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LOW-PRESSURE MICROWAVE DISCHARGE IN A PLASMATRON WITH A RECTANGULARLY SHAPED RESONATOR

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The author presents results of measurements of certain electrophysical characteristics that determine the operation of a microwave plasmatron based on a rectangularly shaped resonator with partial filling of the resonant volume with a plasma. It is established that the distributions of the microwave field and the local electrical conductivity of the plasma along the length of the discharge region are of a periodic character with alternating maxima and minima, and the change in the values of the temperature decreases continuously from the site of input of microwave energy to the resonator.

In connection with the requirement of improving the efficiency of industrial production of microelectronic devices, the problem of development of plasma sources (that ensure the performance of the processes on treated surfaces of a large area and with high technological characteristics) is urgent. These requirements are met by microwave plasma discharges, whose main advantage is that in them one can form plasma volumes with a comparatively high electron density ($N_e \geq 10^{11}$ cm^{-3}) and a large diameter (up to 15–20 cm). The advantage of these discharges is also the absence of electrodes which eliminates the contamination of the reaction medium and the bombardment of the treated materials with energy ions. A matching of the discharge volume with the source of microwave energy simpler than in high-frequency plasma devices is of significance, too.

Since the efficiency of the processes of plasma formation and sustaining of a stable gas discharge is related to a considerable extent to the strength of the electric component of the electromagnetic field E_{ef} in the discharge zone [1], of special interest are resonator-type microwave plasmatrons; in these plasmatrons, a considerable increase in the strength of the electromagnetic-wave field in the zone of plasma formation is ensured not by increasing the power of the microwave-energy source but due to the designs of the system of formation of a microwave field. The following variants of designs using resonator-type devices are possible: with partial filling of the resonant volume with a plasma, with filling of the entire resonant volume with a plasma, and with separation of the resonant and reaction volumes by a vacuum-dense partition with elements of an electromagnetic coupling [2].

Resonator-type microwave devices with a characteristic dimension of the discharge region larger than the length of the plasma-exciting electromagnetic wave are little understood as yet, and the existing designs of resonator-type devices [3, 4] invite comprehensive investigation with the aim of improving and optimizing their designs, developing engineering methods of calculation of the structural elements of discharge units, and working out scientifically grounded recommendations on their use in the processes of vacuum plasma treatment of materials.

Experiment. We investigated the local electrophysical characteristics of the gas-discharge plasma in a discharge device [4] whose basic structural elements are presented in Fig. 1. The plasma discharge was

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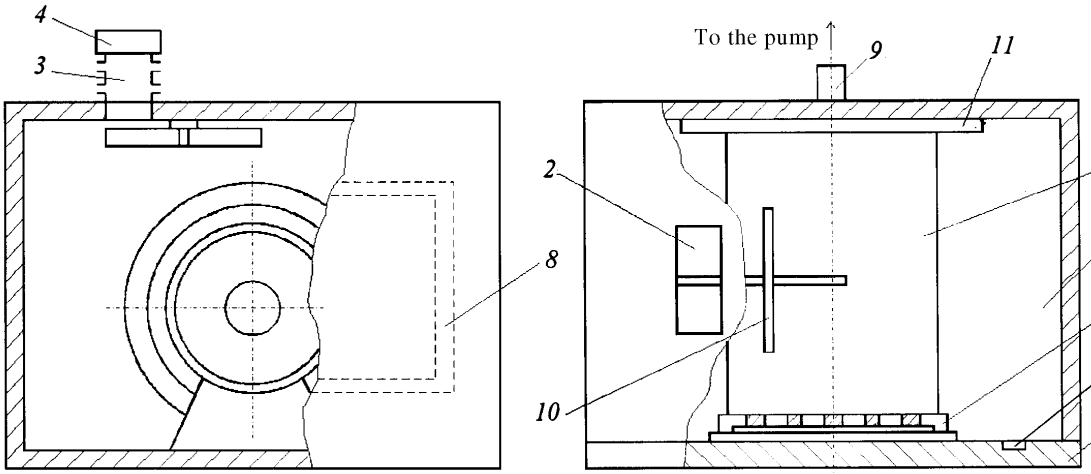

