HEAT NONLINEARITY OF SURFACE WAVES AT INTERFACE BETWEEN FINITE GAS PRESSURE MAGNETIZED PLASMA AND METAL

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This report is devoted to the investigation of the non-linear mechanism of plasma electrons heating on dispersion properties of potential surface waves (SWs) that propagate along interface of metal-magnetized plasma of a finite pressure. The external steady magnetic field is perpendicular to the medium interface. The different mechanisms of electron energy losses in approach of a weak heating are considered. The spatial distribution of plasma electron temperature on the basis of energy balance equation in framework of the non-local electrons heating is obtained. The nonlinear shift of wavenumber and spatial attenuation coefficient at different plasma parameters are researched. The obtained results are valid both for semiconductor and gas plasma.
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1. INTRODUCTION

The properties of SW in plasma-metal structures are subject of intensive theoretical and experimental researches during last 20 years. The interest to these structures is stipulated by their numerous applications in plasma and semiconductor electronics, gas discharge etc.[1]. The linear theory of SW in such structures is developed rather completely. However the SW behavior can become essentially nonlinear even at rather small wave field amplitudes [2]. In dependence from plasma parameters those or other nonlinear self-interaction mechanisms can be dominating. Among of research directions of various nonlinear effects that determine the SW properties in plasma waveguide structures, one can be noted the following ones. So, for example, the resonance excitation of the second harmonic studied in [2], nonlinear damping of SWs [3], self-interaction of SW due to the nonlinearity of a quasihydrodynamics equations [2], the ionization nonlinearity and heating one [4].

The aim of this report is the study of heating nonlinearity of SWs that propagate at interface ‘plasma – metal’ at a presence of external steady magnetic field.

2. TASK STATEMENT

Let us consider the nonlinear process of self-interaction of potential SW due to the plasma electron heating in a field of finite amplitude wave. Let us assume that the wave propagates along interface of metal and plasma of a finite pressure. The warm magnetized plasma occupies a half-space $x > 0$ and bounded by perfect conducting metal in the plane $x = 0$. The plasma – metal interface is supposed sharp that is valid, when the transitional layer size is significantly less than the penetration depth of SW field into plasma. The external steady magnetic field H_0 is directed perpendicularly to the mediums interface (axes x). Such magnetic field is typical for HF and UHF discharges, magnetrons, Penning sources, magneto-discharge pumps, Hall sensors, fusion devices (divertor, limiter) etc.

Let us consider the properties of SW that propagates in weakly collision plasma with effective electron - scattering centers collision frequency $\nu = \nu_{col} + \nu_* + \nu_i$ (ν_{col}, ν_*, ν_i are elastic collisions, excitation and ionization frequency respectively). We assume that ν is much less than the wave frequency ω. The scattering centers in the case of gas plasma are the ions and atoms of working gas, impurity. In the case of semiconductor plasma they are optical and acoustic phonons also.

The mechanism of SW self-interaction consists in that the plasma electrons receive from wave an additional energy and then return its to scattering centers as a result of collisions. It leads to the spatial distribution of electron temperature that determines both electron collision frequency and plasma pressure is changed. It results in the electrodynamic plasma properties and SW dispersion ones are varied also.

It is necessary to note that the heating mechanism of self-interaction is similar to ionization nonlinearity [2, 4]. The growth of SW amplitude results in modifications of spatial distribution of electron temperature and coefficients of elementary processes in plasma. It leads to modification of plasma density distribution and the SW dispersion properties consequently. In the case of weak nonlinearity the wave amplitude is rather small and the perturbations of plasma parameters (temperature and pressure of electrons, collision frequency etc.), caused by wave, are much less than nonperturbed ones. The influence of ionization and heating nonlinearities on wave dispersion can be taken into account by additionally. It allows to study these mechanisms independently from each other.

3. LINEAR THEORY RESULTS

According to the linear theory [5], the considered SWs exist in a frequency region $\omega^2 > \omega_{ce}^2$ (ω_{ce} is electron cyclotron frequency) and necessary condition of their existence is the finite value of electron thermal velocity $V_{Te} = \sqrt{2T / m_e}$ (T is plasma electron temperature). It is necessary to note that the account of plasma electron thermal motion even in a linear approach the expressions of wave potential and wavenumber are cumbersome. Therefore further research of self-interaction of SW will be carried out for rather dense plasma, when condition $\omega_{ce}^2 < \omega^2 << \omega_{pe}^2 / \varepsilon_0$ is valid. Here ω_{pe} is electron Langmuir frequency and ε_0 is dielectric permittivity of semiconductor lattice (in the case of gas plasma $\varepsilon_0 = 1$).

