CATHODE DESIGN EFFECT ON GAS BREAKDOWN AND MODES OF BURNING OF THE GLOW DISCHARGE IN NITROGEN

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This paper reports the breakdown curves and current-voltage characteristics we have measured for the discharge in the dc electric field. It has been found that almost all breakdown curves measured for cathodes of different design (cylindrical one, two stepped cathodes, conical, spherical and pin ones) practically coincide with the curve for the gap value of 5 mm between flat electrodes near to and to the right of the minimum, excluding the sections for conical and pin cathodes within the gas pressure range above 10 Torr. Left-hand branches of breakdown curves diverge somewhat but they still behave themselves as a family of close curves. At low gas pressure the discharge is burning only in the abnormal mode with the smallest current observed with the pin cathode whereas the largest current occurs with the spherical one. At large pressure the normal mode is observed in the broad current range with the spherical and step cathodes and it is almost not seen with the pin one.

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INTRODUCTION

A dc glow discharge is widely applied in high pressure lamps, in the processes of plasma nitriding iron-based alloys as well as for gas discharge laser pumping etc. In order to optimize plasma technologies and devices one has to know the conditions of igniting the discharge in them and their modes of burning. A breakdown curve describes ranges of voltage and gas pressure values within which a gas discharge plasma may be produced. Electrodes of complicated design are often applied in discharge chambers. Therefore it is of much interest to study the ignition and current-voltage characteristics of the glow discharge between the electrodes of different design.

Despite the large number of papers devoted to the research into the gas breakdown in dc and ac electric fields [1–14], the main attention in them is usually devoted to the discharge ignition between flat parallel electrodes or with a point-to-plane design [15, 16]. Researchers also apply various combinations of cathode and anode design: “cylinder-cylinder” [17], “cone-cone” [18], “cone-cylinder” [19, 20], “sphere-sphere” [21], “flat anode – step cathode” [6] and others. The data on discharge ignition between the electrodes of complicated design are contradictory in a number of cases and they need refinement. Therefore the aim of this paper has been to measure breakdown curves and current-voltage characteristics of the glow discharge between the flat anode and the cathodes of several different shapes (step, cone, sphere, pin) within the chamber possessing the inner diameter considerably exceeding that of electrodes.

1. EXPERIMENTAL

In order to study the dc glow discharge ignition we have employed the discharge chamber with the scheme shown in Fig. 1. A glass discharge tube has the inner diameter of 56 mm. For measuring nitrogen pressure values we have employed the capacitive manometers (baratrons) with the maximum value of the registered pressure of 10 and 1000 Torr. The dc power supply was connected to the cathode and the anode was grounded. Experiments have been performed in the nitrogen pressure range of $p = 0.03…250$ Torr with the dc voltage within the limit of $U_{DC} \le 4000$ V.

The flat anode and the cathodes of different design are shown in Fig. 2. The anode 10 mm high and the 2 through 5 cathodes have been made out of a cylindrical rod (of stainless steel) of 12 mm in diameter Fig. 2.

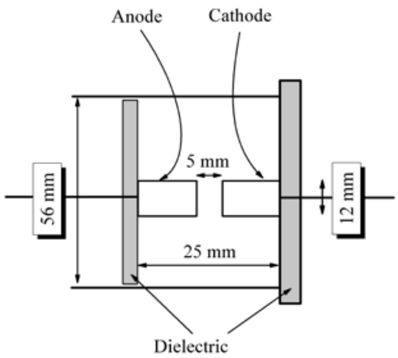
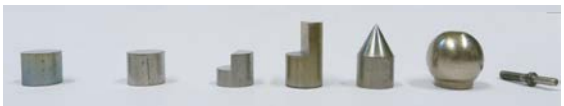


Fig. 1. The scheme of the discharge chamber



1 2 3 4 5 6 7

Fig. 2. Shape of the anode (1) and the cathodes (2-7), employed in this study

The “2” cathode 10 mm high has a conventional cylindrical shape with a flat butt. The “3” and “4” cathodes possessed a step of 5 mm and 10 mm, respectively. The “5” cathode was of conical shape of 10 mm in height. The “6” steel cathode was spherical of 18 mm in diameter. The “7” cathode was also of steel and has a shape of a pin of 8 mm in length and 2.2 mm in diameter.

