Deposition of SiC\(_x\)H\(_y\)O\(_z\) thin film on epoxy resin by nanosecond pulsed APPJ for improving the surface insulating performance

Qing XIE (谢庆)\(^1\), Haofan LIN (林浩凡)\(^1,2\), Shuai ZHANG (张帅)\(^2,3\), Ruixue WANG (王瑞雪)\(^2,3\), Fei KONG (孔飞)\(^2,3\) and Tao SHAO (邵涛)\(^2,3,4,5\)

\(^1\) North China Electric Power University, Baoding 071003, People’s Republic of China
\(^2\) Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, People’s Republic of China
\(^3\) Key Laboratory of Power Electronics and Electric Drive, Chinese Academy of Sciences, Beijing 100190, People’s Republic of China
\(^4\) University of Chinese Academy of Sciences, Beijing 100039, People’s Republic of China

E-mail: st@mail.iee.ac.cn

Received 28 August 2017, revised 31 October 2017
Accepted for publication 1 November 2017
Published 21 December 2017

Abstract
Non-thermal plasma surface modification for epoxy resin (EP) to improve the insulation properties has wide application prospects in gas insulated switchgear and gas insulated transmission line. In this paper, a pulsed Ar dual dielectrics atmospheric-pressure plasma jet (APPJ) was used for SiC\(_x\)H\(_y\)O\(_z\) thin film deposition on EP samples. The film deposition was optimized by varying the treatment time while other parameters were kept at constants (treatment distance: 10 mm, precursor flow rate: 0.6 l min\(^{-1}\), maximum instantaneous power: 3.08 kW and single pulse energy: 0.18 mJ). It was found that the maximum value of flashover voltages for negative and positive voltage were improved by 18% and 13% when the deposition time was 3 min, respectively. The flashover voltage reduced as treatment time increased. Moreover, all the surface conductivity, surface charge dissipation rate and surface trap level distribution reached an optimal value when thin film deposition time was 3 min. Other measurements, such as atomic force microscopy and scanning electron microscope for EP surface morphology, Fourier transform infrared spectroscopy and x-ray photoelectron spectroscopy for EP surface compositions, optical emission spectra for APPJ deposition process were carried out to better understand the deposition processes and mechanisms. The results indicated that the original organic groups (C–H, C–C, C=O, C=C) were gradually replaced by the Si containing inorganic groups (Si–O–Si and Si–OH). The reduction of C=O in ester group and C=C in p-substituted benzene of the EP samples might be responsible for shallowing the trap level and then enhancing the flashover voltage. However, when the plasma treatment time was longer than 3 min, the significant increase of the surface roughness might increase the trap level depth and then deteriorate the flashover performance.

Keywords: nanosecond pulse, atmospheric-pressure plasma jet, flashover voltage, surface charge, epoxy resin

(Some figures may appear in colour only in the online journal)
1. Introduction

Epoxy resin is widely used in gas insulated switchgear and gas insulated transmission line as insulating and strutting parts due to its excellent electrical and mechanical properties [1–5]. However, in DC electric field, a large amount of electric charges are likely to accumulate on the interface between the epoxy resin and gas, which distort electric field and provide charges, and finally cause surface discharge. This phenomenon not only directly reduces the insulating performance, but also affects operation of the power system. A substantial number of researches have been demonstrated that the surface modification can accelerate the surface charge dissipation and improve the insulation properties of epoxy resin [6–10]. The surface modification can be achieved by many chemical or physical methods, including direct fluorination [11–13], nanoparticles doping [14, 15], electron beam irradiation [16, 17], heat treatment [18] and Cr₂O₃ coating treatment [7], etc. However, above methods are still difficult to be widely used in industrial applications due to expensive equipment, complex processes or exhaust gas emission.

