

Plasma Surface Modification for Regulating Material Insulation Performance: Mechanism Diagnostics and Applications

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Abstract. Protecting insulating materials from extreme environmental conditions to maintain their insulation performance, dielectric properties, and long-term durability is a critical challenge that researchers must address. This review examines the mechanisms and applications of plasma treatment technology in enhancing the insulation performance of materials. First, from a material performance perspective, the effects of plasma modification on key endurance characteristics—such as breakdown strength, flashover voltage, and contact angle—as well as various dielectric properties are analyzed. Second, the specific application outcomes of non-thermal plasma treatment technologies, including dielectric barrier discharge (DBD), corona discharge, microwave discharge, and radiofrequency (RF) discharge, are discussed in detail regarding their effectiveness in improving and enhancing the insulation and dielectric properties of insulators. Finally, a comprehensive assessment of recent research progress is provided.

Keywords: plasma surface modification, insulation capability/dielectric strength, surface electric field, charge accumulation, material performance

1. Introduction

Conventional insulating materials, such as polyethylene, polypropylene, and ceramics, exhibit satisfactory insulation properties under normal temperature and pressure conditions. However, their performance often becomes inadequate in complex operational environments. In high-voltage transmission lines, insulation failure may lead to short circuits, arc discharges, or even fires, resulting in significant economic losses and safety hazards [1]. Furthermore, in microelectronic devices, the quality of insulating layers critically determines leakage current and power consumption, thereby influencing overall device performance [2].

These traditional insulating materials face several inherent limitations, particularly concerning non-uniform surface electric field distribution and charge accumulation. Uneven electric field distribution can induce excessively high local field strength, triggering partial discharges or breakdown events [3]. Charge accumulation elevates surface potential, exacerbating field distortion and ultimately degrading insulation performance [4]. For instance, polyethylene tends to develop space charge accumulation under high-voltage DC fields, leading to field distortion and insulation

deterioration [5]. Although ceramic materials possess superior thermal resistance and mechanical strength, their brittleness and surface defects make them prone to partial discharges [6]. Additionally, the inherent difficulty in precisely controlling surface characteristics of these materials aggravates electric field non-uniformity, further increasing insulation failure risks. These issues become particularly pronounced under high-voltage, high-frequency, or extreme environmental conditions (e.g., elevated temperatures or humidity), severely restricting the application scope of conventional insulating materials. This necessitates the development of innovative plasma surface modification techniques for performance enhancement.

Non-thermal plasma (NTP) has attracted significant interest due to its unique properties and broad applications in fields like material science, surface treatment, medicine, and environmental protection. One promising use of NTP is improving the insulation and dielectric performance of outdoor insulators, which often face harsh weather conditions. Non-thermal plasma is created by energizing a gas to form a partially ionized mixture of charged particles (electrons and ions) and neutral molecules. This process, known as ionization, occurs when atoms or molecules gain or lose electrons after absorbing energy. Common methods for generating NTP include dielectric barrier discharge (DBD), corona discharge, and microwave or radio frequency (RF) discharges. Each method involves a specialized plasma generation system tailored to the desired application.

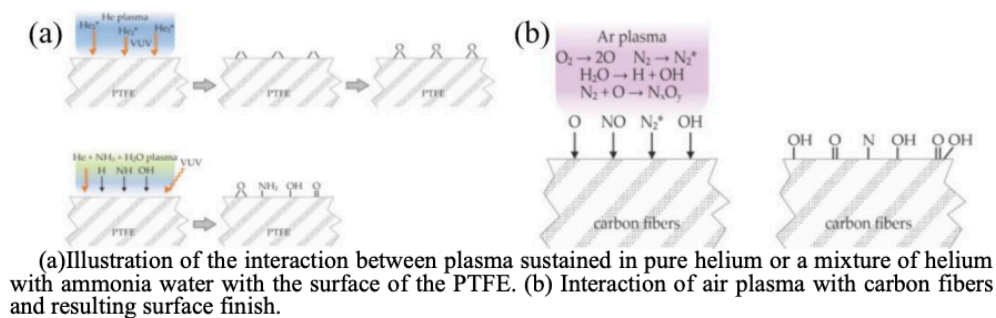


Figure 1. Mechanisms of plasma-material interactions

2. Fundamental principles of plasma surface modification

The interaction between plasma and material surfaces is a complex process involving synergistic effects of both physical and chemical interactions. The physical effects primarily include ion bombardment, sputtering, and energy transfer, while the chemical effects encompass surface chemical reactions and functional group incorporation [7].

