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A Transparent and Simple Synthesis of Superhydrophobic Coating Based on ZnO Microsheet/Epoxy Resin

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ABSTRACT

Environmental conditions and pollution significantly impact the performance of the power system. In dusty and foggy environments, the risks of degradation, leakage current, and pollution flashovers increase. Based on environmental and practical concerns, self-cleaning coatings present a promising solution to prevent power system failure. The current research uses a spray-coating method to apply a robust ZnO nanosheet/Epoxy resin superhydrophobic film onto a porcelain insulator. Hydrophilic ZnO nanosheet is successfully synthesized and modified with oleic acid using a simple wet chemical method. The water contact angle for ZnO/resin coating insulators was obtained at 153º. The obtained results demonstrate that wettability remains unchanged under ultraviolet illumination. A sandpaper abrasion test was then employed to determine the high strength of double-layer ZnO/resin coatings. While coating the glass, the water contact angle was obtained as 151º on the double-layer coated glass. The results further show that compared to the uncoated glass, the coated glass slide transmits 51% visible light. A robust ZnO/resin superhydrophobic coating with high mechanical stability and constant wettability can be effectively used for power line components. ZnO/resin coating can be applied to insulators in soiling sites, preventing contamination fouling. The results also indiacte that the leakage current of the insulator decreases by approximately 42% when using superhydrophobic ZnO/resin coating.

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1. INTRODUCTION

Environmental conditions have significant practical effects on the safety and stability of power system operation [1,2]. The rapid growth of industrial sites and chemical parks has contributed to an increase in dusty weather [3]. The accumulation of impurities on insulators and wires raises the risk of degradation, pollution flashover, and leakage currents [4,5]. Additionally, foggy environments and humid weather lead to the a combination of the water layers and contaminants, thus increasing the current leakage [6,7]. Photovoltaic system efficiency is also significantly reduced by the accumulation of pollution layers on solar panels [8–10]. Dry weather and dust storms promote the deposition of particulates on the power system components [11].

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Various methods have been employed to mitigate the pollution problems in power lines. Water jet cleaning is a standard method for transmission line cleansing [12]. In deserts and other impassable areas, external insulator washing and photovoltaic panel cleansing are expensive and require significant water and labor sources [13]. Aerodynamic insulators can be used in specific areas such as dry regions, where wind assists in cleaning the insulators [14]. Another method is using insulators with silicone or grease coatings. However, these coatings lose their dielectric and viscosity properties and require regular change, depending on the environmental conditions [15]. Room Temperature Vulcanized (RTV) coating offer effective anti-pollution properties but it shows poor performance and low mechanical stability after a while [16]. Other methods involves coatings with specific wettability properties, such as self-cleaning coatings that prevent particle accumulation [17]. The self-cleaning coatings, based on different materials such as aluminum nitride, titanium dioxide, zinc oxide, and hafnium oxide, imprve the electrical stability of insulators [18–20].

Zinc oxide (ZnO) is a non-toxic semiconductor with a wide bandgap (Eg=3.37 eV) and thermal stability [21–23]. ZnO can be synthesized into several dimensional nanostructures that exhibit photocatalytic activity and different wettability behaviors, namely hydrophobicity and hydrophilicity [24,25]. Hydrophobic surfaces have a Water Contact Angle (WCA) greater than 90°, while superhydrophobic surfaces have a WCA above 150°. In contrast, hydrophilic coatings have a WCA of less than 90 [26]. While hydrophobic surfaces are cleaned by rolling water droplets on the surface, hydrophilic surfaces are covered by water sheets that clean the surface. Self-cleaning coatings with hydrophobic properties prevent surfaces from becoming wet. Superhydrophobic coatings help avoid the formation of contaminant layers and water films on insulator surfaces. Oleic acid, a low-surface-energy material, is available in various animal and vegetable fats and oils [27]. Modifying ZnO nanoparticles with oleic acid produces superhydrophobic coatings [28]. The simple and low-cost hydrothermal method is used to modify nanoparticles with oleic acid [29].

