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SLOW SURFACE ELECTROMAGNETIC WAVES AT THE FLAT BOUNDARY "METAL PLASMA / SEMICONDUCTOR PLASMA"

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The properties of surface electromagnetic waves propagating along a planar interface between nondegenerate metal plasma and degenerate semiconductor plasma are studied. Both media were assumed isotropic and lossless. The frequencies of eigenwave, the phase and group velocities are higher for more dense metal plasma. The depth of penetration of the wave fields is much less for metal than for semiconductor.

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INTRODUCTION

In recent years the progress in investigation and application of terahertz wave range take place [1, 2]. One of the promising areas of research is the study of the possibilities of degenerate semiconductors plasmas for generating electromagnetic oscillations and waves and their interaction with charged particle.

The degenerate semiconductors are semiconductors with a high concentration of impurities that cause a narrow gap between the conduction band and the valence band [3, 4].

The main goals are: to derive the dispersion equation for the electromagnetic slow surface eigenmodes of a flat boundary between degenerate semiconductor plasma and nondegenerate metal plasma and to study the properties of these waves at different values of the structure parameters.

1. STATE OF PROBLEM

In our study it was considered the flat interface (YOZ) dividing a half-space of metal plasma $x > 0$ and half-space of degenerate semiconductor plasma $x < 0$. Let's assume the magnetic permeability of these plasmas are $\mu_P = \mu_{S/C} = 1$. The permittivity of metal plasma has well-known form:

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

and the permittivity for a cold collisionless nonmagnetized homogeneous degenerate semiconductor plasma can be written as [4]:

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

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

Calculations were performed for three values of the ratio $\omega_P / \omega_L = 5, 8, 10$. Therefore, we study the metal plasmas with plasma density $n_p \sim 10^{20}\,\mathrm{cm}^{-3}$.

Let us consider the slow surface electromagnetic eigenwave that propagates along this structure. Here the "slow" imply the phase velocity of wave is less then light speed in vacuum.

Let's to look for the solutions of the Maxwell equations [5]. It was assumed that the wave disturbances exponentially tend to zero far away from the separating boundary.

The functional dependence of the wave components on time *t* and coordinates *x* and *z* is expressed by the following form:

$$E, H \propto E(x), H(x) \exp[-\kappa_{1,2}|x|] \bullet \exp[i(k_Z z - \omega t)] . \quad (3)$$

Here $\kappa_{1,2} = \sqrt{k_Z^2 - \varepsilon_{1,2}(\omega)\mu_{1,2}(\omega) k^2}$, $k = \omega / c$, and indexes 1, 2 imply metal and degenerate semiconductor plasmas, respectively.

Satisfying the boundary conditions for tangential wave fields components [4]

$$\{H_Y\}_{x=0} = 0; \ \{E_Z\}_{x=0} = 0 \quad (4)$$

give rise to the dispersion equation for the surface electromagnetic wave of *TM*-polarisation [5]

$$\left(\frac{\omega}{c}\right)\sqrt{\frac{\varepsilon_P(\omega)\cdot\varepsilon_{S/C}(\omega, k_Z)}{\varepsilon_P(\omega) + \varepsilon_{S/C}(\omega, k_Z)}} = k_Z . \quad (5)$$

Because we neglect losses, then for the real values of the wave frequency and wave vector, it requires the condition

$$\mathrm{Im}(\varepsilon_{S/C}(\omega, k_Z)) = 0 , \quad (6)$$

and the dispersion equation (5) transforms into the simplified form

$$\left(\frac{\omega}{c}\right)\sqrt{\frac{\varepsilon_P(\omega)\cdot \mathrm{Re}(\varepsilon_{S/C}(\omega, k_Z))}{\varepsilon_P(\omega) + \mathrm{Re}(\varepsilon_{S/C}(\omega, k_Z))}} = k_Z . \quad (7)$$

In the metal plasma region $x > 0$ the components of *TM*-wave have such form:

$$H_y(x) = e^{-\kappa_1 x} H_y(0),$$
$$E_x(x) = \frac{e^{-\kappa_1 x} k_3 H_y(0)}{\varepsilon_P(\omega) k}, \qquad (8)$$
$$E_z(x) = \frac{-ie^{-\kappa_1 x} \kappa_1 H_y(0)}{\varepsilon_P(\omega) k}.$$