2.1. Physical interactions

Ion bombardment occurs when high-energy plasma ions, accelerated by electric fields to energies ranging from hundreds to thousands of electron volts, impact material surfaces through two dominant mechanisms. Firstly, surface cleaning and roughening are achieved as the bombardment effectively removes organic contaminants (e.g., oils, oxides) and inorganic residues while simultaneously inducing atomic displacement to create micro-to-nanoscale roughness, thereby enhancing surface purity, wettability and adhesion. Secondly, the penetrating ions generate lattice distortions and vacancy defects that modify the material's electronic band structure [8].

Sputtering Effects: Particle-in-cell (PIC) simulations were employed to investigate flashover development on microstructured surfaces. The study simulated electron motion, collisions, and secondary electron emission under electric fields, analyzing the influence of groove quantity and

depth on surface charge density and flashover threshold voltage. Results demonstrated that increasing groove density and depth reduces both surface charge accumulation and anode current, effectively suppressing flashover initiation and improving the threshold. These findings validate the effectiveness of groove microstructures in enhancing vacuum insulation system performance, providing theoretical and experimental support for optimizing insulating material surface microstructures [9].

The energy transfer mechanism involves inelastic collisions between high-energy plasma particles (electrons, ions) and surface atoms, triggering multiple energy conversion processes. The thermal effects and chemical bond breaking occur as electron collisions transfer energy to surface atoms, causing instantaneous localized temperature spikes (up to thousands of Kelvin) that rupture weak chemical bonds (e.g., C-H, C-C bonds). This effect proves particularly crucial in polymer modification, facilitating surface radical formation and creating active sites for subsequent grafting reactions [10].

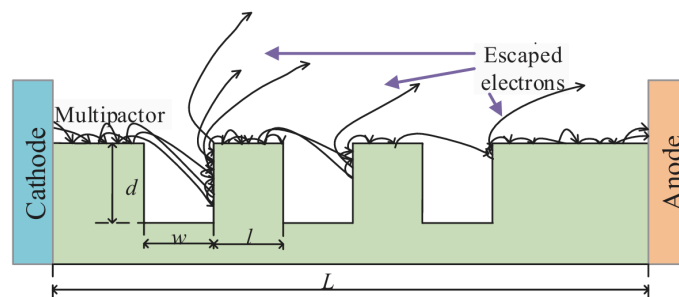


Figure 2. Structure used in the simulation

2.2. Chemical interactions

Plasma modification technology effectively optimizes surface electric field distribution and suppresses charge accumulation by precisely regulating surface chemical composition, morphology, and charge dynamic behavior.

Surface chemical reactions: Reactive species in the plasma (e.g., radicals and excited-state molecules) can undergo chemical reactions with material surfaces, forming new chemical bonds or altering surface composition. For instance, introducing oxygen- or nitrogen-containing functional groups on polymer surfaces significantly enhances wettability and adhesion [11]. Functional group incorporation: By selecting appropriate plasma gases (e.g., oxygen, nitrogen, or ammonia), specific functional groups can be grafted onto material surfaces. For example, oxygen plasma treatment introduces hydroxyl (-OH) and carboxyl (-COOH) groups onto polymers, thereby improving hydrophilicity [12].

