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Inorganic nanofilms for surface charge control on polymer surfaces by atmospheric-pressure plasma deposition

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An effective surface charge removal is critical to diverse applications of polymer and other soft organic materials in electrical devices and systems. Here, we report on the application of atmospheric pressure dielectric barrier discharge (AP-DBD) to deposit SiO_x thin films to improve the surface charge dissipation on an epoxy resin surface. The SiO_x nanofilms are formed at atmospheric pressure, with the replacement of organic groups (C-H, C=O and C=C) with inorganic groups (Si-O-Si and Si-OH) within the thin surface layer. After the plasma deposition, the initial surface charge decreased by 12% and the surface charge dissipation was accelerated. The flashover voltage which characterizes the insulation property of the epoxy resin is increased by 42%. These improvements are attributed to the lower density of shallow charge traps introduced by SiO_x film deposition, which also corresponds to the surface conductivity increase. These results suggest that the SiO_x deposition by AP-DBD is promising to accelerate surface charge dissipation. This method is generic, applicable for other types of precursors and may open new avenues for the development of next-generation organic-inorganic insulation materials with customized charge dissipation properties. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5008645>

I. INTRODUCTION

Accumulated charges distort local electric fields on polymer surfaces and cause direct insulation failures, which lead to serious damage to multi-million-dollar energy transmission systems.^{1–4} Considerable efforts have been made to reduce charge accumulation and accelerate charge dissipation.^{5,6} Surface charges are usually located within interfacial layers of several micrometers thick. Hence, charge accumulation and dissipation are strongly related to the structure of the thin surface layer.⁷ To assist charge transport on polymer surfaces, surface modification methods including reactive ion etching,⁸ chemical vapor deposition,^{9,10} gamma ray irradiation,¹¹ and direct fluorination technology¹² have been employed. The introduced chemical modifications affect the surface conductivity, surface trapping, and secondary electron emission, and hence charge accumulation and transport.^{13,14} However, common problems associated with these methods include the need to operate under extreme conditions and substantial environmental pollution.

To overcome these issues, here, we use atmospheric pressure plasma enhanced chemical vapor deposition (AP-PECVD) featuring highly reactive species and low pollution levels.^{15–17} Importantly, these species penetrate only within a thin nanometer layer, thereby modifying the material's surface without affecting the material's bulk.¹⁸ This localized

surface modification of nanoparticles, polymers, and metal surface enhances their surface properties.^{19–21} However, common surface modifications using corona, glow, or plasma jet discharges suffer from the aging effect due to reorientation of the polar chemical groups.^{22–25} This leads to a significant deterioration of the chemical and electrical properties even after only a few days of storage.

To overcome these drawbacks, instead of surface modification, here, we use a dielectric barrier discharge (DBD) to deposit nanometer-scale-thick silicon oxide (SiO_x) films on an epoxy resin surface to improve the surface charge accumulation and dissipation. Such SiO_x films offer excellent insulating properties and stability.^{26–29} We show that room temperature, atmospheric-pressure deposition of SiO_x nanofilms can effectively reduce the initial charge accumulation level and accelerate the charge dissipation rate. This is enabled because of the increase of surface conductivity and a smaller density of shallow charge traps introduced by the SiO_x thin films. These results demonstrate a feasible and effective technique to enhance the insulation performance of polymers (and more generally a broader class of insulating materials), thereby advancing their applications in diverse fields.

II. EXPERIMENTS

The experimental system includes pulse generator, DBD reactor, electrical measurement system, optical measurement system, and working gas, as shown in Fig. 1. The pulse

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FIG. 1. Schematics of the experimental set-up (inset image: lateral blowing device and DBD reactor).

generator (CMPC-40, Institute of Electrical Engineering, CAS) has a pulse rise time of $0.5 \mu\text{s}$, a pulse width of $8 \mu\text{s}$, and a pulse repetition frequency (PRF) up to 3 kHz . The detailed information for pulse generator can be found elsewhere.³⁰ The DBD reactor is composed of two pieces of circular aluminum plates (diameter: 40 mm) with the upper side covered by K9 glass dielectrics (thickness: 2 mm , side length: 100 mm) and the lower side covered by epoxy resin to be treated. The discharge gap is set as 2 mm . The discharge voltage and current are measured through a $1:1000$ high voltage probe (Tek P6015, $0\text{--}40 \text{ kV}$) and a current probe (Pearson 6595, 1 V/A), respectively. The measured voltage and current data are recorded using an oscilloscope (Tek DPO2024, 200 MHz , 1 G/s). Discharge images are taken by Canon EOS 500D and Tamron lens ($700\text{--}200 \text{ mm}$, $F/2.8$) with the exposure time of 1 s and ISO of 100 .

