UDC 533. 915

STRATIFICATION OF THE POSITIVE COLUMN OF A DC DISCHARGE IN NITROGEN

V.A. Lisovskiy [1,2], V.A. Derevyanko [1], E.P. Artushenko[1], V.D. Yegorenkov [1]
[1] *Kharkov National University*
61022, Kharkov, Svobody Sq., 4, Ukraine
[2] *Scientific Center of Physical Technologies*
61022, Kharkiv, Svobody Sq., 6, Ukraine
E-mail: lisovskiy@yahoo.com
Received 10 September 2012, accepted 25 September 2012

This paper studies the stratification conditions of the positive column of the dc glow discharge in nitrogen in tubes of various radii. In each discharge tube the striations are observed in closed regions with respect to current and applied voltage values within the limited range of gas pressure values. We revealed that the first striation (counted from the cathode end of the positive column) was clearer expressed and it possessed the maximum thickness. Striation length is weakly dependent on discharge current but it decreases with gas pressure growing. Again the striations with a large order number (counted from the cathode edge of the positive column) possess lesser thickness. We find out that positive column stratification obeys similarity laws well. The extinction curves and striation existence regions registered in different discharge tubes and plotted against the product of gas pressure and inter-electrode distance *pL* coincide. Reduced striation thickness d/R (striation thickness d divided by tube radius R) in different tubes also is in good agreement with each other when plotted against *pR*. We observe that the reduced striation thickness obeys the Goldstein-Wehner law $d/R = C/(pR)^m$, the constants for nitrogen being $C = 1.05$ and $m = 0.32$.
KEY WORDS: direct current glow discharge, positive column, striations, nitrogen, low pressure.

СТРАТИФІКАЦИЯ ПОЗИТИВНОГО СТОВПА РОЗРЯДУ ПОСТІЙНОГО СТРУМУ В АЗОТІ

В.О. Лісовський [1,2], В.О. Дерев'янко [1], К.П. Артюшенко [1], В.Д. Єгоренков [1]
[1] *Харківський національний університет*
61022, Харків, пл. Свободи 4, Україна
[2] *Науковий фізико-технологічний центр*
61022, Харків, пл. Свободи 6, Україна
У цій роботі були досліджені умови стратифікації позитивного стовпа тліючого розряду постійного струму в азоті в трубках різних радіусів. Показано, що в кожній розрядній трубці страти спостерігаються в замкнутих областях по струму і прикладеній напрузі в обмеженому діапазоні тисків газу. Отримано, що перша (з катодного кінця позитивного стовпа) страта яскравіше виражена і має найбільшу довжину. Товщина страт слабо залежить від розрядного струму, але зменшується з ростом тиску газу. Також страти з великим порядковим номером (від катодного краю позитивного стовпа) мають меншу товщину. Показано, що стратифікація позитивного стовпа добре підкоряється законам подібності. Спостерігається збіг кривих згасання і областей існування страт, виміряних в різних розрядних трубках і побудованих в залежності від добутку тиску газу і відстані між електродами *pL*. Зведені товщини страт d/R (відношення товщини страт d до радіуса трубки R) в різних трубках також добре узгоджуються між собою при побудові їх в залежності від *pR*. Показано, що зведені товщини страт підкоряються закону Гольдштейна-Венера $d/R = C/(pR)^m$, при цьому для азоту константи $C = 1.05$ і $m = 0.32$.
КЛЮЧОВІ СЛОВА: тліючий розряд постійного струму, позитивний стовп, страти, азот, низький тиск.

СТРАТИФИКАЦИЯ ПОЛОЖИТЕЛЬНОГО СТОЛБА РАЗРЯДА ПОСТОЯННОГО ТОКА В АЗОТЕ

В.А. Лисовский [1,2], В.А. Деревянко [1], Е.П. Артюшенко [1], В.Д. Егоренков [1]
[1] *Харьковский национальный университет*
61022, Харьков, пл. Свободы 4, Украина
[2] *Научный физико-технологический центр*
61022, Харьков, пл. Свободы 6, Украина
В данной работе были исследованы условия стратификации положительного столба тлеющего разряда постоянного тока в азоте в трубках различных радиусов. Показано, что в каждой разрядной трубке страты наблюдаются в замкнутых областях по току и приложенному напряжению в ограниченном диапазоне давлений газа. Получено, что первая (с катодного конца положительного столба) страта ярче выражена и имеет наибольшую длину. Толщина страт слабо зависит от разрядного тока, но уменьшается с ростом давления газа. Также страты с большим порядковым номером (от катодного края положительного столба) имеют меньшую толщину. Показано, что стратификация положительного столба хорошо подчиняется законам подобия. Наблюдается совпадение кривых погасания и областей существования страт, измеренных в различных разрядных трубках и построенных в зависимости от произведения давления газа и расстояния между электродами *pL*. Приведенные толщины страт d/R (отношение толщины страт d к радиусу трубки R) в различных трубках также хорошо согласуются друг с другом при построении их в зависимости от *pR*. Показано, что приведенные толщины страт подчиняются закону Гольдштейна-Венера $d/R = C/(pR)^m$, при этом для азота константы $C = 1.05$ и $m = 0.32$.
КЛЮЧЕВЫЕ СЛОВА: тлеющий разряд постоянного тока, положительный столб, страты, азот, низкое давление.