Studies demonstrate that plasma treatment introduces oxygen-containing functional groups on polymer surfaces, significantly enhancing surface conductivity and thereby mitigating charge accumulation risks [13]. For glass materials, plasma processing induces the formation of nanoscale Protrusions structures (precise translation depends on morphology: "nanoscale protrusions/dimples" or "nanotextured features" may be more accurate than literal Protrusions). This unique surface topography promotes more uniform electric field distribution, further improving anti-static performance [14]. Additionally, plasma treatment effectively reduces charge trap centers on semiconductor surfaces while increasing charge mobility, substantially decreasing charge accumulation likelihood [15]. These results collectively indicate that plasma modification

technology, through multi-scale and multi-mechanism synergistic effects, provides an effective solution for optimizing surface properties, with broad application potential in electronic devices, optical components, and functional materials.

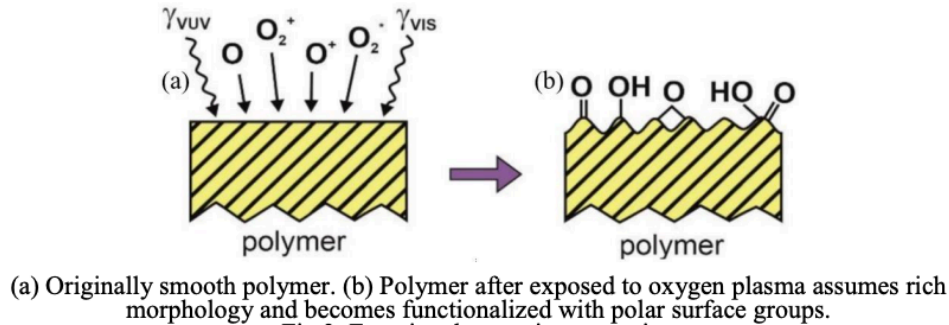


Figure 3. Functional group incorporation

Surface charge accumulation is another critical factor affecting the insulation performance of materials. The processes of charge injection, migration, and dissipation collectively determine the insulation strength and reliability of materials. Charge injection, as the initial stage of surface charge accumulation, typically occurs when charges are injected from electrodes or surrounding media into the surface of insulating materials under an electric field. Charge migration refers to the movement of injected charges along the surface or through the bulk of the material, while charge dissipation describes the gradual reduction of accumulated charges through conduction or recombination [16]. Plasma modification can improve the uniformity of electric field distribution by introducing nanoscale roughness and chemical functional groups on material surfaces [17]. For instance, oxygen plasma treatment introduces conductive functional groups on insulating material surfaces, promoting charge dissipation and reducing charge accumulation [18]. In contrast, fluorine plasma treatment creates insulating functional groups that suppress charge injection and migration, consequently enhancing the material's insulation strength [19]. Additionally, the micro/nanostructures formed by plasma etching can effectively disperse charges and alleviate localized electric field concentration [20].

2.3. Mechanisms of plasma surface modification for insulation performance enhancement

Plasma treatment improves insulation performance through physico-chemical synergy between energetic particles and material surfaces across four dimensions: surface cleaning, chemical composition, morphological structure, and interface properties. The core mechanisms involve ion bombardment, sputtering, and energy transfer, with performance optimization achieved via parameter control.

Surface Cleaning and Defect Repair: Physical sputtering from ion bombardment enables deep cleaning of insulation surfaces. (1) Contaminant removal: O^+ and O_2^+ in oxygen plasma decompose organic pollutants (e.g., hydrocarbons) through chemical reactions, while energetic Ar^+ removes inorganic residues via sputtering. Studies show 98% contaminant removal and 2-order-of-magnitude reduction in leakage current for oxygen plasma-treated epoxy resins [21]. (2) Defect passivation: Ar plasma bombardment induces localized melting at microcrack edges, enabling self-healing. Ar plasma-treated polyimide films exhibit increased breakdown strength from 200 kV/mm to 320 kV/mm due to eliminated electric field concentration points [22].