The precursor TEOS is carried out by argon gas. The TEOS is placed in a bubbling bottle and heated at a constant temperature of 60°C . Ar is pumped into the TEOS at a flow rate of 0.5 standard liter per minute (slm). The Ar/TEOS then is mixed with 2 slm pure Ar and is entered into the DBD reactor through the lateral blowing device, as shown in the inset image. The content of TEOS in the mixed gas is calculated to be 0.4% . The carrier gas Ar ensures uniform DBD discharge, which promotes the densification and uniformity of the deposited film.³¹ Samples used in this experiment are insulation materials made of $\alpha\text{-Al}_2\text{O}_3$ -filled diglycidyl ether of bisphenol-A (DGEBA) epoxy resin. This epoxy resin has been widely used as an insulation material in high-voltage applications.³² The bulk epoxy resin is in a square shape with the side length of 50 mm and thickness of 20 mm . Before the treatment, the samples were rinsed with anhydrous ethanol, acetone, and deionized water in turn, and then cleaned by ultrasound for 10 min . Finally, the cleaned samples were dried in a vacuum drying cabinet (DZF-6020, ZKHS Co, Ltd.) for 6 h under a temperature of 50°C and a gas pressure of 5 Pa . The samples are treated by DBD plasma for several minutes under applied voltage of 11 kV and pulse repetition frequency (PRF) of 1500 Hz .

The Fourier Transform Infrared Spectrum (FTIR) is used to examine the chemical composition of the samples before and after the plasma treatment. The FTIR (Thermo Nicolet iS10) spectra are studied from 4000 to 650 cm^{-1} , with the resolution of 1 cm^{-1} . The water contact angle (WCA) is measured by an optical microscope (JGW-360a). The deionized water droplet ($1 \mu\text{l}$) is dripped on the samples' surface randomly and each sample is measured for 5 times to minimize the accidental error. The experimental parameters are as follows: the wavelength is $190\text{--}930 \text{ nm}$, the polarization angle is 45° , and the range of the incident angle is 70° . The measurement accuracy is $0.01\text{--}0.03 \text{ nm}$. Five points on the sample surface are selected randomly and measured. The morphology of samples is measured by atomic force measurement (AFM, Bruker Dimension Icon). The arithmetic mean roughness (R_m) and root mean square roughness (R_q) are calculated by Nanoscope Analysis. The surface conductivity of test samples is measured by custom-made three electrode device. The measurement details can be found in literature.³³ In high-voltage insulation equipment, the unintended discharge that occurs at the interfaces between a conductor, a gas, and an insulator is called a flashover. The flashover voltage of the samples was measured before and after the plasma treatment. This was performed by measuring the breakdown voltage of the samples when placed between two finger-shaped electrodes (radius: 10 mm , discharge gap: 5 mm). The negative DC power supply (TD2202, Tslaman) is applied to the electrodes. The initial voltage is 0 kV and stepped by -1 kV . If the surface flashover occurs 10 times in 10 experiments under the same voltage, the voltage is defined as the flashover voltage.

An experimental set-up for the surface potential (SP) measurement is shown in Fig. 2. The samples were charged by a corona discharge for 1 min first and then placed on the top of a mobile platform of a Kelvin electrostatic probe (Trek-6000B) driven by a stepping motor to monitor their SP. The discharge needle with a diameter of 1 mm and curvature radius of $80 \mu\text{m}$ is charged by a negative 5 kV DC power supply (71030N, Genvolt). The needle tip is 5 mm

FIG. 2. The surface potential measurement system.

away from the sample surface. It takes 12 s for the samples to move to the measurement spot. The SP of the samples is characterized by two methods: (a) a 2-D scanning of samples surface (20×20 mm, 441 points and 210 s in total) moved in a zigzag shape and (b) the center point of samples measured at a 0.5 s interval to obtain a decay curve. During the experiments, the ambient temperature is maintained at 20°C and the air humidity is kept at 40%. In a thin plate shape sample, the relationship between the SP and the surface charge density can be expressed as follows:³⁴

$$\sigma = \frac{\epsilon_0 \epsilon_r}{d} V, \quad (1)$$

where σ is the surface charge density, V is the SP, d is the sample thickness, ϵ_0 and ϵ_r are the relative permittivity of vacuum and sample, respectively. In our experiments, the film thickness measured by spectroscopic ellipsometer is 261 nm after the 5 min plasma modification, which is much smaller than the original material thickness of 2 mm. The relative permittivity of the plasma treated materials shows a little decrease from 5.0 (before plasma treatment) to 4.5.

