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DETERMINATION OF POSITIVE ANODE VOLTAGE DROP IN DC CF_4 GLOW DISCHARGE USING THE MOVING ANODE METHOD

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In this study, the voltage drop across the anode layer of dc glow discharge in CF_4 was determined using the moving anode method at different pressures (6.65...66.5 Pa) and discharge currents (less than 80 mA). For this purpose, a set of current-voltage characteristics (CVCs) of the discharge was measured for cases where the anode glow does not appear in the studied current range (short distance between the electrodes), appears at low current and then disappears with its increase, and also when it does not disappear with increasing current (longer distances), but the positive column has not yet formed. This family of CVCs for a fixed gas pressure lies between two curves (with and without anode glow), the difference between which allows us to determine the positive anode voltage drop. It is shown that the anode drop at a fixed pressure of CF_4 has a non-monotonic dependence on the magnitude of the discharge current. The magnitude of the anodic drop can be 2-3 times greater than the ionization potential of CF_4 molecules due to the process of dissociative electron attachment.

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INTRODUCTION

Gas discharge plasma in CF_4 is widely used for etching semiconductor materials [1], deposition of polymer films [2], surface modification of biological [3] and polymer [4] materials, etc. Therefore, a large number of research papers are devoted to the study of processes in CF_4 plasmas (see, for example, [5 - 13]). It should be noted that the above works concern mainly RF capacitively coupled and pulsed discharges. However, the processes in dc glow discharges in CF_4 have been studied much less [14 - 18]. One of the important parts of the dc glow discharge is the anode layer [19 - 24], which supplies the current of electrons and negative ions to the anode. Therefore, it is important to study its characteristics in different gases.

The aim of this work was to measure the voltage drop across the anode layer (so-called anode drop) at different CF_4 pressures and discharge currents using the moving anode method. This method, unlike Langmuir probes, does not introduce perturbations into the plasma parameters. It is shown that the anode drop at a fixed CF_4 pressure has a non-monotonic dependence on the discharge current.

1. EXPERIMENTAL CONDITIONS

The diagram of the discharge setup is shown in Fig. 1.

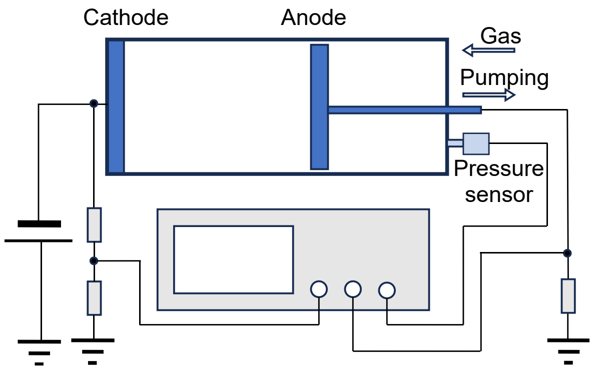

Fig. 1. Block diagram of the experimental setup

The horizontally located discharge tube had an internal diameter of 80 mm. The solid fixed cathode was flat, to which was connected a power supply HSPY-1500-002 with a maximum voltage of 1500 V and a current of up to 200 mA. The anode was movable and grounded. Both electrodes were flat and made of stainless steel. The distance L between the electrodes could vary from 10 to 400 mm. The values of the gas pressure, voltage between the electrodes and discharge current were displayed on an oscilloscope and a computer.

Experiments were conducted with CF_4 in the pressure range $p = 6.65...66.5$ Pa. The gas pressure was measured using a capacitance pressure transducer (Baratron 627) with a maximum measurement value of 133 Pa.

The current range for each pressure value was limited by the stable burning of the discharge. It was influenced by two factors. At high current values, a dielectric polymer film is deposited on the anode surface. As a result, the discharge begins to burn along a longer path than the gap between the electrodes, i.e., it extends to the back (rear part of the anode). The measured data for such conditions were not taken into account when analyzing the experimental results. At a sufficiently high pressure and low current, the discharge burns in the normal mode, covering only part of the cathode surface and running along it. In this case, chaotic oscillations of the current are observed, as a result of which the results for the normal mode were also not taken into account.

