SURFACE WAVE DISCHARGES UNDER LOW PRESSURES AND SOME THEIR APPLICATIONS

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It is shown that in low pressure plasmas sustained by surface waves (SW) the increasing of energy transmission from SW to plasma particles may be carried out due to the resonance heating. The consideration is carried out for an infinite long plasma cylinder with the radius $R + d$ placed in vacuum. The plasma density is assumed to be constant along the cylinder axis (z direction). The plasma is homogeneous with the density n_0 along radius in the region $0 < r < R$. The plasma density varies from n_0 to zero in the region $R < r < R + d$. The thickness of inhomogeneous region d is smaller than the radius of the cylinder R: $d << R$. In the considered structure in the frequency range $\nu << \omega < \omega_{pe} / \sqrt{2}$ (ν is the frequency of electron-atom collisions, ω is the SW eigenfrequency ω_{pe} is plasma frequency in uniform plasma region) the propagation of slow ($\omega / k_3 << c$, where k_3 is the SW wavenumber, c is the speed of light) potential asymmetric SW is possible [1]. The dependence of wave potential Ψ on r and z coordinates, azimuthal angle φ and time t is chosen in the form: $\Psi = \Psi_m(r) \exp[i(k_3 z + m\varphi - \omega t)]$, where m is azimuthal number of the SW. It is supposed that only one harmonic of the SW with azimuthal number m is excited. Assuming the relation $\vec{E} = -\nabla\Psi$ (where $\vec{E}$ is the electric field of the SW) and taking into account that in the transition area $R < r < R + d$ the plasma density sharply changes with r changing it is obtained from Poisson and quasihydrodynamical equations that ω dependence on k_3 and the dimensionless damping rate of the SW γ / ω are :

- In the case of small plasma column radius: ($k_3 R << 1$):

  For $m = 0$ (symmetrical SW):

$$\omega \approx \omega_{pe} k_3 R \sqrt{\left|\ln(k_3 R)\right| / 2}\,;\ \gamma / \omega = \nu / (2\omega) + \pi\eta / \left(2R\left|\ln(k_3 R)\right|\right), \tag{1a}$$

where $\eta = (d\varepsilon / dr)^{-1}_{r = r_0}$, ε - plasma permittivity in transition area, r_0 satisfies the condition $\varepsilon(r_0) = 0$.

For $m = \pm 1$:

$$\omega = \frac{\omega_{pe}}{\sqrt{2}}\left[1 - \frac{k_3^2 R^2}{4}\left(\left|\ln(k_3 R)\right| - 3/4\right)\right]; \quad \gamma/\omega = \nu/(2\omega) + \pi\eta/(4R). \quad (1b)$$

For $|m| > 1$: $\omega = \frac{\omega_{pe}}{\sqrt{2}}\left[1 - \frac{k_3^2 R^2}{4|m|(m^2 - 1)}\right]$; $\gamma/\omega = \nu/(2\omega) + |m|\pi\eta/(4R)$. (1c)

- In the case of large radius of plasma column ($k_3 R >> 1$) these dependencies for any m are:

$$\omega = \frac{\omega_{pe}}{\sqrt{2}}, \quad \gamma/\omega = \nu/(2\omega) + \pi\eta k_3/4 \quad (1d)$$

The power losses per unit length Q in the plasma column is obtained taking into account the resonant absorption for the SW. The equation for Q in the case of small radius of plasma column follows : $Q = Q_0 + Q_{res}, Q_0 \approx \frac{\pi e^2 n\nu m E_z^2(R)}{m_e \omega^2 k_3^2}$ is the power losses in uniform region, $Q_{res} = Q_0 \frac{\pi}{2}\frac{\eta n_c \omega\varepsilon(R)^2 m / R}{\nu n}$ is the power losses connected with resonance energy absorption in the transition area. Here $E_z(R)$ is amplitude of the *z*-component of SW electric field at $r = R$; $\varepsilon(R)$ is dielectric permittivity of plasma at $r = R$; $n_c = m_e\omega^2/(4\pi e^2)$ (m_e is electron mass, *e* is electron electric charge), *n* is plasma density in uniform region. We have carried out the numerical estimations of the collisional damping rate and the damping rate connected with the resonance energy absorption. For the following plasma and structure parameters: $\omega = 2\pi \times 2{,}45 \times 10^9$ s^{-1}, $\nu = 10^8$ s^{-1}, R = 1 cm, $T_e = 1\,\text{eV}$ (T_e is an electron temperature) the value of collisional dimensionless damping rate is $3{,}3 \times 10^{-3}$. In the case of $|m| \geq 1$ for above mentioned parameters the value of dimensionless damping rate connected with the resonance energy absorption in the transition layer is about $3m \times 10^{-3}$. We have estimated η assuming that the plasma density linearly decreases in the transition area. In the above calculations it is assumed that $d \approx 5r_D$ (r_D - Debye radius). From these numerical estimations it follows that for above mentioned parameters of the SW and structure studied in the case of $|m| > 2$ the resonant energy absorption is dominant process at energy transmission from SW to plasma particles. From equations (1) one can see that in the case of small plasma column radius the damping rate connected with resonance energy absorption in the transition layer increases with increasing azimuthal number. The resonance energy absorption rate increases with decreasing plasma column radius. In the case of large radius of plasma column the damping rate increases with growing k_3. Thus , the transmission energy from SW to plasma particles in low pressure plasmas can be enhanced by resonance heating in transition area near the discharge walls where plasma is inhomogeneous. Such method might increase the efficiency of the plasma production.

