ELECTRODYNAMICS

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AXIAL SYMMETRIC ELECTROMAGNETIC WAVES ALONG THE DEGENERATE SEMICONDUCTOR SOLID PLASMA CYLINDER IMBEDDED INTO NON-DEGENERATE GASEOUS PLASMA

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The dispersion of the symmetric surface electromagnetic waves propagating along a cylinder of degenerate semiconductor solid plasma embedded in non-degenerate plasma was studied. Both plasmas were assumed homogeneous, isotropic and lossless. It has been calculated the frequencies of eigenwaves, the phase and group velocities. It was found out that these characteristics are higher for more dense surrounding plasma. Wave fields decrease on both sides from the cylindrical boundary between two plasmas. The depth of penetration of the wave fields in surrounding non-degenerate plasma is a few micrometers. The properties of the waves obtained broaden the scope for using degenerate semiconductor plasma in experiments involving interactions with charged particles.

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INTRODUCTION

Intensive research into the potential applications of terahertz waves is currently underway. The terahertz electromagnetic surface waves described here can be used in control and acceleration of charged particle motion, subwavelength electromagnetic field confinement, the processes of signal transmission/processing, wireless communications, spectroscopy and so on [1, 2].

One of such research is the study of the use of degenerate semiconductor solid plasmas for their interaction with charged particle and generating electromagnetic oscillations and waves [3].

Degenerate semiconductors are semiconductors that have a high concentration of the impurities. This results in a narrow band-gap between the conduction band and the valence one [4, 5].

The main aim of this paper is: to derive the dispersion equation for the electromagnetic slow surface eigenmodes of degenerate semiconductor solid plasma right cylinder imbedded in non-degenerate plasma and to study the properties of these waves at different values of the structure parameters.

1. STATE OF PROBLEM

We consider the cylinder of radius $r < R_C$ consist of the degenerate semiconductor plasma. It is surround by the non-degenerate plasma that occupies unbounded region $r > R_C$. Let's introduce a cylindrical coordinate system (z, r, ϕ). The Z-axis coincides with the axis of the cylinder.

We will assume that both plasmas are homogeneous, isotropic, lossless and the magnetic permeability of these plasmas are $\mu_{S/C} = \mu_P = 1$.

As known, the permittivity for cold non-magnetized collisionless homogeneous degenerate semiconductor plasma can be written in the form [4]:

$$\varepsilon_{S/C}(\omega, k_Z) = 1 - \frac{3}{2}\frac{\omega_L^2}{\omega^2}\left[\left(\frac{\omega}{k_Z V_F}\right)^2 - 1\right] \times \left\{1 - \frac{1}{2}\left(\frac{\omega}{k_Z V_F}\right) Log\left[\frac{\omega + k_Z V_F}{\omega - k_Z V_F}\right]\right\} \quad (1)$$

and the permittivity of non-degenerate plasma has well-known form:

$$\varepsilon_P(\omega) = 1 - \omega_P^2 / \omega^2 . \quad (2)$$

Here ω, k_Z – wave frequency and wave number; ω_P is the Langmuir frequency of non-degenerate plasma, and ω_L is the Langmuir frequency of degenerate semiconductor plasma, typically $\omega_L \approx 10^{13}...5\cdot 10^{15}\, s^{-1}$. For our calculation we choose Gallium Arsenide ($\omega_L = 10^{14}\, s^{-1}$) with the Fermi energy $E_F = 1.42\, eV$ and Fermi velocity $V_F = \sqrt{2E_F / m^*} \approx 0.023c$, c – the speed of light in vacuum; $m^* = 0.067 m_e$ – the effective mass for Gallium Arsenide, m_e – the free electron rest mass.

Let us consider the symmetric surface electromagnetic eigenwave that propagates along this structure. Let's to look for the source-free solutions of the Maxwell equations [5]. The term 'symmetric' here means that the wave fields do not depend on the polar angle ϕ.