2. INFLUENCE OF THE DISTANCE BETWEEN ELECTRODES ON THE DISCHARGE STRUCTURE

To analyze the obtained results, let us determine what happens to the direct current discharge when the distance between the electrodes is changed while keeping the current and gas pressure constant.

At a narrow gap L, when the entire space is filled only with the cathode sheath, the discharge operates in a obstructed mode (Fig. 2, which has been rotated 90° clockwise to save space in the text, with the cathode at the top and the anode at the bottom). When attempting to further reduce the gap, the discharge either extinguishes or can only be sustained at a significantly higher voltage between the electrodes. The obstructed mode corresponds to the left branch of the discharge breakdown curve [25, 26], where electrons emitted from the cathode surface and accelerated by the strong electric field are quickly lost at the anode. Therefore, to identify this mode, it is appropriate to refer to the breakdown curves.

As the gap L increases, the voltage between the electrodes rapidly decreases (Fig. 3) and, after the anode exits the cathode sheath, reaches a minimum value. Thereafter, the anode moves through the negative glow region, during which the voltage between the electrodes changes either slightly (at low current, approximately a few milliamperes) or quite rapidly (at currents above 10 mA) [26]. Visually, the discharge at this stage consists of the cathode sheath, the negative glow, and (at sufficiently large distances) the dark Faraday space begins (Fig. 4). Under these conditions, the anode is reached by the fastest electrons that gained high energy in the cathode sheath and did not lose all of it through inelastic collisions with gas molecules while passing through the negative glow. Additionally, there is a diffusive flux of electrons that can no longer excite or ionize gas molecules but continue moving toward the anode. Near the anode, there is also an anode layer with a negative voltage drop that prevents cold electrons from reaching its surface.

Fig. 2. Photograph of the discharge for CF_4 pressure of 9.3 Pa, discharge current of 5 mA, and interelectrode gap of L = 12 mm. Cathode on top, anode on bottom

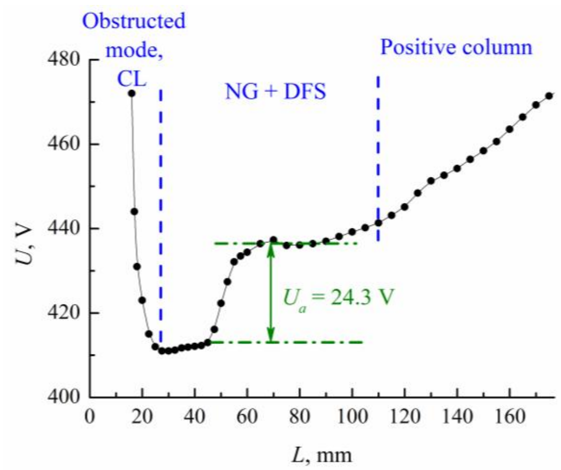

Fig. 3. Voltage vs. interelectrode distance at CF_4 pressure of 11 Pa and discharge current of 1.2 mA. Here CL means cathode layer, NG is negative glow, DFS is dark Faraday space

The most interesting behavior for us begins when the anode has passed approximately halfway through the dark Faraday space and continues to move away from the cathode. Under these conditions, the number of fast electrons decreases significantly, they are no longer able to contribute substantially to the discharge current, so it becomes necessary to accelerate the colder electrons. At this stage, the increasing distance between the anode and cathode is accompanied by a rather sharp rise in the voltage between the electrodes (see Fig. 3), and an anode glow appears near the surface of the anode (Fig. 5).