The dc glow discharge is widely applied in such devices of glow discharge as gas discharge voltage stabilizers (stabilitrons), rectifiers on the ground of glow discharge, as well as gas discharge lasers (neon-helium, carbon dioxide with nitrogen admixture etc) [1]. Positive column stratification lowers the gas discharge laser efficiency therefore it is of considerable interest to study the existence conditions of striations and their characteristics [2-6].

The uniformly glowing positive column under certain conditions is split into striations – consecutive bright and dark regions (layers). In molecular gases they occupy, as a rule, a substantial portion of the positive column whereas in noble gases they are strongly damped or are in a state of constant motion, and their observation is impeded. Standing striations can be seen with a naked eye and they are most easily observed in molecular gases such as hydrogen, nitrogen as well as in mixtures of noble and molecular gases [4,5]. In pure noble gases the steady striations may exist to the anode side of the substantial plasma nonuniformity, e.g. the cathode part of the discharge, a probe with a large negative potential, abrupt tube narrowing; however, their strong damping is observed along the column. An eye cannot observe moving striations because of the large speed of their propagation.

Experimental study and description of standing striations started much earlier than that of moving ones because one did not require special equipment for their observations. Reviews of papers devoted to research into standing and moving striations may be found in publications [4,5,7-9]. However, reviews by Nedospasov [7] and Pekarek [8] devoted only little attention to standing striations. At the same time one can observe standing striations in molecular gases in the broad range of discharge current and gas pressure values and they are most clearly expressed.

From the viewpoint of plasma technology it is most important to elucidate the conditions under which the uniform positive column becomes stratified. The authors of paper [6] presented the diagram of various states of plasma discharge in neon showing the existence regions of the uniform and stratified discharges. Papers [10,11] studied the moving striations in nitrogen. Conventionally a positive column of the glow discharge in nitrogen demonstrates standing striations, therefore for observing moving striations an additional electrode was introduced in the column and a weak alternate voltage of a kilohertz range was applied. Authors of papers [10,11] determined the existence regions for every type of striations, their phase and group velocities, dispersion curves (frequency of ionization oscillations against wave number k) and voltage drop across each type of striations depending on discharge current for different nitrogen pressure values.

Klyarfeld [12] dealt mainly with standing striations and concluded that there is no fundamental difference between standing and moving striations — they are the periodic repetitions of the local perturbation in plasma in the direction of the electron drift. Zaitsev [13] studied moving ionization waves and produced them from outside either with an additional internal electrode or through modulation of the discharge current with the alternate voltage of the frequency close to that of the waves.

The authors of paper [14] studied the formation of moving striations in neon in experiment. They found that the striations were formed out of small anode spots usually oscillating with the growing amplitude, increasing in size and then leaving the anode surface. These striations moved with a high speed to the cathode edge of the positive column and then disappeared. The author of paper [15] suggested a refined method with which he determined the value of the critical current (limiting the existence region of striations) in argon and xenon.

In helium, neon and their mixtures the critical current for ionization wave excitation, the dispersion law, the velocity and the waveform and their dependence on gas temperature were studied in experiment in the discharge tubes of 1 to 3 mm in diameter [16]. The authors of paper [17] performed the spatial-temporal probe measurements of plasma parameters in S- and P-striations in neon. Paper [18] proposed a nonlinear model describing the modes of ionization waves in plasma. This model revealed the hysteresis transition between different modes on changing the discharge current. S-, P- and R- striations which may be observed in dc discharge in noble gases at low pressure and small discharge current were studied in paper [19] employing the numerical solution of the Boltzmann kinetic equation.

Authors of paper [20] found out that the layered positive column in molecular gases acquired a macroscopic instability under certain conditions. This instability manifests itself either in a slow spontaneous displacement of the layered positive column to the anode with the velocity order of 1 cm/min, or in slow longitudinal oscillations of the column as a whole. The existence regions of standing as well as moving striations possess a complicated shape. For hydrogen and oxygen they are given, e.g. in paper [8], and for nitrogen they are obtained in [7]. Comparison between the existence regions of standing and moving striations shows that standing striations, as a rule, are observed at lower gas pressure and current values than moving ones.

