

Electrical modeling of dielectric barrier discharge considering surface charge on the plasma modified material

Hong-Lu Guan(关弘路), Xiang-Rong Chen(陈向荣), Tie Jiang(江铁), Hao Du(杜浩), Ashish Paramane, Hao Zhou(周浩)

Citation: Chin. Phys. B . 2020, 29(7): 075204 . **doi:** 10.1088/1674-1056/ab8a3f
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Influence of vibration on spatiotemporal structure of the pattern in dielectric barrier discharge

Rong Han(韩蓉), Li-Fang Dong(董丽芳), Jia-Yu Huang(黄加玉), Hao-Yang Sun(孙浩洋), Bin-Bin Liu(刘彬彬), Yan-Lin Mi(米彦霖)

Chin. Phys. B . 2019, 28(7): 075204 . **doi:** 10.1088/1674-1056/28/7/075204

UAV flight test of plasma slats and ailerons with microsecond dielectric barrier discharge

Zhi Su(苏志), Jun Li(李军), Hua Liang(梁华), Bo-Rui Zheng(郑博睿), Biao Wei(魏彪), Jie Chen(陈杰), Li-Ke Xie(谢理科)

Chin. Phys. B . 2018, 27(10): 105205 . **doi:** 10.1088/1674-1056/27/10/105205

Effect of actuating frequency on plasma assisted detonation initiation

Si-Yin Zhou(周思引), Xue-Ke Che(车学科), Di Wang(王迪), Wan-Sheng Nie(聂万胜)

Chin. Phys. B . 2018, 27(2): 025208 . **doi:** 10.1088/1674-1056/27/2/025208

Simulation of transition from Townsend mode to glow discharge mode in a helium dielectric barrier discharge at atmospheric pressure

Li Xue-Chen, Niu Dong-Ying, Xu Long-Fei, Jia Peng-Ying, Chang Yuan-Yuan

Chin. Phys. B . 2012, 21(7): 075204 . **doi:** 10.1088/1674-1056/21/7/075204

Aspects of the upstream region in a plasma jet with dielectric barrier discharge configurations

Li Xue-Chen,Jia Peng-Ying,Yuan-Ning,Chang Yuan-Yuan

Chin. Phys. B . 2012, 21(4): 045204 . **doi:** 10.1088/1674-1056/21/4/045204

Electrical modeling of dielectric barrier discharge considering surface charge on the plasma modified material*

Hong-Lu Guan(关弘路)[1], Xiang-Rong Chen(陈向荣)[1,2,†], Tie Jiang(江铁)[1], Hao Du(杜浩)[1], Ashish Paramane[1], and Hao Zhou(周浩)[1]

[1] *Zhejiang Provincial Key Laboratory of Electrical Machine Systems, College of Electrical Engineering, Zhejiang University, Hangzhou* 310027, *China*
[2] *ZJU-Hangzhou Global Scientific and Technological Innovation Center, Hangzhou* 311200, *China*

(Received 13 February 2020; revised manuscript received 25 March 2020; accepted manuscript online 17 April 2020)

We present the variations of electrical parameters of dielectric barrier discharge (DBD) when the DBD generator is used for the material modification, whereas the relevant physical mechanism is also elaborated. An equivalent circuit model is applied for a DBD generator working in a filament discharging mode, considering the addition of epoxy resin (EP) as the plasma modified material. The electrical parameters are calculated through the circuit model. The surface conductivity, surface potential decay, trap distributions and surface charge distributions on the EP surface before and after plasma treatments were measured and calculated. It is found that the coverage area of micro-discharge channels on the EP surface is increased with the discharging time under the same applied AC voltage. The results indicate that the plasma modified material could influence the ignition of new filaments in return during the modification process. Moreover, the surface conductivity and density of shallow traps with low trap energy of the EP samples increase after the plasma treatment. The surface charge distributions indicate that the improved surface properties accelerate the movement and redistribution of charge carriers on the EP surface. The variable electrical parameters of discharge are attributed to the redistribution of deposited surface charge on the plasma modified EP sample surface.