The functional dependence of the TM-wave components $\{E_Z, E_R, H_\phi\}$ on time *t* and coordinates *r,z* is expressed by the following form:

$$E_{1,2}, H_{1,2} \propto E_{1,2}(r), H_{1,2}(r) \bullet \theta(z,t) . \quad (3)$$

Here indexes 1,2 imply degenerate semiconductor and non-degenerate plasmas, respectively, and space-time factor in the form $\theta(z,t) = \exp[i(k_Z z - \omega t)]$.

In the degenerate semiconductor plasma cylinder of radius $r < R_C$ the components of *TM*-wave have such form [6]:

$$E_{Z,1}(z,r,t) = a_1 I_0(ur)\cdot\theta(z,t),$$
$$E_{R,1}(z,r,t) = -a_1 \frac{\mathrm{i}k_Z}{u} I_1(ur)\cdot\theta(z,t), \quad (4)$$
$$H_{\phi,1}(z,r,t) = -a_1 \frac{\mathrm{i}\varepsilon_{S/C}(\omega,k_Z)k}{u} I_1(ur)\cdot\theta(z,t).$$

Here $u = \sqrt{k_Z^2 - k^2\varepsilon_{S/C}(\omega,k_Z)\mu_{S/C}}$, $k = \omega/c$.

Similarly, the field components of *TM*-wave in the region $r > R_C$, occupied by non-degenerate plasma have a form:

$$E_{Z,2}(z,r,t) = a_2 K_0(\nu r)\cdot\theta(z,t),$$
$$E_{R,2}(z,r,t) = a_2 \frac{\mathrm{i}k_Z}{\nu} K_1(\nu r)\cdot\theta(z,t), \quad (5)$$
$$H_{\phi,2}(z,r,t) = a_2 \frac{\mathrm{i}\varepsilon_P(\omega)k}{\nu} K_1(\nu r)\cdot\theta(z,t).$$

Here $\nu = \sqrt{k_Z^2 - k^2\varepsilon_P(\omega)\mu_P}$. In Eqs. (4), (5) functions $I_{0,1}(ur)$ $K_{0,1}(\nu r)$ are the modified Bessel functions.

Satisfying the boundary conditions for tangential wave fields components [6]

$$\{H_\phi\}_{r=R_C} = 0;\ \{E_Z\}_{r=R_C} = 0 \quad (6)$$

give rise to the dispersion equation for the symmetric surface electromagnetic wave of *TM*-polarization [6]:

$$\frac{\varepsilon_{S/C}(\omega,k_Z)}{u}\frac{I_1(uR_C)}{I_0(uR_C)} + \frac{\varepsilon_P(\omega)}{\nu}\frac{K_1(\nu R_C)}{K_0(\nu R_C)} = 0. \quad (7)$$

It should be noted that a similar dispersion equation for the symmetric surface electromagnetic wave *TE*-polarization with components $\{E_\phi, H_Z, H_R,\}$ has no solutions in the considered frequency range.

2. RESULTS

The dispersion properties of surface waves were investigated for two configurations with different Langmuir frequencies ratios of the two plasmas.

We considered complementary relationships between Langmuir frequencies plasmas. For first variant the calculations were performed for seven values of the ratio $\omega_P/\omega_L = 0.0; 0.01; 0.1; 0.2; 0.5; 0.8; 1.0$ and for cylinder of radius $R = R_C\omega_L/c = 20$. Therefore, we study the type of vacuum environment and the plasmas with plasma density $n_P \sim 3\cdot10^{14}...3\cdot10^{18}\,cm^{-3}$ for cylinder radius $R_C = 60\mu m$.

First, let's present the results for the case where the Langmuir frequency of the surrounding plasma is lower then in outer plasma one (Figs. 1–3).