In noble gases [21] the standing striations in neon exist mainly inside the region free of moving striations (with current values of 1 — 10 mA and pressure values of 0.1 — 1 Torr). In papers [22,23] evanescent standing striations were observed in helium, neon and argon with pressures up to 10^{-2} Torr and currents up to 100 mA.

If you intend to elucidate the nature of standing striations, then a question arises on how possible values of their length d depend on discharge conditions. The length of standing striations usually has the order of the tube radius R and it decreases with current increasing approaching a certain constant value [4]. Also the length of standing striations d decreases on increasing pressure p and decreasing radius R according to the empirical law of Goldstein-Wehner [4,24] $(d/R)\cdot(pR)^m = \text{const}$, where $m < 1$ and it depends on the nature of gas. In noble gases standing striations are usually substantially longer than in molecular gases, their length exceeding several times the tube diameter especially at low pressure. Molecular impurity added to a noble gas makes standing striations the shorter the larger is the impurity content [25].

Many researchers [12,22,23,26] remark that the striation closest to the cathode somewhat differs from the rest of them being not only the sharpest but also the longest.

Despite a large number of articles devoted to the research into moving and standing striations in the dc discharge, the references lack data on the link between the existence region of striations and the regions of appearance and existence of the discharge itself (its ignition and extinction curves, respectively). Again, the references do not contain a united opinion about the striation shape. For example, in papers [5,26] the first striation (located at the cathode edge of the positive column) shines brighter but its length equals approximately that of subsequent striations (located closer to the anode). However, as was said above, in papers of other researchers [12,22,23] they report that the first striation closest to the cathode is the longest. Still again, the references do not contain detailed information on the behavior of each separate striation against gas pressure and discharge current. Therefore this paper aims at studying extinction curves of the dc discharge in nitrogen, existence regions of standing striations, as well as lengths of separate striations against gas pressure and current.

EXPERIMENTAL CONDITIONS

In order to study the existence conditions and characteristics of striations in the positive column of the dc discharge we employed the discharge chambers shown schematically in Fig.1. Measurements were performed with the tubes of inner radius $R = 4$ mm, 6 mm, 12.5 mm, 27.5 mm and 39.5 mm. We used the discharge devices of similar design. For example, for the tube of radius 27.5 mm the inter-electrode distance was 395 mm. For other tubes the inter-electrode distance also was about 14.4 times larger than the radius.

The studies were performed in nitrogen within the pressure range $p = 0.05 - 0.5$ Torr. The cathode was fed with the dc potential $U_{dc} \leq 3000$ V. The resistor of 75 kOhm was switched in series between the cathode and the dc source.

Before measurements we cleaned the cathode surface igniting a glow discharge in nitrogen at the pressure of $p \approx 0.1$ Torr and discharge current of $I_{dc} = 5$ mA during 10 minutes. Under these conditions the ion flux onto the cathode is sufficiently high to remove monolayers of gases, which remained on the cathode surface after mechanical grinding and polishing, but the discharge current is still insufficient for producing cathode spots eroding the cathode surface. We did not employ any external ionization sources for discharge igniting.

We have taken photos of striations. The obtained images are downloaded to the computer. In order to process them any program can be applied which can separate a rectangular region (Adobe Photoshop, MBizGroup PhotoEditor etc.). If necessary, the images have to be rotated if the discharge tube is located not horizontally but at some small angle. Fig.2 depicts the photo from which you can see how to determine the first striation thickness. As is seen from the photo, it amounts around 9.3 mm. In the same way you can determine the thickness values for the second striation etc which are usually a little thinner and dimmer than the first one, but in this work they are not important. The matter is that near the boundaries of the pressure range you can observe 1-2 striations and further the positive column glow becomes uniform. Therefore it is expedient to deal with only the first striation as the brightest one, long and existing in the broadest range of gas pressure.

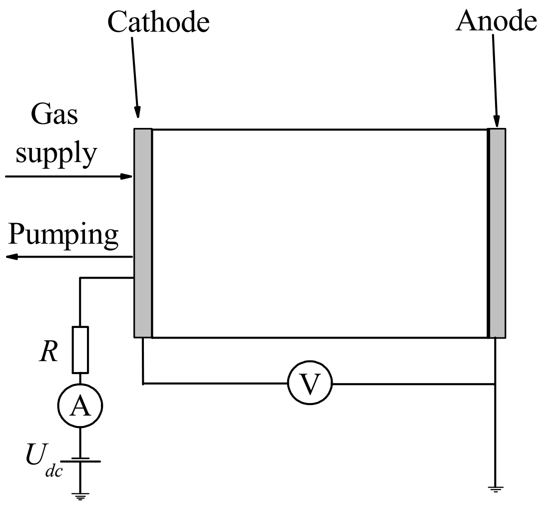


Fig.1. Experimental device setup.