Keywords: dielectric barrier discharge, surface charge, plasma treatment, circuit model

PACS: 52.77.–j, 52.40.Hf, 68.55.aj **DOI:** 10.1088/1674-1056/ab8a3f

1. Introduction

The dielectric barrier discharge (DBD) under the atmospheric pressure is a promising method in industrial applications. It is a convenient, effective, and environmental-friendly method to produce non-thermal plasma with adequate ions, electrons, and active species.[1] Different types of plasma setups based on DBD, such as volume DBD, surface DBD, and plasma jets have been studied for many years and are widely used in ozone production, airflow control, pollutants decomposition, material surface modification, etc.[2] Regardless of the application field of the DBD system and its structure, the amount and variety of active species are the important factors related to the effect of physical and chemical reactions happening in the plasma environment.[3] The generation efficiency of active species mainly depends on the electrical properties of discharge such as consumed power and transferred charge during the discharge per half cycle.[3] The Q–V diagram is an effective method to investigate the electrical properties of the discharge. Q is the measured transferred charge during discharge per cycle, and V is the applied voltage on the DBD generator.

The Q–V diagram tends to be an approximate parallelogram under the low frequency sinusoidal driving voltage.[4] Many equivalent and simplified circuits of the DBD generator were studied to analyze the Q–V diagram.[5] However, when the DBD generator discharges in a filament mode, only limited part of the dielectric surface is covered by the micro-discharge channels and deposited charges.[6] In the filament discharge, the calculated capacitance of dielectric materials is variable under different amplitudes of driving voltage. This is contradictory to the fact that the capacitance of the solid dielectrics is determined by the DBD structure and material properties. Peeters *et al.*[7] proposed a new circuit model considering the partial discharging on the dielectric barrier to correct the calculated electrical parameters of a DBD generator functioning in the filament mode. However, the mechanism of the effect of dielectric material properties on the filament discharge is still unclear. Therefore, it is necessary to investigate the electrical parameters of the DBD with the plasma modified material based on the circuit model proposed by Peeters *et al.*[7]

In the field of material surface modification, e.g., surface coating, etching, fluorination, and direct plasma treatment, the volume DBD generator is widely used since it can produce large-scale plasma and increase the modified area of the material.[8] The uniform discharge is significant in terms of material modification.[9] Many efforts have been made to

*Project supported by the National Key R&D Program of China (Grant No. 2018YFB0904400), the National Natural Science Foundation of China (Grant No. 51977187), the "Science and Technology Innovation 2025" Key Project of Ningbo City, China (Grant No. 2018B10019), the Natural Science Foundation of Zhejiang Province, China (Grant No. LY18E070003), the State Key Laboratory of HVDC, Electric Power Research Institute, China Southern Power Grid (Grant No. SKLHVDC-2019-KF-18), and the Fundamental Research Funds for the Central Universities, China (Grant No. 2018QNA4017).

†Corresponding author. E-mail: chenxiangrongxh@zju.edu.cn

© 2020 Chinese Physical Society and IOP Publishing Ltd

producing a homogeneous or glow-like discharge at the atmospheric pressure.[10] However, the requirements of the generator structure and dielectric materials are rigorous in the literature.[11] Generally, the material modification by the volume DBD requires the material to be inserted directly into the discharge gap. The insertion of external material will inevitably influence the discharge mode of these specially designed DBD generators. Nevertheless, little literature has focused on the influence of plasma modified materials on discharge parameters of the DBD. Furthermore, the existing equivalent circuit model does not consider the effect of the inserted material. In our present study, we find that the discharge parameters (e.g., transferred charge density, areal ratio of micro-discharge on dielectrics surface) of a fixed volume DBD are variable since the moment of inserting the modified material. Thereafter, the filament discharge parameters tend to be stable. The variable parameters in the beginning indicate that the inserted material can influence the discharge parameters of the DBD when the material is being modified. Meanwhile, the time duration of variation is related to the surface state and properties of the material. The plasma treatment can change the surface properties of the modified material, whereas the variable material properties will influence the discharge parameters in turn.

This study aims at investigating the mechanism regarding the effect of plasma modified material on the DBD when the material is being modified. An improved circuit model is built to calculate the electrical parameters considering the inclusion of the plasma modified material. Moreover, surface conductivities, surface potential decay (SPD), surface trap distribution and surface charge distribution of the plasma modified material were measured and calculated to justify the mechanism.

