

Application of Graphene-Modified Self-Cleaning Antireflective Coating in Photovoltaic Glass

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Abstract: Solar photovoltaic power generation is a key support for China's energy transition and the "Dual Carbon" strategy. To address the problems of high reflection loss, severe power attenuation due to dust accumulation, single function and high-temperature curing requirement of conventional coatings for photovoltaic glass, a room-temperature curable graphene-loaded TiO₂ self-cleaning and antireflective composite coating was developed. This coating increases the light transmittance from 91.7% to 94.2%, achieves a power generation gain of 5%–7.1%, and reduces the power attenuation rate to 0.55%. With both superhydrophilic self-cleaning property and high weather resistance, it significantly reduces operation and maintenance costs, providing a feasible solution for high-efficiency and high-performance photovoltaic systems.

1. Introduction

Solar photovoltaic power generation is a critical supporting technology for China to realize the transformation of energy structure and achieve the goals of carbon peaking and carbon neutrality. In recent years, China's photovoltaic industry has maintained rapid growth. By the end of 2025, the cumulative installed capacity of photovoltaic power generation nationwide had exceeded 1200 GW, historically surpassing thermal power and hydropower to become the largest power source category in China. As the core packaging component of photovoltaic modules, the optical performance of photovoltaic glass directly affects the photoelectric conversion efficiency. Traditional low-iron ultra-clear photovoltaic glass suffers from 8%–10% Fresnel reflection loss due to refractive index mismatch with air, which significantly reduces light utilization efficiency. Meanwhile, photovoltaic modules are exposed to outdoor environments for a long time, and the continuous accumulation of dust, particulate matter and organic pollutants not only blocks light incidence but also causes hot-spot effects induced by local shading, accelerating module performance degradation and even leading to permanent damage. Relevant data show that in humid and hot, sandy and arid climate regions of China, the power generation loss of photovoltaic power stations caused by dust accumulation can reach 10%–18%, and the operation and maintenance costs such as manual cleaning and equipment cleaning account for more than 10% of the total operation and maintenance costs of power stations. Antireflective coatings are effective means to improve the light transmittance of photovoltaic glass. However, current commercial antireflective coatings generally suffer from single function, difficulty in balancing mechanical properties and weather resistance, and preparation processes relying on high-temperature annealing above 400 °C. The

high-temperature process not only has high energy consumption and is prone to environmental pollution, but also damages the performance of photovoltaic cells, making it difficult to apply on a large scale in built photovoltaic power stations. Nanoscale photocatalytic self-cleaning technology provides a new approach to solve the problem of module dust accumulation, among which TiO_2 has become an ideal material for self-cleaning coatings due to its good chemical stability, non-toxicity and excellent photocatalytic activity. Nevertheless, TiO_2 itself has a high refractive index of 2.55, which is significantly contradictory to the low refractive index required for antireflective coatings. Excessive addition greatly reduces light transmittance, while insufficient addition results in unsatisfactory self-cleaning effect. In addition, traditional TiO_2 -based coatings require high-temperature treatment to achieve crystallization and curing, which greatly limits industrial application. To break the industry pain point of mutual restriction among optical antireflective performance, mechanical strength and self-cleaning property, this study developed a room-temperature curable graphene-loaded TiO_2 -based self-cleaning and antireflective composite functional coating. Based on the low-temperature sol-gel method and combined with mesoporous SiO_2 composite and graphene modification technologies, the coating forms a firm film without high-temperature calcination, while balancing high light transmittance, self-cleaning property, weather resistance and large-scale construction requirements, providing a practical technical solution for high-efficiency and high-performance photovoltaics and low-cost operation and maintenance.

2. Experimental Section

2.1 Experimental Materials and Instruments

The main raw materials used in the experiment include tetrabutyl titanate, anhydrous ethanol, concentrated nitric acid, mesoporous SiO_2 nanoparticles, graphene dispersion and deionized water, all of analytical grade. Trina Solar standard polycrystalline silicon photovoltaic modules with a power rating of 240 W were adopted in the experiment. The main testing and preparation instruments include FAT200 contact angle measuring instrument, UV-Vis spectrophotometer, adhesion tester, weather resistance test chamber, photovoltaic module power tester, as well as TFCalc optical design software and Materials Studio DFT calculation module, which are used for coating structure simulation and performance optimization.