Fig. 4. Photograph of the discharge at a CF_4 pressure of 9.3 Pa, current of 5 mA, and distance L= 110 mm. The cathode is on the left, the anode on the right

Fig. 5. Photograph of the discharge at a CF_4 pressure of 9.3 Pa, current of 5 mA, and distance L = 140 mm. The cathode is on the left, the anode on the right. An anode glow appears near the anode surface

The thickness of this glow weakly depends on gas pressure and current and is approximately 1…2 mm. Since it is not very bright in CF_4, we increased the overall brightness of the photograph in Fig. 5. This anode glow indicates the formation of a space-charge layer near the anode surface, in which electrons are additionally accelerated as they move toward the anode. The corresponding anode voltage drop is positive.

Further increase in the distance L between the electrodes leads to the appearance of a positive column (in the case of CF_4, it is usually stratified, Fig. 6), but a detailed analysis of its characteristics is beyond the scope of this study.

Fig. 6. Photograph of the discharge at a CF_4 pressure of 9.3 Pa, current of 5 mA, and distance L = 315 mm. The cathode is on the left

3. RESULTS OF DETERMINING ANODE VOLTAGE DROP

We know of three methods for determining the voltage drop across the anode layer. The first of these uses Langmuir probes, where a single probe is placed at the interface between the positive column and the anode layer (a few millimeters from the anode in the absence of a positive column) and the plasma potential is measured relative to the anode (see, for example [20, 21, 23, 26]). This method allows for measuring both positive and negative anode drops, but the probe can disturb the plasma. Also, the probe surface in chemically active plasma can be covered with a dielectric polymer film, which also limits the applicability of this method.

The second method is illustrated in Fig. 3, which shows the value of the positive anode voltage drop U_a and the way it is determined. For this, one must vary the distance between the cathode and the anode while keeping the current and gas pressure constant, and record the voltage between them. The corresponding jump in this voltage as the anode moves away from the cathode through the dark Faraday space is associated with the formation of anode glow and the positive anode voltage drop [19, 26 - 28]. This method is convenient but time-consuming, requiring tens of minutes to obtain a single value of U_a. This is particularly important in gases that deposit polymer films on the electrodes, leading to changes in plasma parameters over time.

Finally, the third method for determining the positive anode voltage drop U_a, proposed by the authors of [22] and used by us as the main method, involves measuring the current-voltage characteristics (CVCs) of the discharge at fixed gas pressure and electrode distances L. Since anode glow appears only at sufficiently large distances between the cathode and anode, no positive anode voltage drop forms at smaller L, and the corresponding CVC is shown, for example, in Fig. 7 for $L = 1.35$ cm. The nearly vertical sections of the CVC at low current values (below 8 mA) correspond to the normal glow regime and were not analyzed further due to the chaotic movement of the discharge across the cathode surface. Once the entire surface of the cathode becomes filled with plasma and the discharge transitions into the abnormal glow regime, the current increases monotonically with voltage, and no glow is observed near the anode surface.

For the distance of $L = 1.5$ cm, anode glow is already present in the normal glow regime, so the CVC for this distance is shifted to the right along the voltage axis due to the additional positive anode voltage U_a across the anode layer. As the voltage and current increase, electrons gain higher energy in the cathode layer and are able to travel farther before being nearly completely slowed down. As a result, the boundary of the negative glow moves closer to the anode. The anode glow starts to become dimmer at a current of approximately 20 mA and completely disappears at currents above 60 mA. The transition from the presence of an anode voltage drop to its disappearance is accompanied by a slower increase in voltage. Subsequently, the CVCs for $L = 1.35$ cm and $L = 1.5$ cm coincide.

For a distance of $L = 2$ cm, the anode glow did not disappear throughout the voltage/current range shown in Fig. 7. The CVC for $L = 2$ cm is shifted to the right of the CVC for $L = 1.5$ cm by the positive voltage U_a. Therefore, the anode voltage drop can be determined for selected current values. For example, in Fig. 7, at a current of 40 mA, the anode voltage drop is 20.3 V. This method allows for rapid measurement of discharge CVCs and determination of U_a over a wide range of discharge currents within a few minutes. As a result, polymer films do not have time to coat the anode surface and significantly disturb the discharge characteristics.

