ISSN 0027-1349, Moscow University Physics Bulletin, 2009, Vol. 64, No. 2, pp. 187–190. © Allerton Press, Inc., 2009.
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Hysteresis Transition between Diffuse and Constricted Modes of DC Discharge in Argon

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Received March 21, 2008

Abstract—The results of theoretical studies of hysteresis transition between the diffuse and constricted modes of a dc glow discharge in argon are presented. It has been shown that the experimentally observed hysteresis of the current voltage characteristic (CVC) at the transition from the constricted to the diffuse mode is caused by the nonlocal formation of the electron energy distribution function (EEDF) while taking into account the heterogeneity of radial fields, namely, the diffusion of high-energy electrons capable of producing gas ionization from the central (constricted) region. The effect of the non-local formation of the EEDF has been described approximately by introducing the effective temperature of the high-energy part of the EEDF and solving the equation for the radial profile of the high-energy part of the EEDF.

Key words: low-temperature plasma.

DOI: 10.3103/S0027134909020180

In gas–plasma physics the phenomenon of the abrupt constriction of a direct current discharge in inert gases at high pressures (tens and hundreds of torrs) when all parameters of the discharge at the region of the critical current change abruptly and the discharge is compressed in a narrow luminous cord [1] is well known. The CVC is bi-stable [1].

The nature and the mechanisms of constriction in inert gases have been studied in several theoretical papers [2–4]. The most complete kinetic model to study the properties and mechanisms of constriction of the direct current discharge in argon at high pressures is presented in [2]. It was shown that heating of the gas, step ionization and influence of electron-electron collisions on the distribution function of electrons in the local field approximation lead to constriction and must be taken into account simultaneously for the quantitative description of constriction. The phenomenon of hysteresis [1] consists in the transition from the diffuse mode to the constricted mode and back to the diffuse one at different values of current. In contrast to constriction, the studying and quantitative description of which has been done extensively, we do not know any self-consistent model where the mechanism of hysteresis was proposed and described. Only in [3] the authors obtained a hysteresis transition in the local model taking into account highly excited levels and radiative transfer. However, the physical nature of hysteresis has not been explained.

Typically, bistability of the CVC reflects some "memory" of a plasma system, the nature of which may be different. For example, hysteresis in the CVC of barrier discharges is due to the normal capacity of dielectrics. However, such a "memory" can also occur in plasma, where the nonlocality of the energy spectrum of electrons in strongly inhomogeneous fields is substantial. One of the examples of the CVC bistability due to the electron kinetics in inhomogeneous fields could be the Gunn effect [5] in semiconductor plasma in the case of the appearance of high-field domains in structures with negative differential conductivity.

This work is a continuation of [4, 6], where a model for neon was developed. The model describes the diffuse and constriction modes, as well as the hysteresis transition between them. In the developed one-dimensional (radial) model the self-consistent system of the following equations was solved: the continuity equation for the concentration of electrons, ions Ar^+ and Ar_2^+ and excited atoms (in the effective metastable state), the heat conduction equation for a neutral gas and the temperature of electrons, the Poisson equation for the radial field, the equation for the longitudinal field (condition of given current) for the parameters of the experiment [7]; the Boltzmann equation was solved as well, taking into account the electron–electron collisions in the local approximation.

The aim of this work is to show using the example of argon that the effect under consideration occurs not only for neon, but also for other inert gases.

In this work we used the same numerical model as in [4]. All calculations were carried out for the pressures $P = 200$ torrs (the tube radius $R = 1$ cm). The list of the model reactions is shown in the table. To describe

The reaction list

1	Excitation	$Ar + e \longrightarrow Ar^* + e$	Calculated k from EEDF by cross sections [11]
2	Ionization	$Ar + e \longrightarrow Ar^+ + e + e$	
3	Step ionization	$Ar^* + e \longrightarrow Ar^+ + e + e$	
4	Conversion	$Ar^+ + Ar + Ar \longrightarrow Ar_2^+ + Ar$	$k = 1.8 \times 10^{-31}(300/T)^{3/4}$ (cm^6/s) [10]
5	Dissociative recombination	$Ar_2^+ + e \longrightarrow Ar^* + Ar$	$k = 4 \times 10^{-5} T_e^{-0.67}$ (cm^3/s) [10]
6	Dissociation by electron impact	$Ar_2^+ + e \longrightarrow Ar^+ + Ar + e$	$k = 5.7 \times 10^{-7}$ (cm^3/s) [13]
7	Three-body recombination	$Ar^+ + e + e \longrightarrow Ar^* + e$	$k = 1.6 \times 10^{-22}/(T[10^3\ K])^{4.5}$ (cm^6/s) [9]
8	Radiative decay	$Ar^r \longrightarrow Ar + h\nu$	$k \approx \theta A$ (s^{-1}) (see text)
9	Level mixing	$Ar^* + e \longrightarrow Ar^r + e$	$k \approx 10^{-8}$ (cm^3/s) [estimation]

