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Plasma Source of Magnetron Type Based on Surface Cyclotron Waves Propagation

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Introduction. At present time study of microwave gas discharges sustained by surface waves (SW) is a typical problem due to their numerous applications in plasma chemistry, plasma processing of solids and so on (see e.g.[1,2] and references therein). Collisionless damping of surface waves is one of possible channels of SW energy transfer into plasma particles. That is why it is actively studied at present time. It was shown that collisionless heating can be predominant at the operating gas pressure of 10 *mTorr* or less, because of low level of electron collision frequency (when inequality $\nu << \omega$ is valid, ω is operating frequency). Microwave gas discharge sustained by the extraordinary polarized surface wave at the second harmonic of electron cyclotron frequency was investigated in [3] for planar model of discharge chamber that was assumed to be immersed into steady magnetic field $\vec{B}_0$ oriented parallel to plasma-dielectric interface. The conditions when collisionless electrons heating can be more effective than the Ohmic heating were found there.

Unlike that case here we consider planar model of discharge chamber when $\vec{B}_0$ is perpendicular to the plasma interface. Indicated orientation of the $\vec{B}_0$ is utilized in magnetron type sources of ion flows (see e.g.[4]), in techniques for magnetically entranced plasma deposition and etching of solids [5], for sputtering of special films on substrates [6]. Such orientation of the $\vec{B}_0$ allows to use confined flow of charged particles during processing of solids, to utilize electron cyclotron resonance during deposition of films with needed properties. Surface cyclotron waves (SCW) is eigen modes of such type of discharge chamber . Dispersion properties of the SCW have been studied in [7]. These waves propagate across $\vec{B}_0$ and their eigenfrequencies belong to the ranges between harmonics of electron cyclotron frequency. Under the condition of dense plasma, when inequality $\Omega_e^2 >> \omega_e^2$ is valid (Ω_e and ω_e are Langmuir and electron cyclotron frequencies, respectively) the SCW group and phase velocities are of opposite directions. The value of the skin depth increases in the ranges of long ($k_1^2\rho_e^2 << 1$) and short ($k_1^2\rho_e^2 >> 1$) wavelengths and has minimum in the range where electron Larmor radius ρ_e is of k_1^{-1} order. The magnitude of the SCW eigenfrequency is mainly determined by the value of the applied steady magnetic field $\vec{B}_0$. Plasma density nonuniformity along $\vec{B}_0$ direction leads only to slight decrease of the SCW eigenfrequencies.

Basic assumptions and equations. Let us consider that plasma produced by microwave gas discharge is situated in the region $z > 0$. It is bounded by plane dielectric layer with infinite thickness and dielectric constant ε_d. This approach means that thickness of the dielectric is supposed to be much greater than penetration depth of the considered wave. The plasma spatial dispersion along $\vec{z}$ axis is supposed to be weak. It means that penetration depth $\lambda_\perp >> \rho_e$. This inequality can be easily satisfied for small values of the electron temperature. Let us suppose also that the produced plasma density and electron temperature are approximately constant at the distance of the SCW wavelength. To describe the SCW electromagnetic fields (E_x, H_y, E_z) the Maxwell equations are utilized. The SCW local dispersion equation can be obtained from this set of equations by Fourier method ($E,H \sim f(z)$ $\exp(ik_1x - i\omega t)$) using linear boundary conditions for tangential components of the SCW fields. To simplify the consideration the slow waves are studied: the SCW phase velocity is supposed to be much less than the light velocity. The considered waveguide structure is also assumed to be uniform in the y direction. To describe plasma particles motion we apply Boltzmann kinetic equation. Distribution function is assumed to be in the form of the sum of isotropic and anisotropic components. The anisotropy of the electron distribution function is supposed to be small. The isotropic component can be chosen [8,9] of Boltzmann type. Kinetic equation has been solved by the method of trajectories, using the boundary condition described the model of mirror reflection of the plasma particles from the plasma-dielectric interface. Then one can find plasma conductivity tensor $\sigma_{ik}(\omega, k_1, k_3)$ that has both hermitian and antihermitian parts and sum of electron's and ion's addenda. We have neglected those ion's addenda that are proportional to their thermal velocity in the σ_{ik} tensor for the case of electromagnetic oscillations at the harmonics of electron cyclotron frequency because of large inertia of ions. To calculate the integrals which determine antihermitian parts of the components of the σ_{ik} tensor the approach of weak plasma spatial dispersion along the normal to plasma interface (along z axis) is applied. From mathematical point of view, it means the validity of inequality $\omega + i\nu - n\omega_e >> k_3 \upsilon_e$ that has been verified in [7] both analytically and numerically (here n=0, ± 1, ± 2, ± 3,... ; υ_e is thermal velocity of electrons). This inequality is satisfied till the SCW remain eigen modes (i.e. their damping rate is less than the eigen frequency) of the considered structure.

