SURFACE WAVE ATTENUATION CAUSED BY SECONDARY ELECTRON EMISSION

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This study aims to contribute to the analysis of the mechanisms of surface-wave-energy absorption. The discussion is based on a consideration of emissive processes from dielectric surface, which is in contact with collisional non-isothermal plasma, and on an analysis of secondary electron motion in the wave-fields. Through electron acceleration due to the action of ponderomotive force, the secondary emission affects the wave behavior. The role of secondary emission in maintenance of wave-produced gas discharges is discussed as well.

PACS: 52.25.Tx, 52.35.Mw

1. INTRODUCTION

It is well known that the efficiency of power transfer from a guided wave to a plasma depends on the dissipation mechanisms, the most important of which are collisions and absorption of wave power by local wave-plasma resonance [1-4]. Depending on the operating gas-pressure and other discharge parameters, some of them can dominate over the other [4]. Here we will consider another mechanism of wave-energy dissipation caused by secondary electron emission (SEE) from dielectric surface. It can be important, e.g. to maintain surface-wave-produced gas discharges.

2. SURFACE WAVES

This study concerns the behavior of surface wave (SW) of frequency ω with wavenumber k_z, propagating in planar plasma waveguides. The waveguide configuration considered here consists of an inhomogeneous non-isothermal ($T_e >> T_i$, T_e and T_i are the electron and ion temperatures) collisional plasma occupying the half-space $x > 0$ and surrounded by dielectric situated in $x < 0$. The inhomogeneous plasma forms a uniform core of the plasma in $x > d$ and a transition layer of the width d in the region $0 < x < d$ close to the plasma-dielectric interface. In the non-uniform transition layer the plasma density drops rapidly from the uniform value n_0 in the core to some finite value at the plasma-dielectric interface. We will consider the strong plasma-density inhomogeneity, when $d << \kappa_p^{-1}$ or what is equivalent to $|d\varepsilon_p / dx| >> |\kappa_p \varepsilon_p|$. Here $\kappa_p^2 = k_z^2 - k^2\varepsilon_p$ characterizes penetration depths of the wave-fields into plasma; $k = \omega / c$ is the vacuum wavenumber, and c is the speed of light in vacuum. The dielectric permittivities of the mediums are denoted by ε_d. for the dielectric and by $\varepsilon_p = 1 - \omega_p^2 /[\omega(\omega + i\nu)]$ for the plasma. In the expression for plasma permittivity, ω_p and ν are the plasma and electron collision frequencies, respectively.

In such waveguides, SWs are well known to be slow E-waves with the phase velocities V_{ph} less than the speed of light in dielectric [3].

The continuity of the tangential wave-field components at the interfaces $x = 0$ and $x = d$ (expressions for the wave-fields under the above-mentioned condition can be found, e.g. in [3]) yields the well-known results for the wavenumber $k_z(\omega)$:

$$k_z = k\sqrt{\varepsilon_p \varepsilon_d / (\varepsilon_p + \varepsilon_d)} \quad (1)$$

and the damping rate: $\gamma = \gamma_{coll} + \gamma_{res}$, caused by both electron collisions:

$$\frac{\gamma_{col}}{\omega} = \frac{\nu}{2\omega} \frac{\varepsilon_d (1 - \varepsilon_p)}{\varepsilon_p^2 + \varepsilon_d}, \quad (2)$$

and excitation of the Langmuir wave near the resonant point x_0, where $\varepsilon_p(x_0) = 0$:

$$\frac{\gamma_{res}}{\omega} = -\pi\eta k \sqrt{-\frac{\varepsilon_p^2}{\varepsilon_p + \varepsilon_d}} \frac{\varepsilon_p^2 \varepsilon_d^2}{\varepsilon_d^2 - \varepsilon_p^3 - \varepsilon_p \varepsilon_d (1 - \varepsilon_p)}. \quad (3)$$

In (1)-(3), $\varepsilon_p \equiv \varepsilon_p(d)$ is respective value in the region of uniform plasma core; $\eta = P(\varepsilon_p(0))(d\varepsilon_p / dx)^{-1}_{x=x_0}$ with $P(y)$ being the unit step function, equal to 0 for $y < 0$, and 1 for $y \geq 0$.

To mark, in these relations it has been taken into account that the electron collision frequency is less than the wave frequency ($\nu << \omega$), and therefore, with the accuracy of the order of $(\nu / \omega)^0$, $\varepsilon_p = 1 - \omega_p^2 / \omega^2$.

