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Study of filamentary behaviour in coaxial dielectric barrier discharge lamp

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In this study, filamentary discharges have been investigated at 1.5 mm dielectric-dielectric electrode gap of a coaxial dielectric barrier discharge (DBD) quartz tube filled with nitrogen gas. Different types of discharge patterns have been established in the tube using alternating field (35-45 kHz). Electrical characteristics of the discharge have been investigated, which mainly depend on gas pressure, applied frequency and voltage amplitude. The on set of the discharge current occurs earlier at higher operating voltage due to the increased value of E/n, where E is the electric field and n is the neutral gas density. The observed phenomenon occurs due to increase in rate of voltage rise time. At higher voltage, increase in net current increases the chances of electron impact. Analysis of the voltage versus charge plot (lissajous figure) supports the theory of capacitances of a double barrier discharge. The energy consumed per cycle of the DBD source measured using lissajous figure is few milli joules. Energy consumption per cycle is the key parameter for evaluating the efficiency of the device.

Keywords: Dielectric barrier discharge, Filamentary discharge

1 Introduction

The dielectric barrier discharge (DBD) is an important source to generate non-equilibrium plasma at atmospheric pressure. This property of plasma is emerging as a promising technology for large-scale industrial applications like the development of new types of UV and VUV spontaneous excimer sources, ozonator, textile industry etc. The classical geometric configuration of DBD is a volume discharge in which either one or both metal electrodes are covered with dielectric layer. Applying sinusoidal voltage (50 Hz ~100 kHz), results in a barrier discharge that occurs in the electrode gap of a few millimeters[1]. The gas pressure, type of gas and the repetition frequency of the applied voltage determine the exact nature of the discharge. In the filamentary mode, the discharge consists of many shots of narrow pulse width with nanosecond durations and each filament of few millimeter radius covering the electrode surface[2].

This paper reports electrical characteristics of the filamentary discharge. Various phenomena are observed during the experiments. At higher operating voltage, the time delay for the onset of breakdown reduces. The gap between opposite electrodes covered by dielectric material transfers small amount of charge in each filament. Furthermore, the lissajous method is used to calculate electrical energy consumed per cycle of the DBD source[4].

2 Experimental Set-up

A coaxial quartz DBD tube has been constructed as shown in Fig. 1 and mounted on the port of the vacuum system. The length of the cylindrical quartz tube is 30 cm. On either side of the gas filled space (1.5 mm) is dielectric quartz of thickness 1.75 mm. The DBD tube has been evacuated up to 3.1×10^{-7} mbar using a mechanical pump and then backfilled with nitrogen (100-810 mbar) for stagnant gas environment. The inner surface of the quartz tube is covered by 0.05 mm thickness of solid AgCu alloy electrode whereas the outer surface is covered by copper mesh electrode, providing active discharge area of around 376.8 cm^2. A high frequency alternating field is used to excite the nitrogen gas in the gap. A high voltage probe (P6015A) and a current probe (Pearson) are used to measure the voltage and current waveforms, respectively across the DBD. A digital oscilloscope (Tektronix TDS3034B, 500 MHz) synchronously displays the voltage and current signals.

3 Results

3.1 Electrical characteristics

The measured voltage-current waveforms represent the filamentary behaviour and corresponding discharge pattern of nitrogen barrier discharge at 400 mbar as shown in Fig. 2(a and b). The nano second

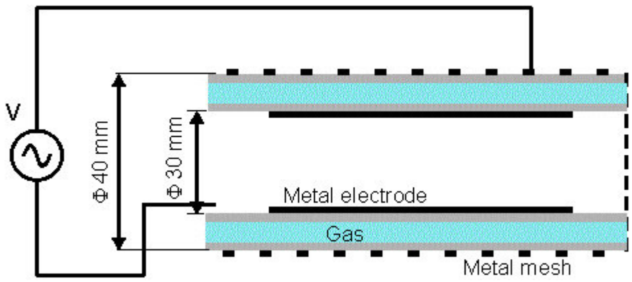

Fig. 1 — Schematic diagram of the coaxial quartz DBD tube

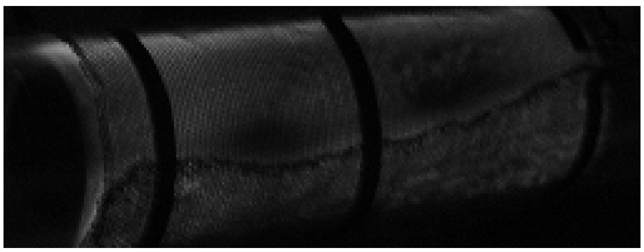

Fig. 2(a) — Discharge patterns at 2 kV respectively

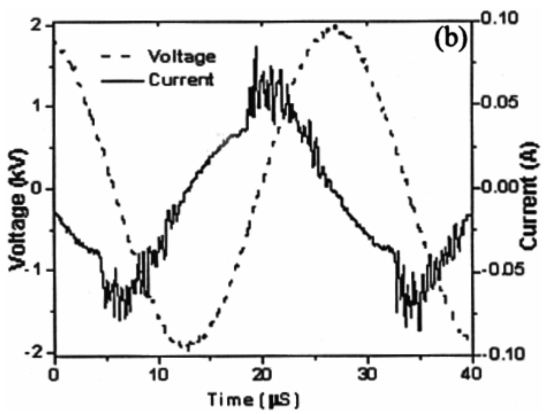

Fig. 2(b) — *V-I* characteristics of filamentary discharges at 2 kV respectively (Gas: nitrogen; *p*: 400 mbar; *f*= 45 kHz)

