Temporal Behaviour of Micro-discharge in Dielectric Barrier Discharges *

YIN Zeng-Qian(尹增谦)[1], DONG Li-Fang(董丽芳)[1**], CHAI Zhi-Fang(柴志方), LI Xue-Chen(李雪辰)[1], WANG Long(王龙)[2]

[1] *College of Physics Science and Technology, Hebei University, Baoding 071002*
[2] *Institute of Physics, Chinese Academy of Sciences, Beijing 100080*

(Received 15 June 2002)

A special dielectric barrier discharge (DBD) device consisting of two water electrodes has been designed. The temporal behaviour of the micro-discharge (filament) in the DBD in air at atmospheric pressure is measured by using an optical method. The nonsymmetrical characteristic of the filament has been discovered for the first time. We propose an equation regarding the discharge moment by considering the memory effect of the accumulated charge and the influence of the fluctuation. The results deduced from the equation give a good explanation of the experimental phenomenon, which show that the decay time constant of the accumulated charges is much larger than 100 μs. The relative intensity of fluctuation amplitude is in the range 2–4% under the present experimental conditions.

PACS: 52. 70. − m, 52. 80. Pi

Dielectric barrier discharges (DBDs) are increasingly used in industry for plasma processing, UV lighting, and in plasma display panels (PDPs).[1,2] An experimental device for the DBD generally consists of two parallel electrodes, at least one of which is covered with a dielectric layer, which surround a gas layer. An ac voltage is applied to the electrodes at a frequency of several hundred hertz to a few hundred kilohertz. For a high production pd of gas pressure p and gas gap width d, the discharge operated in a streamer regime leads to the formation of many narrow micro-discharge channels also referred to as filaments. In order to understand the discharge mechanism, one must first investigate the behaviour of each individual filament. In the last few years, many researchers have attempted to measure the behaviour of individual filaments. Hirth[3] used a well-shielded fast current probe incorporated into the electrode to measure the current pulses of individual filaments stochastically. Klein *et al.*[4] tried to obtain the behaviour of individual filaments using time-resolved (in the microsecond timescale) imaging of patterns in a one-dimensional DBD. Lukas *et al.*[5] measured the behaviour of the single filaments located at a pin reactor which served as one electrode. Brauer *et al.*[6] used the current in a circuit to represent the behaviour of the filament under the condition that there are only two filaments within the active area. However, there has been no report on the non-intrusive and *in situ* measurement of individual filaments in the nanosecond timescale.

In this Letter, the temporal behaviour of an individual filament in the DBD is measured non-intrusively with nanosecond resolution by an optical method. The nonsymmetrical characteristic of the filament temporal behaviour in the DBD has been discovered for the first time. An equation is introduced so that a good explanation of the experimental phenomenon can be presented.

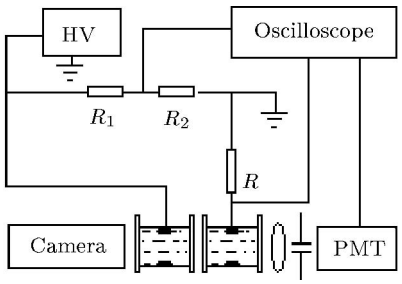

Fig. 1. Experimental set-up: $R_1 = 200\,\mathrm{M\Omega}$; $R_1 = 1.5\,\mathrm{M\Omega}$; $R = 50\Omega$; HV, high voltage; PMT, photoelectron multiplier tube.

The experimental set-up is shown in Fig. 1. Two cylindrical containers with a diameter of 3 cm, filled with ordinary water, are used as electrodes. Two metallic rings connected to the power supply are immersed in the water of the two containers for conducting current. The parallel glass end walls of the containers with a thickness of 1.5 mm serve as dielectric layers. The gap between them is filled with air. Its width can be adjusted in a range from 0.1 to 2 mm with a micrometre caliper. The water also serves as a coolant and transparent media for observation and measurement of discharge filaments. An ac power supply provides a sinusoidal voltage with maximum peak voltage 30 kV and at a frequency of 40.5 kHz. Resistors connected in parallel and in series are used to monitor the applied voltage and discharge current. A lens with a focal length of 10 cm is used to image the filament patterns and an aperture on the image plane is used to choose certain individual filaments. The

* Supported by the Natural Science Foundation of Hebei Province.
** To whom correspondence should be addressed.
©2002 Chinese Physical Society and IOP Publishing Ltd

light emitted from the filaments is detected by a PMT (RCA7265) behind the aperture and recorded with an oscilloscope (Tektronix TDS3052, 500 MHz). A digital camera (Canon Powershot G1) is used to acquire the picture of the patterns.

