Contraction of a discharge in nitrogen and the influence of sound waves on the current–voltage characteristic (CVC) of a pinched discharge were investigated experimentally. The conditions under which sound eliminates the region of hysteresis on the CVC of the discharge and completely eliminates its contraction were determined. In an investigation of modulation of the discharge current by sound waves, it was shown that the depth of modulation increases abruptly when the discharge changes to the contraction mode.

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FREELY LOCALIZED SHF DISCHARGE IN A FOCUSED BEAM

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UDC 533.9

This paper reports the results of research into the spatial and temporal characteristics of an electrodeless shf discharge in air in a focused beam under different discharge generation conditions and in a wide range of variation of gas pressure, inserted energy flux density, and shf pulse duration. An analysis of the mechanisms responsible for rapid heating of the molecular gas is given. A stationary burning discharge is experimentally produced in free space in a focused beam with energy conducted vertically to the discharge from below.

Progress in the development of shf electronics has lead to the possibility of producing a new form of discharge, namely, an electrodeless shf discharge in a focused beam of electromagnetic energy in free space. Intensive research into this form of discharge has been conducted in different institutions since the start of the 1970's [1-3]. Study of the plasma of a freely localized shf discharge, isolated both from the walls of the discharge chamber and from the radiation source, is a pressing problem from

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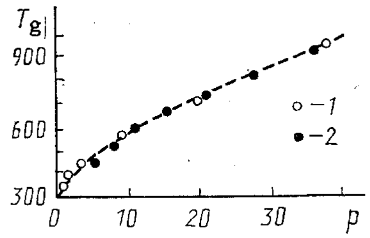


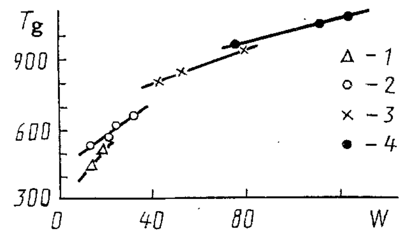


Fig. 1

Fig. 2

Fig. 1. Dependence of the gas temperature (K) versus pressure (torr) for threshold values of applied power: 1) nitrogen, 2) air.

Fig. 2. Gas temperature in an electrodeless shf discharge as a function of pulse power (kW) for different air pressures p: 1) 5, 2) 10, 3) 30, 4) 40 torr.

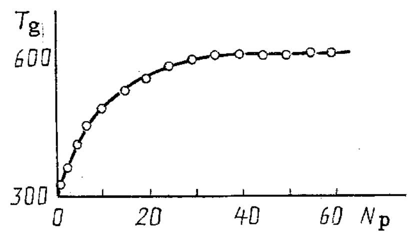


Fig. 3. Gas temperature as a function of number of shf pulses in the series (τ_p = 3 μsec, f_{rep} = 400 Hz).

the point of view of the transport of energy of intense electromagnetic radiant energy from space to the earth through earth's atmosphere [4], for producing artificial radio wave reflecting regions of ionization in the upper layers of the atmosphere [5], for pumping powerful gas lasers [6], for producing extremely pure materials in plasma chemistry [7], and for producing reactive thrust when using an energy source situated outside the apparatus being accelerated [8].

To eliminate the effect of the walls, the experiments were conducted under conditions approaching free space $R/\lambda >> 1$ (λ = 2-10 cm). A converging beam was formed either by a horn-lens antenna or using a phase grating. The duration of the shf pulse was varied from 1 μsec to 10 sec. The electric field amplitude at the focal point of the beam was $E_0 \leq 6$ kV/cm, and the irradiance at the focal region of the beam was $S \leq 6 \cdot 10^4$ W/cm^2. The wave was linearly polarized. The radiation was conducted to a pressure chamber filed with the gas to be studied (nitrogen, air, helium, hydrogen) at pressures of 0.1-1500 torr. A matching load was installed the end of the chamber. Information about the spatial and temporal characteristics (E_0, n_e, T_e, electron energy distribution, T_g, T_vv, Δn) of a freely localized shf discharge in air in a given cycle of the studies was obtained on the basis of a broad complex of traditional and specially developed diagnostic methods of noncontact investigation of a low temperature plasma.