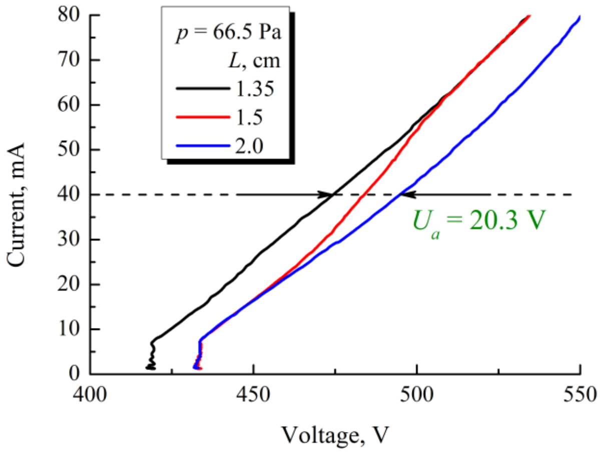

Fig. 7. Current-voltage characteristics of the discharge at CF_4 pressure of 66.5 Pa and interelectrode distances of L = 1.35, 1.5, and 2 cm

Similar CVCs were measured for several CF_4 pressure values. The corresponding values of the positive voltage drop U_a across the anode layer, obtained from these measurements, are presented in Fig. 8. From this figure, we observe that U_a exhibits non-monotonic behavior. At low CF_4 pressures, U_a shows a fairly sharp peak, reaching approximately 46 V, after which it quickly decreases to 30 V. As the gas pressure increases, this peak becomes less pronounced and eventually disappears. At CF_4 pressures of 10.1…34.6 Pa, the U_a values are mostly in the range of 20…30 V. At the highest pressure studied (66.5 Pa), U_a falls below 20 V but still shows non-monotonic behavior.

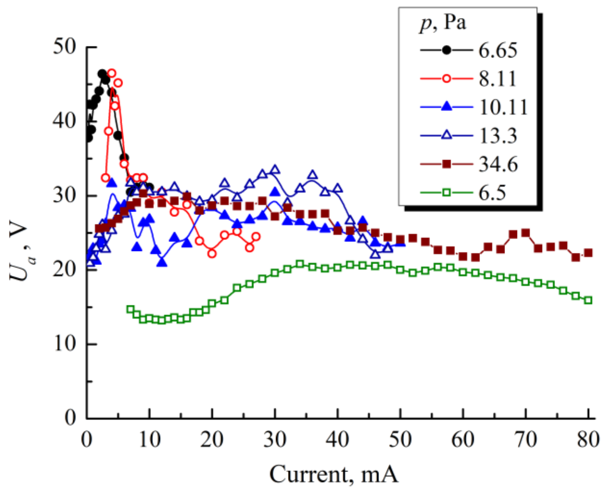

Fig. 8. Dependencies of the anode voltage drop on the discharge current at different CF_4 pressure values

The anode layer regulates the flux of electrons (as well as negative ions in electronegative gases) to the anode surface. The current of negatively charged particles reaching the anode must equal the current in the external circuit. If the anode surface is reached by a flux of fast electrons accelerated in the cathode sheath, the anode voltage drop is negative and no anode glow occurs.

This negative anode voltage drop prevents cold electrons from reaching the anode surface, pushing them back into the discharge volume. Increasing the distance from the anode to the cathode will reduce the flow of fast electrons reaching the anode. These fast electrons lose energy in inelastic collisions with gas molecules and also move out onto the walls of the tube. Electrons that were fast but have lost significant energy and can no longer ionize or excite gas molecules, can also reach the anode and contribute to the discharge current.

If these fast electrons are insufficient, and the flux of cold electrons is less than the current in the external circuit, a positive voltage drop forms in the anode sheath. Cold electrons gain higher energy, and the fastest among them can excite or even ionize gas molecules. When electrons in excited molecules move to a lower energy level, photons are emitted, which we see as anode glow. In electropositive gases, the magnitude of the anode voltage drop is close to the ionization potential of the gas molecules [20, 21].