Therefore, the measured SP distribution is proportional to the surface charge density and is used to characterize the surface charge distribution.

III. RESULTS

A. Electrical characterization

To deposit the SiO_x film on the epoxy resin surface, we used the atmospheric-pressure DBD reactor and the experimental set-up is sketched in Fig. 1. The applied voltage and frequency were chosen to get a stable discharge and avoid arc transition. Figure 3(a) shows the typical discharge image and measured voltage and current waveforms with the applied voltage of 11 kV and PRF of 1500 Hz. The current here corresponds to the total current of 1.49 A. The maximum peak of the discharge current appeared at the rising edge of the pulse voltage accompanied by several small peaks. The negative discharge current and a large jitter appeared at the first falling edge of the pulse voltage due to the reverse charging of capacitor. The discharge image (see the inset) shows that the light intensity of DBD at the upper and lower dielectric barriers was higher and it was lower in the discharge gap. The instantaneous power and input energy for one pulse period are 14 kW and 1.5 mJ, respectively [Fig. 3(b)].

B. Chemical composition analysis

Figure 4 shows the FTIR spectra of the samples before and after the plasma modification. The control group presented multiple absorption peaks of C-H at $3033 \sim 2851 \text{ cm}^{-1}$ and a strong absorption peak of phenyl C-H at 1179 cm^{-1} . The absorption peaks at $1300 \text{ cm}^{-1} \sim 1200 \text{ cm}^{-1}$ are likely associated with the absorption of aromatic and aliphatic ether groups in epoxy resin. The C=O bond at 1730 cm^{-1} confirmed the existence of ester groups on the sample surface. Due to the presence of 1-4 substitute benzene, the absorption peaks at 1506 cm^{-1} and 1607 cm^{-1} of C=C bond and the peak at 826 cm^{-1} of C-H bonds could be observed. The absorption peak at 1457 cm^{-1} was due to the bending vibration of CH_2 and CH_3 . It could be seen that the untreated sample showed typical organic characteristics with C, H, and O as the main components.

FIG. 3. (a) Discharge voltage and current waveforms (inset: discharge image) and (b) calculated power and energy.

FIG. 4. The FTIR spectra of control and plasma treated epoxy resin surface.

After the plasma treatment, the FTIR spectra showed significant differences with the control group. With the plasma treatment for 3 min, the strongest absorption peak appeared at 1046 cm^{-1} due to Si-O-Si stretching. And the absorption peak at 799 cm^{-1} was associated with the collective effect of Si-O-Si symmetric stretching vibration and Si-C stretching vibration in $\text{Si}-(\text{CH}_3)_x$. The organic groups containing C-H, C=O and C=C bonds still existed on the surface but with a lower intensity. When the plasma treatment time was increased to 5 min, the intensity of Si-O-Si and Si-OH increased and the intensity of organic groups decreased. Interestingly, when the plasma treatment time increased to 10 min, the original organic groups disappeared. This indicated that the sample was fully covered by a SiO_x film. Meanwhile, the intensity of Si-O-Si further increased. The polar groups such as OH and Si-C introduced shallow surface traps,³⁵ which are very important for surface charge distribution and will be discussed later.

In order to understand the involved mechanism in the SiO_x film deposition, the optical emission of Ar/TEOS plasma was recorded. As shown in Fig. 5, strong Ar emission from 700 nm to 920 nm, O emission at 777 and 844 nm, and along with weak OH emission at 306–309 nm were observed. The Ar excited state was populated by a one-step process

FIG. 5. The optical emission of Ar/TEOS plasma.

