STABILITY OF A HIGH-FREQUENCY GLOW DISCHARGE IN THE NORMAL COMBUSTION REGIME

G. G. Gladush and A. A. Samokhin UDC 537.523.74

A high frequency glow discharge in its high current form differs from a dc discharge in that there is a significant decrease in the role of the pre-anode region in plasma generation [1], thus leading to greater stability [2]. In a dc discharge the pre-anode current–voltage characteristic (CVC) is falling [3], which causes electrodynamic instability of the plasma column and leads to its contraction over times much shorter than the thermal times [4]. It is characteristic that conductivity in the volume of a dc discharge at moderate pressures is caused by drift of ions from the pre-anode region. In an hf discharge the plasma distribution is symmetric about the midpoint of the interelectrode gap and the space charge zones near the electrodes are separated from the volume by narrow zones with high conductivity. Under such conditions, together with volume ionization processes a noticeable contribution to maintenance of conductivity can be produced by ambipolar diffusion and plasma drift due to disruption of quasineutrality [5, 6]. In order to study the stability of an hf discharge plasma column it is of interest to find the current–voltage characteristic of this part of the discharge under conditions of high longitudinal inhomogeneity and low values of E/p. In connection with the experimentally observed weak current form of the discharge [1, 2], which is characterized by a unique value of the normal current density and lacks a proper theoretical explanation, there has been increased interest in the properties of the hf discharge which are produced by phenomena in the pre-electrode regions. In particular, it is necessary to theoretically confirm the similar properties of the dc discharge and the hf discharge in the normal current density regime. The present study will present results of a numerical calculation of an hf discharge in nitrogen with consideration of space charge effects within the framework of a two-dimensional model and calculated the CVC of a plasma column with the diffusion-drift mechanism for maintenance of conductivity.

Formulation of the Problem. We will numerically study a discharge occurring in nitrogen at a pressure p = 666.6 Pa between two planar electrodes connected in a circuit with resistance R = 250 kΩ and ac voltage source

$$\mathscr{E} = \mathscr{E}_m \sin \omega t, \ \mathscr{E}_m = 700 \text{ B}, \ \omega = 2\pi \cdot 10^6 \text{ sec}^{-1}.$$

Interelectrode distance L = 1 cm, with transverse chamber dimensions of L and 2L, and the discharge is assumed homogeneous along the shorter dimension (z-axis). Direct ionization, recombination, electron and ion drift in the self-consistent electric field, and γ-processes at the cathode were considered. For the electron n_e and ion n_i concentrations we have the equations [7]

$$\frac{\partial n_e}{\partial t} + \nabla \mathbf{j}_e = \alpha j_e - \beta n_e n_i, \ \mathbf{j}_e = \mu_e n_e \nabla \varphi; \tag{1}$$

$$\frac{\partial n_i}{\partial t} + \nabla \mathbf{j}_i = \alpha j_e - \beta n_e n_i, \ \mathbf{j}_i = -\mu_i n_i \nabla \varphi, \tag{2}$$

where α is the first Townsend coefficient for nitrogen, $\beta \cdot 10^{-7}$ cm³/sec is the dissociative recombination coefficient; $\mu_e = 0.88 \cdot 10^5$ cm²/(V·sec) and $\mu_i = 290$ cm²/(V·sec) are the electron and ion mobility coefficients. System (1), (2) is supplemented by boundary conditions at cathode and anode:

$$(\mathbf{j}_e + \gamma \mathbf{j}_i)|_K = 0, \ \mathbf{j}_i|_A = 0 \tag{3}$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 16-26, November-December, 1986. Original article submitted September 9, 1985.

0021-8944/86/2706-0803$12.50

(where γ is the secondary emission coefficient for electrons from the cathode). The potential distribution φ is found from the Poisson equation

$$\Delta\varphi = -\varepsilon_0(n_i - n_e), \tag{4}$$

solved simultaneously with the boundary conditions at the electrodes (x = 0, x = L) and lateral boundaries of the chamber (y = L, y = –L)

$$\varphi(0, y) = 0, \ \varphi(L, y) = U, \tag{5}$$

$$\int_{-L}^{L} \frac{\partial\varphi}{\partial x}\Big|_{x=L} L dy = \varepsilon_0 Q, \ \frac{\partial\varphi}{\partial y}\Big|_{y=\pm L} = 0.$$

Here $\varepsilon_0 = 1.81\cdot10^{-6}$ V·cm, U is the voltage across the discharge, Q is the quantity of excess ions accumulated at the upper electrode (x = L) as a result of unbalance between the current from the plasma and in the extenal circuit. The value of Q satisfies the ordinary differential equation

$$\frac{dQ}{dt} = \frac{\mathscr{E} - U}{R} + \int_{-L}^{L} (j_i - j_e)\,|_{x=L}\, L dy. \tag{6}$$

