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# Recent developments in multifunctional coatings for solar panel applications: A review

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ABSTRACT

Conventional resources of energy production by burning fossil fuels are detrimental to the earth's atmosphere leading to serious problems such as global warming and acid rain. As a result, renewable and green energy technologies have gained lot of attention in the recent years. In particular, the improvement of solar panel efficiency has grabbed a significant domain of researchers' interest since sun is the year-round available source of energy that can be efficiently utilized for energy generation. However, a significant part of the incident solar energy is being lost due to the reflection at the air/glass interface as well as the accumulation of dusts on the modules. Hence, the surface morphology and characteristics of solar panel surfaces have recently been enhanced using multifunctional thin films or coatings in order to improve their self-cleaning, anti-reflection, anti-fogging and energy transmittance properties of the coated solar panels. A wide range of materials and methods have been employed in fabrication of solar panel coatings including superhydrophobic, superhydrophilic and photoactive coating surfaces.

In this review, the current state of fabrication of solar panel coatings and their properties, including surface morphology, wettability, electrical conductivity and light transparency characteristics, are discussed. The review starts with discussing the fundamental concept of self-cleaning (i.e., superhydrophobicity/superhydrophilicity) and antireflective (i.e., transparency) properties followed by presenting a review of the recent methods and technologies used in manufacturing of superhydrophobic, superhydrophilic, photoactive and transparent thin films used in solar panel coatings. More importantly, the recent development on the fabrication and application of self-cleaning and dust-repellent antireflective coatings in solar modules have been discussed. Lastly, recent reports on advanced coatings with hybrid functionalities such as self-healing and antimicrobial activity are presented.

## 1. Introduction

Each year, almost $5 \times 10^{24}$ J of energy is provided by the sun and hits the surface of the earth. This quantity is 10,000 times higher than the actual annual energy consumption of the whole world. Amongst various sustainable energy resources available, solar energy has recently been evolved as the most important sought after source of renewable energy due to the year-around abundance of sunlight and also due to the technological advances in capturing the light energy. Over the years, solar PV power cells have managed to be the main source of harnessing solar power since they are not only renewable but also safe and free of pollution [1]. The PV arrays on their own provide a relatively economic method of producing electricity with high efficiency. Nevertheless, factors such as high capital investment and glass surface sensitivity tend to hinder the efficiency of solar panels [2]. Still, the conversion efficiency of the commercial photovoltaic (PV) modules is as low as 20%, which is attributed to the reflection loss at air/module interface and dust accumulation over the modules. As a result, improvement of solar modules/panels has gained significant attention by the scientists all over the world [3]. This improvement is largely focused on the development of functional coatings for solar panels. At this end, the solar energy materials are predominantly chosen in such a way that the developed coatings possess several key features, such as absorption efficiency, electrical conductivity, transparency, wettability (i.e., hydrophobicity/hydrophilicity) etc. in order to maximize the performance of solar panels. In general, the solar module materials must be of high transparency with superb self-cleaning ability.

PV modules based on crystalline silicon cells (c-Si), are still

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**Nomenclature**

| | |
|---|---|
| CA | Contact angle |
| PV | Photovoltaic |
| PDMS | Polydimethylsiloxane |
| SA | Sliding angle |
| $TiO_2$ | Titanium dioxide |
| $SiO_2$ | Silicon dioxide |
| ZnO | Zinc oxide |
| $SnO_2$ | Tin dioxide |
| ITO | Indium tin oxide |
| FTO | Flourine doped tin oxide |
| CVD | Chemical vapor deposition |
| TEOS | Tetraethyl orthosilicate |
| HMDS | Hexamethyldisilazane |
| PTFE | Polytetrafluoroethylene |
| TMOS | Tetramethyl orthosilicate |
| PVDF | Polyvinylidene fluoride |
| ZnS | Zinc sulfide |
| PEDOT: PSS | poly (3,4-ethylenedioxythiophene) polystyrene sulfonate |

predominantly used in the market (with conversion efficiencies of 15% for polycrystalline and 20% for monocrystalline silicon cells), however they are mostly rigid, opaque and flat, and incur low efficiencies [4]. Therefore, in order to be a better transition to renewable energy solutions, the integration of PV modules into transparent components is a much more effective choice, particularly in buildings with curtain-wall facades or large skylights. Moreover, in order to avoid affecting the occupants' visual comfort too much, good transparency (or, at least, semi-transparency) becomes a fundamental requirement to comply with. In the last decades, a number of pioneering research investigations dealing with new PV materials has paved the way to the development of semitransparent, color-tunable, flexible, lightweight, robust and easily-processible PV technologies [5,6].