While performing experiments with the “2” through “7” cathodes the shortest distance between them and the flat anode was 5 mm in all cases, whereas the maximum possible distance between the anode and the cathode was kept equal to 25 mm (see Fig. 2). We also have used flat electrodes 12 mm in diameter with the distance of them of 5 mm and 25 mm.

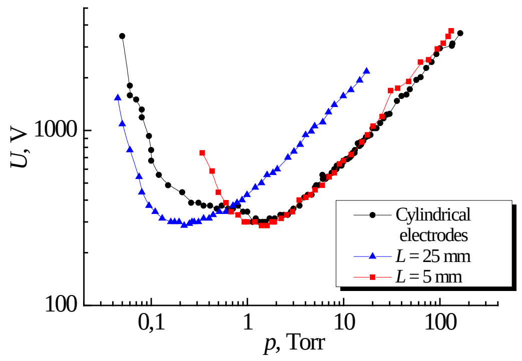


Fig. 3. Breakdown curves in nitrogen with the 5 mm gap between cylindrical electrodes as well as ones for the 5 and 25 mm gap between flat electrodes

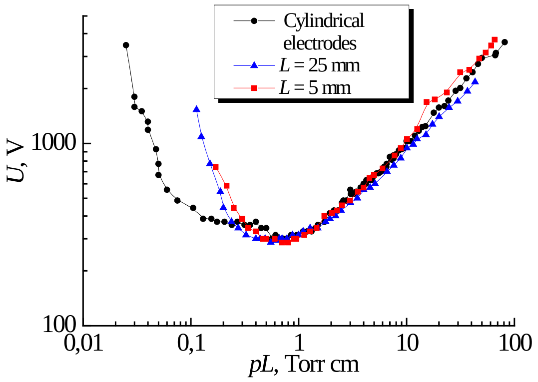


Fig. 4. Breakdown voltage versus pL product for the 5 mm gap between cylindrical electrodes, as well as the same dependence for flat electrodes separated by the gap of 5 and 25 mm

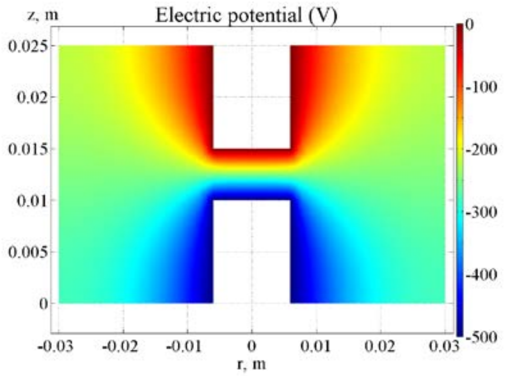


Fig. 5. Potential distribution between cylindrical electrodes for the smallest gap of 5 mm between them

The technique of measuring breakdown curves was as follows. With the nitrogen pressure fixed the voltage across the electrodes was smoothly increased to the breakdown moment, which was determined by the appearance of glow in the inter-electrode gap and the discharge current. We have regarded the maximum voltage before the discharge ignition as the breakdown one.

2. EXPERIMENTAL BREAKDOWN CURVES

Let us first consider the breakdown curves of the discharge in nitrogen we have measured for different values of the gap between the flat cathode and anode. Fig. 3 depicts the breakdown curves (breakdown voltage versus gas pressure) for the distance between flat electrodes of 5 and 25 mm. One observes in this figure that increasing the inter-electrode gap value from 5 to 25 mm has led to the shift of the breakdown curve to the range of lower gas pressure values, whereas the minimum breakdown voltage remaining approximately 286 V for both curves. It follows from Fig. 4 that at the pressure near and to the left of the breakdown curve minima the breakdown curves for different distance values practically coincide when they are plotted to the $U(pL)$ scale, i.e. Paschen's law is met under given conditions.