To initiate the discharge, at the initial moment within the chamber volume there is situated a quasineutral plasma with density of ~10^8 cm^{-3}, monotonically decreasing to zero at the lateral boundaries of the chamber; the voltage on the capacitor at the initial moment is assumed equal to zero:

$$n_e = n_i = 10^8 \sin|\pi y/2L|, \text{ cm}^{-3}, \ Q|_{t=0} = 0. \tag{7}$$

Pre-Electrode Models of Low and High Current Forms of the hf Discharge. Before presenting the solution of Eqs. (1)-(7), we will consider the relationship between the displacement current $j_d = \omega E/4\pi$ and the ohmic current $j_o = e\mu_i n_i E$ in the cathode layer of the hf glow discharge. In the zeroth approximation in the parameter j_o/j_d [8] established that the normal regime of the low current (capacitive) discharge can be achieved under the condition

$$\frac{\ln(1+\gamma^{-1})}{\mu_i pAB}\frac{\omega}{p} \gg 0{,}5. \tag{8}$$

We will perform a similar study for the opposite limiting caes $j_o/j_d \gg 1$, relying on the cathode potential shift theory of Engel and Shteenbek. Let us assume that the characteristics of the cathode layer in the ac discharge occurring in the normal current density regime differ only slightly from the parameters of a dc discharge. Then for the standard approximation of the ionization coefficient $\alpha = Ap\exp(-Bp/E)$ we obtain

$$\frac{j_d}{j_o} = 0{,}22\frac{\ln(1+\gamma^{-1})}{\mu_i pAB}\frac{\omega}{p}.$$

Consequently, the normal regime of the high current (ohmic) discharge can be realized if

$$\frac{\ln(1+\gamma^{-1})}{\mu_i pAB}\frac{\omega}{p} \ll 5. \tag{9}$$

It follows from the above that depending on the value of ω/p there are three types of pre-electrode CVC's. For low frequencies, at which Eq. (8) is not satisfied, only one normal current density exists, corresponding to the ohmic discharge, while in the intermediate frequency range of Eqs. (8), (9) there are two values, one of which corresponds to the weak current form, and the other to the ohmic discharge. Finally, for high enough frequencies, at which Eq. (9) is not satisfied, there is one normal current density corresponding to the weak current regime. Only in the intermediate frequency range of Eqs. (8), (9) does the transition from the weak current stage to the high current one occur discontinuously with an abrupt change in current density at the electrode.

It should be stressed that simultaneous satisfaction of the two severe inequalities (8) and (9) is difficult. Therefore the range of intermediate frequencies at which two normal current densities can be realized, corrsponding to capacitive and ohmic discharges, is very narrow or completely absent. This can be confirmed by comparison of the values of the normal current density in a capacitive discharge $j_0 = Bp\omega/8\pi\psi_1$ ($\psi_1 = 0.57$) [8] and in a dc discharge $j_n = \mu_i pAB^2p^2/6\pi\ln(1 + \gamma^{-1})$. It follows from Eqs. (8), (9) that in the intermediate frequency range

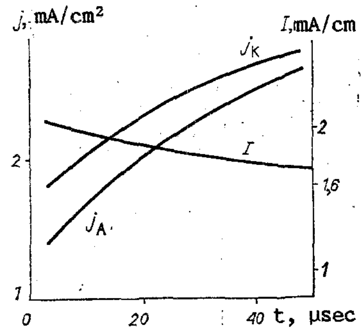

Fig. 1

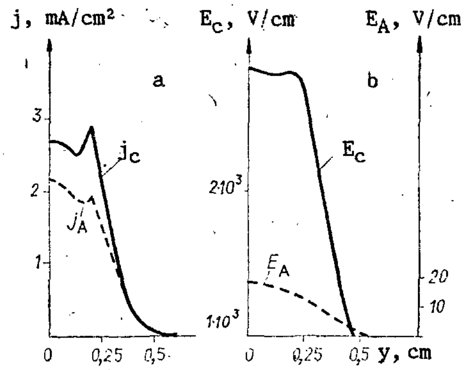

Fig. 2

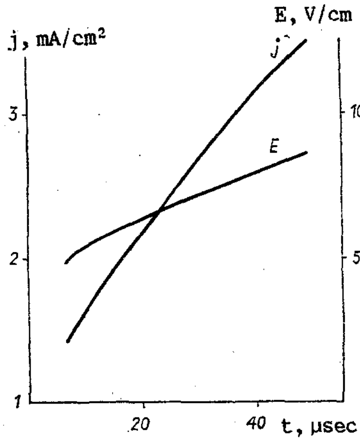

Fig. 3

$$0{,}6j_n \ll j_0 \ll 6j_n.$$

The left side of this relationship contradicts the theoretical concept of increase in ohmic component and decrease in capacitive component with increase in current [8]. In practice also the current density of a high current discharge is less than an order of magnitude greater than that of a weak current discharge, so that it is difficult to identify the given j_n and j_0 values with the current density of these two forms of discharge. It is possible that agreement could be reached by refinement of the pre-electrode models and expansion of the intermediate frequency range. We will note that the modification to the theory would have to be significant, since in practice no limiting value of ω/p is observed above which the normal combustion regime is realized only in the weak current (capacitive) form. Another escape from the difficulties created may be that one of the two forms of the discharge in the normal combustion regime cannot be reduced solely to pre-electrode phenomena, but is related to volume processes. An indication of the role of volume processes is offered by the critical dependence on value of the interlectrode gap L [1].