The subsequent radiative decays emit characteristic Ar lines

The presence of OH and O emissions was due to the electron and metastable excitation of the surrounding air and water vapor molecules.³⁶ Although the energy of metastable state Ar is lower than the threshold excitation energy of O_2 (13.6 eV), the metastable state Ar can dissociate oxygen molecule and excite atomic oxygen to the excited state (reactions (4) and (5)).^{37,38}

In Ar/TEOS plasma, it is believed that TEOS is primarily due to the electron impact dissociation to form SiO_x film (reaction (6)).³⁹ When operated in open air, the effects of air exposure should also be considered. Excited oxygen removes the impurity groups in TEOS and the ligands from the adsorbed fragments on the surface, and thus improves the formation of Si-O-Si bonds (reaction (7)).⁴⁰

The alkane group was removed stepwise and the Si-O-Si chain is left on the epoxy resin surface.

C. Surface morphology study

The surface morphology of epoxy resin before and after the plasma treatment is examined by AFM, as shown in Fig. 6. Before the plasma treatment, a lot of granules and spikes appeared on the original epoxy resin surface. The values of the mean surface roughness (R_m) and the root-mean-square surface roughness (R_q) are calculated from the AFM scans as 133.1 nm and 106.5 nm, respectively (Fig. 7). After the plasma treatment for 3 min, the spikes disappeared and the samples showed a relatively smooth surface. At the same time, the R_m and R_q decreased to 88.9 nm and 68.6 nm, respectively. With the plasma treatment time increased, the whole sample surface became more even, but with one or two big granules. The smooth surface indicated the successful deposition of SiO_x film on the original epoxy resin surface. However, big granules (red arrows) appeared in a long time deposition (>5 min) due to the non-uniformity of the DBD discharge.⁴¹ However, these single granules had a little influence on the surface smoothness. After the plasma treatment for 10 min, the R_m and R_q further decreased to 68.7 nm and 44.7 nm, respectively. Visible solid powder appeared when further increased the plasma deposition time due to the poor binding force between the film and the substrate material. This is why we did not increase the plasma treatment time any further.

FIG. 6. AFM measurement of (a) untreated sample; (b) plasma treatment for 3 min; (c) plasma treatment for 5 min; and (d) plasma treatment for 10 min.

Figure 8 shows the SEM pictures of epoxy resin before and after the DBD plasma treatment for several times. As we can see, a big crack is located in the middle of the pristine epoxy resin surface due to defects in the manufacturing process [Figs. 8(a) and 8(b), red arrows]. With the plasma treatment for 3 min, SiO_x nanoparticles with the diameter around 50–100 nm were visualized. A small fraction of them aggregated into larger clusters. With longer plasma treatment time, the diameter of SiO_x nanoparticles increased to 200 nm but with a poor uniformity. This is consistent with AFM measurement results. Our results demonstrate that DBD plasma-assisted deposition is a

practical method for SiO_x film deposition on a two-dimensional (2D) flat substrate. To extend to three-dimensional (3D) coating, plasma jets or plasma jet arrays could be employed. Plasma jets can be generated in open air rather than in confined discharge chambers, making it suitable for a 3-D treatment.⁴² By applying arrays of multiple plasma jets pointing in the same direction, and with the rotation of substrate, a 3D-uniform coating can be achieved.

D. Surface potential distribution

The 3-D SP distribution of samples (untreated and plasma treated for 3, 5, and 10 min) are presented after removing the charging voltage for 0, 900, and 1800 s (referred as 0, 900, and 1800 s in the rest of the text) in Fig. 9. The SP after removing the charging voltage for 0 s (refers to initial surface potential, ISP) reached -2920 V right after removing the charging. The SP distribution presented with a groove-like shape and it remained unchanged after 900 and 1800 s. After finishing the charging, the samples would be moved from coordinate (10, 10) to (20, 10). During the movement, the needle electrode would be recharged by the negative charges on the samples surface, which induced a groove-like shape distribution of SP. Figures 9(b)–9(d) show the SP decay and distributions of the samples treated for 3, 5, and 10 min, respectively. After the plasma treatment, the SP distributions no longer showed a groove-like shape. Instead, it presented as

FIG. 7. The R_m and R_q calculated from AFM scans.

