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Study on Discharge Dynamics in an Atmospheric Pressure Dielectric Barrier Discharge

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Abstract In this work, the discharge dynamics in an atmospheric pressure dielectric barrier discharge (DBD) is studied in a DBD reactor having parallel plate electrodes geometry. The DBD reactor is powered by a 50 Hz ac high voltage power source through a ballast resistor. The images of filaments occurring in the discharge gap are captured using a high speed intensified charge coupled device camera. The occurrence of frequent synchronous breakdown of micro discharges has been observed across the discharge gap when the electron avalanche happens in the direction from the dielectric surface towards the opposite electrode. The discharge gap dependence on synchronous breakdown is studied by changing the discharge gap. The shape of the filaments has been found to be strongly dependent on the direction of the electron avalanche. It is demonstrated that the diffusion of electrons occurs when the electron avalanche happens in the direction towards the dielectric from the opposite electrode. A smaller diffusion leading to narrower filaments is observed when the electron avalanche happens in the direction from the dielectric to the opposite electrode. This can be explained by the existence of memory charge on the dielectric surface.

Keywords Dielectric Barrier Discharge, Atmospheric Pressure, Filamentary Discharge, Memory Charge

1. Introduction

Dielectric barrier discharge (DBD) is generated when at least one of the electrodes is covered with a dielectric material. The research in DBD, which is also known as silent discharge, atmospheric pressure discharge, and barrier discharge, has received a lot of attention because of its wide applications in industry for ozone synthesis [1-2], removal of gaseous pollutant [3-4], biomedical applications [5-6], surface treatment of materials [7-8], plasma display panels [9], and so on. The DBD can be generated in different discharge modes namely, filamentary, regularly patterned, completely diffuse barrier discharge, which depend on different conditions [10]. In the filamentary mode, which is commonly generated in DBD under atmospheric pressure, a large number of micro- discharge filaments with sub-millimeter size diameter and nanosecond duration may either regularly or randomly distributed over the discharge gap [10-12]. Multiple current pulses can be observed in the current signal obtained for a filamentary mode DBD. Each current pulse represents the total current flowing through one or more filaments that appear in the discharge gap at a particular time. When a current pulse represents the total current flowing through more than one filament at a particular time, it is known as collective filamentary discharge [13].

The dielectric layer prevents the formation of an arc discharge and also limits the discharge current. Due to the existence of dielectric, the charges generated in a DBD may be trapped on the dielectric surface. The charges fall on the dielectric surface do not spread out uniformly on the surface. Instead, they are accumulated at various points on the surface as residual charges. When the polarity of the applied voltage is reversed, the residual charges will cause the formation of filamentary channels at the same location as that in the previous polarity. This is known as the memory effect, where the residual charges are called the memory charges. The memory charges will also affect the secondary emission from the dielectric surface. Many researchers [14-18] have studied the discharge dynamics of filamentary DBD through experimental investigations and modeling. In our earlier work [14], the role of secondary emission on discharge dynamics in an atmospheric pressure dielectric barrier discharge is studied in 5 mm discharge gap.

In this work, the investigation of discharge dynamics in an atmospheric pressure DBD has been carried out using a high-speed intensified charge coupled device (iCCD) camera. The occurrence of frequent synchronous breakdown of micro discharges has been observed across the discharge gap in case of negative current pulse. Compared to earlier work [14], the influence of the discharge gap on synchronous breakdown is studied by changing the discharge gap. Images of filaments corresponding to a single positive or negative current pulse have been obtained in this study. The role of the memory charges in the formation of filamentary mode DBD has been discussed.

2. Experimental Setup and Procedure

Figure 1 shows the schematic diagram of the experimental setup used in this work. The DBD reactor consists of a pair of parallel plate stainless steel (SS304) electrodes of 6 cm in diameter and 1.5 cm in thickness. There is a facility to vary the space gap between the two electrodes. To prevent the localized electric field, the edges of the electrodes are smoothened. A silver string is inserted to stabilize the motion of the electrodes. The dielectric layer is a Pyrex glass sheet of dimension 10 cm × 10 cm and thickness of 2 mm. The dielectric sheet is placed by using two position adjustable dielectric holders. Perspex chamber is used to house the electrodes system. The front window of the chamber is sealed with a glass window. The working gas in this experiment is open air at atmospheric pressure.