Non-thermal plasma treatment is considered as an effective approach to modify the surface of insulating material because of its highly reactive species, flexible operation and low pollution levels, especially, plasma treatment can be carried out at atmospheric-pressure [19–24]. Moreover, these species modify material surface only within a thin nanometer without changing the material bulk. Most of the researches focus on the change of the wettability, surface morphology and chemical composition of materials [25–29], only a few papers present surface charge and flashover characteristics using non-thermal plasma surface modification. Kumara et al [30] investigated the decay of surface charges and their distributions on silicon rubber samples treated by AC or DC corona discharge. Results showed that the surface potential decay was significantly accelerated and the surface traps were shallower after plasma modification. Shao et al [31, 32] found that nanosecond pulse driven dielectric barrier discharge (DBD) introduced F-containing groups and improved the vacuum surface flashover voltage (FV) by increasing the surface roughness and reducing the secondary electron emission coefficient. Zhang et al [33, 34] discovered that non-thermal plasma modification was an effective method to increase surface conductivity and introduce polar groups to insulating material. Although DBD or corona discharge is feasible for improving the insulation performance, their electrode configuration and discharge limit their applications. Besides, the improvement mechanism of insulation properties by plasma is far from being understood.

Instead, atmospheric pressure plasma jet (APPJ) becomes a hot spot in the thin film deposition because of its simple structure, easy operation and capabilities in uneven surfaces treatment even 3D structures [35–39]. Most of APPJs are excited by AC power. However, compared with traditional APPJ driven by AC power supply, the APPJ excited by nanosecond or microsecond pulses can avoid local overheating of micro-discharge and improve discharge homogeneity [40, 41]. Considering the excellent electrical and corrosion resistance of SiC₅H₆O₂ film [42, 43], this paper adopts nanosecond pulse driven APPJ to deposit SiC₅H₆O₂ film on epoxy resin surface to improve its insulation performance. The surface properties of EP before and after the treatment were evaluated by atomic force microscope (AFM), scanning electron microscope (SEM), x-ray photoelectron spectroscopy (XPS), Fourier transform infrared spectroscopy (ATR-FTIR) and high resistance meter. Moreover, the surface charge dissipation and FV were measured.

2. Experimental devices and test system

2.1. APPJ thin film deposition

The APPJ thin film deposition device is shown in figure 1. A copper rod (Φ = 2 mm) was inserted into a T shape hollow quartz tubing (L = 180 mm, Φouter = 10 mm, Φinner = 8 mm) and worked as a high voltage electrode. To avoid glow to arc transition, the copper rod was totally covered by another inner quartz tubing (L = 145 mm, Φouter = 4 mm, Φinner = 2 mm) with one end closed. There was no gap distance between copper rod and inner quartz tubing. A circular copper sheet with width of 10 mm was wrapped on the outside of T-shape quartz tubing as a grounded electrode. The APPJ was driven by pulsed power supply with an adjustable voltage amplitude of 0–15 kV and a frequency of 1 Hz–100 kHz. The discharge voltage and the current were measured by high voltage probe (Tektronix P6015A, 1000:1) and current coil (Pearson, Model 6595, 0.5 V A⁻¹), respectively. The waveforms were recorded by an oscilloscope (TektronixDPO2024, 200 MHz). High-purity Ar (99.999%) was used both as working gas and carry gas. The gas flow rates were controlled by mass flow control meters (D08-4F, Sevenstar Electronics). The working gas was directly inlet into the discharge area with a settled flow rate of 6 slm, while the carry gas got through a gas bottle that filled with predecessor tetraethoxysilane (TEOS) with an alterable flow rate. Before the treatment process, the optical emission spectra (OES) of APPJ was recorded by spectrometer (Andor-SR500i) coupled with an ICCD camera (Andor, iStar DH334T-18). The optical fiber was fixed in the 10 mm front of pipe orifice. The epoxy resin that doped alumina...
nanoparticles was used in the experiments with a proportion of ingredients (EP: curing agent: alumina = 100:50:330), the thickness of 2 mm and size of 50 mm × 50 mm. The EP was placed in the 10 mm front of APPJ for treatment time of 0 min, 1 min, 3 min, 5 min and 10 min, respectively. It was worth mentioning that the EP was cleaned successively by ultrasonic cleaner with acetone, ethyl alcohol and deionized water and then dried in vacuum drying oven before APPJ thin film deposition.

