of Si_3N_4+Tio_2.

Si_3N_4+TiO_2 fabrication is given in Figure-3. This fabrication is more similar to the fabrication of Si_3N_4+Zn_O. It has the same base layer as aluminum due to its best corrosion resistance property. Aluminum forms a good adhesion layer with many substrates and can be easily patterned. This property is essential for creating reliable and durable ARCs in various applications.

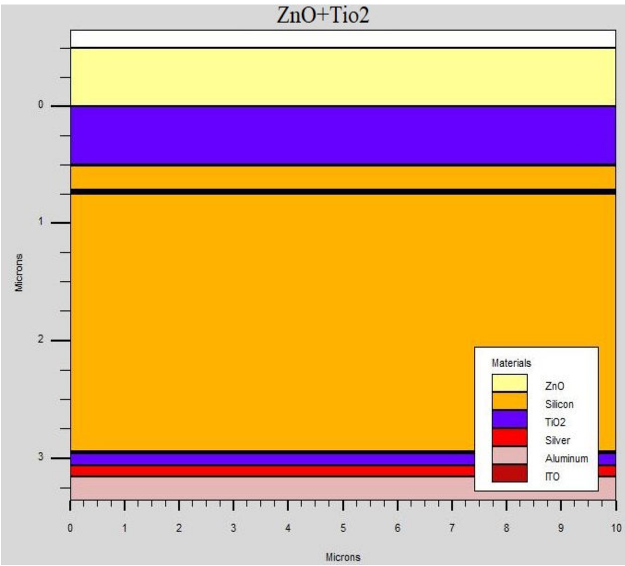

Figure-4. Fabrication of ZnO+Tio_2.

Combination of ZnO+TiO_2 is depicted in the above Figure-4. The topmost layer is formed by ZnO and the second top layer is fabricated by TiO_2. Deposition of silicon has excellent optical properties, making them suitable for use in a wide range of wavelengths.

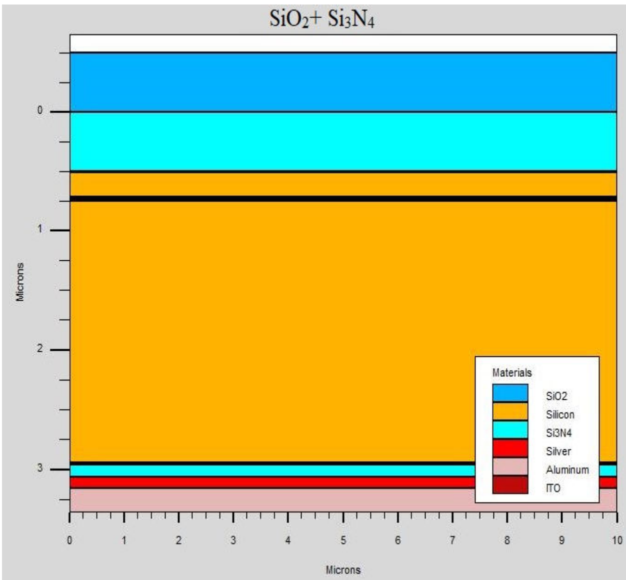

Figure-5. Fabrication of SiO_2+ Si_3N_4.

The fabrication of SiO_2 + Si_3N_4 is very different from other fabrications as Si_3N_4 is divided into two fabrication layers. The first fabrication layer is followed by SiO_2, and the second layer of Si_3N_4 is above silver.

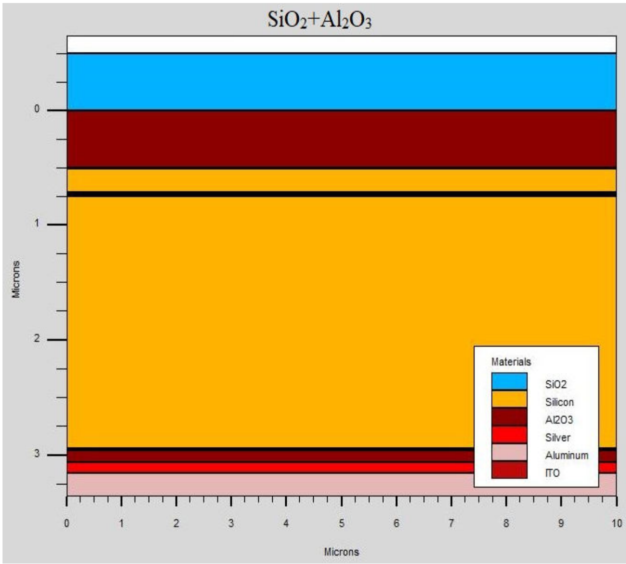

Figure-6. Fabrication of SiO_2+Al_2O_3.