The values of ω and p chosen for the numerical experiment are such that inequality (8) is violated and the weak current form of the discharge is not realized in the normal combustion regime. Here we study an ohmic discharge, while the conditions chosen are such that formation of current spots on the electrodes can be expected [4].

Calculation Results. After connecting the capacitor to the circuit, after about three periods a quasisteady state arc combustion regime is reached — the plasma parameters change from period to period only weakly. With passage of time (over 50 μsec) the amplitude of the current density at the cathode in the center of the electrode j_C monotonically increases from ~1.8 to 2.7 mA/cm², with a corresponding increase at the anode from 1.3 to ~2.6 mA/cm² (Fig. 1: current densities on axis discharge at anode j_C and anode j_A and total current I vs time). In accordance with the estimate made the displacement currents are less than the ohmic ones and current spots develop on the electrode [Fig. 2: current (a) and field intensity (b) distributions over cathode and anode surface at time of maximum total current, t = 49.86 μsec]. The current distribution over the cathode surface is similar to that observed in a dc discharge [4]. However the value of j_C reached at time t = 50 μsec in the hf discharge exceeds the current density in a dc discharge of ~2.4 mA/cm². Moreover, it follows from the time dependence (Fig. 1) that at following times the current density on the electrode in an ac discharge can significantly exceed the normal current density in a steady state discharge.

In the quasisteady state stage a decrease in total current and continuous growth in current density and field intensity in the volume of the quasineutral plasma occur (Fig. 3: current density j and field intensity E at center of discharge vs time). The current density increases from 1.4 to 3.5 mA/cm², while the parameter E/p increases from 0.075 to 0.13 V/(cm·Pa). Under similar conditions in a dc discharge the current in the volume increases to 4 mA/cm², however the field intensity in the volume is markedly higher — E/p = 0.23 V/(cm·Pa) [4]. This difference is related to the important role of the anode region of a dc discharge in generation of ions and maintenance of conductivity in the volume. As in a dc discharge, so in the case under study narrowing of the current channel in the volume occurs: with passage of time the section of the conductive channel in the volume becomes less than at the cathode [Fig. 4: ion density n_i (10^9 cm^{-3}), t = 49.86 μsec].

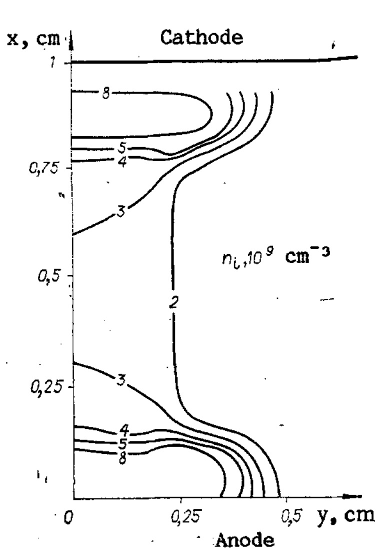

Fig. 4

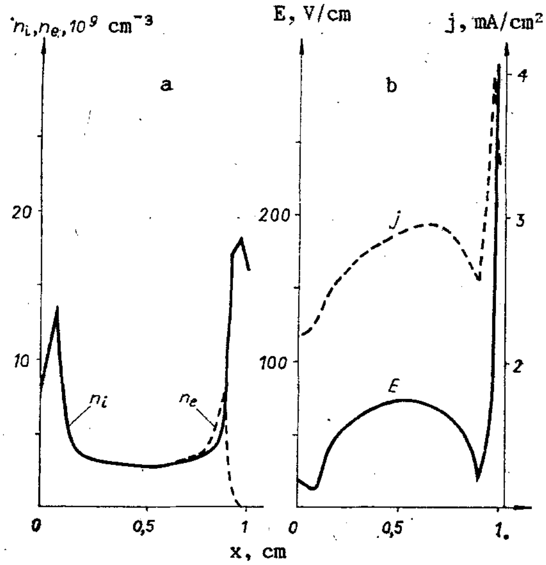

Fig. 5

In the quasisteady state regime the plasma distribution on the discharge axis is symmetric about the midpoint, the plasma density is at a minimum in the center of the chamber and increases monotonically in the direction toward the electrodes from $3 \cdot 10^9$ to $15 \cdot 10^9$ cm^{-3}. Plasma formation about the electrodes is related to ionization processes in the cathode layer, with the role of the anode in ion generation being negligibly small. The mechanism of conductivity maintenance in the volume of the quasineutral plasma deserves special attention. The value of E/p = 0.13 V/(cm·Pa) established is insufficient for ionization maintenance of conductivity. Nor is an ionization mechanism of plasma formation in the volume compatible with the character of the plasma and electric field distributions [Fig. 5: ion and electron distributions (a), current density and field intensity on discharge axis (b), t = 49.86 μsec]: at the electrodes where the plasma density is maximum, the field intensity is at a minimum, while conversely in the center of the chamber where the plasma density is minimum, the intensity is maximum. The analysis to be performed below will show that conductivity within the volume of an hf discharge in the given case is maintained due to ion drift from the electrode regions.

