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Longitudinal combined discharge extinction in low pressure nitrogen

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A B S T R A C T

This paper reports the registered extinction curves of the longitudinal combined discharge in nitrogen when rf and dc voltages were applied to the same electrodes. The application of dc voltage is shown first to lead to an increase in the rf discharge extinction voltage; at the same time, the "cathode" sheath thickness increases and the number of charged particles in the plasma volume decreases. The discharge extinction curve first shifts to the range of higher rf voltage and gas pressure values, and the region of multi-valued dependence of the rf extinction voltage on gas pressure vanishes. At larger dc voltage values, when the "cathode" sheath breakdown occurs, the rf discharge extinction voltage decreases and approaches zero at the dc extinction voltage for the dc self-sustained discharge.

1. Introduction

Gas discharges with a combined (rf + dc) electric field are applied for determining electron transport coefficients in low pressure gases [1,2], as well as in a number of technological devices for spectral–chemical analysis [3], silicon plasma oxidation [4], plasmatrons [5], gas discharge lasers [6,7]. They gave birth to a large number of experimental and theoretical papers devoted to study the characteristics of such combined discharges in various gases (see, e.g., [8–19]). The combination of the constant and alternating electric fields improves the stability of gas discharge permitting to increase the power introduced into the discharge [6,7,10,11].

The extinction curve is one of the important characteristics of such a discharge. It determines the range of rf voltage and gas pressure values where the discharge can be sustained and, as a consequence, the operating range of plasma-technological devices based on such discharges. Extinction curves of rf capacitive discharges have been studied in much detail (see Refs. [20,21] and the references cited therein). However, we did not find in the available references any information on the extinction of the longitudinal combined discharge (when rf and dc voltages are applied to the same electrodes). Therefore it is of interest to study the extinction of such a discharge.

2. Experimental conditions

Experiments were performed at nitrogen pressure $p = 0.01$–10 Torr within the range of rf voltage values $U_{rf} \leq 2000$ V, dc voltages $U_{dc} \leq 500$ V and rf field frequency $f = 13.56$ MHz. The values of the gap between plane parallel stainless steel electrodes were $L = 30$ mm and 8.5 mm. The rf potential was applied to one of the electrodes whereas the second was grounded. Simultaneously, the rf electrode served as a "cathode" because of a negative dc potential applied to it.

Fig. 1 shows the scheme of our experimental setup. A fused silica tube with 100 mm inner diameter was vacuum-sealed between the electrodes. The gas feed system supplied nitrogen through a multitude of tiny orifices in the grounded electrode. The discharge chamber was pumped out via a set of orifices in the same electrode. This arrangement gave the opportunity to feed and pump out the gas uniformly across the electrode area what plays an important role in technological processes (e.g., in etching semiconductor materials). The pumping system provided limiting vacuum conditions in the order of 10^{-6} Torr. An rf generator was connected to the potential electrode via a coupling device of Π-type. A dc source was connected to the same electrode through a choke of $L_c = 4$ mH, to prevent its damage with rf current.

A Rogowsky coil was employed to determine the rf current amplitude, and its signal was fed to the phase difference meter FK 2-12. A signal from the capacitive divider connected to the rf electrode was fed to another input of FK 2-12. This gave opportunity to measure the amplitudes of rf current, rf voltage and the phase shift angle ϕ between them. The phase difference meter FK 2-12 is capable of registering the amplitudes of alternating signals within the frequency range $f_1 = 1$ MHz to 1 GHz and the phase shift ϕ between the signals (between the rf voltage and rf current in our case).

3. Experimental results

Fig. 2 depicts the extinction curves of rf and dc longitudinal combined discharges for the inter-electrode gap of 30 mm. Under

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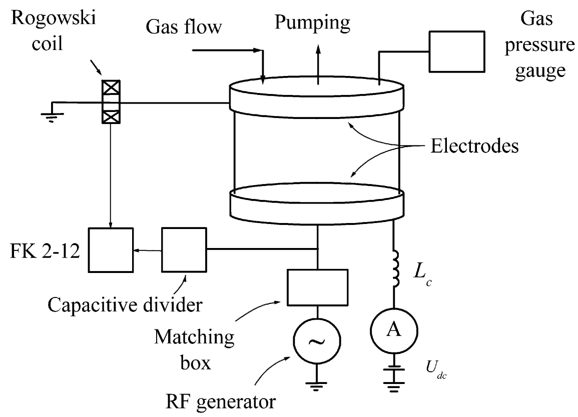

Fig. 1. Schematic of our experimental setup.