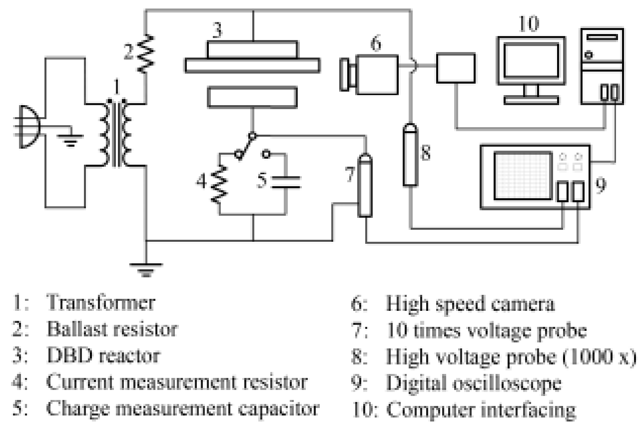

Figure 1. Schematic diagram of the experimental setup. Reproduced from Physics of Plasmas 21, 044502 (2014), with the permission of AIP Publishing.

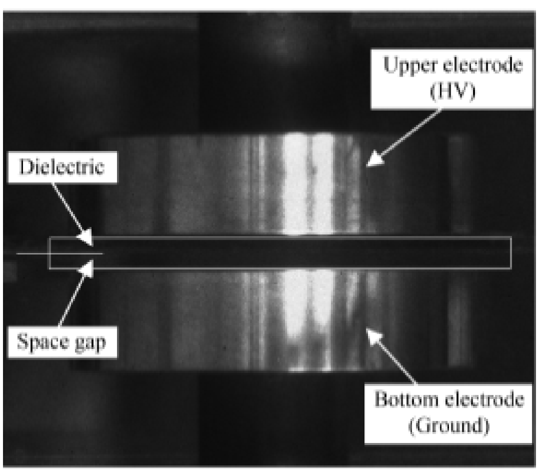

Figure 2. The image of the electrodes and the region of interest (central rectangular area)to be captured by the camera.

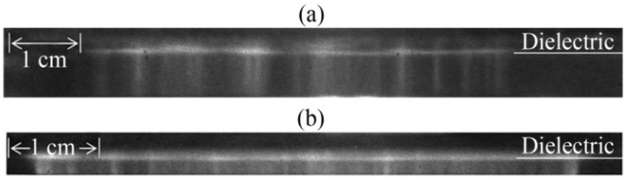

Figure 3.(a): iCCD image of 5 mm gap DBD with exposure time of 500 ms. (b): iCCD image of 2mm gap DBD with exposure time of 1 s.

The DBD reactor is powered by a 50 Hz ac high voltage power supply through a ballast resistor of 8.8 MΩ. The maximum applied voltage is 20 kV (40 kV peak to peak). The upper electrode is electrically connected to the high voltage power supply while the bottom electrode is grounded. The dielectric plate is in contact with the upper electrode. In order to capture the images of filaments occurring in the discharge gap, the iCCD camera (Princeton Instruments make, model: PI-MAX3) is placed at the side of the reactor. Figure 2 shows an image of the electrodes of the DBD reactor and the region of interest to be captured by the iCCD camera. The exposure time of the camera has been adjusted in such a way that the camera captures only filaments corresponding to a single current pulse. The time resolved current and voltage signals are registered simultaneously using a digital oscilloscope (Yokogawa DL6104, bandwidth 1 GHz). The iCCD images of DBD generated in 5 mm and 2 mm discharge gaps is shown in Fig. 3.

3. Results and Discussion

The schematic diagram of negative and positive current pulses [14], which are formed in atmospheric pressure dielectric barrier discharge (in our electrode geometry) is shown in Fig. 4. The negative current pulse is formed due to the electron avalanche from the dielectric surface to the bottom electrode (grounded) and ion streamer movement towards the dielectric surface from the bottom electrode. For the positive current pulse, electrons are flowing towards the dielectric surface from the bottom electrode and ion streamer progresses from the dielectric surface to the bottom electrode.