We will note the properties of the discharge observed in the calculation which are characteristic of the high current form of an hf discharge. First, we have the inhomogeneous distribution of field intensity on the discharge axis, correlating with the distribution of luminosity. Second, the calculated current density at the spot on the electrodes, although less than in the volume, is still not constant as in a steady state discharge with compression in the volume [4], but increases together with the current density in the volume. This can be compared to the property of a high current discharge of having identical normal identical normal current density on the electrodes and within the volume [2].

Quasineutral hf discharge column. In order to compare the possible mechanisms for maintenance of conductivity in the volume of the hf discharge, we will derive equations averaged over a period for motion of the quasineutral plasma in a one-dimensional model. We assume that the plasma concentration varies little over the period:

$$n = \frac{1}{T}\int_0^T n_e(t+\tau)\,d\tau = \frac{1}{T}\int_0^T n_i(1+\tau)\,d\tau,$$

$$n \gg \langle (n-n_e)^2\rangle^{1/2}, \quad n \gg \langle (n-n_i)^2\rangle^{1/2}.$$

Here and below the angle brackets <...> denote averaging over a period of the hf field. The field intensity oscillates and its mean value is close to zero: $\langle E\rangle \ll \langle E^2\rangle^{1/2}$. We note that strict equality $\langle E\rangle = 0$ is not assumed. Dividing Eq. (1) by μ_e and Eq. (2) by μ_i and adding them, after averaging we obtain

$$\frac{\partial n}{\partial t} + \mu_i \frac{\partial}{\partial x}\langle E(n_i - n_e)\rangle = \langle \nu_i\rangle n - \beta n^2. \qquad (10)$$

In accordance with the original formulation of the problem processes of ambipolar diffusion and plasma drift due to dependence of the mobilities μ_e, μ_i on field intensity [9] remains unconsidered here. Detailed analysis reveals that plasma drift due to dependence of mobility on field under hf discharge conditions is always much less than drift due to disruption of the strict equality $n_e = n_i$. Plasma drift due to disruption of quasineutrality is described by the second term on the left side of Eq. (10). With consideration of the Poisson equation it follows from Eq. (10) that

$$\frac{\partial n}{\partial t} + \frac{\mu_i}{2\varepsilon_0}\langle E^2\rangle = \langle \nu_i\rangle n - \beta n^2. \tag{11}$$

It can easily be seen that the term describing plasma drift is nothing else but motion under the action of the gradient in the hf pressure.

From the condition of conservation of electron flux one can find the relationship between the plasma distribution n and the mean square intensity $\langle E^2\rangle$:

$$\langle E^2\rangle = \langle j_e^2\rangle/\mu_e^2 n^2. \tag{12}$$

In this relationship $\langle j_e^2\rangle$ does not depend on the spatial coordinate z and is assumed to be a known function of time, its value being found from the known applied voltage $U_{eff} = \sqrt{\langle U^2\rangle}$ and the resistance of the interelectrode gap:

$$\langle j_e^2\rangle^{1/2} = U_{\text{eff}}\left(\frac{1}{\mu_e}\int\limits_0^L \frac{dx}{n}\right)^{-1}$$

Equations (11), (12), supplemented by the symmetry condition in the center of the chamber $n'_x = 0$ and the asymptotic boundary condition near the electrodes $n = \infty$, describe the quasineutral hf discharge column. Neglecting recombination and ionization, a self-similar solution of Eqs. (11), (12) can be found, describing growth in conductivity in the volume due to drift of ions from the electrode regions. Let $\langle j_e^2\rangle^{1/2} \sim t^a$, then

$$\begin{gathered} n = n_0 N(t/t_{gp})^b,\ b = (2a+1)/3, \\ \frac{(N+0{,}5)\sqrt{N-1}}{N^{3/2}} = \frac{|x-0{,}5L|}{0{,}5L_{pl}}, \\ t_{gp} = \frac{3(2a+1)}{8}\frac{\varepsilon_0 n_0 L_{pl}^2}{4\mu_i E_0^2}. \end{gathered} \tag{13}$$

Here n_0 and E_0 are the plasma density and mean square field intensity at the center of the interelectrode gap at time $t = t_{gp}$; $L_{p\ell}$ is the length of the plasma column, the function N becomes infinite near the electrodes and is normalized by the condition N = 1 in the center of the gap. For a linear increase in current density a = 1, and taking $n_0 = 3\cdot 10^9$ cm^{-3}, $L_{p\ell} = 5$ cm, and $E_0 = 0.45$ V/cm, we find $t_{gp} = 300$ µsec. This value for the characteristic time of increase in conductivity in the chamber volume is three tims greater than follows from calculations. The divergence is related to deviation from a self-similar regime and the two-dimensional nature of the problem. According to the analysis performed ion drift is an efficient mechanism for formation of dependent conductivity in a positive hf discharge arc column.