ZnO self-cleaning coatings can be fabricated through different methods, such as wet-chemical deposition, sol-gel process, hydrothermal spray coating, and Chemical Bath Deposition (CBD) [25,30–34]. Among these methods, spray coating deposition is a simple and cost-effective method for self-cleaning coatings. One challenge faced by older power sites is the replacement of uncoated insulator. To be specific, replacing coated insulators at such sites can be costly, making the spray coating method particularly effective for depositing ZnO/resin self-cleaning coatings onto existing insulators.

Of note, self-cleaning coatings must be highly durable in contaminated and windy environments. ZnO/resin self-cleaning coatings offer a simple and least complex solition for surface coatings. Epoxy resin provides high mechanical stability and good adhesion to treated ZnO nanoparticles (np) [35]. ZnO superhydrophobic np/resin coating has been considered for application on insulators in transmission lines located in extremely dry areas.

In this study, the spray-coating method is used to deposit a superhydrophobic ZnO/epoxy resin self-cleaning coating on a porcelain insulator. The ZnO coating is characterized using a Scanning Electron Microscope (FESEM) to analyze the surface morphology. The wettability of ZnO/resin self-cleaning coating is evaluated by measuring the WCA. The spectra of the ZnO/resin coating Energy are analyzed using an Dispersive X-Ray Analyzer (EDX). Leakage current tests are conducted on the insulator with self-cleaning coating, and the influence of the ZnO/resin coating on the electrical properties of the insulator is analyzed. A visible light transmission test is done to study the transparency of the layer on the glass surface. Finally, a sandpaper abrasion test assesses the mechanical stability and adherence of the coating.

All chemicals used in the experiment were of analytical grade. Zinc nitrate hexahydrate ($Zn(NO_3)_2.6H_2O$) (Aldrich, USA), Sodium hydroxide (NaOH) (Merck, Germany), Oleic acid ($C_{18}H_{34}O_2$) (Merck, Germany), Resin epoxy (Gando, Iran), and Ethanol (C_2H_5OH) (Merck, Germany) were used as reagents. A 0.99 M zinc nitrate hexahydrate solution in deionized (DI) water was prepared to synthesize hydrophilic ZnO nanosheets. In a separate beaker, 2 M sodium hydroxide was dissolved in deionized water. The zinc nitrate solution was then steadily added to the NaOH solution dropwise at a low stirring speed. Subsequently, the blended solution was vigorously stirred at room temperature for 2 hours. The mixed solution was then centrifuged for 10 minutes, and the white precipitates were collected using filter paper. The residue was rinsed with ethanol and DI water three times. Finally, the collected ZnO microstructures were dried in a vacuum at 140-150℃. Fig. 1(a,b) represents the schematic of the ZnO nanosheet production.

To prepare superhydrophobic ZnO nanosheets, 0.14 M ZnO hydrophilic nanosheet and 40 mg oleic acid were dissolved in 6 ml ethanol, as shown in Fig. 1(c). The final solution was stirred at 80 ℃ for 90 minutes. For the first layer, the resin and hardener (in a 3:1 ratio) were dissolved in 10 ml of absolute pure ethanol for the first layer. Subsequently, the epoxy resin mixture was stirred at room temperature for 30 minutes to ensure a precise and uniform solution.