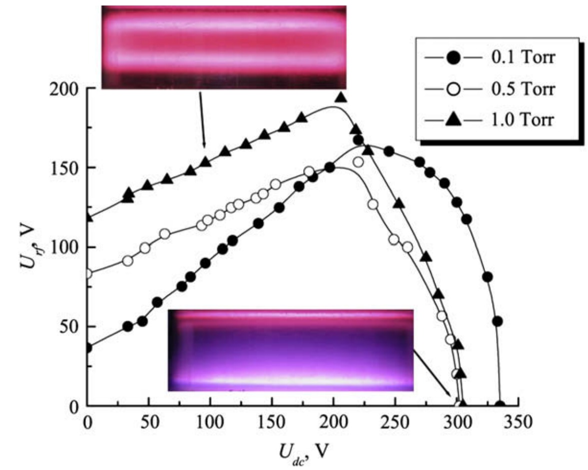

Fig. 3. Rf extinction voltage against the dc voltage at various fixed values of nitrogen pressure, $L = 30$ mm.

an extinction curve of the combined discharge we understand the dependence of the minimum rf voltage U_{rf}, at which the discharge can exist on gas pressure at a fixed value of the applied dc voltage U_{dc}. As is known [20], rf breakdown and extinction curves have similar shapes. Each branch of the rf breakdown curve (diffusion-drift, Paschen and multipactor [22]) corresponds to a similar branch of the extinction curve. In the low pressure range the diffusion-drift branch of the extinction curve at $U_{dc} = 0$ in nitrogen displays a region of multi-valued dependence of the extinction rf voltage U_{rf} on gas pressure p, i.e. two or three rf voltages may refer to one pressure. Within this range the discharge can be extinguished not only by decreasing the rf voltage but also by increasing it. For the reasons of this phenomenon we refer to Ref. [20]. Application of an additional dc voltage leads to the decrease of the multi-valued region width. For $U_{dc} > 100$ V the multi-valued region is absent and the extinction curve of the combined discharge shows a U-shaped form. Increasing U_{dc} is accompanied by a growth of the rf extinction voltage U_{rf} (see Fig. 3). Around $U_{dc} \sim 250$ V the rf extinction voltages reach their maximum values and then decrease. At the dc voltage close to the minimum of the extinction curve of the dc discharge, a sharp minimum occurs in the extinction curve of the combined discharge. When the dc voltage is sufficient to support the self-sustained dc discharge, the rf extinction voltage is equal to zero.

Fig. 3 also gives the photos of the combined discharge for two characteristics cases. At $U_{dc} < 200$ V the application of the dc voltage to the rf discharge leads to the increase of the "cathode" sheath thickness d_c (the "cathode" is located below in all photos). For decreasing rf voltage with fixed U_{dc} the "cathode" sheath thickness increases. The "cathode" and "anode" sheaths overlap practically before the discharge extinction, and the width of the plasma region becomes small. When the generation rate of charged particles in the plasma volume becomes less than the loss rate to electrodes and the walls of the discharge vessel, the discharge is extinguished. At $U_{dc} > 200$ V electron avalanches develop in the "cathode" sheath, the sheath breaks down making the discharge sustainment easier and the rf discharge extinction voltage lower.