2.2. Measurement

The finger-type copper electrodes (discharge gap: 5 mm) were used in flashover experiments as shown in figure 2(a). Every FV measurement was repeated 10 times and the average values were taken for the results. The surface morphology of samples was observed by AFM (Nanoscopy IIIa, USA) images, as well as a SEM (Zeiss Sigma, Germany). The change of the chemical groups on the sample surface was characterized by attenuated total reflection FTIR (ATR-FTIR, Thermo Nicolet iS10). The surface chemical composition and structures of EP samples were examined by XPS (Thermo Fisher ESCALAB 250Xi). According to Chinese Standard GB/T1410-2006, the surface and volume conductivity of the test samples were measured by three-electrode method with high resistance meter (Keithley, 6517B).

A needle-plate electrode was employed for corona charging and the schematic diagram is shown in figure 2(b). A stainless steel needle was connected to the ±DC power supply and the needle tip was placed 5 mm above the sample surface as shown in figure 2(b). The sample was placed on the grounded electrode when it was corona charging. The surface charge test was performed at the temperature of 25 °C with relative the humidity of ~35%. After the corona charging finished, the sample was transferred to the position where the surface potential was measured via a Kelvin electrostatic probe (Trek-6000B-6) coupled with an electrostatic voltmeter (Trek 347), as shown in figure 2(c). More details about surface charging and measurement system are provided in [34].

3. Results

3.1. Discharge characteristics

Figure 3 shows the voltage and current waveforms of APPJ under the following applied parameters: applied voltage of 8 kV, pulse frequency of 8 kHz, pulse rising time of 500 ns, pulse width of 1000 ns and falling edge of 500 ns. It can be found that there were two discharge current peaks during one voltage period, i.e. the positive pulse at the rising edge and the negative pulse at the falling edge. The amplitudes of these two pulses were 0.4 A and 0.25 A, respectively. The negative current was due to the charge accumulations on the dielectric material during first discharge [44]. On the other hand, discharge image of APPJ at Ar (TEOS)/Ar = 1:10 was shown as inset image in figure 3. The concentration of TEOS in the mixed gas was calculated to be 0.192%. With TEOS addition in Ar gas, the plasma plume color changed from purple into bright white, and it was found the uniformity would be damaged with high concentration of TEOS. The optimal gas ratio of Ar (TEOS)/Ar = 1:10 was in all the following experiments.
when the APPJ treatment time exceeded 3 min, both the surface conductivity and volume conductivity of EP were broadly declining. The surface and volume conductivity were sensitive to the ambient temperature, humidity and test time. In our experiments, the above parameters were strictly controlled to reduce errors to minimum. It has been proven that a suitable increase in surface conductivity is helpful for surface charge dissipation [9, 13].