Now let us consider the gas breakdown between cylindrical electrodes. Fig. 5 demonstrates the potential profiles calculated with the FemLab code for cylindrical electrodes of 12 mm in diameter spaced 5 mm apart for the voltage drop of 500 V across the electrodes. The breakdown curve measured for this case is depicted in Figs. 3 and 4. This curve possesses a minimum in good agreement with the location of the breakdown curve minimum for flat electrodes spaced 5 mm apart. Therefore at gas pressure near to and to the right of the minimum the breakdown occurs within the gap between flat butts of the electrodes. However the left-hand branch of the breakdown curve experiences strong deviation to the range of higher gas pressure than one for the flat 5 mm gap. Under such conditions the discharge ignition occurs along a larger path between the lateral surfaces of cylindrical electrodes. At the same time, this left-hand branch for cylindrical electrodes runs higher than one for the 25 mm flat gap.

Gas breakdown in an inhomogeneous electric field E takes place along the “optimum” line of force for which the breakdown criterion holds, i.e.

$$\int_{z_1}^{z_2} \alpha[E(z)]dz = \ln\left(1+\frac{1}{\gamma}\right), \tag{1}$$

where α is the first Townsend coefficient for ionization, γ is the coefficient of the ion-electron emission from the cathode surface, z_1 and z_2 are the coordinates of the beginning (on the cathode) and the end (on the anode) of the line of force, respectively. Electrons moving along a shorter line of force hit the anode having no time to perform a number of ionizing collisions with gas molecules required to meet breakdown criterion (1). The electric field strength along a larger line of force will not be sufficient for the ionization development.

Let us compare between the breakdown curves for cylindrical electrodes and those for the cylindrical anode and step cathode shown in Fig. 6. The breakdown curves for cylindrical electrodes and the cathode with the step 5 mm high coincide practically in the total range of the gas pressure studied. However the left-hand branch of the curve for the cathode with the step 10 mm high runs in the range of lower pressure values. This indicates a possibility of a breakdown along a larger path for this stepped cathode. Fig. 7 presents the 2D potential profile for the cathode with the step 10 mm high. When we employed the cathode with the step 10 mm high its maximum height was 15 mm. Due to such a design the high negative potential is observed in a larger space than for the cylindrical electrodes and the cathode with the step 5 mm high. As the lines of force of the electric field run normally to the equal potential surfaces, it follows from Fig. 7 that the length of these lines for the stepped cathode may be larger than ones for the cylindrical and cathodes with the step 5 mm high.

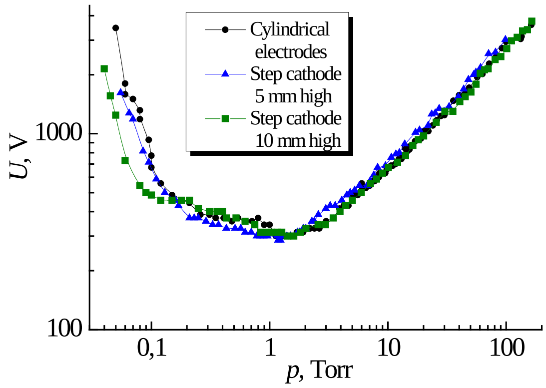


Fig. 6. Breakdown curves for the 5 mm gap between cylindrical electrodes, as well as ones for cathodes possessing the steps 5 and 10 mm high

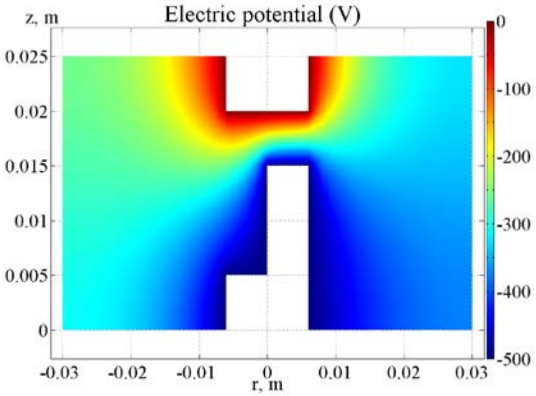


Fig. 7. Potential distribution for the cathode with the step 10 mm high and the cylindrical anode