An increase in the voltage between the electrodes/discharge current leads to an increase in the energy and number of fast electrons escaping from the cathode layer, so they can penetrate deeper into the negative glow plasma and Faraday dark space. For this case, the anode glow appears at a greater distance between the anode and cathode. Therefore, for each value of gas pressure, there is a range of short distances at which the anode glow is not observed. In another range of distances, the anode glow appears at low current, but disappears with increasing current. And there is a range of longer distances in which the anode glow exists over a wide range of currents, since fast electrons no longer reach the anode.

It should be noted that under low-pressure conditions, the positive anode voltage drop can be 2-3 times higher than the ionization potential of CF_4 molecules (15.69 eV [29]).

However, in electronegative gases, electrons not only generate new ion-electron pairs via direct ionization but can also attach to molecules or their dissociation products. During dissociative electron attachment, negative ions such as F^- and CF_3^- are predominantly formed [29]. Moreover, CF_3 radicals produced by the dissociation of CF_4 molecules have a significantly lower ionization potential (10 eV [29]) and effectively act as an easily ionizable impurity in the main gas.

Therefore, the magnitude and sign of the anode voltage drop in CF_4 are determined not only by the gas pressure, discharge current, and the anode position within the electrode gap, but also by the electron energy distribution function in the plasma region near the anode, the frequencies of direct ionization and dissociative electron attachment processes, the dissociation rate of the main gas molecules, and the concentration of radicals with low ionization potential. The presence of such a large number of processes (some facilitating and others hindering electron arrival at the anode) leads to the complex behavior of the anode voltage drop.

CONCLUSIONS

This research is devoted to determining the positive voltage drop across the anode sheath in CF_4 dc glow discharge over a wide range of gas pressures and discharge currents. Using the moving anode method, a set of current-voltage characteristics of the discharge was measured for fixed gas pressures and varying distances between the electrodes. At short electrode gaps, anode glow does not appear throughout the entire studied current range. At greater distances, anode glow emerges and then disappears at a certain current, with a corresponding saturation region observed on the CVC. For longer gaps, the anode glow remains visible. The difference between CVCs with and without anode glow enables the determination of the positive anode voltage drop. It was found that at a fixed CF_4 pressure, the anode voltage drop exhibits a nonmonotonic dependence on the discharge current. Moreover, due to the electronegativity of CF_4, the anode voltage drop can exceed the ionization potential of CF_4 molecules by a factor of 2-3.

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ВИМІРЮВАННЯ ПОЗИТИВНОГО АНОДНОГО ПАДІННЯ НАПРУГИ У РОЗРЯДІ ПОСТІЙНОГО СТРУМУ В CF_4 МЕТОДОМ РУХОМОГО АНОДА

В. Лісовський, С. Дудін, С. Резуненко, В. Єгоренков

За допомогою метода рухомого анода було визначене падіння напруги на анодному шарі розряду постійного струму в CF_4 при різних значеннях тиску (6,65…66,5 Па) та розрядного струму (менше 80 мА). Для цього був виміряний набір вольт-амперних характеристик (ВАХ) розряду для випадків, коли у дослідженому діапазоні струму анодне світіння не з'являється (коротка відстань між електродами), з'являється при низькому струмі та потім з його збільшенням зникає, а також коли воно зі зростанням струму не зникає (більш довгі відстані), але позитивний стовп ще не сформувався. Це сімейство ВАХ для фіксованого тиску газу лежить між двома кривими (з анодним світінням та без нього), різниця між якими дозволяє визначити позитивне анодне падіння напруги. Показано, що анодне падіння при фіксованому тиску CF_4 має немонотонну залежність від величини розрядного струму. Величина анодного падіння може бути у 2-3 рази більшою за потенціал іонізації молекул CF_4 завдяки процесу дисоціативного прилипання електронів.