Similarly, the wave field components of *TM*-wave in the region $x < 0$, occupied by degenerate semiconductor plasma have a form:

$$H_y(x) = e^{\kappa_2 x} H_y(0),$$
$$E_x(x) = \frac{e^{\kappa_2 x} k_3 H_y(0)}{\varepsilon_{S/C}(\omega, k_z) k}, \qquad (9)$$
$$E_z(x) = \frac{ie^{\kappa_2 x} \kappa_2 H_y(0)}{\varepsilon_{S/C}(\omega, k_z) k}.$$

2. RESULTS

The main result is: the considered surface waves can propagate if density of metal plasma is high enough. Minimal value of the Langmuir frequency of metal plasma must be larger than value of Langmuir frequency of degenerate semiconductor plasma. For our concrete choice of semiconductor material (GaAs) the minimal ratio is $\omega_P / \omega_L \approx 4.5$ approximately.

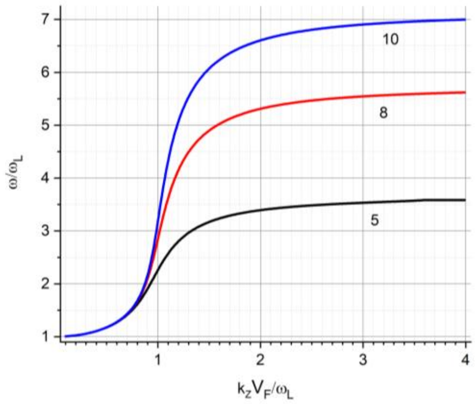

Fig. 1. The dependence of normalized wave frequency on normalized wavevector for different values of ratio $\omega_P / \omega_L = 5, 8, 10$

The results of numerical root findings of the dispersion equation (7) are shown in Fig. 1.

It can be seen that wave frequencies are higher for more dense metal plasma. In addition, the frequency interval of the surface waves existence is noticeably wider for a denser metal plasma.

The dependences of the normalized phase and group velocity on normalized frequency are shown in Figs. 2 and 3.

The phase velocity of considered surface modes as well as group velocity are higher for more dense metal plasma. But at the lower edge of the frequency range of existence, these velocities are the same for different values of the metal plasma concentration.

The extremum points on curves in Fig. 2 are corresponded with the inflection points on curves in Fig. 3 for group velocity.

These waves are forward and slow. For our concrete semiconductor (GaAs) the value of phase velocity is $0.023 \le V_{Ph} / c \le 0.23$.

The group velocity reaches a maximum in the middle of the frequency intervals of existence.

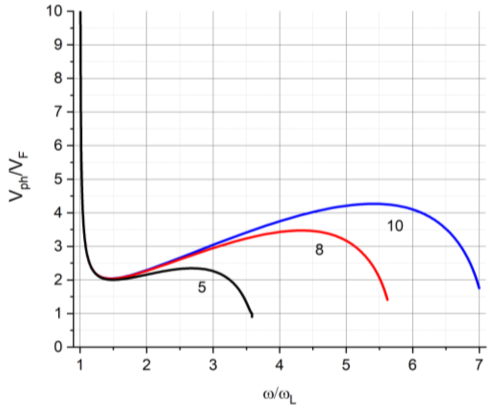

Fig. 2. Normalized phase velocity versus normalized frequency; the numbers on the curves are the same as in Fig. 1

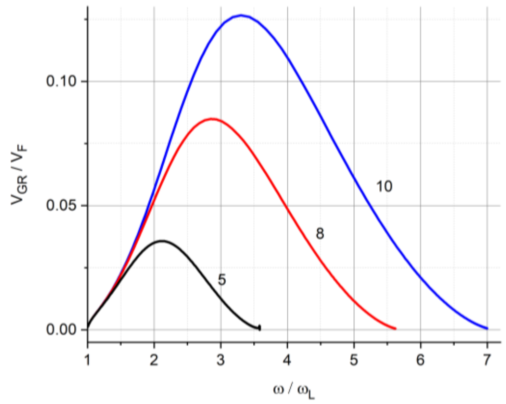

Fig. 3. Normalized group velocity versus normalized frequency; the numbers on the curves are the same as in Fig. 1

At the edges of the frequency range of wave existence the group wave speed tends to zero. This property can be used for wave energy storage.