2. Electric circuit model

Figure 1(a) schematically shows a common volume DBD system with an addition of disk-shaped epoxy resin (EP) sample as the plasma modified material. The DBD setup system includes a high voltage source, a generator system, and a measurement system. The details of the DBD system can be found in our previous research work.[12] The as-received commercial grade EP without any micro or nano-sized fillers was used. The radius of the EP sample is 28 mm and the average thickness is 2 mm. The length and width of square alumina ceramic (dielectric barrier) are 100 mm each. The radius of the copper electrodes is 28 mm.

Figure 1(b) shows the real-time images of a filament discharge under different discharging times. It can be seen that the filaments are distributed sparsely and randomly on the EP sample at the beginning. However, with the increase of discharging and treatment time, the filaments tend to redistribute on the entire EP surface. In addition, the distance between the adjacent filaments is decreased. The increased density of new filaments indicates that the properties of DBD are variable.

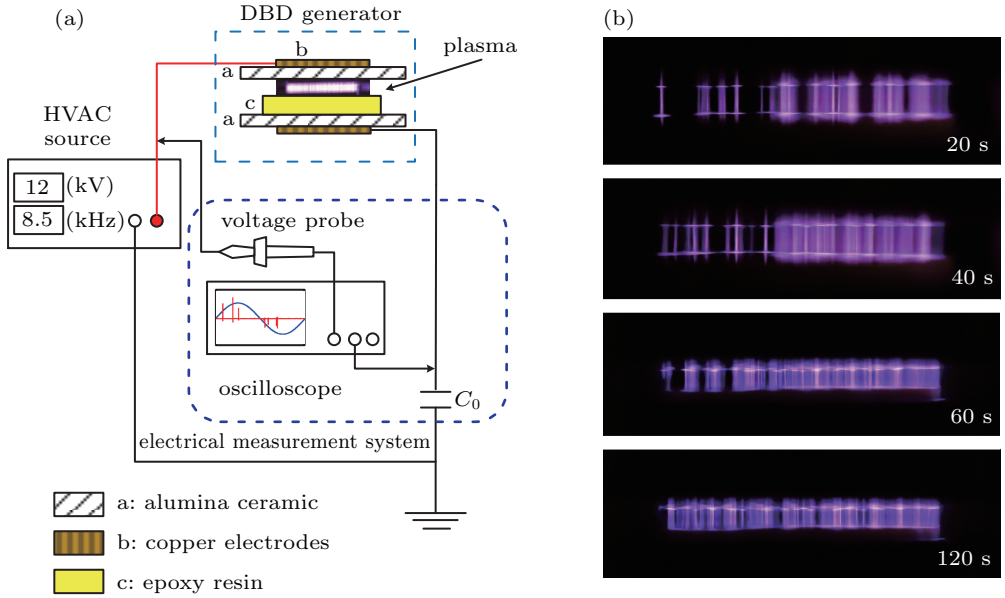


Fig. 1. (a) Schematic diagram of the DBD generation setup with the modified EP sample. (b) Real-time images of a filament discharge under different discharging times.

The diagram of a standard parallelogram Q–V curve is shown in Fig. 2(a), whereas figure 2(b) presents the physical model of filament discharging gap used to illustrate different elements in the circuit model. In Fig. 2(a), the slope of line 1 represents the total capacitance C_{unit} in a non-discharging state, and the slope of line 2 represents the total capacitance C_{dis} during discharging. Figure 2(c) shows the applied equivalent circuit model based on the DBD generator with the plasma modified EP in Fig. 1. In the circuit model, the change between the states of discharging and non-discharging is repre-

sented by a double-throw switch. When the DBD generator is not discharging, the total capacitance $C_{\rm unit}$ equals the series connection of capacitance of solid dielectrics $C_{\rm solid}$ and capacitance of gas gap $C_{\rm gas}$. However, when the DBD generator is discharging, only part of the material surface is covered by the micro-discharge channels and transferred charge, hence the discharge channel of filament is regarded as an extra current source $i_{\rm dis}(t)$ in the equivalent circuit. The stray capacitance is included in the total capacitance of the non-discharging part.[7] According to the circuit model in Fig. 2(c), the total capacitance $C_{\rm dis}$ during discharging is expressed as