duration current pulses are superimposed on the sinusoidal waveform. The measured discharge current also includes the displacement current. Filamentary discharges diffuse with one another to form homogeneous luminous plasma in the whole inter-dielectric gap. The charges during the discharge are accumulated on the surface of quartz dielectric. This phenomenon reduces the value of *E/n* and consequently quenching of the filamentary discharge takes place. Fig. 3(a) represents the current pulse amplitude with time[3] at different onset of breakdown voltage. The voltage curve is the operating voltage for the DBD tube. The time delay for the onset of breakdown decreases with increasing rate of voltage rise time. In addition, the amplitude of breakdown increases with increasing rate of voltage rise time.

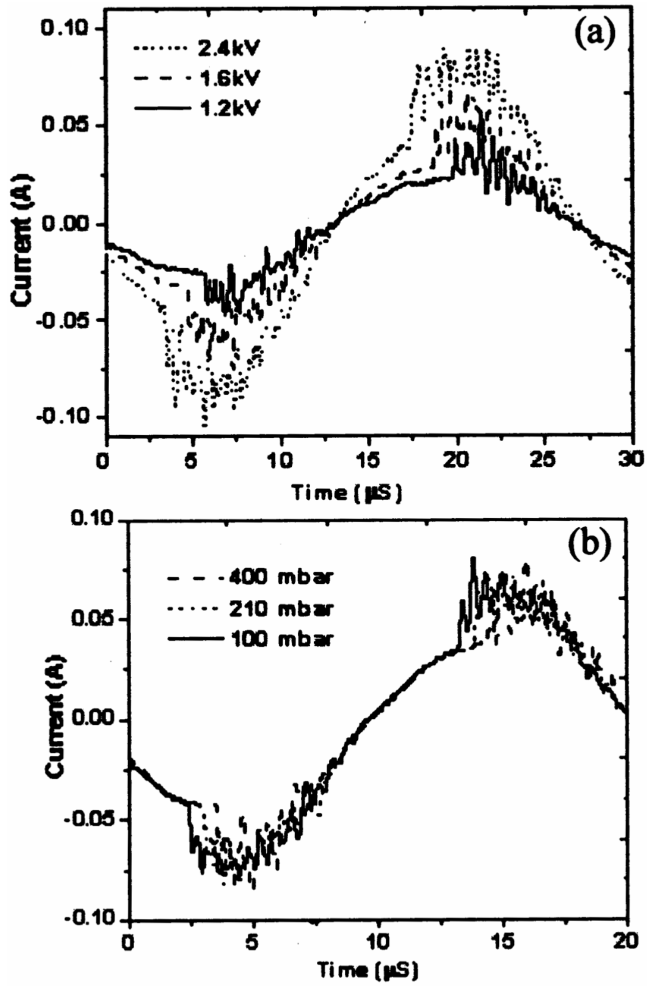

Fig. 3 — Variation of current onset w r t applied voltage at (a) *f*=35 kHz and *p*= 210 mbar, (b) pressure at *f*= 45 kHz

Higher operating voltage increases the value of *E/n* and the increase in net current increases the chances of electron impact. Fig. 3(b) shows that as the pressure increases, *E/n* reduces and the onset of the gas breakdown is delayed. Physical processes such as excitation, ionization and dissociation increase rapidly with increasing *E/n*. This results in increase of the plasma-chemical efficiency.

3.2 Consumed power

The energy consumed per cycle is the key parameter for evaluating the efficiency of the device. The plot between the charge transferred during the discharge, Q and the voltage applied, V_{ap}, is used to calculate the energy injected into the gas. This plot is also called lissajous figure[4,5]. The DBD represents two capacitances connected in series, one for the dielectric, C_d, and one for the gas, C_g. When the discharge is ignited, a resistive channel appears in