At the above mentioned conditions the potential of SW can be written in form

$$\Psi(x,y,t) = A_1 (e^{-\lambda_1 x} - e^{-\lambda_2 x}), \qquad (1)$$

where A_1 is a wave amplitude. The parameters $\lambda_{1,2}$ determine the spatial distribution of SW field in plasma:

$$\lambda_1 = \lambda_1' + i\lambda_1'' = \frac{\omega_{pe}}{V_{Te}\sqrt{\varepsilon_0}}\left(1 - \frac{1}{2}\varepsilon_0 \frac{\omega^2}{\omega_{pe}^2}\left(1 + i\frac{\nu}{\omega}\right)\right), \qquad (2a)$$

$$\lambda_2 = \lambda_2' + i\lambda_2'' = \frac{\omega}{V_{Te}}\sqrt{\varepsilon_0}\frac{\omega}{\omega_{pe}}\left(1 + i\frac{\nu}{\omega}\right). \qquad (2b)$$

The complex value of wave number is equal

$$k_2 = k_2' + ik_2'' = \frac{\omega}{V_{Te}}\sqrt{\frac{\omega^2 - \omega_{ce}^2}{\omega_{pe}^2/\varepsilon_0}}\left(1 + i\frac{\nu}{\omega}\frac{\omega^2}{\omega^2 - \omega_{ce}^2}\right) \qquad (3)$$

4. TEMPERATURE SPATIAL DISTRIBUTION

Let us consider weak heating nonlinearity, when the modification of electron temperature δT in SW field is much less than its equilibrium value T_o: $T = T_o + \delta T$, $\delta T << T_o$. Let us assume also that the modification of collision frequency $\delta\nu = \delta\nu_{col} + \delta\nu_* + \delta\nu_i$ is small enough in comparison with its nonperturbed value ν at absence of SW.

We suppose that the wave frequency ω is much more than characteristic frequency of electron energy transmission $\tilde{\nu}$ into plasma. In this case the process of electron energy transmission to scattering centers can be considered as quasistationary. The perturbation of electron temperature will depend on coordinates and square of wave amplitude module, averaged on wave period: $\delta T = \delta T(x, y, |A_1|^2)$. It can be obtained from stationary equation of energy balance:

$$1/3\,\mathrm{Re}(jE^*) = divQ - P(T), \qquad (4)$$

where Q is heat flux vector, j is a high-frequency electron current density, E^* is a complex conjugate wave electric field.

The term $P(T) = -n_o\tilde{\nu}(T_o)(T - T_o)$ in (4) determines the energy that electrons transmit in a unit of volume to scattering centers with characteristic frequency

$$\tilde{\nu}(T_o) = \gamma\nu_{col}(T_o) + U_*\left.\frac{\partial\nu_*}{\partial T}\right|_{T_o} + U_i\left.\frac{\partial\nu_i}{\partial T}\right|_{T_o}, \qquad (5)$$

where n_o is nonperturbed plasma density, the parameter $\gamma = 2m_e M/(m_e + M)^2$ is a part of electron energy transmitted to scattering centers (with mass M) by electrons at elastic collisions, and U_*, U_i are excitation energy of the first atom level and ionization one. It is necessary to note that in general the characteristic frequency $\tilde{\nu}$ is determined by frequencies of elastic collisions, excitation and ionization of atoms.

The components of heat flux Q in equation (4) are given by expression $Q_i = -\chi_{ij}\partial T/\partial\xi_j$, where χ_{ij} is a tensor of electron thermal conductivity of plasma, vector $\xi = (x, y)$. The left part of the balance energy equation (4) describes the dissipative heating of plasma electrons in SW field. The terms in right part (4) describe the electron energy losses in a unit volume due to finite thermal conductivity and energy transmission to the scattering centers.

