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Plasma Interaction with Boundary Surfaces in Low-Pressure Radio-Frequency Capacitive Discharge

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Abstract—A particular case of a problem on interaction of plasma with a surface is examined experimentally. We study interaction of its own plasma with boundary surfaces in a low-pressure radio-frequency (RF) capacitive discharge (RFCD) by considering their functions. On the basis of the physical model of RFCD substantiated earlier, we examine experimentally the physical conditions taking place in a near-electrode layer of space discharge, which lead to formation of pulsed electron beams and highly non-equilibrium plasma electron energy spectrum. We verify experimentally the known fact that in RFCD it is possible to generate natural oscillating LC circuits modulating the discharge current, and the conditions of their excitation by their own electron beams are clarified.

Keywords: plasma, boundary surfaces, RF capacitive discharge, near-electrode layer of space charge, beam-plasma instability, caviton, electron emission, electron beams

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INTRODUCTION

The interaction of plasma with a surface is a general problem since it depends on the parameters of plasma and the nature of the surface. In addition, the parameters of plasma are very different and it is necessary to understand the effect of each parameter and the synergetic effect of different factors. Only such an approach can ensure the precision control of plasma impact on the surface. Unfortunately, the experimental investigations in this field are not sufficient. The main aim of the present work is to show that, when plasma interacts with the surface, its parameters can change as a result of this interaction. From the presented information on this problem, it is seen that the processes appearing under impact of plasma on the surface are very different and sometimes unexpected for low-power radio-frequency capacitive discharge (RFCD).

EXPERIMENTAL INVESTIGATION OF PLASMA INTERACTION WITH BOUNDARY SURFACES OF RADIO-FREQUENCY CAPACITIVE DISCHARGE

Let us examine low-pressure RFCD interaction with boundary surfaces. In this case plasma interaction with the surface is of interest for investigating the physical mechanism of the discharge itself and for technological development.

The role of the examined interaction in the RFCD mechanism is described in detail in [1]. The main feature of RFCD plasma is as follows: its characteristics depend on all discharge parameters: working gas, pressure p, radio-frequency voltage $V_{\sim}$, field frequency f, electrode materials, and discharge gap configuration. Boundary surfaces in RFCD are characterized by the following feature: to some surfaces (gas-discharge electrodes), external potentials are applied (active surfaces), and to other ones (dielectric walls of discharge pipes), external potentials are not applied (passive surfaces).

As a result, passive surfaces contact the plasma and acquire a negative “floating” potential with respect to the plasma

$$\varphi_{\text{fl}} = \frac{kT_e}{e}\ln\left(\frac{m}{M}\right)^{1/2} \sim (1\text{–}10)T_e\ [\text{eV}],$$

and they are separated from the plasma by a space charge layer with thickness d_s of several Debye radii r_D, where a potential difference of about several electron temperatures (given in eV) is concentrated:

$$d_s \sim (1\text{–}10)r_D, \quad r_D = \sqrt{\frac{kT_e}{4\pi e^2 n_e}},$$

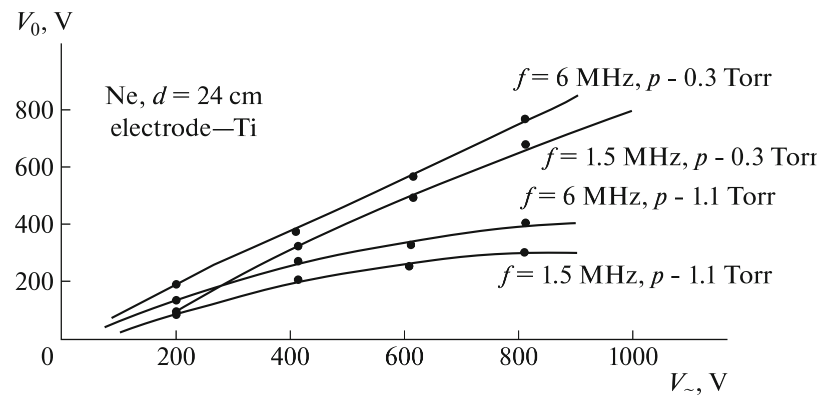


Fig. 1. The relationship between V_0nd RFCD parameters.

where T_e and n_e are the temperature and concentration of electrons, and m and M are the masses of electron and ion, respectively.

