THE INFLUENCE OF A DC ELECTRIC FIELD ON THE RADIO-FREQUENCY MICRODISCHARGE

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The dependence of ionization frequency in a stationary radio-frequency microdischarge on plasma density and DC voltage applied to the discharge plasma is found. Calculation is fulfilled for a plane geometry in assumption of uniformity of radio-frequency electric field.
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Discharges with linear dimensions in mm-range (microdischarges) are actively investigated in the last time in the connection with the numerous possible applications [1]. The promising variant of a microdischarge is a radio-frequency (RF) microdischarge [2,3]. In particularly, it was suggested to use RF microdischarges in plasma panels [4]. Ibidem it was the proposal to use one of the interesting features of a microdischarge consisting in the possibility to control it by a DC voltage applied to the plasma along the small dimension. In the contrast to the usual RF discharges with dimensions much more than the electron Debye radius where an external DC electric field is compensated by the plasma polarization, a microplasma with the dimension about (equal or less than) the Debye radius allow a DC field to penetrate inside the plasma and influence the ionization balance at rather low (about electron temperature) voltage on the plasma boundaries. This influence consists in increasing of the electron loss frequency dew to adding of an electron drift pooling in the DC field to the electrons loss.

In this paper the dependence of electron ionization frequency needed for maintaining of RF discharge on plasma density and DC voltage applied to the plasma is calculated.

We state the basic definitions and assumptions: (1) the plasma contains electrons and positive ions in concentration n_e and n_i respectively; (2) these charges are produced by electron-molecule collisions at the rate $\nu_i n_e$ per unit volume, where ν_i is the frequency of ionization by an electron; (3) the gas pressure is sufficiently high for the particles mean free paths to be small compared to all relevant dimensions. The mean motion of the charged particles will then be determined by diffusion and mobility with coefficients D_e, μ_e, D_i, μ_i. If plasma contains several different sorts of ions, we will suppose them to have the same diffusion and mobility coefficients; (4) charged particles losses dew to recombination are much less than diffusion and drift ones. There is no volume attachment; (5) charged particles reaching the walls stick to them and recombine there. There is no particles repelled or emitted by the walls; (6) the value of DC electric field E is small compared to RF electric field amplitude E_{RF}. Than diffusion and mobility coefficients depends only on the latter; (7) RF electric field is not depend on charged particles densities; (8) discharge occur between parallel flat electrodes with dimensions much more than gas gap. Both RF and DC voltages are applied to these electrodes. In this case RF electric field will be homogeneous in the discharge volume and ν_i, D_e, μ_e, D_i, μ_i will be constant.

Condition (7) is satisfied if discharge dimensions are much less than the vacuum wavelength of the RF field and RF conductivity current density is much less than RF displacement current: $\sigma E_{HF} << \varepsilon_0 \omega E_{HF}$ (σ - plasma conductivity, ω - circular frequency of the RF field, ε_0 - vacuum permeability). It takes place at sufficiently high frequency:

$$\omega >> \frac{e\mu_e}{\varepsilon_0} n_e \, , \qquad (9)$$

where e - charge of electron. For example, in a xenon at the degree of ionization equaled 10^{-8} which is typical for microdischarges in radio-frequency plasma display panel cells [5] condition (1) start to be fulfilled in the meter wavelength range. For the discharge in xenon the condition (3) impose the following restriction on the pressure P and discharge gas gap L: LP>>50 μm×Torr.