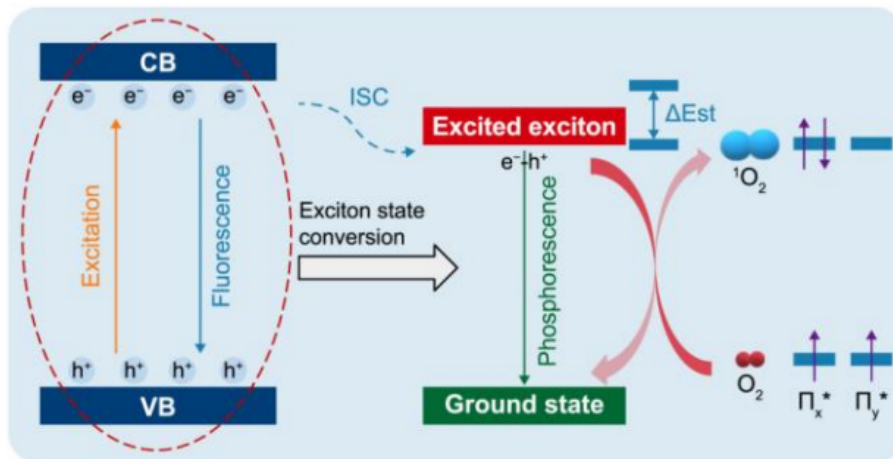


Figure 4. Mechanisms of plasma treatment for enhancing material insulation capability

Surface chemical modification: Combining energy transfer mechanisms, plasma induces surface chemical bond reconstruction. **Insulating functional group introduction:** During nitrogen plasma treatment of polyethylene, high-energy electrons break C-H bonds, and N^+ implantation forms C-N/C=N groups, increasing surface resistivity by 10^4 times [23]. **Insulating layer growth:** In silane plasma treatment, Si^+ generated from SiH_4 dissociation reacts with surface hydroxyl groups to form a thickness-controllable (5-50 nm) SiO_x layer, reducing the polyimide surface dielectric constant from 3.2 to 2.8 [24].

Surface morphology regulation: By adjusting ion bombardment intensity and sputtering modes, functional surface structures are constructed. **Roughness optimization:** Oxygen plasma etching forms nanoscale grooves on PET surfaces, increasing the surface flashover voltage by 40% compared to smooth surfaces [25]. **Electric field homogenization structure:** Argon plasma sputtering creates nano-cone arrays on PVDF, reducing local electric field intensity by 60% and increasing breakdown voltage to 28 kV/mm [26].

Interface optimization: Combining physical sputtering and chemical activation to strengthen the interface between insulating materials and encapsulation media. **Chemical bonding enhancement:** Oxygen plasma treatment generates -COOH groups on epoxy resin surfaces, forming an interpenetrating network with silicone rubber via hydrogen bonds, reducing interface charge trap density by 80% [27]. **Gradient transition layer construction:** During nitrogen plasma treatment of the polyimide/copper foil interface, a Cu_3N transition layer (~10 nm thick) forms on the Cu surface, decreasing the interface dielectric loss from 0.015 to 0.005 [28].

3. Plasma treatments to improve insulation properties

3.1. Breakdown

Several studies have explored the use of plasma treatment to enhance the breakdown strength of insulating materials. For example, B. X. Du et al. [29] investigated gas-insulated substation (GIS) switchgear insulation, where the insulation rod must withstand high electric fields and mechanical stress. Since the outer surface requires proper insulation, fiber-reinforced epoxy composites—such as glass fiber and aramid fiber—are commonly used.

However, aramid fiber has a key drawback: its high crystallinity makes its surface chemically inert, reducing adhesion between the fiber and the polymer matrix. To address this, dielectric barrier

discharge (DBD) plasma treatment was applied, significantly improving interfacial bonding. After treatment, the breakdown strength increased from 29.2 to 32.6 kV/mm, and shear strength rose from 29.38 to 58.93 MPa, enhancing both dielectric and mechanical properties of aramid fiber-reinforced epoxy composites (AFRC).

Other researchers, including N. M. Saman et al. [30], A. Yudhana et al. [31], and R. F. Kurnia et al. [32], studied atmospheric pressure plasma (APP) treatment on silicon dioxide (SiO₂) nanoparticles. When added to low-density polyethylene (LDPE) nanocomposites, these plasma-treated nanoparticles improved partial discharge resistance and breakdown strength. Similarly, Y. Mi et al. [33] used APP to introduce hydroxyl groups to boron nitride nanosheets (BNNS) in epoxy resin, enhancing both AC breakdown strength and thermal conductivity.