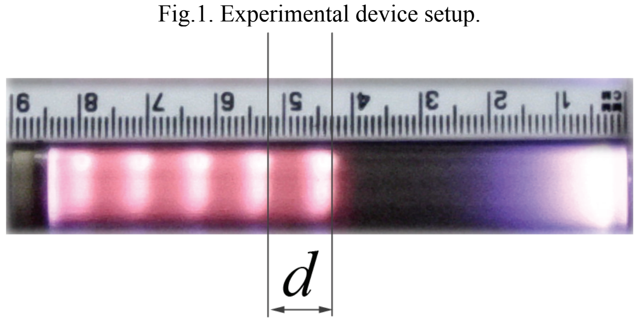


Fig.2. Discharge photo at the nitrogen pressure of $p = 0.6$ Torr and the discharge current of 1.6 mA.
Anode is to the left, and cathode is to the right. d is the first striation thickness. The tube of inner radius $R = 6$ mm.

EXPERIMENTAL RESULTS

The aim of these studied was to clarify the existence conditions for standing striations together with their length for different current and nitrogen pressure values. Fig.3 depicts the discharge extinction curve U_{ext} (the minimum voltage of discharge burning against the product of gas pressure and inter-electrode distance pL) limiting the existence region of standing striations in the glow discharge from below. The voltage U_{high} is the maximum voltage at which the striations disappear. At the section of the U_{high} curve growing with gas pressure the total length of the cathode sheath, negative glow and dark Faraday space approached the inter-electrode distance and the positive column disappeared. Together with it the striations also disappear because they may be observed only in the positive column. Fig.4 presents the photos of the discharge in the tube of 27.5 mm in radius with a stratified positive column for different current values. At small current values we observe only 2-3 first striations located at the cathode edge of the positive column. The rest of the column seems to be uniform visually. However, on increasing the current almost the total positive column becomes stratified, the striations are readily seen and the column length decreases. And at some maximum values of the voltage U_{high} and current I_{high} the positive column with the striations disappears completely.

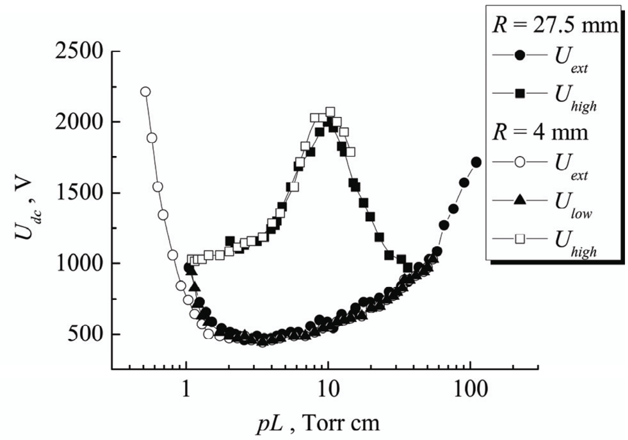


Fig.3. Discharge extinction voltage U_{ext} and maximum voltage of striation existence U_{high} in the tube of 27.5 mm in radius, as well as discharge extinction voltage U_{ext}, minimum and maximum voltage of striation existence U_{low} and U_{high} in the tube of 4 mm in radius against nitrogen pressure.

