GENERATION AND PHYSICAL PROPERTIES OF COMPRESSION PLASMA FLOWS OF A PRESCRIBED COMPOSITION

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We present the results of experimental investigations of new plasma dynamic systems, which generate high-energy compression plasma flows of various compositions.

The production and investigation of controlled dense plasma flows has received considerable attention, which is related not only to the fundamental investigation of such plasma formations, but also to their possible application to various technological processes, such as the processing of materials to increase toughness. This also pertains to compression flows. The existence of compression plasma flows (CPF) was theoretically predicted in [1]. Experimental verification of the possibility of generating gas-discharge CPFs was obtained by Morozov et al. [2] in a coaxial accelerator, called a magnitoplasma compressor (MPC). This device has a core outer anode and a filtered cathode. Later, [3] reported obtaining compression flows in erosion plasma accelerators as well (erosion MPCs). A reasonably detailed analysis of the operation of such devices and the properties of the plasma formations obtained in them is given in [4-6]. The distinguishing features of compression flows are their small divergence and high plasma density. However, the presence of a near-cathode jump in the potential and the instability of the ionization zone in gas-discharge MPCs makes it impossible to vary the parameters and the composition of the compression-flow plasma over wide limits (especially at high discharge current values). And in erosion MPCs, plasma formation takes place in the middle of ablation products from the inner and outer electrodes, and of the separating insulator as well, which makes it impossible to obtain compression flows of a prescribed composition.

New possibilities for obtaining compression gas-discharge plasma flows were revealed when a fundamentally new quasisteady high-power plasma accelerator (QHPA) was devised [7]. Unlike previous accelerators, QHPA is a two-stage plasma dynamic system with magnetic shielding of elements of the accelerator channel. The system operates in the ion current transport regime, in which the magnetized plasma undergoes ion-drift acceleration. The first stage of the accelerator is the input ionization block (IIB), which consists of a set of input ionization chambers (IIC). The task of this first stage is to inject completely ionized plasma currents into the second stage, which is the main accelerator channel, formed of the so-called anode and cathode transformers [7]. The anode transformer emits an ion current into the accelerator channel that is equal to the discharge current of the main stage, while the cathode transformer accepts this ion current. In addition, the magnetic systems of the anode and cathode transformers shield the solid-state elements in their structure from the action of the powerful plasma currents.

One of the models of such a plasma dynamic system is a variant of the quasisteady accelerator with passive anode and semiactive cathode core transformers: the P-50M QHPA (P denotes passive; 50 is the characteristic scale, equal to the inner diameter of the anode transformer in centimeters) [8]. A compression operating regime was realized in this accelerator by matching the parameters of the first and second stages [8]. Subsequent experimental investigations of the physical processes in the P-50M QHPA made it possible to establish the basic laws governing the physical-processes which determine the operating regimes of these plasma dynamic systems. Probes, high-speed photography, interferometry and spectroscopy were used in these investigations. It was determined that the parameters of the plasma current exiting the QHPA depend on the nature of the distribution of the current in the accelerator channel. It was also made clear that the ratio of the ion discharge near the surfaces of the anode and cathode transformers to the value of the discharge current decisively influences the character of the current distribution in the QHPA accelerator channel. In other words, the exchange parameters in the near-anode and near-cathode regions (ξ_a and ξ_c, respectively) are critical. The compression regime of QHPA operation is established when $\xi_c > \eta\xi_a$ (here η

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is some loss factor of the current-carrying ions, related to the construction of the transformers). A compression plasma flow of length ~50 cm forms behind the edge of the cathode transformer. Its diameter in the region of maximum compression is ~3 cm, where under experimental conditions, the electron concentration reaches $\sim 5 \cdot 10^{17}$ cm^3 (the working gas is hydrogen, $I_d \sim 350$ kA). Note that for similar initial conditions in an MPC, it is not possible to obtain plasma flows with these parameter values.

Compression erosion plasma flows (CEPF) of a prescribed composition in air at atmospheric pressure were first obtained with the help of an end discharge device [9, 10] of a single-stage erosion plasma accelerator (SEPA), and later, by using a combination plasma dynamic system consisting of a two-stage erosion plasma accelerator (TEPA) with an end discharge device as the first stage [11].

In the end discharge device, the outer electrode and capacitor bank are filled up by section, each section of the bank being joined by a spark gap to the inner electrode and to one of the sections of the outer electrode of the end device. A core electrode is used as the outer electrode of the second stage. The sectioned bank of the second stage is loaded through a spark gap on the inner electrode of the end device and on the rod of the outer electrode of this stage.