Figure 2 shows a typical stable filament pattern obtained with an applied voltage of 4.5 kV and a gas gap width of 0.6 mm. It consists of 19 filaments and is an irregular pattern. In this pattern, each filament keeps its position for several minutes. The temporal behaviour of the light emission from the individual filament marked by a circle in Fig. 2 is shown in Figs. 3(a) and 3(b). From Fig. 3(a) one can see that the lifetime of the discharge in a breakdown is about 20 ns. Many measurements on individual filaments have shown that the lifetime of an individual filament in one breakdown is about 20 ns, no matter how high the applied voltage is and how wide the gas gap.

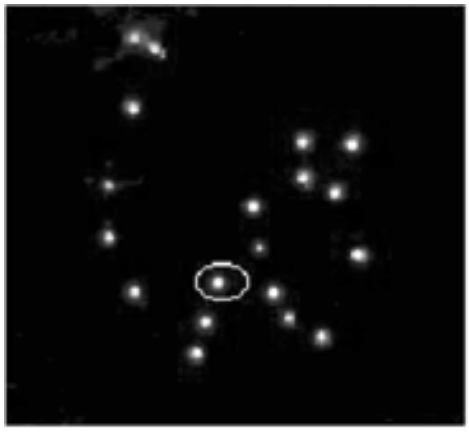

Fig. 2. Picture of the pattern (original size is $4\times4\,\mathrm{cm}^2$). The filament measured is marked by a circle.

Figure 3(b) gives the periodicity of the light emission from the filament. An obvious phenomenon exhibits that long and short intervals between two adjacent discharges appear alternately. It is worth pointing out that our experimental set-up is symmetric and the applied voltage is also symmetric for opposite polarities, so the phenomenon results from the connatural dynamics of the DBD. To investigate the temporal behaviour of an individual filament in detail, the light emission from one discharge filament is monitored for a long period. Due to the limit of the oscilloscope, the largest record time length will be four cycles because the sampling time must not be larger than 10 ns in case some discharge pulses are lost. Thus, the temporal behaviour of an individual filament is recorded every other minute. The evolution of the intervals in 6 min is shown in Fig. 3(c), where the sequence numbers of curves A–G are signed with the successive order of the measurements, n is the sequence number of intervals between adjacent discharges in one waveform recorded, while ΔT_n is the interval between the moments of $(n+1)$th and nth discharges, i.e. $\Delta T_n = t_{n+1} - t_n$, as shown in Fig. 3(b). The dashed line which runs parallel to the horizontal axis represents the half-cycle of the applied voltage. One can see from Fig. 3(c) that the difference between adjacent intervals is large in most cases, and intervals between two adjacent discharges of one individual filament in two consecutive half-cycles appear alternately for a long and a short time. The interval values will distribute to the half-cycle of applied voltage stochastically when the difference between adjacent intervals is small.