Fig. 1. Microwave-discharge device based on a rectangularly shaped resonator: 1) rectangular resonator; 2) coupling hole; 3) waveguide channel; 4) electromagnetic oscillator; 5) reactor; 6) door; 7) reactor cover; 8) choke grooves; 9) outlet pipe; 10) dissector; 11) flange (on the left, view from the side of the door; on the right, top view).

initiated in a cylindrical quartz reactor tube 5 with an outside diameter of 200 mm and a length of 310 mm; the reactor tube was located at the center of a rectangular resonator with internal dimensions 345 × 250 × 380 mm along the longitudinal sides of the resonator. An M-105 magnetron having a matched-load output power of up to 600 W and oscillating at a frequency $f = 2.45$ GHz was used as the source of electromagnetic microwave oscillations. The oscillations arrived at the resonator through a rectangular coupling hole with its longer side along the resonant walls.

We selected the probe and thermocouple methods as methods of investigation. The local distributions of the electric component of the field along the reactor length were measured using an "active" probe; the probe represented a segment of the central inner conductor of a flexible coaxial cable with a wave resistance of 50 Ω whose outer conductor was manufactured of a copper tube and whose inner conductor was made of single-cable copper wire 1.4 mm in diameter extending 5 mm beyond the outer sheath, which is much shorter than the wavelength of the investigated oscillations [5]. The probe was protected against the effects of the plasma by a Teflon cap and a quartz case. The magnitude of the microwave signal induced on the probe is in proportion to the amplitude of the component of the electric field directed along the probe.

The local measurements of the electrical conductivity of the plasma were carried out with probes manufactured in the form of stainless-steel plane electrodes which were spaced in a fixed manner.

The temperature and concentration of the electrons were determined by double probes of molybdenum wire 0.16 mm in diameter sealed into a capillary of molybdenum glass and isolated from each other.

The temperature of heavy particles of the gas discharge was measured with Chromel–Copel thermocouples placed in the capillary of molybdenum glass with vitrification of the site of junction. The probe measuring circuits were thoroughly shielded. The gas temperature of the plasma was determined at the point of cessation of temperature growth.

We used air, oxygen, and argon as plasma-forming media.

Investigation Results. Figure 2 gives typical dependences of the change in the values of the local distribution of the electric component of the field, the electrical conductivity of the plasma, and the temperature of the gas along the reactor length in the oxygen plasma. The form of change of the curves that are presented in the figure is characteristic of the air and argon plasma, too, and illustrates a stable form of the nonuniformity of the density distribution of microwave power in the discharge-zone volume. The readings of

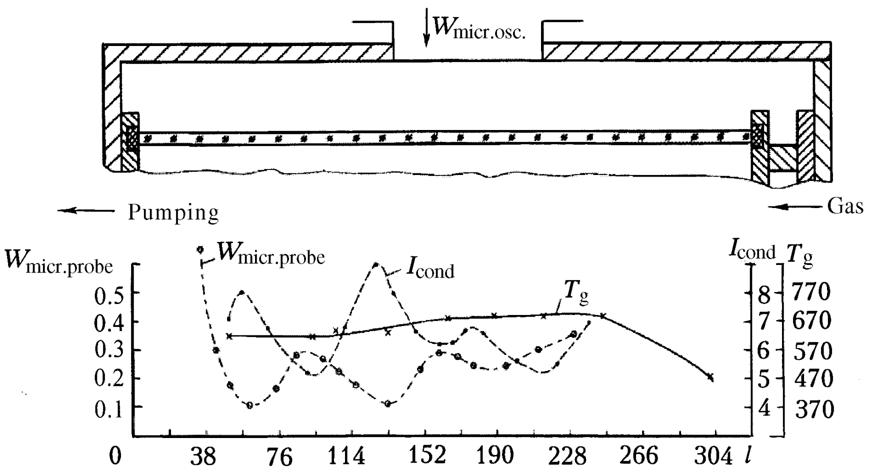

Fig. 2. Readings of the active probe $W_{\text{micr.probe}}$, the electric probes I_{cond}, and the thermocouple T_g in the O_2 discharge along the reactor length l for oxygen pressure p = 140 Pa and microwave-oscillator power $W_{\text{micr.osc}}$ = 650 W. $W_{\text{micr.probe}}$, mW; I_{cond}, mA; T_g, K; l, mm.