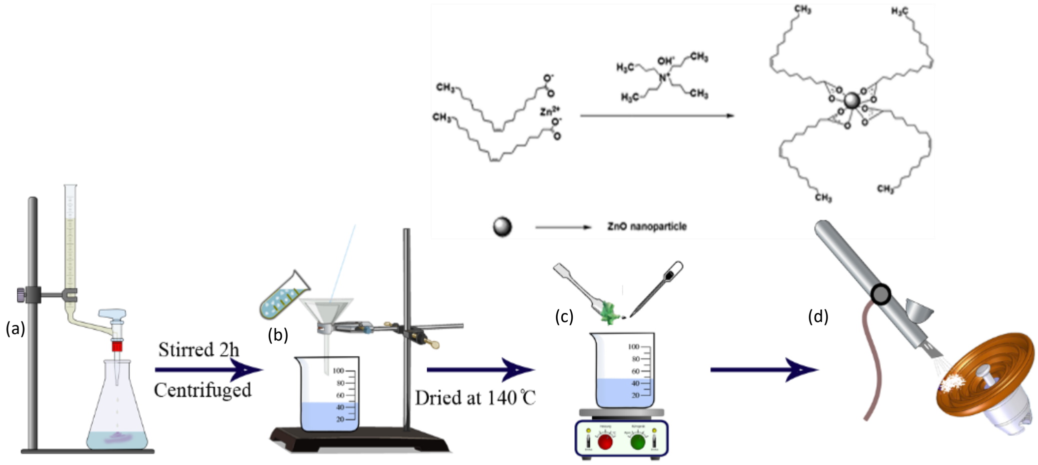

Figure 1: Schematic of superhydrophobic ZnO/resin coating process on insulator surface.

Porcelain insulators and glass slides were chosen as substrates. As a preliminary step, the substrates were cleaned with acetone, ethanol, and DI water. To apply a double-layer coating, the resin and ethanol solution were first sprayed onto the substrates by a spray gun. The airbrush was held at an optimal distance from the substrates to ensure complete surface coverage. The thickness of the coating layer is controlled by adjusting the pressure of the airbrush. For approximately 20 minutes, while the resin was not fully cured, ZnO superhydrophobic nanosheets in ethanol solution were sprayed onto the substrates. The coated surfaces were then allowed to dry at room temperature for 24 hours. The schematic of the superhydrophobic ZnO/resin synthesis process is illustrated in Fig. 1. As shown in Fig. 1(d), when oleic acid combines with zinc oxide, the long chains surround ZnO nanosheets.

The morphological and structural characteristics of the ZnO superhydrophobic coating were investigated using Field Emission Scanning Electron Microscopy (FESEM) images obtained by Hitachi S-4160 (20 kV, Japan). The chemical compositions of the coated surfaces were analyzed by Energy-Dispersive X-ray Spectroscopy (EDS). A UV/visible spectrometer (Perkin-Elmer, Lambda EZ201, USA) was also utilized to study the detector's response to different wavelengths. In addition, electrical properties were examined through leakage current tests. Here, the leakage current was measured on the grounding conductor connected to the insulator. The voltage applied to the conductor varied between 0 kV and approximately 20 kV, and the current was measured using an auto-ranging digital multimeter with true RMS capabilities. The mechanical stability of the self-cleaning coating was measured using a sandpaper abrasion test. A medium sandpaper with about 100-120 grit and a 100-g weight was also used for the stability test.

3. RESULTS AND DISCUSSION

Spray-coating is a simple method for providing a self-cleaning coating on various substrates. This scalable method can be used for power lines in non-laboratory environments. In addition, the spray method facilitates the deposition of multilayer coatings on substrates. In this study, double-layer ZnO nanosheets and epoxy resin coatings were applied to cover the porcelain insulator and glass slide, respectively. The morphology of superhydrophobic coatings containing ZnO nanosheets and ZnO nanosheets/epoxy resin deposited on substrates was investigated by SEM analysis. Fig. 2(a) shows that the modified ZnO nanosheets are well-formed with different lengths and widths with an average thickness of 100 nm. As shown in Fig. 2(b), the ZnO/resin film fully envelops the porcelain insulator. SEM analysis indicates that the epoxy resin layer containing ZnO nanosheets is more uniform than the superhydrophobic ZnO nanosheets.

Moreover, superhydrophobic ZnO nanosheets exhibited different textures within the epoxy resin, as presented in Fig. 2(b). A cross-section image of ZnO nanosheets/resin coating displays the trapping of superhydrophobic ZnO nanosheets in the resin layer (Fig. 2(c)). This double-layer coating allows the ZnO nanosheets to impart super hydrophobicity behavior and high stability.