A concept of a low-energy ion-beam source based on the planar ion-sound surface wave (IASW) discharge under low pressures is proposed. The planar structure considered is formed from a semi-infinite plasma region $x<0$ bounded at the plane $x=0$ by a vacuum gap separating a plasma from a metal. The metal plane $x=s$ is assumed to be ideally conductive. Plasma is assumed to be non isothermal. Therefore, electron thermal motion is taking into account but ion thermal motion is neglected. The ion-acoustic surface wave can propagate in the considered structure in the frequency range $\omega < \Omega_i / \sqrt{2}$ [1] (where $\Omega_i = \sqrt{4\pi e^2 n_0 / m_i}$, m_i - ion mass, n_0 - unperturbed particle density, ω is the SW eigenfrequency). Our numerical investigations have shown that case of wide vacuum gap (the SW skin depth is smaller than the width of vacuum gap) is more prospective for plasma technologies. The IASW field components and the dispersion relation in the case of wide vacuum gap are presented in [1]. It is assumed that between plasma and metal surfaces additional electric field $\vec{E}_0$ is applied. The additional field $\vec{E}_0$ increases the flow of ions at the metal surface. The system of the equations describing the ion motion can be presented in the following form:

- in the vacuum region $(0 < x < s)$: $m_i \dfrac{d^2 x}{dt^2} = eE_x^v + eE_0$, $m_i \dfrac{d^2 z}{dt^2} = eE_z^v$,
- in the plasma $(x < 0)$: $m_i \dfrac{d^2 x}{dt^2} = eE_x^p$, $m_i \dfrac{d^2 z}{dt^2} = eE_z^p$,

where $E_i^{v,p} (i = x; z)$ is *i*-th component of the IASW electric field in vacuum, plasma region, respectively. The numerical study of ion motion in the field of IASW was carried out for argon plasma and some results of this study are presented in the Fig. 1,2. Fig. 1 presents the energy distribution function $f(\varepsilon)$ ($\int_0^\infty f(\varepsilon)d\varepsilon$ is the ratio of the number of incident particles to all the particles accelerated by IASW) of incident particles onto metal surface for various values of the additional field. The curves are obtained for the following parameters: $\omega / 2\pi = 4 \times 10^5 s^{-1}$, $A^v = 300V / cm$ (A^v- amplitude of the SW electric field in vacuum region at $x = 0$); $n_0 = 3{,}2 \cdot 10^{12} cm^{-3}$; $T_e = 3eV$. The curve 1 corresponds to the case when the additional electric field is absent; curve 2 -$E_0 = 0.5A^v$; the curve 3 –to the case when $E_0 = A^v$. Functions $f(\phi)$ of distribution on incidence angles ϕ on the metal surface ($\int_0^{\pi/2} f(\phi)d\phi$ is the ratio of incident particles to all the particles accelerated by IASW; the incidence angle is measured from the normal direction to the surface.) are presented in Fig. 2. The functions $f(\phi)$ are calculated for the same parameters, as curves in Fig. 1. The curve 1 corresponds to the case $E_0 = 0$; 2 — $E_0 = 0.5A^v$; 3 — $E_0 = A^v$. From Fig. 1 and Fig. 2 one can see that average incidence angle of ions on the metal surface and average their energy may be changed by varying amplitude of the IASW field and strength of the additional field. The results of our research of ion motion in the field of IASW also have shown that the average energy, energy spread and incidence angle can be controlled by changing of the IASW frequency , ion density and electron temperature. This method of ion acceleration in the field of IASW may be used for surface processing.

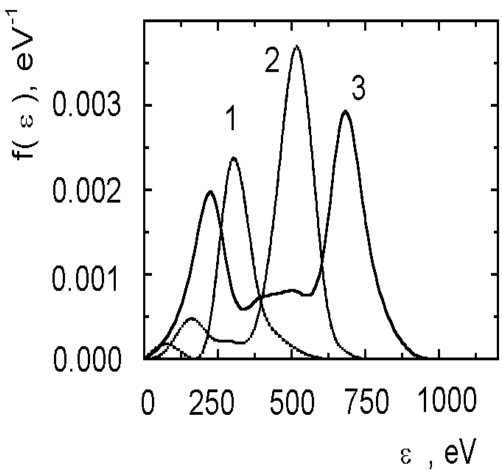

Fig. 1. The energy distribution function of incident particles for various values of the additional field

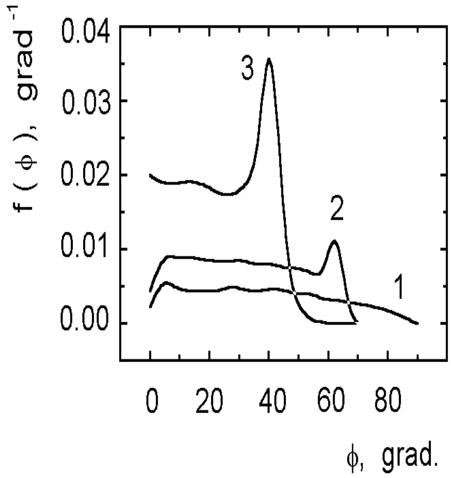

Fig. 2. The angle distribution function of incident particles for various values of the additional field

Acknowledgments

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Reference

[1] Kondratenko A.N.: Surface and volume waves in bounded plasma. Moscow, Atomizdat, 1985, p. 208.