Special conditions at dielectric walls take place only in the area of the edge effect of the radio-frequency field near electrodes, where weakened effects similar to the effects near active surfaces (electrodes) appear [2].

Complicated processes and phenomena appear owing to plasma interaction with active surfaces. In the near-electrode layer of space charge (NELSC) containing mainly positively charged ions because of its nonlinear current-voltage characteristic, the radio-frequency field is rectified (the effect of RF detecting [3]), and a quasi-stationary potential difference V_0 of about the amplitude of applied RF voltage $V_\sim$ and even of $V_0 \leq 2V_\sim$ in a sharply asymmetrical RFCD appears [4]. The value V_0 is a significant function of the main parameters of the discharge (working gas, pressure, $V_\sim$, frequency of RF field f, electrode material, discharge tube diameter, and the distance d between electrodes) (Fig. 1).

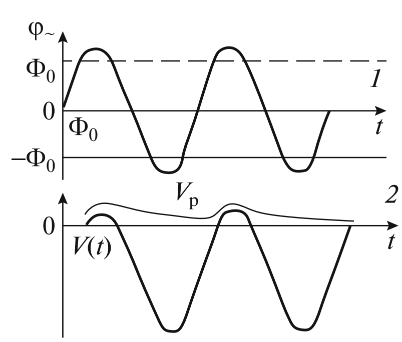


Fig. 2. Instantaneous resultant potential difference of electric field $V(t) = \Phi_0 + \varphi_\sim$ in NELSC of RFCD. Φ_0 (constant) and $\varphi_\sim$ (variable) components of value $V(t)$.

At each moment of time as a result of superposition of the ac field generated by the RF generator and the quasi-stationary field of RF detecting, unipolar electric voltage pulses form in the NELSC (Fig. 2).

Under increased RF voltages $V_\sim$, the positive ions accelerated in the NELSC generate intense electron emission and sputter the material of electrodes. In the experiments with RFCD under increased RF voltages ($V_\sim > 1$ kV) at the electrodes, we see modes with potential (Townsend factor $\gamma \ll 1$) and kinetic [5] ($\gamma \geq 1$) electron emission [1]. In this work, we present original contact-free spectroscopic procedure for measuring the density of emitted electrons n_{e0}, which is determined as follows [6]:

$$n_{e0} = \frac{I_{ki}}{n_a \sigma_{k\,\max} v_{e0} h\nu_{ki}} \frac{\Sigma_r A_{kr}}{A_{ki}},$$

where I_{ki} is the absolute intensity of spectral line, n_a is the concentration of neutral atoms, $\sigma_{k\max}$ is maximum cross section of excitation of the kth level of atom by direct electron kick, v_{e0} is the mean output velocity of electrons emitted from electrode surface [7], $h\nu_{ki}$ is the energy of quantum radiation with frequency ν_{ki}, $\Sigma_r A_{kr}$ is the sum of probabilities for spontaneous transition from the kth level to all lower levels, and A_{ki} is the probability of spontaneous transition $k \rightarrow i$.

Emitted electrons accelerated in the NELSC form pulsed electron beams with field frequency f directed from electrode to plasma. These beams generate luminescence in the near-electrode area of RFCD (Fig. 3, high-speed photography).