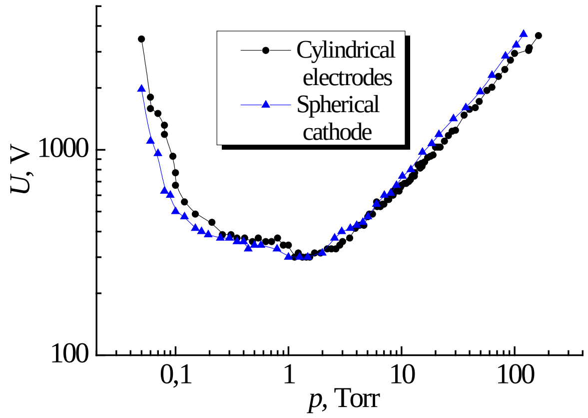


Fig. 8. Breakdown curves for cylindrical electrodes and the spherical cathode

We have also measured the breakdown curve for the spherical cathode (Fig. 8). The breakdown curves for the spherical cathode and cylindrical electrodes coincide practically near to and to the right of their minima. However the left-hand branch for the spherical cathode runs in the range of lower pressure and breakdown voltage values. Near the spherical cathode one observes a vast region with the high negative potential (Fig. 9), due to which gas breakdown development is possible along a longer line of force than for the cylindrical electrodes. Consequently, the loss of charged particles during their motion from the cathode to the anode becomes lower making it possible to break the gas at lower voltage and pressure values.

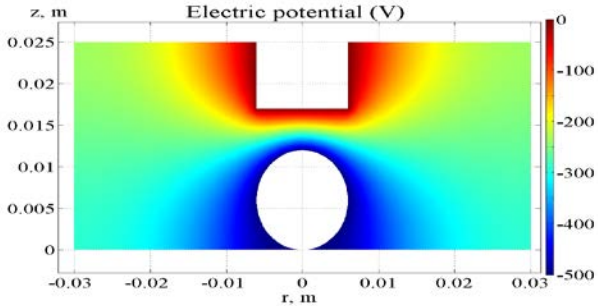


Fig. 9. Potential distribution for the spherical cathode and the cylindrical anode

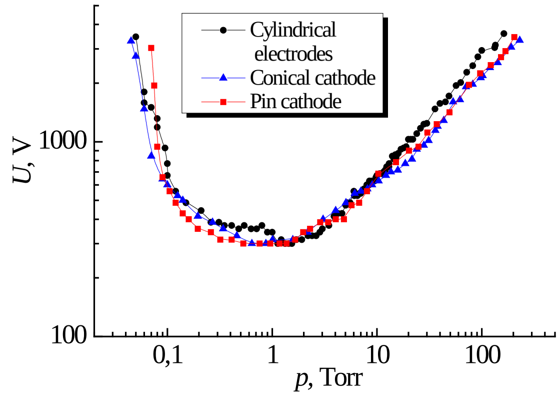


Fig. 10. Breakdown curves for cylindrical electrodes as well as for the conical and pin cathodes