The SCW dispersion relation [7] can be analytically studied in the following two limiting cases: for long ($k_1^2\rho_e^2 << 1$) wavelengths and for short ($k_1^2\rho_e^2 >> 1$) wavelength. Then one can write the following expression for the SCW eigenfrequency: $\omega \approx s|\omega_e|(1+\chi)$, where small parameter χ is proportional to $-(k_1\rho_e)^{2s-2}$, here $S \geq 2$, for the long and to $+(k_1\rho_e)^{-3}$ for the short wavelengths. The SCW fields in the plasma region are found using reverse Fourier transform taking into account both hermitian and antihermitian parts of the plasma permeability tensor:

$$E_x(z) = F_0 \exp(-k_\perp z + ik_1x - i\omega t),$$
$$H_y(z) = -ik(|k_1|)^{-1}\sqrt{\varepsilon'_{11}(\varepsilon'_{33} + f')}F_0 \exp(-k_\perp z + ik_1x - i\omega t), \quad (1)$$
$$E_z(z) = ik_\perp k_1^{-1} F_0 \exp(-k_\perp z + ik_1x - i\omega t),$$

where

$$F_0 \approx E_0[1 + \frac{i|k_1|\upsilon_e\omega h^4}{4\sqrt{\pi}\Omega_e^2 I_s^2(u_e)}\sqrt{(\varepsilon'_{33} + f')\varepsilon'_{11}}, f = 2\varepsilon_{13}k_1k_3^{-1}, u_e = \frac{1}{2}k_1^2\rho_e^2,$$

$$k_\perp = \sqrt{\frac{k_1^2\varepsilon'_{11}}{\varepsilon'_{33} + f'}} << k_1, k = \frac{\omega}{c}, h = 1 - s|\omega_e|\omega^{-1},$$

ε'_{ik} is real part of the dielectrical permeability of magnetoactive plasma ε_{ik} , E_0 is real amplitude of the E_x field on the plasma interface, parameter h determines resonant shift of the SCW frequency in respect to the s-th electron cyclotron harmonic, $\lambda_\perp = k_\perp^{-1}$. In the region of the bounding dielectric layer, the SCW fields are governed by ordinary uniform differential equations of the second order. Consequently, the SCW field decreases proportionally to $\exp(k_1 z)$ in the dielectric region ($z<0$). Then one can see that the SCW field decreases more rapidly when going away from the plasma- dielectric boundary into the dielectric region than into the plasma region. Therefore the main part of the SCW power is located in the plasma region just where ionization of neutral plasma particles takes place. That is why SCW energy losses only in this region are taken into account in the further consideration.