$$C_{\rm dis} = mC_{\rm unit} + nC_{\rm solid}, \tag{1}$$

where the coefficients m and n represent the areal ratios of non-discharging and discharging part of solid dielectrics surface, respectively. Moreover, the sum of m and n is 1. As a result, the coefficients m and n can be calculated by

$$m = \frac{C_{\rm solid} - C_{\rm dis}}{C_{\rm solid} - C_{\rm unit}}, \tag{2}$$

$$n = \frac{C_{\rm dis} - C_{\rm unit}}{C_{\rm solid} - C_{\rm unit}}. \tag{3}$$

The total actually transferred charge $Q_{\rm dis}$ in a discharge duration is expressed as

$$Q_{\rm dis} = \frac{C_{\rm solid}(C_{\rm dis} - C_{\rm unit})}{C_{\rm dis}(C_{\rm solid} - C_{\rm unit})} Q_{\rm total}, \tag{4}$$

and the average charge density $\sigma_{\rm dis}$ of all micro-discharge channel is

$$\sigma_{\rm dis} = \frac{Q_{\rm dis}}{nS}, \tag{5}$$

where $Q_{\rm total}$ is the charge variation including the charge transferred in the micro-discharge channel $Q_{\rm dis}$ and the polarization charge in the capacitance $mC_{\rm unit}$. S is the dielectrics surface area of the capacitance $C_{\rm solid}$.

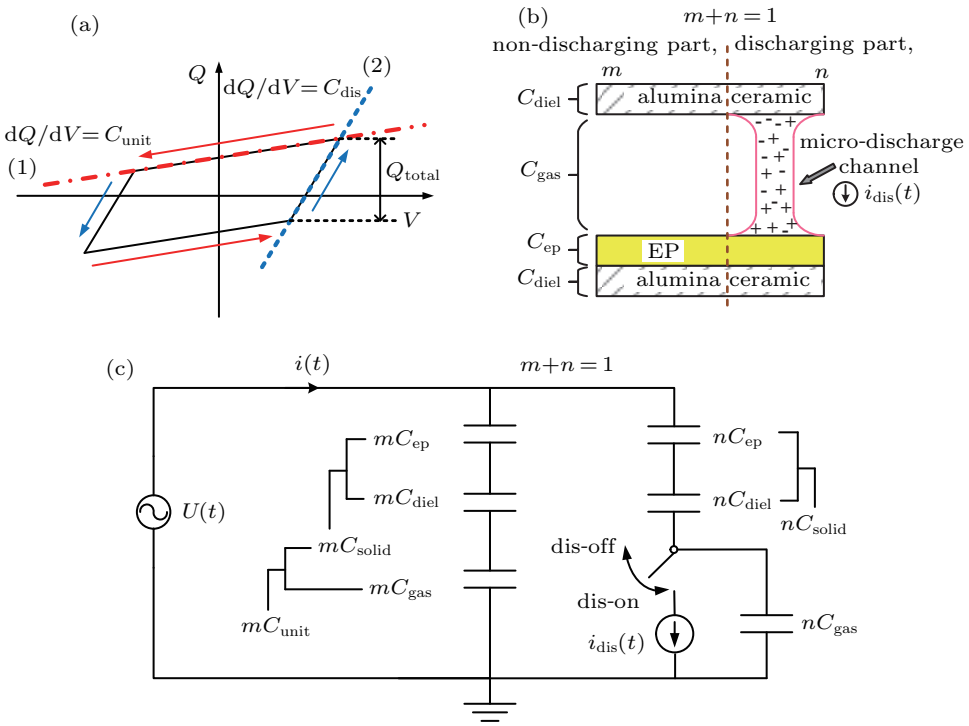


Fig. 2. (a) A standard parallelogram Q–V diagram. (b) Schematic diagram of micro-discharge channels in the gas gap. (c) The proposed circuit model based on the DBD generator with the modified EP in filament discharging mode.