The numerical solutions of the dispersion equation (7) are shown in Fig. 1. We can see that the higher the surrounding non-degenerate plasma density, the higher the frequency of the waves. In addition, the frequency interval of the surface wave existence is noticeably wider for surrounding plasma with less density. Straight dash line is a 'light' line ($\omega = ck$), and curve dash line is a 'vacuum' line ($\omega_P = 0$).

In Fig. 1 the dispersion curves for three ratios $\omega/\omega_L = 0.0; 0.01; 0.1$ are practically coincide.

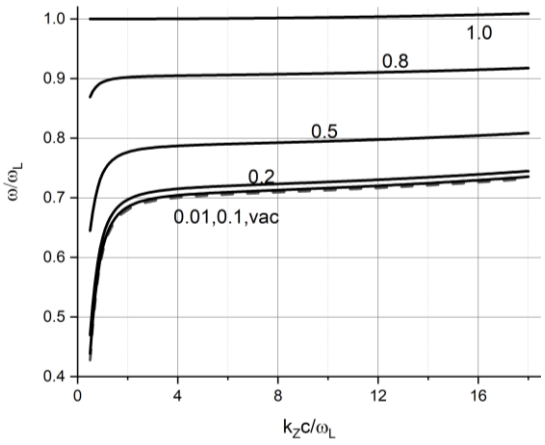


Fig. 1. The dependence of normalized wave frequency on normalized wavevector for different values of ratio $\omega_P/\omega_L = 0.0, 0.01, 0.1, 0.2, 0.5, 0.8, 1.0$

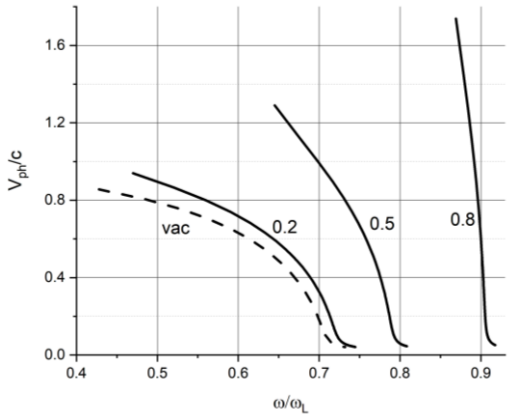


Fig. 2. Normalized phase velocity versus normalized frequency; the numbers on the curves are the same as in Fig. 1

The dependences of the normalized phase and group velocity on normalized frequency are shown in Figs. 2, 3. These waves are forward and slow.

As the frequency of the surface mode increases, the both phase velocity and group velocity approaches zero at the high-frequency edge of the existence range.

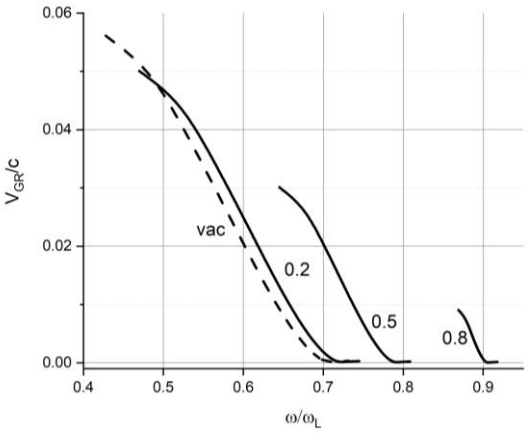


Fig. 3. Normalized group velocity versus normalized frequency; the numbers on the curves are the same as in Fig. 1

In the second set of structural parameters, we assumed that: $R = 10000$ and three values of the ratio

$\omega_P / \omega_L = 2;5;8$. Therefore, we study the surrounding plasma with plasma density $n_p \sim 10^{19}...2 \cdot 10^{20}\, cm^{-3}$ and value of cylinder radius $R_C = 3\, cm$.

Similarly with first variant, wave frequencies are higher for more dense surrounding non-degenerate plasma.