The energy balance equation can be simplified by assuming that the heat transport occurs mainly along magnetic field: $\chi = \chi_{xx} >> \chi_{xy}, \chi_{yx}, \chi_{yy}$. This condition is valid at collision frequencies are much less than electron cyclotron frequency ($\nu << \omega_{ce}$). Taking into account these assumptions, the equation (4) can be written in following form:

$$-\frac{1}{\lambda_T^2}\frac{\partial^2}{\partial x^2}\frac{\delta T}{T_o} + \frac{\delta T}{T_o} = \left(\frac{\delta T}{T_o}\right)_{loc}, \qquad (6)$$

where $\lambda_T^{-1} = 1/\sqrt{3m_e\nu\tilde{\nu}/(5T_o)}$ is a characteristic length of electron thermal conductivity and

$$(\delta T/T_o)_{loc} = -e\,\mathrm{Re}(V_e E^*)/(3\tilde{\nu}T_o) \qquad (7)$$

is a relative modification of electron temperature in a local heating approach. It is necessary to note that the local heating approach is used in many papers. But, at the made above assumption about smallness of frequencies ν and $\tilde{\nu}$ the condition of local heating can be reduced to in equation $\omega_{pe}^2/(\nu\tilde{\nu}) << 1$ that is not valid in the case considered. Moreover, the heating of electrons in the considered task has essentially non-local character [4]. Therefore expression (7) in the considered task characterizes only the spatial distribution of a wave power absorbed by plasma electrons as a result of collisions with scattering centers, and doesn't describe the spatial distribution of temperature.

To determine the spatial distribution of plasma temperature in conditions of non-local heating it is necessary to use the equation (4), solving it together with (7):

$$\delta T/T_o \approx 2/3\,\mu^2 P e^{-2k_2''|y|}(e^{-\lambda_T x} - e^{-2\lambda_2' x}), \qquad (8)$$

where parameter $\mu = e|A_1|/(m_e V_{Te}^2)$ represents a ratio of electron energy in wave field to its thermal energy, $P = 0.6\,\nu^2\omega^2/[\omega^2(\omega^2 - \omega_{ce}^2)]$.

The relative variation of electron temperature achieves the maximum value

$$(\delta T/T_o)_{\max} \approx 2/3\,\mu^2 P e^{-2k_2''|y|} \qquad (9a)$$

at some distance from the plasma – metal interface:

$$x_{\max} = (2\lambda_2')^{-1}\ln(2\lambda_2'/\lambda_T). \qquad (9b)$$

Such behavior is determined by spatial distribution of power that electrons receive from SW field.

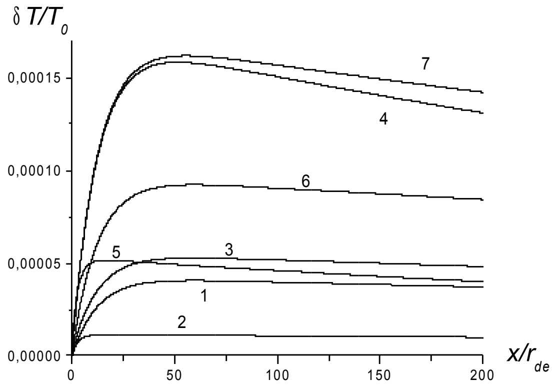
The condition of weak heating $\delta T << T_o$, $|\delta\nu| << \nu(T_o)$ corresponds to the following limitation on the wave amplitude:

$$2/3\,\mu^2 P U_{*,i}/T_o << 1. \qquad (10a)$$

At the same time the results of linear theory are valid at

$$\mu\,[\omega^2/(\omega^2 - \omega_{ce}^2)]^{1/2} << 1. \qquad (10b)$$

The numerical calculation (see Figure) has shown that these conditions are fulfilled at the wave amplitudes $\mu \le 0{,}1$.



No curve	$\sqrt{\varepsilon_0}\omega_{ce}$	$\sqrt{\varepsilon_0}\omega/\omega_{pe}$	ν/ω	$\nu/\tilde{\nu}$	μ
1	0,05	0,2	0,1	10^3	0,1
2	0,05	0,4	0,05	10^3	0,1
3	0,1	0,2	0,1	10^3	0,1
4	0,05	0,2	0,2	10^3	0,1
5	0,1	0,4	0,1	10^3	0,1
6	0,05	0,2	0,1	10^3	0,15
7	0,05	0,2	0,2	$2*10^3$	0,1

Spatial electron perturbation temperature distribution

The growth of wave amplitude (μ) and collision frequency (ν/ω) results in increase of Joule SW losses and essentially influences on plasma heating. It is necessary to note that the effective transmission of SW energy into plasma takes place when the wave frequency come close to electron cyclotron one. The growth of $\nu/\tilde{\nu}$ leads to the increase of characteristic length of thermal conductivity ($\lambda_T^{-1} \propto \sqrt{\nu/\tilde{\nu}}$). It leads to more smooth decrease of temperature in plasma.