3. Electrical properties and discussion

As the structure of the DBD generator is fixed, the capacitances of $C_{\rm unit}$ and $C_{\rm solid}$ are assumed to be constant, and the measured value of $C_{\rm unit}$ is 178 pF, the $C_{\rm solid}$ is 273 pF with the EP sample. Moreover, the measured value of $C^*_{\rm unit}$ is 275 pF, and the $C^*_{\rm solid}$ is 1379 pF for the DBD generator without the EP sample. The capacitance of solid dielectrics $C_{\rm solid}$ is measured using the short-circuit method. Two pieces of copper foil are inserted between the two alumina ceramic plates of the DBD generator and the EP sample, thereby the alumina ceramic plates and the EP sample are connected by the copper, and the gas gap is short-circuited. The inserted copper foil is 28 mm in radius and 0.2 mm in thickness, the same radius as the top and bottom copper electrodes. Then a 1 kV high voltage is applied on the top copper electrodes. Since the Q–V diagram is an oblique line under the voltage, the capacitance of solid dielectrics $C_{\rm solid}$ is calculated through the slopes of the oblique line. The calculated area S is 2462 mm^2. According to the measured Q–V diagram after discharging times of 20 s, 40 s, 60 s, and 120 s under the voltage of 12 kV and

8.5 kHz, the calculated areal ratios m and n, and the average charge density $\sigma_{\rm dis}$ of all micro-discharge channel are plotted in Fig. 3. Five different EP samples were measured to calculate the average parameters.

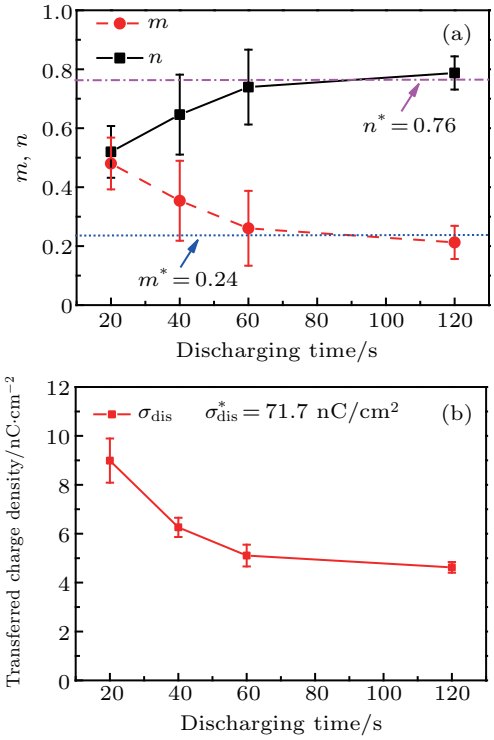


Fig. 3. (a) The calculated areal ratios of the discharging part (n) and non-discharging part (m) on the EP sample surface. (b) The calculated average transferred charge density in all micro-discharge channels. The m^*, n^*, and $\sigma^*_{\rm dis}$ are the parameters of the DBD generator without the EP sample.

Figure 3(a) implies that at the beginning of the discharge, only 52% of the EP sample surface area is covered by the micro-discharge channel. Furthermore, the areal ratio n of micro-discharging is increased with the increment of discharging time, and is stabilized to nearly 78.7% after 120 s plasma treatment. On the contrary, the areal ratio m under the non-discharging condition of the EP sample surface is decreased gradually with the increased plasma treatment time. The coverage of micro-discharge on the EP sample surface includes many filament channels during a half duration of applied voltage, and the placement of different filaments that occurred at a different time could be overlapped. Figure 3(b) illustrates that the average transferred charge density in all micro-discharge channels decreases with the increase of discharging time and becomes stable after 120 s. The reduction is due to the increased number of filaments.[13] The variation of the average transferred charge density and the areal ratio of micro-discharge on sample surface indicates that the parameters of filament discharging in the initial stage are unstable. Moreover, the variation is attributed to the changed properties of the plasma modified EP samples' surface, since the charge carriers movement on the sample surface could be accelerated after the plasma treatment. The m^*, n^*, and $\sigma^*_{\rm dis}$ in Fig. 3 are parameters of the designed DBD generator without the EP sample. Figure 3 also indicates that the parameters of DBD with the inserted EP sample are different from the parameters of the designed DBD generator without EP samples. It is further proved that the insertion of external material will inevitably influence the discharge mode of these specially designed DBD generators.