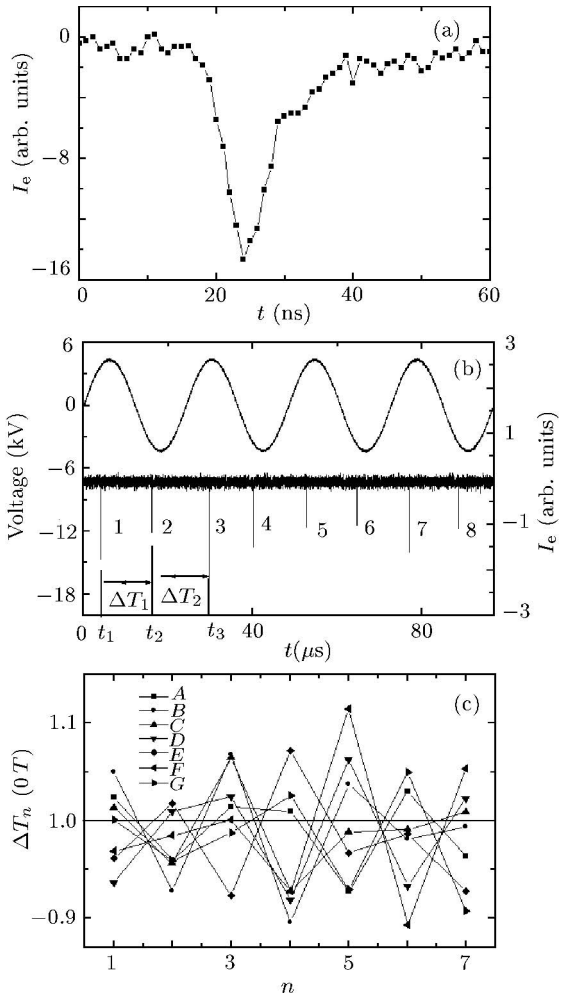

Fig. 3. Light emission from one filament. (a) The waveform of a filament pulse. The interval between two adjacent data points is 1 ns. (b) The periodicity of the light pulse. The number n (1–8) represents the nth discharge. The nth discharge moment is t_n. (c) The interval between two adjacent breakdowns of one micro-discharge channel in 6 min. The interval $\Delta T_n = t_{n+1} - t_n$. T is the cycle of applied voltage.

It is generally believed that charges associated with electrons and ions flowing in the discharge volume accumulate on the dielectric layers during the discharges of one filament in the DBD. The charges generate an electric field opposite to the applied field in the half-cycle. The discharge expires when the

net electric field falls below the maintaining field. When the applied voltage reverses its polarity in the next half-cycle, the electric field generated by the accumulated charges on the dielectrics aids the applied voltage. When the net field is above the breakdown field, the next discharge occurs.

The equations connecting the discharge moments of a current pulse and the next one for one filament can be written from the conditions of discharge termination and breakdown as follows

$$\begin{aligned} &|E_0 \sin(\omega t_n)| - E_c = E_m, \\ &|E_0 \sin(\omega t_{n+1})| + E_c \mathrm{e}^{-\frac{t_{n+1}-t_n}{\tau}} = E_b. \end{aligned} \tag{1}$$

Here E_0 and ω are the amplitude and circular frequency of the applied electric field respectively; t_n is the termination moment of the nth discharge; t_{n+1} is the breakdown moment of the next discharge, where the time origin is the moment at which the applied field equal to zero and the termination moment of the first discharge is t_1 (shown as Fig. 3(b)). E_c is the electric field of the accumulated charge at t_n, which decays with a time constant τ, and E_m and E_b are the maintaining electric field and breakdown field, respectively.

Relations (1) are generally valid for any two consecutive moments t_n and t_{n+1}. The dependence of t_{n+1} on t_n can be deduced from Eq. (1). As shown above, even though the experimental parameters vary in a large range, the duration of micro-discharge is of the order of 20 ns, which is much smaller than the cycle of applied voltage. So t_{n+1} can also be used as the moment at which the second discharge terminates. Obviously, a sequence of t_n values is generated and then the intervals between two adjacent discharges can be obtained. The calculated results obtained by a large variation range of parameters, such as E_b/E_0 from 0.5 to 0.9, E_m/E_0 from 0.05 to 0.15, τ from $0.5\,T$ to ∞ (where T is the cycle of the applied voltage), show that the intervals between adjacent discharges of one filament will be the same as the half-cycle of applied voltage if the decay time constant is smaller than several times of half-cycle of the applied voltage, while the intervals will vary between long and short ones alternately if the decay time constant is much longer than the half-cycle. Therefore, we can conclude that the decay time constant is much larger than 100 μs by comparing the calculation results with the present experimental results mentioned above.

Of course, the experimental results show that the 'long' (or 'short') intervals are not the same. This indicates that the fluctuation also affects the discharge. We discuss this as follows.

A large number of spatial charges and excited molecules distribute in the discharge gap of the DBD, especially at high pressure, so the conditions of discharge breakdown and termination will be changed by the influence of spatial charges and other factors varying stochastically, which serves as fluctuation. Equations (1) can be rewritten as follows when the decay time constant $\tau \to \infty$:

$$|\sin(\omega t_n)| + |\sin(\omega t_{n+1})| = \frac{E_b}{E_0} + \frac{E_m}{E_0}. \tag{2}$$

By considering the influence of the fluctuation, Eq. (2) can be rewritten as

$$|\sin(\omega t_n)| + |\sin(\omega t_{n+1})| = \frac{E_b}{E_0} + \frac{E_m}{E_0} + \delta, \tag{3}$$

where δ is the value of the fluctuation. The random number is used to simulate the influence of the fluctuation veritably as the fluctuation varies stochastically in a range, which can be written as

$$\delta = 2k\Big(\frac{E_b}{E_0} + \frac{E_m}{E_0}\Big)(0.5 - \mathrm{Ran}),\ \mathrm{Ran} \in (0,1),$$

where Ran is the random number, and $k(E_b/E_0 + E_m/E_0)$ is the amplitude of the fluctuation.