2.2 Controllable Preparation of Composite Coating

In this study, a low-temperature sol-gel route was used to prepare graphene-loaded TiO_2 -based composite coating sol. Firstly, tetrabutyl titanate was dissolved in anhydrous ethanol, and dilute hydrochloric acid was slowly added dropwise under stirring to adjust the pH to 2–3, controlling the hydrolysis rate to obtain a stable TiO_2 precursor sol. Subsequently, graphene dispersion with a mass fraction of 0.5%–1.5% was added to the sol, followed by ultrasonic treatment for 30 min to achieve uniform dispersion. The high electrical conductivity of graphene was utilized to improve the separation efficiency of photogenerated carriers and prolong the self-cleaning efficiency. On this basis, mesoporous SiO_2 nanoparticles were introduced to adjust the coating refractive index, and strong bonding force between the coating and the glass substrate was realized through Ti-O-Si chemical bonds. Finally, the composite sol was uniformly coated on the surface of photovoltaic glass by spraying method, and cured at room temperature for 30 min to form a continuous and dense composite film with both antireflective and self-cleaning functions. The whole process requires no high-temperature treatment, which is environmentally friendly and low in energy consumption.

2.3 Performance Testing and Characterization

To comprehensively evaluate the comprehensive performance of the coating, systematic tests were carried out from the dimensions of optical performance, self-cleaning property, mechanical properties, weather resistance stability and actual power generation performance. The light transmittance in the wavelength range of 380–1100 nm was tested by UV-Vis spectrophotometer to calculate the antireflective efficiency; the water contact angle was characterized by FAT200 contact angle measuring instrument to evaluate the superhydrophilic self-cleaning performance; outdoor exposure and dust accumulation test was conducted for 15 days to compare the self-cleaning effect of the coating. The coating adhesion was tested according to GB/T 9286, and the mechanical wear resistance was evaluated by a wear testing machine; the long-term stability of the coating under harsh environments was evaluated through accelerated tests such as wet-freeze cycle, damp-heat aging and ultraviolet aging. Meanwhile, a contrast test array was built in an actual distributed photovoltaic power station to continuously monitor the output power, power generation and attenuation of ordinary modules and coated modules, and quantitatively evaluate the contribution of the coating to power generation gain.

3. Results and Discussion

3.1 Coating Structure and Optical Performance Optimization

With the help of TFCalc optical simulation software and DFT theoretical calculation, this study accurately optimized the coating thickness, refractive index and mesoporous structure. The results show that when the coating thickness is controlled at 100–120 nm and the refractive index is adjusted to 1.25–1.35, the optimal antireflective effect can be achieved in the core response spectrum of photovoltaic cells (380–1100 nm). Graphene loading and mesoporous SiO₂ composite can effectively balance light transmittance and self-cleaning performance. Pure TiO₂ coating has a light transmittance of only 90.3% due to its high refractive index; after introducing mesoporous SiO₂, the coating forms a porous structure, the refractive index drops to 1.28, and the light transmittance increases to 94.2%; the introduction of graphene does not reduce light transmittance, but broadens the photoresponse range and improves the long-term self-cleaning property. Actual tests show that the light transmittance of photovoltaic glass coated with composite coating is increased by 2.5 percentage points compared with ordinary glass, and the light transmittance gain alone can increase the output power of modules by 1.5%–2%, laying a foundation for power generation gain^[1].

3.2 Self-Cleaning Mechanism and Performance

The self-cleaning effect of the composite coating originates from the synergistic effect of photocatalytic degradation and superhydrophilic stripping. Under light irradiation, electrons in the valence band of TiO₂ jump to the conduction band, generating electron-hole pairs, which react with oxygen and water to produce strongly oxidizing hydroxyl radicals and superoxide radicals. These radicals can decompose organic pollutants on the surface into carbon dioxide and water, reducing pollutant adhesion fundamentally. Meanwhile, ultraviolet light induces the formation of a large number of hydroxyl groups and oxygen vacancies on the coating surface, reducing the water contact angle to below 5° and presenting a stable superhydrophilic state. Rainwater spreads rapidly on the surface to form a continuous water film, scouring and stripping dust and particulate matter, significantly reducing dust accumulation. The introduction of graphene further improves the self-cleaning efficiency. Its high electrical conductivity can rapidly transfer photogenerated

electrons, inhibit electron-hole recombination, prolong the self-cleaning action time, and reduce electrostatic adsorption of dust to decrease the probability of particle adhesion. Outdoor exposure and dust accumulation tests show that the dust accumulation of coated modules is reduced by more than 65% after 15 days, maintaining a high light transmittance state without manual cleaning, and the self-cleaning effect is stable and reliable^[2].

3.3 Mechanical Properties and Weather Resistance Evaluation

Mechanical properties and weather resistance are key indicators for the long-term outdoor application of coatings. The room-temperature curable coating prepared in this study is firmly bonded to the substrate through Ti-O-Si chemical bonds, achieving Grade 0 in adhesion test and withstanding more than 1000 wear cycles, meeting the mechanical requirements for long-term outdoor use. Accelerated aging test results show that after 1000 hours of ultraviolet aging, 50 wet-freeze cycles and damp-heat aging at 85 °C/85% RH, the coating has no phenomena such as peeling, cracking and yellowing, the light transmittance attenuation is less than 1%, and the superhydrophilic property remains stable, possessing a 25-year long-term service potential matching photovoltaic modules. Comparative experimental data show that the average output power attenuation rate of ordinary photovoltaic modules after outdoor aging is 0.58%, while that of coated modules is only 0.55%, indicating better stability, which can effectively delay module performance degradation and extend service life.