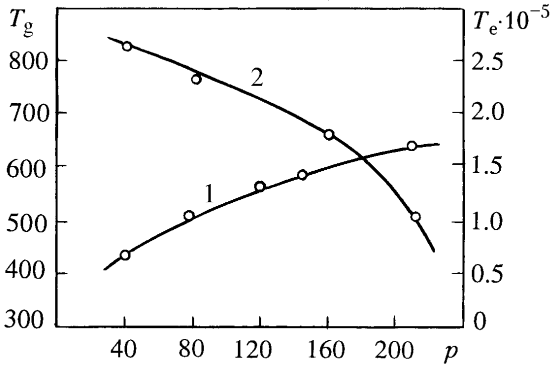

Fig. 3. Gas temperature (1) and electron temperature (2) vs. oxygen pressure in the reactor for a 100 W input of microwave power to the discharge. T_g, T_e, K; p, Pa.

the "active" probe and of the electric probes measuring the conduction current of the plasma are of a periodic character along the discharge-chamber length; the interval of alternation of the maxima and the minima is approximately 70 mm, which is much larger than the half-length of the plasma-exciting electromagnetic wave. The extremum values of the conduction current and the power of the electric component of the field are out of phase, i.e., the discharge regions with a local maximum field strength correspond to the minimum values of the electrical conductivity, and conversely. This state is attributable to the manifestation of the effect of skinning (attenuation) of the field as a function of the local concentration of the electrons. Where the concentration of the electrons is higher, the effect of skinning (skin-effect) is stronger, and conversely.

The temperature of the electrons T_e measured with the double probes at a fixed position in the reactor on the source side of pumping of the reaction volume was $(2.5–1) \cdot 10^5$ K and the concentration was $(8–9) \cdot 10^{10}$ cm^{-3} respectively. The investigations carried out on the change in the electron temperature as a function of the oxygen pressure in the reactor showed (Fig. 3) that the temperature decreases considerably as the pressure increases in the range from 40 to 200 Pa.

The data of Fig. 2 on the change in the gas temperature along the reactor length show that no temperature extremes are observed in the reactor, except for the site of injection of gases into the reaction volume, where the value of the temperature is minimum and constitutes a magnitude of the order of 470–490 K. In the zone of input of electromagnetic energy to the resonant volume, we observe a temperature plateau with an excess of the values of temperatures in the range 30–70 K over the constant temperature in the pumping region of the reaction volume. No correlation of the changes in the discharge temperature with the readings of the "active" and electric probes is observed. The absence of abrupt changes in the readings of the thermocouple along the reactor length is attributable to the smoothing of the temperature field due to the heat transfer from more heated regions to less heated ones.

As is seen from the data of Fig. 3, the gas temperature in the discharge increases with increase in the oxygen pressure, whereas the electron temperature decreases. This tendency is also characteristic of discharges in air and argon. Such changes in discharge parameters are attributable, on the one hand, to the increase in the concentration of heavy particles in the plasma, and on the other hand, to the decrease in the free path length of the electrons with increase in the pressure.

Thus, as a result of the investigations carried out on the spatial change in the local values of the electrical conductivity of the plasma, the distribution of the electric component of the electromagnetic field, and the temperature of the gas discharge in a plasmatron based on a resonator chamber with partial filling of the resonant volume with a plasma, we established the presence of spatial nonuniformity in discharge parameters, which is caused by the special properties of the distribution of microwave electromagnetic waves in bounded resonant volumes.

The data of the experiments show that the probe methods of investigation of the local characteristics of a plasma discharge are efficient and acceptable in investigating microwave discharges. The correctness of the results obtained is confirmed by the correspondence of the experimental procedure to theoretical propositions of the method and by the set of statistical data and their reproducibility.

NOTATION

N_e, concentration of the electrons, cm^{-3}; E_{ef}, effective strength of the electric component of the electromagnetic field, W/cm; $W_{micr.probe}$, induced power of the microwave signal, mW; I_{cond}, magnitude of the current between plane probes, mA; T_g, gas temperature in the discharge, K; l, distance from the flange of the reactor, mm; p, pressure, Pa; $W_{micr.osc}$, microwave-oscillator power, W; T_e, electron temperature, K. Subscripts: e, electron; ef, effective; probe, probe; cond, conduction; g, gas; osc, oscillator.

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