This fabrication has only six layers where the topmost layer is occupied by SiO_2 followed by Al_2O_3 which is depicted in the above Figure-6. SiO2 as the top layer helps in minimizing reflection losses, while Al_2O_3 acts as passivation layer.

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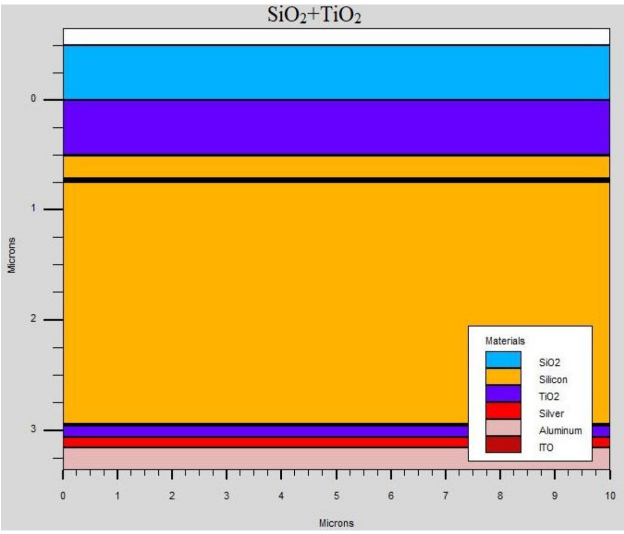

Figure-7. Fabrication of SiO_2+TiO_2.

The fabrication of SiO_2 +TiO_2 is represented by each layer in the above Figure-7. In this method of fabrication, it does not have a Si_3N_4 layer and TiO_2 is deposited above silver as well as above silicon.

3. RESULTS AND DISCUSSIONS

A possible result for ARC with quantum efficiency could be improvement in quantum efficiency of photovoltaic devices.

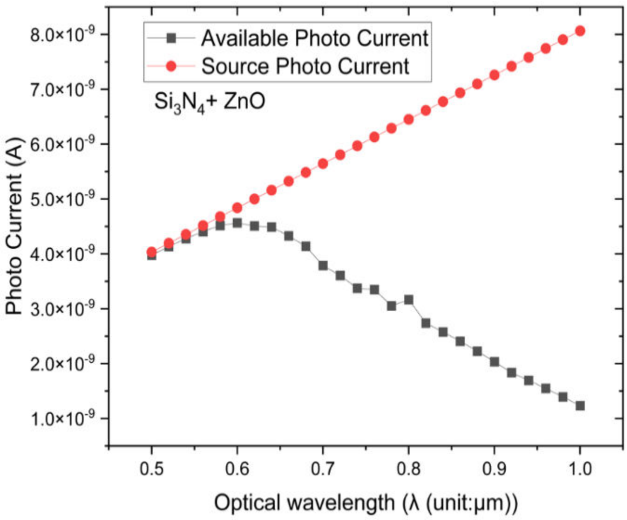

Figure-8. Optical wavelength Vs photocurrent.

The above Figure-8 shows the correlation for the combination of Si_3N_4+ZnO to both available and source photo current plotted against optical wavelength with unit µm and photocurrent in amps. Source photocurrent ramps to the wavelength of 1 µm at 8nA.

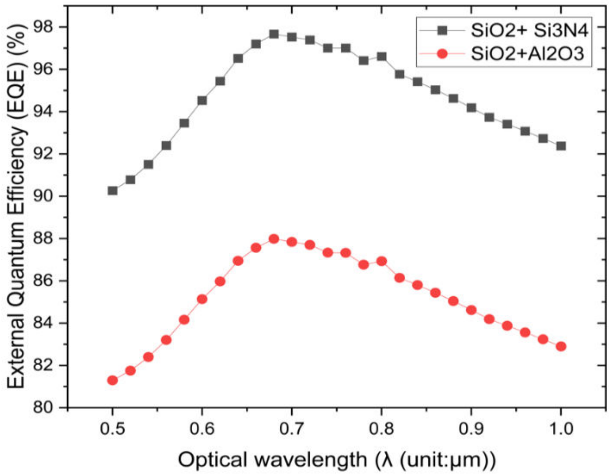

Figure-9. Quantum Efficiency vs optical wavelength.