In the first stage, an electrodeless shf discharge was studied at an antinode of the field. A spherical mirror was placed in the discharge chamber opposite the shf lens that permitted additional focusing of the beam, and conditions are realized in the chamber that are close to those associated with standing waves. The shf generator delivered frequent short pulses (λ = 10 cm, τ_p = 3 μsec, f_{rep} = 400 Hz). The discharge was a localized plasma formation, stably igniting in a fixed location of free space at an antinode of the field. The distribution of the electric field intensity along the axis of the discharge chamber, the variation of the electric field intensity of in the discharge plasma were obtained as functions of air pressure, applied power, and duration of the action [9]. As follows from experiments [10], the energy distribution of high-speed electrons (ε > 11 eV) is close to a Maxwell distribution with temperature $T_e \sim 1.5$ eV, and the concentration of electrons depend in a complex way on the gas pressure and the duration of the shf pulse, which is explained by the balance of capture and escape of electrons from negative oxygen ions.

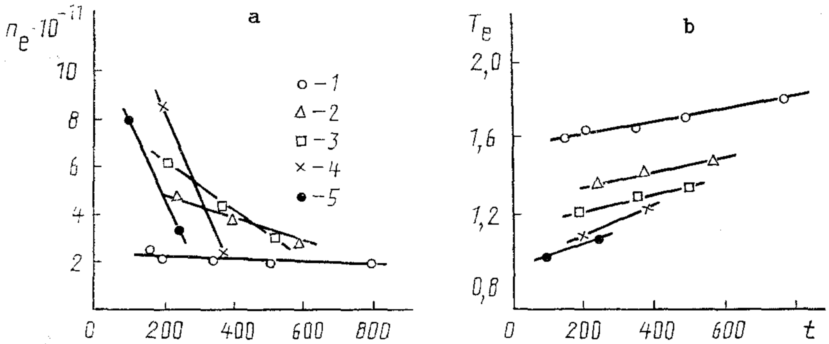


Fig. 4. Time-variation of the concentration (a) and temperature (b) of the electrons in the plasma of a running shf discharge with nitrogen pressure p: 1) 0.5, 2) 1, 3) 2, 4) 3, 5) 5 torr; n_e, cm^{-3}; T_e, eV; t, μsec.

The translational temperature is one of the most important parameters of a nonequilibrium plasma of an shf discharge in molecular gases. At the start of this cycle of research, the mechanism leading to rapid heating was not clear. The first experiments showed that the gas temperature weakly depends on the type of gas (technical grade nitrogen, air), increasing with increasing pressure (Fig. 1) and the energy applied to the discharge (Fig. 2). The experiment on measuring the variation of the temperature T_g with number N_p of shf pulse in the series (Fig 3) was one of the first experiments, after which it was suggested that the energy stored in the vibrational degrees of freedom during the action of the shf pulse influences the heating of the molecular gas, and after the end of the pulse not only cooling of the gas can occur, but also the transfer of energy from vibrational to translational degrees of freedom. This was in fact substantiated in later experiments on the study of the properties of a traveling shf discharge.

Under the condition that the electric field intensity in the focused beam exceeds the threshold, the gas is probed in the focal region of a matched discharge chamber. The plasmoid formed at the focus of the beam does not stay in one place, but moves toward the focusing antenna at speed of $\sim 10^5$ cm/sec. After some time, in the course of which the plasmoid reaches the peripheral boundaries of the threshold region, electromagnetic energy is admitted to the focal region of the beam and gas breakdown takes place again at the focal point. The process takes place periodically during the operating time of the shf energy. For the studied range of shf radiation wavelengths, the concentration of electrons in the plasma of a traveling shf discharge in nitrogen reaches a critical value n_{ec} and increases with increasing gas pressure, while T_e monotonically decreases with increasing pressure [3]. The concentration of electrons in subsequent plasmoids (Fig. 4a) arising during the shf pulse decreases, while T_e (Fig. 4b) increases, and n_e and T_e increase faster in time with increasing p than at low pressures. This is explained by the effect of gas heating and the collision of second generation electrons with vibrationally excited nitrogen molecules, the population of which increases with the operating time of the shf energy [3].