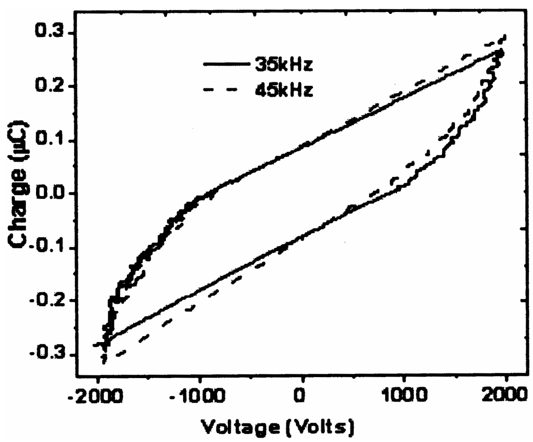

Fig. 4 — Lissajious figure obtained at 400 mbar of nitrogen. (Operating condition: 2 kV)

parallel to C_g and charges transferred by plasma filaments increase abruptly. As long as the plasma is in ON state, the discharge current, $I(t)$, leads the sinusoidal applied voltage, V_{ap}. Fig.4 shows lissajous figures obtained at different frequency. The charge Q, transferred by filamentary discharges is obtained by integrating $I(t)$. For the complete period, the lissajous figure is a parallelogram whose area is proportional to the power injected into the gas. The energy consumed per cycle is more at higher operating frequency. For instance, the breakdown voltage at 400 mbar for nitrogen in a gap of 1.5 mm is 837 V and 883 V at 35 kHz and 45 kHz, respectively. These values are in close approximation with paschen curve of nitrogen for the same pressure times distance. The values of capacitance for the dielectric and gas gap measured using the following expression:

$$C = dQ / dV_{ap} \quad \ldots(1)$$

where C is the capacitance, dQ and dV_{ap} are the small change in charge and voltage, respectively. Thus, the electric energy consumed per voltage cycle is :

$$E_{el} = 4C_d V_{br}(V_{ap} - V_{br}C_g / C_d) \quad \ldots(2)$$

where V_{br} is the breakdown voltage of the gas gap. The values of gas capacitance calculated from lissajious figures are 92 nf and 1010 nf at 35 kHz and 45 kHz respectively.

The power consumed per second is given by :

$$P = fE_{el} \quad \ldots(3)$$

where f is the applied frequency and E_{el} is the electrical energy.

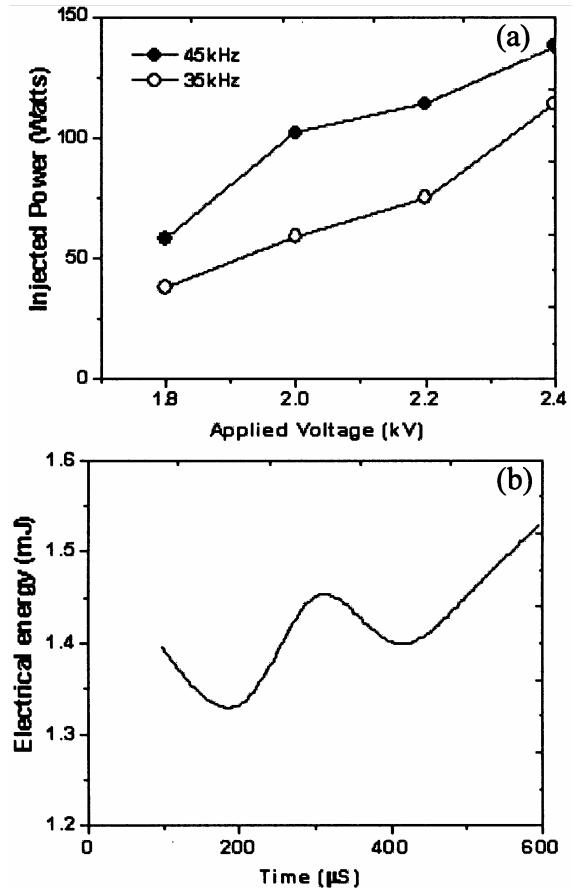

Fig. 5 — (a) Power injected versus (a) applied voltage (p= 400 mbar nitrogen), (b) pressure (f= 45 kHz; V_{appl}= 2 kV)

The electrical energy consumed per voltage cycle is 1.68mJ and the power consumed per second is 58.8W at 2 kV and 35 kHz of the operating condition. The injected power is a function of the applied voltage and frequency as shown in Fig. 5(a). The observed increase in the injected power may be due to an increase in charges transferred by each of the plasma filament and an increase in number of plasma filaments per unit of time[6]. Fig. 5(b) shows energy consumption per cycle determined from the lissajous figure. At higher pressures, the energy increases. This observation is in agreement with that of Mildren *et al*[7]. i.e. at higher-pressure energy consumption increases for the *ac* circuit.

4 Conclusion

Filamentary discharges were established in the coaxial quartz DBD tube using medium frequency generator. The discharge potential follows the Paschen curve. It was found that in the excitation processes, due to increase in the operating voltage and earlier onset of discharge current, *E*/*n* of the discharge was increased and consequently, the reaction rates. Therefore, it is desirable to operate the DBD at high E/n for high plasma-chemical efficiency. The lissajious method was used to measure the injected power and hence, the electrical energy consumed per cycle. An increase in plasma filaments per unit time increased the injected power of the discharge in the gap.

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