Quantum efficiency in ARC refers to the coating effectiveness in enhancing the device ability to convert incident photons into electrical current.

EQE quantifies the percentage of incident photons that are converted into electrical current by the device. It's a ratio of the number of charge carriers generated by absorbed photons to the number of incident photons. Figure-9 depicts the plot between optical wavelength of unit µm in x axis and percentage of quantum efficiency in y axis for ARC combination of SiO_2+Si_3N_4 and SiO_2+Al_2O_3. From the graph, SiO_2+Si_3N_4 exceeds 96% of quantum efficiency. On the other hand, SiO_2 +AlO_3 has almost an efficiency of 88%.

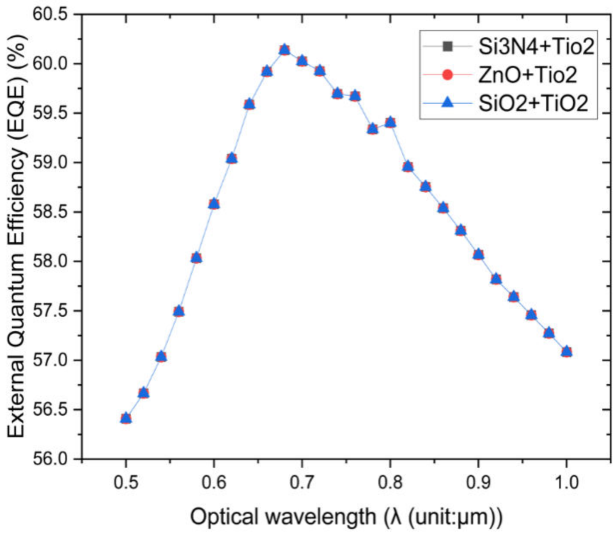

Figure-10. Quantum Efficiency vs optical wavelength.

The three different ARC combinations of materials like Si_3N_4+TiO_2, ZnO+TiO_2 and SiO_2+TiO_2 where all three curves coincide each other when plotted against optical wavelength and quantum efficiency.

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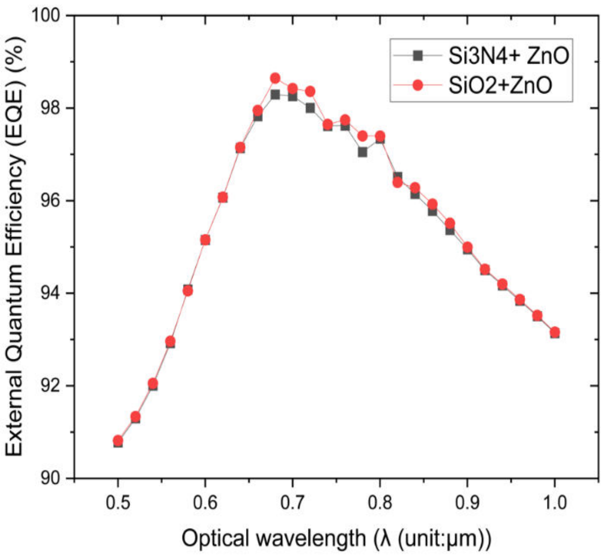

Figure-11. Quantum Efficiency vs optical wavelength.

At initial onset in Figure-11, where Si_3N_4+ZnO and SiO_2+ZnO materials curves overlap, that suggests they have the same quantum efficiency, which also indicates that they perform similarly in terms of reducing reflection, however beyond 97% they diverge.

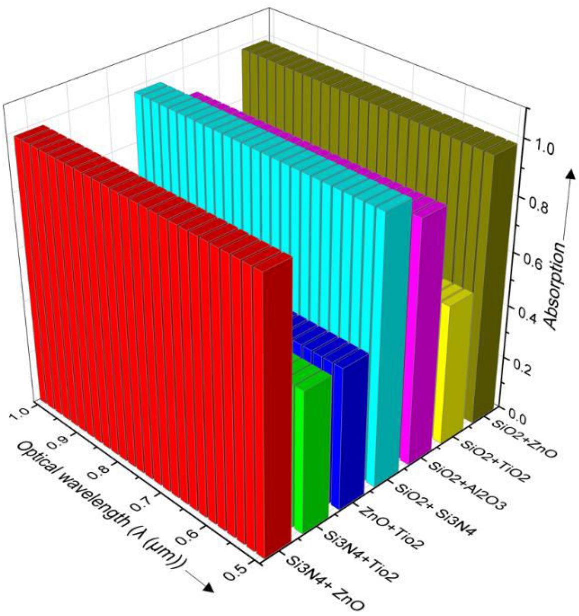

Figure-12. Absorption.