CVC of Quasineutral Column with Drift Mechanism of Conductivity Maintenance. Since compression of the current channel in the volume of the quasineutral plasma was observed in the calculations, it is of interest to find the CVC of this portion of the discharge on the basis of Eqs. (11), (12).

In this section we will not consider ambipolar plasma diffusion, assuming the thickness of the diffusion region located directly about the electrodes to be much less than the length of the plasma column, i.e., $2L_D \ll L_{p\ell}$.

Transforming to dimensionless variables $\xi = |x - 0.5L|/0.5L_{p\ell}$ and $w = \langle E^2\rangle/E_0^2 = (n_0/n)^2$, where E_0 and n_0 are the mean square field intensity and plasma density at the center of the interelectrode gap, we obtain

$$w''_{\xi\xi} + \lambda^2/w = 0; \tag{14}$$

$$w(0) = 1,\ w'_\xi(0) = 0,\ w(1) = \frac{\langle j_e^2\rangle}{(\mu_e E_0 n_*)^2}; \tag{15}$$

$$\lambda = \sqrt{\frac{\beta\varepsilon_0}{2\mu_i\mu_e^2}}\frac{L_{pl}\langle j_e^2\rangle^{1/2}}{E_0^2}, \tag{16}$$

where n_* is the plasma density on the boundary of the plasma column and the electrode layer. Under the conditions considered the state of the electrode layer experiences a weak disturbing action from the quasineutral volume. The parameter involved is the ratio of the ion fluxes from the electrode layer into the quasineutral volume and onto the electrode surface, averaged over an oscillation period. The ion flux into the volume can be evaluated from the rate of recombination losses in half the interelectrode gap:

$$0{,}5\int_0^L \beta n^2 dx \simeq 0{,}5\beta n_{\text{char}}^2 L_{pl},$$

for $n_{\text{char}} = 5\cdot 10^9$ cm^{-3}, $L_{p\ell} = 1$ cm this value is equal to $3\cdot 10^{12}$ cm$^{-2}\cdot$sec^{-1} or 10^{-3} mA/cm^2, which is much less than the ion current density of 1 mA/cm^2 on the electrode. Thus, the assumption of independence of the electrode layer from the quasineutral column is justified, and in this case the plasma distribution in the electrode layer depends only on the value of the current, i.e., on $\langle j_e^2\rangle^{1/2}$. It is natural to assume that the limiting value of the plasma density n_* is also caused only by the current density in a first approximation.

The solution of Eq. (14) can be expressed in terms of an error function

$$\operatorname{erf} z = 2/\sqrt{\pi}\int_0^z \exp(-z'^2)\,dz'.$$

With consideration of Eqs. (15), (16) we have

$$\operatorname{erf}\sqrt{\ln w^{-1}} = \sqrt{\frac{2}{\pi}}\,\lambda\xi; \tag{17}$$

$$\operatorname{erf}\sqrt{2\ln\left(\frac{E_0}{E_*}\right)} = \sqrt{\frac{2}{\pi}}\,\lambda, \tag{18}$$

where $E_* = \langle j_e^2\rangle^{1/2}/\mu_e n_*$ is the mean square intensity of the electric field on the boundary of the electrode layer. For a known relationship between n_* and $\langle j_e^2\rangle^{1/2}$ Eq. (18) defines the dependence of E_0 on current density. Differentiating Eq. (18) with respect to $j_{\text{eff}} = e\langle j_e^2\rangle^{1/2}$, we obtain

$$\hat{E}_0 = (1 + Q - \hat{n}_*)/(1 + 2Q); \tag{19}$$

$$Q = \lambda\left(\frac{E_0}{E_*}\right)^2\sqrt{\ln\left(\frac{E_0}{E_*}\right)}. \tag{20}$$

Here and below $\wedge$ indicates the double logarithmic derivative with respect to current, for example, $\hat{E}_0 = d\ln E_0/d\ln j_{\text{eff}}$. The effective voltage on the plasma column

$$U_{\text{eff}} = E_0 L_{pl}\int_0^1 W^{1/2}d\xi = \sqrt{\frac{\pi}{3}}\frac{E_0 L_{pl}}{\lambda}\operatorname{erf}\sqrt{3\ln(E_0/E_*)}. \tag{21}$$