the step ionization two lower metastable levels (11.54 and 11.72 eV) were combined into one effective metastable level, and the two resonant levels (11.62 and 11.82 eV) were combined into one effective resonant level. In doing so, it was assumed that the resonant levels are deactivated by emission of radiation with the frequency A. For the typical escape factor for our conditions $\theta \approx 10^{-3}$–10^{-2} and $A \sim 3 \times 10^8$ s^{-1} we obtain the frequency of radiative decay $\theta A \sim 3 \times 10^5$–$3 \times 10^6$ s^{-1}. For the ionization rate coefficient from resonant and metastable levels $k^* \sim 10^{-8}$ cm^3/s with the concentration of electrons $n_e \sim 10^{12}$ cm^{-3}, we get $k^* n_e \sim 10^4$ s^{-1}. Therefore, we believe that the frequency of the radiation quenching is much higher than both the frequency of the step ionization and the frequency of mixing of the resonance and metastable levels by electron impact. This means that the concentration of resonant levels is much lower than the metastable ones and does not affect the step ionization.

In the diffuse mode the loss of charged particles takes place mainly due to their diffusion and recombination on a wall. In this mode the main ion is Ar_2^+. Its concentration is determined by the balance of ion conversion and dissociation by electron impact (reactions 4 and 6) and radial profile by diffusion to the wall. In the constricted mode the loss of charged particles mainly occurs in the discharge region in the reaction of dissociative recombination (5). The radial distributions of electron density in the diffuse and constricted modes are shown in Fig. 1.

The values of the electron and ion mobility and other coefficients were taken from [8–10]: $\mu_e N = 3 \times 10^{22}$ cm^2/(s V), $\mu_i N = 4.83 \times 10^{18}$ cm^2/(s V), $\mu_{2i} N = 7.25 \times 10^{18}$ cm^2/(s V), the diffusion coefficient of electrons was determined from the relation D_e/μ_e [10], for the ions $D_i = 3.8 \times 10^{-3} T^{1.6}/P$ cm^2/s, $D_{2i} = 5.7 \times 10^{-3} T^{1.6}/P$ cm^2/s, for excited atoms $D^* = 0.014 T^{1.7}/P$ cm^2/s.

The rates of direct ionization, the ionization of the excited metastable level, and the excitation of the effective metastable level were determined from the calculation of EEDF by electron cross sections [11].

The main difficulty in describing hysteresis is the transition of the system from the constricted to the dif-

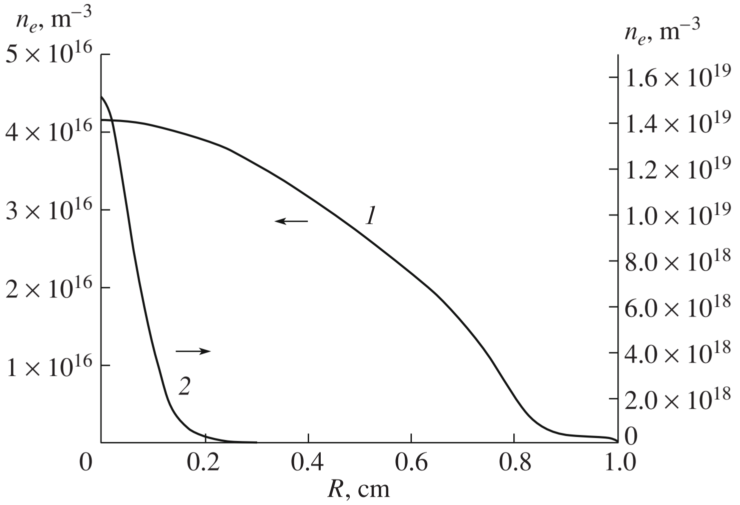

Fig. 1. The radial distribution of the electron density in the diffuse (1) and constricted (2) modes

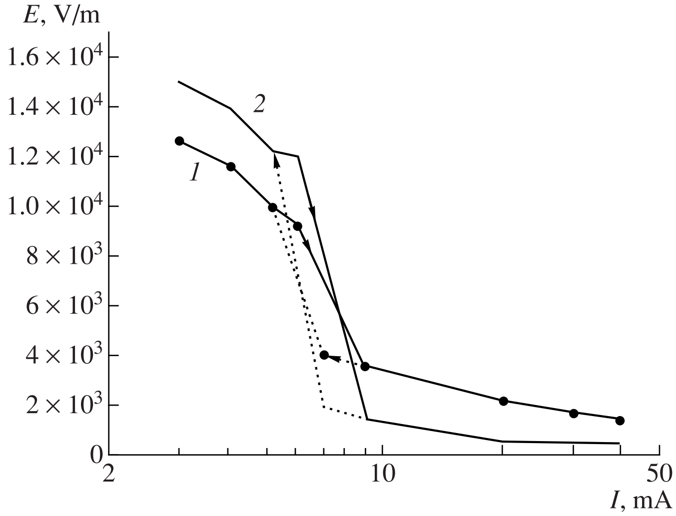

Fig. 2. The VAC of the tube discharge in the region of transition between the diffuse and the constricted states. *1*, experimental data [1]; *2*, results of the calculations