Investigation of the kinetics of the heating of a molecular gas in the region where a traveling shf discharge exists showed [3, 11-13] that there is rapid heating of the gas when the field is pulsed. Under the experimental conditions of [11] (τ_p = 100 μsec, p = 35 torr, S = 10^4 W/cm^2), in the first 10-15 μsec heating occurs with a rate of up to 40 K/μsec. The resulting heating rate in the active phase of the discharge cannot be explained either by elastic heating or by the liberation of energy due to VV- and VT-relaxation. According to [14], the characteristic vibrational relaxation time of the nitrogen molecule under our conditions is ~2 msec, which is two orders of magnitude greater than the value observed in experiment. In [12] it is shown that after the end of the pulse, T_v remains almost constant for ~1 msec, i.e., the vibrational relaxation time under the experimental conditions is at any rate greater than a millisecond. This result is in good agreement with data obtained by different methods on the kinetics of heating air after the end of the shf pulse for a few microseconds with a rate of ~0.1 K/μsec [3]. Calculations show that the heating rate observed in the plasma deionization stage is completely provided by vibrational–translational relaxation.

In order to explain the heating of a molecular gas in the active phase of a discharge at high values of the reduced electric field E/n, a mechanism was proposed in [3, 11-13, 15, 16] that is related to the transfer of energy to translational degrees of freedom with the quenching of the metastable states of nitrogen. To explain the role of electronically excited states of nitrogen, a numerical calculation was performed for the temporal evolution of the concentration of nitrogen molecules in the states $A^3\Sigma_u^+$, $B^3\pi_g$ and the gas temperature. The calculations showed (Fig. 5) that an increase in the reduced electric field leads to a sharp increase in the gas heating rate, and the examined mechanism of energy transfer to translational degrees of freedom

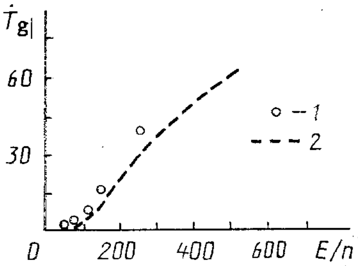


Fig. 5

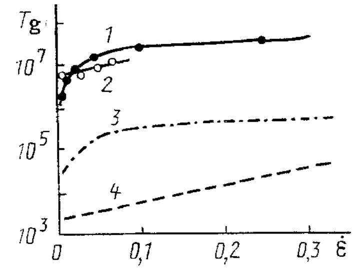


Fig. 6

Fig. 5. Variation of the rate of heating with applied electric field: 1) experiment, 2) calculated. $\dot{T}_g$, K/μsec; E/n, Td.

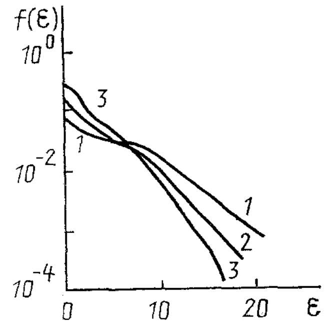
Fig. 6. Variation of the rate of gas heating as a function of energy stored per molecule: 1) experiment; 2) calculated from the equations of balance allowing for the experimentally measured rate of pumping of electronically excited states of nitrogen; 3) calculated allowing only for VV- and VT-relaxation; 4) calculated allowing for only elastic heating). $\dot{T}_g$, K/sec; ε, eV/(mole $\cdot\mu$sec).

of the molecular gas with the extinction of the electronically excited states of the molecules can provide the experimentally observed heating rate.