Hence, differentiating with respect to current, we find

$$\hat{U}_{\text{eff}} = \frac{3-2\delta^{-1}}{1-2Q}\left(\frac{2+Q-\delta^{-1}}{3-2\delta^{-1}} - \hat{n}_*\right); \tag{22}$$

$$U_{\text{eff}} = \delta L_{pl}E_0,\ \delta = \sqrt{\frac{2}{3}}\frac{E_0}{E_*}\frac{\operatorname{erf}\sqrt{3\ln\left(\frac{E_0}{E_*}\right)}}{\operatorname{erf}\sqrt{2\ln\left(\frac{E_0}{E_*}\right)}}. \tag{23}$$

It follows from Eq. (22) that the CVC of a quasineutral column with conductivity maintained by plasma drift from the electrodes is an increasing function, if

$$\hat{n}_* < \hat{n}_{*0} = \frac{2+Q-\delta^{-1}}{3-2\delta^{-1}}. \tag{24}$$

The quantities λ, δ, and $\hat{n}_{*0}$ are, according to Eqs. (18), (23), (24), functions of the parameter E_0/E_*, which characterizes the degree of inhomogeneity of the plasma. With increase in plasma inhomogeneity λ, δ, and $\hat{n}_{*0}$ increase monotonically (Fig. 6: $\hat{n}_{*0}$, δ, and λ vs degree of plasma column inhomogeneity).

We will represent the CVC in parametric form. Using Eqs. (16), (23) for a nitrogen plasma [$\beta = 2\cdot 10^{-7}$ cm^3/sec, $\mu_e P = 5.9\cdot 10^7$ cm$^2\cdot$Pa/(V$\cdot$sec), $\mu_i P = 1.9\cdot 10^5$ cm$^2\cdot$Pa/(V$\cdot$sec)] we

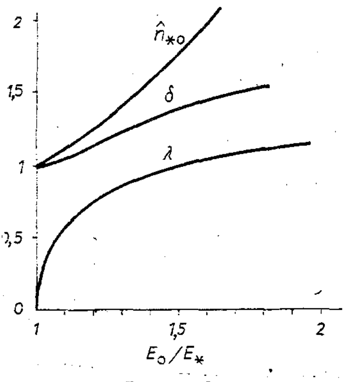

Fig. 6

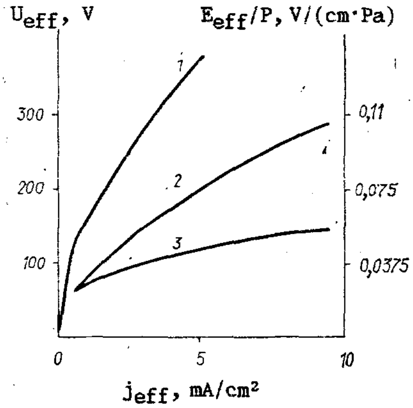

Fig. 7

obtain

$$\frac{\tilde{n}_*^2}{j_{eff}} = \frac{0,07\sqrt{p}}{L_{pl}}\left(\frac{E_0}{E_*}\right)^2\lambda, \; U_{eff} = 0,1\delta L_{pl} p j_{eff}/\tilde{n}_*. \tag{25}$$

Depending on the value of $\hat{n}_* = d\ln n_*/d\ln j_{eff}$ three cases exist:

1) $\hat{n}_* < 0.5$. The CVC is increasing everywhere, the degree of inhomogeneity in the plasma distribution is maximal in the low current range and decreases monotonically with increase in current density:

$$\lim_{j_{eff}\to 0}(E_0/E_*) = \infty, \; \lim_{j_{eff}\to 0}(E_0/E_*) = 1;$$

2) $0.5 < \hat{n}_* < 1$. The CVC is increasing everywhere, the degree of inhomogeneity in the plasma distribution increases monotonically with increase in current:

$$\lim_{j_{eff}\to 0}(E_0/E_*) = \infty, \; \lim_{j_{eff}\to 0}(E_0/E_*) = 1;$$

3) $\hat{n}_* > 1$. The CVC in the low current range is decreasing, and increasing in the high current range. The degree of plasma inhomogeneity corresponding to the voltage minimum in the CVC can be found from the condition $\hat{n}_* = \hat{n}_{*0}$ (Fig. 6). With increase in current the plasma inhomogeneity increases monotonically:

$$\lim_{j_{eff}\to\infty}(E_0/E_*) = \infty.$$

Thus, for a quasineutral column with drift mechanism for formation of conductivity the possibility of existence of a normal current density and the character of the plasma distribution along the field are determined by the form of the functional dependence of the plasma density on the column boundary upon current density. One may, for example, consider the plasma density in the electrode layer of the hf discharge to be proportional to the ion concentration in the cathode potential step, described by the theory of Engel and Shteenbek. Then $n_* \sim j_{eff}$ and the plasma column proves stable. In order to ascribe the experimentally observed quasisteady state compression of the plasma column to instability, it is necessary to assume a quite strong dependence of plasma density n_* on current density. This could be related, in particular, to an active role being played by the anode region in plasma generation. Nor can it be excluded that in the calculations a process of transition into a steady state is being observed. Unfortunately, limited availability of computer time prohibited an unambiguous answer to this question.