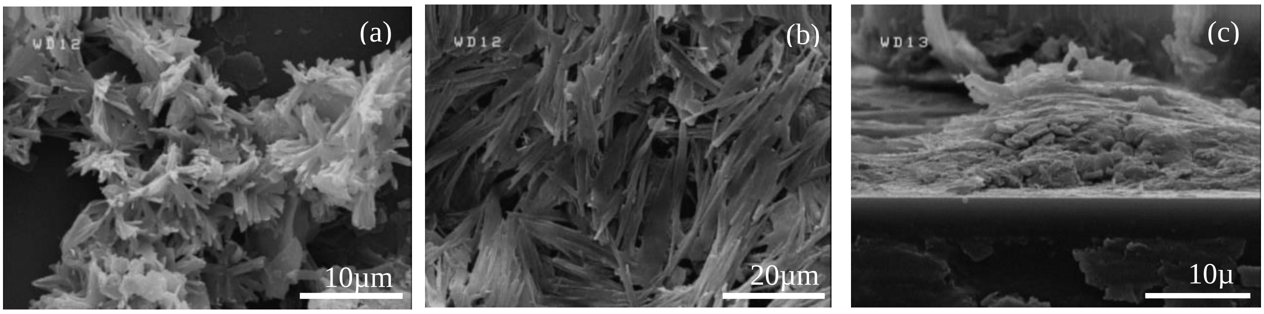

Figure 2: SEM images of (a) ZnO superhydrophobic microsheets, (b) ZnO NS/Resin superhydrophobic coating and (c) ZnO NS/Resin Coating cross section.

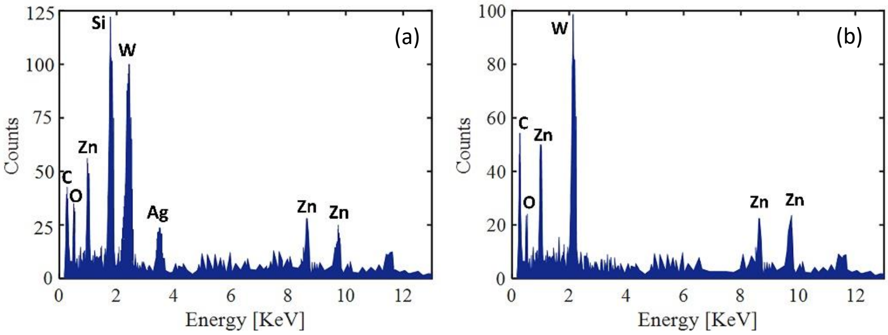

Figure 3. EDS analysis of (a) modified ZnO nanosheets and (b) ZnO/resin coating.

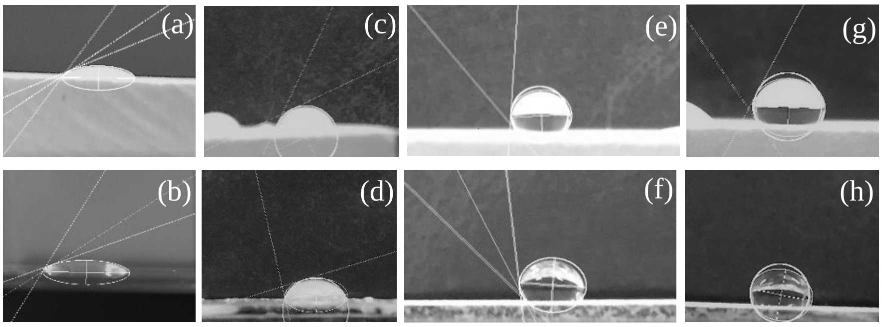

Figure 4. Water droplet on (a) porcelain insulator, (b) glass substrate, (c) resin coating on porcelain, (d) resin coating on glass substrate, (e) double-layer ZnO/resin coating on porcelain insulator, (f) double-layer ZnO/resin coating glass substrate, (g) porcelain with double-layer coating and (h) glass with double-layer coating after sandpaper abrasive test.