At the above assumptions stationary charged particles balance equations and Poison equation take the following form:

$$\frac{d\Gamma_e}{dx} = \frac{d\Gamma_i}{dx} = \nu_i n_e \, , \qquad (10)$$

$$\Gamma_e = -D_e \frac{dn_e}{dx} - \mu_e E n_e \, , \qquad (11)$$

$$\Gamma_i = -D_i \frac{dn_i}{dx} + \mu_i E n_i \, , \qquad (12)$$

$$\frac{dE}{dx} = \frac{e}{\varepsilon_0}(n_i - n_e) \, , \qquad (13)$$

here Γ_e and Γ_i - electron and ion flows. We point out that RF electric field does not influence on the mean motion of charged particles, it only determines the value of kinetic coefficients. In accordance to conditions (4,3) charged particles densities and flows should satisfy the following boundary conditions:

$$n_{e,i}(x_1) = n_{e,i}(x_2) = 0 \, , \; \Gamma_{e,i}(x_1) \le 0 \, , \; \Gamma_{e,i}(x_2) \ge 0 \, , \qquad (14)$$

where $x_{1,2}$ - electrodes coordinates (x_2-x_1=L). Choose the origin of coordinate in the center of the gas gap and use dimensionless variables with normalization factors:

length- $x_n = L/2$, density - $n_n = \dfrac{4\varepsilon_0 D_e}{e\mu_e L^2}$, electric field- $E_n = \dfrac{2D_e}{\mu_e L}$, particles flow - $\Gamma_n = \dfrac{\varepsilon_0}{e}\dfrac{D_e^2}{\mu_e}\left(\dfrac{2}{L}\right)^3$, voltage - $U_n = \dfrac{D_e}{\mu_e} = T_e$ (T_e - electron temperature).

In terms of the dimensionless variables equations (10-14) becomes:

$$\Gamma_e' = \Gamma_i' = \alpha n_e \ , \tag{15}$$

$$\Gamma_e = -n_e' - E n_e \ , \tag{16}$$

$$\Gamma_i = -\beta n_i' + \gamma E n_i \ , \tag{17}$$

$$E' = n_i - n_e \ , \tag{18}$$

$$n_{e,i}(1) = n_{e,i}(-1) = 0 \ , \ \Gamma_{e,i}(-1) \le 0 \ , \ \Gamma_{e,i}(1) \ge 0 \ , \tag{19}$$

where $\alpha = \dfrac{\nu_i L^2}{4D_e}$, $\beta = \dfrac{D_i}{D_e}$, $\gamma = \dfrac{\mu_i}{\mu_e}$. In non-equilibrium plasma which a plasma of RF discharge belongs to, the following relations between parameters are fulfilled:

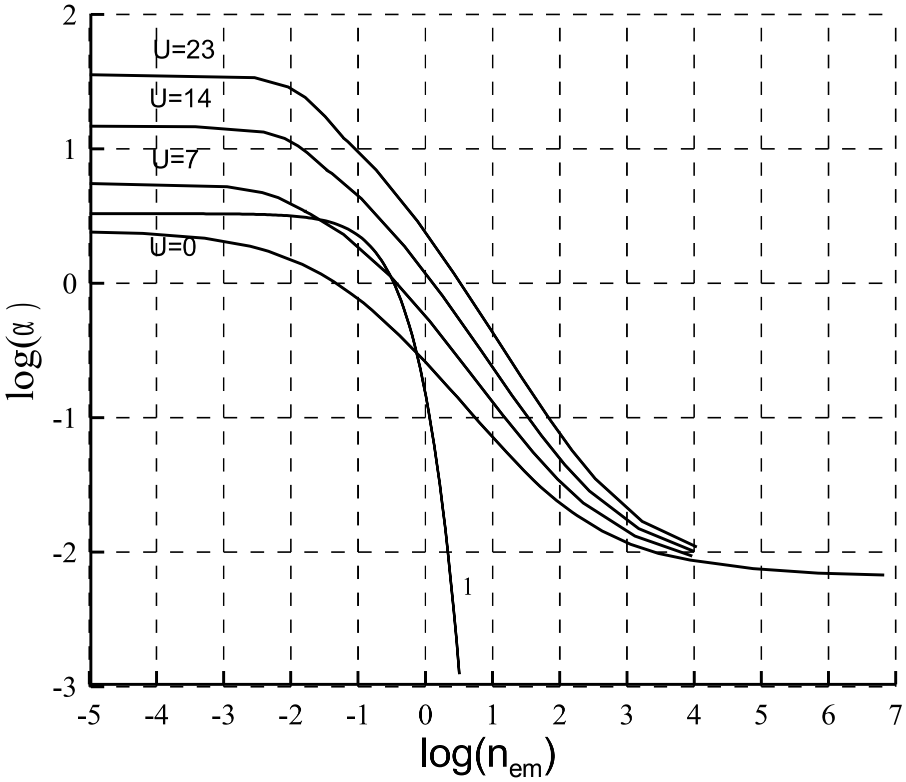
$$\beta << \gamma << 1 \ .$$

DC voltage on the electrodes is:

