MODELING OF GAS DISCHARGE ON AZIMUTHAL SURFACE WAVES IN CYLINDER WAVEGUIDE STRUCTURE

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A great interest to the problem of gas discharges sustained on the surface waves (SW) is caused by their numerical applications for coating by plasma- enhanced chemical vapor deposition or etching for microelectronics. Parameters of such discharges depend on many factors, among them: geometry and constructive peculiarities of the discharge chamber, pressure and kind of operating gas, value and orientation of external steady magnetic field, type of used electromagnetic SW and so on [1].

The theoretical model of the plasma source based on the azimuthal surface waves (ASW) propagation in a plasma filled cylindrical metal waveguide is presented. The ASW propagate across external axial steady magnetic field and posses the eigenfrequencies in the range between upper hybrid frequency and cut-off frequency for HF volume wave [2]. We study the case of the ASW in the range of relatively high frequencies, because the wave frequency in this range depends weakly on waveguide radius, so it would be more suitable to perform series of the experiments using the same generator of HF power in the discharge structures with different geometric sizes. The problem is studied using a local hydrodynamic approach and taking into account the collisional wave damping. The equation of the energy balance in discharge structure and local dispersion equation for the applied surface waves are utilized.

We assume that the electric field of the considered waves is slowly changed on the distance of electron Larmor radius. Taking into account that the eigen frequency of the waves is larger than electron cyclotron frequency, temperature of the microwave gas discharges is relatively low $T_e \approx 1eV$ one can write the inequality described the cold plasma approach in the following form $|m|\upsilon_{Te} << a\omega_e$, where υ_{Te} is electron thermal velocity, m is the ASW azimuthal wave number, a is the radius of the discharge chamber, ω_e is electron cyclotron frequency. The dependence of the perturbed parameters on azimuthal coordinate φ and time t in the considered problem is as follows:

$$A(\vec{r},t) = A_0(r,\varphi)\exp(im\varphi - i\omega t). \qquad (1)$$

We also suppose that magnitudes of the perturbed parameters are approximately independent on the angular coordinate $\frac{1}{A_0}\frac{\partial A_0}{\partial\varphi} << |m|$. In our consideration we assume that ionization process in gas discharge is caused by collisions between electrons and neutral species.

The ASW field is described by set of Maxwell equations. To obtain the ASW local dispersion equation we use the following boundary condition:

$$E_\varphi(r = a) = 0 . \qquad (2)$$

To solve the problem we also apply the equation of the wave power balance between the ASW power flow and the wave power absorbed by the plasma:

$$\frac{1}{r}\frac{dS}{d\varphi} = -Q , \qquad Q = \frac{1}{2}\int_0^a \vec{j}\vec{E}^* dr \qquad (3)$$

where S is the wave power flow, which transfers across unit square along azimuth angle, Q is the absorbed power per unit axial length of the discharge. Thus the Maxwell equations and the set of Eqs. (1-3) allows one to find spatial distribution of the ASW field and to estimate the microwave gas discharge parameters. Result of numerical research of the ASW field's distribution along radius of the chamber is presented at Fig. 1.

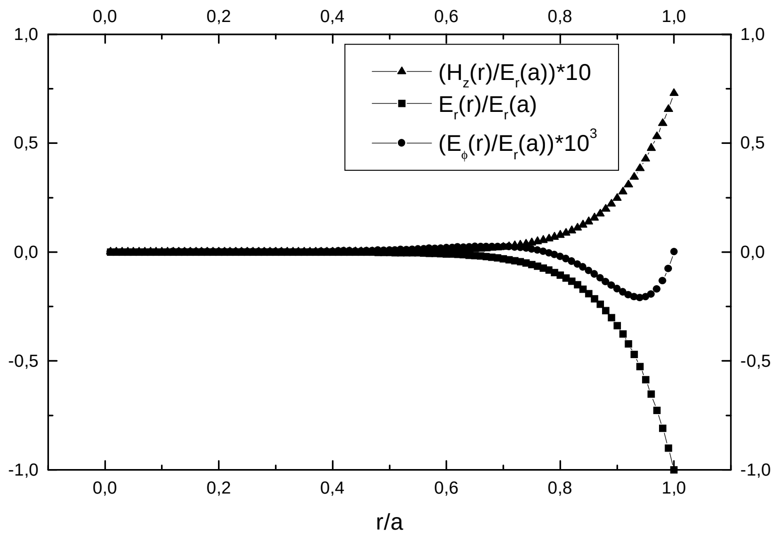

Fig.1. The space distribution of the ASW electromagnetic field for the following parameters of gas discharge: $m = -2$, $\varphi = \pi/8$, $k_{eff} = mc/a\omega_e = 2$, $\Omega_e^2 = 1000 \cdot \omega_e^2$.