5. SW SELF-INTERACTION

As noted above the perturbation of electron temperature results in collision frequency modification $\delta\nu$. Taking into consideration the value $\delta\nu$ and the variation of plasma electron pressure $\delta p = n_o \delta T$ in the equation of electron motion and solving its together with the continuity and Poisson's equations one can obtain the expression of wavenumber in following form:

$$k_{2NL} = k_{2L}(1 + S_{\delta\nu} + S_{\delta p}). \qquad (11)$$

Here k_{2L} is the wavenumber value (3) obtained from the linear theory and $S_{\delta\nu}$, $S_{\delta p}$ describe the influence of plasma electron heating.

The analysis has shown that the nonlinear addition to the complex wavenumber is determined mainly by $\delta\nu$ value. The growth of magnetic field value leads to increase of the nonlinear addition to the real part of wavenumber. The magnetic field influence on the nonlinear addition to the imaginary part of wavenumber has a more complicated character. So, at weak magnetic fields nonlinear addition increases with magnetic field growth. But at rather strong fields, when the wave frequency comes close to electron cyclotron one, it decreases and can changes its sign. And when it is closed to zero, the value of δp becomes important for the SW attenuation. The influence of $\delta\nu$ on SW dispersion is determined by dependence $\nu(T)$. So, if $\partial\nu/\partial T|_{T_o} > 0$ then the nonlinear shift of real part of wavenumber is negative. At weak magnetic fields the nonlinear decrement decreases and at rather strong fields it decreases in comparison with its linear value. In opposite case when $\partial\nu/\partial T|_{T_o} < 0$ there is a contrary dependence.

The analysis of parameter $\nu/\tilde{\nu}$ influence has shown that the nonlinear correction to spatial damping factor due to electrons heating are most essential under rather high gas pressure.

6. CONCLUSIONS

It is obtained and investigated the linear dispersion equation of considered SWs. In an approach of non-local plasma heating the spatial distribution of electron temperature is obtained. The nonlinear dispersion equation of SW considered is investigated. The perturbation of electron temperature results in collision frequency modification $\delta\nu$ and in the variation of plasma electron pressure $\delta p = n_o \delta T$. It is shown that the nonlinear addition to the complex wavenumber is determined mainly by $\delta\nu$ value. The growth of magnetic field value leads to increase of the nonlinear addition to the real part of wavenumber. The dependence of nonlinear addition to the imaginary part of the wavenumber on magnetic field value is more complicated. The results of the carried out researches are valid both for semiconductor and gas plasma.

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НАГРІВНА НЕЛІНІЙНІСТЬ ПОВЕРХНЕВИХ ХВИЛЬ НА МЕЖІ МАГНІТОАКТИВНОЇ ПЛАЗМИ КІНЦЕВОГО ТИСКУ З МЕТАЛОМ

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Дана робота присвячена вивченню впливу нелінійного механізму нагріву електронів плазми на дисперсійні властивості потенціальних поверхневих хвиль (ПХ), що поширюються уздовж межі метал - магнітоактивна плазма кінцевого тиску. Зовнішнє стале магнітне поле спрямоване перпендикулярно межі розподілу середовищ. В наближенні слабкого нагріву розглянуто різні механізми втрати енергії електронів. Отримано просторовий розподіл температури плазми в рамках нелокального нагріву електронів на основі рівняння балансу енергії. Досліджено нелінійний зсув хвильового числа та нелінійний декремент просторового загасання ПХ в залежності від параметрів плазми. Отримані результати справедливі як для напівпровідникової, так і для газової плазми.

НАГРЕВНАЯ НЕЛИНЕЙНОСТЬ ПОВЕРХНОСТНЫХ ВОЛН НА ГРАНИЦЕ МАГНИТОАКТИВНОЙ ПЛАЗМЫ КОНЕЧНОГО ДАВЛЕНИЯ С МЕТАЛЛОМ

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Данная работа посвящена изучению влияния нелинейного механизма нагрева электронов плазмы на дисперсионные свойства потенциальных поверхностных волн (ПВ), распространяющихся вдоль границы металл - магнитоактивная плазма конечного давления. Внешнее постоянное магнитное поле направлено перпендикулярно границе раздела сред. В приближении слабого нагрева рассмотрены различные механизмы потери энергии электронов. Получено пространственное распределение температуры плазмы в рамках нелокального нагрева электронов на основе уравнения баланса энергии. Исследованы нелинейный сдвиг волнового числа и нелинейный декремент пространственного затухания ПВ в зависимости от параметров плазмы. Полученные результаты справедливы как для полупроводниковой, так и для газовой плазмы.