The surface conductivity is one of the main factors related to the movement of the surface charge on the EP sample surface. The DC surface conductivity of the EP sample was measured using a three-electrode structure in a temperature controllable oven with a temperature of 30 ℃.[12] The calculated surface conductivity is tabulated in Table 1. It can be seen that the surface conductivity of the EP sample increases evidently after the plasma treatment, even though the treatment time is very short. In addition, the longer plasma treatment time leads to a higher surface conductivity. The enhanced surface conductivity after plasma treatment would accelerate the movement of the accumulated charge on the EP sample surface.

Table 1. Surface conductivities (in 10^{-16} Ω^{-1}) of the samples under different plasma treatment durations.

Treatment time/s	0 (untreated)	20	40	60	120
Surface conductivities	0.22	3.74	12.03	23.90	44.94

The charge carriers transferred in the filament channel would accumulate on the EP sample surface, thereby influencing the distribution and ignition of different filaments. Because of the small volume and high mobility of negative charge carriers, the negative charge plays a significant role in the filaments ignitions.[14] The electron trap distribution is another important factor relevant to the charge movement, since the negative surface charge carriers could be trapped by the electron traps on the EP sample surface. In order to investigate the variation of electron trap distribution before and after the plasma treatment, the surface potential decay (SPD) of the EP sample after corona charging in open air at 25 ℃ was measured.[12] Thereafter, the electron trap distribution is calculated through the method proposed by Zhou *et al.*[15] using the measured SPD curves. The calculated trap distributions are illustrated in Fig. 4. As the trap density is directly proportional to $t\,{\rm d}V/{\rm d}t$, the product of $t\,{\rm d}V/{\rm d}t$ is used to represent the trap density in Fig. 4.[16] It is shown that the trap energy decreases continuously with the increase of the plasma treatment time. The trap density of shallow traps having low trap energy is increased. The increased amount of shallow traps makes it easier for the trapped surface charge to de-trap and to accelerate the movement and redistribution of the accumulated surface charge.

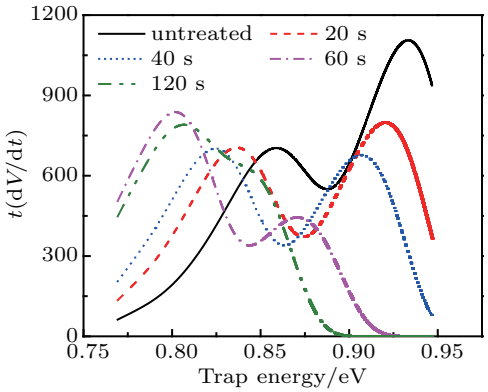


Fig. 4. Electron trap distributions on EP sample surface under different DBD plasma treatment durations (untreated, 20 s, 40 s, 60 s, and 120 s).

The measured surface potential distribution on EP sample surface was also used to calculate the surface charge density and distribution through the inversion algorithm.[17] Figure 5 shows the net surface charge density of the untreated and plasma treated EP samples after corona charging. It should be noted that the actual polarities of the various charges at different positions on the surface are unknown, since only the sum of the charge densities is observed at each point in Fig. 5. It can be seen that both net positive and net negative charges are accumulated on EP surface even though the sample was only charged by positive corona, because the negative charge is induced inside the EP samples or drifted from open air.[18] It has been observed that there are net hetero-polarity charges existing simultaneously and distributed adjacently on the dielectric surface when discharging.[19] Hence, the variation of surface charge density on the EP surface after corona charging can be used to analyze the movement of deposited hetero-polarity surface charge when discharging. It is obvious that the surface charge density of the 120 s plasma treated EP sample decreases more rapidly than the untreated samples. Moreover, the peak locations of charge density are changed for the plasma treated samples. However, the peak location remains unchanged for the untreated samples. The results indicate that the plasma treatment can enhance the movement of the surface charge carriers on the EP sample surface.