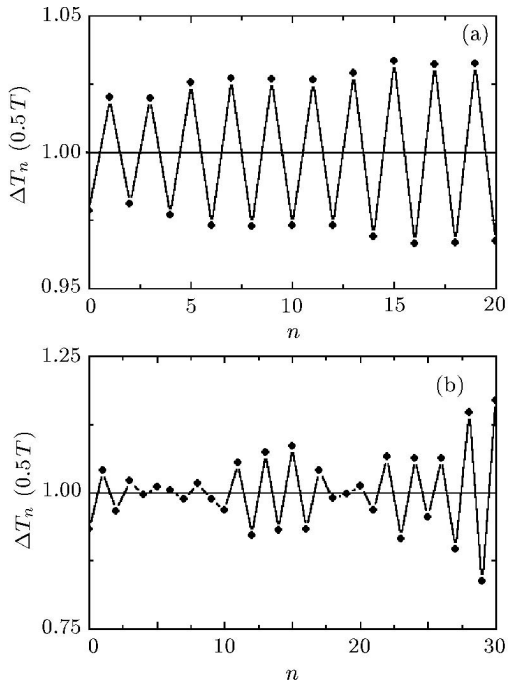

Fig. 4. Intervals between two adjacent breakdowns of one micro-discharge channel varying with time but the influence of the fluctuation has been considered. The relative intensities of the fluctuation are (a) 0.5%. and (b) 3.625%.

The sequence of intervals under different values of parameters, such as E_b/E_0, E_m/E_0 and k, can be deduced from Eq. (3). Two typical results are shown as Fig. 4 from which one can see that intervals will vary between long and short intervals alternately if the relative intensity of fluctuation k is smaller than 1%. This indicates that the temporal behaviour of the discharge is mainly decided by the memory effect of the accumulated charge in this case. If k exceeds 5%, it

may happen that the sequence of intervals cannot be deduced from Eq. (3), i.e. as a result of the cumulative effect of fluctuation, the condition of breakdown may be not satisfied when t_n is larger than a certain value. While intervals vary between long and short ones alternately in most cases if k is in the range of about 2–4%, however the order of the long and short intervals may be reversed when the difference between the long and short intervals is very small. The adjacent long and short intervals are both close to the half-cycle of the applied voltage. The experimental results would be the case in which both the memory effect of the accumulated charge and the fluctuation influence the temporal behaviour of the filament jointly. The former is the dominant factor compared with the latter as the probability of the reversal of the order of long and short intervals is very small in the experiment. Thus the intensity of the fluctuation is in the range from 2% to 4% related to $E_b + E_m$.

In conclusion, the temporal behaviour of one filament is studied experimentally by using a specially designed DBD set-up. The nonsymmetrical characteristic of the discharge of an individual filament is discovered. The equation is proposed by considering the memory effect of accumulated charge and the influence of the fluctuation. The results deduced from the equation give a good explanation for the experimental phenomenon. This shows that the decay time constant of the accumulated charges is much larger than 100 μs. The relative intensity of fluctuation amplitude is in the range from about 2% to 4% related to $E_b + E_m$ under present experimental conditions.

References

[1] Eliasson B and Kogelschatz U 1991 *IEEE Trans. Plasma Sci.* **19** 309
[2] Dong L F, Li X C and Yin Z Q et al 2001 *Chin. Phys. Lett.* **18** 1380
[3] Hirth M 1981 *Beitr. Plasma Phys.* **20** 1
[4] Klein M, Miller N and Walhout M 2001 *Phys. Rev.* E **64** 026402
[5] Lukas C, Spaan M and von der Gathen V S et al 2001 *Plasma Sources Sci. Technol.* **10** 445
[6] Brauer I, Bode M and Ammelt E et al 2000 *Phys. Rev. Lett.* **84** 4104