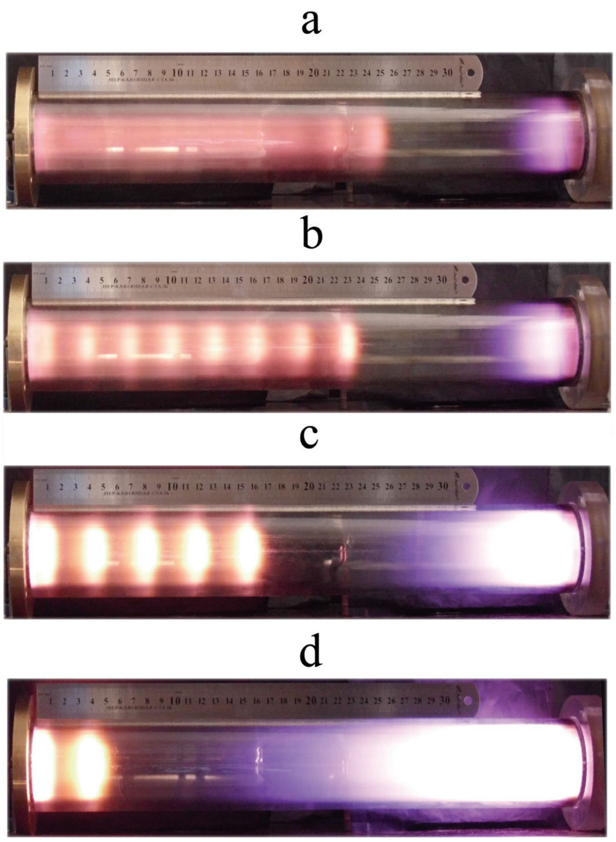


Fig.4. Discharge photos at nitrogen pressure of p = 0.2 Torr and discharge current values:
a) 0.7 mA; b) 1.7 mA; c) 9 mA; d) 29.3 mA.
Anode is to the left, and cathode is to the right.

At the descending section of the curve U_{high} the positive column did not disappear with the current growing but the striations were broadened and the column became uniform. At nitrogen pressure above 1 Torr (for the tube of 27.5 mm in radius) the striations were not observed in the total range of discharge current values studied in the present paper.

As the experiments were performed in geometrically similar tubes then the discharge characteristics had to obey similarity laws. Let us check whether similarity laws apply to a stratified glow discharge.

As we observe in Fig.3, the extinction curves registered for discharge tubes of 27.5 mm and 4 mm in radius and plotted to the scale U_{ext} (pL) actually match each other. The maxima voltage values U_{high} for the striation existence in both tubes also match. It indicates the validity of similarity laws in describing the processes of discharge stratification and extinction. The descending section of the maximum voltage U_{high} in the narrow tube was not registered due to technical reasons because at large gas pressure a strong discharge current flowed through the tube leading to substantial cathode sputtering and discharge chamber heating. However the knowledge of the behavior of this descending section in a wide tube may help us to predict its path for a narrow tube.

Photos in Fig.4 demonstrate that the striation thickness does not remain constant at gas pressure fixed but it experiences changes with the discharge current growth. Fig.5 shows the dependence of the first striation thickness (counted from the cathode end of the positive column) on discharge current at different nitrogen pressure values. The first striation thickness demonstrates a nonuniform pattern with discharge current growth remaining almost constant. The pressure increase leads to the decrease in the first striation thickness.

Photos in Fig.4 also demonstrate that the striations in the positive column do not have the same value because the first of them counting from the column cathode end is thicker and brighter than subsequent ones. The authors of papers [12,22,23,26] also observed that the first striation is the longest one. Fig.6 depicts the striation thickness against its ordinal number (counted from the column cathode end) registered for three different sets of discharge conditions. The figure evidences that the farther is the striation from the cathode end of the positive column the narrower it is. But the striations with large ordinal numbers (N > 4) have approximately equal thickness.

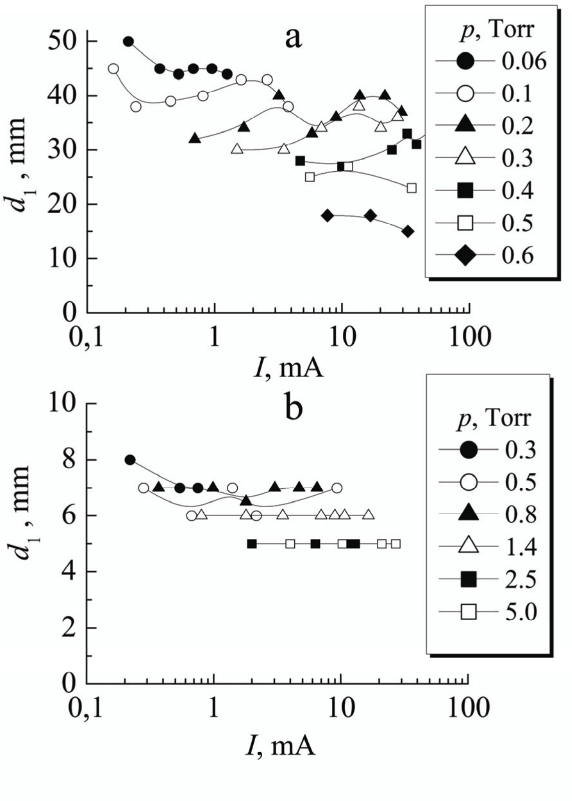


Fig.5. Thickness of the first striation against discharge current at different nitrogen pressure values. Tube radius is 27.5 mm (a) and 4 mm (b).

As follows from Fig.5, the striation thickness experiences little variation with the discharge current increasing. Therefore we averaged the striation thickness value for each fixed gas pressure value. Fig.7 shows the average thickness of the first three striations thus found against nitrogen pressure. In the figure we observe that the average thickness of striations uniformly decreases with gas pressure, the speed of their narrowing with pressure being about equal.