The applied voltage measurement shows that there is a dip on the voltage waveform corresponding to a current pulse as shown in Figs. 5, 6, 7, and 8. This is attributed to an opposite charge transported through the space gap when the filamentary discharge occurs. . The total applied voltage to the DBD reactor is determined from the total deposited charge supplied by the power supply on the two electrodes. The total deposited charges on the DBD reactor decrease instantaneously when the opposite charges generated by the filamentary discharge reach the electrode. The distorted voltage requires a certain time to recover to the initial voltage. This provides an alternative approach to the determination of the occurrence time of the filaments. The occurrence time of the filaments is found to be 77 ns, which can be estimated from the current pulse and the voltage waveform.

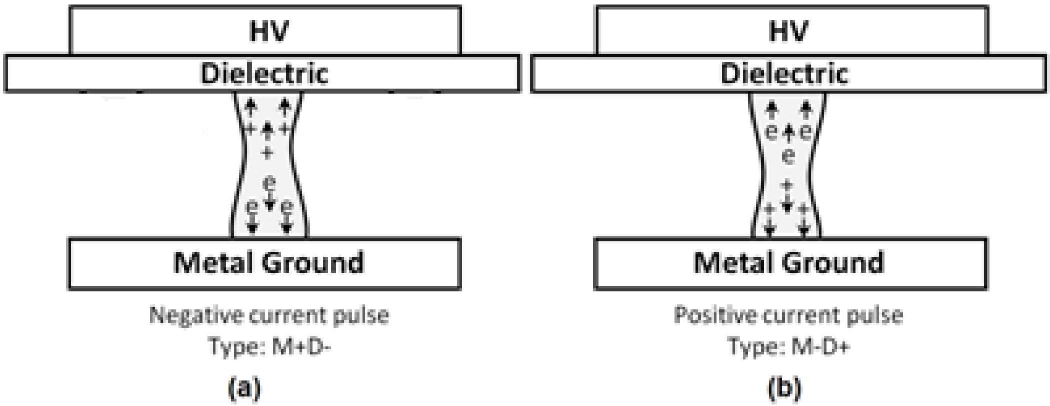

Figure 4. (a):The flow direction of the electrons and ions in negative current pulse (M –metal electrode, D – dielectric). (b): The flow direction of the electrons and ions in positive current pulse (M – metal electrode, D – dielectric).Reproduced from Physics of Plasmas 21, 044502 (2014), with the permission of AIP Publishing.

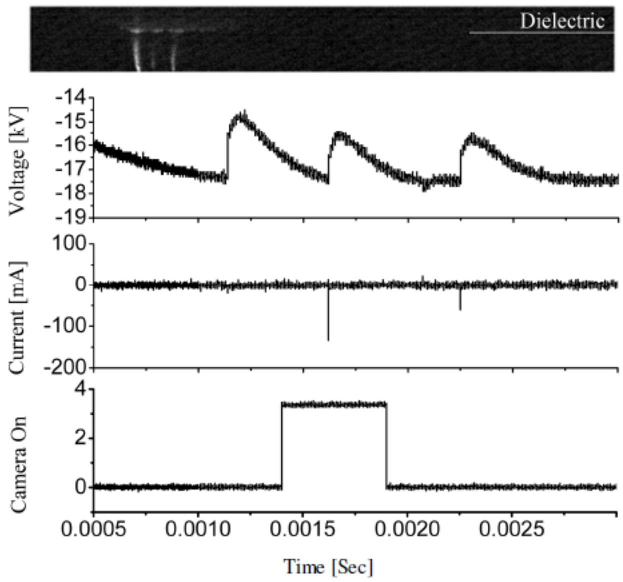

Figure 5. iCCD image of negative pulse in 5 mm gap DBD with exposure time of 500 µs (upper). The relative timing of the current, voltage, and camera signal (bottom) are also shown. The camera on (y-axis) represents the f-number. Reproduced from Physics of Plasmas 21, 044502, (2014), with the permission of AIP Publishing.