CVC of Quasineutral Column with Consideration of Ambipolar Plasma Diffusion. A real quasineutral plasma column is composed of a segment with diffusion mechanism for maintenance of conductivity, located close to the electrode, and a segment with drift mechanism, located at the center. In the majority of cases the thickness of the diffusion layer is very small, and its conductivity is high, so that the contribution of this region to the overall voltage drop is negligibly small. Nevertheless, the diffusion region is of significance, since plasma diffusion affects the character of the dependence of plasma density on the boundary of the drift segment upon current density, and thus, upon the column CVC. Neglecting ionization processes and considering ambipolar diffusion, on the basis of Eqs. (11), (12) we obtain

$$\frac{d}{dx}\left\{\frac{\mu_i \langle j_e^2\rangle^{1/2}}{2\varepsilon_0\mu_e^2}\frac{d}{dx}\left(\frac{1}{n^2}\right)-D_a\frac{dn}{dx}\right\}+\beta n^2=0. \tag{26}$$

If the diffusion coefficient is independent of the electric field intensity, the limiting density value which separates the segments with diffusion and drift mechanisms of conduction formation is equal to

$$n_* = \left\{\frac{\mu_i}{2\varepsilon_0 D_a}\left(\frac{j_{\text{eff}}}{e\mu_e}\right)^2\right\}^{1/3} = \frac{1{,}5\cdot 10^7}{T_e^{1/3}}(pj_{\text{eff}})^{2/3}. \tag{27}$$

The right side of Eq. (27) was calculated for a nitrogen plasma; T_e is the characteristic electron energy in eV. It is necessary to require continuity of n and the derivative n'_x on the boundary of the two regions. For simplicity we will assume that for the diffusion region on the boundary the condition $n = n_*$, $n'_* = 0$ is satisfied to sufficient accuracy. From the balance equation $D_a n''_{xx} = \beta n^2$ we find the density distribution and length L_D:

$$\Phi\left(\frac{n}{n_*}\right)=\frac{L_D-x}{l_D},\ \Phi(z)=\int_1^z\frac{dz'}{\sqrt{z'^3-1}},$$
$$l_D=\sqrt{3D_a/2\beta n_*},\ L_D=l_D\Phi(n^*/n_*), \tag{28}$$

where n^* is the plasma density on the boundary of the diffusion and electrode regions. If n^*/n_* increases with increase in current, L_D proves to be a nonmonotonic function, reaching a maximum at $n^*/n_* \simeq 1.4$. We do not consider the effect of this factor on the plasma column CVC here. Let $n^* \gg n_*$, then $L_D = \ell_D\Phi_\infty$ and the length of the diffusion region, according to Eqs. (27), (28) proves to be a monotonically decreasing function of current density. From the condition $L_D = 0.5L_{p\ell}$ and Eqs. (27), (28) we determine the current density

$$j_{\text{eff}}=6\sqrt{6}\,\Phi_\infty^3\frac{e\mu_e D_a^2}{\beta L_{pl}^3}\sqrt{\frac{2\varepsilon_0}{\beta\mu_i}},$$

which when exceeded produces a segment with drift mechanism for maintaining conductivity at the center of the interelectrode gap. If $j_{\text{eff}} < j_{\text{tr}}$, then the diffusion mechanism extends over the entire column and the voltage across the plasma is proportional to the current:

$$U_{\text{eff}}=\frac{\beta L_{pl}^3 j_{\text{eff}}}{6\Phi_\infty^2 e\mu_e D_a}.$$

If $j_{\text{eff}} > j_{\text{tr}}$ the full voltage is composed of the voltages across the diffusion and drift segments. On the basis of Eqs. (16), (23), (27), (28) the column CVC can be written in parametric form as

$$U_{\text{eff}}=U_{\text{tr}}+U_{gp},\ U_{\text{tr}}=\Phi_\infty\sqrt{\frac{12\varepsilon_0 D_a^2}{\beta\mu_i}},$$
$$U_{gp}=L_{pl}\delta\sqrt{\frac{2\varepsilon_0 D_a}{e\mu_e\mu_i}}\left(j_{\text{eff}}^{1/3}-j_{\text{tr}}^{1/3}\right),$$
$$\left(\frac{j_{\text{eff}}}{j_{\text{tr}}}\right)^{1/3}=1+\sqrt{\frac{2}{3}}\frac{\lambda}{\Phi_\infty}\left(\frac{E_0}{E_*}\right)^2.$$