To confirm this conclusion, a model experiment was done to investigate the kinetics of heating of a molecular gas for a pulsed discharge in air [17]. This discharge is ignited in a tube 1 cm in diameter and 10 cm active region length at a pressure of 0.1-10 torr. A modulator generated pulses of up to 100 μsec in length with a voltage from 1 to 25 kV, and the pulse current could be varied from 0.1 to 20 A. Figure 6 shows curves of the heating rate as functions of the amount of energy stored per molecule. It is clear that the calculated gas heating rate values when allowing only for the transfer of energy to translational degrees of freedom with the quenching of long-lived electronic states of nitrogen are in satisfactory agreement with the experimentally measured values.

Figure 7 shows the electron energy distribution in air (p = I torr, i = 3 A, τ_p = 50 μsec, E/n = 100 Td). Different regions of electron energy discharge are distinct on the stationary distribution (vibrational excitation of nitrogen molecules, excitation of metastable states and ionization). Measurement of the electron energy distribution at different points in time of the plasma deionization showed that T_e rapidly drops to the level of T_v, and not T_g, and remains for a prolonged time at this level, slowly decreasing with the vibrational temperature (see Fig. 8). This behavior of T_e is explained by collisions of second generation electrons with vibrationally excited nitrogen molecules. The obtained results are in good agreement with the behavior of T_e, T_v, and T_g after turning off the field that were calculated from the nonstationary equations of balance.

With a shf breakdown in beams with a small convergence angle, the breakdown wave and along with it the zone of most effective energy liberation (due to scattering of the applied shf radiation) rapidly departs from the focal point toward the energy flux, which does not make it possible to rigorously fix the position of the discharge in space. There are various means of localizing a shf discharge in a fixed location of free space. In this cycle of research, the regime of programmed action was used for this aim, consisting in the fact that gas breakdown is accomplished by an intense short pulse, in the course of which the discharge is not able to leave the focal region, while the discharge is maintained by a second low-amplitude pulse that is not independently able to affect the breakdown of the gas, but if breakdown is accomplished, then the shf power of the pump pulse is sufficient to maintain the discharge for an extended time. By varying the amplitude of the second pulse, it is possible to control a localized shf discharge over a wide range of parameters (the size, rate of propagation of the discharge, the concentration and temperature of the electrons, and the heating of the gas) [3]. To clarify the role of electronically excited nitrogen molecules, measurements of the gas heating rate were conducted in the plasma of a localized shf discharge (see Fig. 5). The experimental data are in satisfactory agreement with the calculated curve. With increasing delay of the pump pulse relative to the trailing edge of the first pulse, the rate of gas heating in a localized discharge is decreased from 15 to 4 K/μsec for t_{del} = 1 msec, while the vibrational temperature remains constant for all delays, i.e., the energy stored in the vibrational reservoir in heating the gas does not vary here.



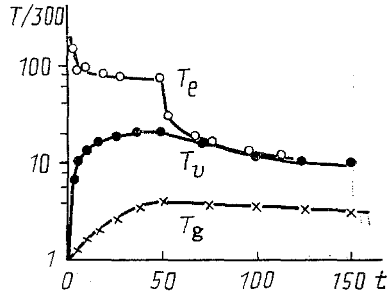


Fig. 7

Fig. 8

Fig. 7. Electron energy distribution in the plasma of a pulsed discharge in air (p = 1 torr, i = 3 A, E/n = 100 Td) at different points in time t during the pulse: 1) 5, 2) 15, 3) 30 μsec. f(ε), $eV^{-3/2}$; ε, eV.

Fig. 8. Kinetics of the temperatures (electron, vibrational, and gas) in the active phase of the pulsed discharge in air and at the plasma deionization stage. T, K.

Studies using shadow photography of the dynamics of the formation and decay of the pocket (zone with decreased gas density) in the region where the localized discharge exists showed that the pocket is a region with distinct boundaries. Inside the pocket no sharp gradients in the concentration of gas molecules is observed, the formation time of a hole in the density decreases with increasing air pressure, while the rate of propagation of the boundaries of the pocket is less than the speed of sound in air [3].