Discussion of the obtained results. We apply the wave power balance equation that is widely used [1-3]) to study stationary gas discharges sustained by the surface waves. It connects the wave power and energy that is absorbed by plasma. The SCW energy absorbed by the plasma particles consists of two addenda. First of them is the Ohmic dissipation, its value $Q_{col} \sim \mathrm{Re}\,\sigma_{ik} E_k E_i^*$, where $\mathrm{Re}\,\sigma_{ik}$ is hermitian part of the plasma conductivity tensor. To find analytical expression for Q_{col} the electron collision frequency is taken into account, then one can find:

$$Q_{col} \approx \frac{\nu \Omega_e^2 I_s(u_e) E_0^2 s^2}{8\pi\omega^2 h^2 u_e \exp(u_e) k_\perp}\left(1 + \frac{2u_e k_\perp^2}{s^2 k_1^2 h}\right) \qquad (2)$$

Quantity of the SCW energy absorbed due to Ohmic heating is directly proportional both to the SCW skin depth and produced plasma density. It also increases with increasing of the SCW wavelength, number s of the applied cyclotron harmonic. Maximum value of operating gas pressure is restricted only by necessity to satisfy inequality $\omega >> \nu$. Thus in this case, Ohmic dissipation can not be the most effective mechanism of the plasma heating. That is why let us study the collisionless electron heating during microwave gas discharge sustained by the SCW. One can calculate quantity of resonantly absorbed power of the SCW taking into account antihermitian parts of the σ_{ik} tensor for the case of long wavelengths

$$Q_{res} \approx \frac{E_0^2 \omega \Omega_e^2 (s^2-1)^2 (k_1^2 \rho_e^2)^{2S-3}}{2\pi k_\perp \omega_e^2 16^s (S!)^2} \exp(\zeta) \qquad (3)$$

here $\zeta = \omega^2 h^2 \lambda_\perp^2 \upsilon_e^{-2}$, and for the case of short wavelengths

$$Q_{res} \approx \frac{2E_0^2 \omega \Omega_e^6 \exp(\zeta)}{\pi^{5/2} k_\perp \omega_e^6 (k_1 \rho_e)^9} \qquad (4)$$

As it goes from analysis of eqs.(2)-(4) the regime of collisionless electron heating prevails over collision heating for long and short wavelengths of the SCW apart from the $\nu\omega^{-1}$ value . One can realize the collisional electron heating regime only for that wavelength range ($k_1\rho_e \sim 1$), because just in this range parameter $\zeta \sim 1$ .The spatial scale L_{res} wherein the SCW energy can be resonantly absorbed is less or equal to ρ_e. On the other hand the distance L_{col} wherein the SCW energy can be dissipated due to the collisions between plasma particles is approximately determined by the SCW collisional damping rate [7],

$$L_{col} \approx \omega \nu^{-1} \left| h k_1^{-1} \right| . \qquad (5)$$

The distance $L_{col} \sim \rho_e$ for the short and long wavelengths, but it is much greater than ρ_e in the range $k_1\rho_e \sim 1$. The smallness of the L_{res} value as compared with the L_{col} can be explained, first, by strong interaction between the SCW and electrons that are rotating in the planes oriented parallel to the plasma interface and, second, by relatively small value of the SCW group velocity in the both short and long wavelength regions. The parameter $\lambda_\perp$ in the range of long wavelengths gradually trends to k_1^{-1} value with increasing of the SCW wavelength unlike the range of short wavelength where it is much greater than $2\pi k_1^{-1}$. The SCW wave power flow increases with increase of the following parameters $\omega, \lambda_\perp, k_1^{-1}$.

Conclusions. Electron collisionless heating is found to prevail in the both indicated above ranges. The SCW energy is absorbed resonantly at distances of the order of electron Larmor radius along the SCW propagation, but distance of some hundred of the ρ_e is requested for the wave power absorption in transverse direction. Orientation of the external steady magnetic field sufficiently effects on the type and properties of eigen surface mode of the considered discharge chamber and consequently on the damping process of this mode. Thus kinetic damping of the examined SCW is proved to be much greater than for the case studied in [3]). The presented results can be applied for explanation of experiments on plasma processing of solids, study of the most suitable conditions for technological application of magnetron type devices.

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