Absorption plays a major role by reducing the amount of light reflected, as a result, it boosts the transmission of light through the surface. The above Figure-12 represents the absorption value at different optical wavelengths for various combinations of ARC material. Si_3N_4+TiO_2 has least absorption overall.

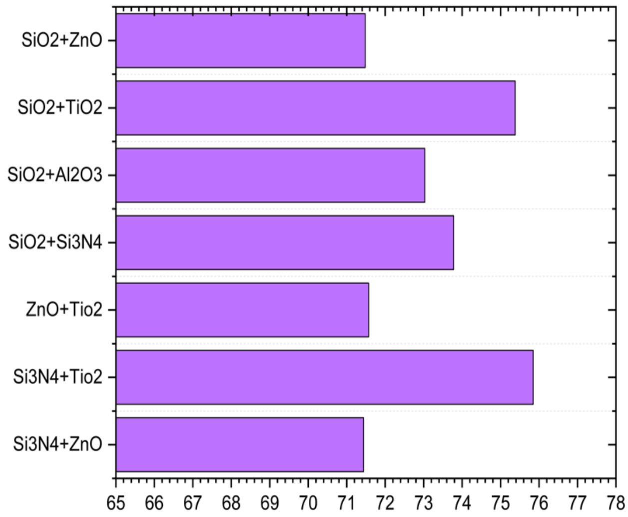

Figure-13. Fill factor.

Fill factor refers to the ratio of coated area to total surface area of the substrate. A higher fill factor is necessary to achieve reduced reflection and improved optical performance. The statistics of Figure-13 show the fill factor range from 65-78 for various combinations of ARC materials. Si_3N_4+TiO_2 has a supreme fill factor value of 76.

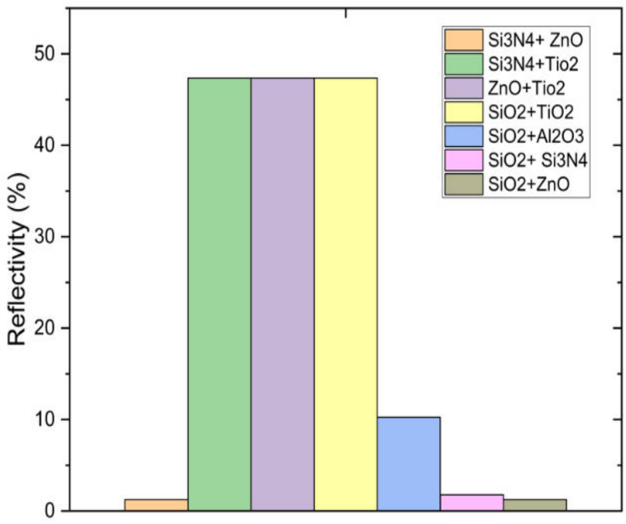

Figure-14. Reflectivity vs ARC.

The percentage of reflectivity for ARC should be ideally low in the range of 0-50%, which indicates only a smaller amount of light is reflected from the coated surface while the majority passes through. Figure-14 shows SiO_2+ZnO and Si_3N_4+ZnO provide the least reflective percentage, other compounds provide like Si_3N_4+TiO_2, ZnO+TiO_2 and SiO_2+TiO_2 provides a reflective percentage.