During the experiments, we detect lighting oscillations from the flat end of the tube opposite to the active discharge electrode. Lighting oscillations are in the radial direction. Lighting oscillation is caused by two mechanisms of its excitation: (1) pulsed beams with frequency f and (2) radio-frequency field exciting lighting with frequency $2f$. Thus, the spatial distribution of amplitudes of lighting oscillation at field fre-

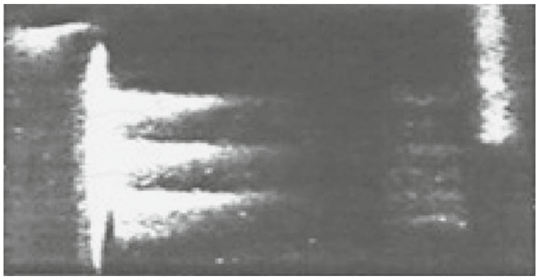


Fig. 3. Space-time variation of lighting near the electrode in RFCD. He, $p = 0.7$ Torr, $f = 3.3$ MHz, $V_{\sim} = 2.8$ kV. The electrode is on the left.

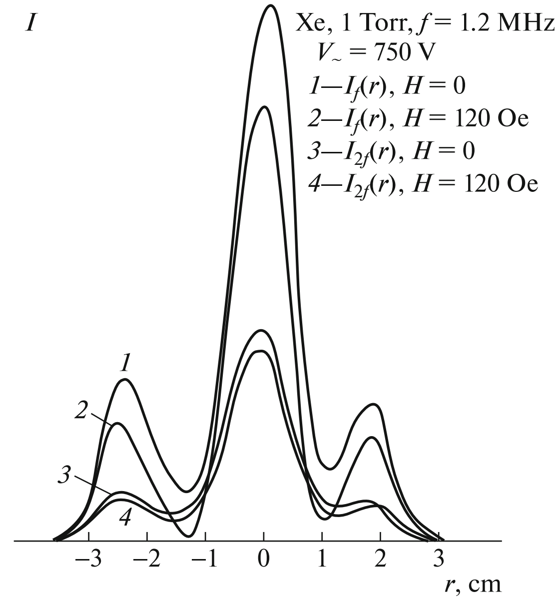


Fig. 4. Distribution of $I_f(r)$ and $I_{2f}(r)$ with longitudinal magnetic field and without it in radial direction of RFCD.

quency I_f and of its second harmonic I_{2f} demonstrates the intensity of local manifestation of the mentioned mechanisms, including the "edge" effect with formation of "wall" electron beams (Fig. 4).

It is necessary to point out that we reveal the important particular case of plasma interaction with the electrode surface of radio-frequency capacitive discharge when transport of plasma electrons to the electrode by the traditional diffusion mechanism cannot be implemented. We present a new mechanism of electron transport to the electrode with the help of potential lacunas formed in NELSC [1].

In the present work, we verify experimentally the effect of parasitic longitudinal oscillating LC circuits with resonant eigenfrequencies, for which the reactive elements are generated by plasma inductance L and capacitance C of near-electrode layer, respectively, which were predicted in [8]. The discharge current oscillograms show that alternative mechanisms for exciting the mentioned circuits are possible (Fig. 5).