3.4. Surface charge

Figures 5(a)–(f) show the evolution of surface charge distributions for EP samples of different treatment time under positive and negative DC voltages. In the test process, ±5 kV DC voltages were applied on the corona needle to charge the EP samples for 1 min. The surface potentials were measured at 0, 15 and 30 min. Figures 5(a) and (d) are the evolution of surface charge distributions of untreated EP samples after charging by ±5 kV DC voltages, respectively. It can be found that the surface charge distributions presented cone-shape with a vertex of 58 pC mm\(^{-2}\) for +5 kV DC voltage and −65 pC mm\(^{-2}\) for −5 kV DC voltage at 0 min. And then as time went on, the distributions of surface charge were still cone-shape with vertexes of the ‘cone’ dissipated to 45 pC mm\(^{-2}\) and −55 pC mm\(^{-2}\) for ±5 kV DC voltages at 30 min, respectively. Figures 5(b) and (e) are the evolution of surface charge distributions of EP samples treated for 3 min. The surface charge distributions presented line-shape with maximum value of 42 pC mm\(^{-2}\) for +5 kV DC voltage and −46 pC mm\(^{-2}\) for −5 kV DC voltage at 0 min. The distributions of surface charge were still line-shape but the surface charge densities were approximate 0 for both ±5 kV DC voltages at 30 min. Figures 5(c) and (f) are the evolution of surface charge distribution of EP samples treated for 10 min. The surface charge distributions presented swell-shape with maximum value of 46 pC mm\(^{-2}\) for +5 kV DC voltage and −52 pC mm\(^{-2}\) for −5 kV DC voltage at 0 min, but the distributions of surface charge became similar line-shape with surface charge density of 20 and −35 pC mm\(^{-2}\) for ±5 kV DC voltages at 30 min.

From the above results, we can conclude that the surface charge dissipation rate was significantly improved after plasma treatment. And the dissipation rate was faster with the increasing the treatment time from 0 to 3 min. Interestingly, the dissipation rate decreased when plasma treatment time exceeded 3 min. Researches show that the surface charges have three dissipation ways at the same time, i.e. neutralizing by the different charges in the gas, conduction along the surface and injection into the bulk [45–47]. In our experiments, it was not found the crater-shape distribution of surface charge in the dissipation process. The charge neutralization by the different charges in the gas was not dominant in our experiments. On the other hand, injection into the bulk was not possible because the maximum normal electric field strength was far below the threshold electrical field strength for charges injecting. Therefore, we can speculate that the surface charge was mainly dissipated along the material surface.
3.5 Trap level

Surface charge trap level distribution is an important electrical property parameter, which reflects the surface charge dissipation rate and insulation properties of insulation materials [48–50]. The surface trap level distributions were calculated according to the isothermal decay current theory based on the decay curve in figure 5. The details for calculation can be found in literatures [51, 52]. Figure 6 shows the surface trap level distributions of EP samples for different treatment time. It can be found that the maximum value of center level depth appeared at 0.87 eV for the untreated EP samples. In addition, the trap level reached its minimum at 0.78 eV at plasma treatment time of 3 min. Further increase of plasma treatment induced the depth level increase. The results demonstrated that the plasma treatment introduced shallow charge traps and decreases the trap density, but the excess treatment time can also cause the opposite effect.

3.6 Surface topography

The AFM images show the change of surface morphology between the untreated, treated for 3 min and 10 min EP samples, as shown in figures 7(a)–(c), respectively. In figure 7(a), it clearly shows that the surface of untreated EP samples was uneven and there were many protuberances and depressions. Compared with untreated samples, the surface of treated for 3 min samples showed a large area of plateaus and a few protuberances. But the sharp protuberances seemed

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface conductivity (S)</th>
<th>Bulk conductivity (S mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>$8.2 \times 10^{-16}$</td>
<td>$6.3 \times 10^{-17}$</td>
</tr>
<tr>
<td>Treated for 1 min</td>
<td>$8.3 \times 10^{-15}$</td>
<td>$7.6 \times 10^{-17}$</td>
</tr>
<tr>
<td>Treated for 3 min</td>
<td>$6.2 \times 10^{-14}$</td>
<td>$1.0 \times 10^{-16}$</td>
</tr>
<tr>
<td>Treated for 5 min</td>
<td>$7.9 \times 10^{-14}$</td>
<td>$9.2 \times 10^{-17}$</td>
</tr>
<tr>
<td>Treated for 10 min</td>
<td>$2.1 \times 10^{-13}$</td>
<td>$8.9 \times 10^{-17}$</td>
</tr>
</tbody>
</table>

Figure 5. Surface charge distribution of EP as a function of treatment time. ((a), (d)) untreated, ((b), (e)) treated for 3 min, ((c), (f)) treated for 10 min, respectively. ((a)–(c)) positive and ((d)–(f)) negative DC voltage.