Later we will use the total wave-energy stored up in the plasma and dielectric per unit of the area:

$$W_s = \frac{E_0^2}{16\pi} \sqrt{-\frac{\varepsilon_p + \varepsilon_d}{\varepsilon_d^2}} \frac{\varepsilon_d^2 - \varepsilon_p^3 - \varepsilon_p \varepsilon_d (1 - \varepsilon_p)}{k\varepsilon_p^2} \exp(-2\gamma t),$$

where E_0 being the amplitude value of E_z-field at the plasma-dielectric interface ($x = 0$). According to this expression, the energy of SWs dissipates, that the power transferred to a plasma per unit of the area is equal to $2\gamma W_s$. The part $2\gamma_{coll} W_s$ of this power is liberated to a plasma layer of the width of about the wave-field penetration depth κ_p^{-1} into the plasma. The remaining power $2\gamma_{res} W_s$ is transferred to the Langmuir wave and goes to a narrow resonant layer, the width of which is of the order of $\kappa_p d^2$ [3]. Thus, spatial distribution of the wave-power input to the plasma is determined by factor $\gamma_{coll}/\gamma_{res}$ and contracts, under a low gas-pressure, when $\gamma_{coll}/\gamma_{res} << 1$, to the narrow resonant layer.

To note, both these attenuations (collisional and resonant) are reputed to be most important for SWs. But, among of a variety of dissipative mechanisms, there is another one, whose effect on SWs is surprisingly high and can dominate, under certain conditions, over those of the collisions and resonance. This mechanism is connected with secondary electron emission.

3. SECONDARY ELECTRON EMISSION

First, let us briefly consider main features of the secondary emission. As it is well known [5], when a dielectric surface is bombarded by plasma particles, it is charged negatively, building up that electric field, which brakes plasma electrons and accelerates plasma ions to the surface. At the same time there is a SEE from the dielectric. In dynamic equilibrium, the dielectric potential φ can be found from equation:

$$(1-\sigma_{ee})V_{Te}\exp(e\varphi/T_e)=\sqrt{-4\pi e\varphi/m_i}\,. \tag{4}$$

It should be noted that in (4) the SEE yield σ_{ee} is determined by energy of the incident electrons [6]. Usually, this dependence is characterized by a maximum σ_m, which is attained under the incident electron energy $E_e = E_m$ (for fused silica $\sigma_m \cong 2.1$, $E_m \cong 400$ eV [5]). For low energies, $E_e << E_m$, this dependence is linear. For gas-discharge plasmas, the latter condition is fulfilled inside a wide range of the electron temperature T_e. Therefore we will use a linear approximation of the very beginning of this curve, where it can be represented as the following [5]:

$$\sigma_{ee} = 4\sigma_m E_e / E_m \tag{5}$$

For the Maxwellian distribution of the incident electrons, the mean energy is given by

$$E_e = \frac{T_e}{2}\left(1+\frac{2}{\sqrt{\pi}}\,\frac{\sqrt{-e\varphi/T_e}\,\exp(e\varphi/T_e)}{1-erf\sqrt{-e\varphi/T_e}}\right) \tag{6}$$

with the error function erf.

Solving equation (4) with (5) and (6), one can get the dielectric potential φ and SEE coefficient σ_{ee} as functions of the electron temperature T_e, sort of gas and dielectric characteristics. To mark, the mean velocity V_0, with which secondary electrons arrive at the plasma core, after their acceleration in the electric field of the transition layer, is of the order of the thermal velocity V_{Te}, and, because the SWs considered have phase velocities much more than V_{Te} [3], $V_0/V_{ph} << 1$. This fact will be used later, in the secondary electron motion computation.

4. RESULTS AND DISCUSSION

The secondary electron flux can lead to the significant, especially under a low gas-pressure p, wave attenuation. It is connected with the fact that the wave-fields decrease exponentially deep into the plasma. It leads to acceleration of the secondary electrons in the wave-fields due to the action of ponderomotive force, which pushes them out to the region of weaker fields. Damping rate of this attenuation γ_{see} one can find from the energy balance equation. Introducing the dimensionless wave-field amplitude $\tilde{E}_0 = eE_0k_z/(m_e\omega^2)$ and electron velocity $\tilde{V} = V/V_{ph}$, the normalized damping rate can be written as

$$\frac{\gamma_{see}}{\omega} = -F(\tilde{V}_0,\tilde{E}_0)\sigma_{ee}\,\frac{\exp(e\varphi/T_e)}{\sqrt{2\pi}}\,\frac{V_{Te}}{V_{ph}}\cdot\sqrt{-\frac{\varepsilon_p}{\varepsilon_d}}\,\frac{\varepsilon_p\varepsilon_d(1-\varepsilon_p)}{\varepsilon_d^2-\varepsilon_p^3-\varepsilon_p\varepsilon_d(1-\varepsilon_p)}. \tag{7}$$