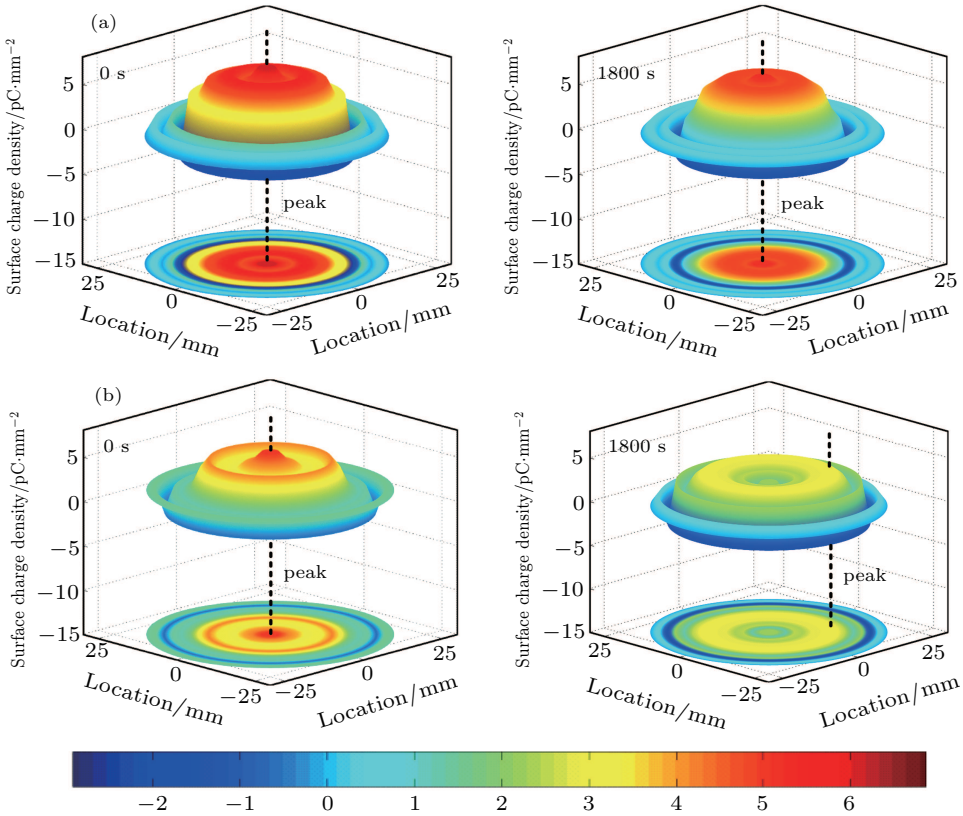


Fig. 5. Surface charge density on untreated and plasma treated EP sample surface: (a) untreated: at 0 s (left) and 1800 s (right) after removing the charging voltage, (b) 120 s plasma treated: at 0 s (left) and 1800 s (right) after removing the charging voltage.

For a new EP sample without plasma treatment, with the applied sinusoidal voltage rising to the ignition of the filament discharge, only limited parts on the surface are covered by the micro-discharge channels.[7] The initiated micro-discharge could be extinguished because of the reduction of electric field intensity caused by the accumulated charge. Fresh micro-discharge would occur in other places on the EP surface in the remaining half period. With the increase of surface conductivity and the increased amount of shallow traps on the EP sample surface, the movement of the accumulated surface charge is accelerated. Therefore, the surface charge is promoted to spread over the sample surface as the seed electrons for new filaments, and the ignition of the new filaments becomes easy after the voltage is reversed. Finally, the number of micro-

discharge channels increases and the coverage of filaments on the sample surface is also increased. Moreover, the increase of filaments occurring at the same time implies that the distance between them is decreased, leading to a more uniform modification of the sample surface. It has been reported elsewhere that the surface conductivity and trap distribution of dielectrics could influence the uniformity of the DBD.[20,21] The variation of surface properties of the plasma modified EP samples could also influence the discharge in the gas gap through the redistribution of the residual surface charge. The influence of the plasma modified material on DBD is due to the movement of the deposited surface charge.