FIG. 8. SEM micrographs of the epoxy resin treated with plasma (a) 0 min, (b) 3 min, (c) 5 min, and (d) 10 min at a magnification of 10 000, inserted images: at a magnification of 50 000.

an inclined plane along the measurement. The ISP decreased to less than -2000 V after a 3 min treatment and it was even lower after 5 and 10 min treatments. Besides, the inclination degree after removing the charging voltage for 900 and 1800 s was clearly smaller than that of 0 s. Moreover, after 5 and 10 min of the plasma treatment, the SP was almost zero and featured a flat shape. The charge decay was significantly faster in the first few minutes which is in line with other observations.⁴³ Our results indicate that after the film deposition, the surface charge distribution became more uniform and the dissipation rate was accelerated.

The decay rates of ISP and SP at the center point of the sample were calculated as follows:

$$D_i = \frac{|V_{i0}| - |V_{it}|}{|V_{i0}|}, \quad (8)$$

$$D = \frac{|V_0| - |V_t|}{|V_0|}, \quad (9)$$

where D_i is the decay rate of ISP, V_{i0} is the ISP at 0 min, and V_{it} represents ISP after different plasma treatment time; D is the decay rate of SP, V_0 is the SP at 0 min, and V_t represents SP after a different plasma treatment time. As shown in Fig. 10, the ISP dropped linearly from 0 min to 3 min. However, it showed a significant decrease after 3 min plasma treatment and decreased to 12% of initial value after 10 min of the plasma

treatment. Besides, the surface charges dissipated quickly after removing the charging voltage. Before the plasma treatment, the sample showed a rapid decay in the first 300 s and saturated around 60%. Along with the increase in the plasma treatment time, the charge decay rate in the first 150 s was even faster and almost reached 100% after 3 min of the plasma treatment.

E. Flashover voltage test

The effect of the plasma treatment leading to the higher flashover voltage was studied. As shown in Fig. 11, the flashover voltage increased with plasma treatment time. After the plasma treatment for 0.5 min, the flashover voltage increased from 6.54 kV (untreated sample) to 7.50 kV. The flashover voltage increased by 42% compared with the untreated sample after 10 min of the plasma treatment (9.28 kV). The surface property of insulating dielectrics is a key factor influencing the surface flashover performance. By introducing SiO_x on the epoxy resin surface, the amount of accumulated surface charge decreased and decayed at a faster speed. The electrical field distortion caused by the surface charge accumulation is weakened and the partial discharge is suppressed.^{44,45} Hence, the flashover voltage is increased.

IV. DISCUSSIONS

In the study of surface charging and charge dissipation, the charges generated by a corona discharge is the main source

FIG. 9. Three-dimensional distribution of surface potential under different treatment times. (a) Untreated (left to right): after removing the charging voltage for 0, 900, and 1800 s, (b) treated for 3 min (left to right): after removing the charging voltage for 0, 900, and 1800 s, (c) treated for 5 min (left to right): after removing the charging voltage for 0, 900, and 1800 s, (d) treated for 10 min (left to right): after removing the charging voltage for 0, 900, and 1800 s.

FIG. 10. The decay curves of: (a) ISP and (b) SP time dependence.

FIG. 11. The relationship between the flashover voltage and the plasma treatment time.

for surface charge accumulation.^{46,47} In our experiments, charges created by a negative corona discharge move to the epoxy resin surface and are captured by surface charge traps. The measured ISP is determined by two factors: the number of charges and the density of the surface charge traps. The granules and spikes that appear on the untreated epoxy resin surface may enhance the electric field strength and create more charges compared with the plasma deposited samples. However, the simulation results show that no obvious electric field distortion can be seen when a DC voltage is applied to the pristine sample (Fig. 12). This is probably because the granules with a diameter of several nanometers can be neglected compared with a large discharge distance of 5 mm. Depending on the type of defects, surface traps may capture electrons or holes that have been injected into or generated

within the material under the application of electric field.^{48,49} The surface trap depth and distribution are calculated based on decay curves of SP (Fig. 9), as shown in Fig. 13. The details of the calculations can be found elsewhere.⁵⁰ The trap depth for untreated sample is 0.85 eV, but with the plasma treatment for 3, 5, and 10 min, the trap depth decreases to 0.82 eV, 0.78 eV, and 0.72 eV, respectively. At the same time, the trap density also decreases along with the increase in the plasma treatment time. Our results demonstrate that the plasma treatment introduces shallow charge traps and decreases the trap density. The smaller number of charges and shallow traps with a lower density lead to a lower ISP of the plasma deposited samples.