Z. Li et al. [34] examined insulation breakdown in insulated gate bipolar transistors (IGBTs) using metal-based printed wiring boards (MB-PWBs). They found that micro-fillers reduce breakdown strength under partial discharge, but adding nano-fillers improved both breakdown strength and partial discharge resistance. While micro-Al₂O₃ fillers increase thermal conductivity, they weaken breakdown strength—a major trade-off.

Plasma treatment has also been applied to transformer oil. Studies [35,36] show that APP-treated SiO₂ nanoparticles, when dispersed in oil (using helium as the discharge gas), enhance AC breakdown strength. This modification improves nanoparticle interaction with the oil, boosting insulation properties. I. H. Zakaria et al. [36] confirmed that plasma-treated silica nanoparticles bond more effectively with liquid molecules, increasing breakdown voltage—a key factor in improving transformer efficiency and dielectric performance. Similar findings were reported in other works [33,34,37].

Table 1. For treated and Untreated Nanofluid (UNF) samples at different concentration of SiO₂

Percentage Concentration of SiO ₂	Percentage enhancement of breakdown voltage strength for un-treated sample (%)	Percentage enhancement of breakdown voltage strength for plasma-treated sample (%)
0.5% SiO ₂	8.43	40.94
0.1% SiO ₂	21.9	45.45
0.01% SiO ₂	8.1	25.25

The addition of silica nanoparticles significantly improves the AC breakdown voltage of transformer mineral oil. Studies have compared untreated nanofluid (UNF) samples with plasma-treated nanofluid (PTNF) samples containing different concentrations of silica nanoparticles. Using Weibull analysis, researchers like I. H. Zakaria et al. [36] were able to evaluate the AC breakdown strength enhancement.

Experimental results show that adding 1%, 3%, and 5% weight concentrations of nano-silica - both untreated and plasma-treated - increases AC breakdown strength. For pure LDPE samples, the breakdown strength measured 160.15 kV/mm, 159.78 kV/mm, and 170.71 kV/mm. After plasma treatment, these values increased significantly to 173.01 kV/mm, 174.70 kV/mm, and 176.44 kV/mm respectively.

3.2. Flashover

Flashover voltage is the minimum voltage required to cause dielectric breakdown across an insulator's surface, resulting in disruptive discharge or arcing. This phenomenon critically impacts

power system reliability and safety, as it represents the failure point where insulation materials allow electrical discharges to jump across the insulator surface.

T. Shao et al. [38] found that flashover voltage initially increases with plasma treatment duration, but decreases significantly when treatment exceeds 5-10 minutes. Their study also revealed an inverse relationship between flashover voltage and corona charging voltage - as charging voltage increases, flashover voltage decreases.

Surface charge accumulation significantly affects flashover characteristics, as demonstrated by T. Shao et al. [38] and Y. A. N. Jiyuan et al. [39]. Experiments with plasma-treated epoxy resin layers showed that: Plasma treatment reduces surface charge peaks. Flashover voltage strongly depends on surface charge quantity. Surface charges with the same polarity as the discharge can lower flashover voltage.

For vacuum applications, T. Shao et al. [38] and S. Li et al. [40] improved surface flashover performance using non-thermal argon plasma jets for hydrophilic modification. Their setup employed a microsecond-pulsed generator (0-30 kV range) and 300 ns rise time pulses.

Results showed higher flashover voltages with shorter pulse durations, with the lowest values occurring at 50/60 Hz power frequency [41].

T. Shao et al. [42] demonstrated that atmospheric pressure dielectric barrier discharge (DBD) treatment can significantly improve the surface flashover strength of polymethyl methacrylate (PMMA). Their study showed that as surface resistance increased from 5.72×10^{13} ohms for untreated PMMA to 1.88×10^{14} ohms and 2.63×10^{14} ohms for plasma-treated samples, the surface flashover performance showed corresponding improvement.