The rf extinction curve for $U_{dc} = 0$ V in Fig. 2 for the 30 mm gap consists almost completely of the diffusion-drift branch. However, with smaller inter-electrode gaps other branches of the rf extinction curve may be observed. The rf extinction curve at $U_{dc} = 0$ V for a narrow gap of $L = 8.5$ mm shown in Fig. 4 contains the diffusion-drift branch at rf voltages below values of about 250 V, as well as the Paschen branch (at lower pressure $p \leq 1$ Torr). It is clear from the figure that the diffusion-drift branch of the rf extinction curve also displays a multi-valued region in this case which disappears when applying the dc voltage. The extinction curve for $U_{dc} = 100$ V shown in Fig. 4 does not contain the diffusion-drift branch within the total range of nitrogen pressure we studied. At the same time, the Paschen branch of the rf extinction curve coincides practically with the extinction curve for $U_{dc} = 100$ V at low nitrogen pressure. Further increase of the dc voltage leads to the decrease of the rf extinction voltage within the total pressure range. At the dc voltage of $U_{dc} = 270$ V a rather sharply expressed minimum appears in the extinction curve which is located at the same pressure value as the

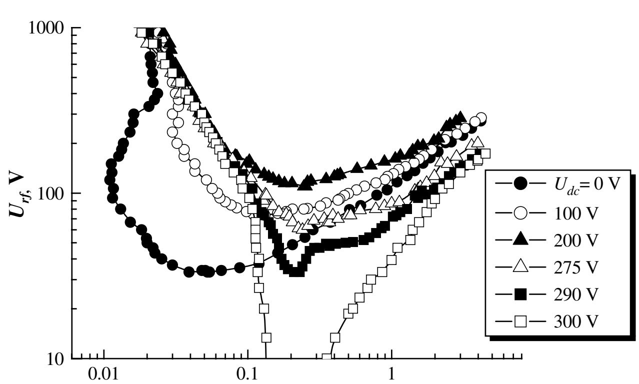

Fig. 2. Rf extinction curves at various fixed values of the dc voltage, $L = 30$ mm.

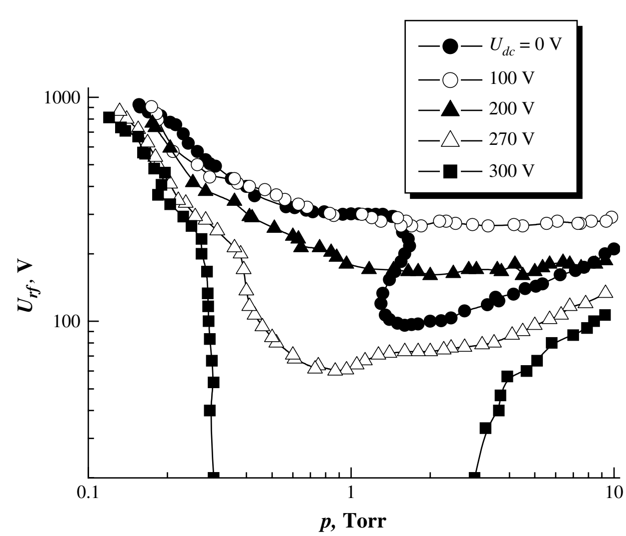

Fig. 4. Rf extinction curves at various fixed values of the dc voltage, $L = 8.5$ mm.

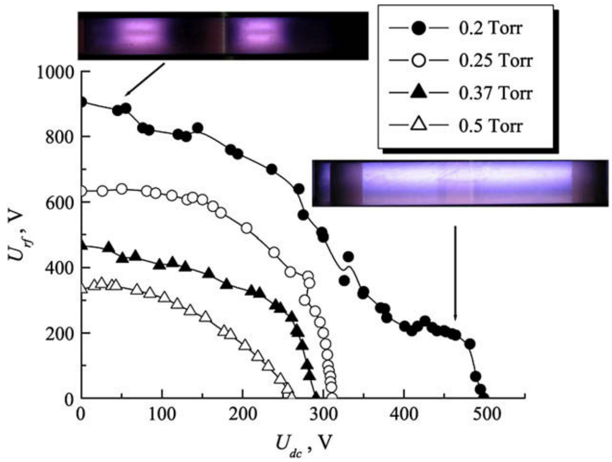

Fig. 5. Rf extinction voltage against the dc voltage at various fixed values of nitrogen pressure $p = 0.2$–0.5 Torr, $L = 8.5$ mm.