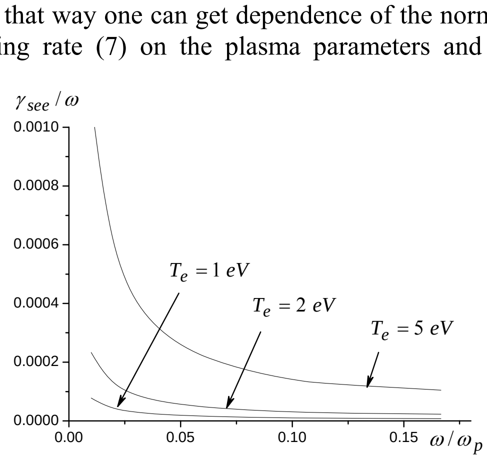
Thus, the total damping rate is $\gamma = \gamma_{coll}+\gamma_{res}+\gamma_{see}$. The parameter $F(\tilde{V}_0,\tilde{E}_0) = <(\tilde{V}^2-\tilde{V}^2)/\tilde{E}_0^2>$ in (7) can be found from the equation of electron motion in the wave-fields:

$$\frac{d\tilde{V}_x}{d\tilde{t}} = -\frac{\tilde{E}_0}{\sqrt{-\tilde{\varepsilon}_p}}[-1+A(\tilde{V}_z+1)]\sin\tilde{z}\exp(-\sqrt{-\tilde{\varepsilon}_p}\,\tilde{x}),$$
$$\frac{d\tilde{V}_z}{d\tilde{t}} = -\tilde{E}_0[\cos\tilde{z} - A\tilde{V}_z\sin\tilde{z}]\exp(-\sqrt{-\tilde{\varepsilon}_p}\,\tilde{x}), \tag{8}$$
$$\frac{d\tilde{x}}{d\tilde{t}} = \tilde{V}_x,\quad \frac{d\tilde{z}}{d\tilde{t}} = \tilde{V}_z,$$

where $\tilde{t} = t\omega$, $\tilde{x} = k_z x$, $\tilde{z} = k_z(z - V_{ph}t)$, $\tilde{V}_x = V_x/V_{ph}$, $\tilde{V}_z = V_z/V_{ph} - 1$, $A = (1+\tilde{\varepsilon}_p)/\sqrt{-\tilde{\varepsilon}_p}$, $\tilde{\varepsilon}_p = \varepsilon_p/\varepsilon_d$.

The system (8) has been solved numerically with the following initial conditions for the secondary electrons: $\tilde{x}_0 = 0$, $\tilde{V}_{0x} << 1$, $\tilde{V}_{0z} = -1$. The initial electron positions $\tilde{z}_0$ has been varied from 0 till 2π. After averaging of the coefficient $(\tilde{V}^2-\tilde{V}^2)/\tilde{E}_0^2$ over the initial positions $\tilde{z}_0$, the parameter $F(\tilde{V}_0,\tilde{E}_0)$ has been calculated. The maximum $\max F(\tilde{V}_0,\tilde{E}_0) \approx 2.0$ is achieved under $\tilde{\varepsilon}_p = -1$ (the quasistatic surface waves), whereas the minimum $\min F(\tilde{V}_0,\tilde{E}_0) \approx 0.5$ is reached under $\tilde{\varepsilon}_p \to -\infty$.

In that way one can get dependence of the normalized damping rate (7) on the plasma parameters and wave-



Dimensionless SEE-induced damping rate frequency (see Figure). The analysis of the dependence reveals, the SEE mechanism of wave-energy dissipation is especially effective for low-frequency SW propagating in dense plasmas with high electron temperature.

Let us compare the SEE-induced damping rate (7) with the resonant one (3). To note, contribution of SEE to the SW attenuation increases with a growth of plasma permittivity (or with a wave-frequency drop). However, in the high-frequency range, where $\varepsilon_p(0) \geq 0$, the resonant attenuation predominates over the SEE-induced damping, that the latter can be neglected.