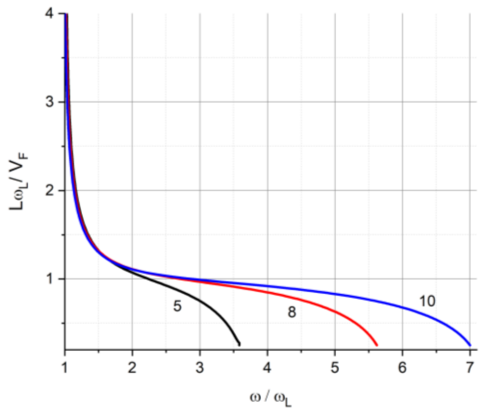

Fig. 4. Normalized skin depths versus normalized frequency; the numbers on the curves are the same as in Fig. 1

Let's introduce the skin depths $L = 1/|\kappa_1|$ to characterize the penetration of wave field into the metal plasma. Fig. 4 shows the attenuation (in e times) depths of the wave fields into the metal plasma for three different values of ratio of Langmuir frequencies $\omega_P / \omega_L = 5, 8, 10$. The penetration depths decrease with the wave frequency increasing.

Unexpectedly, but the range within which the depth of field penetration into a metal varies is almost independent of the metal plasma concentration.

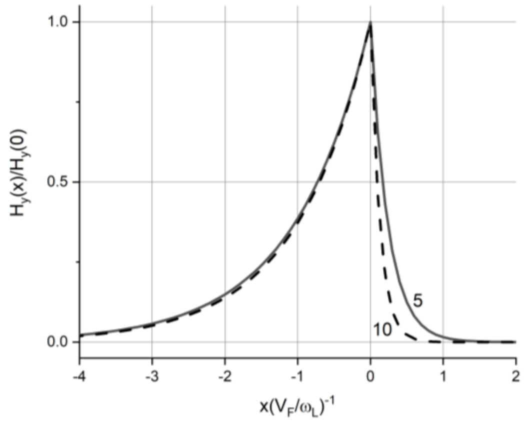

Fig. 5. Distributions of the magnetic wave field versus normalized normal coordinate; the numbers on the curves are the same as in Fig. 1

The penetration of the wave field into the metal is much weaker than the penetration into the semiconductor (Fig. 5). The character of the wave field distribution almost does not change for different points of the dispersion curve.

CONCLUSIONS

In the present research, it was found that the surface electromagnetic wave can propagate along the flat separating boundary between metal plasma and degenerate semiconductor plasma. The frequency intervals of the considered surface waves existence are more wide for a more dense metal 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 more value of metal plasma density.

The properties of these waves give hope that these waves can be used for generating terahertz electromagnetic waves and their control and acceleration of charged particle.

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ПОВІЛЬНІ ПОВЕРХНЕВІ ЕЛЕКТРОМАГНІТНІ ХВИЛІ НА ПЛОСКІЙ МЕЖІ «ПЛАЗМА МЕТАЛУ / НАПІВПРОВІДНИКОВА ПЛАЗМА»

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Досліджено властивості поверхневих електромагнітних хвиль, що поширюються вздовж плоскої межі розділу між плазмою металу та виродженою напівпровідниковою плазмою. Обидва середовища вважались бездисипативними та ізотропними. Виведено дисперсійні рівняння для власних мод такої хвилеводної структури та отримано його розв'язки. Частоти власних хвиль, фазові та групові швидкості вищі для більш густої плазми металу. Діапазон, у якому змінюється глибина проникнення полів цих поверхневих хвиль у металеву плазму, не залежить від густини цієї плазми. Глибина проникнення полів хвилі помітно менша до металу, аніж до напівпровідника. Отримані властивості хвиль відкривають можливості використання виродженої плазми напівпровідників для генерації електромагнітних коливань та хвиль та їх взаємодії із зарядженими частинками.