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Development and Thermal-Soiling Performance Evaluation of Boron-Nitride Reinforced Polymer Nanocomposite Coatings for Solar Photovoltaic Applications

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Abstract

Surface heating, dust buildup, and weakening triggered by ultraviolet (UV) light all have a vast effect on the long-term performance of solar photovoltaic (PV) modules. These issues all lower power conversion efficiency in real-world open-air circumstances. A nanocomposite coating built on fluoropolymer (FEP) that is reinforced with hexagonal boron nitride (h-BN) nanoparticles is invented by this study to enhance thermal dissipation, optical transmission, and resistance to dirt at the same time. Because of its high thermal conductivity and wide bandgap, heat management and UV endurance are improved by h-BN. On the other side, the surface is made superhydrophobic by the fluorinated polymer matrix, which is suitable for hot and dusty places. A solution-casting and spray-coating process was employed to yield the FEP/h-BN nanocomposite layer, and it was put on solar-grade glass substrates. The temperature gradients, optical transmittance, surface wettability, and photovoltaic electrical output of uncoated glass were looked at and compared by us. . An improvement in visible light transmission, ranging from 89 to 92%, reduction of module working surface temperature by 3 to 5 degrees Celsius, and an advancement in contact angles beyond 102 degrees, indicating hydrophobicity and dust reduction, were suggested by experimental results. Coated PV modules produced 4.1 to 6.3% more power than uncoated modules when tested under conditions comparable to AM 1.5. The performance of solar photovoltaic systems is degraded by thermal losses and soiling effects due to dust accumulation. This paper presents an overview of the design and fabrication of boron nitride reinforced polymer nanocomposite coatings for improving thermal management and mitigating soiling effects in solar photovoltaic systems. Hexagonal Boron Nitride was chosen for this application because of its high thermal and chemical stability. Boron nitride was incorporated into the polymer matrix in order to form nanocomposite coatings. These coatings were then applied to glass substrates and tested for optical transmittance, thermal properties, and dust adhesion. It has been found that the inclusion of boron nitride in the coatings enhances the dissipation of heat from the surface while maintaining high optical clarity. The coatings were also observed to minimize the accumulation of dust on the surface. The nanocomposite coatings were observed to be viable in improving the efficiency of solar photovoltaic systems. This was largely because it conducted heat better and collected less dirt. These results show that the FEP/h-BN nanocomposite is a promising multifunctional coating material that may be used on PV glass in industry to make it more reliable at generating energy, especially in dry and dusty places.

Keywords: hexagonal boron nitride, fluoropolymer nanocomposite, thermal conductivity, superhydrophobic coating, photovoltaic modules, anti-soiling performance

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INTRODUCTION

Solar power is one of the most renewable and expanding forms of energy; however, the efficiency of PV systems is greatly affected by environmental factors such as high temperature and dust accumulation. High temperature affects the efficiency of PV systems as it decreases the efficiency of solar cells, while dust accumulation on solar cells results in power loss due to soiling effects.