In order to compare between the striation behaviour in the tubes of various radii it is expedient to use a dimensionless (reduced) tube thickness. To this end we divide the striation thickness d by the tube radius R in which the striations were measured. Fig.8 shows in logarithmic scale the reduced average thickness of the first striations against the pR product for all discharge tubes we employed. The figure clearly demonstrates that the striation reduced thickness is well described by the following dependence

$$\frac{d}{R} = \frac{C}{\left(pR\right)^m}, \tag{1}$$

that is called the Goldstein-Wehner law [4, 24]. However we remark that Wehner [24] presented in his paper contradictory data. He approximated his data for the striation reduced thickness (black squares in Fig. 8) with the curve (1) corresponding to the constant values $C = 2$ and $m = 0.32$, though actually the best match between his measured data and formula (1) is observed with the value $C = 0.6$. Our results also are well described with formula (1) but with $C = 1.05$. From axial profiles of discharge glow at different nitrogen pressure values given in paper [5] we determined the thickness of the first striations and also presented it in Fig.8. This figure demonstrates good agreement between the reduced thickness values for the first striations with our results. In the broad range of discharge conditions the thickness of the first striation comprises from one to two radii of the discharge tube. We also determined the thickness of the first striation in nitrogen from the axial profile of the electric field strength measured by Graham [30] (see Fig.12 [30]). The obtained value is also shown in Fig.8 and it is above the results of our work and that of paper [5]. One can see from the description of the experimental conditions given in [30], that Graham employed the mercury manometer therefore the nitrogen in his tube was contaminated with mercury vapour. As the mercury atoms possess a low ionization potential, their presence makes the ionization process easier and makes striations longer. The mercury manometer in [30] was vacuum-sealed without grease and, consequently, organic contamination in nitrogen was absent.

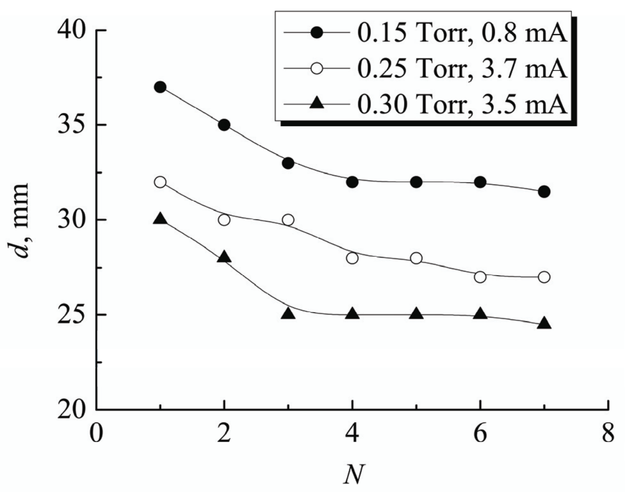


Fig.6. Striation thickness against its ordinal number. Tube radius is 27.5 mm.

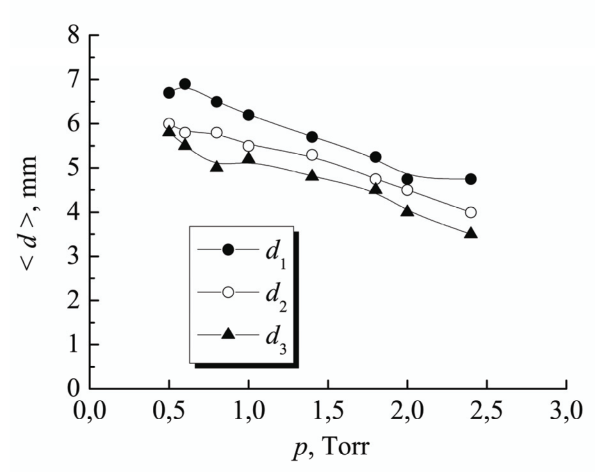


Fig.7. Average thickness of the first three striations against nitrogen pressure. Tube radius is 4 mm.

Note that Wehner made vacuum sealing with cement containing resin and wood oil therefore due to the presence of organic vapour the striation thickness values he had obtained happened to be remarkably lower than in our work and in paper [5].) The admixture of air does not affect noticeably the applicability of the Goldstein-Wehner law. This can be observed from our results for air presented in Fig.8.