In the present research, EDS analysis was employed to determine the chemical composition of ZnO coating. According to the EDS results, zinc, oxygen, and carbon were observed, confirming the successful formation of modified zinc oxide nanosheets (Fig. 3). The other elements detected originated from the coating layer used for EDS analysis and the substrate. Further, the EDS analysis revealed the atomic percentage of zinc and oxygen atoms as 13.7% and 86.3%, respectively (Fig. 3(a)). In contrast, the atomic percentages of zinc and oxygen atoms in the ZnO/resin film were 18.7% and 81.3%, respectively (Fig. 3(b)). As shown in Fig. 3(b), there are two peaks in the EDS spectrum attributed to tungsten (W) and carbon (C) elements in the epoxy resin. Silicon (Si) and silver (Ag) peaks in the EDS spectrum are attributed to the substrate and EDS tests. Additionally, the similarity between the EDS spectrums indicates that the ZnO structures remained stable even after being mixed with resin epoxy.

The wettability is the most crucial figure of merit in characterizing the coatings. The WCA measurement was used to assess the wettability of double-layer ZnO/resin coating deposited on the porcelain insulator and glass substrates. According to Fig.4 (a,b), the WCA values for porcelain and glass without coating were obtained as 25±5° and 30±5°, respectively, indicating that the initial substrates were hydrophilic. For comparison, the WCA of the pure resin coating was measured on porcelain and glass substrates. As shown in Fig.4, the WCAs of porcelain and glass substrate with resin coating were 60±5° and 50±5°, respectively. On the contrary, the WCAs of the coated porcelain insulator and coated glass reached 153.7±5° and 151.2±5°, respectively (Fig. 4). These results show that the pure resin coating possesses hydrophilic properties while double-layer ZnO/resin coating exhibits superhydrophobic characteristics on both surfaces. As shown in Figs. 4 (g) and 4(h), the WCAs did not change on either substrate following the sandpaper abrasive test. For several times, both porcelain insulator and glass slide with superhydrophobic coating were exposed to ultraviolet (UV) light and according to the results, the WCA of the surfaces did not change with UV exposure. Additionally, there was no crack in the wettability behavior after UV exposure, a critical characteristic for some hydrophilic materials. The combination of pollution and water accelerates the aging process and increases the risk of leakage current.

Figure 5. Leakage currents test for (a) Uncoated and (b) coated insulators.

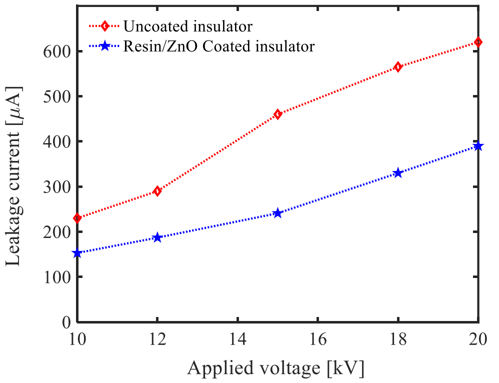

Figure 6. Leakage currents versus applied voltage for superhydrophobic ZnO/resin self-cleaning coating on insulator surface.

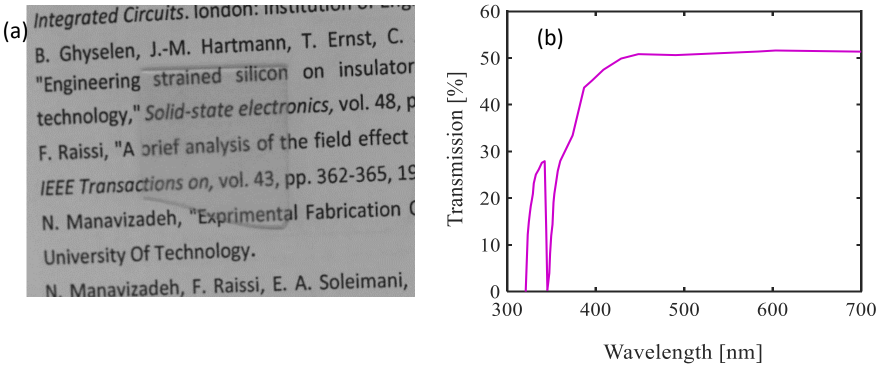

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Figure 7: (a) small glass slide with ZnO/resin superhydrophobic coating and (b) transmittance of glass with ZnO/resin coating in optical spectra.