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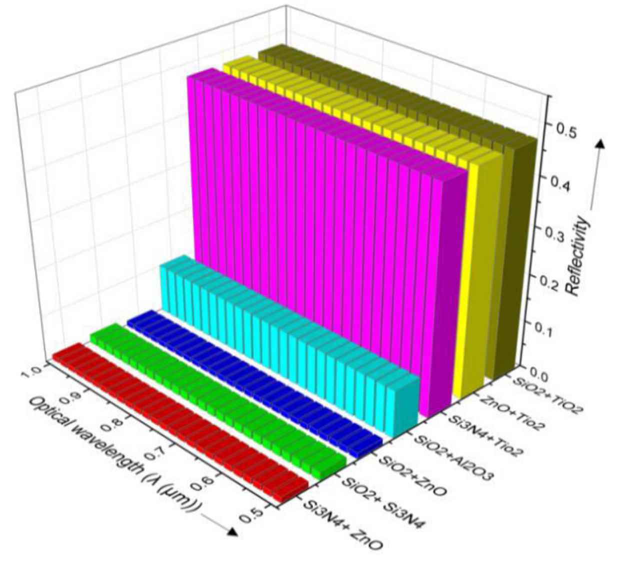

Figure-15. Reflectivity vs optical wavelength.

The reflectivity and optical wavelength are governed by refractive index and absorption coefficient. Figure 15 shows the statistical analysis of reflectivity for a range of optical wavelengths in µm.

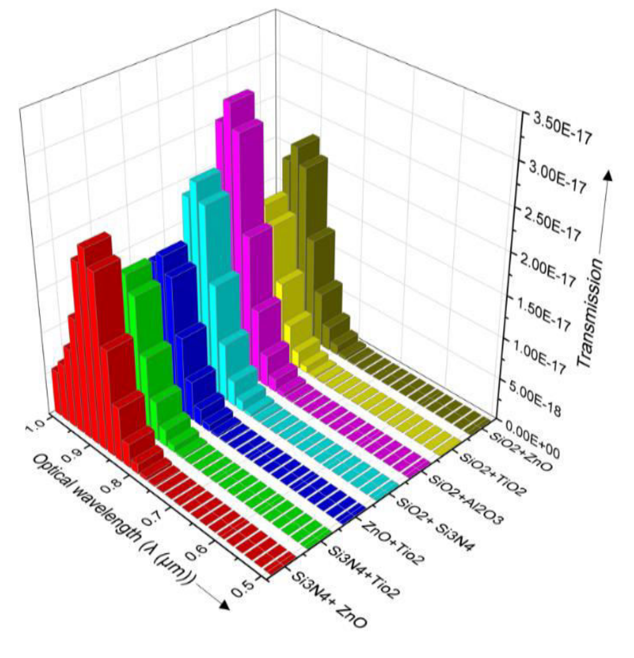

Figure-16. Transmission vs optical wavelength.

For ARC coating, the transmission should be high across the entire optical wavelength, which indicates that the coated surface allows as much light as possible to pass through. Figure-16 shows the transmission ability for the ARC combination of materials. SiO_2+Al_2O_3 exceed the transmission value of 2.50E-17.

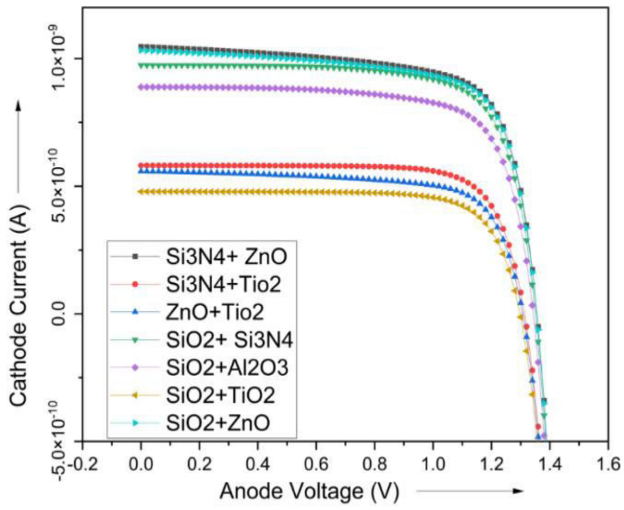

Figure-17. Anode voltage vs cathode -VI characteristic.

In ARC materials, the cathode current needs to be carefully controlled to ensure uniform optical coating properties. Figure-17 shows the VI characteristics of ARC materials. The graph is plotted between the anode voltage on the x axis and the cathode current on the y axis. Initially, the anode current produces a saturated value for increasing voltage. At a certain increase in anode voltage, the cathode current drops to zero. Si_3N_4+TiO_2, ZNO+TiO_2, SiO_2+TiO_2 has saturated anode current of 5 X 10^{-10}A.