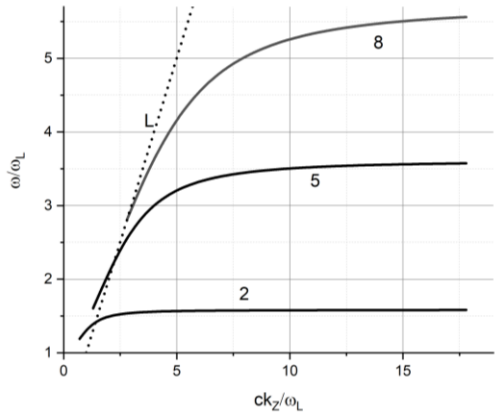


Fig. 4. The dependence of normalized wave frequency on normalized wavevector for different values of ratio $\omega_P / \omega_L = 2,5,8$

But the frequency interval of the surface wave existence is noticeably wider for surrounding plasma with higher density.

So, we have the following relationship: the closer the frequencies of degenerate and non-degenerate plasmas are to each other, the narrower the frequency range in which surface modes exist in a given structure.

These waves are forward and slow too. The dependences of the normalized phase and group velocity on normalized frequency for the second parameter set are shown in Figs. 5, 6.

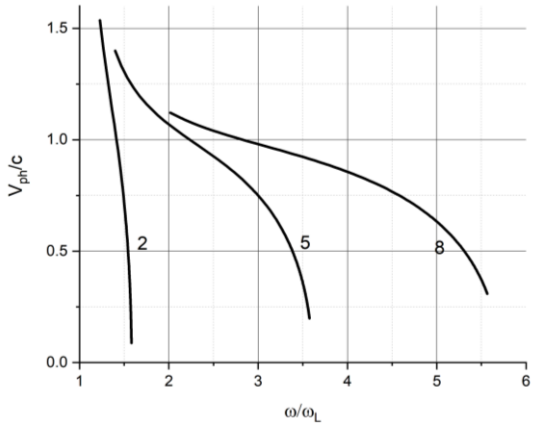


Fig. 5. Normalized phase velocity versus normalized frequency; the numbers on the curves are the same as in Fig. 4

The features of the frequency dependencies of the phase and group velocities is similar to that of the first set of parameters. As the frequency of the eigenmodes increases, the both phase velocity and group velocity decreases. The denser the surrounding plasma, the greater the phase and group velocities.

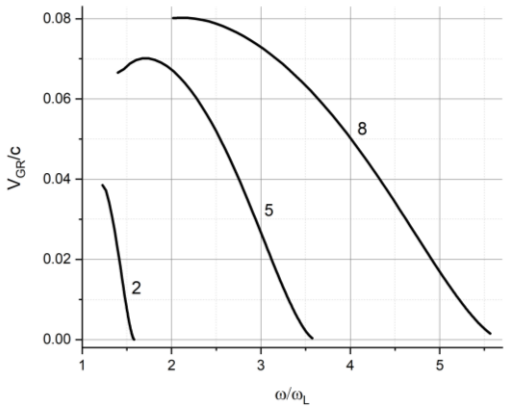


Fig. 6. Normalized group velocity versus normalized frequency; the numbers on the curves are the same as in Fig. 4

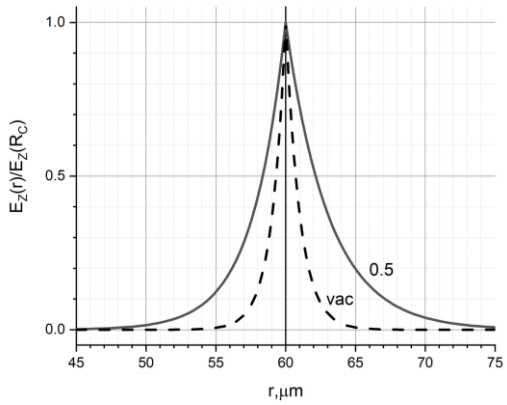


Fig. 7. The radial dependence of a wave fields for cylinder with radius $R_C = 60\mu m$ *; the numbers on the curves are the same as in Fig. 1*

Wave fields strongly decrease on both directions from the cylindrical boundary between two plasmas (Fig. 7). The dash curve corresponds with such parameters ($\omega_P / \omega_L = 0$, $\omega = 0.6949$; $k_Z = 3.0$) and the solid one with another ($\omega_P / \omega_L = 0.5$, $\omega = 0.7486$; $k_Z = 1.1$).