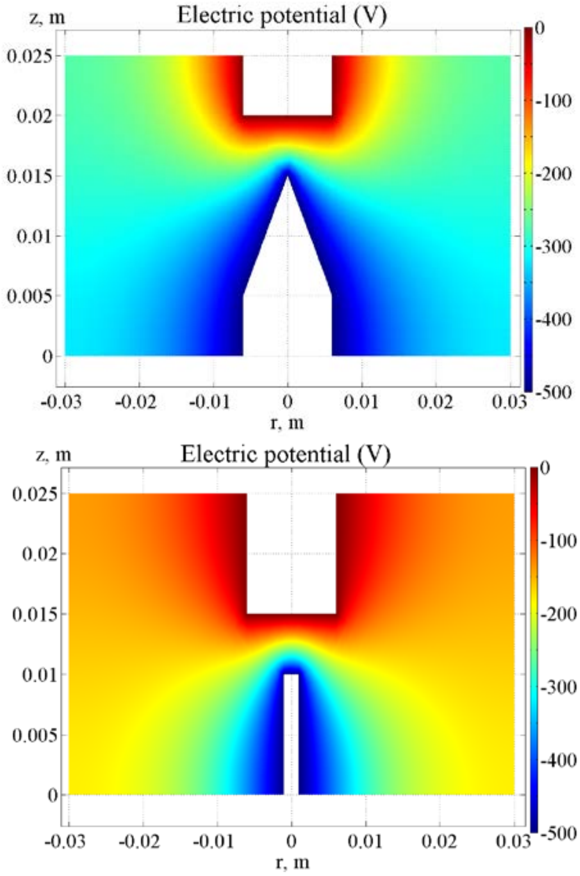


Fig. 11. Potential distribution for the conical and pin cathodes and the cylindrical anode

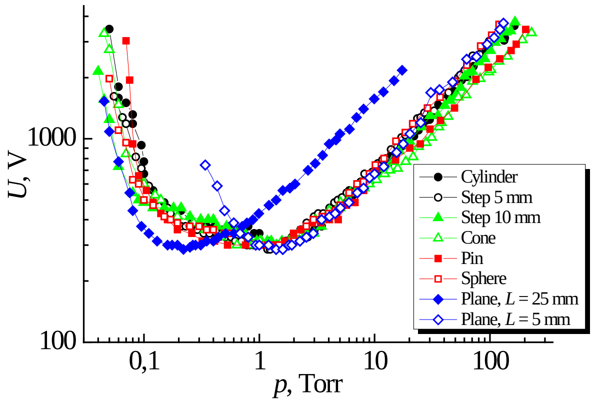


Fig. 12. Breakdown curves for cylindrical electrodes, for the cathode with the step, for the spherical cathode, for the conical and pin cathodes, and for the 5 and 25 mm gap between plane electrodes

As one can observe in Fig. 10, at the gas pressure above 10 Torr the breakdown curve for the conical cathode runs remarkably lower than one for the cylindrical electrodes. At lower gas pressure values the breakdown curves for the conical and cylindrical cathodes coincide practically down to their minima. However the minimum for the cylindrical electrodes is more clearly expressed and with further pressure lowering the corresponding breakdown curve runs in the range of higher breakdown voltage values. Then in the pressure range below 0.3 Torr the left-hand branches of the breakdown curves for the conical and cylindrical cathode run very close to each other. The field is observed to be the most inhomogeneous near the cone tip (Fig. 11) what may have a strong effect at high gas pressure. A similar inhomogeneous distribution of the potential also takes place when one employs a pin cathode. The breakdown curve for the pin cathode has happened to be close to one for the conical cathode almost in the total gas pressure range we studied excluding a small region with the smallest pressure values.

Almost all measured breakdown curves near to and to the right of the minimum coincide practically with the curve for the 5 mm gap between flat electrodes (Fig. 12), with the exception of the sections of breakdown curves for the conical and pin cathodes in the gas pressure range above 10 Torr. At the nitrogen pressure below 0.8 Torr one observes a certain divergence of the left-hand branches of breakdown curves for the cathodes of different design. However as a whole the breakdown curves for the cathodes of different shape demonstrate similar behavior.

3. CURRENT-VOLTAGE CHARACTERISTICS

The cathodes we have employed possessed not only different shape but also different area. This circumstance has affected the discharge CVCs and the ranges of current in which the discharge is burning in the normal or abnormal modes. As the cathode and the processes taking place in the sheath near it play the most important role [22 - 25], then its surface area determines the discharge current value. Fig. 13 compares the current-voltage characteristics for the cathodes of different shape at two different values of the nitrogen pressure. At the pressure of 0.2 Torr the discharge in the total current range was burning in the abnormal mode covering the cathode surface. As it should be expected, the smallest discharge current has been observed with the employment of the pin cathode with a small surface area. The largest current has been obtained with the spherical cathode, i.e. its area was the largest of all cathodes in our experiments.