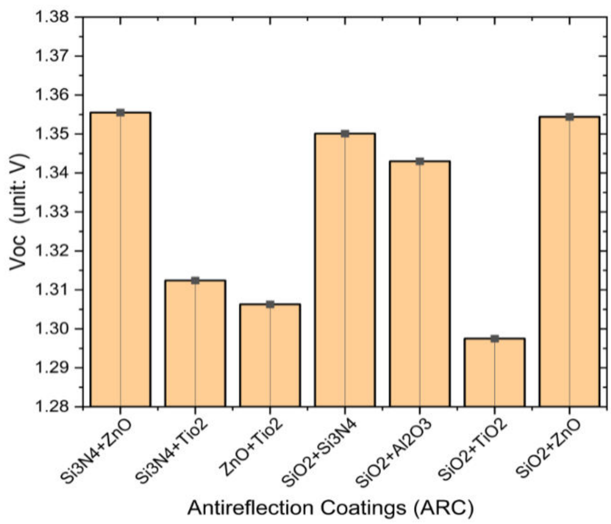

Figure-18. Open Circuit Voltage Vs ARC.

Open circuit voltage is not directly related to effectiveness of anti-reflective materials. Circuit voltage is a term primarily used in electrical engineering and refers to the voltage across a circuit when there is no current flowing through it. Anti-reflective coatings are applied to optical surfaces, like solar panels, to reduce reflection and increase transmission of light. The performance of these coatings is typically evaluated based on optical properties such as transmittance, reflectance, and durability rather than electrical characteristics like voltage. However, an adequate voltage is required to create a coating. Figure-18 shows the open circuit voltage for all different combinations of ARC materials. Si_3N_4+ZnO has a voltage of 1.355V. Whereas the SiO_2+TiO_2 has a voltage of 1.295

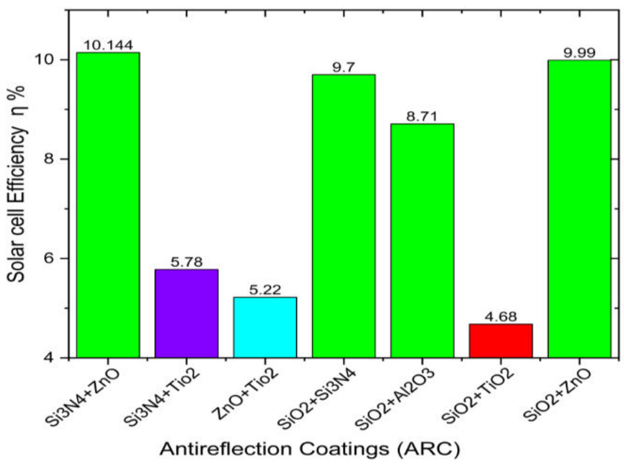

Figure-19. Solar efficiency vs ARC.

Anti-reflection coatings play an important role in enhancing the efficiency of solar cells. In ARC materials used for solar cells, such coatings are essential for maximizing the amount of sunlight that can be captured and converted into electrical energy. This is especially important in improving the overall efficiency and performance. Si_3N_4 has efficiency 10.144η %. The next highest efficiency is 9.7η% that is for SiO_2+Si_3N_4. Solar cell efficiency of 4.68η% corresponds to SiO_2+TiO_2.

Table-3. Input data of Antireflection Coatings (ARC) used in the ATLAS.

S. No	ARC Coating	Fill Factor =Pm/(Jsc*Voc)*100	Solar cell Efficiency % η
1	Si_3N_4+ ZnO	71.44	10.144
2	Si_3N_4+Tio2	75.85	5.78
3	ZnO+Tio2	71.57	5.22
4	SiO_2+ Si_3N_4	73.78	9.70
5	SiO_2+Al_2O_3	73.03	8.71
6	SiO_2+TiO_2	75.38	4.68
7	SiO_2+ZnO	71.48	9.99

The input data of ARC used in ATLAS and corresponding fill factor and solar cell efficiency.

4. CONCLUSIONS

Simulation results confirmed that the reflectance for Silicon nitride and zinc oxide could be reduced to zero only at a single wavelength. This reduction in reflectance of visible light suggested better utilization of the incident solar radiation. The highest efficiency of 10.144% was achieved for Si_3N_4+ ZnO-based devices when compared to 9.99% for SiO_2+ZnO and 9.70% for SiO_2+ Si_3N_4.

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