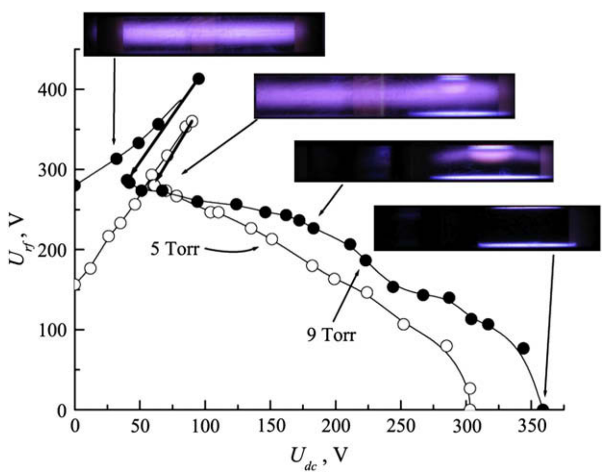

Fig. 6. Rf extinction voltage against the dc voltage at nitrogen pressures $p = 5$ Torr and 9 Torr, $L = 8.5$ mm. All photos are taken for $p = 9$ Torr, the arrows show the points at which the discharge photos were taken.

minimum of the dc extinction curve for the inter-electrode gap value $L = 8.5$ mm. And when the dc voltage approaches the value sufficient for sustaining a burning dc discharge ($U_{dc} = 300$ V at gas pressure $p = 3$ Torr), the rf extinction voltage vanishes.

Fig. 5 shows the rf extinction voltage of the combined discharge against the applied dc voltage U_{dc} at low nitrogen pressure $p = 0.2$–0.5 Torr and the inter-electrode gap of $L = 8.5$ mm. In this gas pressure range the increase of U_{dc} leads to the decrease of the rf extinction voltage. The discharge photos presented in the same figure show that at U_{dc} below 400 V (see the curve for $p = 0.2$ Torr) the discharge before extinction is burning in the form of columns occupying only a portion of the electrode surface. With fixed U_{dc} and decreasing the U_{rf} the glow intensity and the number of these columns decreased, until the last of them was extinguished. The presence of such nonuniform structure across the electrode area limits the applicability of the combined discharge in narrow gaps. However, we may improve the discharge uniformity using higher rf voltages. At $U_{dc} > 400$ V the discharge acquired a structure similar to a dc discharge, as observed in the photo.

At high nitrogen pressures (see Fig. 6 with the data for 5 Torr and 9 Torr) the application of a moderate dc voltage $U_{dc} < 100$ V leads to an increase in the thickness of the "cathode" sheath, what is especially expressed before discharge extinction. It induces an increase of the rf extinction voltage. However, further increasing U_{dc} leads to the breakdown of the "cathode" sheath and forms a brighter glowing column against the background of uniform luminosity. At the same time, the rf extinction voltage decreases abruptly, probably due to the increased ionization within the "cathode" sheath. At higher U_{dc} the uniform glow vanishes, and only a brighter glowing plasma column remains. When the rf extinction voltage approaches zero, only the dc discharge in the normal mode is burning between the electrodes [23].

4. Conclusions

This paper presents the extinction curves of the longitudinal combined discharge (rf/dc) in nitrogen taken in a broad range of gas pressure, rf and dc voltage values when applying rf and dc voltages to the same electrodes. The application of the dc voltage is shown first to shift the discharge extinction curve to higher rf voltage and gas pressure values. At the same time, the region of multi-valued dependence of the rf extinction voltage on the gas pressure vanishes. However, when the dc voltage approaches the dc extinction potential of the dc discharge, the rf extinction voltage tends to zero. The dc voltage U_{dc} leads to an increase of the rf discharge extinction voltage with growing thickness of the "cathode" sheath and, thus, decreasing plasma volume. When it attains a sufficient value for breaking down the "cathode" sheath, the rf extinction voltage decreases and approaches zero for the U_{dc} of a self-sustained dc discharge.

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