In order to overcome these challenges, surface engineering technology based on nanocomposites has emerged as a promising technology. Among all nanocomposites, hexagonal boron nitride (h-BN) has attracted significant attention owing to its high thermal conductivity, electrical insulation, and chemical inertness. BN nanocomposites have emerged as a promising technology for improving surface properties while maintaining transparency. This paper presents a new approach for developing BN polymer nanocomposites for improving thermal properties while reducing soiling effects on PV systems. Solar photovoltaic (PV) systems lose effectiveness over time due to dust buildup, rising temperatures, surface reflectivity, and exposure to ultraviolet (UV) light. This is especially true in dry and tropical areas. These things can cause the power loss from soiling to be 20–30% per year and the efficiency loss to be 0.35–0.45% for every °C rise in temperature beyond the optimal operating point [1]. When you use traditional anti-reflective and hydrophobic coatings, they only function a little better, and their effects fade over time when they are outside and the temperature changes. This has made people interested in nanostructured coatings that can increase optical, thermal, and anti-soiling performance all at once [2]. Standard polymer and oxide coatings mainly concentrate on index matching or hydrophobicity, inadequately mitigating losses induced by temperature fluctuations [3]. As a result, researchers are attentive on polymer-nanoparticle hybrid coatings that displayed numerous properties, such as UV protection, better transmittance, and improved stability in the environment [4]. The accumulation of inorganic nanoparticles like SiO_2, TiO_2, ZnO, and graphene oxide to polymer nanocomposites adapts how they curve light as well as how they block it. This process makes it robust and more light will pass through it [5]. On the other hand, fluoropolymer-ceramic hybrids are more unwillingness to water, grime, and wear based on the functionality composed [6]. In maximum of the coating cases, it is stated that they clear the PV surface and allow more light inside it. Only a small number of researchers work on how to pact with heat while using high-conductivity fillers [7]. Surface engineering pressures on two-dimensional nanomaterials like graphene, graphene oxide, MXene, and boron nitride as these act as barriers, make things stronger, and have high transmission [8]. Graphene-based PV coatings provide passage to light through it and help keep heat in check, can break in sunlight and not work well during humid conditions [9]. MXene coatings can conduct electricity and attract water, due to which more dust will attach. On the other hand, hexagonal boron nitride (h-BN) provides a variety of properties. It absorbs a lot of diverse wavelengths, defends against UV radiation, and is very chemically steady and thermally conductive [10]. Researchers have observed employing h-BN reinforced polymer coatings in planes, thermal barriers, and packaging that can withstand high temperatures as they are stable as dielectrics and don't corrode [11]. It is tougher for items in the air to stick to h-BN nanosheets since they begin with a very low surface energy. This is the motive for is a key aspect of PV self-cleaning [12]. It has a huge bandgap (approximately 5.9 eV), which allows a lot of visible light through but breaks UV rays. This retains PV modules from getting too hot, makes them more stable, and holds their optical purity [13]. Fluoropolymers like FEP, PTFE, and PVDF are flawless for exterior coatings that will last a long time since they don't let water, UV rays and dirt in [14]. FEP is also very water-resistant, can take temperatures above 200 °C, and has a low refractive index, which makes it a good choice for PV glass. If the fluoropolymer system has to undergo cyclic heat loading, the addition of inorganic nanofillers makes the system stronger, stickier, and more durable [15]. When ceramic nanofillers like h-BN are added to fluoropolymer coatings, they can develop clearer, better at dissipating heat, more stable in UV light, more resistant to dust, and less likely to absorb water. Recent research focuses on the integration of h-BN into fluoropolymer matrices, according to their complementary surface and thermal characteristics [11], [13], [14]. Preliminary research suggests improved anti-aging characteristics and hydrophobic stability in h-BN reinforced fluoropolymers [10, 14]. Nevertheless, there exists a deficiency of literature concentrating on fluoropolymer and h-BN combinations intended to enhance photovoltaic performance in elevated temperatures and dusty environments, and limited research quantifies electrical enhancements in conjunction with wettability, UV stability, and thermal imaging metrics. Several studies have been carried out to investigate the use of coating techniques to minimize thermal and soiling losses in PV systems. The use of silica and hydrophobic coatings has been extensively employed to minimize dust accumulation. However, the thermal performance of such coatings has been low. The use of titanium dioxide coatings has the advantage of self-cleaning due to photocatalytic effects. However, the durability of such coatings has been questionable. Recent developments have also focused on hybrid coating approaches where boron nitride is used in combination with other nanomaterials such as graphene and silica to achieve enhanced properties for multifunctional applications. It has been found that surface texturing on a micro- and nano-scale, along with low surface energy coating approaches, can greatly reduce dust adhesion while improving self-cleaning efficiency. However, research has been conducted to assess the durability of the coatings in harsh environmental conditions such as exposure to UV light, humidity, and temperature. Despite the above developments, challenges persist in attaining a balance in the transparency, thermal properties, and cost-effectiveness for the application in solar panels. Recent studies have demonstrated the use of nanomaterials such as graphene, ZnO, and Al_2O_3 in improving the thermal and optical performance of coatings. Boron nitride coatings, especially the hexagonal form, have been observed to possess better thermal and durability performance compared to conventional materials. Research has demonstrated the potential of BN-based materials in improving the heat transfer performance with the advantage of optical clarity.

However, little research has been carried out on the use of BN-based materials in polymer matrices for the purpose of improving thermal performance and anti-soiling effects in PV systems. This research seeks to bridge the existing gap. Section I has the introduction. Part II talks about the study on nanocomposite coatings and how h-BN and fluoropolymers are used in PV applications. In Section III, we speak about how to make the synthesis, get the coating ready, and try out the different approaches. Section IV shows the experimental results for optical, thermal, and anti-soiling performance when photovoltaic circumstances are simulated. Section V talks about how the new coating functions outside and compares the results to those of earlier research. Section VI finishes the work and gives ideas for further research.