3.4 Application Effect in Actual Photovoltaic Power Station

In the demonstration application carried out in a 30 MWp distributed photovoltaic power station in Yunnan, a coated module array and an ordinary module array were set for long-term comparative monitoring. The results show that coated modules achieve a power generation gain of 5%–7.1% compared with ordinary modules, with an average annual power generation benefit of 6.2%. The self-cleaning function of the coating can extend the cleaning and maintenance cycle from 1–2 months to more than 6 months, reducing manual and equipment cleaning costs by more than 50%, and significantly easing the operation and maintenance pressure of power stations. Based on the electricity price of 0.4 RMB/kWh, a 1 MW photovoltaic power station can increase annual revenue by more than 40,000 RMB, and the investment payback period is shortened from 6 years to 4.5 years, with outstanding economic benefits. Under extreme sandstorm and rainfall weather, the power stability of coated modules is significantly better than that of ordinary modules, with no obvious hot-spot effect, adaptable to complex outdoor environments and valuable for large-scale promotion and application^[3].

4. Technical Advantages and Industrialization Prospects

4.1 Core Technological Innovations

Compared with traditional antireflective coatings and self-cleaning technologies, the composite coating developed in this study has a number of core advantages. The coating simultaneously realizes four functions: antireflection and transmittance enhancement, photocatalytic self-cleaning, superhydrophilic dust prevention and long-term weather resistance, solving the performance defects of single coatings and meeting the multi-functional requirements of photovoltaic modules. The room-temperature curing process abandons high-temperature annealing at 400 °C, reducing energy consumption by 30%, free of organic solvent pollution and environmentally friendly. It can be directly used for the renovation of existing power stations, breaking through the application

limitations of traditional high-temperature processes. Through optical simulation and material composite, precise control of refractive index, thickness and pore structure is realized, effectively reconciling the contradiction between optical performance and mechanical properties, ensuring that the coating has excellent mechanical strength and weather resistance while maintaining high light transmittance^[4]. The coating has low preparation equipment investment, readily available raw materials and simple spraying construction, suitable for large-area industrial production and on-site construction, with significant cost advantages and large-scale potential.

4.2 Industrialization Application Prospects

China's annual new installed photovoltaic capacity exceeds 300 GW, and the cumulative installed capacity exceeds 1200 GW. The market size of self-cleaning antireflective coatings exceeds 10 billion RMB, with strong application demand. This technology can be widely used in scenarios such as centralized power stations, industrial and commercial distributed photovoltaics, residential photovoltaics and BIPV, compatible with various battery technologies such as monocrystalline silicon, polycrystalline silicon, TOPCon and perovskite, with strong versatility. At the policy level, the national "Dual Carbon" strategy and renewable energy development plan continue to promote the upgrading of the photovoltaic industry, and high-efficiency and low-operation-cost technologies have become market rigid demands. At the market level, power station operators have an urgent demand for power generation gain and cost reduction. The coating technology does not require module replacement and is fast in construction, with strong market competitiveness. With the continuous improvement of technology and promotion of standardization, this coating is expected to become a standard functional layer of photovoltaic glass, driving the photovoltaic industry towards high-efficiency, intelligent and low-cost development.

5. Conclusion

This study successfully prepared a room-temperature curable self-cleaning and antireflective composite coating of graphene-loaded TiO₂/mesoporous SiO₂. Through structural optimization and process regulation, the synergistic improvement of antireflective performance, self-cleaning property, mechanical strength and weather resistance is realized. The coating can increase the light transmittance of photovoltaic glass from 91.7% to 94.2%, achieve an actual power station power generation gain of 5%–7.1%, reduce the output power attenuation rate to 0.55%, and possess stable superhydrophilic self-cleaning function, reducing cleaning and maintenance costs by more than 50%. The room-temperature curing process is environmentally friendly, low-cost and can be applied on a large scale in new and existing photovoltaic power stations, with outstanding economic benefits and application value. In the future, the visible light response range of the coating can be further expanded, the self-cleaning efficiency in weak light environment can be improved, special formulas for extreme climates can be developed, and the formulation of standards and research and development of automatic construction equipment can be promoted to accelerate industrialization. This study provides a new idea for the design of multi-functional coatings for photovoltaic glass, and is of great significance for improving photovoltaic power generation efficiency, reducing operation and maintenance costs and promoting the high-quality development of the photovoltaic industry.

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