Figure 6. The trap level distributions of EP samples under different treatment time.
much less and the depressions became shallower even disappeared, as shown in figure 7(b). However from figure 7(c), it can be found that a large number of swellings appeared after plasma treatment for 10 min. The corresponding average roughness ($R_a$) and mean square root roughness ($R_q$) of EP samples at different treatment time were calculated by the Nanoscope software, as shown in figure 7(d). It can be seen that both $R_a$ and $R_q$ decreased firstly and then increased with the increase of APPJ treatment time.

The surface morphology of the untreated samples and treated for 3 min samples were also characterized by SEM, as shown in figure 8. Figure 8(a) shows the untreated samples surface at magnification of 1000×. There were holes, bulges and many small particles on the untreated samples surface. Figure 8(b) shows the topography of the EP surface before APPJ thin film deposition using a magnification of 10,000×. It indicated that some small particles were on, or embedded in the sample surface. The particles embedded in the sample surface were mainly composed of alumina which was the filler used in the experimental samples because a large amount of Al element was detected by EDS, while the particles on the surface were impurity powder. Compared with untreated samples, sample surface treated for 3 min was more compact, without hollow or bulge (figure 8(c)). Moreover, it can be found that the bulges and voids in the origin surface were completely covered by the SiC$_x$H$_y$O$_z$ film (figure 8(d)).

### 3.7. Surface compositions

The surface compositions were tested mainly by the methods of FTIR and XPS spectroscopy. The FTIR results show the change of surface chemical group before and after the plasma modification, as shown in figure 9. From (a) in figure 9, it can be found that the FTIR result of untreated EP samples mainly contained of characteristic absorption peaks of C–H, C=O, C=C, C–C i.e. strong characteristic absorption peaks of C–H bond in phenyl at 1179 cm$^{-1}$, C–H multiple absorption peak at 826 cm$^{-1}$, 2851–3033 cm$^{-1}$, flexural vibrational characteristic absorption peaks of CH$_2$ and CH$_3$ at 1457 cm$^{-1}$, C=O in ester group of aliphatic and aromatic at 1730 cm$^{-1}$, and C=C in p-substituted benzene at 1506 and 1607 cm$^{-1}$. In summary, there was no other group, such as Si containing groups except typical organic groups of C, H, O containing groups. However, as shown in (b)–(d) of figure 9, a marked change had taken place in surface chemical group of the EP samples after APPJ treatment. The original C, H, O...
containing groups were gradually replaced by Si containing
groups, such as Si–O–Si at 1046 and 799 cm\(^{-1}\) along with
Si–OH at 960 cm\(^{-1}\). The appearance of a Si–OH group
indicates the appearance of the SiO\(_2\) thin
film on the ER surface. On the other hand, a slightly difference of FTIR
results was found among the EP samples that treated for 1, 3
and 10 min. With the increase of treatment time, the peak
values of C–H, C=O, C–C, C=C further reduced a little bit
while that of Si–O–Si and Si–OH slightly elevated. This
phenomenon indicated that the surface of EP had been almost
completely covered by SiC\(_x\)H\(_y\)O\(_z\) thin film after treatment of
1 min. In order to get the thickness of the films, epoxy resin is
specially treated: in each process of thin film deposition, just a
half of the EP surface is exposed, while other half is covered
with adhesive tape to prevent the surface from plasma
deposition. After plasma deposition, the film thickness was
measured by 3D microscope (Keyence VHX-900F). The test
position of film thickness was on the center of the EP. The
thicknesses were 81 nm and 213 nm after 1 and 3 min plasma
deposition, respectively.