The negative current pulse image for discharge gap 5 mm is shown in Fig. 5. It is seen from the figure that in case of 5 mm discharge gap, there are three simultaneously ignited filaments in a single negative current pulse. It is due to the collective effect and synchronous breakdown [13]. The synchronous breakdown is defined as the condition, where multiple filaments are ignited simultaneously in the discharge gap corresponding to a single current pulse [13].To study the discharge gap dependence on synchronous breakdown, discharge gap is changed from 5mm to 2mm. In case of 2mm discharge gap (Fig. 6), synchronous breakdown seems to have occurred. More filaments have been observed for a single current pulse in case of 2mm discharge gap. However, the intensity of the micro discharges is much lower than that of 5 mm discharge gap. In addition, the discharge column is smaller in case of 2 mm discharge gap compared to that of 5 mm discharge gap.

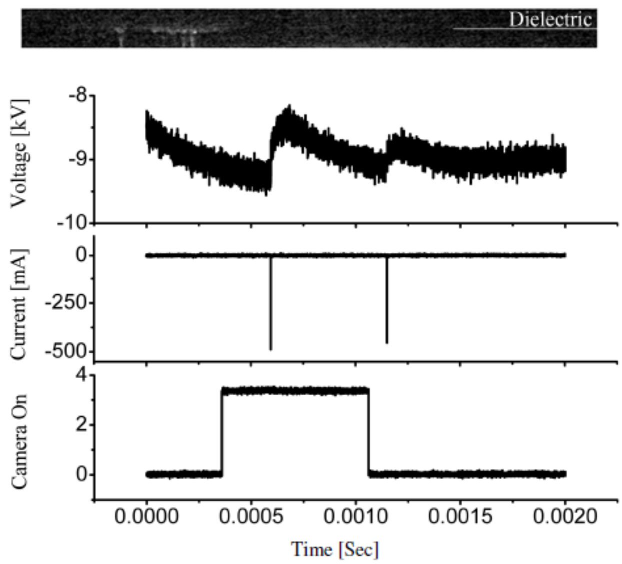

Figure 6. iCCD image of synchronous breakdown in 2mm gap for negative pulse. The camera on (y-axis) represents the f-number.

The positive current pulse images for discharge gaps 5 mm and 2 mm are shown in Figs. 7 and 8. It is seen from the figure that in case of 5 mm discharge gap, single filament ignites. The diffusion of free charges in the discharge gap is also observed in the captured image. Diffusion of charges is clearly observed near the dielectric surface in case of positive current pulse. This is attributed to the flow direction of electron and ion streamer in the M+D- or M-D+ geometry.

The mobility of the electrons in the discharge gap is larger than that of ions in case of positive pulse (M-D+). When the electrons reach the dielectric surface, the negative charges trap on the dielectric surface and an opposite electric field is developed. This electric field prevents further accumulation of electrons at the same position. Therefore, the electrons spread out and this leads to a wider discharge column near the dielectric surface. Due to this effect, the diffusion of electrons near the dielectric surface is enhanced. For positive single current pulse in 2 mm discharge gap, the intensive diffused column is clearly observed as shown in Fig. 8. The mechanism is different in case of negative pulse (M+D-). The negative charges flow directly into the bottom electrode. There is no charge trapping on the surface of the metal electrode. Therefore, in case of negative pulse, the diffusion is less significant than that of positive pulse.

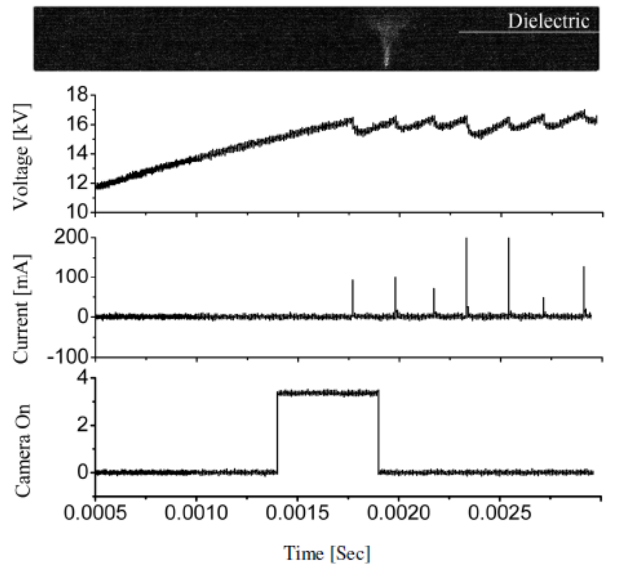

Figure 7. iCCD image of positive pulse in 5 mm gap DBD captured with exposure time of 500 µs (upper). The relative timing of current, voltage, and camera signal (bottom) are also shown. The camera on (y-axis) represents the f-number. Reproduced from Physics of Plasmas 21, 044502 (2014), with the permission of AIP Publishing.