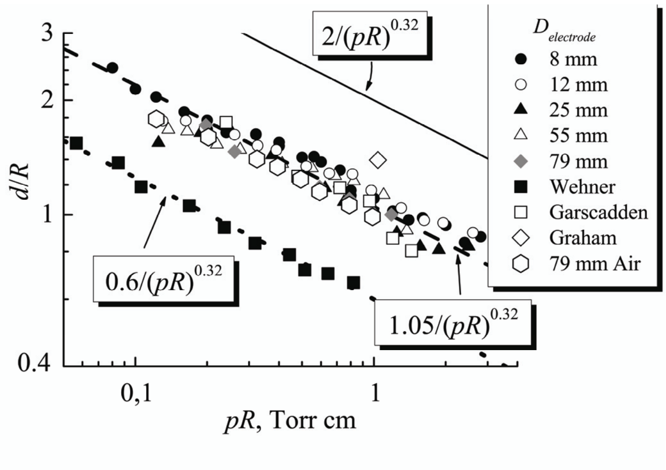


Fig.8. Ratio of averaged thickness of the first striation to tube radius against the product of gas pressure and tube radius.

CONCLUSIONS

This paper clarifies the stratification conditions of the positive column of the dc glow discharge in nitrogen in tubes of radii R = 4 mm, 6 mm, 12.5 mm, 27.5 mm and 39.5 mm. The striations are observed in closed regions with respect to current and applied voltage values within the limited range of gas pressure values. We found that the first striation (counted from the cathode end of the positive column) is clearer expressed and it possesses the maximum thickness. Striation length is weakly dependent on discharge current but it decreases with gas pressure growing. Again the striations with a large order number (from the cathode edge of the positive column) possess lesser thickness.

We found out that positive column stratification obeyed similarity laws well. The extinction curves and striation existence regions registered in different discharge tubes and plotted against the product of gas pressure and inter-electrode distance pL coincide. Reduced striation thicknesses d/R (striation thickness d divided by tube radius R) in different tubes also are in good agreement with each other when plotted against pR.

We observed that the reduced striation thickness obeyed the Goldstein-Wehner law $d/R = C/(pR)^m$, the constants for nitrogen being C = 1.05 and m = 0.32.

REFERENCES

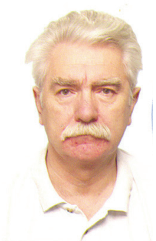
1. Trager F. (Ed.) 2007 Springer Handbook of Lasers and Optics (New York: Springer Science + Business Media, LLC)
2. Raizer Y.P. Gas Discharge Physics. – Berlin: Springer, 1991. - 450p.
3. Granovsky V.L. Electric current in gases. - Moscow: Nauka, 1971. - 490p.
4. Francis G. The glow discharge at low pressure // Encyclopedia of Physics, Ed. by Flugge S., Vol. 22 (Gas discharge 2), Berlin: Springer, 1956. – P.53-208.
5. Garscadden A. Ionization Waves in Glow Discharges. // Gaseous Electronics, Ed. by. Hirsh M.N. and Oskam H.J., Vol.1 (Electrical Discharges), New York: Academic Press, 1978. – P.19-64.
6. Pfau S., Rutscher A., Wojaczek K. Das Ähnlichkeitsgesetz für quasineutrale, anisotherme Entladungssäulen // Beitrage Plasmaphys. – 1969. – Vol.9, №4. - P.333-358.
7. Nedospasov A.V. Striations // Soviet Physics Uspekhi. – 1968. – Vol.11, №3. – P.174-187.
8. Pekarek L. Ionization waves (striations) in a discharge plasma // Soviet Physics Uspekhi. – 1968. – Vol.11, No.3. – p. 188-226.
9. Golubovsky Y.B., Kudryavtsev A.A., Nekuchaev V.O., Porokhova I.A., Tsendin L.D. Kinetics of electrons in a nonequilibrium gas discharge plasma. – SPb: St. Petersburg University Publishing. – 2004. – 248 p.
10. Venzke D. Messungen an der geschichteten Niederdruck-Entlandung in Stickstoff // Beitrage Plasmaphys. – 1971. - Vol.11, №2. - P.141-148.
11. Laska L., Exner V.L. Ionization Waves in Nitrogen // Czech. J. Phys. B – 1971. - Vol.21, №2. - P.126-147.
12. Klyarfeld B.N. Formation of striations in a gas discharge // Journal of Experimental and Theoretical Physics. – 1952. - Vol. 22, №1. - P.66-77.
13. Zaitsev A.A. Oscillatory modes and moving layers in the discharge // Reports of USSR Academy of Sciences. - 1952. – Vol. 84, №1. - P.41-44.
14. Coulter J. R. M., Armstrong N. H. K. and Emeleus K. G. Moving Striations and Anode Spots in Neon // Proc. Phys. Soc. – 1960. - Vol. 77, №2. - P.476-482.
15. Sato M. On the critical current of ionisation waves in gas discharges // J. Phys. D: Appl. Phys. – 1982. – Vol.15, №7. – P.1181-1185.
16. Amemiya H. Characteristics of striations of He and Ne plasmas in small-diameter discharge tubes // J. Phys. D: Appl. Phys. - 1984. – Vol. 17, №12. – P. 2387-2398.
17. Golubovskii Yu.B., Kozakov R.V., Wilke C., Behnke J. and Nekutchaev V.O. Oscillations of the positive column plasma due to ionization wave propagation and two-dimensional structure of striations // Plasma Sources Sci. Technol. – 2004. – Vol. 13, №1. – P.135–142.
18. Dinklage A., Bruhn B., Testrich H., and Wilke C. Hysteresis of ionization waves // Physics of Plasmas. – 2008. – Vol.15, №6. – P. 063502.
19. Golubovskii Yu.B., Skoblo A.Yu., Wilke C., Kozakov R.V. and Nekuchaev V.O. Peculiarities of the resonant structure of the electron distribution function in S-, P and R-striations // Plasma Sources Sci. Technol. – 2009. – Vol.18, №4. – P. 045022.
20. Kagan Y.M., Mitrofanov N.K. The energy spectrum of the electrons in a layered column of a glow discharge in hydrogen // Technical Physics. – 1971. - Vol. 41, №10. - P.2065-2072.
21. Ruzicka T. The connection between moving and standing striations in a d.c. glow discharge in Ne // Czech. J. Phys. Ser. B. –