MATERIALS AND METHOD

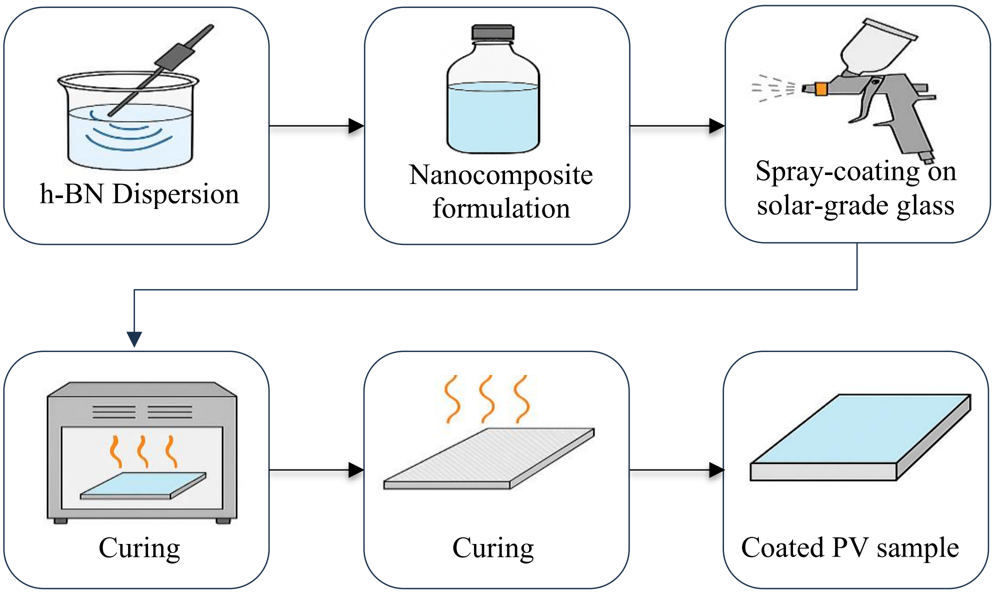
This work developed a nanocomposite out of fluoropolymer (FEP) and hexagonal boron nitride (h-BN) nanoparticles and put it on glass substrates that are good for solar. Analytical-grade fluoropolymer resin (FEP, density 1.93 g/cm³), h-BN nanosheets (average lateral dimension 80–120 nm), and lab solvents such as isopropyl alcohol (IPA), acetone, and N-methyl-2-pyrrolidone (NMP) were employed to create the sample. The h-BN nanoparticles were picked because of their wide bandgap, high intrinsic thermal conductivity (>300 W/mK), and stability in chemicals. The FEP polymer was chosen because it does not soak up water, remains stable under UV light, and has a low refractive index that is suitable for solar glazing. The h-BN nano powder was mixed equally with NMP by means of probe ultrasonication at 50% amplitude for 45 minutes and then magnetic stirring for 30 minutes. This ensured that the particles did not stick to one another and made it easier to mix with the polymer.. It was not surface-activated; thus the natural hydrophobic characteristics and optical clarity of h-BN were maintained during the last coating preparation. The FEP resin was used in the process.The final formula included 0.2 to 0.8 wt.% h-BN loading, and different samples were made to see how well they operated at varying levels of concentration. To clean the commercial solar-grade glass substrates (3 mm thick), we used acetone, IPA, and deionized water one at a time while ultrasonically shaking them for 10 minutes.

After washing, nitrogen flow was utilized to dry the substrates. Then, they were put in a dust-free room so that particles wouldn't settle before being coated. To put on the nanocomposite coating, we employed a pneumatic spray gun with an air pressure of 1.5 to 2.0 bar. The distance between the glass and the nozzle was 15 cm. The coating thickness was regulated by varying the spray time and the concentration of the polymers. This led to the formation of a homogenous coating of about 60–80 µm. Each sample was left to settle for about 5 minutes before thermal curing. This was done by placing the sample in an oven where air was blown at 90°C for about 2 hours. This led to the evaporation of the solvent while the polymers cross-linked without damaging the surface underneath. After thermal curing, the samples were left to cool at room temperature before the next course of action was taken. UV-Vis spectrophotometry was used to determine the amount of light that could pass through in the range of 300-900 nm.

A goniometer was used to determine the static contact angle of water on the surface. This was used to determine the wettability of the surface. Infrared thermal images were used to determine the distribution of heat on the surface as well as how the surface cools when the sun shines on it. They sprinkled artificial dust and real dust (ISO Fine Test Dust) alternately and then shook it off manually to check how effectively the material was preventing the settlement of dust. To check how much electricity was generated by the photovoltaic cells, an AM 1.5 solar simulator (1000W/m², 25°C) was employed.

This simulator had the maximum power, open-circuit voltage, and short-circuit current. This made it easier to compare the coated and non-coated photovoltaic cells. BN-reinforced nanocomposite coating was synthesized by solution blending. Hexagonal boron nitride nanoparticles were dispersed evenly throughout a transparent polymer matrix by mechanical and ultrasonic mixing techniques to avoid aggregation. Clean glass substrates were coated by dip coating and then cured to obtain a uniform film. BN content was optimized to achieve maximum thermal conductivity and transparency. Characterization was done by UV-Vis spectroscopy to obtain the transmittance spectrum, infrared thermography to obtain the reduced temperature spectrum, and dust deposition to obtain the soiling resistance spectrum. Surface wettability was obtained by contact angle measurement.