The surface charge dissipation processes are influenced by many factors, such as, gas pressure, gas composition, material conductivity, and surface state.⁵⁰ There are three pathways for surface charge dissipation^{51,52}

- (1) Charge transport into material's bulk;
- (2) Charge conduction along the material's surface; and
- (3) Charge neutralization by the oppositely charged particles in air.

In our experiments, the maximum electric field strength of the sample surface was about 1.5 kV/mm (untreated surface potential 3 kV/film thickness 2 mm), which was far below the threshold electric field strength (10 kV/mm) for charge injection. The groove-like shaped potential distribution caused by a reverse discharge to needle electrode further confirmed that pathway (1) is not likely to happen in our experiments. The simulation results⁵³ showed that if pathway (3) were the dominant mechanism, the SP distribution would have formed a crater-like shape, which also excludes pathway (3) in our case. Thus, surface conduction mechanism (2) can reasonably be assumed to be the dominant mechanism for the surface charge dissipation.

FIG. 12. The simulated electric field distribution with an applied voltage of -5 kV: (a) epoxy resin and (b) after plasma treatment for 5 min.

FIG. 13. Surface charge trap depth before and after the plasma treatment.

The current density generated by charge dissipation is determined by tangential electric field and surface conductivity⁵⁴

$$j(t) = E_t(t)S, \quad (10)$$

where $j(t)$ is the current density, S is the surface conductivity, $E_t(t)$ is the tangential electric field. Within time interval t , the number of charges on the surface can be calculated as

$$d_{Q(t)} = \left(\int S \cdot E_t(t) \cdot d_s \right) dt, \quad (11)$$

where $d_{Q(t)}$ is the charge number, and d_s is the cross-sectional area. Thus, higher surface conductivity helps effective charge dissipation.

The surface conductivity of the samples under different plasma treatment times are measured. As shown in Fig. 14, the surface conductivity increased with the plasma treatment time. With the plasma treatment time of 0.5 min, the surface conductivity increased by one order of magnitude (from $2.23 \times 10^{-15} \Omega^{-1}$ to $1.46 \times 10^{-14} \Omega^{-1}$) and it further reached $5.47 \times 10^{-11} \Omega^{-1}$ after the 10 min plasma treatment. This conductivity was three orders magnitude higher compared with the pristine sample. It is believed that the surface

FIG. 14. Surface conductivity of epoxy resin before and after the plasma treatment.

conductivity is composed of (1) charge hopping transport between surface traps and (2) charge migration in absorbed water on the material surface.⁵⁵ In our results, shallow traps introduced by plasma modification help the increase in surface conductivity. The increase in the surface conductivity facilitates charge migration, or in other words, accelerates surface charge dissipation.

Surface traps not only account for initial surface charge accumulation, they also play a very important role in surface charge dissipation. Polar groups such as OH, Si-OH and Si-C introduced by the plasma will lower the surface trap depth. A similar effect⁵⁶ showed that modifications by the plasma treatment and fluorination introduced shallow traps. The negative corona discharge creates charges that are captured by the surface traps. When the applied field is removed, the amount of trapped charges decreases with time, known as charge decay. The charges that are located in shallow traps decay at a faster speed than the charges in deep traps, which in turn accelerates the surface charge dissipation. The processes for charge creation, injection, and dissipation are shown in Fig. 15. A rigorous account for nanoscale surface texture, surface charge balance, and interactions of plasmas with surfaces^{57,58} would make the description of surface charge phenomena more accurate and is the subject of future work.

FIG. 15. The processes for charge creation, injection, and dissipation.

V. CONCLUSION

In summary, we have demonstrated that AP-DBD is an effective and environmentally friendly method for SiO_x thin films deposition to accelerate the surface charge distribution and improve the insulation properties of epoxy resin. The results show that with the increase in the plasma treatment time, the inorganic groups on the epoxy resin surface were gradually covered by Si-containing groups, indicating the formation of SiO_x thin films. The SiO_x thin films with a thickness of 50–200 nm introduced a lower density of shallow traps and increased the surface conductivity, which in turn reduced the surface charge accumulation and accelerated charge dissipation. Finally, it was shown that the flashover voltage increased by 42% after the plasma deposition. The results of this study provide a new pathway for insulation improvement in commercial high-voltage, high-frequency, and pulsed power systems.

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