The powers of the shf generators used in the experiments was not sufficient to independently breakdown the gas for P > 100 torr. It is known, however, that if the discharge is stimulated by one or another means, it can be maintained for a long time under conditions of subthreshold fields (for an unperturbed gas). By initiating a discharge by a spark, a homogeneously emitting plasma formation was produced at atmospheric pressure in air in the regime of a single-pulse of shf radiation with a duration of 1 msec. At the start of the pulse, a brightly emitting channel is formed, which after some time is transformed into a homogeneously glowing plasma bead and later expands uniformly in all directions with a speed of $\sim 10^3$ cm/sec [3]. The gas is heated in the vicinity of such a discharge to high temperatures on the order of 6000 K. After the end of the shf pulse, this plasma formation continues to glow for several milliseconds in the visible spectral region and for ~100 msec in the infrared region [18]. This circumstance is also exhibited in the thermal character of the ionization, and the discharge appears as a quasi-equilibrium plasma formation. Calculation of the ionization temperature from the Saha equation using the measured values of $n_e(t)$ is in good agreement with the temperature of the plasma determined by spectral techniques [3]. With increasing flux density of the applied energy, the concentration of electrons reached toward the end of the pulse increases [19], i.e., by changing the amount of energy applied to the discharge it is possible to control the parameters of the plasma of the discharge under study. The distributions of $T_g(z)$ and $n_e(z)$ along the axis of the discharge chamber are close to columnar with rather sharp boundaries, which is typical for the mechanism of the propagation of a shf discharge in the slow burning regime, while in the latter stages of deionization of the plasma, convective gas flow forms mushroom-shaped structures [19]. At low air pressures, strong vibrational-translation nonequilibrium $T_v/T_g \sim 10$ is formed, which disappears when P > 300 torr [19].

The question arose of whether it is possible to maintain a shf discharge stationary in a fixed place in free space in a focused beam. Experiments have shown that when using long pulses ($\tau_p > 100$ μsec) for $S \sim 10^3$ W/cm² the discharge is a more or less uniformly glowing plasma formation, stretched in the direction of the focusing antenna [3]. The speed of the leading edge of the discharge is $\sim 5 \cdot 10^2$ cm/sec. With a decrease in the shf energy flux density ($S < 10^3$ W/cm²) a discharge is obtained in the form of an isolated plasma formation with a size on the order of a centimeter, propagating in free space toward the focusing antenna in the slow burning regime. The propagation speed of the discharge is controlled by changing the inserted energy flux density, during which the minimum speed of propagation of the discharge of ~5 cm/sec with $S \approx 200$ W/cm² was observed [20], while the experimentally obtained variation of the speed v with radiant intensity S was approximated well by the expression $v = 5.2(S - 200)^{1/2}$ (v, cm/sec; S, W/cm²).

For horizontal application of the shf energy, there are two distinct directions: horizontal direction of propagation of the discharge and vertical direction of the most effective removal of heat from the discharge due to convection currents. The discharge as a whole begins to move toward the flux of the inserted energy and simultaneously, floats upward, leaving the threshold region, where it can be maintained. In order to completely establish the discharge and maintain it in a fixed location of free space for a prolonged time, i.e., to establish a stationary glow discharge in a focused beam, we proposed and experimentally realized a means of vertical conduction of shf energy into the discharge from below [20] similar to an experiment in the laser field [21]. In this case, the discharge moving down toward the applied energy reaches the edge of the threshold region where it should be extinguished. However, due to the convective removal of heat upward, the region above the discharge is strongly heated, the gas density there is lower than the density of the undisturbed gas in front of the discharge. At the same time, the electric field intensity in the focal region due to focusing of the beam is higher than at the boundary of the threshold region, i.e., in the focal region, favorable conditions for maintaining the discharge are created. With the aid of this method a shf discharge was realized in a focused beam, burning in a fixed location in free space for ~10 sec. Different regimes of shf discharge were experimentally observed as a function of the level of the applied energy flux density: vertical motion downward with different rates, localization in the focus of the beam, or motion of a plasma ball 10-30 cm in diameter with a speed of $\sim 10^2$ cm/sec vertically upward [3].