The quantities δ and λ are monotonically increasing functions of the parameter E_0/E_*, Eqs. (18), (23) (see Fig. 6). With unlimited growth in E_0/E_* $\delta \to \sqrt{2/3}(E_0/E_*)$, $\lambda \to \sqrt{\pi/2}$ and the voltage on the column $U_{\text{eff}} \sim j_{\text{eff}}^{1/3}$. It follows from Eq. (27) that

$$E_*=(2\varepsilon_0 D_a j_{\text{eff}}/e\mu_e\mu_i)^{1/3}.$$

In the normal current density regime for an ohmic discharge E_*/p proves to be independent of pressure, and for a discharge in nitrogen, for example, $E_*/p = 0.19$ V/(cm·Pa). Hence it following that in the high current form of the discharge no drift segment exists in the plasma, and the diffusion region either directly transforms to a region with volume ionization, or is limited by the length of the discharge chamber. For the weak current form of the discharge in the normal current density regime $j_{\text{eff}} \sim \omega p$ and the value $E_*/p \sim (\omega/p)^{1/3}$ decreases with increase in pressure. For a discharge in nitrogen at a frequency of 13.6 MHz at a pressure of 0.23 Pa [1] we obtain $E_*/p = 0.04$ V/(cm·Pa). Consequently, the theory of the diffusion-drift column presented above is applicable to description of an hf discharge in weak current form. Examples of the CVC are presented in Fig. 7 (lines 1-3 are voltage U_{eff} on plasma column, field intensity E_0/p, E_*/p on current density in nitrogen, p = 0.23 Pa, $L_{p\ell}$ = 2 cm). Thus it is evident that the quasineutral column in a weak current discharge is stable.

We will offer some clarification regarding the ambipolar diffusion of the plasma which remains unconsidered in the calculations performed. It follows from the analysis performed that in a real experiment the basic mechanism for maintenance of conductivity in an hf discharge column under the conditions considered is plasma diffusion. Of the calculation results, the conclusion of formation of a current spot on the electrode with the same normal current density retains its significance. It also seems probable that with consideration of plasma diffusion the quasisteady state compression of the plasma column is maintained. In fact, both diffusion and drift lead to qualitatively identical plasma distributions on the discharge axis, both mechanisms encouraging movement of the plasma from the electrode regions to the volume. It is simple to show that as in the case of a drift mechanism for maintenance of conductivity, the CVC of a quasineutral column with diffusion mechanism of conductivity maintenance is nonmonotonic when and only when the plasma density on the column boundary n^* increases sufficiently rapidly with current ($\hat{n}^* > 1$). There is also a difference which appears in a real space: ambipolar diffusion is isotropic, while drift is described by a tensor diffusion coefficient

$$-\frac{\mu_i}{2\varepsilon_0\mu_e^2}\partial_\alpha\left\{\langle j_\alpha j_\beta\rangle\,\partial_\beta\left(\frac{1}{n^2}\right)\right\}.$$

If the plasma column compression observed in the calculations is caused by this fact, then compression of a diffusion column would be impossible.

The authors express their gratitude to N. A. Yatsenko for information provided during the course of the study, and to L. G. Gryukanov for performing the numerical calculations and assistance in formulating the results.

LITERATURE CITED

1. N. A. Yatsenko, "Relationship of high constant plasma potential to combustion regime of a moderate pressure hf capacity discharge," Zh. Tekh. Fiz., 51, No. 6 (1981).
2. V. N. Myshenkov and N. A. Yatsenko, "Prospects for use of hf electric fields," Kvantovaya Elektron., 8, No. 10 (1981).
3. S. B. Pashkin, "The anode region of a high voltage diffusion discharge at moderate pressures," Teplofiz. Vys. Temp., 14, No. 3 (1976).
4. A. M. Dykhne and A. P. Napartovich, "Pre-electrode instability of a gas discharge plasma," Dokl. Akad. Nauk SSSR, 247, No. 4 (1979); G. G. Gladush and A. A. Samokhin, "Theoretical study of electrodynamic instability of a glow discharge. Normal current density law," Preprint IAE-3103 [in Russian] (1979); "Numerical study of current pinching on electrodes in a glow discharge," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1981).
5. G. I. Shapiro and A. M. Soroka, "Development of forced ambipolar diffusion under the action of an hf electric field," Pis'ma Zh. Tekh. Fiz., 5, No. 3 (1979).
6. A. D. Barkalov and A. A. Samokhin, "Plasma balance in the volume of an hf glow discharge," Preprint IAE-4147 [in Russian] (1985).
7. S. Braun, Elementary Processes in a Gas Discharge Plasma [in Russian], Atomizdat, Moscow (1961).
8. A. S. Smirnov, "Electrode layers in a capacitive hf discharge," Zh. Tekh. Fiz., 54, No. 1 (1984).
9. Yu. S. Akishev, F. O. Visikailo, et al., "Quasisteady state discharge in nitrogen," Teplofiz. Vys. Temp., 18, No. 2 (1980).