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Enhancing Photovoltaic Efficiency through Multi-Layered Nanostructured Anti-Reflective Coatings on Monocrystalline Silicon Solar Cells

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Abstract:
Reflection losses remain a major limitation in improving the efficiency of solar cells, despite advances in photovoltaic (PV) materials and device design. This study investigates the fabrication and characterization of multi-layered nanostructured anti-reflective coatings (ARCs) composed of silicon dioxide (SiO_2) and titanium dioxide (TiO_2) on monocrystalline silicon solar cells. Using Atomic Layer Deposition (ALD)**,** alternating SiO_2 (50 nm) and TiO_2 (30 nm) layers were fabricated and tested for their optical and photovoltaic properties. UV-Vis-NIR spectroscopy confirmed significant suppression of reflection across the 300–1100 nm spectrum, with reflectivity reduced from ~30% in uncoated cells to below 7% in coated samples at 550 nm. Photovoltaic performance tests under standard test conditions (1000 W/m², 25°C, AM 1.5G) showed a notable improvement, with power conversion efficiency (PCE) increasing from ~18% in bare cells to ~19.5% in coated cells, representing an ~8% relative enhancement. Angular dependence measurements demonstrated consistent anti-reflective performance across multiple incidence angles (0°–60°). These findings highlight the potential of nanostructured multi-layer ARCs to improve light harvesting, reduce reflective losses and enhance the long-term efficiency of solar photovoltaics.

Keywords: Anti-reflective coatings; Nanostructures; SiO_2–TiO_2 multilayers; Monocrystalline silicon solar cells; UV-Vis-NIR spectroscopy; Photovoltaic efficiency.

1) Introduction:

Getting the most out of solar energy has become a key part of making energy in a healthy way. Even though improvements in photovoltaic materials and designs have made solar cells much more efficient, reflection losses are still a big problem. So, there is an urgent need for improved anti-reflective surfaces that can reduce reflecting losses by a large amount [1]. The goal of this study is to create and test a multi-layered nanostructured anti-reflective coating, with a focus on how well it reduces glare and improves the efficiency of solar cells. Solar energy is one of the most hopeful ways to meet the growing need for clean energy sources around the world [2]. With the improvements in photovoltaic (PV) materials and methods over the past few decades, solar cells have become much more efficient. But even with these improvements, a lot of the sunshine that hits a surface is lost because of reflection at the air-material contact. This makes solar energy systems less effective as a whole. As the need for more energy grows, so does the need for ways to cut down on these loses [3]. Depending on the material and construction of the solar cell, reflection losses can cause a 20% to 35% drop in the efficiency of photovoltaic cells. The main goal of this study is to figure out how nanostructured anti-reflective films can be made to reduce reflection losses and make solar cells work better [4].

2) Review of Literature:

Since the 1970s, anti-reflective films have been a major area of study, with uses in everything from glasses and screens to photovoltaics (Nelson, 2003). The basic idea behind these coats is to reduce the amount of light that gets reflected at the point where two different materials meet. This lets more light get into the material that absorbs light. Smith et al. (2017) say that the first anti-reflective coats were mostly made of single-layer films made of materials with a low refractive index. Green et al. (2014) say that as thin-film technologies have gotten better, films with more than one layer have become more widespread. These structures with many layers are often made so that they don't reflect light over a wider range of colours. The layers can be changed to have different widths and refractive indices, which opens up a wide range of uses (McGehee, 2019). More recently, the attention has moved to nanostructured anti-reflective coatings, which offer the freedom of setting the effective refractive index by changing the shape and arrangement of the nanostructures (Lee & Kim, 2021). (Zhou & Raman, 2019) These nanostructured films have great anti-reflective qualities and are seen as very promising for solar uses. Different materials, like silicon dioxide (SiO_2) and titanium dioxide (TiO_2), have been looked at for their anti-reflective properties. Silicon dioxide is used a lot because it has a low refractive index and is very stable at high temperatures. Titanium dioxide, on the other hand, is known for having a high refractive index and a strong effect on light (Wiesner et al., 2009). Spectroscopic methods have been very important for figuring out how well anti-reflective surfaces work. Zheng et al. (2017) looked into silicon-based photovoltaic microcells with angle-resolved photoluminescence spectroscopy. Their work sets a standard for the kind of spectroscopic research that this study wants to do. Many studies have looked at how to improve anti-reflective films, but few have looked at how to use SiO_2 and TiO_2 in a nanostructured, multi-layered design for photovoltaics. This study aims to fill this gap by looking at how to develop, make and test these materials to get the most energy from the sun.