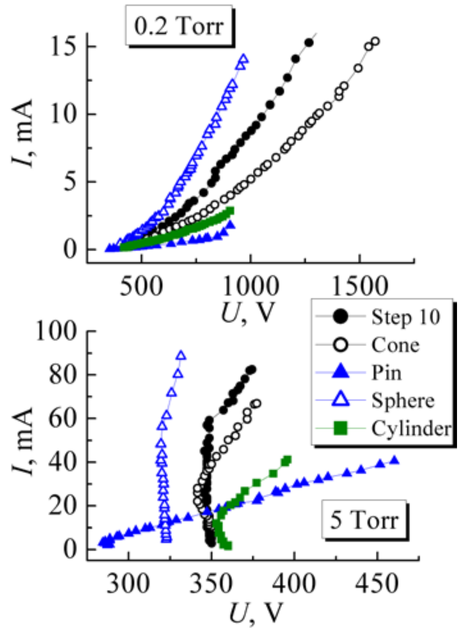
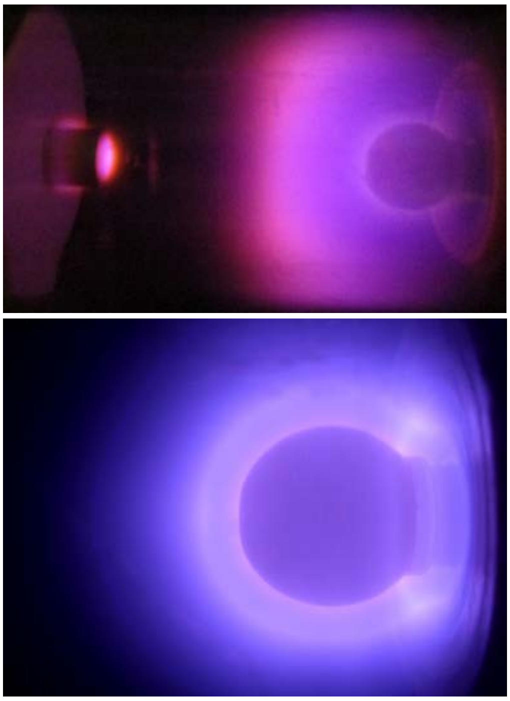


Fig. 13. Current-voltage characteristics of the glow discharge at the nitrogen pressure of 0.2 and 5 Torr for the cathodes of different shape

At the gas pressure of 5 Torr the behavior of the current-voltage characteristics changes substantially. With low current values a normal mode of burning appears when the discharge occupies the cathode surface only partially, and the current growth is achieved due to the increase of the cathode surface area occupied by the discharge. The normal mode is weakly expressed on the current-voltage characteristics for the pin electrode, because due to its small area the discharge occupies all its surface already at small currents. For other cathodes with a larger surface in the normal mode the current increase takes place with the weak decrease of the voltage across the electrodes (for the spherical and step cathodes), and for the cylindrical and conical cathodes the voltage decrease becomes substantial. Correspondingly, for the cathodes of larger surface area the normal mode is observed in a wider range of current values until the discharge spot will occupy their entire surface.