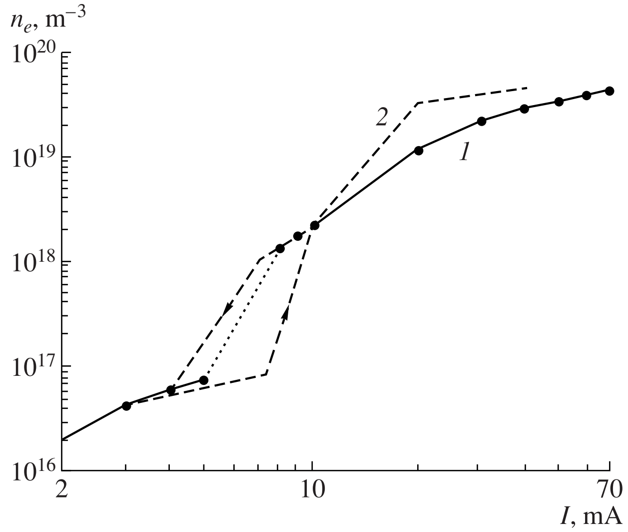

Fig. 3. The dependence of the electron density on the axis of the tube on the discharge current. *1*, experimental data, *2*, results of the calculations

fuse mode, which is usually ignored in the papers on constriction (only the direct transition is described). The calculations within our model showed that the reverse transition cannot be obtained using the local approximation. When the current decreases in the local approximation, the system does not go out of the constricted state, the field remains relatively low, and electron concentration on the axis remains high (which is typical for the constricted mode); a reduction of current is achieved through the continuous narrowing of constricted region. As the current decreases below the value at which the transition from the constricted to the diffuse mode occurs, the system “remembers” parameters of the discharge plasma, which were in the constricted mode. This effect occurs due to the fact that in the constricted mode in the central region the distribution function is close to the Maxwellian distribution, thus in the central part the ionization rate is high. This increases the degree of ionization and the Coulomb collisions maxwellize the distribution function. In the peripheral areas, by contrast, the electron density is low, and the distribution function is low in the high energy region, thus in this region ionization does not take place. Therefore, in the central part of the discharge tube the degree of ionization is maintained at a rather high level, but in peripheral areas it is low. When the size of the constricted region becomes less than electron energy relaxation length, transition to the diffuse mode occurs. In fact, radial diffusion of fast, high-energy electrons is faster than low-energy ones. This changes the EEDF throughout the central part of the discharge tube. To describe these effects the model was modified to take into account the nonlocal effects of EEDF formation by introducing the two-temperature distribution function. Based on this model it was shown that the transition from the constricted to the diffuse mode is due to the effect of the nonlocal formation of the electron energy distribution function.

Figure 2 shows the CVC of the modeled discharge and the electron density on the axis (Fig. 3) as function of the discharge current. We see that in the diffuse mode both the electric field and electron density are close to the experimental values (for the current 3 mA gas temperature on axis $T = 520$ K). In the constricted mode the calculated value of the electric field is much lower than the experimental value (for the current 20 mA gas temperature at the axis $T = 850$ K). This range of the pressure and electric field, according to [12], corresponds to constricted stratified discharge. The constricted mode of discharge [7] was also stratified. The measured fields are likely to correspond to the average for areas with high and low electric field (striation). In our one dimensional radial model the description of the constricted mode corresponds to the discharge parameters in the striation, where the field is significantly lower the average one. In this work we have not dealt with the description of longitudinal stratified profiles of plasma parameters. This will be the subject of our further research.

The discrepancy in the values of the electric field E may also be due to the use of some approximations in the model: the model takes into account only the ions Ar^+ and Ar_2^+ and lower levels—metastable and resonant ones, and does not take into account the higher excited states and more complex ions. Perhaps, in the diffuse mode because of the relatively slow loss of charged particles conversion into complex ions and the processes of excitation–deexcitation of high excited levels of argon become substantial; in addition, nonlocal effects are taken into account in the approximate two-temperature approach.

Despite the discrepancy of the calculated longitudinal electric fields and concentration with the experimental values for the constricted mode transitions, both direct and inverse, occur at the same values of discharge current for both neon and argon. It can be concluded that the developed model takes into account all main processes, not only those leading to constriction, but also those taking the system out of the constricted mode. As far as we know, this is the first model (together with [4]) allowing one to self-consistently describe the phenomenon of hysteresis at the transition between the diffuse and constricted modes in inert gases.

In this work the model we developed for neon [4] was modified for argon, and it showed that taking into account the non-locality of EEDF formation is necessary to describe hysteresis transition (transition from the constricted to the diffuse mode) in inert gases. The calculations within this model showed that the method we used, viz., taking the non-locality of EEDF formation into account, makes it possible to describe experiments for the diffuse and constricted modes and reproduce the hysteresis transition between these modes.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 7101.2006.2.

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