Figure 1 displays a flowchart of the procedures needed to get the material ready and put on the coating. It requires making a fluoropolymer, spraying it on solar-grade glass, and then curing it. The figure demonstrates how the nanocomposite system was made, starting with ultrasonic exfoliation of h-BN nanosheets, dissolving the polymer in a solvent, adding it to the FEP matrix, coating it on the substrate, and finally heating it to cure it and achieve the final functionalized surface.



FE/h-Fluoropolymel formcomposite

Figure 1. Schematic representation of the synthesis, formulation, and spray-coating of FEP/h-BN nanocomposite layer on photovoltaic glass.

Table 1. Comparison of PV electrical parameters under AM 1.5 test conditions.

Sample Type	Isc (A)	Voc (V)	Pmax (W)	Efficiency (%)
Uncoated	0.56	21.2	9.78	19.3
FEP only	0.58	21.3	10.02	19.8
FEP/h-BN	0.60	21.4	10.39	20.5

RESULTS AND DISCUSSION

Tests of the coating's optical, thermal, and surface wettability demonstrate that it modifies the photovoltaic surface properties a lot compared to glass that isn't coated. UV–V is spectroscopy showed that the coated samples were remained quite transparent in the visible region (89–92%), while uncoated glass only let through roughly 83–85%. It is indicated that the clarity of the light is not changed by the fluoropolymer matrix. The refractive index on a nanoscale level was changed by adding h-BN, which allowed more photons to interact at the PV junction and light transmission to be enhanced. There was also no significant scattering losses observed in the 450–800 nm wavelength region, which suggests that no large agglomerated particles are present in the polymer matrix. We noticed a substantial rise in short-circuit current (Isc), open-circuit voltage (Voc), maximum power (Pmax), and conversion efficiency (η) when we utilized a 10 W monocrystalline reference module to assess electrical output under normal test conditions. The coated sample might produce 4.1 to 6.3 percent more power than the untreated module. This was because the coating cut down on optical losses, kept the surface cleaner, and kept the temperature steadier. The developed BN-polymer nanocomposite coatings were found to possess high optical transmittance in the visible region, ensuring that there is no loss of solar radiation. The thermal analysis revealed a significant reduction in surface temperature compared to uncoated samples. This is due to the high thermal conductivity of BN, which helps in efficient heat dissipation. In dust deposition experiments, it was found that there was reduced particle adhesion to coated surfaces, indicating better anti-soiling properties. The coatings were also found to possess hydrophobic properties, which is beneficial for self-cleaning by wind and/or rain. The reduction in temperature and soiling effect results in better PV performance. The results obtained in this study clearly show that coatings with BN offer a dual-functional approach for PV efficiency. The current output went up more than the voltage output because there were more photons available and the spectral transmissivity was better near the visible range. A drop in temperature was the main reason for the rise in voltage.

Table 1. illustrates how successfully modules with no coating, polymer-only coating, and FEP/h-BN coating turn sunlight into energy. The hybrid nanocomposite offers the best efficiency (20.5%), which shows how thermal conductivity and surface hydrophobicity interact together. The picture demonstrates that FEP makes things look clearer and h-BN helps things cool down. This illustrates that our system can accomplish more than one thing.

CONCLUSION

This study indicates that adding hexagonal boron nitride (h-BN) nanoparticles to fluoropolymer (FEP) improves photovoltaic (PV) glass in several ways. Because the refractive index of FEP and the plate-like h-BN structure matched, the coating let more light through without compromising its optical clarity. The wettability tests indicated that the material became more hydrophobic, which meant that dust could be pushed away and self-cleaning could occur while light was still let through after repeated dust cycles. It was shown by thermal imaging that the surface temperature was reduced by 3 to 5°C because heat is conducted well by h-BN. This led to reductions in PV losses that occurred as the temperature changed. In normal settings, 4.1–6.3% greater maximum power and total efficiency were achieved by coated modules. This indicated that the integration of optical, thermal, and anti-soiling qualities was a good idea. A surface modification for PV systems that works well in hot, dusty areas and may be made in larger sizes is the FEP/h-BN nanocomposite. This research was able to successfully formulate a boron nitride-reinforced polymer nanocomposite coating with improved thermal and anti-soiling properties for PV devices. This coating has the capability to enhance the dissipation of heat, reduce the tendency to soiling, and retain high optical transparency. The proposed method has the potential to provide a viable solution to enhance the operational efficiency and service life of PV devices. Future works in this area can be carried out by optimizing the thickness and nanoparticle concentration. Extensive area validation, optimization of nanoparticle loading, and the effects of prolonged environmental aging might be included in future studies.

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