The XPS images show the change of surface chemical
elements and their contents between the untreated EP samples
and treated for 3 min EP samples, as shown in figures 10(a)
and (b), respectively. From figure 10(a), it can be found that C
and O were the dominant elements in the untreated EP, which
indicated that the EP was an organic material. Furthermore,
there was also a small quantity of Si elements due to the
impurities in the materials manufacture process. There were a
few Al elements even though there were abundant doped
alumina nanoparticles in the EP samples. From figure 10(b), it
can be found that the peak value of Si and O elements
increased markedly while the peak value of C element
decreased significantly. A comparison of the fractions of C, O
and Si before and after APPJ treatment was made by calcu-
ling the photoelectron peak area, as shown in table 2. It
shows that the percentage of O content increased from 25.8%
to 35.05% and the percentage of Si content increased from
5.02% to 25.21% in the EP sample treated for 3 min, while
the percentage of C content decreased from 64.22% to 39%.
From FTIR and XPS, the surface included Si, OH, C and O

Figure 8. SEM images of EP surface at different treatment time. (a) Untreated (1000×), (b) untreated (10 000×), (c) treated for 3 min (1000×) and (d) treated for 3 min (10 000×).

Figure 9. FTIR spectra of EP at different treatment time.
Untreated and the brackets were errors of element content. Not only that, the molecule spectra of OH was dominated by Ar spectra lines. In addition, there were 900 nm. From Figure 11 shows the OES of Ar APPJ in range from 200 to 3.8. Reaction process the element or groups for 3 min sample. So it is better to regard Figure 10.

Figure 10. XPS spectra of EP at different treatment time. (a) Untreated and (b) treated for 3 min.

Figure 11. Typical OES of APPJ.

The changes in C, O and Si contents. The numbers inside the brackets were errors of element content.

<table>
<thead>
<tr>
<th>Element content (%)</th>
<th>C</th>
<th>O</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>64.22 (2.70)</td>
<td>25.68 (0.84)</td>
<td>5.02 (2.15)</td>
</tr>
<tr>
<td>Treated for 3 min</td>
<td>39 (3.42)</td>
<td>35.05 (5.11)</td>
<td>25.21 (1.43)</td>
</tr>
</tbody>
</table>

Table 2. The changes in C, O and Si contents. The numbers inside the brackets were errors of element content.

According to the OES above, we can roughly speculate the reaction process of APPJ deposition of SiC,H,O thin film, as shown in figure 12. Firstly, according to bond energy and length data of chemical bond that listed in table 3, the TEOS molecules collided with high-energy electrons and excited state argon atoms. It mainly caused the breakage of C–O bonds and the formation of Si(O)n(C2H5)y–n (n = 1, 2, 3, 4) (equation (1)) [53]. The further collision caused the breakage of Si–O bonds and the formation of Si–O–Si (equation (3)) and even Si and O atoms (equations (4) and (5)) (seen the existence of Si and O atom spectra in figure 11). The Si atoms reacted with OH radical (may from impurity H2O molecular by equation (7)) to generate Si–OH groups (equation (8)). At the same time, the high-energy electrons and excited state argon atoms in Ar APPJ can also destroy the original chemical bonds on the surface of EP and then produced reactive groups. Hence, the reactive groups on surface of EP reacted with the Si–O–Si and Si–OH groups to form SiC,H,O thin film, while the C2H5 groups may become some kind of gas (equation (6)) that did not deposit on the EP surface (seen C–H, C=O, C–C FTIR spectra disappear in figure 9).