Y. Nie et al. [43] investigated ozone treatment of low-density polyethylene (LDPE) surfaces for various durations (0-6 hours) and found that 4-hour ozone treatment increased surface flashover voltage by 25.59% compared to untreated samples. Similarly, H. Guan et al. [44] studied DBD plasma treatment of silicon rubber in ambient air, observing that DC surface flashover voltage initially increased but then decreased with prolonged treatment time due to enhanced charge carrier mobility on the sample surface.

X. Chen et al. [45] examined epoxy resin samples with nano-aluminum nitride (AlN) treated by DBD plasma in both air and vacuum conditions. Their results showed significant improvements: the first sample's flashover voltage increased from 11.23 kV to 14.91 kV (32.77% improvement) after 4 minutes of treatment, while the second sample improved from 14.64 kV to 16.55 kV (13% increase) with the same treatment duration.

Table 2. Comparison of flashover voltage in untreated and plasma-treated silicone rubber

Sample Type	Treatment Duration	Flashover Voltage (kV)	Performance Change
Untreated control	None	17.26	Baseline
180s plasma-treated	180 seconds	20.40	+18.2% increase
300s plasma-treated	300 seconds	18.76	+8.7% increase

X.-L. Sun et al. [46] focused on micro-hole effects on vacuum insulator performance under high pulsed voltages, finding that hole dimensions significantly influence flashover properties. Their work also highlighted how gas pressure affects surface flashover voltage through enhanced electron collision processes in compressed gas [47].

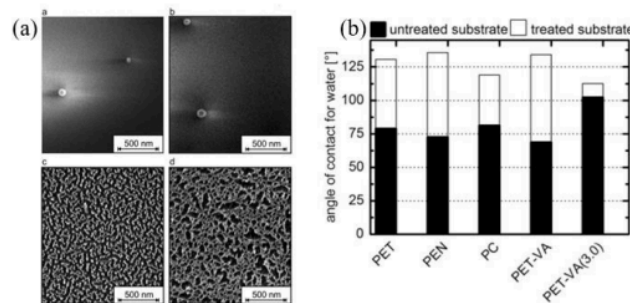
Table 3. Lashover voltage of epoxy resin before and after treatment

Sample	Untreated (kV)	Treated (kV)	Treatment Time	Increase (%)
1	11.23	14.91	4 min	32.77
2	14.64	16.55	4 min	13.00

Extensive research has investigated flashover characteristics across various conditions, including different insulator materials (Teflon, PMMA, Nylon), electrode materials (stainless steel, copper, aluminum), and voltage types (DC, AC, microsecond pulses) [41,48-59]. Recent studies using nanosecond pulses (10 ns rise time, 30 ns FWHM) have further explored critical factors including gas pressure, electrode geometry, and insulator-electrode contact styles [58,60-65], providing comprehensive insights into flashover behavior under diverse experimental conditions.

3.3. Water contact angle

Plasma treatment significantly enhances the surface energy of materials by introducing polar functional groups (e.g., hydroxyl and carboxyl groups), enabling superhydrophobic or superhydrophilic modification. For instance, after oxygen plasma treatment, the surface contact angle of polytetrafluoroethylene (PTFE) decreases from 110° to 30°. This superhydrophilic property facilitates the formation of a continuous water film on high-voltage insulator surfaces, preventing surface discharge caused by localized charge accumulation. Concurrently, surface chemical modification accelerates the hydrolytic removal of contaminants, reducing the risk of surface leakage current and thereby improving the long-term reliability of the insulation system [66].



(a) SEM image after plasma treatment; (b) Variation of water contact angle after plasma treatment

Figure 5. Plasma treatment enhances the surface energy of materials

Multiple studies have investigated the alteration of water contact angles on material surfaces through plasma modification. For instance, the team led by B.X. Du [67] examined aramid fiber-reinforced epoxy composites (AFRC) and found that dielectric barrier discharge (DBD) plasma treatment significantly enhanced interfacial adhesion. This treatment reduced the water contact angle on the aramid fiber surface from approximately 80° to about 50°, markedly improving the hydrophilicity between the fibers and the polymer matrix. Research by N.M. Saman and A. Yudhana [68] demonstrated that after atmospheric pressure plasma (APP) treatment of silica (SiO₂) nanoparticles, surface modification reduced their water contact angle from around 110° to approximately 60°, enhancing wettability within the polymer matrix.