In humid conditions, leakage currents flow across the surface of contaminated insulators. Lower leakage currents reduce the need for repairs in the distribution system and minimize the energy loss. The leakage current of coated and uncoated insulators was measured in a power transition simulation. Both types of insulators were connected to the power lines, and their surfaces were sprayed with water (Fig. 5). The leakage current was then measured for both coated and uncoated insulators under wet conditions, the results of which are plotted in Fig. 6 at different applied voltages. For the uncoated insulators, at 15 kV, the leakage current reached approximately 460 µA. By comparison, for the coated insulators at 15 kV voltage, leakage current dropped to 241 µA. Overall, the leakage currents in the coated insulators decreased by 42%, compared to uncoated ones.

The performance of solar panels is similarly affected by dusty weather conditions. The double-layer ZnO/resin superhydrophobic coating prevents dirt accumulation on the surface. Fig. 7(a) shows a glass slide with a double-layer ZnO/resin coating. Moreover, the transparency of ZnO/resin superhydrophobic coating makes it suitable for use in lighting applications. The transmission spectra show that the average transmittance of the coated substrate was 51% in the visible range of 400–700 nm (Fig. 7(b)).

Self-cleaning coatings are utilized in various places, specifically outdoors, where high mechanical stability is required. In this regard, a sandpaper abrasion test was conducted. The coating surface was subjected to a 100-g weight during the test. The sandpaper was then moved over a distance of 15 cm with a pressure of 5 kPa, and the scratching action was repeated 100 times. Afterward, the water contact angle was measured. The WCA of both the porcelain insulators and glass surfaces with ZnO/resin coating showed no significant change after 100 abrasion cycles, and the coating maintained its superhydrophobic properties.

4. CONCLUSION(S)

The robust double-layer zinc oxide superhydrophobic/resin coating was fabricated by spray-coating on a porcelain insulator and glass slide. Zinc oxide nanosheets were successfully synthesized by the one-step wet chemical method and further enhanced by oleic acid during a hydrothermal process, resulting in superhydrophobic behavior. In contaminated environments, the coating deposition on the insulator surface reduces replacement costs and offers significant technical and economic benefits. SEM analysis revealed that the double-layer modified ZnO nanosheets/resin coated the insulator densely and uniformly. The Water Contact Angles (WCAs) were approximately 153.7±5° and 151.2±5° on the porcelain insulator and glass slide with ZnO/resin coating, respectively. Double-layer ZnO/resin coating on glass and porcelain insulator surfaces represents superhydrophobic behavior. The superhydrophobic coating prevents water from flowing on the surface of the substrate. One of the most notable features of the coating is its stability in superhydrophobic behavior even after ultraviolet exposure.

According to the electrical results, the leakage current on the insulator surface decreased by about 42%. For the uncoated porcelain insulator at 15 kV, the leakage current was 460 µA while the coated porcelain showed a reduced current of about 241 µA at the same voltage. The double-layer ZnO/resin superhydrophobic coating also demonstrated high mechanical stability during the sandpaper abrasion test. Further, the transmission spectra of the coated glass showed 51% optical transmittance in the visible range of 400–700 nm—allowing potential applications in lighting such as solar panels. Self-cleaning ZnO/resin coatings are considerably suitable for reducing pollution in porcelain insulators, wires, and other components. The simple implementation method, high strength, and constant superhydrophobic behavior of double-layer ZnO/resin coating make it an effective solution for power line systems in polluted environments.

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