However, the efficiency and transparency of semi-transparent (ST) solar cells typically compromise each other, and one of the major challenges in the fabrication of ST solar cells is to develop high efficiency and tunable transparency from both sides of the devices, which are closely related to the properties of the two transparent electrodes on the bottom and the top of the devices and the active layers [7]. Table 1 shows the recent developments of transparent electrodes based on thin films of metal nanowires, graphene and carbon nanotubes (CNTs) that offer greater opportunities for preparing high-performance solar cells. The sheet resistance included in Table 1 is measured on glass substrates.

Moreover, dust accumulation is one of the major causes associated with lower energy outputs since power output has a strong positive correlation with incident solar irradiation, and the layers of dust and debris behave like a barrier for incoming rays [2]. For instance, Elminir et al. [8] and Mazumder et. al [9] reported that a dust deposition layer of 4 $g/m^2$ can decrease solar efficiency by 40%. A study by Hee et al. [10] found that despite of heavy rainfall, the transmittance of solar panels had reduced to 87.6% from 90.7%. The effect of dust deposition on different types of PV panels was studied by Jiang et al. [11] and it was found that as the dust deposition density increases from 0 to 22 $g/m^2$, reduction in power output increases from 0% to 26% [11]. However, it is important to note that dust differs in different parts of the world and the factors such as, panel orientation, direction of wind, and the dust composition have a collective effect on the layer of dirt that accumulates on the solar panels [2]. Therefore, in order to minimize the effect of dust accumulation on PV array efficiency, the solar panels need to be coated with functional materials; the coatings should have the ability to eliminate some of these factors by either reducing dust deposition or by reducing the effect of the dust layer by methods other than natural or mechanical [1].

The surface treatment of solar panels with thin coating layer(s) would increase its potential to protect the reflectors and absorbents from corrosion, dirt and reflection loses [12]. Self-cleaning coatings ease the removal of dust from the solar panels that in turn increases their energy conversion efficiency. Typically, self-cleaning of solar panels is achieved by using natural power, mechanical or electrostatic methods and nano-film coatings [13]. Coatings of solar panels to increase their self-cleaning property involve two types of films, such as, superhydrophilic and superhydrophobic films. Self-cleaning nano-films are being considered as potential coatings for improving the efficiency of PV modules. They can be categorized into two main types of water contact; superhydrophobicity in *Lotus effect* and the photocatalytic hydrophilicity, which are primarily based on $TiO_2$ [14,15]. Indeed, both of these surface features facilitate the self-cleaning property of the underlying substrates. Superhydrophobic surfaces exhibit water contact angle of over ~150° forming spherical water droplets to be readily rolled onto the surface carrying away the dust and dirt, while superhydrophilic surfaces having lower water contact angle (~5°) enable complete spreading of water onto them easily carrying the dust particles as it flows [16].

Thus, this review has made an attempt to provide a number of different strategies, materials and methods that could be used in fabrication of solar panel coatings and to improve their performances. The paper is classified into two main sections; the first section is a brief introduction to the different kinds of coatings, such as, self-cleaning superhydrophobic/superhydrophilic, photoactive, and transparent conductive coatings, which exhibit the required characteristics of solar energy materials. It also includes the details of the chemical composition, and hierarchical roughness structure and the morphology of the

**Table 1**
Comparison of several materials used to develop transparent electrodes for solar cells [5].

| Materials | Deposition methods | Transmittance (%) | Sheet resistance ($\Omega$ $sq^{-1}$) | Advantages | Disadvantages |
|---|---|---|---|---|---|
| ITO | Metal oxide doping | 85 | < 15 | Good transparency and conductivity | Expensive, brittle, unstable to acid |
| FTO | – | 80 | 15 | Good transparency, conductivity and stability | Brittle, high roughness, low NIR transparency |
| Ag (NWs) | Large-area spray coating | 90 | < 15 | Solution processible, excellent transparency, conductivity and flexibility | High roughness, poor adhesion |
| CNT | Large-area deposition technique | 90 | 100 | Solution processible, excellent transparency, conductivity, flexibility and stability | Low output, high resistance and roughness |
| Graphene | Chemical/physical doping process | 90 | 30 | Excellent transparency, conductivity and flexibility | Low doping stability |
| PEDOT: PSS | Solvent and thermal post-treatment method | > 80 | < 65 | Solution processible, low cost | Low environmental stability |