The team led by Z. Li [69] discovered that plasma treatment of nanofillers decreased the water contact angle on insulating material surfaces from about 90° to around 40°, significantly improving hydrophilicity while enhancing partial discharge resistance and breakdown strength. Studies by Y.

Mi's team [70] revealed that introducing hydroxyl groups into epoxy resin via APP reduced its water contact angle from approximately 70° to about 30°, concurrently improving AC breakdown strength and thermal conductivity.

Research by I.H. Zakaria's team [71] showed that plasma-treated silica nanoparticles dispersed in transformer oil reduced the oil's water contact angle from around 55° to about 35°, significantly optimizing nanoparticle-oil interactions and improving insulation performance. The team led by Y.A.N. Jyuan [72] found that plasma treatment lowered the surface charge peak of epoxy resin layers while reducing their water contact angle from approximately 65° to 45°, thereby improving flashover characteristics.

Table 4. Flashover voltage of epoxy resin before and after treatment

Plasma-Treated Material	Untreated Water Contact Angle (°)	Water Contact Angle After Plasma Treatment (°)
Aramid Fiber-Reinforced Epoxy Composite	80	50
Silica Nanoparticles	110	60
Nanofillers	90	40
Epoxy Resin	70	30
Silica Nanoparticles in Transformer Oil	55	35
Epoxy Resin Layer	65	45

4. Conclusion and prospects

Plasma treatment improves material insulation through four key mechanisms. First, it cleans surfaces and repairs defects by removing contaminants and smoothing microcracks, eliminating electric field concentration points. Second, it modifies surface chemistry—nitrogen plasma introduces C-N/C=N bonds in polyethylene, boosting resistivity by 10⁴ times, while silane plasma forms SiO_x layers on polyimide to reduce dielectric constant. Third, it controls surface morphology: oxygen plasma-etched PET develops nano-grooves to increase flashover voltage, and argon plasma-sputtered PVDF forms nanocone arrays to lower local field strength. Fourth, it optimizes interfaces—oxygen plasma creates -COOH groups on epoxy resin to form hydrogen bonds with silicone rubber, while nitrogen plasma generates Cu₃N transition layers at polyimide/copper interfaces to reduce dielectric loss. The treatment significantly enhances breakdown voltage, such as raising AFRC's breakdown strength from 29.2 to 32.6 kV/mm. It also improves hydrophilicity—AFRC's water contact angle drops from 80° to 50°, epoxy resin from 70° to 30°, and silica nanoparticles in transformer oil from 55° to 35°. These changes optimize material performance for high-voltage applications.

Looking ahead, the development of plasma surface modification technology for insulating materials should focus on three key directions: process optimization, multidisciplinary integration, and industrial-scale applications. The integration of artificial intelligence and machine learning will enable precise control of plasma parameters, allowing for customized design of material surface properties. Concurrently, interdisciplinary convergence with nanotechnology and bioengineering will give rise to novel multifunctional insulating materials, such as medical coatings combining high dielectric strength with biocompatibility. A central challenge will be developing cost-effective, high-efficiency atmospheric pressure plasma systems to facilitate large-scale industrial adoption, particularly in critical sectors like renewable energy equipment and smart grids. Advancements in

characterization techniques (e.g., in-situ electron microscopy and ultrafast spectroscopy) are expected to provide deeper insights into the dynamic interactions between plasma and material surfaces, establishing a foundation for the rational design of next-generation high-performance insulating materials. Breakthroughs in this technology promise not only to overcome the performance limitations of conventional insulators in extreme environments but also to potentially redefine material application paradigms across power electronics, aerospace, and related industries.

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