Note that at low gas pressure discharge current values (e.g., 0.1 Torr and 0.1 mA) the boundary of the cathode sheath is almost flat for any cathode design over- lapping the tube cross section and rounding a little bit near its walls (see photo for the spherical cathode in Fig. 14,a). In the photo the cylindrical anode is located on the left (with the anode glow on its surface), and the cathodes is on the right. With the current growing the cathode thickness decreases and then the sheath boundary shape becomes close to a spherical one even with the cathodes possessing the shape different from the spherical one. At large pressure (say, 1 Torr) the cathode sheath thickness is small, for nitrogen it is close to 2…3

mm, the thin sheath is pressed to the cathode surface and it replicates its shape (see photo in Fig. 14,b). In this photo the clear region corresponds to the cathode sheath and further the negative glow extends itself.



a

b

Fig. 14. The photo of the complete discharge (a) and the near-cathode region (b) for the spherical cathode at the smallest distance between the electrodes of 50 mm: a) nitrogen pressure of 0.1 Torr, discharge current of 0.15 mA; b) 1 Torr, 20 mA

CONCLUSIONS

The paper reports the breakdown curves and current-voltage characteristics of the glow discharge in nitrogen we have measured for the fixed inter-electrode distance of 5 mm. The investigations have been performed for the cylindrical anode and the cathodes of the following design: cylindrical, having steps 5 and 10 mm high, conical 10 mm high, spherical and pin-like. In addition we have measured the breakdown curves for flat electrodes spaced 10 and 15 mm apart.

We have demonstrated that almost all measured breakdown curves near to and to the right of the minimum happen to be close to the breakdown curve for the flat electrodes spaced 5 mm apart. Only portions of the breakdown curves in the pressure range above 10 Torr for conical and pin cathodes form an exclusion. However as a whole the breakdown curves for the cathodes of different design consist of a family of closely located curves.

We have demonstrated that the difference in the cathode areas affects substantially the current-voltage characteristics and modes of burning of the discharge. At low gas pressure the discharge was burning in the abnormal mode, and the smallest current was observed with the pin cathode (the smallest among them), whereas the largest current was observed for the spherical cathode (the largest one among them). Correspondingly, at large pressure the normal mode exists in the narrow current range with the pin cathode and in the wide current range for the spherical one.

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ВЛИЯНИЕ ГЕОМЕТРИИ КАТОДОВ НА ПРОБОЙ ГАЗА И РЕЖИМЫ ГОРЕНИЯ ТЛЕЮЩЕГО РАЗРЯДА В АЗОТЕ

В.А. Лисовский, Р.О. Осмаев, В.Д. Егоренков

Измерены кривые зажигания и вольт-амперные характеристики разряда в постоянном электрическом поле. Почти все кривые зажигания, измеренные для катодов различной формы (цилиндрической, двухступенчатой, конической, сферической и штыревой), практически совпадают с кривой для зазора 5 мм между плоскими электродами вблизи и справа от минимума, за исключением участков для конического и штыревого катодов в диапазоне давлений выше 10 Торр. Левые ветви кривых зажигания несколько расходятся, но ведут себя как семейство близких кривых. При низких давлениях газа разряд горит только в аномальном режиме с наименьшим током на штыревом и наибольшим током на сферическом катоде. При больших давлениях нормальный режим наблюдается в широком диапазоне токов для сферического и ступенчатого катодов и почти не виден для штыревого катода.

ВПЛИВ ГЕОМЕТРІЇ КАТОДІВ НА ПРОБІЙ ГАЗУ ТА РЕЖИМИ ГОРІННЯ ТЛІЮЧОГО РОЗРЯДУ В АЗОТІ

В.О. Лісовський, Р.О. Осмаєв, В.Д. Єгоренков

Виміряні криві запалювання і вольт-амперні характеристики розряду в постійному електричному полі. Майже всі криві запалювання, виміряні для катодів різної форми (циліндричної, двоступінчастої, конічної, сферичної та штирьової), практично співпадають з кривою для проміжку 5 мм між плоскими електродами поблизу і праворуч від мінімуму, за винятком ділянок для конічного і штирьового катодів у діапазоні тиску вище 10 Торр. Ліві гілки кривих запалювання дещо розходяться, але ведуть себе як сімейство близьких кривих. При низькому тиску газу розряд горить тільки в аномальному режимі з найменшим струмом на штирьовому і найбільшим струмом на сферичному катоді. При високому тиску нормальний режим спостерігається в широкому діапазоні значень струму для сферичного та ступінчастого катодів і його майже не видно для штирьового катоду.