For the low-frequency waves, when $\varepsilon_p(0) < 0$, the plasma resonance is absent, and wave attenuation is determined by plasma electron collisions and SEE only. Thus, under a low gas-pressure, contribution of SEE to the wave-energy dissipation becomes comparable with that of electron collisions. The numerical estimates carried out for the argon plasma under the gas-pressure $p = 5 mTorr$, electron temperature $T_e \approx 2eV$, plasma density $n_0 \approx 1.7 \cdot 10^{11} cm^{-3}$, and the collision frequency $\nu \approx 2.9 MHz$, reveal that a wave with the frequency $\omega/(2\pi) = 360 MHz$ $(\varepsilon_p = -100)$ damps with the normalized rate $\gamma/\omega = (\gamma_{coll} + \gamma_{see})/\omega = 3.0 \cdot 10^{-5}$. To note, for this conditions the contributions of both mechanisms are equal: $\gamma_{see}/\gamma_{coll} = 1.0$. Investigation of the electron temperature effect on dependence of $(\gamma_{see}/\gamma_{coll})(\nu/\omega_p)$ on the normalized wave-frequency for argon plasma bounded by fused silica has shown that the SEE-induced damping is especially essential for low-frequency SWs with $\omega << \omega_p$.

Below we will apply the results obtained to planar waveguide discharges maintained by SWs. No doubt, this model is too simple to describe surface-wave-produced discharges, but it allows to better understand the processes lying on the basis of this phenomenon.

First of all, SEE from dielectric surface leads to an additional wave-energy dissipation channel and, as a result, to an increase of the wave-power transferred into a plasma. Secondly, besides the main energy source (by surface wave) for discharge maintenance, an additional source (by SEE) arises. The power of surface wave and that of SEE transferred for plasma sustention can be of the same order:

$$\frac{P_{SW}}{P_{SEE}} = \frac{\gamma}{\gamma_{see}} \frac{F(\tilde{V}_0, \tilde{E}_0)\tilde{E}_0^2}{F(\tilde{V}_0, \tilde{E}_0)\tilde{E}_0^2 + 2\tilde{V}_0^2}, \quad (9)$$

especially under a low gas-pressure p of a dense plasma ($\omega_p/\omega >> 1$), when $\gamma \approx \gamma_{see}$. That situation is also typical of near a discharge end, where the wave-field amplitude decreases that $\tilde{E}_0 \leq \tilde{V}_0$. In those discharge regions, plasma is sustained, mainly, by SEE. At the same time, not only amount of the power transferred to a plasma but also its spatial distribution, which determines that of plasma parameters, are relevant. So, in contrast to the surface wave power maintaining plasma in a layer with the width of $\kappa_p^{-1} \approx \sqrt{-\varepsilon_d/\varepsilon_p}\, k_z^{-1} << \lambda$, the SEE can sustain it within a layer of several wavelengths λ.

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ЗАТУХАНИЕ ПОВЕРХНОСТНЫХ ВОЛН ВСЛЕДСТВИЕ ВТОРИЧНОЙ ЭЛЕКТРОННОЙ ЭМИССИИ

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Проведен анализ механизмов поглощения энергии поверхностных волн. Рассмотрены эмиссионные процессы с поверхности диэлектрика, находящегося в контакте с низкотемпературной плазмой. Проведен анализ движения вторичных электронов в поле волны. Показано, что вторичная электронная эмиссия приводит к дополнительному затуханию волны, обусловленному ускорением вторичных электронов в поле волны, вследствие действия силы высокочастотного давления. Проведен анализ влияния вторичной эмиссии на поддержание разряда на поверхностных волнах.

ЗАГАСАННЯ ПОВЕРХНЕВИХ ХВИЛЬ УНАСЛІДОК ВТОРИННОЇ ЕЛЕКТРОННОЇ ЕМІСІЇ

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В роботі проведено аналіз механізмів поглинання енергії поверхневих хвиль. Розглянуто процеси емісії з поверхні діелектрика, що знаходиться у контакті з низькотемпературною плазмою. Проведено аналіз руху вторинних електронів в полі хвилі. Показано, що вторинна електронна емісія приводить до додаткового загасання хвилі, обумовленого прискоренням вторинних електронів в полі хвилі, унаслідок дії сили

високочастотного тиску. Проведено аналіз впливу вторинної емісії на підтримку розряду на поверхневих хвилях.