4. Discussions

The FVs are influenced by a lot of factors, such as surface charge, trap level, morphology and chemical composition. Our results show that after plasma treatment, the maximum of FV increased by 18% and 13% under negative and positive DC voltages, respectively (figure 4). Accordingly, many physical and chemical properties of EP samples changed significantly by plasma treatment. In our opinion, comprehensive analysis suggests that the APPJ thin film deposition process includes three stages in our experimental environment, i.e. (1) treatment time far below 3 min: the original organic groups (mainly C–H, C–C, C=O, C=C) were largely destroyed by APPJ and reacted gradually with the Si containing inorganic groups (mainly Si–O–Si and Si–OH). It resulted in the SiC,H,O thin film growing little by little on the EP surface; (2) treatment time about 3 min: it was really happened that the deposition of abundant Si containing inorganic groups that almost entirely covered the EP samples and replaced the original organic groups. At the same time, it resulted that the EP surface became smooth with few protuberances and depressions; (3) treatment time far more than 3 min: because of the SiC,H,O thin film entirely covering the EP samples, continuous Si containing inorganic groups began to grow on the SiC,H,O thin film surface. At the same time it came about the numerous bulges and the surface morphology looked like more uneven.

The change of EP surface morphology and compositions determined the variation of insulating performance. It can be speculated that when the Si containing inorganic groups deposited on the EP sample, the decrease of C=O in ester
group and C=C in p-substituted benzene of the EP samples resulted in the reducing of energy level [54, 55]. A lower energy level meant shallower traps in EP samples and the trapped charge could easily de-trap from shallower trap [56]. The shallowing of the trap level and the increasing of surface conductivity resulted in the promotion of surface charge dissipation rate (figures 5 and 6). The higher decay rate of surface charge and the smoother sample surface led to the weakening of distortion of surface electric field distribution, which ultimately suppressed partial discharge and enhanced FV [57, 58]. On the other hand, when the Si containing inorganic groups began to grow on the SiC, O atoms and OH radicals were produced in the APPJ deposition process. Comprehensive analysis suggested that the decrease of C=O and C=C helped shallow trap level and then enhance voltage-resisting performance. Unfortunately, the voltage-resisting performance failed when the APPJ treatment time exceeded a certain value. It was probably due to that the significant increase of surface roughness could deepen the trap level depth and then deteriorate the flashover performance.

5. Conclusions

In this paper, we demonstrated that the voltage-resisting performance of EP sample was significantly improved by SiC,H,O thin films deposition. The optimal FVs of the EP sample were increased by 18% and 13% under negative and positive voltage, respectively. Accordingly, the surface conductivity of EP increased approximately two orders of magnitude and the center trap level depth shallowed from 0.87 to 0.78 eV. It was found that sharp protuberances seemed much less and depressions became shallower even disappeared. The original organic groups were gradually replaced by the Si containing inorganic groups (Si–O–Si and Si–OH), and similarly, the percentage of Si and O content increased while the percentage of C content decreased. The OES showed that there were obvious Si and O atom spectra, and OH (A-X) molecule spectra besides of Ar spectra lines, which proved that Si, O atoms and OH radicals were produced in the APPJ deposition process. Comprehensive analysis suggested that

<table>
<thead>
<tr>
<th>Bond</th>
<th>C–C</th>
<th>C–O</th>
<th>C–H</th>
<th>O–H</th>
<th>Si–O</th>
<th>Si–C</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (kJ mol⁻¹)</td>
<td>346</td>
<td>358</td>
<td>411</td>
<td>459</td>
<td>452</td>
<td>318</td>
</tr>
<tr>
<td>r (pm)</td>
<td>154</td>
<td>143</td>
<td>109</td>
<td>96</td>
<td>163</td>
<td>185</td>
</tr>
</tbody>
</table>

Figure 12. Schematic diagram of SiC,H,O thin film deposition process.

References

[2] Li S T, Yu S H and Feng Y 2016 High Volt. 1 122
[38] Li X C et al 2015 Plasma Sources Sci. Technol. 24 065020
[42] Premkumar P A et al 2009 Plasma Sources Sci. Technol. 6 693
[49] Liu N et al 2016 High Volt. 1 95
[56] Li C Y et al 2016 AIP Adv. 6 025017
[57] Zhang G Y et al 2002 Appl. Phys. Lett. 80 3742
[60] Li C Y et al 2017 J. Phy. D: Appl. Phys. 50 065301