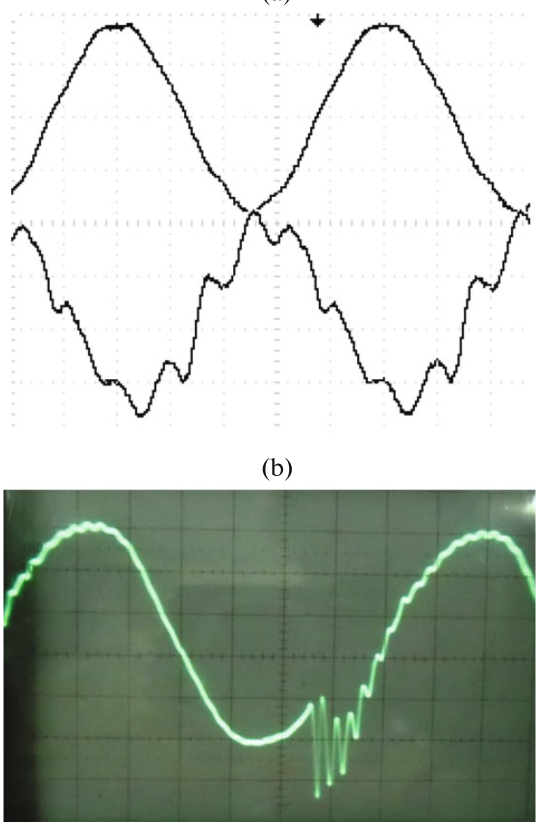
DISCUSSION

Let us examine the obtained experimental data showing the results of gas-discharge plasma interaction with active boundary surfaces in RFCD. First of all, there is well-known information on the value and behavior of the electric field in NELSC separating the electrode surface and plasma for actual experimental conditions. It is known [1] that, as a result of response reaction of the surface, high-energy near-electrode electron beams enriching the plasma electron energy spectrum (EES) in electrons with increased energy are formed. The situation with the state of the surface of the tube wall in the area of "edge effect" is clarified, where the "wall" beams in the radial direction from the wall reacting to the longitudinal constant magnetic field **H** are added to the main electron beam from the electrode (Fig. 4).

Thus, plasma interaction with the surface in RFCD can significantly change the characteristics of the plasma, especially its electron energy spectrum. In addition, physical phenomena appearing under plasma interaction with the surfaces can cause RFCD instability. We reveal that, under the respective modes of RFCD, the characteristic electron beams can excite beam-plasma instability and increase the effective electron temperature to $T_e \sim 10^6$ K [1]. Another example of RFCD instability is the instability caused by "parasitic" oscillating LC circuits [8]. And we show that, by changing the experimental conditions, it is possible to excite the mentioned circuits appearing as a result of non-linear processes in RFCD caused by RF field harmonics (Fig. 5a) and by characteristic pulsed electron beams appearing in the negative half-period of the RF field. In these two experiments, the electron beam density for the case presented in Fig. 5a is significantly lower than for the second case presented in Fig. 5b since the area of the active electrode differs greatly for the first and second experiments. Therefore, if the electrode diameter is large, the electrons do not excite LC circuits since the electron beam density is small. The information on low-power RFCD with the specific instability mode under which space cavitons are formed generating X-ray radiation and free neutrons in nuclear fusion reactions in deuterium is of interest [9]. The interaction between specific plasma of this discharge with such additional factors as X-ray radiation and free neutrons and the surface was not examined.

RFCD with external electrodes when all plasma factors impact not the metallic surface of the electrode but its dielectric coating makes it possible to sputter dielectrics. In addition, this makes it possible to have pure plasma without metal vapors. Such plasma is suitable for acting on medical objects.

(a)



(b)

Fig. 5. RFCD current oscillogram for the mode with parasitic oscillating LC circuits. (a) Upper ray is the oscillogram of the applied RF voltage. Bottom ray is the oscillogram of RFCD current. Ne, $p = 0.5$ Torr, $f = 4$ MHz, $V_{\sim} = 800$ V, area of active electrode $S_e = 8$ cm^2. (b) Oscillogram of RFCD current. Ne, $p = 0.5$ Torr, $f = 1$ MHz, $V_{\sim} = 500$ V, area of active electrode $S_e = 0.8$ cm^2.

It is necessary to point out that the surface morphology also is important for secondary processes taking place in plasma systems. For example, by using electrodes with different curvatures, we are able to focus near-electrode electron beams in RFCD at a certain distance from the electrode by additionally increasing the density of "superheated" electrons in a given area of space.

CONCLUSIONS

We examine the particular case of plasma interaction with the surface—interaction of self-plasma with boundary surfaces in RFCD; and we reveal the following: the mentioned interaction is self-consistent, changing the parameters of the plasma and surface, since several processes and phenomena appear and generate different factors impacting the surface and initiate different effects: from electronic (oscillating LC circuits) to nuclear effects (generation of free neutrons in the fusion reaction of deuterium nuclei under low-power RFCD). The general picture of plasma interaction with the surface consists of different mechanisms of impact of individual functional factors and possibly of synergetic processes, which have not been studied properly.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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