$$U = \int_{-1}^{1} E dx \ .$$

There are well known the solutions of this problem at high and low plasma density limits. At high plasma density or large discharge size when $r_d << 1$ ($r_d = \sqrt{\dfrac{1}{n_e}}$ - dimensionless electron Debye radius), nontrivial solution satisfying boundary conditions exists at:

$$\alpha = \alpha_1 = \left(\frac{\pi}{2}\right)^2 \gamma \ .$$



Dependence of α *on* n_{em} *at different U.* $\gamma = 2.67\cdot10^{-3}$ *; curve 1 is loading curve or RF generator*

In this case the value of the ionization frequency needed for maintaining of the discharge does not depend on the DC voltage applied to the electrodes because external DC field is compensated in plasma by the volume charges of the thin electrode sheets and does not influence on the ambipolar diffusion of charged particles to the electrodes. In the another limit - low plasma density or small discharge size - when $r_d >> \sqrt{\frac{1}{\gamma}}$, the condition for nontrivial solution existing is:

$$\alpha = \alpha_2 = \left(\frac{\pi}{2}\right)^2 + \left(\frac{U}{4}\right)^2 .$$

In this case the plasma volume charge is too small to influence the electron motion (and to change the external field). Electron losses are determined by free electron diffusion and drift in the external electric field.

In the intermediate region $\sqrt{\frac{1}{\gamma}} \le r_d \le 1$ parameter α takes values in the interval (α_1,α_2). This region occupies some orders of value of the electron density.

The dependencies of α on the maximum electron density n_{em} in a discharge in xenon ($\gamma = 2.67\cdot10^{-3}$) at different U obtained by numerical calculations are shown on the figure. There is also the typical loading curve of RF source: the dependence of ionization frequency realized by RF source on plasma density (curve 1). Stationary states of discharge takes place in the intersection points of curve 1 with appropriate curve α (n_{em}). As equations (15-19) always have trivial solution, without plasma, one can see from the figure that system can have one, two or three stationary states depending on parameters γ, U and parameters of RF source: output amplitude and output impedance. Stationary state is stable if at n_{em} increasing, curve $\alpha(n_{em})$ goes above loading curve 1, in another case stationary state is unstable. When system have three stationary state, two of them are stable - without plasma (discharge switch off) and with plasma (discharge switch on). That means that such a discharge cell has a "memory" feature which is of great importance in some applications. Driving the DC voltage on the electrodes it is possible to control discharge: both to tune discharge parameters in some extent and to switch the state of the discharge making it "turn on" or "turn off".

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ВЛИЯНИЕ ПОСТОЯННОГО ЭЛЕКТРИЧЕСКОГО ПОЛЯ НА ВЫСОКОЧАСТОТНЫЙ МИКРОРАЗРЯД

Н.А. Богатов

Рассчитана зависимость частоты ионизации в стационарном высокочастотном микроразряде от концентрации плазмы и постоянного напряжения, приложенного к плазме разряда. Расчет выполнен для плоской геометрии в предположении однородности высокочастотного поля.

ВПЛИВ ПОСТІЙНОГО ЕЛЕКТРИЧНОГО ПОЛЯ НА ВИСОКОЧАСТОТНИЙ МІКРОРОЗРЯД

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Розрахована залежність частоти іонізації в стаціонарному високочастотному мікророзряді від концентрації плазми і постійної напруги, прикладеної до плазми розряду. Розрахунок виконаний для плоскої геометрії в припущенні однорідності високочастотного поля.