During discharge, the fundamental erosion plasma flow is formed at the inner electrode of the end device. The flow composition is determined by the predominant material of this electrode, as has been shown by spectroscopy. The plasma flames, which are formed at the ends of the external electrode as a consequence of the electrodynamic interactions with the fundamental plasma flow, are inclined away from (repulsed by) the latter. The formation of the fundamental erosion plasma flow of the first stage is completed in ~40 μsec. Within this time, the second-stage bank is switched on, whose discharge takes place between the outer TEPA electrode and the macrostable erosion flow that has formed, and is a plasma (virtual) continuation of the inner electrode. Since each section of the bank is independently discharged, while the capacitance of an individual section of the second-stage bank is less than the capacitance of a section in the first-stage, the second-stage bank succeeds in discharging simultaneously with the first. Because the discharge of the second-stage bank takes place directly in the compression plasma flow and finishes practically simultaneously with the first, the effective input of energy into this flow is guaranteed. The flow of the plasma is of a quasisteady nature, since the time of stable existence of the erosion plasma flow is significantly greater then the transit time. The stable existence of the erosion plasma flow for small divergences, and also the large ratio of the length of the flow (~20 cm) to its diameter (~1 cm) indicates the compression character of the flow of the plasma. The composition of the plasma is determined first of all by the material of the central electrode. In this case, for the same total initial energy W_0 of the capacitor accumulators for the end device and for the combined plasma dynamic system, the parameters of the plasma flow are higher in the combined system. Thus, for $W_0 = 30$ kJ ($C_0 = 2400\ \mu F$), the velocity of the plasma in the end device is $\sim 3 \cdot 10^6$ cm/sec, while it is $5 \cdot 10^6$ cm/sec in the combined system; the maximum plasma temperatures are $22 \cdot 10^3$ and $40 \cdot 10^3$ K, respectively.

Thus, the gas-discharge and erosion plasma dynamic systems considered here make it possible to generate high-energy compression plasma flows of various compositions.

NOTATION

ξ_a, ξ_c, local exchange parameters in the near-anode and near-cathode regions; η, loss factor for the current-carrying ions; I_d, total discharge current; W_0 is the energy stored in the capacitor bank.

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STATE OF THE ART AND APPLICATIONS OF LOW-PRESSURE HF DISCHARGE PHYSICS

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Features are examined for a high-frequency discharge between planar electrodes as widely used in plasma etching in microelectronics. Averaging in space and time over the fast electron motions enables one to simplify the discharge description considerably. The discharge can be analyzed for elevated pressures, when the electron distribution is determined by the instantaneous local electric field, by solving the equation of motion for the ions in the average fields. At low pressures, allowance must be made for the fact that the electron energy distribution is nonlocal. A simple kinetic equation is derived for that case. The effects of the nonlocality on the discharge parameters have been examined.

By high-frequency HF low-pressure discharge is usually meant a discharge at 1-100 MHz and pressures below 1 torr. We restrict consideration to a capacitative discharge, which is formed when a high-frequency voltage is applied to planar electrodes. The latter may be metallic or be coated with insulator. We consider the particle motion in the alternating electric field. Figure 1a shows the electron paths in the x–t plane. The electrons move along periodic paths in the bulk of the plasma. The paths to the right of boundary B reach the electrode, so electrons are absent from them in the absence of emission. Near the electrode, there is a layer of thickness L in which electrons are absent for part of the period. The displacement of the ions during the period is much less, so their paths in Fig. 1 would be vertical lines. Phases of positive space charge (to the right of curve B), when the mean electric field accelerates the ions to the electrode, and the plasma phases alternate in the electrode layers, with $n_e \approx n_i$ in the latter. If $4\pi\sigma_i| < \omega < |4\pi\sigma_e|$, in which $\sigma_{e,i} = ne^2/m(\nu_{e,i} + i\omega)$, the current in the plasma is a conduction current, while that in the space-charge phase is a displacement current. The electric field here considerably exceeds the field in the plasma and most of the potential drop is localized there if the gap between the electrodes is not too large. The electrode layers determine the characteristic features of the HF discharge and most of the applications, so HF discharge physics is in essence the physics of the electrode layers.

In [1] we find the first simple model that describes the current transport in the layers; there it was assumed that the ion concentration in a layer is constant and is equal to the concentration in the bulk of the plasma, without allowance for the distribution of the ionization sources or the ion drift in the mean electric field. A theory for the electrode layers has been constructed [2] for conditions where the characteristic dimensions of the plasma and layer exceed the electron energy relaxation length λ^*, which involved solving the equation of motion for the ions in the mean field:

$$\frac{d}{dx}\left[-(D_a + D_{hf})\frac{dn}{dx} + Vn\right] = I_1 + I_2. \tag{1}$$

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