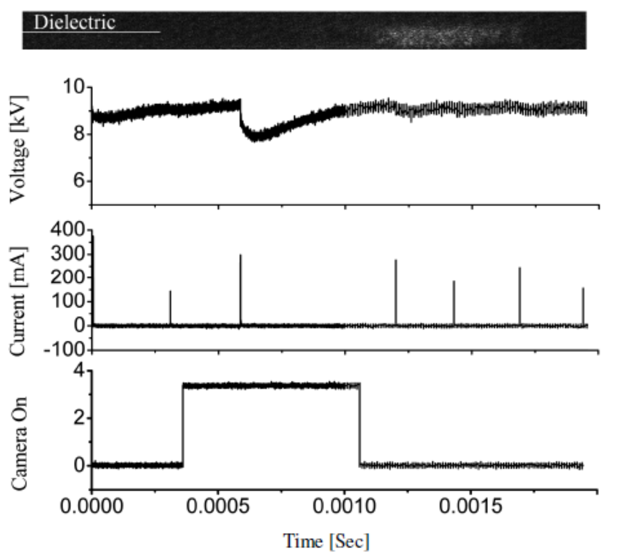

Figure 8. iCCD image of intensive diffused micro-discharge in 2mm gap for positive pulse. The camera on (y-axis) represents the f-number.

It is observed that there is a frequent synchronous breakdown of micro-discharge in case of negative current pulse. On the other hand, the synchronous breakdown is rarely observed in case of positive current pulse. In case of negative current pulse, the secondary emissions from the dielectric cathode provide sufficient electron density to enhance the filamentary discharge in shorter time [19]. Hence, brighter filaments have been observed in case of negative current pulse where the avalanche electrons are accelerated to the metal electrode, which is not blocked by the dielectric.

The collective effect that has been studied by Guaitella *et al.* [20] explains these observations. The first filamentary discharge triggers the subsequent filamentary discharges due to the collective effect, and thus causes the formation of multiple filaments. However, the collisions of the ions and electrons clouds do not trigger the filamentary discharge simultaneously due to the long progress time.

4. Conclusions

Using high speed imaging technique, it is demonstrated that in a 50 Hz atmospheric pressure DBD, the discharge filaments are ignited at random locations in the discharge gap. In the case where the dielectric covers the high voltage electrode, synchronous breakdown in the discharge gap is frequently observed in the case of negative current pulse. In the case of positive current pulse, synchronous breakdown is rarely observed and the intensity of individual filament is less than that observed for negative current pulse. These observations confirm the role of deposited memory charge on the dielectric surface, which enhances electrons avalanche from the dielectric during a negative current pulse. However, in the case of positive current pulse, the memory charge has been observed, which enhance the diffusion of charges on the dielectric surface, thus results in a less intense filament. The intensity of the micro discharges of 2mm discharge gap is lower than that of 5 mm discharge gap. However, more synchronous breakdowns have been observed for a single current pulse in the case of the 2mm discharge gap. This is attributed to the shorter distance between the filament channels of 2mm discharge gap. The number of synchronous breakdown is believed to be depended on the photo intensity, work function of the dielectric electrode, and the distance between the discharge channels. Hence, the photo intensity of filament discharge of 2mm discharge gap is sufficient to ignite more synchronous breakdowns on nearby channels.

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REFERENCES

[1] Eliasson B., Hirth M. and Kogelschatz U. (1987).Ozone synthesis from oxygen in dielectric barrier discharges. J. Phys. D-Appl. Phys, 20, 1421-1437.

[2] Ramasamy R.K., Rahman N.A. and Wong C.S. (2001). Effect of temperature on the ozonation of textile waste effluent. Color. Technol, 117, 95-97.