1968. - Vol. 18, №7. - P. 928-936.
22. Twiddy N. D. Electron Energy Distributions in Plasmas. III. The Cathode Regions in Helium, Neon and Argon // Proc Roy. Soc. Ser. A. – 1961. - Vol. 262, №1310. - P. 379-394.
23. Twiddy N. D. Electron Energy Distributions in Plasmas. V. A Search for Evidence of a High Anomalous Rate of Energy Exchange between the Electrons of a Low-Pressure Discharge // Proc Roy. Soc. Ser. A. – 1963. - Vol. 275, №1362. - P. 338-356.
24. Wehner F. Schichtabstand und Schichtpotentialdifferenz in der positiven Glimmentladung // Annalen der Physik. – 1910. – Vol.337, №6. – P. 49-85.
25. Zaitsev A. A., Miskinova N. A. On the moving and stationary striations in Ne and Ne-H2 // Radiotekhnika i elektronika. – 1967. - Vol. 12, №7. - P. 1318-1320.
26. Lee D. A., Garscadden A. Standing Striations as Solutions of the Pekarek Equation // Phys. Fluids. – 1972. - Vol. 15, №10. - P. 1826-1830.
27. Schulz G.J., Brown S.C. Microwave Study of Positive Ion Collection by Probe // Phys. Rev. – 1955. – Vol.98, №6. – P. 1642–1649.
28. Zakrzewski Z., Kopiczynski T. Effect of collisions on positive ion collection by a cylindrical Langmuir probe // Plasma Physics. – 1974. – Vol.16. – P. 1195–1198.
29. Tichy M., Sicha M., David P., David T. A Collisional Model of the Positive Ion Collection by a Cylindrical Langmuir probe // Contrib. Plasma Phys. – 1994. – Vol.34, №1. – P. 59–68.
30. Graham W.P. Ueber den Verlauf des Potentialgradienten in Geissler'schen Rohren // Annalen der Physik und Chemie. - 1898. - Vol.64, №1. - P. 49-77.

Valeriy A. Lisovskiy - Ph.D. in physics and chemistry of plasmas. From 2001 to 2004, he was at the Ecole Polytechnique, Palaiseau, France, as a post-doctoral research associate. He obtained the Dr. Sc. degree in physics of plasmas from Kharkov National University in 2008. He is currently a Full Professor at Kharkov National University.
His research interests include low-pressure rf, lf, dc, combined and dual-frequency gas discharges, plasma processing, electron transport in gases, plasma sterilization.

Veronika A. Derevyanko (Koval) - graduated from Department of Physics and Technology of V.N. Karazin Kharkov National University in 2010. She is currently a second year Ph.D. student.
Her research interests are in the DC glow discharges, gas breakdown in the long tubes, stratification of the positive column of the dc glow discharge. She is the author and the co-author of 7 papers in the scientific journals.

Ekaterina P. Artushenko - received the B.S. degree in applied physics from Kharkov National University in 2011. She is currently M.S. student.
Her research interests are in the DC glow discharges in electronegative gases, stratification of the positive column of the dc glow discharge in different gases. She is the author and the co-author of 2 papers in the scientific journals.



Vladimir D. Yegorenkov - Dr.Sc. in physics and chemistry of plasmas. He is currently a Full Professor at Kharkov National University.
His research interests concentrate on studies of physics of fusion plasmas and gas discharge, general physics, lecture demonstration experiments in physics.