The ASW dispersion relation can be obtained from the expression for E_φ electric field component using boundary condition (2). It has the following form:

$$\frac{m\varepsilon_2 I_m(ka\psi_0)}{\varepsilon_1 ka\psi_0} + I'_m(ka\psi_0) = 0, \tag{4}$$

where $\varepsilon_1 = 1 - \frac{\Omega_e^2(\omega + i\nu)}{\omega\left[(\omega + i\nu)^2 - \omega_e^2\right]}$, $\varepsilon_2 = -\frac{|\omega_e|\Omega_e^2}{\omega\left[(\omega + i\nu)^2 - \omega_e^2\right]}$, $\psi_0 = \sqrt{\frac{\varepsilon_2^2 - \varepsilon_1^2}{\varepsilon_1}}$,

$\omega = kc$, Ω_e is Langmuir frequency, ω_e is cyclotron frequency, ν is effective value of the frequency for collision between electrons and operating gas particles. The ASW eigenfrequency depends weakly on the waveguide radius a, it increases with increasing of the applied magnetic field value.

Using equations for the space distribution of the ASW electromagnetic field it is easy to write the following expression for the wave power flow S:

$$S = -\frac{c}{4\pi\psi_0} A_1^2 \int_0^a \left[\frac{\varepsilon_2}{\varepsilon_1} I_m(kr\psi_0) I'_m(kr\psi_0) + \frac{m}{kr\psi_0} I_m^2(kr\psi_0)\right] dr. \tag{5}$$

The integral in the right part of Eq. (5) can be analytically calculated only in the limiting cases when either inequality $ka\psi_0 \ll 1$ or inequality $ka\psi_0 \gg 1$ is satisfied. Magnitude of the absorbed power Q is determined by the process of Joule heating of the sustained plasma column. Under the condition of dense plasma that is of great interest for practical applications one can write the differential equation of the first order for the produced plasma density n, using substitution of Eq. (5), and explicit expression for the Q into the wave power balance Eq. (3). Its solution allows one to find the angular dependence of the produced plasma density n in the following form:

$$n \approx n(\varphi = 0)(1 - \varphi / \varphi_0). \tag{6}$$

Here, the parameter φ_0 is named as angular discharge length. It characterizes the distance from excited antenna to the point where produced plasma density becomes in exponent times less as compared with $n(\varphi = 0)$. Azimuthal angle $\varphi = 0$ indicates the position of external exciting system (antenna). In the case of narrow plasma cylinder ($ka\psi_0 \ll 1$) the expression for the angular discharge length can be written in the following form:

$$\varphi_0 = \frac{(|m| - 1)(\Omega^2 - 1)^2}{2|m|Y(\Omega^2 + 1)(\Omega - 1)}, \tag{7}$$

where $Y = \frac{\nu}{|\omega_e|}$ is normalized collision frequency between electrons and operating gas particles, $\Omega = \frac{\omega}{|\omega_e|}$ is normalized wave frequency. One can see from Eq. (7) that φ_0

increases with increasing of external magnetic field and the ASW frequency ω. In the case when inequality $ka\psi_0 >> 1$ is valid the angular discharge length φ_0 has another dependence on waveguide parameters.

But using typical parameters of experiments for microwave gas discharges sustained by the surface waves [1], one can estimate that usually the equality $ka\psi_0 \approx 0.001 \div 0.1$ is taking place. Therefore in practice of modern microwave gas discharge if inequality $B_0 > 100$ Oe is valid just the case of a narrow waveguide ($ka\psi_0 << 1$) is realized. Thus under the typical for microwave gas discharge magnetic field values the magnitude of the parameter φ_0 is large. And the ASW could propagate on the large angular distance $\varphi_0 > 2\pi$ till their amplitudes would be sufficiently decreased. It means that microwave gas discharge sustained by the ASW would be characterized by effective ASW energy losses caused by the ionization, because of their energy is not going away from the waveguide structure. On the other hand the ASW are the eigenmodes of the considered waveguide structure so they could be excited with large efficiency.

Taking into account all circumstances mentioned above, one can make a conclusion, that microwave gas discharge sustained by the ASW propagation along azimuthal direction across external magnetic field could be used for production of dense plasma column with large axial sizes and approximately uniform plasma density profile in cross section of the applied cylinder chamber because of validity of approach of a narrow plasma waveguide. It is caused by the large value of the ASW penetration depth into plasma. Parameters of this discharge can be controlled by change of the external magnetic field value.

Acknowledgements

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References

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