[3] Hashim S.A., Wong C.S., Abas M.R. and Dahlan K.Z.Hj. (2010). Discharge Based Processing Systems for Nitric Oxide Remediation. SainsMalaysiana, 39, 981-987.

[4] Zhu C., Wang X., Huang Q., Huang L., Xie J., Qing C. and Chen T. (2013). Removal of gaseous carbon bisulfide using dielectric barrier discharge plasmas combined with TiO_2 coated attapulgite catalyst. Chemical Engineering Journal, 225,567-573.

[5] Kostov K.G., Rocha V., Koga-Ito C.Y., Matos B.M., Algatti M.A., Honda R.Y., Kayama M.E. and Mota R.P. (2010). Bacterial sterilization by a dielectric barrier discharge (DBD) in air. Surf. Coat. Technol., 204, 2954-2959.

[6] Isbary G., Zimmermann J.L., Shimizu T. Li Y.-F., Morfill G.E., Thomas H.M., Steffes B., Heinlin J., Karrer S. and Stolz W. (2013). Non-thermal plasma—More than five years of clinical experience. Clinical Plasma Medicine, 1, 19-23.

[7] Wagner H.-E., Brandenburg R., Kozlov K.V., Sonnenfeld A., Michel P. and Behnke J.F. (2003). The barrier discharge: basic properties and applications to surface treatment. Vacuum, 71, 417-436.

[8] Niu Z., Zhang C., Shao T., Fang Z., Yu Y. and Yan P. (2013). Repetitive nanosecond-pulse dielectric barrier discharge and its application on surface modification of polymers. Surf. Coat. Technol., 228, S578-S582.

[9] Boeuf J.P. (2003). Plasma display panels: physics, recent developments and key issues. J. Phys. D: Appl. Phys, 36, R53-R79.

[10] Kogelschatz U. (2002). Filamentary, patterned, and diffuse barrier discharges. IEEE Trans. Plasma Sci., 30, 1400-1408.

[11] Kogelschatz U., Eliasson B. and Egli W. (1997). Dielectric-barrier discharges. Principle and applications. Journal de Physique IV, **7** (C4), 47-66.

[12] Kogelschatz U. (2003). Dielectric-barrier discharges: Their history, discharge physics and industrial applications. Plasma Chemistry and Plasma Processing, 23, 1-46.

[13] Allegraud K., Guaitella O. and Rousseau A. (2007).Spatio-temporal breakdown in surface DBDs: evidence of collective effect. Journal of Physics D-Applied Physics, 40, 7698-7706.

[14] Tay W.H., Kausik S.S., Yap S.L. and Wong C.S. (2014). Role of secondary emission on discharge dynamics in an atmospheric pressure dielectric barrier discharge. Phys. Plasmas, 21, 044502-4.

[15] Tay W.H., Kausik S.S., Yap S.L.,Wong C.S. and Muniandy S.V. (2014). Statistical modelling of discharge behavior of atmospheric pressure dielectric barrier discharge. Phys. Plasmas, 21, 113502-9.

[16] Fan W.L., Sheng Z.M., Zhong X.X., Wang W.M., Li Y.T. and Zhang J. (2013). Particle simulation of filamentary structure formation in dielectric barrier discharge. Appl. Phys. Lett., 102, 094103-5.

[17] Wagenaars E., Brandenburg R., Brok W.J.M., Bowden M.D. and Wagner H.E. (2006). Experimental and modelling investigations of a dielectric barrier discharge in low-pressure argon. J. Phys. D: Appl. Phys., 39, 700-711.

[18] Eliasson B., Egli W. and Kogelschatz U. (1994).Modelling of dielectric barrier discharge chemistry. Pure & App. Chem, 66, 1275-1286.

[19] Holder T., Brandenburg R., Basner R., Weltmann K.D., Kozlov K.V. andWagner H.E. (2010). A comparative study of three different types of barrier discharges in air at atmospheric pressure by cross-correlation spectroscopy. J. Phys. D: Appl. Phys., 43, 124009-8.

[20] Guaitella O., Thevenet F., Guillard C. and Rousseau A. (2006). Dynamic of the plasma current amplitude in a barrier discharge: influence of photocatalytic material. J. Phys. D: Appl. Phys., 39, 2964–2972.