4. Conclusions

In summary, we have found that the Q–V diagram is variable after the insertion of the modified material into the gap of a DBD generator. Based on this phenomenon, an equivalent circuit model proposed by Peeters *et al.*[7] is built and applied for a DBD generator with discharging in the filament mode, considering the partial occupation of micro-discharge channels on the plasma modified material surface in this study. Disk-shaped EP samples are used as the modified material, and the electrical parameters of the DBD with the modified EP sample are calculated through the proposed circuit model. It is found that the area ratio of filaments to the EP sample surface is increased with the increment of discharging time. This indicates that the number of filaments is increased and the ignition of new filaments is enhanced. Moreover, the surface conductivity and density of shallow traps on EP surface are increased. The improved surface properties of the EP samples make it easier for the deposited surface charge to spread over the entire EP sample surface, thereby enhancing the electric field in the gas gap. Therefore, the ignition of new filaments is attributed to the redistribution of deposited surface charge. It has been proved that the plasma modified material can affect the parameters of the discharging in return during the process of the modification.

Acknowledgements

The authors thank the group members of Advanced High Voltage Technology, Zhejiang University, China for their help.

References

[1] Shao T, Liu F, Hai B, Ma Y F, Wang R X and Ren C Y 2017 *IEEE Trans. Dielectr. Electr. Insul.* **24** 1557
[2] Li D, Liu D X, Nie Q Y, Li H P, Chen H L and Kong M G 2014 *Appl. Phys. Lett.* **104** 204101
[3] Barni R, Esena P and Riccardi C 2005 *J. Appl. Phys.* **97** 073301
[4] Jiang H, Shao T, Zhang C, Yan P and Liu H B 2018 *IEEE Trans. Plasma Sci.* **46** 3524
[5] Liu S H and Neiger M 2003 *J. Phys. D: Appl. Phys.* **36** 3144
[6] Wild R, Benduhn J and Stollenwerk L 2014 *J. Phys. D: Appl. Phys.* **47** 435204
[7] Peeters F J J, Rumphorst R F and van de Sanden M C M 2016 *Plasma Sources Sci. Technol.* **25** 03LT03
[8] Dou S, Tao L, Wang R L, Hankari S E, Chen R and Wang S Y 2018 *Adv. Mater.* **30** 1705850
[9] Dimitrakellis P, Zeniou A, Stratakos Y and Gogolides E 2016 *Plasma Sources Sci. Technol.* **25** 025015
[10] Qi F, Li Y Y, Zhou R S, Zhou R W, Wan J J, Xian Y B, Cullen P J, Lu X P and Ostrikov K K 2019 *Appl. Phys. Lett.* **115** 194101
[11] Liu W Z, Ma C L, Cui W S, Yang X, Wang T H and Chen X Y 2017 *Appl. Phys. Lett.* **110** 024102
[12] Guan H L, Chen X R, Du H, Paramane A and Zhou H 2019 *J. Appl. Phys.* **126** 093301
[13] Tang J, Duan Y X and Zhao W 2010 *Appl. Phys. Lett.* **96** 191503
[14] Zheng Y S, He J L, Zhang B, Zeng R and Yu Z Q 2011 *IEEE Trans. Plasma Sci.* **39** 1644
[15] Zhou T C, Chen G, Liao R J and Xu Z Q 2011 *J. Appl. Phys.* **110** 043724
[16] Kumara S, Ma B, Serdyuk Y V and Gubanski S M 2012 *IEEE Trans. Dielectr. Electr. Insul.* **19** 2189
[17] Zhang B Y and Zhang G X 2017 *J. Appl. Phys.* **121** 105105
[18] Li C Y, Lin C J, Chen G, Tu Y P, Zhou Y, Li Q, Zhang B and He J L 2019 *Appl. Phys. Lett.* **114** 202904
[19] Tschiersch R, Nemschokmichal S, Bogaczyk M and Meichsner J 2017 *J. Phys. D: Appl. Phys.* **50** 105207
[20] Li M, Li C R, Zhan H M, Xu J B and Wang X X 2008 *Appl. Phys. Lett.* **92** 031503
[21] Choi J H, Lee T I, Han I, Oh B Y, Jeong M C, Myoung J M, Balk H K, Song K M and Lim Y S 2006 *Appl. Phys. Lett.* **89** 081501