It takes place a high localization of wave field outside near the cylinder. We introduce the skin depths $D = 1/\nu$ to characterize the penetration of wave field into the surrounding plasma.

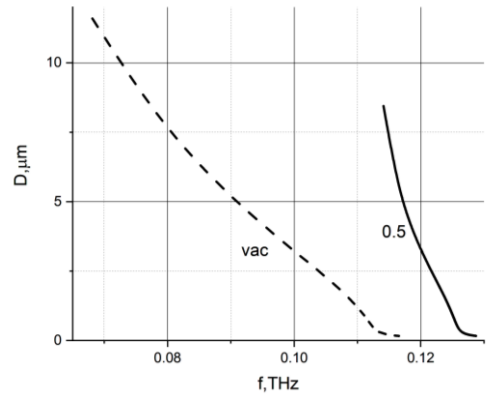


Fig. 8. The dependence of the penetration depth of a wave field into the surrounding plasma versus frequency

Fig. 8 shows the attenuation (in ~1/e times) depth of the wave fields in surrounding plasma for a cylinder radius $R_C = 60\mu m$ both ratio $\omega_P / \omega_L = 0.2$ ($n_p = 1.3 \cdot 10^{17} cm^{-3}$) and $\omega_P / \omega_L = 0$. This depth is about three orders of magnitude less in comparison with the vacuum wavelength.

CONCLUSIONS

In the present research it was found that the TM symmetric surface electromagnetic wave can propagate along the cylinder of degenerate semiconductor plasma imbedded in non-degenerate plasma.

We found out that: the considered surface waves can propagate if the Langmuir frequency of degenerate semiconductor plasma is as well more and less then the Langmuir frequency of non-degenerate surrounded plasma.

These waves are slow and forward (i.e., the directions of phase velocity and group velocity are coincides).

The frequencies of these eigenwaves, its phase and group velocities are higher for higher Langmuir frequency of non-degenerate surrounding plasma.

It has been revealed that: the closer the frequencies of degenerate and non-degenerate plasmas are to each other, the narrower the frequency range in which surface modes exist in a given structure.

The properties of the surface waves discussed here can be utilized in a variety of experiments.

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АКСІАЛЬНО-СИМЕТРИЧНІ ЕЛЕКТРОМАГНІТНІ ХВИЛІ ВЗДОВЖ ЦИЛІНДРА З ВИРОДЖЕНОЇ ТВЕРДОТІЛЬНОЇ ПЛАЗМИ НАПІВПРОВІДНИКА, ВБУДОВАНОГО В НЕВИРОДЖЕНУ ГАЗОВУ ПЛАЗМУ

В.К. Галайдич

Було досліджено дисперсійні властивості симетричних поверхневих електромагнітних хвиль, що поширюються вздовж циліндра з виродженої напівпровідникової плазми, зануреного у невироджену плазму. Обидві плазми вважалися однорідними, ізотропними та безвтратними. Визначено частоти власних хвиль, фазові та групові швидкості. Встановлено, що ці характеристики є вищими для більш щільної навколишньої плазми. Хвильові поля різко зменшуються по обидва боки від циліндричної межі між двох плазм. Глибина проникнення хвильових полів у невироджену плазму становить кілька мікрометрів. Отримані властивості хвиль збільшують можливості використання виродженої плазми напівпровідників у експериментах по взаємодії з зарядженими частинками.