NOTATION

R, radius of the discharge chamber; λ, wavelength of the shf radiation; E_0, electric field amplitude; S, energy flux density; n_e, electron concentration; T_e, electron temperature; T_g, gas temperature; T_v, vibrational temperatures of the lower levels of the ground state $X^1\Sigma_g{}^+$ of nitrogen; v, speed of the discharge front; n, density of the gas; Δn, change in the density of the gas; τ_p, width of the shf pulse; f_{rep}, pulse repetition frequency; ε, electron energy; N_p, number of the shf pulse in the series; n_{ec}, critical concentration of electrons; p, gas pressure; $\dot{T}_g$, rate of heating of the gas; E/n, reduced electric field; i, discharge current; t_d, time interval between the probe pulse and the pump pulse.

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PHYSICAL INVESTIGATIONS OF A HIGH-CURRENT VACUUM ARC DISCHARGE

G. A. Dyuzhev and S. M. Shkol'nik UDC 537.5

The experimental data on the processes at the electrodes and in the interelectrode gap of a high-current vacuum arc discharge that were accumulated by different researchers are systematized. A critical analysis is conducted on the essentially static discharge models proposed earlier. A dynamic model of a two-component plasma is described and substantiated, which, in the opinion of the authors, better explains the current results of experimental studies into this type of electric discharge than the static models.

In distinction from many other types of electric discharge, such as, for example, an arc with a glowing cathode, glow-discharge, HF-discharge, etc., a high-current vacuum arc discharge (HCVAD) until recently was little studied as a physical object. Interest in HCVAD is due to the wide potentials of its application in technology (switching devices, spark gaps, etc.) [1]. The history of the research encompasses more than one decade, but interest in HCVAD particularly rose in the last decade, when it became quite obvious that far from all technical problems can (and practically) be solved using solid-state switching devices.

Usually, physical studies were conducted with plane-parallel geometry electrodes (the ends of cylinders of diameter D of a few centimeters, interelectrode gap of $H \sim 1$ cm, $D/H >> 1$). The range of currents is from a few hundred to several thousand amperes. The main efforts were concentrated on studying processes at the electrodes. In addition to the traditional interest in cathode processes for a vacuum arc when studying HCVAD, a good deal of attention is devoted to anode phenomena, since an increase in the discharge current above some so-called critical current leads to contraction of the discharge in the anode region and the formation of an anode spot. The spot causes strong erosion and a definite prolongation of the recovery of the electrical stability after extinction of the arc. Clarification of the conditions and the causes of the formation of the anode spot is one of the main directions of research into HCVAD. Integrated characteristics were investigated for along time, volt-ampere characteristics have been measured, streak photography of the discharge has been done, the thermal flux to the electrodes, the temperature, and the rate of erosion of the electrodes were determined, etc. [2-5]. Beginning with the middle of the seventies, papers began to be published on the measurement of parameters of the plasma in the interelectrode gap [6-9].

Several different models of HCVAD, and correspondingly explanations of the causes of the formation of the anode spot, were proposed as the basis of the studies that were performed [10]. These models combine the idea that the interelectrode gap is filled with a column of homogeneous plasma (the concentration of which is proportional to the discharge current), based on a set of spots scattered chaotically over the cathode. In the diffuse mode (without the anode spot) the anode is treated as a passive element, almost completely absorbing the flux of plasma incident on the anode (Fig. 1 [11]). Thus, all models are essentially static. The distinction of the models appears only when examining the question of the character of the ion motion: a) the directional speed of the plasma from cathode to anode is much greater than that of the thermal motion [11]; b) the directional speed is less than (or comparable) to the thermal speed of the ions [12]. (Note that in the latter case, it is still unclear what the mechanism is for the loss of momentum by the plasma jets, emanating at high speed from the individual cathode spots.)

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