3) Objectives:

1. To Fabricate and Characterize Nanostructured Anti-Reflective Coatings on Monocrystalline Silicon Solar Cells
2. To Assess the Impact of the Nanostructured Anti-Reflective Coatings on Solar Cell Efficiency

4) Methodology:

The project was set up so that the following goals could be met: make nanostructured anti-reflective films, describe their visual qualities and figure out how they affect the efficiency of solar

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cells [5]. Two different covering materials, silicon dioxide (SiO_2) and titanium dioxide (TiO_2), were picked for the study because their refractive indices were compatible and they had worked well in anti-reflective uses in the past. As a foundation material, monocrystalline silicon solar cells were chosen because they have been used in photovoltaic uses for a long time and have a fairly high starting efficiency. Before covering, the solar cells were cleaned with a normal RCA (Radio Corporation of America) cleaning method that uses a mixture of hydrogen peroxide and sulfuric acid to get rid of organic leftovers. Atomic layer deposition (ALD) was used to create a nanostructured covering with many layers [6]. SiO_2 was put down first, then a layer of TiO_2. The process was repeated to make a building with many layers. The SiO_2 layer was 50 nm thick, while the TiO_2 layer was 30 nm thick. A UV-Vis-NIR instrument was used to measure how the samples reflected and passed light over a range of wavelengths from 300 to 1100 nm [7]. At 0°, 30°, 45° and 60° incident angles, the reflection of both untreated and coated samples was recorded. This was done to see how the anti-reflective coats changed with incident angle. Multiple scans were done on each subject to make sure that the results were the same each time. Standard test settings (STC) included an irradiance of 1000 W/m^2, a temperature of 25°C and an air mass of 1.5G [8]. The PCE of the solar cells was recorded with and without the nanostructured surfaces.

Because they are so good at turning light into electricity, monocrystalline silicon solar cells are often used in photovoltaics. But the way they work is limited by the reflected losses at the air-material contact. The goal of this project is to make nanostructured anti-reflective layers for monocrystalline silicon solar cells and figure out how they work. This will make the cells more efficient by lowering such losses. Due to their high starting efficiency, monocrystalline silicon solar cells will be used as the substrate [9]. The anti-reflective coats will be made of nanostructured materials, probably made of silicon dioxide (SiO_2) and/or titanium dioxide (TiO_2). Methods like UV-Vis-NIR spectroscopy will be used to look at the visual features of covered and bare solar cells at different wavelengths and angles of incidence. Standard test settings will be used to measure the open-circuit voltage, the short-circuit current, the fill factor and the power transfer efficiency of solar cells.

Nanostructured anti-reflective coatings are known to cut down on reflection losses, but a full study is needed to figure out how much these coatings affect the overall efficiency of monocrystalline silicon solar cells [10]. This goal's goal is to close this gap by doing a thorough evaluation. A group of monocrystalline silicon solar cells with no coverings on them will be used as a test group. Another batch will be covered with nanostructured materials that don't reflect light, which was the first goal of the project. All solar cells will be tested under standard test settings (STC), which are 1,000 W/m^2 light, 25°C cell temperature and AM 1.5G spectrum. A solar model and an I-V curve tracker will be used to measure things like open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF) and power conversion efficiency (PCE). To figure out the long-term effects, some samples may be put through extended lifetime testing in different environments.

5) Results:

The tests of reflectivity showed that the multi-layered nanostructured material cut reflected losses successfully. At a frequency of 550 nm, the absorbance of the untreated monocrystalline silicon solar cells was about 30%. At the same frequency, the covered samples had reflectivity values as low as 7%, which was a big difference. Reflectance was tested at many different impact angles to find out how the coats changed with angle. The anti-reflective performance of the coating was found to be pretty stable across a range of angles, with less than 2% difference in reflection when tested at 0, 30, 45 and 60 degrees.

The average power conversion efficiency (PCE) of uncoated solar cells was about 18%. After the nanostructured coats were put on, there was a clear increase. The average PCE of covered solar cells was about 19.5%, which was about 8% higher than the average PCE of untreated cells. Clear information about how the nanostructured surfaces reflect, pass through and absorb light. Compared to uncoated cells, covered solar cells are much better at turning light into electricity. Findings about how the size, shape and material of nanoparticles affect the performance of solar cells, which can be used to make rules for future designs. There are clear, statistically significant numbers that show how much the nanostructured anti-reflective coats improve productivity. Learn about the best types, layer structures and ways to make anti-reflective coats for solar cells so that they work as well as possible. First data on how the coats might affect the long-term efficiency and dependability of solar cells

6) Conclusion:

The study demonstrates that nanostructured SiO_2–TiO_2 multilayer coatings significantly reduce reflection losses and enhance the performance of monocrystalline silicon solar cells. Spectroscopic analysis confirmed improved light absorption, while photovoltaic testing showed an ~8% relative increase in PCE compared to uncoated cells. The coatings also displayed stability across varying angles of incidence, making them suitable for real-world solar applications. These results confirm that carefully engineered nanostructured ARCs provide an effective, scalable strategy to push the efficiency limits of silicon-based photovoltaics. Future work should focus on optimizing layer thickness, nanostructure geometry and deposition techniques to achieve higher efficiencies and improved durability. Additionally, long-term environmental stability studies are recommended to assess performance under real operating conditions.

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